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Risk Assessment of Future Human Intrusions into Deep Geological Repositories for Radioactive Wastes

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주 희 재

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이 논문을 공학박사 학위논문으로 제출함

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Abstract

Risk Assessment of Future Human Intrusions into Deep Geological Repositories for Radioactive Wastes

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Disposing of spent nuclear fuels into geological repository inevitably involves long-term safety and safeguards problem. Future human intrusion, the risk given by future human action on a radioactive waste repository, is the most troublesome issue because of its severe negative consequence on the public safety and the nuclear security. Aggregating the uncertainty and risk originated by future human intrusion needs to account for the complexity of various conceivable circumstances with the long-term evolution of society or technology. This study tries to suggest a new assessment approach to properly incorporate the risk and uncertainty originated from future human intrusion into geological repository. Two human intrusion cases are concerned: inadvertent (impact on long-term safety) and clandestine (impact on nuclear security and safeguards) human intrusion.

Inadvertent human intrusion addresses a situation of human activity causing direct release of radionuclides from a repository to human environment with no intention to intrude repository. Therefore, the inadvertent human

intrusion may undermine long-term safety of a repository. In case of a repository for high-level wastes or spent nuclear fuels, an occurrence of inadvertent human intrusion event in future can cause serious radiological exposure to people nearby a repository. The regulatory process has tried to minimize the risk of inadvertent human intrusion with conservative estimations of the probability of future inadvertent human intrusion is very significant. However, uncertainties in inadvertent human intrusion scenario has been controversial issue due to not only lack of historic experiences on underground technologies but also absence of appropriate assessment approach, especially in countries with high population densities. Consequently, the literatures in past has assumed a time independent drilling frequency typical of today for assessing the risk of inadvertent human intrusion.

Moreover, recent trend on deep drilling practice shows that both drilling frequency and speed have been increasing. To make long-term prediction, a systematic Monte Carlo model has been developed in this thesis. The new assessment approach is consisted of three different methodologies to properly account effects of both technological and societal factors on an integrated treatment as follows. First, system dynamics is applied to facilitate the consideration for the dynamic behavior and the feedback mechanism of key factors which affect an occurrence of inadvertent human intrusion event. Second, Markov chain analysis is applied to incorporate a change of spatial condition of land encompassing a repository which affect the inadvertent human intrusion frequency. Finally, Monte Carlo simulation technique is introduced so that the results can be statistically analyzed. As a result, the model is capable of demonstrating the dynamic behavior of a drilling frequency in the future.

Such new approach is very useful because it helps improve our understanding the behavior of various uncertainties in inadvertent human intrusion system. First, it facilitates qualitative prediction on the risk of inadvertent human intrusion thereby making selection of significant uncertainties be possible. Second, the effect of various societal, technical, and design factors can be quantitatively assessed. Accordingly, the results from the model can aid decision on design of a repository as well as SNF management policy.

Results on inadvertent human intrusion model from this thesis show that the probability of inadvertent human intrusion would possibly increase up to about 10 times that of currently expected. This implies that the past studies may have underestimated the risk. Because the current model considers drilling only for groundwater, temporal increase in demand for other underground resources would cause increase in the risk of inadvertent human intrusion. In such context, conservative results should be used for estimation of the risk of inadvertent human intrusion. The conservative estimation results of the model imply that a geological repository having similar design with the hypothetical repository will be vulnerable to deep groundwater development in the future. Accordingly, the risk of inadvertent human intrusion of a repository for high-level waste for spent nuclear fuels is estimated to exceed the regulatory criteria of ROK. Therefore, careful design and policy approaches are required to reduce the risk of inadvertent human intrusion.

Clandestine human intrusion at repositories has been postulated as covert operations for recovering of significant nuclear material such as plutonium. Recently, this issue led to international consensus that long-term safeguards of a repository is unavoidable. Since significant amount of plutonium will remain as reactor grade over 10,000 years in one disposal canister for spent nuclear fuels, safeguards measures should be continued to prevent unauthorized recovery of plutonium. However, earlier investigations provided little information on the relationship between safeguards efforts and attempts of clandestine intrusion thereby provoking disagreement on significance of safeguards program for a geological repository during post-closure period. The lack of understanding on such long-term safeguards problem would cause confusion in determination of SNF management policy.

In this thesis, the relationship between safeguards efforts by safeguards agent and desirability of clandestine intruder is explained by a qualitative system analysis model and a quantitative assessment approach is suggested by game theory model. The basic assumption of the developed approach is that the decision of malicious actors would be determined by cost and benefit of their strategies. Key parameters constituting safeguards program for a closed repository are incorporated in the plutonium mine game model so that a decision maker quantitatively considers various factors regarding that problem.

Results of the basic clandestine human intrusion model developed in this thesis imply that safeguards cost can be excessively high for preventing unauthorized attempts to recovery plutonium. Such expenditure would be expected to last until about 70,000 years after repository closure unless the value of plutonium becomes worthless. Although further studies are required to facilitate the application of the model to a real repository, such results show that the overall comparison of safeguards cost between various nuclear fuel cycles needs to be reassessed considering safeguards program for a closed repository.

Based on the results of this dissertation, recommendations are made to reduce the safety risk of inadvertent human intrusion and the safeguards cost of clandestine human intrusion. In viewpoint of repository design, three approach will be effective for human intrusion problem. The first suggestion on the design of repository is a double-layered repository concept that places an intermediated level waste repository above SNF repository. The design will keep hazard recognition for inadvertent intruders. The second possible design suggestion is a deep vertical borehole repository concept or a deep horizontal repository concept that will not only reduce the probability of inadvertent human intrusion but also reduce the motivation for clandestine intruder. The last design suggestion is a deployment of artificial boulder layer above a disposal tunnel to physically deter a drilling operation.

More fundamental recommendations have been made in viewpoint of spent nuclear fuels management policy. The first is the reduction of radiotoxicity of spent nuclear fuel by partitioning and transmutation of transuranic elements including plutonium to intrinsically reduce the risk of human intrusions into a geological repository. In all cases, it is recommended to establish the reversibility and retrievability policy to a repository project to facilitate a flexibility in decision making for disposal programs considering any change in information and conditions that potentially affect the prior decision on radioactive waste management. The last policy suggestion is a multinational cooperation approach for a radioactive wastes repository to assure long-term restriction on repository site by multiple countries for both safety and safeguards over long period of time.

Keywords
Human intrusion
Spent nuclear fuel
Radioactive waste
Deep geological repository
Risk assessment
Systematic model
Plutonium mine
Nuclear safeguards

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Chapter 1 Introduction

1.1 Background

Today, nuclear energy is one of our essential energy resources for not only the prosperity of humankind but also protection of environment. Utilization of nuclear energy, however, has produced a significant amount of spent nuclear fuel (SNF) containing an immense quantity of long-lived radionuclides. A release of these radionuclides to a biosphere causes severe and irreversible radiological impact on both human and ecosystem. In addition, some of radionuclides such as fissile plutonium and uranium have potential to be utilized for diversion to nuclear explosive. Accordingly, reliable protection system is required to minimize the safety and the security risk originating from radionuclides contained in SNF. Currently, a permanent disposing of SNF or high lever waste (HLW) from reprocessing of SNF in a deep geological repository has been considered as a primary option for SNF problem.

A disposal system for SNF or HLW should assure its performance over 10,000 years with high reliability owing to long half-lives of significant radionuclides. No successful project with such that long timeframe has existed in human history yet. Consequently, an existence of various problematic uncertainties throughout the performance assessment process is inevitable. To minimize the risk originating from that problem, all conceivable uncertainties in performance assessment should be quantified in reasonable manners. Most studies in past have mainly concentrated on the uncertainties regarding a migration scenario[1] of radionuclides whereas less studies have concerned with the uncertainties regarding human actions in future. However, history shows that a failure of engineered system is largely dependent on an error induced by human. That implies that a deficient consideration on the uncertainty in future human action for a repository may cause an unjustifiable burden to future. Not to handover the burden originating from a present society to a future generation, more careful approach is required for quantifying the risk of future human action on a repository. This chapter highlights the outline of the problem of a future human action on a SNF or HLW repository, including gap in a perception of the problem, significance, and objective.

1.2 A geological repository and human intrusion

The role of a geological repository is isolation of long-lived radionuclides from human access for the purpose of safety and security over a million years. In general, multiple physical barriers are designed in compliance with a defense-in-depth approach to assure high reliability for an isolation system. The multiple barrier system of a geological repository is expected to be effective to deter and to mitigate a migration of radionuclides by groundwater (Arnold et al., 2003; De Marsily et al., 1977; De Windt et al., 2004; Higgo, 1987; Hwang

[1] A migration scenario refers the scenarios of radionuclides release through various possible groundwater flow under normal or anticipated condition of a geological repository surroundings. natual process? (IAEA term)

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). However, a future human activity with underground development will potentially negate the multiple physical barriers and produce accessible pathway to an isolated waste. The scenario regarding such that human activity is human intrusion scenario. Two kinds of human intrusion scenario can be categorized according by its motivation: inadvertent and intentional. Inadvertent human intrusion indicates a situation of human activity causing direct release of radionuclides in a repository to human environment with no intention to intrude repository. Therefore, inadvertent human intrusion regards with long-term safety of a repository. On the other hand, intentional (or clandestine) human intrusion indicates a situation of intentional illicit intrusion to a repository for recovering of significant nuclear material such as plutonium. Thus, intentional human intrusion regards with nuclear security of a repository. This section describes the concerns for human intrusion problem in view of long-term safety and security of a geological repository.

1.2.1 Inadvertent human intrusion and the long-term safety of a geological repository

An occurrence of inadvertent human intrusion event in future can cause serious radiological exposure to people nearby a repository. Since that reason, international organizations including International Atomic Energy Agency (IAEA) and International Commission on Radiological Protection (ICRP) have concerned inadvertent human intrusion into a geological repository (IAEA, 2012; ICRP, 2000). In particular, the problem of inadvertent human intrusion is much significant in a country with high population density. Accordingly, most countries with high population density try to reduce a radiotoxicity of SNF by recycling rather than directly dispose of SNF in geological repository as shown in Figure 1.1 [ref]. Nevertheless, the probability of inadvertent human intrusion for a recycling waste should still be very small to comply with the safety criteria (Figure 1.2). Therefore, to minimize the uncertainty originating from long-term management project of SNF, it is critical to reduce the probability as low as possible and a methodology to reasonably assess the probability should be required.

A deep geological repository itself is expected to reduce the probability of inadvertent human intrusion. In this case, 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 an inadvertent 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 inadvertent human intrusion for a geological repository 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. Two representative cases showing change in drilling activity over time are depicted in Figure 1.3. Specifically, deep exploratory and exploitative 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). Currently, the human intrusion frequency in WIPP is estimated to be about 1.5 times higher than the first estimated value in 1996. Accordingly, it became necessary to reassess the WIPP 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). In practice, the drilling frequency of groundwater well with a depth deeper than 160m has been increasing. Currently, the observed frequency of deep groundwater well drilling is about 10 times higher than the one observed in early 1970s (Ministry of Land Infrastructure and Transport, 1997-2016). 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, the probability of human intrusion in future will be higher than that of today.

Considering the severe radiological consequences of a human intrusion scenario (Greneche et al., 2008; Smith et al., 2013), the approach for an inadvertent human intrusion in past cannot assure high reliability of a performance assessment. Thus, improved assessment approach is required to quantitatively consider various technological and societal factors affecting an inadvertent human intrusion. Thereby, the uncertainty in long-term safety of a repository originating from future human activity can be minimized.

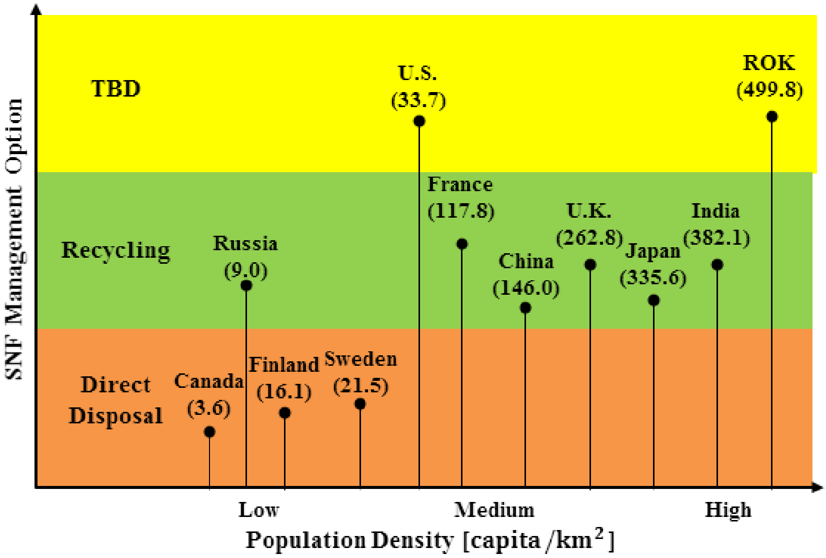

Figure 1.1 The management policy of spent nuclear fuel in various countries with their population density

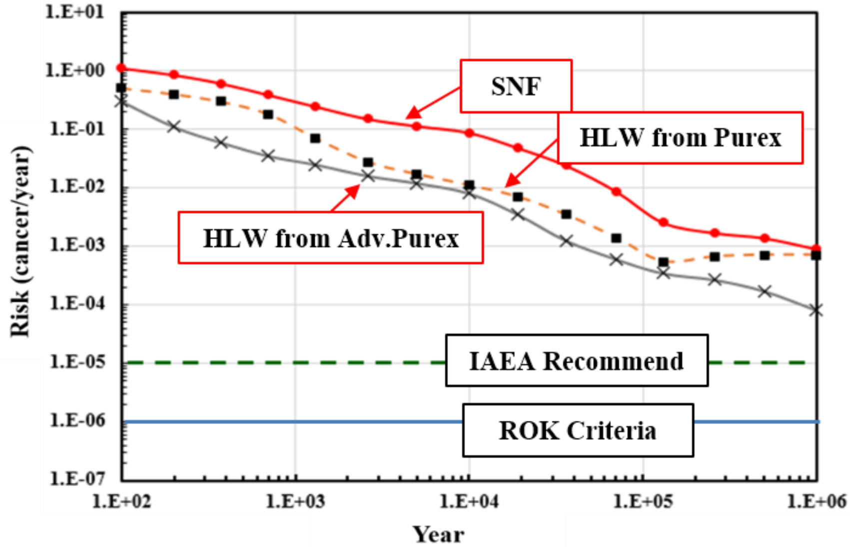

Figure 1.2 The risk of inadvertent human intrusion of SNF and recycling waste when a probability of human intrusion is one

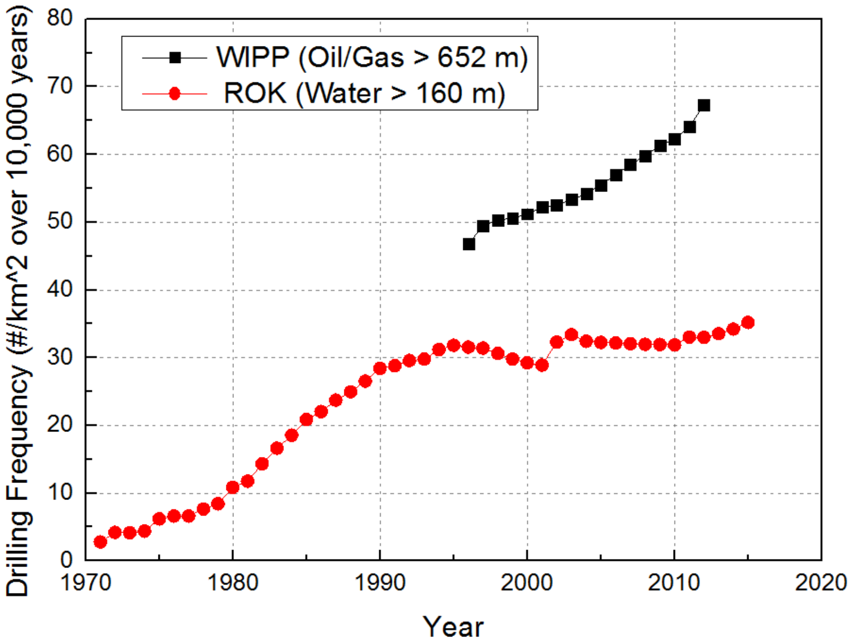

Figure 1.3 Change in drilling frequency of oil/gas well nearby WIPP (DOE, 2007) and groundwater well in ROK (Ministry of Land Infrastructure and Transport, 2016) over time

1.2.2 Clandestine human intrusion and the long-term security of a geological repository

SNF is definitely subject to safeguards[2] due to a significant amount of nuclear materials contained. The objective of international safeguards is timely detection and deterrence of unauthorized activities regarding diversion of such materials from peaceful nuclear activities to the manufacture of nuclear explosives (IAEA, 1972). The key of safeguards program is to verify that the objective materials locate within the destined place by maintaining continuity of knowledge (CoK) about the materials and by applying effective containment and surveillance (C/S) measures. However, the traditional safeguards program to conventional nuclear facilities has been challenged by a deep geological repository. Unlike conventional nuclear facilities, a geological repository is located entirely underground. The only pathway to access the place where SNF is emplaced is access tunnel or shaft. Therefore, a geological repository is never visible entirely so that the traditional safeguards program is not applicable.

The lifetime of a geological repository is divided into construction, operation, decommission, and post-closure period. Fortunately, investigations on and experience of safeguards program before post-closure period of a geological repository have been accumulating (IAEA, 2010; Mongiello et al.,

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[2] In this dissertation, the meaning of safeguards includes the monitoring activity as a part of national physical protection program for nuclear security. In general, the safeguards means a measure by the Agency to deter proliferation attempt of a nation.

2013; Okko and Rautjrävi, 2004, 2006; Saari and Malm, 2015a). However, investigations on safeguards program during post-closure period of a geological repository are very limited and involves potential weaknesses. Clandestine human intrusion is concerned with the safeguards program during the post-closure period of a geological repository.

The reason that the safeguards program is required even after decommission of a repository is due to the utility of SNF. Particularly, plutonium in SNF is classified as Reactor-Grade plutonium (RG-Pu) with an isotopic composition of fissile plutonium isotopes (mainly Pu239) around 60 ~ 80 wt%. The use of RG-Pu is an attractive option for nuclear diversion because this material is expected to be directly used as explosive (IAEA, 2010; Mark et al., 2009; Peterson, 1996; Swahn, 1992). In ROK, two types of SNF exist: SNF from pressurized water reactor (PWR) and from Canada Deuterium Uranium reactor (CANDU). Figure 1.4 shows the isotopic composition of plutonium in SNF from PWR and CANDU. As the figure shows, plutonium in SNF will be usable as RG-Pu until about 10,000 years of cooling time for PWR and 100,000 years of cooling time for CANDU. Considering the design of disposal canister for SNF (Choi et al., 2013), about from 18 kg to 23 kg of plutonium is contained in one disposal canister in early time and the amount gradually decreases over 100,000 years (Figure 1.5). The quantity of RG-Pu required for one nuclear explosive is estimated to be from 4 kg to 8 kg (IAEA, 2010; Swahn, 1992). Therefore, the acquisition of one disposal canister containing SNF will potentially lead to the construction of a few nuclear explosives until about 70,000 years after the closure of a geological repository.

The point of safeguards problem during post-closure period of a geological repository is the termination time of safeguards. Under safeguards agreements between the IAEA and the states, safeguards shall terminate provided that the State and the Agency agree that the nuclear material is '*practicably irrecoverable*' (IAEA, 1972). Whether a disposed SNF emplaced in a geological repository under a depth of around 500 m is practically irrecoverable or not depends on the feasibility, and the potential possibility of a clandestine human intrusion. However, investigations on this issue was very limited thereby the appropriate assessment approach to answer the long-term safeguards problem has not been developed yet.

The problem of long-term safeguards program for a geological repository during post-closure period is significant due to its implications on security, principal objective of a geological repository, and economic cost. Without long-term safeguards for a repository, the risk of nuclear security would be much increased than that of today if the motivation for clandestine human intrusion is sufficient. In this case, long-term safeguards over 10,000 years would be required and continuous economic cost will burden to future generation. Considering that the principal objective of a geological repository is minimization of burden to future originating from SNF generated by current generation, the investigation of that issue is urgent.

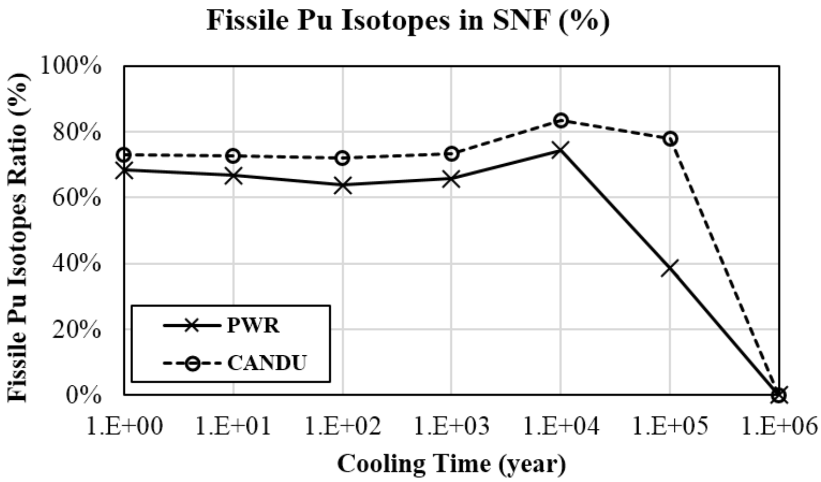

Figure 1.4 Isotopic composition of plutonium in SNF vs Cooling time

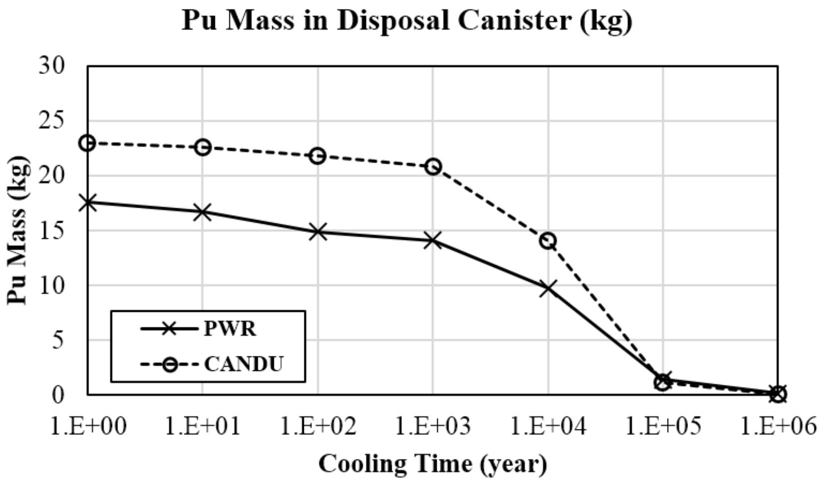

Figure 1.5 Quantity of plutnium in one disposal canister vs Cooling time

1.3 Objective

The main objective of this dissertation is to develop a new assessment approach to minimize the uncertainties in future human action on a geological repository. Specifically, the assessment model for inadvertent and clandestine human intrusion has to be developed to achieve the main objective. The expected results from developed model should be utilizable as not only an important design parameter of a repository but also criteria for decision making of SNF management policy.

The model for an inadvertent human intrusion should properly incorporate various societal and technological factors affecting the potential probability in future. The expected results would be the probabilities with different reliability. In addition, the quantitative effect of various factors would be estimated. Owing to critically long assessment timeframe for a SNF or HLW repository, consideration of all possible scenarios for a future inadvertent human intrusion is inherently not feasible. Thus, the model would be developed based on historic experiences on underground activity and conservative, reasonable assumptions such that the uncertainties are reduced as low as possible.

The model for clandestine human intrusion should quantitatively show the dynamics between the motivation of an intruder and a protection system to detect and deter an intrusion. The expected result of this model would be minimum cost required for an appropriate protection system so that the cost can be considered as a decision making parameter for a modification of repository design or determination of SNF management policy.

Chapter 2 Literature Review

2.1 International recommendation on human intrusion

2.1.1 Safety standards for inadvertent human intrusion

As introduced in the previous chapter, an inadvertent human intrusion is considered as one of safety cases which need to be assessed. In this section, the recommendations by international organizations and national safety criteria of various countries regarding an inadvertent human intrusion are described. Table 2.1 summarizes the national and international safety standards on an inadvertent human intrusion: IAEA, ICRP, Republic of Korea, the United States, the United Kingdom, Canada, and Finland.

Both IAEA and ICRP recommend assessing the consequences of human intrusion into geological repositories by developing stylized scenarios (IAEA, 2012; ICRP, 2000). In its publication 81, ICRP suggested setting a generic reference level for human intrusion at an annual dose of 100 mSv. If the annual dose exceeds this limit, intervention should be justifiable. An intervention is an action to reduce radiation exposure from specific radiation sources. On the other hand, if an annual dose of human intrusion is below 10 mSv, intervention is not likely to be justifiable (ICRP, 2000). Likewise, IAEA adopted an upper limit of 20 mSv and a lower limit of 1 mSv from ICRP publication 103 (ICRP, 2007) for the safety criteria of human intrusion (IAEA, 2012).

When intervention is needed, either the radioactivity of wastes or the likelihood of human intrusion should be reduced to achieve the principle of As Low As Reasonably Achievable (ALARA). Such an activity is defined as “the optimization of protection” (ICRP, 1991). Owing to a very high annual dose of human intrusion into a repository of high-level waste (HLW), most countries require the optimization of protection to maintain the probability or consequences of human intrusion as low as possible.

Accordingly, most countries set an annual risk to human intruder as regulatory criteria instead of an annual exposure dose. It is required that the risk of inadvertent human intrusion is less than 10^{-6} per year in Canada (AECB, 1987), the United Kingdom (NIEA, 2009), and the Republic of Korea (NSSC, 2012). The Finnish Radiation and Nuclear Safety Authority (STUK) recommends that the estimated results must be compared with the annual dose constraint of 0.1 mSv or specific constraints of radioactive release to the environment (STUK, 2013).

In the United States, a normalized cumulative release of radioactive nuclides until 10,000 years after disposal is used to regulatory criteria for probabilistic human intrusion assessment. The Environmental Protection Agency (EPA) specifies the probability to be 10^{-1} for a case of exceeding one times of cumulative release limit and 10^{-3} for a case of exceeding ten times of the limit (EPA, 1985). This requirement is stated in the Code of Federal Regulation (CFR) 40 Part 191.13 for SNF, HLW, and transuranic (TRU) wastes except for the Yucca Mountain. Instead of the risk of a single event at a specific time, the total cumulative risk or the total cumulative environmental impact until the specific time is a basis of regulatory judgement. On the other hand, the other countries use different regulatory approaches to ensure long-term reliability of repository performance. They assess the risk of human intrusion at a specific time rather than the cumulative risk until the specific time.

Table 2.1 Safety standards and criteria for inadvertent human intrusion around the world

Country	Regulatory Criteria	Description
IAEA (IAEA, 2012)	1–20 mSv	For annual dose in the range 1–20 mSv, optimization of facility is required. For annual dose over 20 mSv, alternative options are required such as deep geological repository or separation of the radionuclide content.
ICRP (ICRP, 2000)	10–100 mSv	10 mSv: generic reference level below which intervention is not likely to be justifiable 100 mSv: generic reference level above which intervention should be considered almost always justifiable
Finland (STUK, 2013)	0.1 mSv or release rate constraint	Where possible, unlikely events like human intrusion shall be assessed and compared with the dose constraint or release rate.
U.S (EPA, 1985)	Likelihood of 1/10 for 1 EPA unit Likelihood of $1/10^3$ for 10 EPA unit	EPA unit: normalized cumulative releases of radionuclides
Canada (AECB, 1987)	10^{-6} /yr	Risk shall be reduced though optimization
U.K. (NIEA, 2009)	Risk of 10^{-6}	The developer/operator shall consider the measure to reduce the probability by optimization of the facility design as low as reasonable achievable (ALARA).
ROK (NSSC, 2012)	Risk of 10^{-6}	The risk here indicates fatal cancer and serious genetic effects.

2.1.2 Clandestine human intrusion

In INFCIRC/153 (IAEA, 1972), the Agreement between the IAEA and States required in connection with the treaty of the non-proliferation of nuclear weapon, the IAEA states about the termination time of safeguards in paragraph 11 as follow:

> *'The Agreement should provide that safeguards shall terminate on nuclear material subject to safeguards thereunder upon determination by the Agency that it has been consumed, or has been diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable.'*

Complying with the Agreement, the safeguards on a geological repository for SNF cannot terminate until one of the three conditions in paragraph 11 are met. With regards to the conditions for termination of safeguards, the IAEA states in paragraph 35 that:

> *'The Agreement should provide that safeguards shall terminate on nuclear material subjective to safeguards thereunder under the conditions set forth in paragraph 11 above. Where the conditions of that paragraph are not met, but the State considers that the recovery of safeguarded nuclear material from residues is not for the time being practicable or desirable, the Agency and the State shall consult on the appropriate safeguards measures to be applied.'*

Therefore, to terminate safeguards on a geological repository for SNF the state should convince the IAEA that the recovery of nuclear material from disposed SNF is no longer practical and desirable option.

Unfortunately, a clear definition of the term ‘practicably irrecoverable’ is absent yet (IAEA, 1996). Nevertheless, the IAEA states that a recovery of nuclear material subject to safeguards from a geological repository during post-closure period is feasible by clandestine human intrusion (IAEA, 2010). Accordingly, to terminate safeguards on repository, the state needs to prove that a clandestine human intrusion is not desirable without clear guideline for this issue. This may lead discord between the international agency and the state. In practice, STUK, the radiation and nuclear safety authority in Finland, pointed out the concern for non-termination of safeguards on the geological repository in Finland (Okko et al., 2014).

2.2 Assessment approach for inadvertent human intrusion

2.2.1 Consequence analysis

An inadvertent human intrusion indicates a human action resulting in a direct disturbance of a repository, causing the immediate release of radioactivity (IAEA, 2012). However, the future activities, civilization, and technology of the human race are inevitably unpredictable. Since that reason, we cannot consider all possible human intrusion scenarios. Instead, some representative cases called stylized scenarios (OECD NEA, 1995) based on existing societal and technological experience have been developed with simplified and conservative assumptions to estimate the consequence of an inadvertent human intrusion.

Literatures of radiological consequence estimation of an inadvertent human intrusion are summarized in Table 2.2. The most probable inadvertent human intrusion scenario for a geological repository is deep drilling for resource exploration or exploitation, resulting in radiological exposure to workers or residents. The majority of developed stylized scenarios consider resource exploration including oil/gas and natural mineral as the motivation for an inadvertent human intrusion. In this case, a radiological exposure to drillers and geotechnical workers by drill core was generally assumed (Gierszewski et al., 2004; JNC, 2000; M Kelly and Jackson, 2007; Nordman and Vieno, 1989; Smith et al., 2013). Some studies considered a radiological exposure to site occupiers, owing to contaminated surface ground by drill core (Gierszewski et al., 2004; M Kelly and Jackson, 2007).

In some studies, radiological exposure by utilizing contaminated groundwater though a deep well near a repository was also considered (Hellä et al., 2008; J.A. Keith Reid et al., 1989; Lee and Jeong, 2010; Nordman and Vieno, 1989). However, the stylized scenarios of groundwater utilization in past do not comply with the definition of an inadvertent human intrusion because the considered deep well does not cause a direct disturbance of a repository. Therefore, these scenarios have been excluded in safety assessment of an inadvertent human intrusion.

The radiological dose estimated by various stylized scenarios was expected to be greater than a few sieverts for HLW and SNF with negligible differences (Gierszewski et al., 2004; Greneche et al., 2008; JNC, 2000; Smith et al., 2013). The differences between estimated values are due to different assumptions on drilling technologies as well as the repository site characteristics considered in a stylized scenario. The BIOPROTA, which is an international collaboration project that addresses the key uncertainties in long-term assessments of contaminant releases into the environment arising from radioactive waste disposal, summarized current drilling practices and the radionuclides release mechanism arising from drilling events (Smith et al., 2013).

2.2.2 Probability estimation

The future probability of an inadvertent human intrusion through drilling activities has been estimated on the basis of historical records of regional, and domestic drilling activities. In numerous studies, the drilling frequency, which is critical to the probability of inadvertent human intrusion, was considered as a time independent variable. In addition, a change of the condition nearby a repository over time was not incorporated neither even though it will affect the probability. Accordingly, a time independent probability was applied to the assessment of the risk of inadvertent human intrusion. In other word, an occurrence of inadvertent human intrusion was considered as Poisson process.

The literatures regarding the estimation of probability for inadvertent human intrusion are also listed in Table 2.2. Japan Nuclear Cycle Development

Institute (JNC), Nirex in U.K., and Ontario Power Generation (OPG) in Canada estimated the frequency of inadvertent human intrusion based on historic drilling frequency for resource exploration (mainly for oil/gas). The estimated annual frequency was an order of 10^{-6}~10^{-5} per year and assumed to be time invariant (Bailey and Littleboy, 2000; Gierszewski et al., 2004; JNC, 2000). The U.S. DOE assessed human intrusion into the WIPP as a Poisson process with the constant probability based on historic database of oil/gas exploration, and exploitation (DOE, 2014).

However, a drilling frequency as well as an inadvertent human intrusion frequency are obviously a time-dependent variable influenced by various factors including societal changes, technological evolution, and economic variations. As introduced in Chapter 1, Delaware Basin's monitoring records for oil/gas exploration drilling near the WIPP (DOE, 2007) prove the importance of considering these factors to properly estimate the frequency of inadvertent human intrusion. Accordingly, a few studies tried to incorporate some factors influencing the frequency.

Woo suggested a time-dependent probability model for inadvertent human intrusion that considered the effect of societal factors using Markov chain analysis (Woo, 1989, 1993). Woo's study considered the transfer of knowledge of the repository site and regulation enforcement of the future generation, which mitigates the probability of human intrusion and eventually reduces its risk too. Sumerling et. al. suggested the qualitative Markov chain model showing that the future probability of human intrusion would increase (Sumerling et al., 1995). They argued that the future generation could have stronger motivation to explore resources as historical records of drilling activities keep increasing.

2.2.3 Factors affecting inadvertent human intrusion

2.2.3.1 Factors mitigating inadvertent human intrusion

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 their 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, G. 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).

2.2.3.2 Factors enhancing inadvertent human intrusion

The most critical motivation driving future human intrusion into a deep 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. Moreover, improvements in drilling systems has facilitated faster and cheaper 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.

2.2.4 Gap in literatures of an inadvertent human intrusion

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 U.K. (Bailey and Littleboy, 2000), Posiva in Finland (Neall et al., 2007), JNC in Japan (JNC, 2000), and the Department of Energy in the U.S. (DOE, 2014) have used a time-independent frequency of human intrusion that is only based on the statistics of historical drilling records. However, as mentioned above, the human intrusion frequency changes with time and is affected by various factors. Moreover, the increasing exploration of underground resources discussed in Chapter 1 implies a potential increased human intrusion risk in the future.

Therefore, the approaches developed in past studies lack a scientific basis, resulting in a low acceptability for these models. In addition, quantitative analyses of the factors affecting future human intrusion were limited owing to the absence of the systematic consideration of human activities. In other words, the effectiveness of various repository designs as remedies for human intrusion could not be assured.

Table 2.2. Summary on literatures of an inadvertent human intrusion (cont.)

Literatures	**Motivation**	**Stylized scenario**	**Probability estimation**
Japan, H12 (JNC, 2000)	Resource exploration (oil/gas, metal, geothermal)	▪ Radiological exposure by drill core analysis ▪ Radiological exposure of drilling worker	▪ Time independent drilling frequency ▪ Estimation by oil/gas and mineral exploratory drilling history
U.K., Nirex (M Kelly and Jackson, 2007)	Oil/gas or mineral resource exploration	▪ Radiological exposure by drill core release, contamination of surface soil ▪ Release of radionuclides by groundwater flow through borehole	
U.K., Nirex (Bailey and Littleboy, 2000)	Oil/gas or mineral resource exploration		▪ Time independent drilling frequency ▪ Estimation by regional resource exploration drilling history
Canada (Gierszewski et al., 2004)	Resource exploration	▪ Drill core sample analysis, contaminated drilling mud release ▪ Radiological exposure to core technician, drilling worker, construction worker, and resident	▪ Time independent drilling frequency ▪ Event tree analysis ▪ Estimation by exploratory drilling history
Canada (J.A. Keith Reid et al., 1989)	Groundwater development	▪ Release of radionuclides by use of groundwater	

Literatures	Motivation	Stylized scenario	Probability estimation
U.S. WIPP (DOE, 2014)	Oil/gas exploration and exploitation	▪ Radionuclides release by cutting, caving, spalling, direct brine release, and long-term release following drilling	▪ Poisson process
U.S. WIPP (DOE, 2007)	Oil/gas exploration and exploitation		▪ Poisson process ▪ Time independent drilling frequency ▪ Estimation by oil/gas development drilling history
Finland (Nordman and Vieno, 1989)	Resource exploration Groundwater development	▪ Radiological exposure by drill core ▪ Radiological exposure by drinking of contaminated groundwater	
Sweden (Hellä et al., 2008)	Groundwater development	▪ Release of radionuclides by use of groundwater	
ROK (Lee and Jeong, 2010)	Groundwater development	▪ Release of radionuclides by use of groundwater	
BIOPROTA (Smith et al., 2013)	Resource exploration	▪ Radiological exposure by drill core ▪ Summary of current deep drilling practice ▪ 58 different scenarios depending on the applied drilling types and site conditions	

2.3 Assessment approach for clandestine human intrusion

2.3.1 Feasibility of clandestine human intrusion

Removal of nuclear material from a geological repository during post-closure period by constructing clandestine pathway to the repository tunnel has been considered as a technically feasible diversion scenario (IAEA, 2010). Therefore, studies on this concentrated on investigating a desirability of recovery of nuclear material by clandestine human intrusion to suggest safeguards program for a geological repository during post-closure period. The desirability shall be discussed in viewpoint of detectability and economic feasibility of clandestine human intrusion. The detectability of a clandestine human intrusion is regarded with the required time for intrusion and the detectable physical signal originating from it. The economic feasibility is regarded with the cost of a clandestine intrusion. With the high detectability and the low economic feasibility, recovery of nuclear material from a geological repository by a clandestine human intrusion in future would be undesirable. The summary of literatures for this is in Table 2.3.

The desirability of clandestine human intrusion was first estimated by the International Nuclear Fuel Cycle Evaluation (INFCE, 1979). Two geologic conditions of a repository including salt and granite were considered. For a geological repository in salt, three scenarios for clandestine human intrusion were investigated based on conventional mining techniques: shaft mining, reconstruction of original access tunnel, and solution mining.

In shaft mining scenario, retrieval of one disposal canister through a vertical shaft with a diameter of one meter, and a depth of 600 meters was considered. The time for drilling one shaft was estimated to be four to five weeks based on drilling practice at that time. Conservatively, it was assumed that these drilling time may be decreased by a factor of about two. Although it was assumed that the driller knows the general location of a repository, the study estimated that about ten shaft drilling is required to hit a disposal canister due to inaccuracy in drilling technique. Accordingly, the operation time of shaft mining was suggested to be about two months for recovery of one disposal canister. Therefore, clandestine human intrusion by shaft mining was assessed to be undesirable because the high level of activity makes the intrusion be difficult to conceal.

The INFCE was concerned that intrusion though reopened access tunnel is credible approach to attempt recover a large quantity of nuclear material. In this case, however, a large scale of construction activity is required due to high temperature and radiation of a repository. Accordingly, the operation time was estimated to be 12 to 18 months so that a concealment of such a large, long-term operation would be difficult. Therefore, this scenario was assessed to be undesirable either.

The last potential scenario of INFCE for salt condition, solution mining, is possible only for a repository in salt formation. The scenario considered that a large cavity with about 60 meters of diameter would be constructed in a repository by conventional solution mining technique. The operation time for recovery of 80 to 120 disposal canister by solution mining was estimated to be two to three months. Thus, solution mining was suggested as the most desirable scenario of clandestine human intrusion for a geological repository in salt formation.

The INFCE shortly discussed the potential of clandestine human intrusion for a repository in granite condition. Two scenarios including shaft drilling and reconstruction of original access tunnel were considered.

The operation time of recovery of nuclear material by shaft drilling was estimated to be about four months to one year depending on the number of drilling rigs used. Accordingly, it was assessed that the intrusion activity would be highly visible. In addition, the cost for shaft drilling with a diameter of one meter scenario was estimated to be an order of 25 million dollars. Conversing to the value of today, 25 million dollars in 1979 correspond to about 79 million dollars today. Therefore, this scenario was assessed to be undesirable. For reconstruction scenario, the operation time was estimated to be about 12 to 18 months; the cost was estimated to be 100 million dollars, which correspond to 273 million dollars today. Accordingly, reconstruction scenario was assessed to be undesirable either.

In 1996, Peterson followed up the study of INFCE and reassess the desirability of clandestine human intrusion for a repository in granite condition (Peterson, 1996). He pointed out that the desirability of clandestine human intrusion should be discussed based on the comparison with the cost and the duration of plutonium production by existing nuclear power program. The results were very impressive. First, the cost of plutonium recovery by clandestine human intrusion into a geological repository was much lower than that of plutonium production by dedicated nuclear reactor program (Figure 2.1). The cost of constructing clandestine access tunnel was estimated to 2.5 million to 7.4 million 1992$ with plutonium recovery rate of 700 kg per year while the capital investment of dedicated reactor program was estimated over one billion dollars (1992$) with plutonium production rate of 100 kg per year. Second, the duration of clandestine human intrusion was also estimated to be lower than that of dedicated reactor program. The estimated duration required for dedicated reactor program was 3 to 7 years depending on the capacity of the reactor. On the other hand, duration of tunnel construction was 6 to 44 weeks. He also pointed out that to seismicity signal from operation of tunnel boring machine (TBM) is very low and similar to those from heave street traffic so that the detection of such activity would be difficult. Based on the results, Peterson asserted that the desirability of clandestine human intrusion is significantly high and suggested removal of plutonium from final waste stream to avoid long-term safeguards problem of a geological repository.

On the other hand, Lyman asserted that a geological disposal of SNF will actually reduce the future safeguards burden rather than increase (Lyman and Feiveson, 1998). He pointed out that due to inaccuracy of tunneling operation, 50 tunnels are required to contact with a repository resulting in increased cost for clandestine human intrusion. Accordingly, the probability of detection of such activity was assessed to be high enough that the long-term safeguards effort required for a geological repository will be very small. Therefore, he concluded that the long-term safeguards burden of SNF disposal will be lower than that of partitioning and transmutation facility of SNF.

However, quantitative estimation for long-term safeguards burden did not conducted.

2.3.2 Safeguards measures during post-closure period

Safeguards measures which are applicable to a closed geological repository are very limited due to its unique purpose: assuring the long-term safety without any additional efforts including institutional control. Because all pathways to a repository will be sealed for the purpose of safety, the only possible safeguards approach is to apply indirect measures. During post-closure period, the objective of C/S would be the detection of all activities that may relate to a construction of undeclared pathway to a sealed repository. The IAEA suggested five applicable safeguards measures including satellite imagery, aerial surveillance, inspection, geophysical monitoring, and open source information as potential tools to be deployed (IAEA, 2010). However, detailed methodology of safeguards during post-closure period has not been investigated yet. The safeguards model for the post-closure period has only been developed on a conceptual level based on the potential safeguards tools suggested by the IAEA.

Sandia National Laboratories (SNL) investigated on the status and gap of current safeguards approach for geological repository (Mongiello et al., 2013). The study proposed three safeguards measures which are applicable during post-closure period of a repository including unannounced random visual inspection, satellite and/or aerial monitoring, and seismic monitoring. A satellite surveillance aims to detect optical signal induced from clandestine human intrusion activity. Detection of road construction, digging, or changes of geographical features by overlaying images from different date were suggested as examples. A seismic monitoring system detects a micro-seismic signal induced from blasting and excavation operation for tunnel construction. The study indicated that baseline data are required to identify the source and the location of the suspicious signal. Because verification of SNF emplaced in a sealed repository is impossible, a source from monitoring measures would be the objective of verification by random inspection. However, the study pointed out that the investigation on sensitivity and detection ability of these monitoring measure will be required to be increased.

A possible applicability of micro-seismic monitoring program to a geological repository was discussed by Posiva Oy in 1999 (Saari, 1999). The study investigated design parameter of micro-seismic stations for the observation of excavation induced seismic signal. Six to twelve seismic stations were suggested to observe micro-seismic signal with a magnitude range of over -4 M_L. The actual application of micro-seismic monitoring program to a geological repository has been implemented since February 2002 (Saari and Malm, 2015a; Saari and Malm, 2015b). Currently, total seventeen seismic stations are under operation to observe construction related activity nearby a repository. The monitoring results have shown that excavation related activities have been appropriately located so that sufficiently low potential of undeclared activity has been convinced. The minimum magnitude of observed signal was -3.5 M_L.

Use of satellite imagery as a monitoring measure of safeguards on nuclear facilities has been discussed by various investigator (Andersson, 1999; Pabian, 2015; Zhang, 2001). The IAEA suggested satellite monitoring as an effective decision supporting tool for inspection and also expected cost saving by reduction in on-site inspections (Andersson, 1999). Accordingly, satellite monitoring would be utilized as efficient tool for planning on-site inspections on a closed repository, provided sufficient detection probability. In JRC technical report, European Atomic Energy Community concerned the increased use of countermeasures for such monitoring activity including camouflage concealment, deception against overhead detection, identification, and assessment (Pabian, 2015). With regards to this concern, the study concluded that such efforts for countermeasures are rarely completely successful in case of large conventional nuclear facilities such as underground reactor, or reprocessing plant. However, the detection probability of satellite monitoring on underground repository is still uncertain.

2.3.3 Gap in literatures on clandestine human intrusion

It has been shown that recovery of plutonium from a geological repository by a clandestine human intrusion is technically feasible options for both proliferator and sub-state malicious actor. Therefore, under the safeguards agreement between the IAEA and states, long-term safeguards on a geological repository will be required unless desirability of clandestine human intrusion is sufficiently reduced. As past studies showed, however, assessment tool to quantify the relationship between the desirability of intrusion and efforts required to safeguards a repository has been absent. These two factors have been respectively investigated as shown in Section 2.3.1 and Section 2.3.2. The absence of such tool for long-term safeguards problem on a geological repository has caused confusion in determination of SNF management policy, consequently making disturbance on building consensus. Two conflicting arguments by Peterson and Lyman have representatively shown this confusion (Lyman and Feiveson, 1998; Peterson, 1996).

To fill such gap, the assessment approach in past should be modified to synthetically consider the desirability of intruder and the safeguards effort. Both factors are possible to quantified in a view point of cost/benefit approach. In case of desirability of clandestine intrusion, the cost and the duration of plutonium recovery operation are needed to be reassessed complying with the current technological level. The cost and the detection probability of potential safeguards measures are also required to be estimated based on current technical basis. Such approach would suggest a reference for determining SNF management option that reduces future safeguards burden.

Table 2.3 Summary on literatures of desirability of a clandestine human intrusion into a geological repository in granite condition

Desirability parameter	INFCE (INFCE, 1979)	Peterson (Peterson, 1996)	Lyman (Lyman and Feiveson, 1998)
Cost			
Duration			
Detectability			

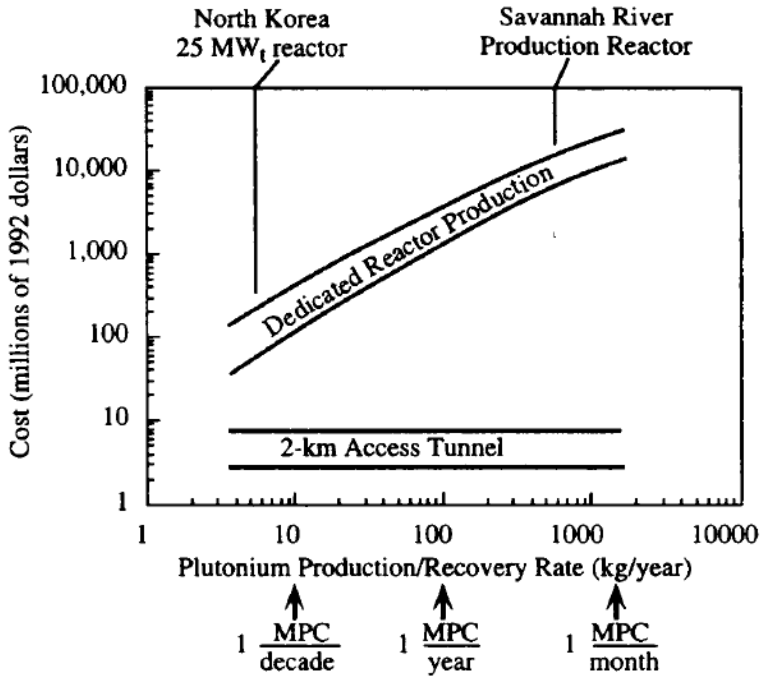

Figure 2.1 Cost comparison between plutonium recovery by clandestine human intrusion and plutonium production by dedicated nuclear reactor program (Peterson, 1996)

Chapter 3 Rationale and Approach

3.1 Rationale

The gaps in the past approach for inadvertent human intrusion are pointed out from the review in Chapter 2 as follow:

(1) system analysis on factors affecting future drilling frequency was deficient;

(2) changes of condition nearby repository over time which may affect an occurrence of inadvertent human intrusion event were not properly incorporated;

(3) consequently, quantitative effect of various design parameters on inadvertent human intrusion cannot be properly discussed.

Such gaps are required to be filled owing to following reasons. First, technology trends on underground development have shown that the drilling frequency will change over time. The drilling frequency is the most critical factor for determining the probability of future inadvertent human intrusion. Although Sumerling suggested that the future drilling frequency may increase owing to increased motivation for resource, his work only relied on qualitative analysis (Sumerling et al., 1995). To suggest reliable quantitative assessment results, statistical analysis on historic underground development database is required.

Second, a drilling activity nearby repository site will be determined by physical and societal conditions of repository changing over time. In addition, an inadvertent human intrusion event will also affect such conditions. Accordingly, consideration of feedback loop between conditions of repository and human intrusion event should be incorporated. Assumption of homogeneous Poisson process for inadvertent human intrusion has missed such gap in the existing approach (Bailey and Littleboy, 2000; DOE, 2014).

Third, quantitative assessment on effectiveness of various design parameters of a geological repository against inadvertent human intrusion is obviously required. Without such tool, reliability of safe repository system will not be satisfied.

In a view point of long-term safeguards problem of a geological repository, the desirability of clandestine human intrusion and safeguards efforts required need to be reassessed. As discussed in Section 2.3.3, the missing gap in past studies existed because comprehensive consideration on these two factor was absent. Consequently, disagreement between two approach with different viewpoint has disturbed to build consensus on this problem. To derive mutual content to the long-term safeguards problem on a geological repository, modified assessment approach would be required.

3.2 Research goals and questions

This dissertation attempts to suggest a new assessment approach for the estimation of risk of future human intrusion in disposing of radioactive waste in geological repository. Its goals are suggesting appropriate design parameters to reduce the uncertainty and the risk induced by human action on a repository and providing tool to support decision making on SNF management policy. To achieve such goals, two research questions related with human intrusion problems have been explored.

The first research question is related with uncertainty in long-term safety of inadvertent human intrusion. As pointed out in previous section, the answer to this question has to consider the two missing gaps: factors affecting the frequency of drilling, potential conditions of repository interacting with inadvertent human intrusion event. The comprehensive consideration for these two gaps shall fill the third gap: lack of quantitative assessment on effectiveness of various design parameter to prevent human intrusion. Therefore, the question is:

> How the probability of future inadvertent human intrusion be adequately predicted with consideration for various time dependent factors and conditions affecting the event?

The second research question is related with long-term safeguards problem of clandestine human intrusion. The gap in the existing studies originates from respective consideration on desirability of intruder and long-term safeguards program. In fact, two factors are intimately related. The answer to the second question has to suggest assessment approach to quantitatively connect these factors. Therefore, the second question is:

How can the termination time and the cost of long-term safeguards on a geological repository be reasonably assessed?

3.3 Research design and approach

3.3.1 Research Design

3.3.2 Approach

In this section overall research approach is described (Figure 3.1). In the first step, this study explored the literatures related with the risk of future human intrusion in a geological repository and points out the gaps and the rationale of the dissertation. The exploration for the research questions is described from the next section. Owing to its significantly long assessment timeframe, consideration for all possible phenomena related with future human action on a geological repository is inherently impossible. For this reason, this dissertation selects the cases that can be widely referred for other possible human actions. Based on the reference cases, conceptual model incorporating various parameters is suggested. Then, the parametrization and the validation of the suggested model are conducted with technical and societal database of the reference cases. The developed model is implemented by applying the model to a hypothetical repository. Finally, the study discusses the implication of the assessment results and suggest SNF management approach to minimize the potential risk of human intrusion.

The one baseline of research approach for this dissertation is conservativeness. The uncertainties in future may have either positive or negative effect on the risk of human intrusion and their effect would depend on assumptions for the model. For example, one can assume that an improvement of drilling technique will reduce the probability of inadvertent human intrusion because of improved capability of drilling machine that detects hazard. On contrary, improved drilling speed would enable future generation to drill deep region easily, increasing the probability of inadvertent human intrusion. However, a judgment on such contrasting two possibility is not predictable. Nuclear engineering has always complied with conservative viewpoint when a decision is required for such hardly predictable problem with significant consequence. The objective of such conservative approach is to minimized uncertainties and to secure public acceptance. For the same reasons, conservative approach is also applied for developing the model of human intrusion in this study.

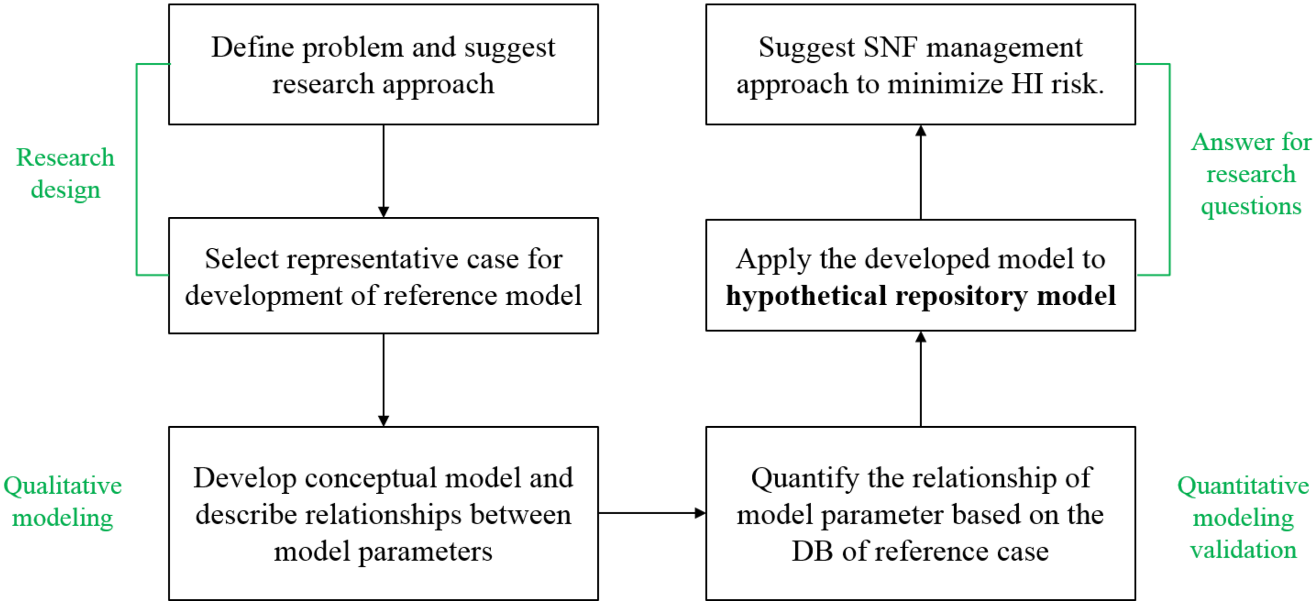

Figure 3.1 Overall research process flow

3.4 Methodology

3.4.1 Methodology for inadvertent human intrusion modeling

Three research methods have been combined to analysis dynamic stochastic process of inadvertent human intrusion: a combined method of ‘system dynamics’, ‘Markov chain analysis’, and ‘Monte Carlo simulation technique’. The system dynamic approach on inadvertent human intrusion model facilitate the consideration for the dynamic behavior and the feedback mechanism of various factors which affect an occurrence of inadvertent human intrusion event over time. The stochastic behavior of inadvertent human intrusion with conditional probability is analyzed by applying Markov chain analysis approach. Because the mathematical expression of the model is probabilistic, Monte Carlo simulation technique is used so that the results can be statistically analyzed. For the quantitative analysis on the model, the reference case is selected based on the criteria suggested in this study. The following sub- section briefly explain the methods and the rationale for application of such methods to help readers follow up this study.

3.4.1.1 System dynamics

System dynamics was developed by Jay Forrester to understand and analysis a structure of complex system and its dynamic behavior over time (Forrester, 1961). A system is defined ‘an interconnected set of elements that is coherently organized in a way that achieves something’ (Meadows, 2008). The key of system dynamics is a thinking of causalities and feedback loops of elements consisting of a system. For example, suppose that there is a simple system filling a glass of water (Figure 3.2). In this system, a water flow is controlled based on an information of water level in the glass in such way that the level of water in the glass is adjusted to a goal. The interesting point in such system is that there is no starting or ending point. Every element in the system is interconnected so that all actions are controlled by system itself, not by a single element. Therefore, in

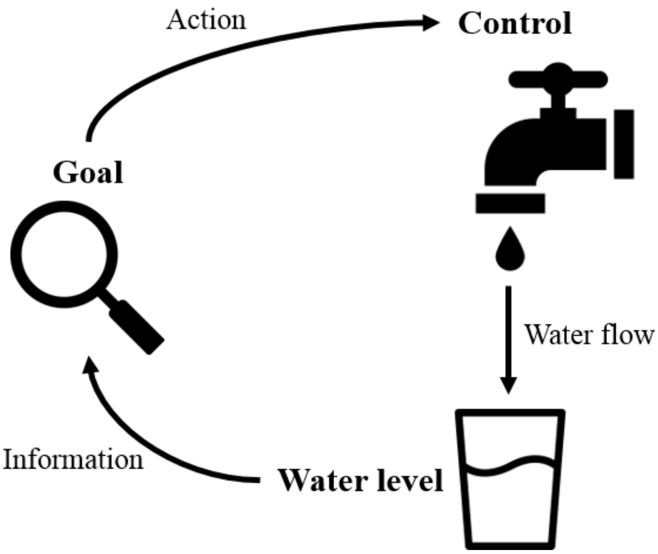

Figure 3.2 A simple system filling a glass of water

3.4.1.2 Markov chain analysis

3.4.1.3 Monte Carlo simulation

3.4.1.4 Selection of reference case

A number of motivations that shall lead an inadvertent human intrusion event have existed in in modern civilization. However, to incorporate all possible inadvertent human intrusion cases in a single model is not only impossible but also inappropriate approach. First, owing to the long assessment timeframe over 10,000 years, prediction for the potential motivation of future civilization which has not been observed yet is meaningless and impossible. For this reason, the investigation on inadvertent human intrusion has to explored based on historic experiences. Second, significance of motivations is different each other. For example, both civil project and resource exploration shall lead inadvertent human intrusion in future. However, the frequency of civil project would be much lower than that of resource exploration so that the motivation for resource exploration is more significant for inadvertent human intrusion. Therefore, this study focuses on selection of the case that can be a reference for inadvertent human intrusion systems.

Four possible motivations for inadvertent human intrusion are considered based on historic experiences: drilling for civil project, utilization of groundwater, mineral mining, and oil/gas development. Five criteria are considered to select the reference case: depth range, continuity in demand, spatial distribution, frequency, and existence of information for underground before beginning of activity (Figure 3.3). The motivation would be significant for inadvertent human intrusion when the following drilling activity has sufficient depth range to reach the location of a repository; the demand will be continuously maintained in future; the spatial distribution of following drilling activity is widely dispersed to be likely to occur nearby a repository; the frequency of following drilling activity is high; and pre-information of underground characteristics is low.

Based on such criteria, the case of groundwater development is selected as reference for the model development. The rationales are followed: First, the depth of drilling for groundwater utilization is up to a few kilometers. Second, a groundwater well has been continuously drilled since primitive society (Kent, 2001; Kuhn, 2004) so that the motivation would be expected to be sustain in future[3]. Third, a groundwater well has been dispersively developed

[3] On the other hand, the extensive exploration and exploitation of petroleum only

not only nearby city but also nearby rural area. Forth, the frequency of well development is high enough[4]. At last, pre-information of developable aquifer is relatively insufficient comparing with the that of other cases. For example, the hydrogeological map of ROK has not contained the spatial distribution of developable aquifer in deep lithosphere region.

began in the 19th century.

[4] In ROK, about 0.8 groundwater was drilled per square kilometer in 2015.

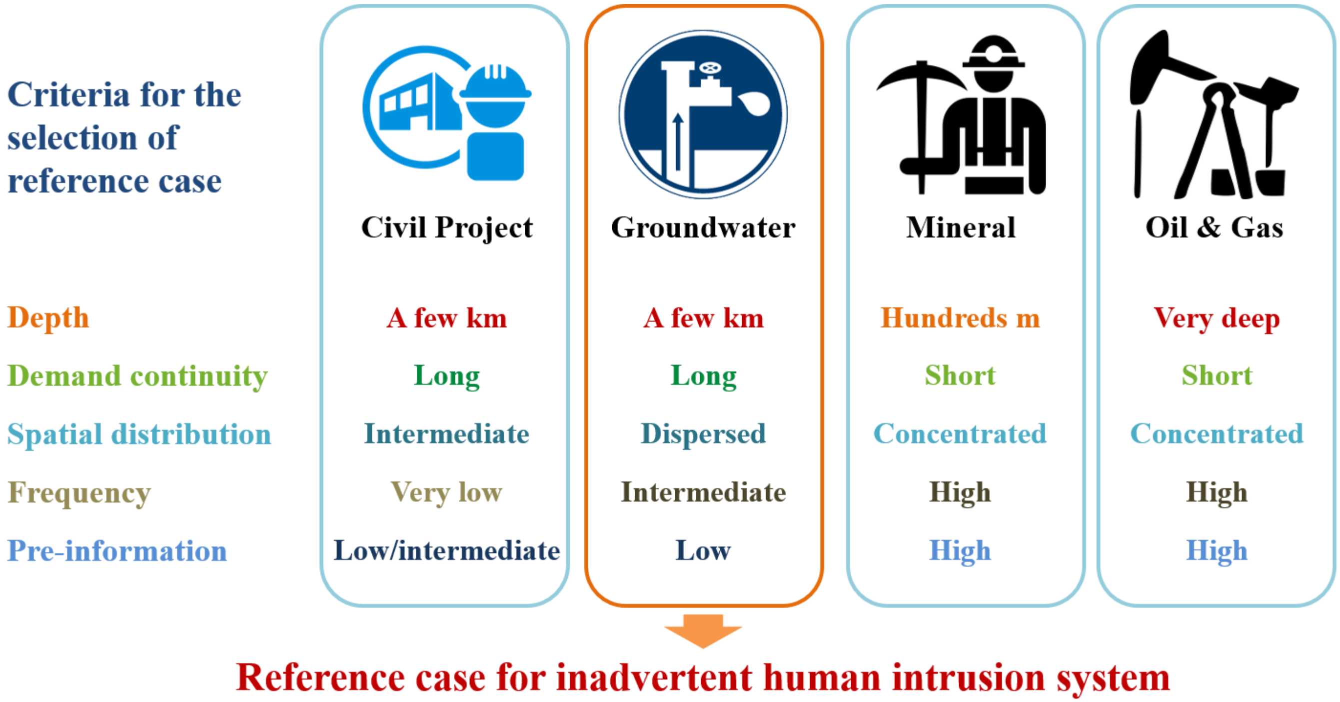

Figure 3.3 Criteria for the selection of reference case for inadvertent human intrusion system

3.4.2 Methodology for clandestine human intrusion modeling

The game theory is significantly useful method to improve understanding the situation of strategic decision making. This study has applied the game theory for quantitative analysis on the relationship between the desirability (motivation) of clandestine intruder and the efforts of safeguards subject. As described in Section 3.3, the reference case is also selected for clandestine human intrusion model. The following sub-section briefly explains the methodology for clandestine human intrusion.

3.4.2.1 Game theory

3.4.2.2 Selection of reference case

Various strategies can exist for both intruder and safeguards agent. In this study, existing mining technology are considered as possible intrusion strategies. Currently, two mining technology are applicable: tunnel excavation and borehole drilling. Therefore, these two technology are selected as reference cases for strategies of intruder.

Likewise, tow monitoring measures are considered as strategies for safeguards agent: micro-seismic and satellite monitoring.

The conventional mining technology includes

3.4.3 Hypothetical repository model

The risk of human intrusion into a deep geological repository varies depending on the design, and the condition of repository. Therefore, this dissertation considers a hypothetical repository model for the assessment of human intrusion risk. Figure 3.4 illustrates the generic design of hypothetical repository. It is assumed that SNF or HLW would be disposed in tunnel mined borehole located at a depth of 500 m below a surface. Currently various rock conditions including salt, and granite are considered for potential repository. In this dissertation, hard granite is considered for the hypothetical repository model. In addition, developable aquifer for groundwater well is deposited nearby the hypothetical repository, although it does not exist exactly above the repository. It is also assumed that future generation will be free to access the repository site after institutional control period. As mentioned in Section 3.4.1.4, groundwater development is considered as a motivation for inadvertent human intrusion. As clandestine human intrusion strategies, tunnel excavation, and drilling and chemical extraction are considered (see Section 5.2.1).

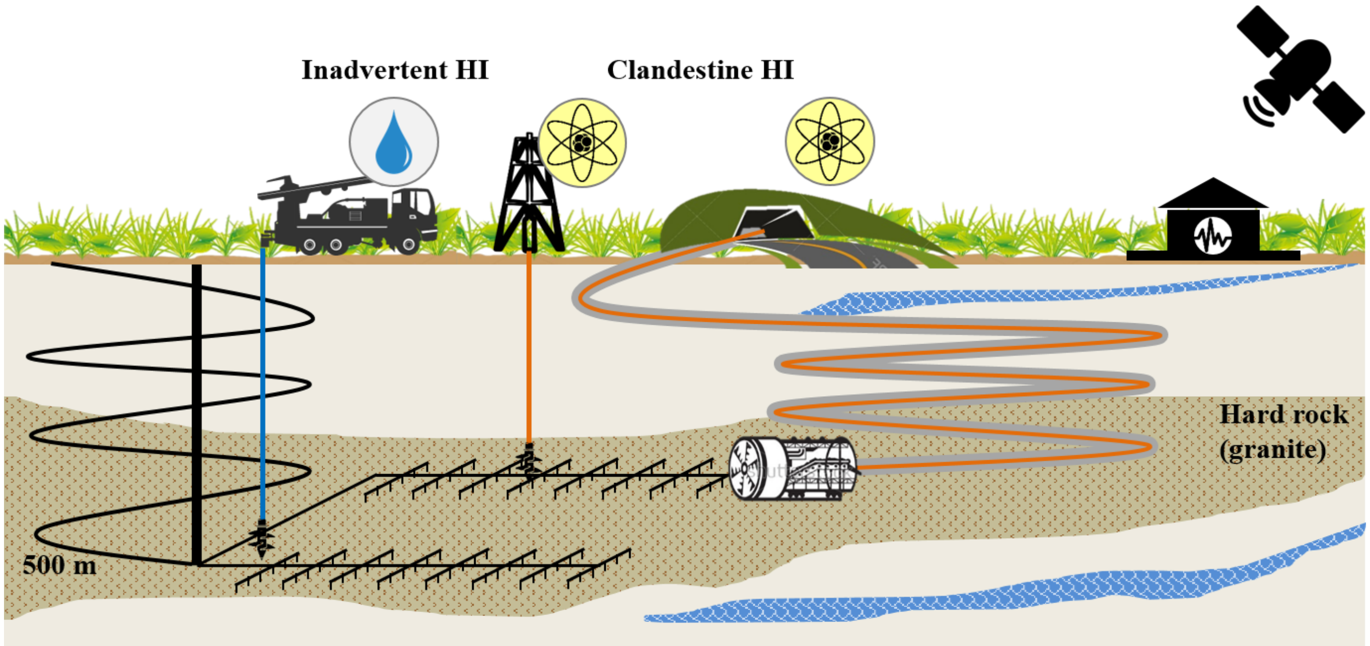

Figure 3.4 Illustration of hypothetical repository model

3.4.4 Modeling tool: GoldSim

Chapter 4 Probability Estimation Model for Inadvertent Human Intrusion

4.1 System of inadvertent human intrusion

4.1.1 Conceptual model

The behavior of future human intrusion originates from the combinations of possible circumstances near a repository consisting of various factors affecting a human intrusion system. The possible circumstances include the existence of a protection system such as institutional control, the utility of the surface land above the repository, the motivation for drilling, etc. For this reason, the assessment of human intrusion should consider circular causality and the feedback mechanisms of the factors. A linear system is not expected.

Several factors consisting of inadvertent human intrusion system are listed in Table 4.1. There are three kinds of factor: repository design, repository condition, and society condition. The factors related with repository design include the depth, and area of a geological repository. The factors related with repository condition include institutional control, continuity of knowledge about a repository, resource deposition, and surface activity on a repository site. The factors related with society condition include technology improvement, demand for and supply of resource, and population density. The effects of such factors are expressed as plus or minus sign. The plus sign means positive relationship between the factor and the effect. For example, increased depth of a repository would reduce human intrusion probability which is negative relationship; high amount of resource deposit near repository would increase the drilling frequency followed by increase of human intrusion probability which is positive relationship.

Figure 4.1 depicts the overall modeling approach developed in this study. To consider the dynamic behavior of future human intrusion, system dynamics (Forrester, 1961) was applied to develop the structure of new model as discussed in Section 3.4.1. The arrows in Figure 4.1 show circular causality and the feedback mechanism between human intrusion and the circumstances affecting the probability. The circumstances were categorized into two groups: the conditions of the repository and the level of drilling activity. It is assumed that the possibility of drilling activity above the repository would be determined by the conditions of the repository, including the protection system, the repository design, and the surface activity above the repository. The level of drilling activity determines the drilling frequency. By a combination of these circumstances, the probability of human intrusion could be determined.

The occurrence of events including human intrusion or the transition in circumstances over time is stochastic process with a conditional probability. For example, Figure 4.3 depicts the stochastic process for the transition of a surface activity circumstance. It was assumed that the surface activity above a repository would correspond to one of three purposes: derelict, livelihood, and farming. The initial state of the repository surface would be derelict land until institutional control of the repository collapses. Without institutional control, the surface activity above a repository will change over time from derelict to livelihood or farming with a conditional probability of P_{LD} or P_{FD}. For the corresponding stochastic process, the concept of a Markov chain (Ching and Ng, 2006) was applied to the new model.

Because the dynamic behavior of future human intrusion consists of various factors with complex causality, the uncertainties in and reliability of the model cannot be analytically estimated. For this reason, a Monte Carlo method was used for each stochastic process so that the results can be statistically analyzed.

Table 4.1 Consideration of factors affecting inadvertent human intrusion and their qualitative effect

Category	Factors	Effect	
		Drilling frequency	Human intrusion
Repository design	Repository depth		−
	Repository area		+
Repository condition	Institutional control		−
	Continuity of knowledge		−
	Resource deposition	+	+
	Surface activity	+	+
Society condition	Technology improvement	+	+
	Resource demand	+	+
	Resource supply	−	−
	Population density	+	+

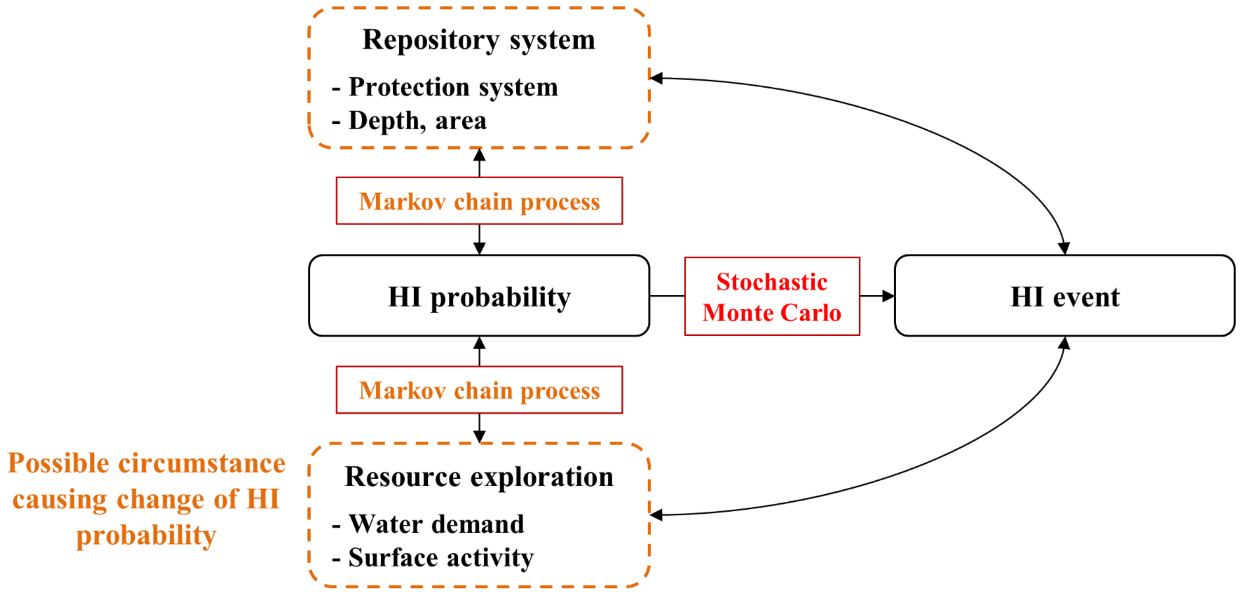

Figure 4.1 Schematic diagram of conceptual model for inadvertent human intrusion

4.1.2 Model structure

Figure 4.2 shows the overall structure of the model developed in this study. The causalities between the factors in the model were determined by analyzing the groundwater development database and assumptions. A detailed explanation of the assumptions is presented in Sections 4.2.1 and Section 4.2.2. The parametrization of the variables is discussed in Section 4.2.3.

Box C in Figure 4.2 indicates the factors for the conditions of a repository that determine the possibility of drilling above the repository. A repository design includes the depth and area of the repository. Other factors, including the protection system and surface activity, are circumstances that change over time.

The possible state of the surface-activity circumstance is depicted in Figure 4.3. As mentioned in Section 4.1.1, a transition in the circumstance occurs though a Markov chain process with a conditional probability. Human intrusion will only occur when the surface activity above the repository is livelihood or farming in the case of groundwater development. In contrast, a human intrusion event would make the repository area derelict land when intruders are aware of the existence of a hazard due to a radiological impact.

For the protection-system circumstance, the Markov model developed by Woo (Woo, 1989, 1993) was adopted (Figure 4.4). The possible states for the protection-system circumstance were considered with the combination of institutional control and knowledge about the repository site. It was assumed that human intrusion can only occur when institutional control is absent.

Moreover, the probability of human intrusion would be mitigated until knowledge about the repository site vanishes. As in the surface-activity circumstance, it was assumed that a human intrusion event may cause reactivation of the protection system due to a radiological impact.

Boxes A, B, and E include factors determining the level of drilling activity. It was assumed that the motivation for drilling is driven by the supply of and demand for groundwater (Box B). The demand for groundwater is classified into residential and farming purposes. On the basis of the historical data, the demand for residential and farming water is assumed to be proportional to the population and farm land area, respectively (see Section 4.2.2). To calculate the domestic land area distribution, a Markov chain model for the surface-activity circumstance was used (Figure 4.3).

Box D shows the circular causality diagram for estimating the human intrusion probability. Here, the probability is calculated in form of an annual frequency considering the drilling frequency, surface-activity circumstance, protection-system circumstance, and repository design. Finally, a human intrusion event is estimated by a Monte Carlo method. The arrows from the human intrusion event indicate the effects of the event on the surface-activity and protection-system circumstances.

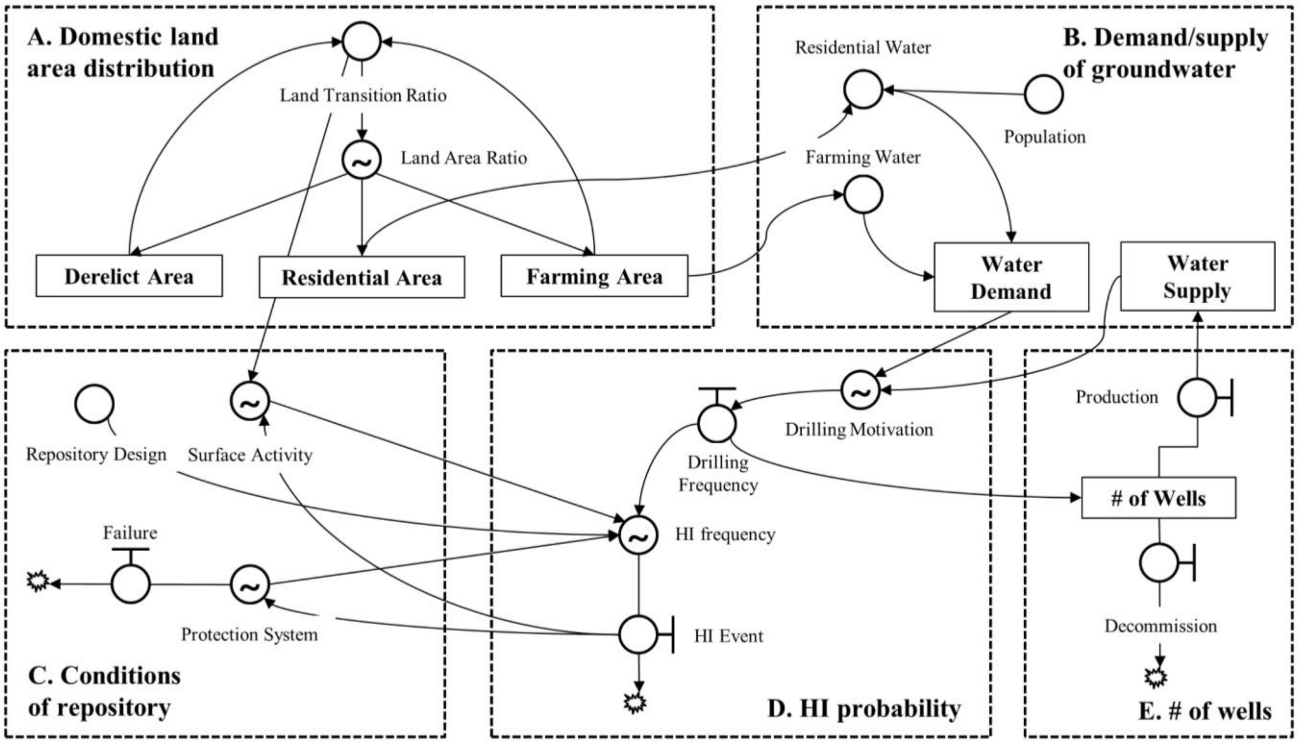

Figure 4.2 Structure of systematic model for inadvertent human intrusion

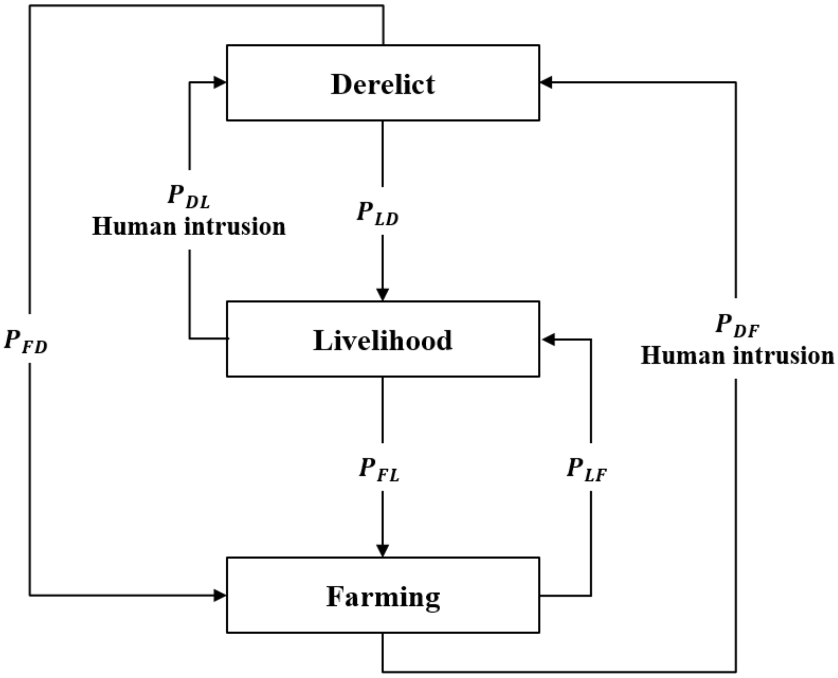

Figure 4.3 Diagram for Markov chain model for surface activity

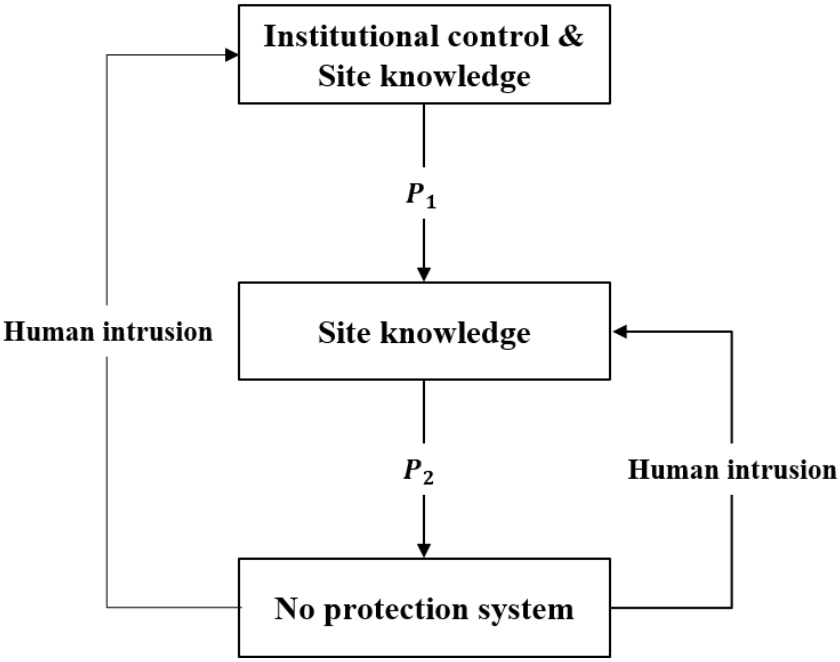

Figure 4.4 Diagram for Markov chain model for protection system of a repository to prevent inadvertent human intrusion (Woo, 1989, 1993)

4.1.3 Feedback loop restraining inadvertent human intrusion

The dynamic behavior of a system is determined by feedback loop consisting of various parameters. There are three feedback loops in systematic model of inadvertent human intrusion: feedback loop of drilling activity, surface activity, and protection system. Depending on the characteristics of feedback loops in the model, the probability of inadvertent human intrusion may either only increase or converge to a specific value. In following sub-sections, the behavior of inadvertent human intrusion system is qualitatively assessed by analyzing feedback loops in such system.

4.1.3.1 Feedback loop of drilling activity

As depicted in Figure 4.2, feedback loop of drilling activity consists of three parameters including groundwater supply, motivation, and drilling activity. The causal loop diagram is shown in Figure 4.5. High drilling activity increases the supply of groundwater. The supply of groundwater has negative influence on the drilling motivation. Finally, the drilling motivation has positive relationship with drilling activity. Therefore, the feedback loop of drilling activity is negative because only one negative exists. Consequently, the frequency of drilling activity is expected to be converged.

4.1.3.2 Feedback loop of repository condition

Figure 4.6 shows causal loop diagram of surface activity and protection system feedback on inadvertent human intrusion. The key assumption of this causal loop is that an occurrence of inadvertent human intrusion would possibly be recognized by future generation due to its significant radiological impact; assumptions used for the model development are described in Section 4.2.1. The recognition of the hazard will cause reactivation of protection system on repository or exclusion of human activity nearby repository. Such reaction of future generation reduces the probability inadvertent human intrusion. Thus, both feedback loops are negative so that the frequency of inadvertent human intrusion is expected to be converged.

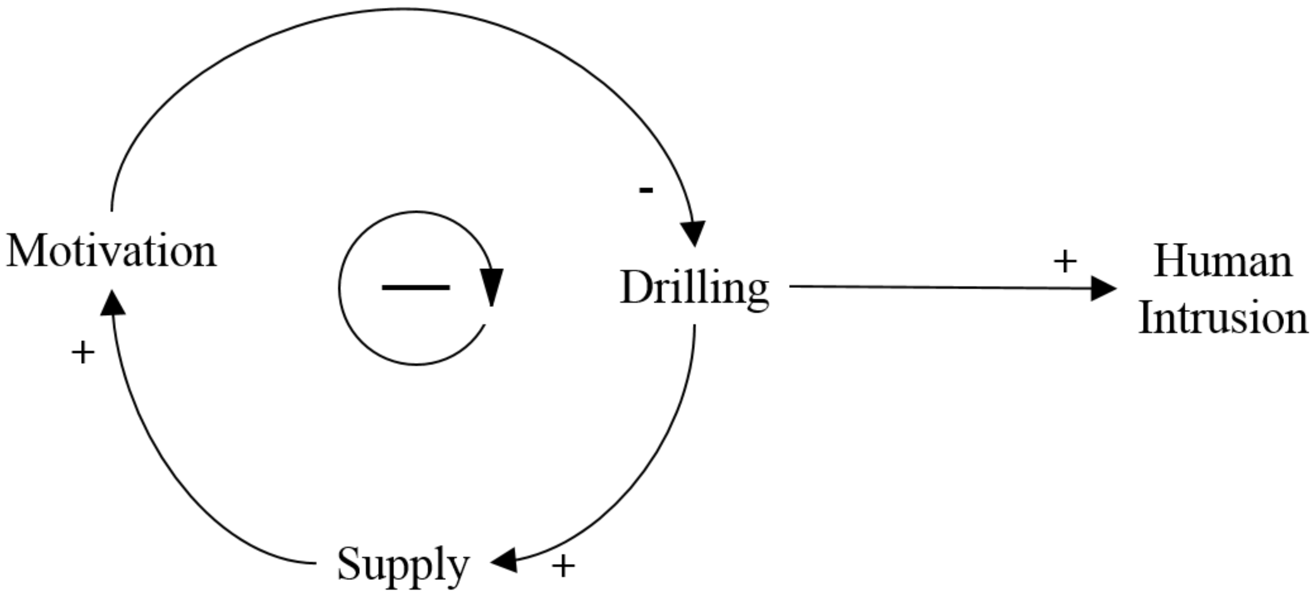

Figure 4.5 Causal loop diagram of drilling activity feedback

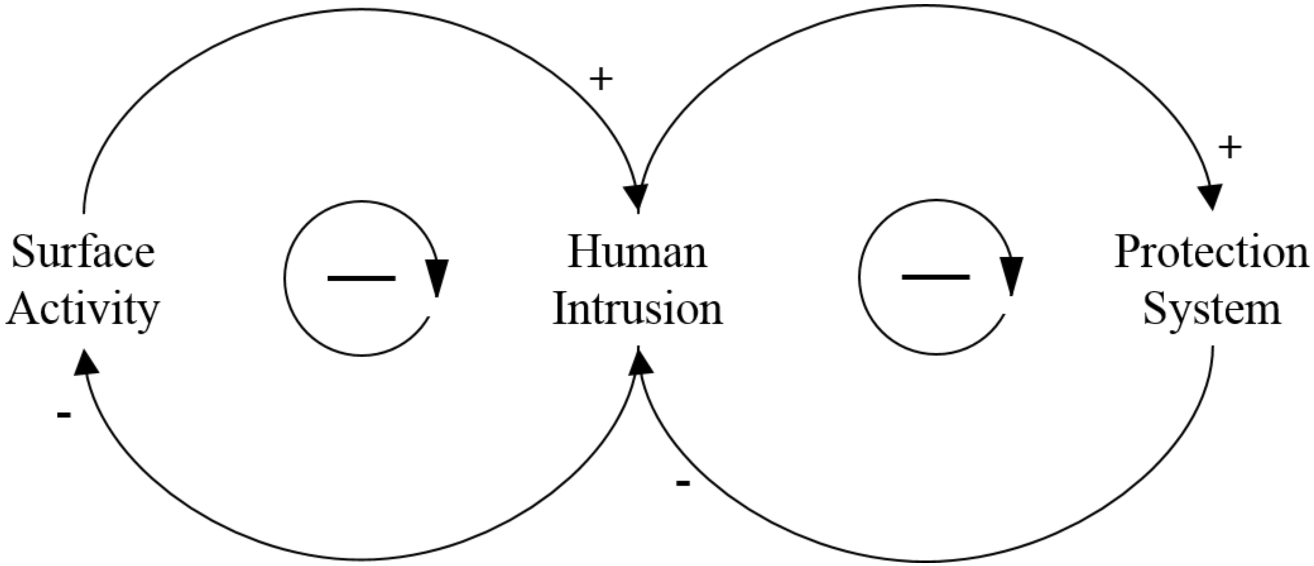

Figure 4.6 Causal loop diagram of surface activity and protection system feedback

4.2 Parametrization and validation of the model

4.2.1 Assumptions

The following assumptions were made to quantify the causalities between factors:

(1) The conditional probabilities of a surface activity transition are time-independent.

(2) The water demand for farming purposes is proportional to the farm land area.

(3) The water demand for residential purposes is proportional to the population.

(4) The water dependency on the groundwater will increase until the developable groundwater is fully developed.

(5) The well drilling frequency is determined by the demand for and supply of groundwater.

(6) Drilling is more likely to occur in a region where the difference between the demand for and supply of groundwater is higher.

(7) The motivation for drilling above the repository is zero when the groundwater supply near repository is sufficient.

(8) A protection system will mitigate future human intrusion.

Parametrization the model based on the assumptions above is described in next section. In Section 4.2.3, the validity of the assumptions is checked.

4.2.2 Mathematical model

4.2.2.1 Estimation of the Level of Drilling Activity

Let $\boldsymbol{A}^{(n)}$ be the distribution of the domestic land area at *n*-th time step:

$\boldsymbol{A}^{(n)} = (A_D^{(n)} \quad A_F^{(n)} \quad A_R^{(n)})$	Eqn. 4.1

where A_F and A_R are the surface land areas for farming and residential purposes, respectively, and A_D is the derelict land area. Then, $\boldsymbol{A}^{(n+1)}$ is expressed as follows:

$\boldsymbol{A}^{(n+1)T} = \boldsymbol{P}^{(n)}\boldsymbol{A}^{(n)T}$	Eqn. 4.2
$\boldsymbol{P}^{(n)} = \begin{pmatrix} P_{DD}^{(n)} & P_{DF}^{(n)} & P_{DR}^{(n)} \\ P_{FD}^{(n)} & P_{FF}^{(n)} & P_{FR}^{(n)} \\ P_{RD}^{(n)} & P_{RF}^{(n)} & P_{RR}^{(n)} \end{pmatrix}$	Eqn. 4.3

where $\boldsymbol{P}^{(n)}$ is the transition probability matrix at the *n*-th time step, and P_{ji} is the probability of a land transition from i to j. The transition probability was assumed to be constant in time in this model.

Figure 4.7 shows the relationship between the farm land area and the water demand. The two factors exhibit a linear relationship. Accordingly, the water demand for farming is calculated as follows:

$WD_F(t) = k_F \cdot A_F^{(T)} + C$	Eqn. 4.4

where $WD_F(t)$ is the annual demand for farming water ($\mathrm{m^3/yr}$), k_F is the proportionality coefficient for the demand for farming water ($\mathrm{m^3/(km^2 \cdot yr)}$), and C is a constant ($\mathrm{m^3/yr}$).

Figure 4.8 shows the trend in the ROK domestic residential water demand per capita (k_R, $\mathrm{m^3/(capita \cdot yr)}$) from 1965. The value of k_R steadily increases until the mid-1990s, but recently, it has saturated at a constant value. Thus, the demand for residential water is assumed to be proportional to the population as follows:

$WD_R(t) = k_R \cdot \mathrm{population}(t)$	Eqn. 4.5

To calculate the demand for groundwater, the portion of groundwater to total water demand is required. Figure 4.9 shows the trend in the water demand dependency on groundwater. Since the early 1990s, the percentage of groundwater has steadily increased. Therefore, the model assumes that the water demand dependency on groundwater will linearly increase until the total developable groundwater is fully developed. This assumption seems reasonable when considering that the groundwater regionally occupies up to 87.6% of the total water demand in the ROK (Ministry of Land Infrastructure and Transport, 2016). Therefore, the groundwater demand is expressed as follows:

$GWD(t) = \varepsilon \cdot (WD_F + WD_R)$	Eqn. 4.6

where GWD is the demand for groundwater (m^3/yr), and ε (%) is the water demand dependency on groundwater.

The groundwater supply at a specific time can be expressed as follows:

$GWS(t) = \eta \cdot N(t)$	Eqn. 4.7

where GWS is the groundwater supply (m^3/yr), η is the groundwater production per well ($\mathrm{m}^3/(\mathrm{well} \cdot \mathrm{yr})$), and N is the number of groundwater production wells. The required number of groundwater wells at a specific time is as follows:

$N_{req}(t) = GWD(t) / \eta$	Eqn. 4.8

Then, from assumption (5) in Section 4.2.1, the annual drilling frequency of groundwater wells is calculated as follows:

$\dot{N}_{gen}(t + \Delta t) \cdot \Delta t = N_{req}(t) - N(t) + \varphi \cdot N(t) \cdot \Delta t$	Eqn. 4.9

where $\dot{N}_{gen}$ is the annual drilling frequency, and φ is the decommission rate of production wells ($1/yr$). To validate Eqn. 4.9, the calculated number of wells over time was compared with the domestic observation data from 1999 to 2014 (Figure 4.11).

The annual drilling frequency in Eqn. 4.9 is an average value for an overall region. For a region in which the well density is lower or higher than that of another region, the regional drilling frequency would be higher or lower than the average. A lower or higher density means an undersupply or oversupply of groundwater. In other words, the regional well density tends to converge to the average well density. Accordingly, to estimate the drilling frequency near a repository, the model considers the difference between the well density at the repository and the average well density. To derive a mathematical expression, suppose that the well density at a repository at a specific time is less than the average density:

$d_{\text{other region}}(t) > d_{\text{repository}}(t)$	Eqn. 4.10

The well density is expressed as follows:

$d_{\text{repository}}(t) = \dfrac{N_{\text{repository}}(t)}{A_{\text{repository}}}$	Eqn. 4.11

$d_{\text{other region}}(t) = \dfrac{N(t) - N_{\text{repository}}(t)}{A_{\text{total}} - A_{\text{repository}}} \simeq \dfrac{N(t) - N_{\text{repository}}(t)}{A_{\text{total}}}$	Eqn. 4.12

where $N_{\text{repository}}$ is the number of wells near a repository, A_{total} is the total area where drilling occurs, and $A_{\text{repository}}$ is the area of a repository. Then, the number of wells after Δt can be expressed as follows:

$N_{\text{repository}}(t + \Delta t) = N_{\text{repository}}(t) + r \cdot \dot{N}_{gen}(t + \Delta t) \cdot \Delta t$	Eqn. 4.13
$N(t + \Delta t) = N(t) + \dot{N}_{gen}(t + \Delta t) \cdot \Delta t$	Eqn. 4.14

where r is fraction of well drilling in a repository area.

Because the regional well density tends to be the same, the well density of a repository after Δt would be similar to the average value:

$d_{\text{other region}}(t + \Delta t) \simeq d_{\text{repository}}(t + \Delta t)$	Eqn. 4.15

Substituting Eqn. 4.13 and Eqn. 4.14 into Eqn. 4.15, we have

$$f_{\text{repository}}(t+\Delta t) \equiv r \cdot \dot{N}_{gen}(t+\Delta t) = \frac{\left\{ \dfrac{d_{\text{other region}}(t) - d_{\text{repository}}(t)}{\Delta t} + \dfrac{\dot{N}_{gen}(t+\Delta t)}{A_{\text{total}}} \right\}}{\left\{ \dfrac{1}{A_{\text{total}}} + \dfrac{1}{A_{\text{repository}}} \right\}}$$	Eqn. 4.16

where we define $f_{\text{repository}}(t+\Delta t)$ as the drilling frequency near a repository.

When the well density at a repository at a specific time is greater than the average density, there is no motivation for drilling near a repository. Thus, the motivation factor m is defined, and Eqn. 4.16 is modified as follows:

$$m \equiv \begin{cases} 0 & \cdots \quad d_{\text{repository}}(t) > d_{\text{other region}}(t) \\ 1 & \cdots \quad d_{\text{repository}}(t) \le d_{\text{other region}}(t) \end{cases}$$	
$$f_{\text{repository}}(t+\Delta t) \equiv m \cdot r \cdot \dot{N}_{gen}(t+\Delta t)$$	Eqn. 4.17

4.2.2.2 Estimation of the Human Intrusion Frequency

The drilling frequency in Eqn. 4.17 means the level of drilling activity near a repository determined by the factors included in Boxes A, B, and E in Figure 4.2. To derive a mathematical expression for the human intrusion frequency, the conditions of a repository should be considered.

The states of the surface-activity and protection-system circumstances are determined through a stochastic Markov chain process over time. As mentioned in Section 3.2.2, human intrusion would not be possible when the state of surface activity is derelict. Here, the mitigation factor of the surface activity l is defined as follows:

$l \equiv \begin{cases} 0 & \cdots \quad \text{derelict} \\ 1 & \cdots \quad \text{residential or framing} \end{cases}$	

Similarly, the mitigation factor of the protection system p is defined as follows:

$p \equiv \begin{cases} 0 & \cdots \quad \text{With institutional control \& knowledge} \\ 0.1 & \cdots \quad \text{Knowledge about repository exists} \\ 1 & \cdots \quad \text{No protection system} \end{cases}$	

Another factor considered in the model is the depth of a repository. Because a geological repository is located a few hundred meters beneath the surface, a sufficient depth of the well is also required for human intrusion. Therefore, the fraction of wells deeper than some depth $\theta(depth)$ is defined as follows:

$\theta(depth) \quad \cdots \quad$ Ratio of well deeper than *depth*	

Considering all of the factors related to the conditions of a repository, the human intrusion frequency is defined as follows:

$f_{\mathrm{HI}}(t) = l \cdot p \cdot \theta(depth) \cdot f_{\mathrm{repository}}(t)$	Eqn. 4.18

The computational model was built using GoldSim (GoldSim Technology Group, 2014), a Monte Carlo simulation tool. Using Monte Carlo simulation results from multiple realizations, the effective time-averaged human intrusion frequency is calculated as follows:

$\overline{f}_{\mathrm{HI}}(T) = \int_{T_0}^{T} f_{\mathrm{HI}}(t)dt \,/\, (T - T_0)$	Eqn. 4.19

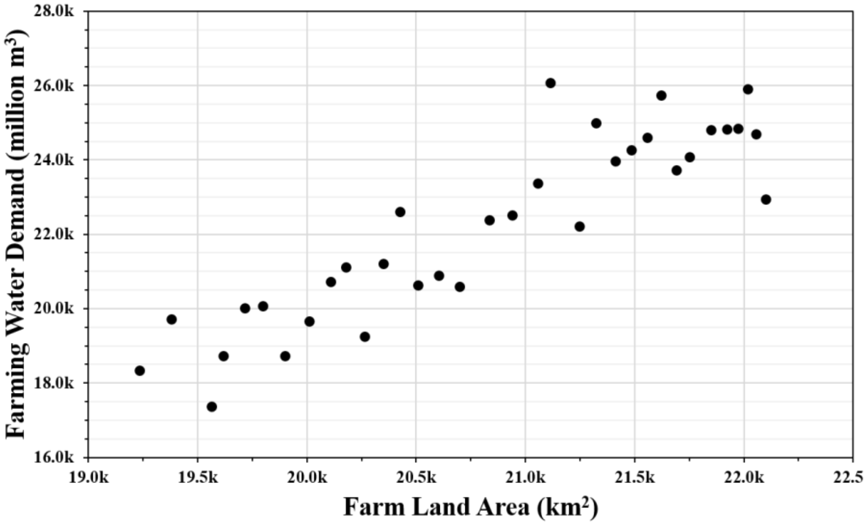

Figure 4.7 Correlation between farming water demand and farm land area

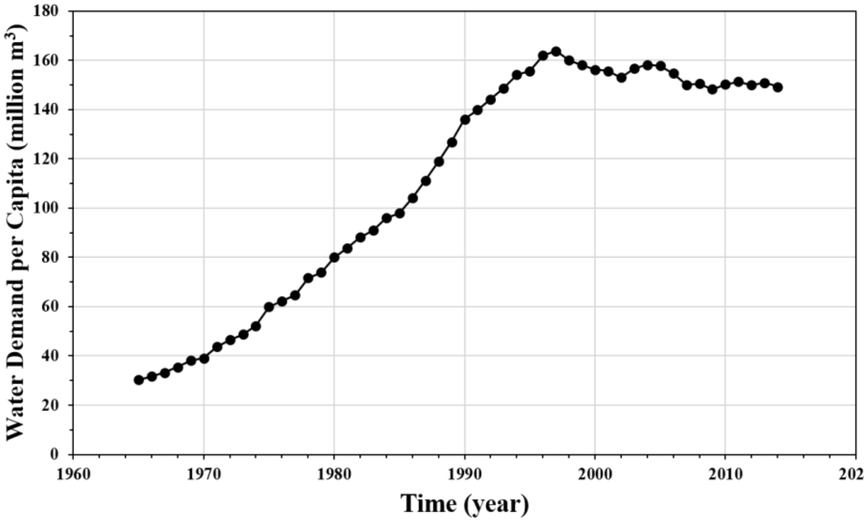

Figure 4.8 Change of annual residential water demand per capita from 1965 to 2015

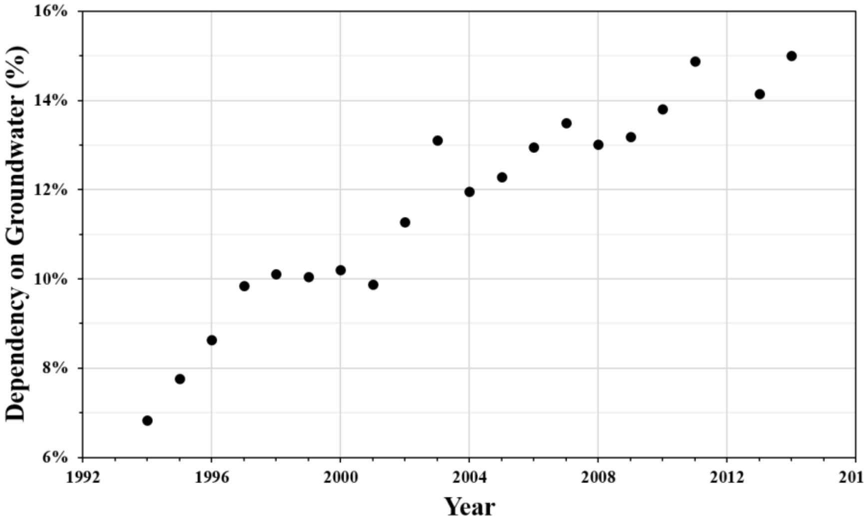

Figure 4.9 Water demand dependency on groundwater over time

4.2.3 Parametrization

The model was parameterized on the basis of the public historical database reported by the government of the ROK. The database references and the values for the parameters are listed in Table 4.2.

4.2.3.1 Parameters for the estimation of the level of drilling

The values for the probability matrix of a surface-activity transition $\boldsymbol{P}$ were estimated by the historical statistics of land transition from the year 1999. Data over 15 years were averaged and used for model. The estimated distribution of the land area over time is compared with the real values in Figure 4.10, supporting assumption (1) in Section 4.2.1.

For the parameterization of the variables in Eqn. 4.4 and Eqn. 4.5, the historical data of the water demand from the Water Resource Management Information System were analyzed (Water Resources Management Information System, 2017). The results are shown in Figure 4.7 and Figure 4.8. The results support assumptions (2) and (3) in Section 4.2.1.

The data in the groundwater annual report from 1997 to 2016 were used for the parametrization of the variables in Eqn. 4.7 and Eqn. 4.9. The average annual groundwater production rate per well is estimated to be $4.06\times10^{6}\ \mathrm{m^3/well\cdot yr}$, and the decommission probability of a well is $1.43\times10^{-2}\ 1/\mathrm{yr}$.

The validity of the model is a key issue for the estimation of the future human intrusion probability. It is critical to determine the level of drilling, i.e., the annual drilling frequency, when estimating the human intrusion probability because the human intrusion frequency is calculated on the basis of this factor. For this reason, the number of wells estimated by the model is compared with the historical database in the ROK. Figure 4.11 shows a comparison of the results from 1999 to 2014. The lines marked with open circles indicate the estimated numbers of wells with the 5% and 95% quantiles of the Monte Carlo simulation results. The model results fit well with the historical data, meaning that the estimated drilling frequency is valid.

4.2.3.2 Parameters for the condition of repository

It was assumed that the probability of institutional control vanishing is 10^{-2} 1/yr because a few hundred years is considered to be the monitoring period after the post-closure of a repository (Bailey and Littleboy, 2000; EPA, 1985; Gierszewski et al., 2004; IAEA, 2011; JNC, 2000; NIEA, 2009; OECD NEA, 1995). The probability of lost knowledge is assumed to be $1/500$ 1/yr.

The distribution of the well depth was derived on the basis of a database from the National Groundwater Information Center in the ROK. The distribution was fit to a lognormal distribution as follows:

$f(d)=\dfrac{1}{d\sqrt{2\pi d}}e^{\frac{(\ln(d)-\ln(\mu))^2}{2\sigma^2}}$	Eqn. 4.20

where d is the depth, μ is the median, and σ is the standard deviation. Then, $\theta(depth)$ is derived as follows:

$\theta(depth) = \frac{1}{2} - \frac{1}{2} erf(\frac{\ln(depth) - \ln(\mu)}{\sqrt{2}\sigma})$	Eqn. 4.21

The fitting results for various regions in the ROK are summarized in Table 4.3. Figure 4.12 shows the complementary cumulative distribution function (CCDF) of the total regional average in the ROK. The fraction of wells with a depth exceeding $depth$ is plotted along the y axis of the CCDF. Considering that the depth of a geological repository is commonly designed to be 500 m, the fraction of wells reaching a certain depth in a repository varies with the region, e.g., 2.23×10^{-3} for Gyeongsangnam-do, 3.13×10^{-4} for Jeola-do, and 1.02×10^{-3} for the total regional average in the ROK. In this study, the value for Gyeongsangnam-do where the Wolsung repository is located was used (Park et al., 2009).

However, it is noted that the median of the distribution of the well depth tends to increase. Table 4.4 summarizes the changes in the distribution of the well depth since 2002. This implies that the fraction of wells deeper than some depth in the future will be much higher than that now. Therefore, a discussion of this trend is required. Accordingly, a sensitivity analysis of the fraction of wells deeper than some depth was conducted and is discussed in Section 4.3.2.

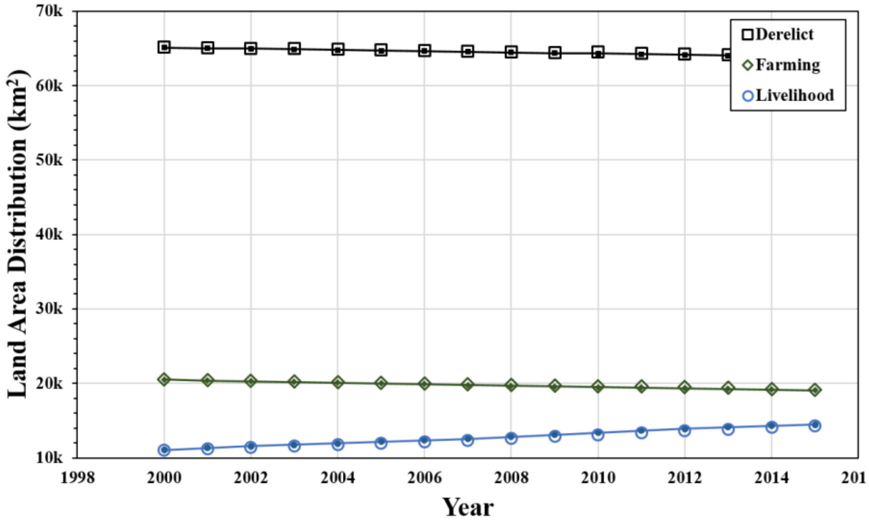

Figure 4.10 Comparison between estimated land area distribution and real historic data (line: observed, blank mark: estimation)

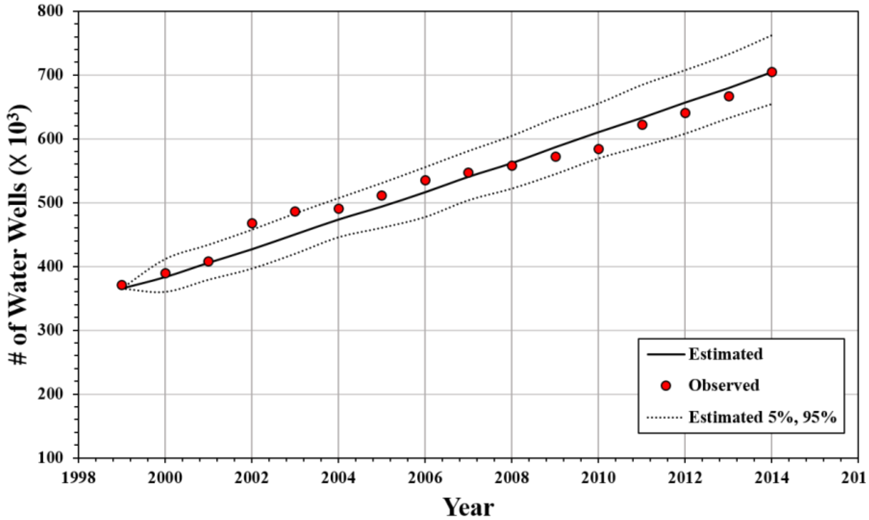

Figure 4.11 Change of the number of well over time

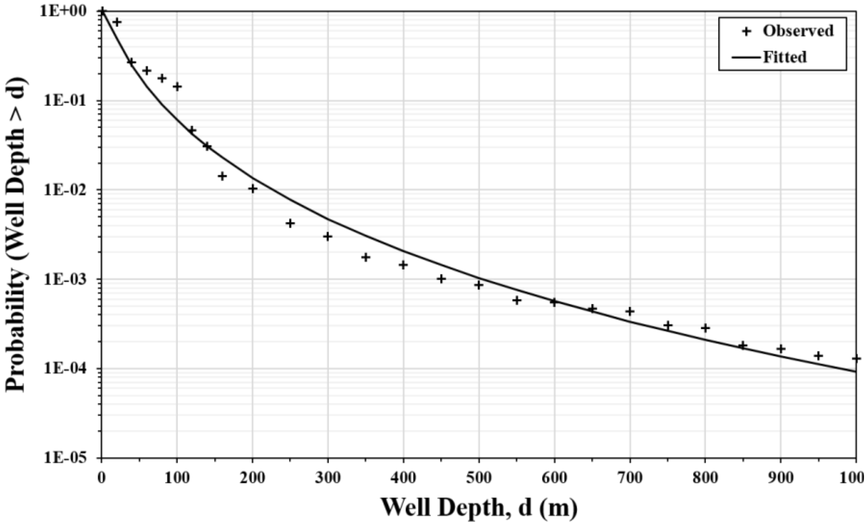

Figure 4.12 Complementary cumulative distribution of well depth in ROK

Table 4.2 Parametrization of the values for systematic model for inadvertent human intrusion (cont.)

Variables	**Values**	**Sources**
Probability matrix of land transition, $\boldsymbol{P}$	$\begin{pmatrix} 0.9921 & 0.0000 & 0.0079 \\ 0.0001 & 0.9987 & 0.0012 \\ 0.0041 & 0.0007 & 0.9952 \end{pmatrix}$	It was assumed that a forest represents derelict land. Data on changes in the forest area were taken from reports by the Korean Forest Service (Korean Forest Service, 1999-2012). Data on changes in the farming land area were taken from reports by the Ministry of Agriculture, Food and Rural Affair (Ministry of Agriculture Food and Rural Affair, 2015). Data on changes in the residential area were taken from reports by the Ministry of Land, Infrastructure and Transport (Ministry of Land Infrastructure and Transport, 2015).
k_F (million $\mathrm{m}^3/(\mathrm{km}^2 \cdot \mathrm{yr})$)	Normal$(2.53,\ 0.03^2)$	The water demand history is reported in the Water Resources Management Information System (Water Resources Management Information System, 2017).
C (million $\mathrm{m}^3/\mathrm{km}^2 \cdot \mathrm{yr}$)	-3.04×10^3	
k_R ($\mathrm{m}^3/\mathrm{capita} \cdot \mathrm{yr}$)	150	
η ($\mathrm{m}^3/\mathrm{well} \cdot \mathrm{yr}$)	4.06×10^6	Historical data for groundwater wells were taken from reports by the Ministry of Land, Infrastructure and Transport (Ministry of Land Infrastructure and Transport, 1997-2016).
φ ($1/\mathrm{yr}$)	1.43×10^{-2}	

Variables	Values	Sources
$\theta(depth = 500\ \mathrm{m})$	2.23×10^{-3}	Data for about 200,000 groundwater wells with the depth were obtained from the National Groundwater Information Center (National Groundwater Informantion Center, 2017). A lognormal distribution was obtained. Here, the distribution for Gyeongsangnam-do, the region where the Wolsung repository is located, was used.
Probability of institutional control vanishing, P_1 $(1/\mathrm{yr})$	$1/100$	Institutional control is assumed to vanish once in a hundred years. Knowledge about a repository is expected to last for 500 years.
Probability that knowledge about a repository is lost, P_2 $(1/\mathrm{yr})$	$1/500$	
Repository area, $A_{\mathrm{repository}}$ (km^2)	5.27×10^{-1}	The area was assumed on the basis of the Korean Reference. Repository System (KRS) for the disposal of 26,000 MTU SNF (Yoon and Ahn, 2010). - Area: $5.27\times10^{-1}\ km^2 = 420(\mathrm{tunnel})\times 251(\mathrm{L},\ m)\times 5(\mathrm{W},\ m)$

Table 4.3 Distribution of well depth for various region in ROK

Region	**ln(μ)**	σ	**Mean (m)**
Seoul	3.73	0.98	67.29
Busan	4.24	0.84	98.42
Incheon	3.22	1.04	43.11
Ulsan	4.32	0.69	95.4
Daejeon	3.21	0.98	39.78
Daegu	4.10	0.91	91.16
Gwangju	3.61	0.81	51.14
Gyeongsangbuk-do	3.25	1.00	42.34
Gyeongsangnam-do	3.63	0.91	57.23
Gangwon-do	2.91	1.07	32.64
Gyeonggi-do	3.00	1.07	35.36
Jeola-do	1.99	1.24	15.66
Chuncheongbuk-do	2.63	1.12	25.92
Chuncheongnam-do	2.58	1.09	23.88
ROK average	**2.98**	**1.05**	**34.08**

Table 4.4 Change of distribution of well depth in ROK since 2002

Year	$\ln(\mu)$	σ	**Mean (m)**
2002	2.85	0.99	28.26
2003	2.86	0.99	28.63
2004	2.87	1.00	29.02
2005	2.88	1.00	29.41
2006	2.89	1.01	29.80
2007	2.90	1.01	30.20
2008	2.91	1.02	30.61
2009	2.91	1.02	31.02
2010	2.92	1.02	31.44
2011	2.93	1.03	31.86
2012	2.94	1.03	32.29
2013	2.95	1.04	32.73
2014	2.96	1.04	33.17
2015	2.97	1.05	33.62

4.3 Application to hypothetical repository

4.3.1 Probability of inadvertent human intrusion

The estimates for the human intrusion frequency are shown in Figure 4.13. The solid and two dotted lines indicate the mean and the 5% and 95% quantiles of the frequency, respectively. The reliability of the model is calculated using 1,000 Monte Carlo simulations. The frequency of human intrusion at an early time is low but highly dependent on the protection system of a repository. An early failure of the protection system would significantly increase the frequency. Conversely, a stable protection system would effectively reduce the frequency. Accordingly, the results show a high uncertainty in the early period. After that, the frequency converges to a value around $5.89 \times 10^{-4}\ 1/yr$ with a small deviation due to the feedback loop of the model.

The red dash–dot line is constant with time in Figure 4.13 and indicates the human intrusion frequency estimated though a past approach. The mathematical expression for the past approach is as follows:

$f_{\mathrm{HI}} = \dfrac{\#\text{ of wells during } \Delta T}{\Delta T \times \text{Total Area}} \cdot \text{Repository Area}$	Eqn. 4.22

In the Gyeongsangnam-do region, 137 wells deeper than 500 m have been drilling since 1970. According to Eqn. 4.22, the future human intrusion frequency is $1.52 \times 10^{-4}\ 1/\mathrm{yr}$. At an early time, the past approach indicates a higher human intrusion frequency. However, in the long term, the frequency estimated by the proposed model exceeds that of the past approach.

The critical limitation of the past approach is a lack of consideration of time-dependent variables. This study attempts to overcome this limitation through the use of system dynamics and a Markov chain approach. As a result, the new model considers the dynamic behaviors of various circumstances affecting future human intrusion. The model predicts a reduced human intrusion frequency at an early time and an increased frequency in the long term compared with the results of the past approach.

The lower frequency of the new model at an early time originates from mitigation by the repository conditions including the protection system and surface activity. At an early time, a protection system is more likely to be valid, resulting in a reduction in the human intrusion frequency. Likewise, the surface activity of a repository corresponds to a derelict area at an early time, also resulting in a reduced human intrusion frequency. However, at intermediate times, the conditions of the repository tend to correspond to farming or residential areas without a protection system, resulting in increased motivation for well drilling. Accordingly, the frequency increases.

The reason for the long-term convergence of the human intrusion frequency is the saturation of the groundwater well density near a repository. In the initial period, the motivation for drilling is high owing to the low density of groundwater wells near the repository. This high motivation will result in an increased human intrusion frequency, as mentioned above. However, as drilling occurs, the motivation will decrease because the density of wells near the repository increases. Then, the rate of increase in the frequency gradually decreases, resulting in a converged human intrusion frequency.

The differences in these results imply that the systematic behavior of a human intrusion system is reasonably considered in the new model. By considering various factors resulting in increased or decreased motivation, the new model facilitates a systematic quantitative analysis of future human intrusion.

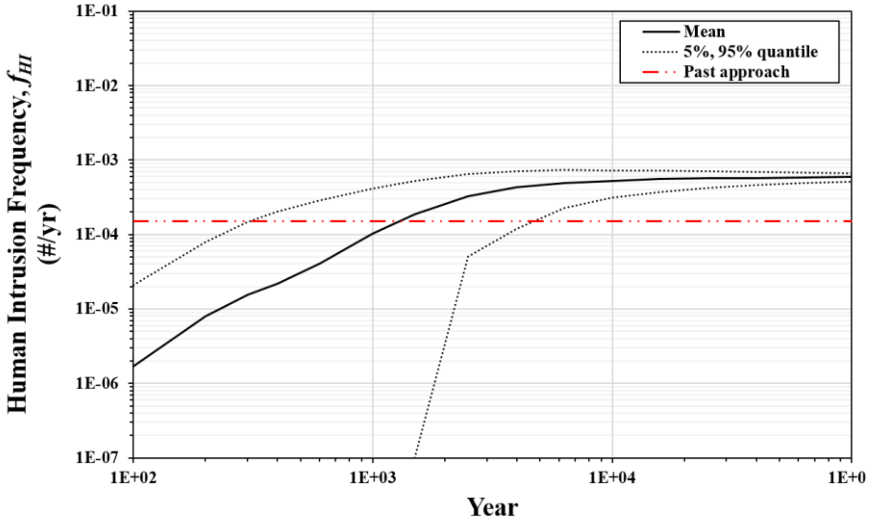

Figure 4.13 The human intrusion frequency for a hypothetical geological repository (well depth distribution of Gyeonsangnam-do region is used)

4.3.2 Sensitivity of representative design parameters

A sensitivity analysis of two factors, $A_{repository}$ and $\theta(depth)$, is presented in this section. The area of a repository is selected because it varies with the type of waste. For example, the repository area for HLW from reprocessing would be smaller than that for an SNF repository. The fraction of wells deeper than some depth is selected for two reasons. First, the depth of a repository is the main design parameter as a physical barrier to human intrusion. Therefore, a sensitivity analysis of this factor should be required for repository design. Second, the average depth of a well has been increasing, which implies a high uncertainty in the future. Accordingly, the sensitivity of the fraction of wells deeper than some depth is needed to assure the reliability of a human intrusion risk assessment.

Figure 4.14 shows the correlation between the long-term converged human intrusion frequency versus the repository area for different values of $\theta(depth)$. The frequency increases with the repository area unless the frequency reaches an upper boundary value of around 2.18×10^{-3} 1/yr . The upper boundary value of the human intrusion frequency results from the mitigation effect due to the reactivation of a protection system. A higher human intrusion frequency results in an increase in the number of human intrusion events. Thus, the protection system for a repository is more frequently reactivated. As a result, the frequency converges to an upper value. Compared with the assessment by the past approach (see Eqn. 4.22), the mitigation effect of the reduced area is less effective.

The sensitivity analysis results for the fraction of wells deeper than some depth is shown in Figure 4.15. Similar to the sensitivity analysis of the repository area, the frequency increases with the fraction of wells deeper than some depth before the frequency converges to an upper boundary value. The reason for convergence is the same. Considering the current distribution of the well depth, protection from human intrusion via design of the repository depth is an effective countermeasure. For example, in the Gyeongsangnam-do region, current fraction of wells deeper than 1,000 m is about 1.6×10^{-4}, resulting in a human intrusion frequency of about 1.0×10^{-4} 1/yr, which is 20 times lower than that for a repository with a depth of 500 m.

However, it is noted that the tendency for the increase in the well depth may weaken the capability of mitigation via the repository depth and area in the future. Unfortunately, there is a lack of scientific basis for determining the future limit on the well depth. For this reason, the perspective that an increased depth and a reduced repository area will effectively reduce the human intrusion risk seems to be optimistic. Rather, it would be more appropriate to assume an upper boundary frequency of 2.18×10^{-3} 1/yr for a conservative assessment.

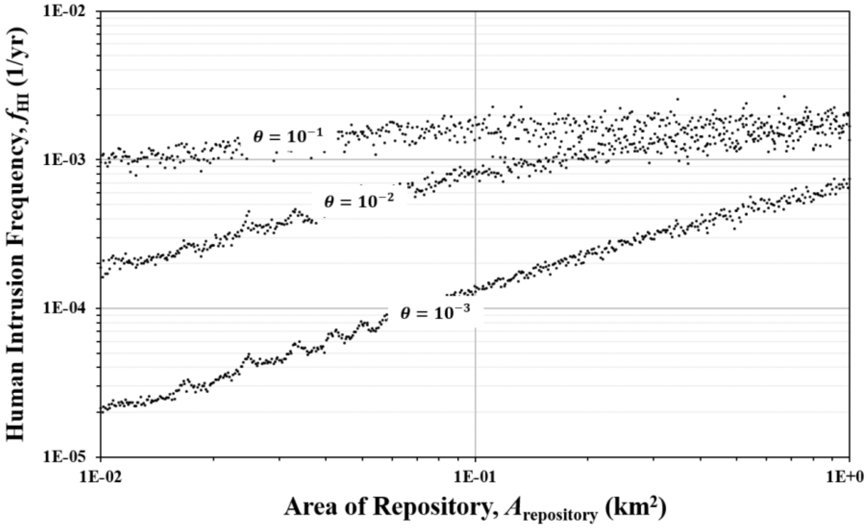

Figure 4.14 Sensitivity of repository area on long-term converged human intrusion frequency with various fraction of deep well

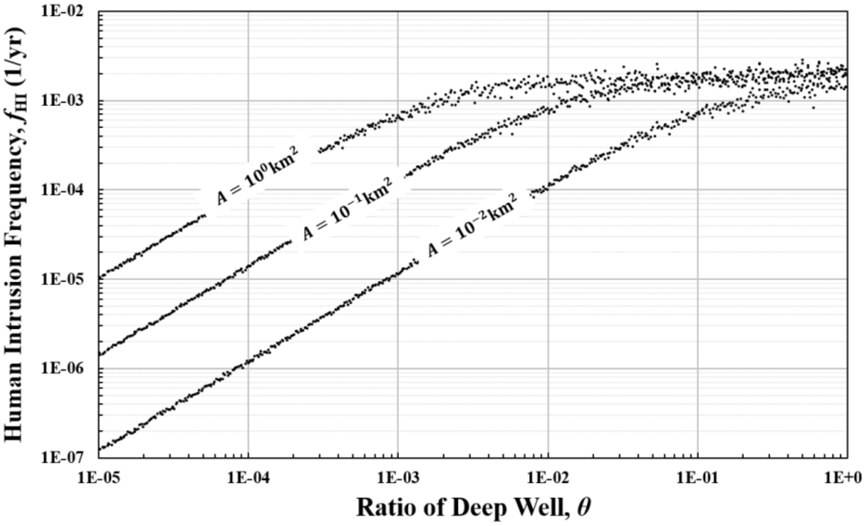

Figure 4.15 Sensitivity of fraction of deep well on long-term converged human intrusion frequency with repository area

4.3.3 Risk of inadvertent human intrusion

In this section, we compare the human intrusion risk of SNF and HLW repositories. It is assumed that the area and depth of the SNF repository are $5.27\times10^{-1}\ \mathrm{km}^2$ and 500 m, respectively, from the KRS design concept (Lee et al., 2007a; Yoon and Ahn, 2010). Assuming an Advanced Korean Repository System (A-KRS), the area and depth of the HLW repository are $1.92\times10^{-2}\ \mathrm{km}^2$ and 500 m, respectively (Yoon and Ahn, 2010). We consider two cases with different values of $\theta(depth = 500\ \mathrm{m})$: one with the value of 2.23×10^{-3} based on the current distribution of the well depth in the Gyeongsangnam-do region and another with a value of 1 representing the upper boundary of the human intrusion frequency. Conservatively, it is assumed that drilling core exactly penetrates a disposal canister.

The radiological exposure dose for inadvertent human intrusion is estimated using the model developed by BIOPROTA, the collaborative research Forum to address the key uncertainties in long-term assessment of radioactive waste disposal (Smith et al., 2013). An exposure dose from inadvertent human intrusion would vary depending on parameters and assumptions used in scenario. To assure enough safety margin, the model in this study conservatively assume that drilling worker would be exposed directly by contaminated drill core containing a part of SNF. Any radiology protection measure is not considered so that the exposure pathways are ingestion, inhalation, and external exposure. The parameters and their values for the estimation of radiological exposure are summarized in Table 4.5.

Figure 4.16 shows the human intrusion risk of the SNF and HLW repositories with a fraction of wells deeper than some depth of 2.23×10^{-3}. The dashed and dotted lines indicate the 5% and 95% quantiles of the SNF and HLW repositories, respectively. The human intrusion risk given for SNF disposal cannot satisfy the risk criterion of 10^{-6} 1/yr, whereas that given for HLW disposal is barely in compliance. The lower risk for HLW disposal is due to the smaller area of the repository and the lower radiotoxicity of the waste itself. However, considering the uncertainty (95% quantile) in the estimated probability, it is hardly concluded that the disposal of HLW is free from human intrusion.

The results for $\theta=1$ are shown in Figure 4.17. The results show that both SNF and HLW disposal cannot satisfy the human intrusion risk criteria. In addition, the risk of HLW disposal is not significantly reduced compared with that for $\theta=2.23\cdot10^{-2}$ because the mitigation effect from the reduced area is weakened, as mentioned in Section 4.3.2. In this case, the reduced risk of the HLW originates from a reduction in the radiotoxicity concentration of the rad-waste.

Table 4.5 Summary of values of parameters for estimation of radiological exposure

Parameters	Values	Note
Distance from contaminated drill core	1 m	
Bulk density of core	2,700 kg/m^3	Bentonite
Drill bit radius	7 cm	Diamond core drilling
Exposure time	40 hours	(Gierszewski et al., 2004)
Dust concentration in air	2 mg/m^3	
Respiration rate	3 m^3/hr	Adult male
Intake rate	17 mg/hr	

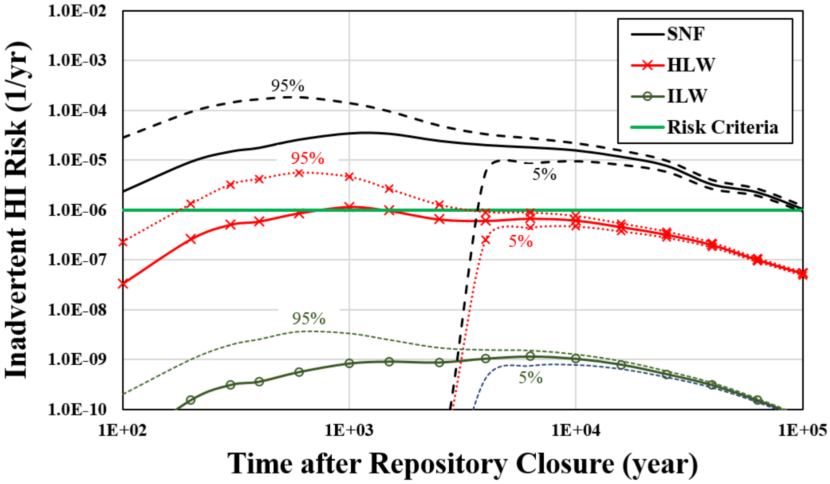

Figure 4.16 Inadvertent human intrusion risk of SNF and HLW repository with current fraction of deep well of Gyeongsnagnam-do region. The dashed and dotted lines indicate 5% and 95% quantiles of SNF and HLW case respectively

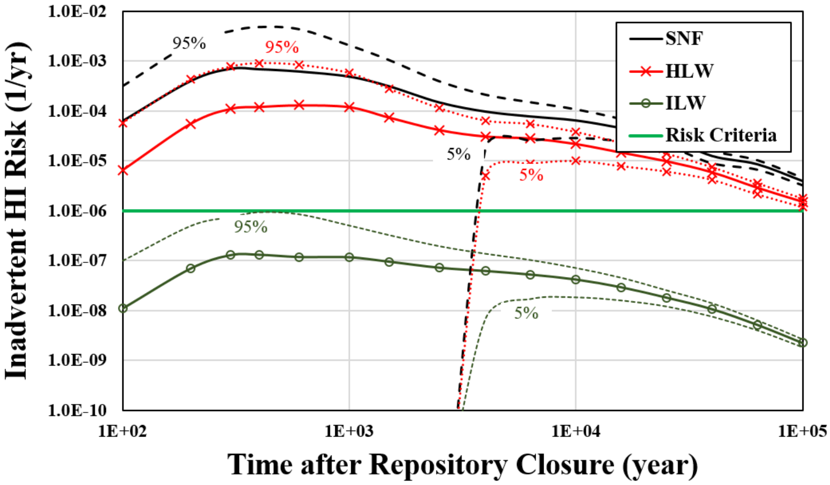

Figure 4.17 Inadvertent human intrusion risk of SNF and HLW repository with upper boundary of human intrusion frequency. The dashed and dotted lines indicate 5% and 95% quantiles of SNF and HLW case respectively

Chapter 5 Cost Benefit Model for Clandestine Human Intrusion

5.1 Game theory approach on clandestine human intrusion

5.1.1 System analysis on clandestine human intrusion

System analysis on clandestine human intrusion help us to improves our understanding on the relationship between desirability of intruder and safeguards efforts. The investment on safeguards system by the agent of a nation is determined by conceived diversion risk. High conceived diversion risk results in increase of safeguards efforts. The diversion risk would be a function of efforts by malicious actor[5] because the increased efforts results in increased diversion risk. The key question in clandestine human intrusion is the relationship between the safeguards efforts and the intruder's efforts (desirability of intrusion).

Figure 5.1 depicts the causal loop diagram of safeguards design. Depending on the relationship between safeguards efforts and intruder's efforts, the feedback loop can be either positive or negative. Disagreement between Peterson and Lyman was aroused from this point (Lyman and Feiveson, 1998;

[5] In case of clandestine human intrusion, malicious actor indicate a potential intruder.

Peterson, 1996). In viewpoint of Peterson, intruder's efforts increase along with safeguards efforts to recovery plutonium in a repository so that the positive feedback loop is built. In this case, social cost for safeguards would continuously increase, thereby a disposal of SNF is no longer preferable. On the other hand, Lyman guessed that safeguards efforts reduce intruder's efforts because reinforced safeguards system would reduce the probability of success of intrusion. Accordingly, negative feedback loop is formed so that minimized diversion risk can be expected with the low fixed safeguards cost. Consequently, a new model for clandestine human intrusion should prove the relationship between safeguards efforts and intruder's efforts.

Efforts of intruder is closely related with the desirability of intrusion. If the desirability is high, intruder would invest more efforts to recover plutonium in a repository; in the contrary case, intruder would not invest. In economic viewpoint, intruder would reduce or increase his/her efforts on clandestine intrusion if the expected economic payoff of the intrusion is negative or positive value. Therefore, this dissertation assumes that the desirability is determined by cost benefit motivation of intruder.

Figure 5.2 depicts the causal loop diagram of cost-benefit motivation feedback. The factor of intruder's efforts in Figure 5.1 is subdivide into three factors including benefit to intruder, intruder's motivation, and intrusion attempt so that the effect of safeguards on the desirability of intruder can be clearly shown. Reinforced safeguards system increases detection probability of clandestine human intrusion. Therefore, safeguards efforts have negative effect on intruder's motivation because reinforced safeguards would increase the cost of intrusion. Because the motivation and intrusion attempt have positive relationship, negative feedback loop is formed. Accordingly, the diversion risk can be minimized with the low fixed safeguards cost. However, the external constraint, benefit of intruder, shall undermine the negative effect of the feedback loop. The benefit to intruder is expected economic gain to intruder in case of successful intrusion. If the benefit is higher than the intrusion cost increased by reinforced safeguards, the negative effect of safeguards on the motivation would be invalid. Consequently, safeguards cost burden on society would increase.

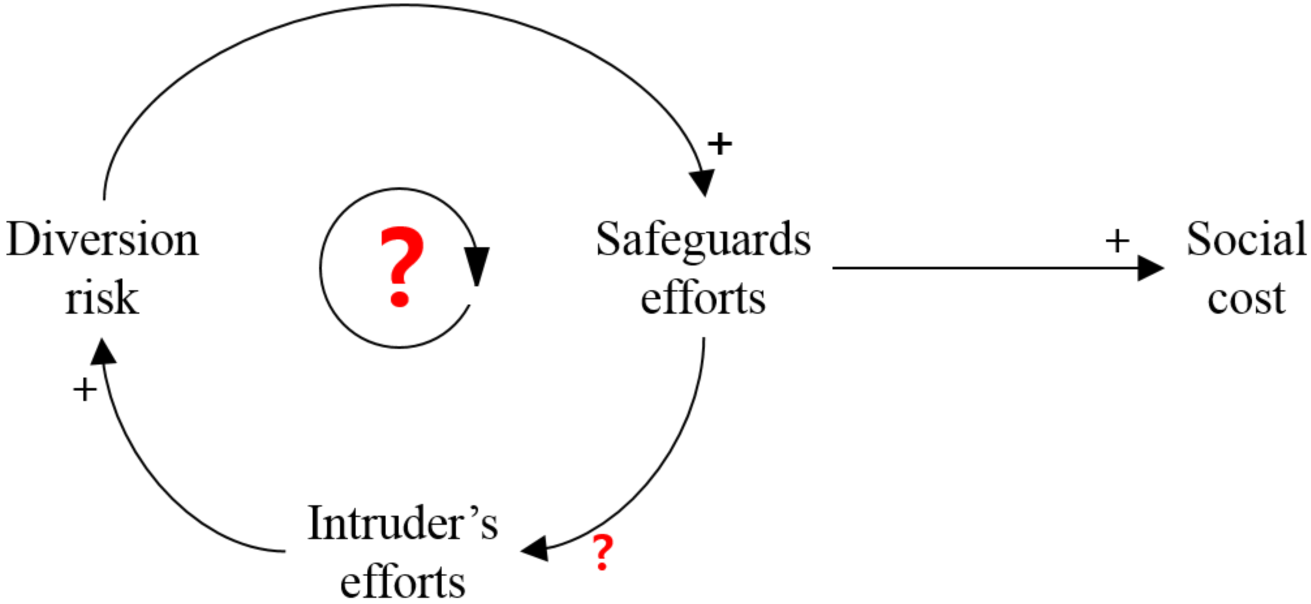

Figure 5.1 Causal loop diagram of uncertain feedback of safeguards design

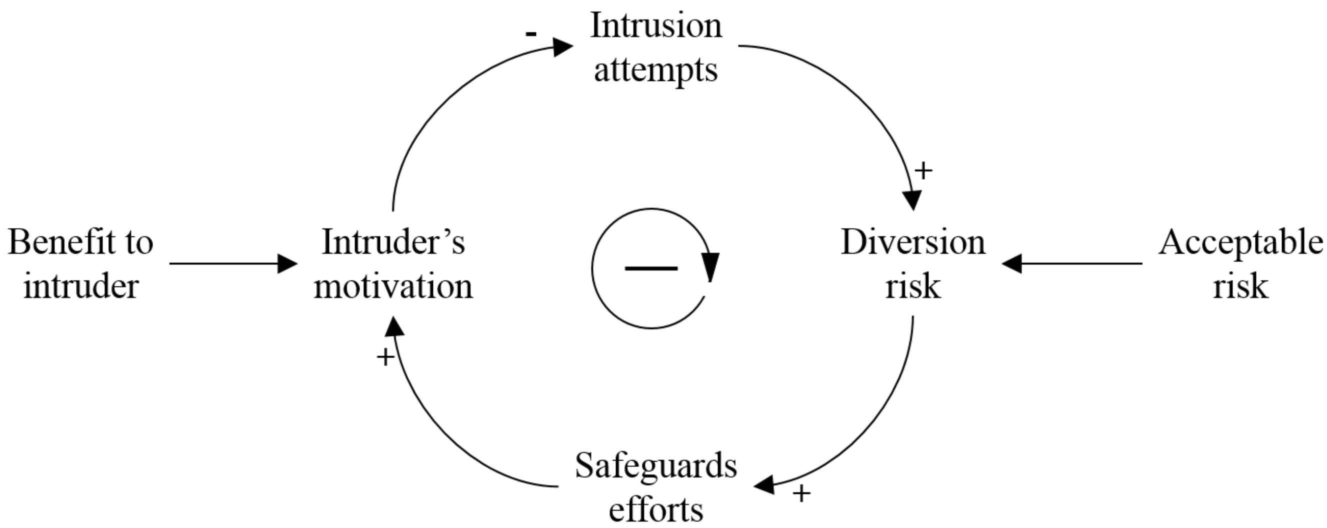

Figure 5.2 Causal loop diagram of cost-benefit motivation feedback

5.1.2 Plutonium mine game

System analysis on clandestine human intrusion in previous sections shows that cost benefit of intruder is the determinant for decision of intrusion. However, system analysis cannot present the criteria for decision making situation. Game theory provides a useful language to improve our understanding on such strategic decision making situation.

A problem of clandestine human intrusion can be though as plutonium mine game. The players participating in plutonium mine game represent two groups including the group of malicious actors who try to procure plutonium and society who try to defend a repository from malicious actor group. For convenience, the group of malicious actors is designated by intruder; and society is designated by safeguards agent[6]. Figure 5.3 illustrates simple strategic form of plutonium mine game. Each player has two strategies. Safeguards agent chooses one of two strategies, either safeguards or no safeguards: and simultaneously intruder chooses one of strategies described in columns, intrude or not intrude. Accordingly, four strategy combinations exist. Each strategy combination defines a pair of payoff for each player. For example, the strategy combination of (*safeguards, intrude*) results in payoff *a1* for safeguards agent and payoff *a2* for intruder. In this study, payoff is defined in a

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[6] In this study, society includes the Agency and Nations. Note that the cost burden to safeguards agent is equivalent to the cost burden to society.

view point of cost. Therefore, plus sign of payoff means cost burden to player whereas minus sign means benefit to player.

The preference of decision of each player is determined by the decision of another player. The intruder has incentive to intrude a repository owing to significant value of plutonium. The safeguards agent would like to assure so that intrusion attempt does not exist, but doing so requires cost for safeguards system. If intruder does not try to intrude, the safeguards agent would prefer no safeguards strategy. Such preferences of each player are marked with red arrows in. The circular arrow structure in Figure 5.3 shows that there is no strategy combination satisfying both players: that means no equilibrium state. Assuming that the players in game are rational, they try to maximize their payoff. Therefore, the players will mix their strategy with a certain probability to lead an equilibrium of the game. The equilibrium of the game is formed when both players are indifference with their decision. When preference exists, the equilibrium will collapse owing to circular preference arrow.

Consider that intruder chooses to intrude a repository with the probability of p. Then the payoff to the safeguards agent with safeguards strategy is expressed as follows:

$\text{Payoff} = \mathrm{a}_1 \cdot p + \mathrm{c}_1 \cdot (1-p)$	Eqn. 5.1

Likewise, the payoff to safeguards agent with no safeguards strategy is expressed as follows:

$\text{Payoff} = \mathrm{b}_1 \cdot p + \mathrm{d}_1 \cdot (1-p)$	Eqn. 5.2

The safeguards agent is indifferent on his decision when the values of Eqn. 5.1 and Eqn. 5.2 are same. Thus, the equilibrium probability of intrude strategy, p^*, is defined as follows:

$p^* = (\mathrm{d}_1 - \mathrm{c}_1)/(\mathrm{a}_1 + \mathrm{d}_1 - \mathrm{b}_1 - \mathrm{c}_1)$	Eqn. 5.3

Similarly, the equilibrium probability of safeguards strategy, q^*, is defined as Eqn. 5.4.

$q^* = (\mathrm{d}_2 - \mathrm{b}_2)/(\mathrm{a}_2 + \mathrm{d}_2 - \mathrm{b}_2 - \mathrm{c}_2)$	Eqn. 5.4

The equilibrium probability of each player is the criteria for decision making. Intruder would intrude if the frequency of safeguards actions is lower that the equilibrium probability of safeguards strategy, q^*. Safeguards agent would not safeguards if the frequency of intrusion is lower than the equilibrium probability of intrude strategy, p^*. Accordingly, minimum safeguards cost required to defense clandestine intrusion can be estimated.

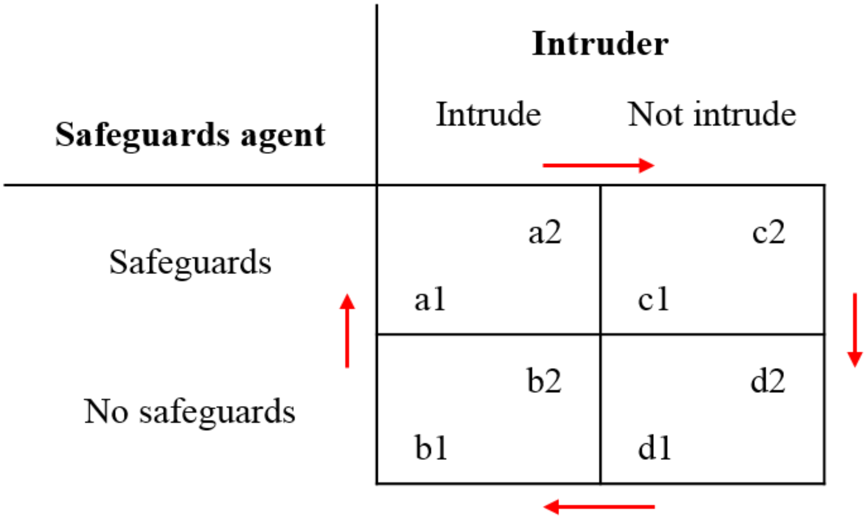

Figure 5.3 Strategic form of plutonium mine game with the preference of each player (red arrow)

5.2 Strategy of Pu mine game

5.2.1 Strategy of intruder

In this study, possible strategies for clandestine human intrusion are developed based on existing mining technologies. Technology which is not matured such as plasma drilling are not considered in this study because application of such technology to assessment would be so much controversial. Accordingly, two intrusion strategies are considered: intrusion through tunnel excavation and borehole drilling. As reference strategy, illicit trafficking of plutonium through black market is considered. In following sub-sections, details are described.

5.2.1.1 Tunnel excavation

Intrusion by clandestine tunnel construction would be the most credible strategy for intruder ensuring high quantity of plutonium at once. In this case, intruder constructs an access tunnel reaching a geological repository to recover plutonium contained in a disposal canister. Because intruder would directly access to a repository and transport stolen canister, a diameter of access tunnel would be in a range of a few meter. Considering that the slope of the access tunnel of ONKALO repository is 1:10 (Saanio et al., 2013), the minimum required tunnel length is assumed to be 5 km[7]. However, intruder may try to

[7] The depth of hypothetical repository is 500m.

construct a tunnel with longer length to start a construction at a location outside the monitored area. For example, the radius of monitoring area for the geological repository in Finland is 10 km; in this case, intruder may try to construct tunnel with more than 10 km length to conceal the entrance.

As past studies estimated, the duration of plutonium recovery by tunnel excavation strategy would be mainly determined by the tunnel construction time. Owing to a long length of tunnel, intruder would use tunnel boring machine (TBM) to reduce the cost and the duration of intrusion. The estimation of these two factors is conducted in Section 5.3.2. Once intruder successes to construct tunnel, he/she can recover multiple disposal canisters containing old SNF. In this study, it is simply assumed that the economic gain of intruder is proportional with a recovered quantity of plutonium. Therefore, the payoff of intrusion by tunnel excavation is the difference between the cost of intrusion and the economic gain from recovered plutonium.

5.2.1.2 Borehole drilling and chemical extraction

As INFCE and Lyman pointed out, physical recovery of a single disposal canister though vertical borehole (or shaft) with a diameter of about one meter has low probability of success because a drill should perfectly penetrate the location of SNF (INFCE, 1979; Lyman and Feiveson, 1998). However, the probability can be increased when chemical extraction mining technology is combined with. Conventional wet-reprocessing technology has proved that critical nuclear materials in SNF including uranium and plutonium are highly soluble in acid chemical (Benedict et al., 1981; Carrott et al., 2012; Gupta et al., 2000; Marc et al., 2017; Mineo et al., 2012; Patil et al., 1980; Rudisill et al., 2008). Therefore, significant quantity of plutonium can be leached when acid chemical fluid is injected through borehole.

The similar concept of chemical leaching mining technology has been proved by in situ mining of uranium (Bokovoya et al., 2014; Commonwealth of Australia, 2010; Edwards and Oliver, 2000; EPA, 2006; IAEA, 1992, 2001; Seredkin et al., 2016). Conventional in situ uranium mining process is simply divided into four processes: injection of acid chemical fluid, transportation of infected fluid through uranium baring layer, leaching of uranium in ore baring layer, and eject of fluid containing leached uranium. Among the processes, transportation of injected fluid is the most critical and difficult because widely distributed uranium ore should contact with the chemical by this process. However, plutonium in a geological repository is concentrated in a disposal canister so that such process is not required. In addition, deposition hole and backfill material surrounding a canister are solid hydraulic barrier. Such hydraulic barrier would effectively confine SNF and acid fluid like chemical reaction chamber excluding a loss of leached plutonium. Therefore, the application of in situ mining technology to recovery of plutonium in a repository would be much easier than conventional in situ mining process.

For such reasons, this study suggests recovery of plutonium by borehole drilling and chemical extraction as one of potential strategies for clandestine human intrusion. It is assumed that plutonium in one disposal canister is recovered by single drilling operation. The cost and the duration of intrusion are estimated based on historic database of drilling. The details values are described in Section 5.3.2. Like tunnel excavation intrusion, the payoff of intrusion by calculated by the difference between the cost of intrusion and the economic gain from recovered plutonium.

5.2.1.3 Illicit trafficking though black market

Illicit trafficking of plutonium though black market is considered as the reference strategy for malicious actor. The reference strategy is required as the comparative option for strategic decision making of malicious actor. It is assumed that malicious actor tries to traffic plutonium through black market, if both strategies of clandestine human intrusion are not desirable. The payoff of black market is set to be zero as a reference.

5.2.2 Strategy of safeguards

Figure 5.4 describes safeguards system for a geological repository during post-closure period. Unlike conventional nuclear facilities, direct monitoring on and verification of nuclear material are impossible for a sealed repository due to long-term safety problem (details in Section 2.3.2). Therefore, objectives of safeguards system for geological repository are the detection and verification of a suspicious activity that possibly relates with clandestine intrusion. In this study, two strategies are considered for monitoring options and verification options respectively. The monitoring strategies include seismicity and satellite imagery monitoring; the verification strategies include onsite inspection and physical security.

5.2.2.1 Monitoring strategy

The target of seismic monitoring is micro-seismicity signal induced by drilling or tunnel excavation. Considering cumulative experiences in Finland, an occurrence of micro-seismic event as well as its location with Richter magnitude scale over -4 M_L would be detectable by seismic monitoring system (Saari and Malm, 2015a). Therefore, the detection probability of seismic monitoring for tunnel excavation is assumed to be high[8]. However, micro-seismic signal of borehole drilling would be undetectable by seismic monitoring system. First, magnitude of seismic signal by borehole drilling is expected under -4 M_L which is hardly detectable by remote seismic station (Goertz et al., 2012). Second, the duration of drilling operation would be very short: an order of a few days[9]. For such reasons, this study assumes that clandestine borehole drilling would be undetectable by seismic monitoring system. In addition, only full-time operation is assumed to be possible for

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[8] Some seismic events which were not located by seismic monitoring system were reported. However, such uncertainty is ignored because long-term duration of tunnel excavation work would reduce such uncertainty.

[9] Frequent seismic signal is required for micro-seismic event due to background noise problem.

seismic monitoring.

Satellite monitoring detects a perturbation of geographical features such as aerial, thermal imagery. In case of tunnel excavation, pile of excavated rock debris and movement of vehicles related with construction activity can be clue for clandestine intrusion. The scale of activity related with tunnel excavation would be large so that high detection probability is expected unless the intrusion is conducted outside of monitoring area. However, the possibility of effective countermeasure to satellite monitoring including camouflage concealment, deception against overhead detection, identification, and assessment cannot be excluded. Therefore, medium-high detection probability is assumed for satellite monitoring for tunnel excavation. On the other hand, the detection probability of drilling activity would be relative smaller. Figure 5.5 shows examples of in situ leaching uranium mine well[10] which are very similar to common groundwater well. Accordingly, application of countermeasures to clandestine borehole drilling would be much efficient than that of tunnel excavation. Therefore, medium-low detection probability is assumed for satellite monitoring for borehole drilling and chemical extraction strategy. Unlike seismic monitoring, the annual frequency can be designed for

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[10] Left figure from the IAEA (https://www.iaea.org/newscenter/multimedia/photoessays/where-uranium-found-and-how-it-processed-nuclear-energy), right top from Wikipedia (https://en.wikipedia.org/wiki/In_situ_leach), and right bottom from the WNA (http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/kazakhstan.aspx)

satellite monitoring.

5.2.2.2 Verification strategy

The verification probability is assumed to be high for both strategies including onsite inspection and physical security. The difference between two strategies is the frequency of such action. In this study, it is assumed that only full-time operation is possible for physical security whereas frequency of onsite inspection can be designed. The strategic decision making of safeguards agent is assumed to be totally dependent on the cost.

Figure 5.4 Safeguards system for a geological repository during post-closure period

Figure 5.5 In situ leaching uranium mine (left: Beverley South Australia, right top: Czech, right bottom: Kazakhstan)

5.3 Parametrization

5.3.1 Mathematical model

Let $\mathrm{P}_{\mathrm{intruder}}$ be the payoff of intruder:

$P_{\mathrm{intrusion}} = C_{\mathrm{intrusion}} - B_{\mathrm{intrusion}}$	Eqn. 5.5

where $C_{\mathrm{intrusion}}$ is the cost of intrusion, and $B_{\mathrm{intrusion}}$ is the expected benefit of intrusion.

The expected benefit of intrusion is defined as follows:

$B_{\mathrm{intrusion}} = (1 - PD_{\mathrm{intrusion}}) \cdot \mathrm{UP}_{Pu} \cdot M_{Pu}$	Eqn. 5.6

where $PD_{\mathrm{intrusion}}$ is the detection probability for intrusion, UP_{Pu} is the unit price of plutonium in black market, and M_{Pu} is the plutonium mass recovered.

The reference strategy, illicit trafficking of plutonium though black market, would be payoff zero to intruder. Such assumption is physically reasonable because the cost and benefit would be same in this case. Therefore, at equilibrium, payoff of each strategy is zero:

$P_{\mathrm{excavation}} = P_{\mathrm{drilling}} = 0$	Eqn. 5.7

Accordingly, the equilibrium detection probability of safeguards system for intrusion is defined as follows:

$PD^*\Big\vert_{\text{excavation}} = 1 - \dfrac{C_{\text{excavation}}}{\text{UP}_{Pu} \cdot M_{Pu}}$	Eqn. 5.8
$PD^*\Big\vert_{\text{drilling}} = 1 - \dfrac{C_{\text{drilling}}}{\text{UP}_{Pu} \cdot M_{Pu}}$	Eqn. 5.9

where $PD^*\big\vert_i$ is the equilibrium detection probability of safeguards system for intrusion strategy i.

In this study, random monitoring with a certain frequency is assumed. Therefore, the detection probability of monitoring system is defined as:

$PD = 1 - \sum_{k=0}^{k=N} Pois(\lambda, k) \cdot (1-pd)^k$	Eqn. 5.10
$N = \lambda \cdot (1\ \text{year})/\text{T}_{\text{intrusion}}$	Eqn. 5.11

where $Pois(\lambda, k)$ is the probability of occurring k monitoring events during the duration of intrusion with Poisson process, λ is the average number of monitoring events during duration of intrusion, N is annual frequency of monitoring activity, pd is probability of detection per one monitoring event, and $\text{T}_{\text{intrusion}}$ is the duration of clandestine intrusion.

As described in Section 5.2.2, only full-time operation is possible for seismic monitoring strategy. For this reason, Eqn. 5.10 is only applicable to satellite monitoring. It is assumed that the detection probability of seismic monitoring is high ($PD=1$) for tunnel excavation and low ($PD=0$) for drilling intrusion.

Then, the payoff of society $\mathrm{P}_{\text{society}}$, is assumed to consist of the cost of safeguards and the contingency cost of terror. Accordingly, the payoff of society is expressed as follows:

$\mathrm{P}_{\text{society}} = C_{\text{safeguards}} + C_{\text{contingency}}$ $= C_{\text{monitoring}} + C_{\text{verification}} + C_{\text{contingency}}$	Eqn. 5.12

where $\mathrm{C}_{\text{safeguards}}$ is the cost of safeguards consisting of the cost of monitoring, $\mathrm{C}_{\text{monitoring}}$, and verification, $\mathrm{C}_{\text{verification}}$, and $\mathrm{C}_{\text{contingency}}$ is the contingency cost of terror.

The cost of monitoring is determined by the frequency of monitoring measures and estimated as follows:

$C_{\text{satellite}} = N_{\text{satellite}} \cdot \mathrm{UC}_{\text{satellite}}$	Eqn. 5.13
$\mathrm{C}_{\text{seismic}} = \mathrm{UC}_{\text{seismic}}$	Eqn. 5.14

where UC_i is unit cost of monitoring measure i, and $N_{\text{satellite}}$ is annual frequency of satellite monitoring.

Verification of suspicious action is required when the detection signal from monitoring system is accepted. Thus, the cost of verification is defined as follows:

$C_{\text{inspection}} = PD_{\text{monitoring}} \cdot f_{\text{intrusion}} \cdot \text{UC}_{\text{inspection}}$	Eqn. 5.15
$\text{C}_{\text{physical security}} = \text{UC}_{\text{physical security}}$	Eqn. 5.16

where C_j is the cost of verification measure j, $PD_{\text{monitoring}}$ is the probability of detection of clandestine intrusion, and $f_{\text{intrusion}}$ is the frequency of clandestine intrusion. It is assumed that both verification strategies will effectively deter the detected intrusion attempts.

The contingency cost for terror is defined as follows:

$C_{\text{contingency}} = (1 - PD) \cdot f_{\text{intrusion}} \cdot D$	Eqn. 5.17

where D is expected terror damage by diverted nuclear explosive.

There are four possible strategy combinations for safeguards agent: (*seismic, inspection*), (*seismic, physical security*), (*satellite, inspection*), and (*satellite, physical security*). The model for clandestine human intrusion in this study consider (*satellite, inspection*) as reference for safeguards agent because their frequency is under control. If the cost by such strategy combination is higher than others, other options would be chosen. For reference safeguards strategy, the payoff of society is expressed as follows:

$P_{\text{society}} = N \cdot \text{UC}_{\text{satellite}} + PD \cdot f_{\text{intrusion}} \cdot \text{UC}_{\text{inspection}} + (1-PD) f_{\text{intrusion}} \cdot \text{D}$	Eqn. 5.18

At equilibrium, the payoff of society would be minimum. Thus, the solution for the equilibrium is:

$\left.\frac{\partial P_{\text{society}}}{\partial N}\right\|_{N^*,\, f_{\text{intrusion}}^*} = 0$ $= \text{UC}_{\text{satellite}} + \left.\frac{dPD}{dN}\right\|_{N^*} \cdot f_{\text{intrusion}}^* \cdot \text{UC}_{\text{inspection}} + (1 - \left.\frac{dPD}{dN}\right\|_{N^*}) \cdot f_{\text{intrusion}}^* \cdot \text{D}$	Eqn. 5.19

Finally, from Eqn. 5.19, the equilibrium probability of clandestine intrusion is derived as follows:

$f_{\text{intrusion}}^* = \dfrac{-\text{UC}_{\text{satellite}}}{\left.\frac{dPD}{dN}\right\|_{N^*} \cdot \text{UC}_{\text{inspection}} + (1 - \left.\frac{dPD}{dN}\right\|_{N^*}) \cdot \text{D}}$	Eqn. 5.20

5.3.2 Parametrization on input parameters

The values of parameters and their descriptions are summarized in Table 5.1.

The cost and the duration of intrusion strategies are estimated based on historical records of the projects or experiments of tunnel excavation and drilling. The hypothetical repository considered in this study has hard rock formation. Therefore, data in hard rock condition with uniaxial compressive strength range over 70 to 300 MPa are used.

The strategy of clandestine tunnel excavation considers the reference scenario of construction of access tunnel with the length of 5 km and the diameter of 3m. The construction cost is estimated based on the cost estimation model developed by Rostami (Rostami et al., 2013). The duration is determined by the speed of TBM. Table 5.2 summarizes hard rock tunnel excavation projects worldwide. The data is referred from database of The Robbins Company (The Robbins Company, 2017). Considering the best month performance, the tunnel with 5 km length is expected to be constructed within about 4.6 months. In case of the project in ROK, the best performance of 14.4 m/day is reported (Bae et al., 2015). Such variation of ROP records is used for sensitivity assessment of the model.

The strategy of drilling and chemical extraction considers the reference scenario of drilling single borehole with a depth of 500 m. The cost of borehole drilling is referred from cost estimation study by Augustine (Augustine et al., 2006). The ROP data of drilling in hard rock condition are summarized in Table 5.3.

Table 5.1 Parametrization of the values for clandestine human intrusion model (cont.)

Parameters	**Value**	**Note**
Cost of tunnel excavation, $C_{\text{excavation}}$	39.2 M$	Scenario description: Excavation of clandestine tunnel with the length of 5 km and the diameter of 3 m Cost is estimated by model of (Rostami et al., 2013): $\text{Cost}=10^{(0.319+0.901\cdot\log(\textit{length})+1.34\cdot\log(D))}$ M$ ROP of TBM: 14.4 m/day (Bae et al., 2015)
Duration of tunnel excavation, $\text{T}_{\text{excavation}}$	11.5 months	
Cost of drilling, C_{drilling}	227 k$/borehole	Scenario description: Drilling one borehole with 500 m depth Cost estimation from (Augustine et al., 2006) ROP drilling: 5 m/hr (Lee et al., 2016)
Duration of drilling, $\text{T}_{\text{drilling}}$	4.16 days/borehole	
Unit price of Pu, UP_{pu}	5.84 M$/kg	Pu price is referred from (DOE, 2017)

Parameters	Value	Note
Unit cost of satellite monitoring, $UC_{satellite}$	0.5 k\$/(25 $km^2 \cdot$ imagery)	Cost data is referred from (Pabian, 2015)
Unit cost of seismic monitoring, $UC_{seismic}$	2.8 M\$/yr	Cost data is referred from (CRECH, 2003)
Unit cost of onsite inspection, $UC_{inspection}$	15 k\$/(person $\cdot$ day)	Inspection cost of IAEA for ROK is referred from (IAEA, 2016b)
Unit cost of physical security, $UC_{phsical\ security}$	40 M\$/yr	Personal communication[11]

[11] IlSoon Hwang, November 17, 2017

Table 5.2 Historical records of tunnel excavation projects in hard rock condition (cont.)

Year	Location	Project name	*D* (m)	*L* (km)	Rock (MPa[12])	Best ROP	Average ROP
1989	Norway	Svartisen Hydroelectric	4.3	6	Complex (100 -300)	75.8 m/day 312 m/week 1,068 m/month	3.8 m/hr
1989	Norway	Svartisen Hydroelectric	4.3	11.8	Complex (100-300)	90.2 m/day 360.5 m/week	3.5 m/hr
1989	Norway	Svartisen Hydroelectric		4	Complex (100-300)		3.7 m/hr
1991	Hong Kong	Hong Kong Cable Tunnel	4.8	5.4	granite, quartz, volcanic		100 m/week 2.8 m/hr

[12] Uniaxial Compressive Strength (USC)

Year	Location	Project name	*D* (m)	*L* (km)	Rock (MPa[12])	Best ROP	Average ROP
1993	USA	San Manuel Mine Tunnel	4.6	10.5	Complex		30 m/day
1998			10.05	9.6	metamorphic		290 m/month
2001	USA	Cobb County Sewer Tunnel	5.58	14.6	Hard (150-230)		650 m/month
2005	China	Dahuofang Water Tunnel	8.03	20	migmatite		475 m/month
2005	China	Dahuofang Water Tunnel	8.03	16	migmatite		500 m/month

Year	Location	Project name	*D* (m)	*L* (km)	Rock (MPa[12])	Best ROP	Average ROP
2006	Iceland	Kárahnjúkar Hydropower Project	7.63	14.3	(300)	93 m/day 864.6 m/month	
2007	Iceland	Kárahnjúkar Hydropower Project	7.23	14.1	(300)	106.1 m/day	
2007	Iceland	Kárahnjúkar Hydropower Project	7.23	11.4	(300)	115.7 m/day 428.8 m/week	
2008	India	Kota City Water Supply Project	1.5	0.05	(200-250)		1.5 m/hr
2009	USA	East Side Access Project	6.7	5.2	(100-275)		2.0 m/hr

Year	Location	Project name	*D* (m)	*L* (km)	Rock (MPa[12])	Best ROP	Average ROP
2009	Canada	Seymour Capilano	3.8	7.2	Granite (200-265)	29 m/day	
2010	USA	East Side Access Project	6.7	5.2	(100-276)		2.2 m/hr
2010	Malaysia	Pahang Selangor Raw Water Tunnel	5.23	44.6	Granite (200)	3.5 m/hr	
2013	Turkey	Kargi Hydroelectric Project	10	7.8	(140)	600 m/month	
2014	Turkey	Kargi Hydroelectric Project	10	7.8	(140)	39.6 m/week 723 m/month	

Table 5.3 Drilling ROP in various rock formations (cont.)

Rock type	UCS (MPa)	ROP (m/min)	Reference
Monozonit	57.6	0.52	(Hoseinie et al., 2009)
Granite	87.5	0.35	
Limestone	51.3	0.44	
Travertine	50.5	0.58	
Travertine	53.7	0.81	
Silica	112	0.1	
Nepheline cyanite	76.5	0.22	
Sandstone	14.2	1.25	
Magnetite	191.7	0.557	(Ataei et al., 2015)
Magnetite	126.1	0.682	
Magnetite	177.7	0.628	
Magnetite	99.9	0.76	
Magnetite	97.3	0.87	

Rock type	**UCS (MPa)**	**ROP (m/min)**	**Reference**
Magnetite	241.5	0.39	
Magnetite	206.9	0.507	
Magnetite	181.3	0.61	
Magnetite	171.9	0.49	
Waste rock	134.2	0.653	
Magnetite	227.0	0.494	
Granite		0.083 (D=300mm)	
Granite		0.0625 (D=500mm)	(Lee et al., 2016)
Granite		0.0416 (D=7500mm)	

5.4 Application to hypothetical repository

5.4.1 Minimum safeguards cost and behavior of intruder for the reference scenario

The minimum annual safeguards cost[13], $C^{*}_{\text{Safeguards}}$, at the beginning of repository post-closure period is estimated based on parameters' values in Table 5.1 as a function of an objective amount of plutonium for intruder (Figure 5.6). It is assumed that 20 kg of RG-Pu is contained in one disposal canister at that time. The reference safeguards strategy, (*satellite, inspection*), is used for the estimation. Four regions divided by the two lines are marked with the text boxes. A region indicates expected decision of intruder under a certain condition consisting of investment on safeguards cost by safeguards agent and an objective amount of plutonium for intruder. To reduce the motivation of intrusion, safeguards cost must be included in region I.

The blue line in Figure 5.6 indicates the minimum safeguards cost corresponding to drilling strategy of intruder. Because multiple drillings are required to recover multiple disposal canisters at once, detection of drilling attempt gets easier when intruder intends to recover plutonium greater than 20 kg at once. Therefore, minimum safeguards for drilling strategy reduces with objective amount of plutonium for intruder. The peak of blue line (yellow star

[13] Equilibrium safeguards cost

mark on blue line) corresponds to 20 kg of plutonium, maximum recoverable plutonium by a single drilling attempt. At that point, the payoff of drilling strategy is maximized so that the greatest safeguards effort is required. Considering reasonable intruder, an intruder would try to steal 20 kg of plutonium because his/her payoff is maximum at that point. Conservatively, the minimum safeguards cost of 1.04 M$/yr would be required for drilling strategy of intruder. According to the results, it can be considered that an intruder will try to intrude by drilling for plutonium unless the safeguards cost is higher than 1.04 M$/yr.

The red line in Figure 5.6 indicates the minimum safeguards cost corresponding to tunnel excavation strategy of intruder. Unlike drilling strategy, intruder is able to recover multiple disposal canisters at once through a single clandestine tunnel. Therefore, minimum safeguards for drilling strategy increases with objective amount of plutonium for intruder. In ROK case (Choi et al., 2013), the total amount of plutonium in repository at the beginning of repository post-closure period is assumed to be about 278 tone. Like drilling strategy, safeguards effort would be greatest when the payoff of excavation strategy is maximum. Conservatively, 92.3 k$/yr of minimum safeguards cost would be required for tunnel excavation strategy of intruder.

A content of plutonium in a single disposal canister changes over time as shown in Figure 1.5. However, due to significantly long half-life, an amount of plutonium will not decrease a lot until 10,000 years after repository post-closure. Accordingly, a reduction of minimum safeguards cost will be slight until that time. The change of minimum safeguards cost over time is summarized in Table 5.4. The table shows that an order of million dollars of minimum safeguards cost would be required to protect a repository from clandestine drilling intrusion over 10,000 years. In the reference safeguards scenarios, monitoring and verification measures are identical for both drilling and tunnel excavation strategies. Therefore, it is expected that the safeguards efforts for drilling intrusion is able to cover a protection of repository from clandestine tunnel excavation. A content of plutonium in a disposal canister will be lower than the minimum quantity for nuclear explosive at about 70,000 years after repository post-closure. However, the model estimates that the safeguards cost will be needed even after 70,000 years because only a small quantity of plutonium is still valuable. In practical, intruder would not intrude if the quantity of plutonium in a disposal canister is lower than the one required for a nuclear explosive.

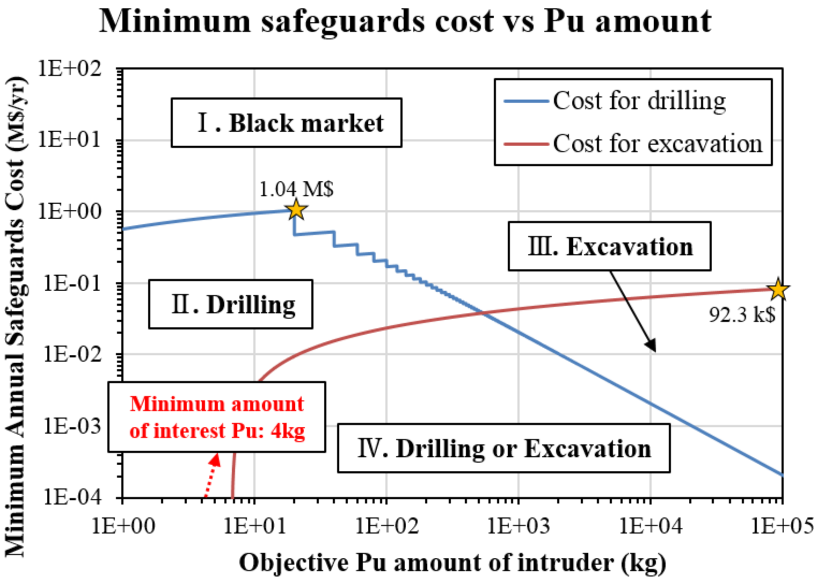

Figure 5.6 Minimum annual safeguards cost by an objective plutonium amount of intruder

Table 5.4 Minimum safeguards cost for clandestine intrusion over time

Time after post-closure	Minimum safeguards cost	
	Drilling (M$/yr)	Tunneling (k$/yr)
Beginning	1.04	92.3
10 year	1.04	92.0
100 year	1.03	91.1
1,000 year	1.02	90.7
10,000 year	0.97	87.4
100,000 year	0.61	71.4

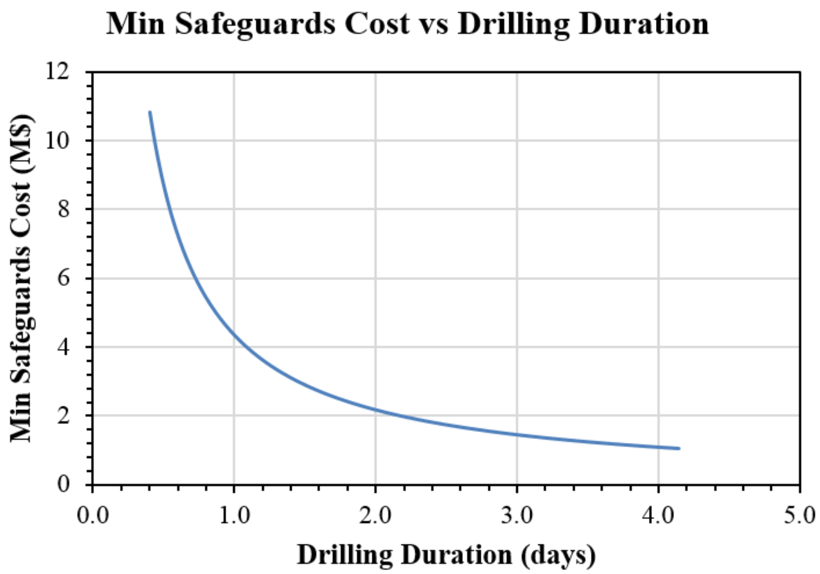

Figure 5.7 Sensitivity of minimum safeguards cost on the duration of drilling intrusion

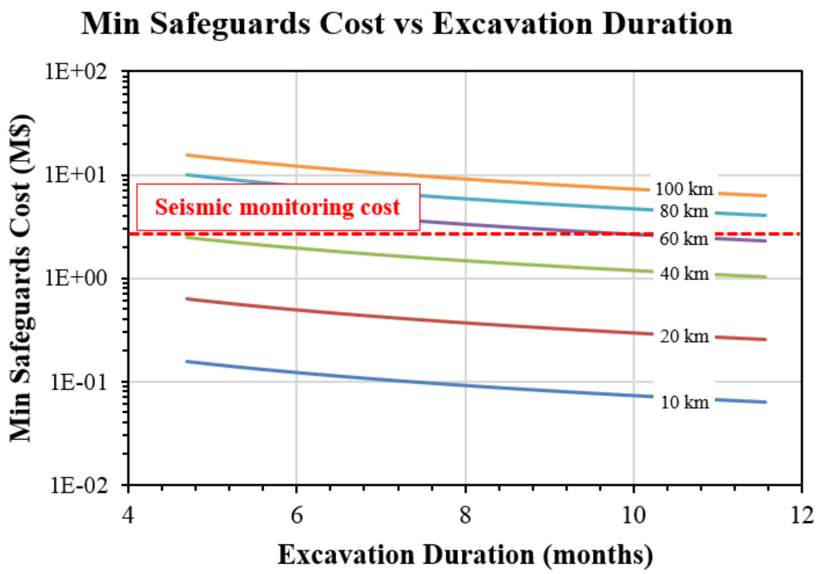

Figure 5.8 Sensitivity of minimum safeguards cost on the duration of tunnel excavation intrusion

Chapter 6 Implication of the Study

6.1 Implication of the model for inadvertent human intrusion

6.1.1 Implication of the model

The dynamic Monte Carlo model has been developed in this study for the estimation of safety risk of inadvertent human intrusion. The capability of the model is helpful not only for improving our understanding on uncertainties in inadvertent human intrusion but also for supporting our decision on design and political approach for SNF problem.

First, the importance of uncertainties in inadvertent human intrusion are clearly derived by systematic modeling approach. As previously pointed out, numerous uncertainties inevitably exist owing to long assessment timeframe over 10,000 years and all the uncertainties are not able to be considered. Therefore, an assessment of inadvertent human intrusion should show the behavior of currently conceivable uncertainties in future based on conservative assumptions derived from our historical experiences. Such consideration has not been properly done in the past investigations. The model developed in this study facilitate both qualitative and quantitative analysis on societal and technological uncertainties which are currently conceivable. As a results, understanding on the uncertainties and their importance has been able to much improved.

Despite such improvement, it should be noted that the results from the model are not exact answer because there will be currently unconceivable uncertainties in future. However, such modeling approach reasonably incorporates currently conceivable uncertain factors so that the results can support the decision on repository design, and SNF management policy. Especially, relative comparison between various SNF management policy, like Figure 4.16 and Figure 4.17, would be used as scientific basis for society's decision making process.

6.1.2 Implication of the results

The qualitative and quantitative assessment results on the risk of inadvertent human intrusion into hypothetical repository model show that the past studies have underestimated the risk. The frequency of drilling activity will increase to a certain value in future while it has been assumed to be time constant variable in past approaches. Accordingly, the case assessment results in this study show that the probability of inadvertent human intrusion would possibly increase up to about 10 times higher than that of currently expected. Since the values of modeling parameters are estimated based on the historical database of groundwater development in ROK, the results may not be applicable to other countries with different societal conditions. The representative societal factor which would affect the results of inadvertent human intrusion is population density. The risk of inadvertent human intrusion may be estimated to be low for countries with low population density, because they would have low probability of using repository site for purposes of human activity. Such tendency of increasing probability of inadvertent human intrusion in future would generally applicable to other countries with high population density such as Southeast Asia region. However, we should note that if population worldwide would continuously increase as today, an inadvertent human intrusion will be the concern for all countries.

Such probability is estimated in consideration of only drilling activity for groundwater development. Demand for other underground resources would cause an additional motivation for inadvertent human intrusion even though the motivation would not continuous as groundwater case. Considering the feedback loop of drilling activity, illustrated in Figure 4.5, temporal increase in the probability of human intrusion will occur in such situation. Therefore, the results of inadvertent human intrusion would be the baseline probability. The actual human intrusion probability can increase. In such context, conservative results should be used for estimation of the risk of inadvertent human intrusion. When applying to a real repository, consideration of additional safety margin to probability estimation would be appropriate.

The results on the risk of inadvertent human intrusion is estimated for two cases: the first case assumes that the future depth distribution of groundwater well will be same as today; another case assumes that a deep well reaching to the hypothetical repository will be frequent in future. This dissertation suggests to apply second case because not only an average depth of groundwater is increasing but also a conservative approach is required as discussed in previous paragraph. The risk estimation results of second case shows that emplacement of SNF or HLW into the hypothetical repository design would not satisfy the regulatory criteria. Such results imply that a geological repository having similar design with the hypothetical repository will also be vulnerable to deep groundwater development in the future. Noting that drilling for groundwater has been conducted with less concern and information about a site than that for other resources, careful design and policy approaches are required to reduce the risk of inadvertent human intrusion. As discussed in Section 4.3, possible approach to minimize the risk includes reducing the area of a repository, increasing the depth, and reducing the radiotoxicity of the waste. Detailed suggestions on design modification on a repository and SNF management policy proposed in Section 6.3.

6.2 Implication of the model for clandestine human intrusion

6.2.1 Implication of the model

The relationship between safeguards efforts by safeguards agent and desirability of clandestine intruder is explained by qualitative simple system analysis model and quantitative assessment approach is suggested by game theory model. The game theory model, named plutonium mine game in this dissertation, is developed based on the assumption that the decision of malicious actors would be determined by cost benefit of their strategies. Considering that such approach has used to be applied not only to conventional nuclear facilities but also other conflict situation, the developed model is appropriate tool for decision making on safeguards program during repository post-closure period. It would be expected that the suggested model helps society to derive solution for clandestine human intrusion problem and to build consensus which has not been accomplished.

Key parameters considered in the developed model are as follows: cost and benefit for clandestine intruder, detection probability of safeguards program as a function of cost, and economic damage on society as a function of an amount of stolen plutonium. Parametrization of plutonium mine game model is conducted based on the information given by the literatures so that the cost burden by long-term safeguards is preliminarily estimated. Although the parametrization of the model requires a little modification to apply to real repository system, it is obvious that such approach would be useful tool for judging and designing the safeguards program for a repository.

6.3 Recommendation for minimizing human intrusion risk

6.3.1 Suggestions on repository design

Several design approach to minimize the risk of human intrusion are suggested in this Section.

Two possible design approach can be considered for minimizing the risk of inadvertent human intrusion: improvement in hazard recognition system, and reducing the probability of drilling The first is related with the causal loop of surface activity and protection system feedback illustrated in Figure 4.6. An early recognition of radiological hazard would protect radiological exposure situation by inadvertent human intrusion. The design suggestion to improve hazard recognition system for future generation is a double-layered repository concept. The double-layered repository concept has been considered as an option to reduce an area of the repository for a country with small land area such as ROK (Lee et al., 2017). In viewpoint of inadvertent human intrusion, emplacement of low-intermediate radioactive wastes (LILW) upper layer would help inadvertent intruder to recognize potential radiological hazard before he/she penetrates a HLW or SNF emplaced in bottom layer. As shown in Figure 4.16, the risk of inadvertent human intrusion by ILW is acceptable. Consequently, such double-layered repository option would reduce the risk of inadvertent human intrusion.

For the second design approach for reducing the probability of drilling, there are three suggestions as follows: a repository with deeper depth; a deployment of boulder layer; and selection of rock condition with low drillability. As shown in Figure 4.15, the deeper a depth of repository the lower a probability of inadvertent human intrusion. Therefore, a repository at a depth of more than a few kilometers would reduce the risk of inadvertent human intrusion. A deep vertical borehole repository concept (Brady et al., 2012; Lee et al., 2016) or a deep horizontal repository concept (Muller, 2016) would be able to be considered as possible options. In underground development industry, an existence gravel or boulder layer has been a challenging issue for drilling or excavation. In such layer, drill machine spins with no traction so that it cannot advance. Therefore, a deployment of artificial boulder layer above a disposal tunnel would effectively deter a drilling attempt. In the same context, hard rock condition with low drillability would reduce the probability of drilling.

In a viewpoint of clandestine human intrusion, the second design approach for inadvertent human intrusion would increase clandestine intruder's effort to recover nuclear materials in a repository. Therefore, an application of one of three design suggestions above would reduce the minimum safeguards cost for clandestine human intrusion.

6.3.2 Suggestions on SNF management policy

The results in this study shows that human intrusion problem in disposing of SNF should not be ignorable. Although several suggestions on a design of repository to reduce originating from human intrusion problem are proposed in previous section, policy on a geological repository supporting the design approach is required. First, development of a modified repository design takes a lot of time and investment. An urgent country facing significant accumulation of SNF would not be relaxed until modified repository design is scientifically and socially approved. Second, design approach itself cannot fully eliminate potential uncertainties in human intrusion problem. Additional measures providing acceptable risk even in unexpected situation are required. Therefore, policy measures which are feasible in near term are required to complement limitations of design modification approach.

Institutional control on repository site and continuity of knowledge are representative examples of policy measures which are currently considered for various geological repositories to support performance of repository design and to reduce potential uncertainties. Institutional control would be the most promising way to prevent both inadvertent and clandestine human intrusions because a repository site is restricted as exclusion area. However, considering that one of the primary objective of geological repositories is minimizing long-term burden to future generation, maintaining institutional control over long-term would not be preferable. Continuity of knowledge will reduce the probability of inadvertent human intrusion. However, judging until when such knowledge will be continuous is so much uncertain that we cannot rely on this measure.

Therefore, three other policy suggestions are proposed in this study. The first is reduction of radiotoxicity of spent nuclear fuel by partitioning and transmutation (P&T) fuel cycle. Because the content of critical radionuclides in radioactive wastes can be reduced through P&T fuel cycle, the uncertainties of human intrusions into a geological repository are intrinsically reduced. In addition, this option would be feasible in very near term because numerous technologies have already been developed (Bowman et al., 1992; Croff et al., 1980; Inoue et al., 1991; Jung et al., 2012; OECD NEA, 2012; Salvatores and Palmiottib, 2011). There shall be additional concern on the potential proliferation risk during P&T cycle yet. Comparing with disposal of SNF into deep geological repository, uncertainties in proliferation risk of P&T facilities are much more insignificant because proven safeguards program for conventional nuclear facilities is applicable to the facility. Moreover, considering the long-term safeguards program for SNF repository, safeguards cost for P&T cycle is expected to be more acceptable.

Another policy suggestion is application of *reversibility* and *retrievability* (R&R) to a design of repository. The term reversibility denotes 'the possibility of reversing one or a series of steps' in disposal procedures at any stage of the program (OECD NEA, 2001). The placement of reversibility facilitates a flexibility in decision making for disposal program in consideration of any change in information and conditions that potentially affect the prior decision on radioactive waste management. In the context of reversibility, retrivability denotes the possibility of retrieving emplaced waste when reversion of decision on radioactive waste disposal program has been made for a certain reason. The R&R approach would gain time for an urgent country to assure reliability of its disposal program and give additional opportunity to fix an incident problem broken out by unexpected uncertainty. In other word, a geological repository would function as a '*long-term*'[14] storage before the R&R policy has been withdrawn. Such function is especially significant for assessment of human intrusions because the accumulated observation on technological and societal change would be used to enhance the verification on the approach to estimate the risk of human intrusions.

The last policy suggestion is a multinational cooperation approach for a radioactive wastes repository. This approach denotes development a regional

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[14] Here, the word '*long-term*' denotes a timeframe of about a few hundred years while in other parts of this paper it denotes a timeframe of over 10,000 years.

repository shared and operated by a cooperation of multiple nations. The details about such approach is well discussed by IAEA (IAEA, 2016a). The main reason that human intrusions into a geological repository is a significant challenge is that the access of future generation on repository site cannot be restricted. By the same reason, not only monitoring of safeguards program for clandestine human intrusion would be disturbed but also the cost would be high. In contrast, continuous restriction on unauthorized access of general public would be feasible because international cooperation would facilitate long-term superintendence on a repository. In addition, cost sharing by participating countries would also reduce the safeguards cost burdening to each country.

Chapter 7 Conclusion

7.1 Conclusion

Disposing of spent nuclear fuels into geological repository inevitably involves long-term safety and safeguards problem. Future human intrusion, the risk given by future human action on a radioactive waste repository, is the most troublesome issue because of its severe negative consequence on the safety of the public and on the nuclear security. Aggregating the uncertainty and risk originated by future human intrusion needs to account for the complexity of various conceivable circumstances with the long-term evolution of society or technology. This study tries to suggest a new assessment approach to properly incorporate the risk and uncertainty originated from future human intrusion into geological repository. Two human intrusion cases are concerned: inadvertent (impact on long-term safety) and clandestine (impact on nuclear security and safeguards) human intrusion.

Inadvertent human intrusion indicates a situation of human activity causing direct release of radionuclides in a repository to human environment with no intention to intrude repository. In other word, inadvertent human intrusion regards with long-term safety of a repository. In case of a repository for high-level wastes or spent nuclear fuels, an occurrence of inadvertent human intrusion event in future can cause serious radiological exposure to people nearby a repository. The literature in past has tried to minimize the risk of inadvertent human intrusion as low as possible so that the reasonable estimation of the probability of future inadvertent human intrusion is very significant. However, assessing possible uncertainties in inadvertent human intrusion scenario has been critically burdensome issue due to not only lack of historic experiences on underground technologies but also absence of appropriate assessment approach. Consequently, the literatures in past has assumed a time independent drilling frequency of today for assessing the risk of inadvertent human intrusion.

However, recent observation on deep drilling practice shows that a drilling frequency has been increasing. To fill such gap between the literature and reality, systematic Monte Carlo model has been developed in this dissertation. The suggested new assessment approach combines three different methodologies to properly reflect effects of various technological and societal factors on a single model. First, system dynamics is applied to facilitate the consideration for the dynamic behavior and the feedback mechanism of various factors which affect an occurrence of inadvertent human intrusion event over time. Second, Markov chain analysis is applied to incorporate a change of condition of a repository which affect the dynamic behavior of inadvertent human intrusion system. Finally, Monte Carlo simulation technique is used so that the results can be statistically analyzed. As a result, the model is able to demonstrate the dynamic behavior of a drilling frequency.

Such new approach is very meaningful because it helps us to improve our understanding the behavior of various uncertainties in inadvertent human intrusion system. First, it facilitates qualitative prediction on the impact of unexpected situation on the risk of inadvertent human intrusion thereby making selection of significant uncertainties be possible. Second, the effect of various societal, technical, and design related factors can be quantitatively assessed. Accordingly, the results from the model is able to scientifically support current society's decision on design of a repository and SNF management policy.

The results of inadvertent human intrusion model show that the probability of inadvertent human intrusion would possibly increase up to about 10 times higher than that of currently expected, implying that the past studies have underestimated the risk. Because the model considers only drilling for groundwater, temporal increase in demand for other underground resources would cause increase in the risk of inadvertent human intrusion. In such context, conservative results should be used for estimation of the risk of inadvertent human intrusion. The conservative estimation results of the model imply that a geological repository having similar design with the hypothetical repository will be vulnerable to deep groundwater development in the future. Accordingly, the risk of inadvertent human intrusion of a repository for high-level waste for spent nuclear fuels is estimated to be above the regulatory criteria of ROK. Therefore, careful design and policy approaches are required to reduce the risk of inadvertent human intrusion.

Clandestine human intrusion indicates a situation of intentional illicit intrusion to a repository for recovering of significant nuclear material such as plutonium. Accordingly, clandestine human intrusion regards with long-term safeguards problem during a post-closure period of a repository. Since significant amount of plutonium in one disposal canister for spent nuclear fuels will remain as reactor grade over 10,000 years after repository closure, safeguards measures should be considered to prevent unauthorized recovery of plutonium from a repository by clandestine human intrusion. A few literatures investigated on the safeguards issue of a geological repository. However, little concentration was made on investigating the relationship between safeguards efforts and a motivation of clandestine intrusion thereby arising disagreement on significance of safeguards program for a geological repository during post-closure period. The absence of consensus on such long-term safeguards problem would cause confusion in determination of SNF management policy.

In this dissertation, the relationship between safeguards efforts by safeguards agent and desirability of clandestine intruder is explained by qualitative simple system analysis model and quantitative assessment approach is suggested by game theory model. The base assumption of the suggested approach is that the decision of malicious actors would be determined by cost benefit of their strategies. Key parameters constituting safeguards program for a closed repository are incorporated in the plutonium mine game model so that a decision maker quantitatively considers various factors regarding that problem.

The preliminary results of clandestine human intrusion model imply that safeguards cost of about an order of million dollars would be annually expended to prevent unauthorized attempts to recovery plutonium. Such expenditure would be expected to last until about 70,000 years after repository closure unless the value of plutonium becomes worthless. Although further studies are required to facilitate the application of the model to a real repository, such results show that the overall comparison of safeguards cost between various nuclear fuel cycles needs to be reassessed considering safeguards program for a closed repository.

Based on the results of this dissertation, some suggestions are proposed to reduce the safety risk of inadvertent human intrusion and the safeguards cost of clandestine human intrusion. In viewpoint of repository design, two approach will be effective for human intrusion problem. The first suggestion on a design of repository is application of a double-layered repository concept to enhance hazard recognition system for inadvertent intruder. The second possible design suggestion is a deep vertical borehole repository concept or a deep horizontal repository concept not only to reduce the probability of inadvertent human intrusion but also to reduce the motivation of clandestine intruder. The last design suggestion is a deployment of artificial boulder layer above a disposal tunnel to physically deter a drilling operation.

Additional suggestions in viewpoint of spent nuclear fuels management policy are also proposed to support the design suggestions. The first is reduction of radiotoxicity of spent nuclear fuel by partitioning and transmutation fuel cycle to intrinsically reduce the uncertainties of human intrusions into a geological repository. Another policy suggestion is application of reversibility and retrievability to a design of repository to facilitate a flexibility in decision making for disposal program considering any change in information and conditions that potentially affect the prior decision on radioactive waste management. The last policy suggestion is a multinational cooperation approach for a radioactive wastes repository to assure long-term restriction on repository site by multiple countries.

7.2 Future work

Further investigation is required to enhance our understanding on uncertainties in human intrusion into a deep geological repository which have not been considered in this study. This dissertation describes how future generation causes human intrusions into a deep geological repository. The interaction among a motivation of intrusions, repository system, and safeguards program is specified by a new assessment approach. It is necessary to verify and refine the model by updating historical cases related with human intrusion system. For inadvertent human intrusion system, consideration on demand and supply mechanism of other underground resources such as geothermal energy, civil project, and technically important material would not only expand the applicability of the model but also the validate of the model. For clandestine human intrusion, analysis on database of failure cases of safeguards system is required. Such analysis has not been conducted in this dissertation because the data are classified as confidential. In addition, the risk attitude of society and clandestine intruder needs to be investigated.

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초 록

사용후핵연료 심지층 처분의 문제는 본질적으로 장기간의 안전과 안전조치 문제를 수반한다. 특히 미래 세대의 활동에 따라 발생할 수 있는 처분장 인간침입은 결과적으로 심각한 악영향을 야기할 것으로 기대되기 때문에 합리적인 위험도 평가가 필수적이다. 하지만 기타 '안전 사례(safety case)'와는 달리 인간침입의 경우 시간에 따라 변하는 사회적, 기술적 요소들의 복합적인 영향을 고려해야 한다. 수 만년이 넘는 처분장의 긴 수명을 고려할 때, 이러한 복합성은 매우 큰 불확실성을 수반하며 이로 인해 인간침입의 장기 위험도 평가 문제는 사용후핵연료 처분장의 난제로 인식되어 왔다. 이러한 문제 의식을 바탕으로 본 연구는 심지층 처분장의 인간침입 위험도를 합리적으로 평가할 수 있는 방법론을 제시하는 것을 목표로 하였다. 세부적으로, 처분장의 안전성 측면에서 '의도치 않은 인간침입(inadvertent human intrusion)'의 위험도에 대한 연구와 핵안보, 안전조치 측면에서 '의도적인 인간침입(clandestine human intrusion)'에 대한 연구를 진행하였다.

의도치 않은 인간침입은 자원 탐사와 같은 지하 개발 활동으로 인해 의도치 않은 처분장 침투가 발생하여 최종적으로 작업자 혹은 인근 거주자들이 방사선 피폭을 입게 되는 사건을 의미한다. 사용후핵연료 혹은 고준위방사성폐기물의 경우 그 독성으로 인해 의도치 않은 인간침입이 일어날 경우 피폭자에게 심각한 위해를

야기하게 된다. 따라서 이러한 사건의 확률을 낮춤으로써 위험도를 최소화하는 노력이 필수적이다. 즉, 의도치 않은 인간침입의 위험도 평가의 핵심은 처분장에 대한 시추 확률 평가이다. 하지만 과거 연구들의 경우 합리적인 확률 평가의 기반이 되는 역사적 시추 기록이 불충분 하였으며 적절한 평가 방법론이 부재하였으며, 결과적으로 현재 예측되는 시추 확률이 미래에도 동일할 것이라는 가정을 통해 인간침입 위험도를 평가해왔다.

그렇지만 최근 지하 개발 활동의 동향은 처분장의 시추 확률은 계속해서 증가하고 있음을 말해주고 있으며 이는 실제와 가정 사이의 간극을 의미한다. 본 연구에서는 이와 같은 간극을 극복하기 위한 복합적인 평가 방법론 및 이를 적용한 모델을 개발하였다. 첫째로, 의도치 않은 인간침입에 영향을 줄 수 있는 기술적, 사회적 요소들의 복합적 거동을 묘사하기 위해 시스템 다이나믹스를 적용해 모델의 체계를 도출하였다. 이러한 요소들의 조합에 따라 결정되는 처분장의 조건들의 확률론적 분포의 경우 Markov chain 분석을 통해 제시하였다. 의도치 않은 인간침입 시스템의 확률론적 거동을 평가하기 위해 몬테카를로 기법을 적용하였다. 이와 같은 방법론을 적용하여 개발된 모델을 통해 최종적으로 시추 확률의 동적 거동을 예측할 수 있었다.

새롭게 제시된 방법론은 의도치 않은 인간침입과 관계된 불확실성 요소들을 이해하는 데 있어 유용하다. 첫째, 인간침입의 안전도 평가에 핵심적인 요소의 선정이 정성적 시스템 다이나믹스 분석을 통해 가능하다. 둘째, 기술적, 사회적 요소 및 처분장의 설계와 관련된 요소들에 대한 정량적 평가가 가능하기 때문에

사용후핵연료 처리/처분과 관련된 현 세대의 결정에 대한 과학적 근거를 제시할 수 있을 것이다.

이와 같은 모델을 가상의 심지층 처분장 모델에 적용하여 의도치 않은 인간침입의 확률을 평가한 결과 현재 예상치의 약 10배까지 증가할 수 있음을 확인할 수 있었다. 이러한 결과는 현재까지 의도치 않은 인간침입 확률이 저평가 되어왔음을 시사한다. 게다가 이러한 결과는 심층 지하수 개발로 인한 의도치 않은 인간침입만을 고려한 결과이다. 다른 지하 광물에 대한 수요의 일시적 증가는 결과적으로 인간침입 확률의 상승으로 이어지기 때문에 확률은 더욱 더 증가할 수 있을 것이다. 이러한 점을 고려할 때, 인간침입 확률은 보수적인 값을 적용하는 것이 합리적일 것이다. 본 연구의 보수적 확률평가를 이용해 의도치 않은 인간침입 위험도를 평가한 결과 고준위폐기물 혹은 사용후핵연료 처분장의 경우 그 위험도를 낮추기 위한 추가적인 조치가 필요함을 알 수 있었다.

의도적인 인간침입은 처분장에 처분된 폐기물 내에 존재하는 핵물질을 불법적으로 활용하기 위해 침투하는 사건을 의미한다. 사용후핵연료의 경우 하나의 처분 용기 내에 원자로급 플루토늄(reactor-grade plutonium)이 만년 이상 보관되어 있기 때문에 결과적으로 처분장 폐쇄 후에도 의도적인 인간침입을 막기 위한 안전조치가 필요하다. 과거 처분장의 장기 안전조치 문제에 대한 몇몇 연구가 진행되었지만 결과적으로 이러한 문제의 심각성을 결정하는 데 있어 상당한 의견 차이가 존재해 왔다. 처분장 폐쇄 후 장기 안전조치 문제에 대한 원자력 집단의 합의 부재는 결과적으로

국가 내 사용후핵연료 관리 정책 결정에 있어 혼선을 초래할 것이다. 따라서 이에 대한 합리적인 평가 방법론이 필요하다.

처분장의 장기 안전조치 문제에 대한 의견 불일치는 안전조치 수준과 잠재적 침투자의 침투 동기 사이의 상관관계를 설명할 수 있는 모델의 부재에서 비롯한다. 본 연구에서는 두 요소 사이의 관계가 침투자와 안전조치 기관이 고려할 수 있는 전략적 선택지와 이에 따른 비용편익에 의해 결정된다고 가정하였다. 이러한 가정을 바탕으로 게임 이론을 적용한 비용편익 분석 방법론을 도출하였다. 이 때, 안전조치 기관이 선택할 수 있는 전략적 선택지들을 고려함으로써 이와 관계된 의사 결정자로 하여금 제시된 방법론을 통해 합리적이고 정량적인 분석을 가능하게 하였다.

의도적인 인간침입 모델의 예비평가 결과는 처분장에 대한 핵물질 탈취를 방어하기 위해 연간 수 백만 단위의 안전조치 비용이 발생할 수 있음을 보여 주었다. 이와 같은 안전조치 비용 지출은 사용후핵연료 내 핵물질의 가치가 하락하지 않는 이상 약 70,000년 동안 필요할 것으로 예측 되었다. 비록 정확한 비용을 산출하기 위해 처분장 폐쇄 후 안전조치 프로그램에 대한 세부적인 연구가 보충되어야 하지만, 이러한 예비평가 결과는 사용후핵연료 주기 전반에 대한 안전조치 비용 재 평가가 필요함을 시사한다.

결과적으로 본 연구의 평가 결과를 통해 처분장에 대한 의도치 않은 인간침입의 위험도 및 의도적인 인간침입에 따른 안전조치 비용을 낮추기 위한 추가적 노력이 필요함을 알 수 있다. 이에 위한 처분장 설계 측면에서 적용될 수 있는 제언은 다음과 같다. 첫째는 복층 개념의 처분장 설계(double-layered repository concept)이다. 이와

같은 처분장 설계는 상층 부분에 방사능농도가 작은 중저준위방사성폐기물을 배치할 경우 의도치 않은 침투자로 하여금 방사능 위해를 감지할 수 있도록 할 것이며 이에 따라 위험도를 낮출 수 있을 것이다. 두 번째는 처분장의 깊이를 수 키로미터까지 확대하는 것으로 심층수직공 처분장 혹은 심층수평공 처분장이 가능한 옵션이다. 세 번째 옵션은 처분장 터널 상단에 자갈층 혹은 호박돌층을 배치함으로써 시추 드릴의 진행을 물리적으로 막는 방안이다. 두 번 째와 세번째 옵션의 경우 의도치 않은 인간침입뿐만 아니라 의도적인 인간침입에도 효과적일 것이다.

사용후핵연료 관리 정책과 관련해서는 다음과 같은 옵션이 제안될 수 있을 것이다. 첫째는 사용후핵연료의 제염 및 핵변환 기술을 통해 처분용기 내 방사능 농도 및 핵물질의 양을 줄이는 옵션으로 이는 본질적으로 인간침입의 불확실성을 줄일 것이다. 두 번째는 사업에 대한 가역성 및 처분장의 폐기물에 대한 회수 가능성(reversibility and retrievability)을 유지하는 것이다. 이는 사용후핵연료 관리 사업의 융통성을 보장함으로써 최종적으로 불확실성을 줄일 수 있는 방안이다. 마지막 정책적 옵션은 처분 사업에 대한 국제 협력 체계(multinational approach)이다. 이 경우 처분장에 대한 장기적인 제한이 유용하다는 측면에서 인간침입을 억제할 수 있을 것이라 기대된다.

주요어: 심지층 처분장, 인간침입, 사용후핵연료, 방사성폐기물, 위험도 평가, 시스템 다이나믹스 모델, 안전조치 비용 평가
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