Methodology for Proliferation Resistance for Advanced Nuclear Energy Systems

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METHODOLOGY FOR PROLIFERATION RESISTANCE FOR ADVANCED NUCLEAR ENERGY SYSTEMS

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SUMMARY/ABSTRACT

The Technology Goals for Generation IV nuclear energy systems highlight Proliferation Resistance and Physical Protection (PR&PP) as one of the four goal areas for Generation IV nuclear technology. Accordingly, an evaluation methodology is being developed by a PR&PP Experts Group. This paper presents a possible approach, which is based on Markov modeling, to the evaluation methodology for Generation IV nuclear energy systems being developed for PR&PP. Using the Markov model, a variety of proliferation scenarios can be constructed and the proliferation resistance measures can be quantified, particularly the probability of detection. To model the system with increased fidelity, the Markov model is further developed to incorporate multiple safeguards approaches in this paper. The approach to the determination of the associated parameters is presented. Evaluations of diversion scenarios for an example sodium fast reactor (ESFR) energy system are used to illustrate the methodology. The Markov model is particularly useful because it can provide the probability density function of the time it takes for the effort to be detected at a specific stage of the proliferation effort.

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1. INTRODUCTION

The technology Goals for Generation IV nuclear energy systems, developed during the Roadmap project [1], highlight Proliferation Resistance and Physical Protection (PR&PP) as one of the four goal areas for Generation IV nuclear technology. Accordingly, the Generation IV International Forum (GIF) convened an International Experts Group to develop an evaluation methodology for PR&PP. The framework [2, 3] being developed for PR&PP evaluation is to define a set of challenges, to obtain the system responses, and to assess the outcomes. A Markov chain method was suggested in The Guidelines for the Performance of Nonproliferation Assessments [4] for possible application to scenario assessment of proliferation because of the large number of uncertainties, the unpredictability of human performance, and the effect of changing conditions with time. The current study is an implementation of a Markov chain model for the evaluation of the proliferation resistance characteristics of nuclear energy systems.

The approach of the Markov model for PR&PP evaluation is generally an extension of the well-established probabilistic risk assessment (PRA) methodology that has been used in reactor safety studies over the years. It follows the general approach established by the PR&PP Experts Group [3] to perform proliferation resistance measure calculations for threats based on misuse of the reactor and diversion of materials from the fuel cycle systems. The threat definition includes characteristics of both the actor (host states for PR), and the actor’s strategies, etc. The system responses are evaluated through a sequence of events and actions (i.e., proliferation pathways) that may lead to the success of the proliferation, i.e., the assessment of outcomes heavily relies on pathways with the defined threats as initiating events. The challenges to the nuclear system are given by the threats posed by potential proliferators and malevolent adversaries. The characteristics of the Generation IV systems, both technical and institutional, are used to evaluate the system response and to determine the system’s resistance against the proliferation threats and robustness against sabotage, theft, and terrorism threats. The outcomes of the system response are expressed in terms of proliferation resistance and physical protection measures.

A Markov model is suitable for modeling dynamic aspects of stochastic process in particular when the transition rates from one state to the other depend on the status of the system which, of course, changes with time. For the case of PR evaluation, the system response is being analyzed by a Markov chain model whereby the proliferation pathways are represented by a sequence of connected nodes. Each node represents certain element or subsystem of the nuclear energy enterprise, with associated events or activities followed by the proliferators. One of the key outcomes of the PR evaluation is the determination of the probability of detection, one of the PR measures of interest. The Markov model described here allows for different detection rates for continuous detection depending on the specific activity to be detected. The Markov model is particularly powerful because it can provide the probability density function of the time it takes for the effort to be detected at a specific stage of the proliferation effort. Thus it not only gives the time it takes to detect the proliferation attempt but also the stage of the proliferation pathway when this detection takes place. Hence, in the current work, the proposed Markov model is used in the system response step (definition of possible pathways) and a part of the pathway evaluation since it provides (when solved) the value of some of the attributes (e.g., probability of detection).

In a previous proliferation resistance study [5] using the Markov model, only MUF (Material Unaccounted For) safeguards approaches were used to detect the proliferation. Obviously, safeguards approaches based on MUF are not the only detection means that are available. There is a need to further develop the Markov modeling technique to consider applications of multiple safeguards approaches in addition to MUF approaches [5, 6]. A method is presented here to model the composite safeguards using an equivalent parameter to address multiple safeguards approaches. This also reduces the complexity of the Markov model while taking into account uncertainty of each safeguards approach. An abrupt diversion is studied using the modified Markov model for an ESFR nuclear energy system, which is a hypothetical reactor selected by the PR&PP group to aid in the development of the evaluation methodology. It is loosely based on the Integral Fast Reactor [7] and thus provides a design which is both advanced and for which design parameters have been reasonably specified for the purposes of the example analysis.

The Markov modeling approach has been implemented in a software tool called PRCALC [5] to calculate various proliferation resistance measures. This software tool can: (1) generate the pathways automatically for different scenarios to be evaluated; (2) compute particular PR measures, such as the detection probability, shortest path in terms of least time or cost, and a technical difficulty index; (3) conduct sensitivity analysis of PR measures with respect to various parameters; (4) provides insights to different proliferation scenarios and information to enhance safeguards.
2. INCORPORATION OF MULTIPLE SAFEGUARDS APPROACHES IN MARKOV MODEL

A general description of Markov modeling approach and its application to misuse and diversion scenarios can be found in [5] and will not be discussed in detail here. Safeguards approaches play a key role in the proliferation resistance evaluation of a nuclear energy system. In reality, there are many other safeguards approaches that can be adopted in a nuclear energy system. Each of the safeguards approaches is associated with certain time parameters that have direct impacts on the detection, which should be modeled in the Markov chain representation of the energy system.

The most important parameters in the Markov models are the transition rates between states. The transition rates used in Markov models are actually the inverse of the average transition time periods between the states. Thus, the detection rate is the inverse of the time period it takes to detect the anomalies caused by the diversion and to confirm that the anomalies are actually caused by a true diversion rather than a false alarm. The detection rate is thus reflected by the nature of the available safeguards approaches used in the nuclear energy systems. Multiple safeguards approaches are very likely to be available for detecting diversion in each facility of the energy system [8, 9]. The equivalent detection rates for multiple safeguards approaches can be defined. This is illustrated in Figure 1, where there are two types of states: “Normal Flow” which indicates the normal operation of a declared facility and “Being Detected” that indicates the end of proliferation. Because states of “Being Detected” are all absorbing states, they can thus be represented by a single state of “Being Detected” with an equivalent detection rate that is the sum of all detection rates of the safeguards approaches.

It is noted that detection rate $r_i$ at Stage (facility) $i$ is defined as $r_i = \frac{1}{T_{D_i}}$, where $T_{D_i}$ represents the time of assuring the occurrence of the diversion or misuse activities using a specific detection means. If several detection approaches are used, $T_{D_i}$ becomes the equivalent detection time and the equivalent detection rate satisfies

$$r_i = \frac{1}{T_{D_i}} = \sum_{j=1}^{n} r_{(i,j)} = \sum_{j=1}^{n} \frac{1}{T_{D_{(i,j)}}}$$  (1)

**Figure 1: Equivalent Detection Rate for Multiple Safeguards Approaches**

where $n$ is the number of the safeguards approaches, and $T_{D_{(i,j)}}$ is the detection time for using approach $j$ at Stage $i$.

Note that the transition time is the mean value of a certain distribution in terms of time period it takes to transit between two states. From equation (1), the distribution for the equivalent parameter is impacted by uncertainties embodied in the individual distributions. $T_{D_{(i,j)}}$ or $T_{D_i}$ can consist of several terms such as the average time period ($T_{I_{(i,j)}}$) of inspection, the time ($T_{DA_{(i,j)}}$) it takes to detect an anomaly, and the time ($T_{VA_{(i,j)}}$) it takes to verify and confirm that the anomaly was caused by the diversion or misuse, i.e.,

$$T_{D_{(i,j)}} = T_{I_{(i,j)}} + T_{DA_{(i,j)}} + T_{VA_{(i,j)}}$$  (2)

Note $T_{I_{(i,j)}}$ is non-zero only for periodic inspection activities. For each stage where the material is diverted, the parameter for the detection rate can be determined by available safeguards approaches associated with the average time periods. For the instantaneous detection rate, the factors of detection of an anomaly and verification of the cause of anomaly should also be included. $T_{I}$ indicates the IAEA inspection period that is usually 2 – 3 months. For the
physical inventory period it is usually one year, and for reviewing surveillance camera records, it is usually one day. We take the average time period of 10 weeks for inspection related safeguards, 52 weeks for inventory related safeguards, and days for surveillance related safeguards. $T_{\text{DA}}$ indicates the detection of an anomaly after inspection. It should be very quick and could be in days or even shorter. $T_{\text{VA}}$ indicates the verification of an anomaly. It is usually very quick except for the seal on containment since it has to be sent out to the Agency’s laboratory for inspection. We assume the number of 2 weeks for laboratory verification of a fake or tampered seal.

Four different types of safeguards approaches that could be used by the inspectors were identified and discussed extensively in [8]. According to the applicability of these safeguards approaches, each facility inside the nuclear energy system may adopt one or several of these approaches to safeguard the facility. The parameters of the four types of safeguards approaches can be obtained based on the above discussion. The equivalent detection parameters of the composite safeguards are evaluated using equation (1) and (2). The details are not presented here due to the limited space.

3. AN EXAMPLE OF DISTRIBUTED DIVERSION IN ESFR SYSTEM

3.1 ESFR Energy System

The concept of a hypothetical energy system, the Example Sodium Fast Reactor (ESFR), is used to represent an advanced nuclear energy system in this study. Insights derived from the study of this example are expected to be useful for the proliferation resistance aspects of the design of Generation IV nuclear energy systems. The ESFR system consists of (1) four identical sodium fast reactors; (2) staging area/subassembly washing station adjacent to the reactor buildings used for fresh and spent fuel in transit and for washing spent fuel subassemblies before storage; (3) storage building to store spent fuel (SF) discharged from the reactors and the re-fabricated fuel to be loaded to the reactors; (4) light water reactor (LWR) spent fuel storage facility to store the LWR spent fuel as a source of make-up fissile material for the reactors; and (5) recycle facilities that dissolve the pins of spent fuel from LWR and ESFR reactors and cast new pins of fresh fuel (NF). More details on the ESFR system can be found in [5]. Note that in each facility, there is a transfer port where the transfer occurs between two facilities.

The network diagram of the normal material flow in ESFR is shown in Figure 2. The input of the ESFR system is the LWR spent fuel and/or ESFR reactor fresh fuel. Note at least partial fresh fuel is from the ESFR recycle facilities. Both fresh fuel and spent fuel of ESFR reactor are stored inside the storage basket. The spent fuel (SF) of the LWR and ESFR reactors are transported to the recycle facilities. They are processed in different ways, which is differentiated using Recycle Facility I1-1.1 and Recycle Facility I1-1.2. Spent fuel in the form of pins will be disassembled and chopped into bulk material in Recycle Facility I1-1, and transferred into Recycle Facility I for further processing, e.g., extraction of transuranics (TRU). After dissolution of the LWR spent fuel and ESFR spent fuel, new fuel pins will be fabricated in Recycle Facility I1-2. The new fuel pins will be transferred to SF & NF storage cell, and finally reach the fresh fuel storage of ESFR reactor via various transfer ports. Thus, the recycled fresh fuel will be re-burned by the ESFR reactors. The waste from Recycle Facility I1-2 will be stored in waste storage. U-product indicates depleted uranium, and its destination is not modeled here. The transfer stages indicate only the shipment between two buildings inside the ESFR system except the one after the LWR SF storage. The diversion might occur at each of these facilities. Through the transportation stage, the diverted material will be further processed in a clandestine PUREX facility to obtain plutonium for the purpose of weapon fabrication.

Possible proliferation scenarios for ESFR have been discussed in [3, 5]. The proliferator may misuse the ESFR reactor to irradiate undeclared uranium, and then, ship it to clandestine facilities for weapon fabrication. Diversion may occur at the LWR spent fuel storage, staging/washing area, ESFR SF and NF storage cell, ESFR recycle facility, various transfer ports, and during the scheduled transfers. The diverted material will be shipped to clandestine facilities for further processing into nuclear weapons. Potential pathways for diversion to the clandestine facilities are shown in Figure 2. Misuse scenarios require different pathways and they have been developed in [5]. All of these scenarios or so-called pathways can be evaluated separately (the diversion scenario or misuse scenario) or together (mixed scenario).

The ESFR system is divided into 17 stages for the study, as shown in Figure 2. The following distinctions are noted in the study of the ESFR diversion scenarios: (1) diversion from transfer port during unscheduled and scheduled transfers because of different impacts on detection; (2) diversion from Recycle Facility I and II (material in different forms); (3) diversion of material from LWR spent fuel and ESFR spent fuel; (4) diversion of material from fresh fuel storage basket and spent fuel storage basket inside ESFR reactor. These distinctions are made because diversion of different material and/or in different forms makes significant difference in terms of detection.
The parameters of the Markov model are determined with the goal of obtaining one significant quantity (1SQ) of plutonium (8 kg) based on the amount of the material flow in the ESFR facilities. The detection at each stage will be affected by various factors such as locations, types of materials, etc. The material flows of the ESFR system are taken from [3]. In accord with the diversion goal, i.e., to obtain 8 kg plutonium, it is estimated that diverting LWR spent fuel related material solely will take 1.44/σ weeks and diverting ESFR reactor spent fuel related material solely will take 0.1728/σ weeks, where σ is the percentage of the material to be diverted. The value of σ is based on the detection threshold derived from the uncertainty of identifying material unaccounted for (MUF) [6].

3.2 Distributed Diversion of ESFR System

Two types of studies are usually of interest. The first type of study is a general evaluation of the whole energy system (distributed diversion). This is a much more general case because proliferators may not limit their diversion activities to certain facilities only. Most of the studies in [5] and the case in [10] are distributed diversion scenarios based on the assumption of continuous material diversion from the energy system. The transition periods between two stages are determined according to the diversion rate and the amount of equivalent plutonium in the material. If diversion occurs at more than one location, the transition periods need further adjustment in accord with the diversion rates needed to meet the goal of obtaining 1 SQ of plutonium. The second type of study is the evaluation of individual diversion (concentrated diversion). In this case, only the time parameters of the set of the inspection activities related to this diversion will be considered in the model. A generic tool can be built to incorporate both types of diversion scenarios and then corresponding anomalies and inspections in an exhaustive manner.

For a particular diversion, corresponding anomalies will be identified. Available follow-up actions for each anomaly are then considered. The key information is the time each of them takes. Combinational effects of detection times will be calculated and applied in the Markov model. For any diversion scenario, the diversion could either be finished within a very short time period, say within a couple of days, or a relatively long time period depending on actions of the proliferators. The material can be diverted in the form of assemblies or pins or bulk material. We assume that an abrupt distributed diversion strategy is adopted by the proliferators here, i.e., one significant quantity (1 SQ) of material will be diverted equally from each facility. The material quality and amounts thus obtained would not be simply reactor grade plutonium or mixed oxide fuel. It would be some hybrid, which would pose a challenge to the proliferators in making a weapon. This complication would be considered in the modeling of technical difficulty in the clandestine processing and fabrication facilities. Here, 1 SQ is equivalent to 2 LWR assemblies, or 1 assembly (110 pins) of ESFR fresh fuel or spent fuel, or 10 kg transuranic (TRU) bulk material [3]. It is assumed in the current study that the time to accumulate 1 SQ material via distributed diversion is two days, i.e., the diversion will be finished in two days. The abrupt diversion is only a special case of protracted diversion with a very high diversion rate. The detailed Markov model of this diversion scenario is almost identical to that in [10] except for the parameters. The diversion scenario presented here might not be optimum for a proliferator in terms of obtaining the desired material composition for fabrication of a weapon. We chose this scenario to illustrate a spectrum of options—all shown within a single calculation. Alternatively, calculations could be performed with abrupt or protracted diversion from a single stage. Such calculations are being performed using the software tool PRCALC and will be reported elsewhere.

The overall detection probability, successful diversion probability, and failure probability inside the clandestine facilities due to technical difficulties encountered by the proliferators are shown in Figures 3, 4, and 5. Figure 3 shows the overall detection probability of the whole diversion process by accumulating the detection probability of each stage. It is noted that the success probability is around 15% and is very high compared to concentrated diversion results which are not shown here. This is the reason that a distributed diversion strategy might attract the proliferators, i.e., 1 SQ equivalent material can thus be accumulated in very short time period with very low diversion rates. On the other hand, a higher success probability requires more resources because the proliferators would need to have many people with access to several facilities in the ESFR system. Figure 5 gives the cumulative failure probability due to technical difficulties in operating clandestine facilities (PUREX and Fabrication).
Figure 2: Diversion Scenario of ESFR System
Figure 3: Overall Detection Probability of ESFR System Diversion

Figure 4: Success Probability of ESFR System Diversion Scenario
4. CONCLUSIONS

It has been successfully demonstrated that multiple safeguards can be modeled readily within the Markov scheme being developed for the PR&PP evaluation of next generation nuclear energy systems. The modeling method enables inclusion of various safeguards designs for individual facilities inside the energy system to be studied.

All the parameters used in the Markov modeling method are physically meaningful and can be determined according to capability and availability of each safeguards approach, design features of each facility, and possible diversion strategies and scenarios of a particular energy system. The parametric modeling of safeguards approaches provides a quantitative evaluation tool for safeguards systems design and improvement. This is expected to be able to help improve IAEA safeguards designs for the future energy system, as proposed in [1].

Taking the ESFR system as an example, the Markov model approach is adapted to the problem of quantitatively analyzing proliferation resistance. Composite safeguards approaches are incorporated in the Markov model to better reflect characteristics of practical systems. Scenarios or pathways for diversion of plutonium were developed and cast into the form of a Markov model. The probability of success for the proliferator and the probability of detection of this activity were computed. In addition, the probability of technical failure of the clandestine process was also computed. Compared to the case in which only MUF is modeled [10], the inclusion of multiple safeguards indicate that detection probability can be significantly increased. The safeguards approaches that appear to have a significant impact are properly employed surveillance cameras because they are able to detect an anomaly quickly.

It should be pointed out that the results presented here are preliminary. They are not at a stage that conclusions should be drawn with regard to the proliferation resistance of particular facilities and operations. Rather, the results are presented to illustrate the form of prediction and display. Sensitivity studies can be done very quickly within this framework using the tool PRCALC. Thus alternative input sources and assumptions can be tested for their impact. The aim of the methodology is to present a holistic picture of the scenarios considered – complete at a high level. Both qualitative and quantitative insights are gained from this approach, which is consistent with probabilistic analysis in the safety arena. Future work should incorporate more realistic information on safeguards and more detailed models of the systems being evaluated.

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