Game-Theoretic Approach for Safeguards Program of a Geological Repository for Spent Nuclear Fuels During Post-Closure Period

Heejae Ju [1], Il Soon Hwang [2], and Sungyeol Choi [1,*]

[1]Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea

[2]Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea

*sungyeolchoi@kaist.ac.kr

1. Introduction

The traditional safeguards approach to conventional nuclear facilities has been challenged by a deep geological repository (DGR) for spent nuclear fuels (SNF). One of the key questions on the safeguards of a DGR is that when the safeguards can be terminated. Since significant amount of plutonium will remain over 10,000 years in one disposal canister, long-term safeguards on DGR should be required to prevent an unauthorized access unless rigid physical protection by a repository itself is provided. Recently, this issue led to international consensus that long-term safeguards of a repository is unavoidable. In this case, continuous safeguards cost can be imposed. Considering that the principle objective of a DGR is the minimization of burden to future generation, a possibility of long-term economic cost by safeguards program of DGR should be discussed in decision making process for SNF management policy. This paper suggests a game-theoretic approach for an assessment of economic cost by safeguards on a DGR during post-closure period.

2. Literature review

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 [1]. Therefore, plutonium in SNF will be weapon-usable over 10,000 years of cooling time [2].

Under the 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’ [3]. Unfortunately, a clear definition of the term ‘practicably irrecoverable’ is absent yet [4]. Nevertheless, the IAEA states that a recovery of nuclear material subject to safeguards from a DGR during post-closure period is feasible by clandestine human intrusion [1]. Accordingly, to terminate safeguards on a DGR, 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 DGR in Finland [5].

3. Methodology

The game theory is 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. A game theoretic approach to safeguards problems is reasonable because the both players in the game would be rational: they should be intelligent enough to carry out their strategies which need advanced knowledge on nuclear engineering. However, such consideration for safeguards system of a decommissioned DGR has not been made. Therefore, this thesis tries to suggest a game theoretic model to find optimized safeguards option for safeguards agents for a decommissioned DGR.

4. Pu Mine Game Model

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 safeguards agent who tries to defend a DGR from malicious actor group. For convenience, the group of malicious actors is designated by intruder. Fig. 1 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.

The preference of decision of each player is determined by the decision of another player. The intruder has incentive to intrude a DGR 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 Fig. 1 shows that there is no strategy combination satisfying both players. Rational players would try to maximize their payoff. Therefore, the players will mix their strategy with a certain probability to lead an equilibrium of the game.

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

$$\text{Payoff} = a_1 \cdot p + c_1 \cdot (1-p) \qquad (1)$$

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

$$\text{Payoff} = b_1 \cdot p + d_1 \cdot (1-p) \qquad (2)$$

The safeguards agent is indifferent on his decision when the values of (1 and (2 are same. Thus, the equilibrium probability of intrude strategy, p^*, is defined as follows:

$$p^* = (d_1 - c_1)/(a_1 + d_1 - b_1 - c_1) \qquad (3)$$

Similarly, the equilibrium probability of safeguards strategy, q^*, is defined as follows:

$$q^* = (d_2 - b_2)/(a_2 + d_2 - b_2 - c_2) \qquad (4)$$

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 safeguard 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.

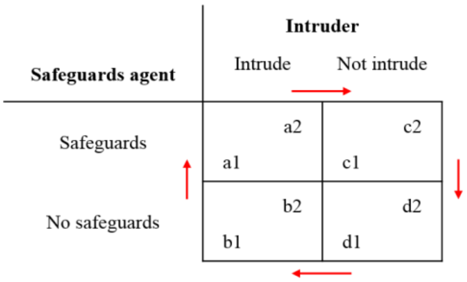

Fig. 1. Strategic form of plutonium mine game with the preference of each player (arrow).

5. Conclusion

The game theory model, named plutonium mine game model, is suggested 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 suggested approach would be appropriate for decision making on safeguards program during post-closure period. It would be expected that the suggested model helps society to build consensus on long-term safeguards problem on a DGR which has not been accomplished.

REFERENCES

[1] IAEA, “Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste”, IAEA (2010).

[2] H. Ju, “Risk Assessment of Future Human Intrusions into Deep Geological Repositories for Radioactive Wastes”, SNU (2018).

[3] IAEA, “The Structure and Contents of Agreements Between the Agency and States Required in Connection with Treaty on the Non-Proliferation of Nuclear Weapon (INFCIRC/153)”, IAEA (1972).

[4] IAEA, “Issues in radioactive waste disposal (IAEA-TECDOC-909), IAEA (1996).

[5] O. Okko, et. al., “Developing Safeguards for Final Disposal of Spent Nuclear Fuel in Finland”, Symposium on International Safeguards, IAEA (2014).