System Understanding of Long-term Safeguards for a Closed Repository

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1. Introduction

Spent nuclear fuel is a common global challenge. It contains Pu having potential to be misused for nuclear weapons. Unfortunately, the weapon-usable potential of the Pu is enhanced with time because the half-life of fissionable Pu-239 is much longer than that of non-fissionable Pu-238. Also, the self-protection of spent nuclear fuel due to strong gamma radiation disappears rapidly. This fact causes a heated discussion within international domains for long-term safeguards on final disposal, which eventually increases the total costs of nuclear energy.

2. Long-term safeguards requirements

2.1 Utility of SNF as explosives

The quality of Pu in SNF improves over time as the concentration of Pu239 increases due to its long half-life. In addition, the decay heat and radioactivity of reactor-grade Pu reduces over time so that handling becomes easier. Accordingly, the utility of Pu grows [1]. Mark et. al. concluded that [2]:

(1) "Reactor-grade plutonium with any level of irradiation is a potentially explosive material";

(2) "The need for safeguards to protect against the diversion and misuse of separated plutonium applies essentially equally to all grades of plutonium".

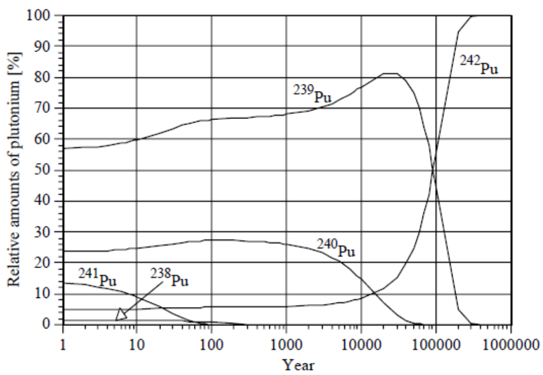

Fig. 1. Isotopic composition of reactor-grade Pu over cooling time [1].

2.2 IAEA safeguards

The safeguards agreement, INFCIRC/153, requires the conditions for the termination time of safeguards in paragraph 11 as follow [3]:

"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."

Detailed explanation of the conditions above is stated in the paragraph 35 in the same document:

'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.'

A clear definition of the term 'practicably irrecoverable' is absent yet. Nevertheless, the IAEA considers that SNF in a closed repository is the subject to safeguards [4]. Hence, no clear guideline to prove that a recovery of Pu from a closed repository exist.

3. System thinking on the long-term safeguards of a closed repository

3.1 System analysis

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.

3.2 Game theory of Pu mine

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. 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.

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.

4. Results

Simple example model is developed using current available data. The estimated players' strategic decision map is depicted in Fig. 2.

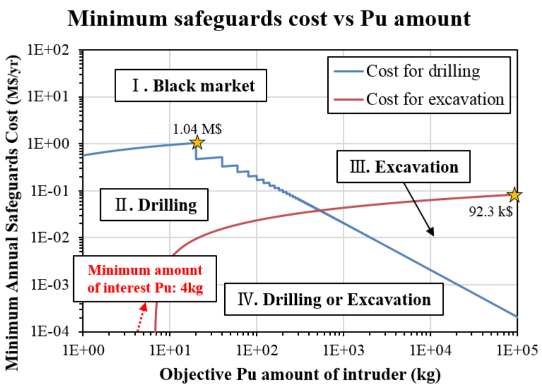

Fig. 2. Minimum safeguards cost by Pu recovery.

5. Conclusion

This paper analyses the costs and benefits of long-term safeguards on final disposal by combining a game theory with a system thinking model. The existing studies only focuses on why safeguards need rather than how to implement. Proliferation scenarios of a closed repository were identified by considering technological innovation in the field of underground mining. Then, strategic interactions between a proliferator and a safeguards agent was defined. A case model showed that the suggested approach can support political decision making of spent nuclear fuel management.

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