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A COMPARISON OF PROLIFERATION RESISTANCE MEASURES OF MISUSE SCENARIOS USING A MARKOV APPRAOCH

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ABSTRACT

Misuse of declared nuclear facilities is one of the important proliferation threats. The robustness of a facility against these threats is characterized by a number of proliferation resistance (PR) measures. This paper evaluates and compares PR measures for several misuse scenarios using a Markov model approach to implement the pathway analysis methodology being developed by the PR&PP (Proliferation Resistance and Physical Protection) Expert Group. Different misuse strategies can be adopted by a proliferator and each strategy is expected to have different impacts on the proliferator's success. Selected as the probabilistic measure to represent proliferation resistance, the probabilities of the proliferator's success of misusing ESFR system are calculated using the Markov model based on the pathways constructed for individual misuse scenarios. Insights from a comparison of strategies that are likely to be adopted by the proliferator are discussed in this paper.

1. INTRODUCTION

Misuse of declared nuclear facilities is one of the important proliferation threats. The robustness of a facility against these threats is characterized by a number of proliferation resistance (PR) measures. This paper evaluates and compares PR measures for several misuse scenarios using a Markov model approach to implement the pathway analysis methodology being developed by the PR&PP (Proliferation Resistance and Physical Protection) Expert Group [1].

Scenarios considered in this study involve different strategies of misusing a hypothetical ESFR (Example Sodium Fast Reactor) facility for an undeclared production of fissile material. It is assumed that the proliferator intends to obtain 1SQ (Significant Quantity, usually defined as 8 kg of plutonium) plutonium by misusing the ESFR facility.

Similar to a previous study [2], specific stages involved in the misuse of ESFR system are: fabrication and irradiation of fuel assemblies, removal and cool-down of irradiated assemblies, shipment offsite of assemblies, and extraction of plutonium in an undeclared fuel processing facility. Obviously, misuse involves both declared and undeclared facilities that should be included in the Markov model. In addition, features captured in the Markov model [3] include composite safeguards and associated false alarms, intrinsic barriers to proliferation, concealment activities, and human performance in exercising safeguards inspections. Outputs of Markov model are different probabilistic measures that are affected by these features.

Different misuse strategies can be adopted by a proliferator and each strategy is expected to have different impacts on the proliferator's success. A misuse scenario could be a covert or an overt (i.e., an abrogation) process. A covert misuse is detectable by IAEA safeguards. For an overt misuse, safeguards become irrelevant and the misuse can only be stopped by international intervention or technical difficulties encountered by the proliferator. Another strategy is a delayed overt misuse, i.e., the proliferator starts overtly misusing the ESFR facilities after the covert misuse is detected. The impact of the Additional Protocol (AP) is also considered as part of the variation of scenario analysis.

Section 2 briefly reviews the Markov model approach. Misuse pathways are identified in Section 3 as the first step of building the Markov model. Selected as the probabilistic measure to represent proliferation resistance, the probability of the proliferator's success of misusing ESFR system is calculated using the Markov model based on the pathways constructed for individual misuse scenarios. Insights from a comparison of strategies that are likely to be adopted by the proliferator are also discussed in Section 3. Section 4 presents a summary of results and conclusions of this study.

2. A MARKOV MODEL APPROACH FOR THE PR&PP EVALUATION OF NUCLEAR ENERGY SYSTEMS

2.1 AN OVERVIEW OF MARKOV MODEL APPROACH

Different methods have been investigated and explored to demonstrate the pathway analysis based PR & PP evaluation methodology. These methods include a qualitative approach, an event tree/fault tree approach, and a Markov approach [1]. Details and applications of the Markov were extensively discussed in [2, 3, and 4] and will only be briefly reviewed in this paper.

The Markov process consists of a set of random variables whose future and past states are independent, given the present states. Markov model of a system is usually described by a state transition diagram characterized by transition parameters from one state to another state. Therefore, the Markov approach is a suitable tool for the pathway analysis for PR & PP evaluation. The Markov method has the capability to account for some of the dynamic features of proliferation, namely the large number of uncertainties, the unpredictability of human performance, and the effect of changing conditions with time.

In applying the Markov approach to proliferation study of nuclear energy systems, the normal flow of nuclear material in the fuel cycle (e.g., front and back ends) are accounted for and the abnormal flow due to proliferation activities are modeled as a time dependent random process. Major activity modules in the fuel cycle (e.g. a physical process in a recycle facility) and the proliferation pathway (e.g. the act of diversion from a declared facility) are represented by a number of discrete stages in the Markov chain. In addition, absorbing states (terminal states) are used to represent the effective termination of the proliferation activity due to intrinsic (e.g. radiation) or extrinsic (e.g. international safeguards) barriers.

The transition between stages is treated as a random process with a given probability distribution. The transition rate is characterized by time parameters that are based on physical processes. For example, the transition time from one process to the next in the fuel cycle facility is derived from the rate of material flow in the actual recycling process. In modeling safeguards the rate of detecting an anomaly is derived from the frequency of executing safeguards approaches. The realization of the random process at each stage is then a random variable and the expected values of these random variables constitute the state (solution) space. Thus by mapping the stages of a proliferation scenario into a Markov chain model the likelihood of all possible outcomes can be determined systematically.

2.2 MODELING FEATURES RELEVANT TO THE PR&PP EVALUATION OF NUCLEAR ENERGY SYSTEMS

In the Markov model for PR&PP evaluation, the proliferator will encounter a number of intrinsic and extrinsic barriers at each stage of the pathway. The transitions to other stages or to a terminal state are characterized by time parameters that are physically meaningful. Therefore, all features of the nuclear energy system that have impacts on transition parameters of the Markov model should be considered accordingly.

Given the uncertainty of human actions responding to changing environment, it is extremely difficult to model impacts of all these relevant features in a precise manner. However, based on an understanding of the mechanisms behind the barriers, mathematical representations of their impacts can be formulated such that at least the trend of the corresponding impacts and the boundary conditions of the impacts, i.e., with and without a specific feature, can be captured using the introduced parameters that characterize the nature of these barriers. In particular the following features of the barriers have been included in the Markov model for PR&PP study:

1) An effective detection rate is introduced to account for the implementation of multiple safeguards approaches at a given strategic point. Uncertainties related to the accuracy/sensitivity of measurement methods are also considered in the model. The potential for false alarm due to over-sensitivity of safeguards equipment is accounted for by a parameter, the confidence level of diversion confirmation;
2) A "proliferation failure" state is introduced to reflect the inability of the proliferator to overcome the intrinsic barriers originated from either the design of the facility or the properties of the material in the facility;
3) Concealment to defeat or degrade the performance of safeguards is implemented in the Markov model. It is considered as a tactic of the proliferator and is assumed to prompt more immediate and concerted responses from the safeguards inspectors;
4) Human performance in the safeguards area is incorporated in the Markov model by modifying the time parameter of a human action (e.g. the transition time associated with an inspection) with a success

factor that takes into consideration the probability of human errors.

Details of mathematically formulating extrinsic barriers, intrinsic barriers, concealment, and human factors have been discussed in [3] and will not be discussed further in this paper. Example studies have been done to demonstrate the impacts of different features on the PR measures for the fuel facility of the ESFR system [2, 3, and 4].

2.3 A CONCEPTUAL MARKOV MODEL APPRAOCH OF MULTI-STEP PROLIFERATION

In earlier PR & PP studies using the Markov approach [2, 3, and 4], a proliferation was considered a continuous process. Once it is started, it will not stop until one of the following situations is encountered: (1) being detected by the safeguards; (2) being failed due to intrinsic barriers and/or technical difficulties; and (3) 1SQ material has been successfully obtained.

A realistic issue is that a proliferator may change the strategies during proliferation. The proliferator may perform proliferation in discrete steps or switching to different strategies. For example, the proliferator may intend to obtain nuclear material via a diversion first. If the diversion is detected, the proliferator can start an abrogation immediately. This strategy might increase likelihood of a successful proliferation because of the earlier undetected diversion.

A conceptual Markov model that represents multi-step proliferation as a continuous process is proposed in this paper. The key point is that the Markov model, consisting of the same Markov states that represent the system elements, will be used with different initial status and transition parameters that reflect different steps of the proliferation. An application of this multi-step proliferation Markov model to misuse scenarios will be further discussed.

3. ESFR REACTOR MISUSE SCENARIOS

The scenarios considered in this study mainly involve a misuse of the ESFR reactors (the ESFR system has totally four fast reactors) for an undeclared production of fissile material, which is similar to the misuse case of a LWR reactor in an earlier study [2]. Detailed information of the ESFR facility can be found in [3] but is not needed for the analysis because the number of ESFR system elements involved in misuse is limited and will be presented below. It is assumed that the proliferator intends to obtain 1SQ plutonium by misusing the ESFR system elements. Because the ESFR system is owned and operated by the host state, it is reasonable that the host state is an industrial state that possesses advanced technical skills and nuclear capabilities, and sufficient resources.

Specific stages involved in misuse of the ESFR system are identified [2]:

1) Acquisition of fertile material (fresh UO_2), fabrication of target assemblies for fresh fuel and loading target assemblies into the blanket region of the reactors during regular refueling;
2) Irradiation of the fertile material inside ESFR reactors for one fuel cycle;
3) Removal of the irradiated material from the core of the ESFR reactor in the next refueling;
4) Cool-down of target assemblies in temporary storage rack of the spent fuel pool;
5) Shipment of target assemblies offsite; and
6) Extraction of plutonium from the irradiated target assemblies in an undeclared fuel processing facility.

All of the above major stages involve misusing the declared ESFR system elements. It is assumed that technical difficulties in misusing the declared facility are minor because the declared facility are owned and operated by the proliferator. The misuse, however, can be detected by various safeguards. It is further assumed that the assemblies will be shipped offsite and plutonium will be extracted in an undeclared processing facility. In the undeclared facility, technical difficulties might also be encountered. If the Additional Protocol is not in force, it is assumed that there will be no detection of the clandestine processing of the material.

3.1 COVERT AND OVERT MISUSES

Misuse scenarios can be divided into two types, i.e., a covert or an overt misuse (an overt misuse is also an abrogation). Regarding the misuse strategies, a covert misuse may take longer time to finish but the detection probability may be relatively low. Another strategy is an overt misuse from the very beginning. A mixed strategy may also be adopted, e.g., a delayed overt misuse. In this case, the proliferator starts overtly misusing the ESFR facilities only after the covert misuse is detected.

A covert misuse is detectable because some anomalies will be generated, e.g., burn-up value of fuel assemblies in the misused reactors will deviate from the normal values. Surveillance equipment is assumed to be available at each facility. A summary of a covert misuse scenario is shown in Table 1. Because not all the safeguards approaches associated with each declared ESFR element can be used to detect the misuse, Table 1 identifies some major safeguards that might be capable of misuse detection for each individual ESFR element. Safeguards approaches that may be compromised (degraded or defeated) by concealment are also identified for each stage of the pathway in Table 1. Detailed explanation of safeguards approaches and a complete safeguards definition for each ESFR element can be found in [3]. Minor technical difficulty means that technical failure can be neglected.

Table 1: Summary of an ESFR Covert Misuse Scenario

Stage of Misuse Scenario	ESFR System Elements Being Misused	Major Safeguards for Misuse Detection	Compromised Safeguards by Concealment	Technical Difficulty	Duration Time
Target Assembly Fabrication	Assembly	1B, 1C, 1G, 2A, 2B, 2C, 2E, 2F, 3C, 4B	3C	Minor	2 weeks
Irradiation	ESFR Reactor	3D	3D	Minor	52 weeks
Off-loading	ESFR Transfer	1A, 1B, 1D, 1E, 1H, 2A, 2B, 2C, 2D, 2F, 2G, 2H, 3B	1A, 1B, 1D, 1E, 3B	Minor	3 weeks
Cool-down	Storage Basket: Spent Fuel	1B, 1E, 1F, 2A, 2B, 2C, 2D, 2F, 2H, 3B	1B, 1E, 1F, 3B	Minor	52 weeks
Transportation	None	None	None	Minor	1 week
Extraction	None	None	None	Assumed	7.2 weeks

Duration time of each stage is assumed in terms of weeks in Table 1.

For an overt misuse of ESFR elements, the same major stages are involved. The differences between the overt and covert misuse are that (1) safeguards do not play any role in the Markov model of the overt misuse. Instead, external interventions are modeled as a means to terminate the overt misuse; and (2) the time required to complete each stage is expected to reduce significantly because the proliferator does not have to pretend a normal operation of the facilities. The transportation and the undeclared extraction facility are still needed to complete the pathway of 1SQ material acquisition.

The major misuse stages are shown in Figure 1. Both declared and clandestine facilities are identified in the figure. The misuse pathway, as shown in Figure 1, is ready to be translated into Markov model. It should be noted that only one of the four reactors needs to be considered in the Markov model. A stage can be further expanded to represent the Markov states diagram, as shown in the lower right corner of Figure 1. In Figure 1, Stage V of "Shipment Offsite" can be represented by a Markov state transition diagram, where the shipment offsite of irradiated assemblies (1) may be detected by safeguards (for a covert misuse) or terminated by interventions (for an overt misuse); or (2) may fail due to technical difficulties encountered in shipping; or (3) may move to next stage if it is neither detected (terminated) nor failed. Each stage can be expanded in the same manner to build the Markov model of the entire misuse pathway. States of being failed, being detected or terminated, or success are absorbing states in the Markov model. Outcomes of the Markov model are probabilities of being detected or being terminated, being failed, or proliferation success and all of them can be directly calculated.

3.2 MISUSE SCENARIOES

Misuse Scenario 1

The first misuse scenario is straightforward. As shown in Table 1, the proliferator covertly misuses the declared ESFR reactors to irradiate the fertile material to produce plutonium. Since the proliferator owns and operates the ESFR system, technical difficulties associated with the misuse should be minor except in the last stage, the extraction of plutonium in an undeclared facility.

Misuse Scenario 2

The second scenario is an overt misuse of the same declared ESFR elements. In this scenario, safeguards are irrelevant and only external intervention or the technical failure in the undeclared facility can stop the abrogation. The mean time for the intervention to take effects is assumed to be one week.

Another assumption is that each stage can be completed much more quickly than in the covert misuse because the proliferator does not hide its activities in the declared facilities any more. It is assumed that the completion time of each of the first four stages (misuse of declared ESFR facilities) is reduced by 80% compared to the covert misuse defined in Table 1, e.g., target assemblies that have to be irradiated for one fuel cycle in the covert misuse can now be completed within about two and a half months in the overt misuse. However, the proliferator still tries to covertly extract plutonium and there is no detection of this covert extraction because the Additional Protocol is not assumed.

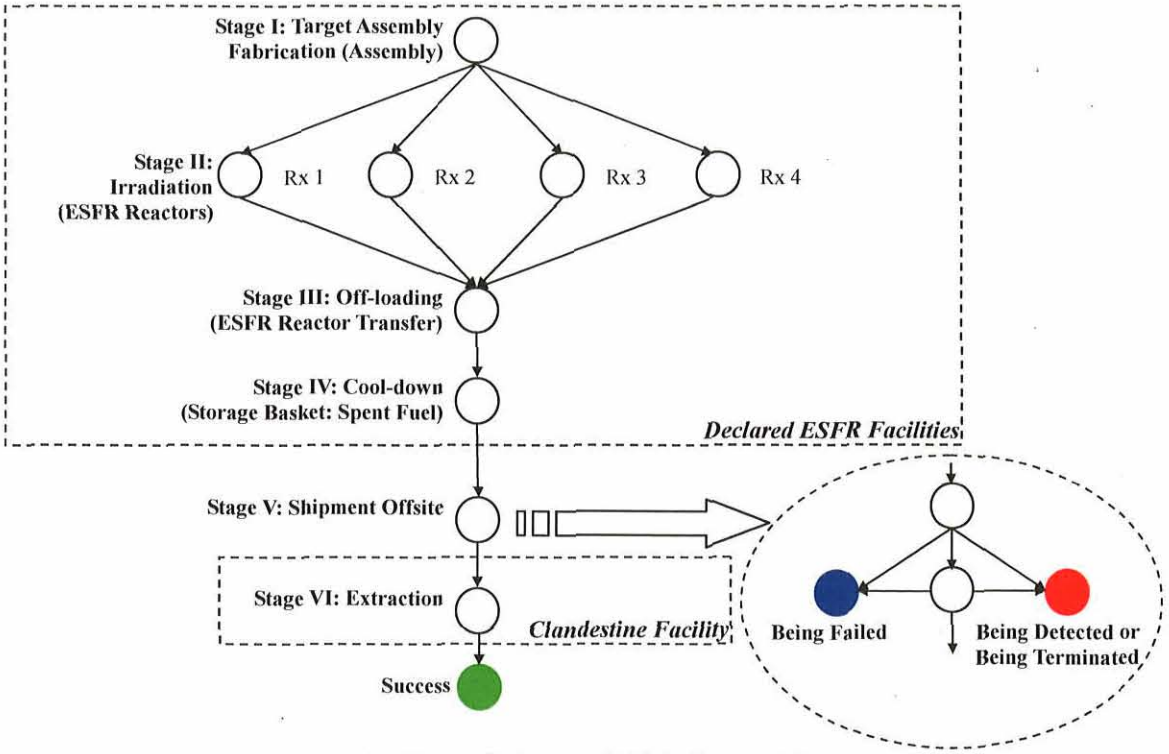

Figure 1: Misuse Pathway of ESFR System Elements

Misuse Scenario 3

The third scenario is a delayed overt misuse, i.e., the proliferator covertly misuses the declared ESFR elements first. Once the covert misuse is detected, an overt misuse is started immediately by the proliferator. For the proliferator, a higher likelihood of success is anticipated compared to Misuse Scenarios 1 and 2 because an undetected misuse helps the host state accumulate certain amounts of nuclear material.

A criterion is proposed here to determine when the covert misuse should be considered to be detected. Here it is assumed that the covert misuse is considered to be detected after the detection probability (the sum of probabilities in all states of being detected, as illustrated in Figure 1) exceeds 0.6. When the detection probability is larger than 0.6, some material of interest has been produced via the covert misuse. The covert misuse can be cut off at different detection probabilities. A detection probability of 0.6 is just selected here to show how a delayed overt misuse can be evaluated using the Markov model approach. This detection probability and the misuse failure probability reflect the likelihood of the material being held back in declared facilities.

A Markov model corresponding to the covert misuse is first created and solved up to the time when the covert misuse is terminated by the assumed condition of detection probability exceeding 0.6. The Markov evaluation is then continued by using an overt misuse model, in which transitions to terminal states associated with safeguards are now replaced by transitions associated with external intervention due to treaty abrogation. The initialization of the overt phase of the evaluation requires an initial probability of having 1SQ equivalent of material within the declared facilities. The inter-phase condition between the covert and overt phases of the evaluation is defined according to the following probability statement: success probability at the end of the convert phase plus the sum of initial probability of all states associated with declared facilities in the overt phase equals to 1.0.

Misuse Scenario 4

This misuse scenario is the same as the Misuse Scenario 2 except that the Additional Protocol is assumed, i.e., the proliferator overtly misuses the ESFR elements and the processing using undeclared extraction facility becomes detectable now. It is anticipated that the likelihood of misuse success is less than that in Misuse Scenario 2.

3.3 SUMMARY OF RESULTS OF MISUSE SCENARIOS

Results of the four misuse scenarios are summarized in Table 2 below. In Table 2, Column 2 presents termination probability (for overt misuses, i.e., abrogation) or detection probability (for covert misuses). Column 3 shows the failure.

Table 2: Summary of Misuse Results

Misuse Scenarios	Termination or Detection Probability	Technical Failure Probability	Success Probability	Proliferation Time (weeks)
Scenario 1: A covert misuse	0.79	0.08	0.13	117.2
Scenario 2: An overt misuse	0.77	0.09	0.14	30
Scenario 3: A delayed overt misuse after a covert misuse	0.61	0.15	0.24	35
Scenario 4: An overt misuse under the AP	0.92	0.04	0.04	30

probabilities of misuses due to technical difficulties encountered by the proliferator. Success probabilities are shown in Column 4. Proliferation time in Column 5 is the sum of time to acquire 1SQ equivalent of material and the time needed to extract plutonium in undeclared facility.

Table 2 shows that the success probability of the delayed overt misuse scenario (Misuse Scenario 3) is the highest, which indicates that the strategy of a delayed overt misuse might be likely adopted by the proliferator. This indicates that a delayed abrogation can increases the success probability under the assumptions of the performance of safeguards and also cutoff detection probability at which the covert activity is considered to be detected. The reason is that the undetected covert misuse can accumulate some material of interest and therefore, less time and effort are needed in the overt misuse.

Based on the assumptions of this study, the success probability of the overt misuse (the Misuse Scenario 2) is slightly higher than that of the covert misuse (the Misuse Scenario 1), and the time to obtain 1SQ material for the overt misuse is much shorter than that for the covert misuse.

Finally, the success probability of the overt misuse (Scenario 4) is very small under the Additional Protocol, as expected. A bar diagram that represents success probabilities of different misuse scenarios is shown in Figure 2.

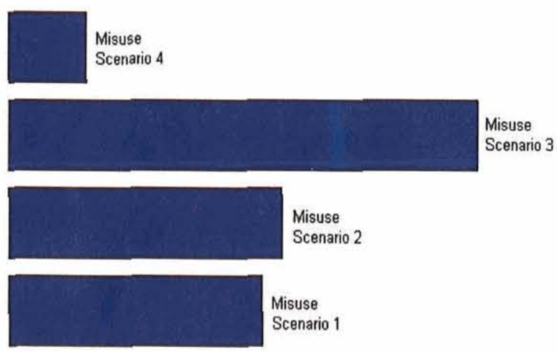

Figure 2: Success Probabilities of Misuse Scenarios

The approach discussed here can be applied to study misuse of other ESFR elements, such as the electro-refiner, as indicated in [3].

4. SUMMARY AND CONCLUSIONS

The Markov model approach is further developed in this paper. Modeling a multi-step proliferation using the Markov model approach is demonstrated and details of the implementation are illustrated. Considering that multi-step strategies are very likely to be adopted by the proliferator, this development significantly enhances the flexibility of the Markov approach. Immediate application of this enhancement to a delayed overt misuse is discussed in this paper.

Four different misuse scenarios are studied in this paper. The results show that a delayed overt misuse of declared facilities is able to increase the chance of misuse success under assumed safeguards performance and cutoff detection probability. Potentially, the strategy of delayed overt misuse or abrogation would arguably be adopted by the proliferator. More attention should be paid to these types of scenarios in the abrogation study by proliferation analysts.

The numbers and conclusions presented in this report should not be taken as absolute predictions. Instead, these are considered as outcomes of the assumptions used in the Markov models. The Markov models and parameters in this study are both preliminary. The models need to be refined and parameters need to be further developed and validated, e.g., it was assumed that the acquired nuclear material is processed using undeclared facilities only. In practice, it is not the only means to obtain weapon usable material. It is also possible that the host state makes use of other facilities such as an electro-refiner in the ESFR facility to accelerate the production of the plutonium. This will be further investigated in the future.

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