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Quantitative Assessment of Probabilistic Measures for Proliferation Resistance

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INTRODUCTION

An evaluation methodology for proliferation resistance (PR) and physical protection (PP) is under development by a PR&PP Experts Group [1]. It involves pathway evaluation and quantification of associated measures for PR and PP. In this paper, probabilistic risk assessment approaches are used to further develop the evaluation procedure for proliferation resistance. This work is part of the Generation IV methodology development that is being sponsored by the U.S. Department of Energy. Detailed pathway analysis and quantitative assessment of the proliferation resistance measures for specific scenarios are addressed using a Markov chain approach [2] [3].

APPROACHES

A Markov representation of the fuel cycle for a nuclear energy system has been developed in a generalized framework. The Markov modeling approach integrates a large number of uncertainties, the unpredictability of human performance, and the effect of changing conditions with time that are embedded in proliferation scenarios. Various proliferation scenarios such as misuse, diversion, and mixed scenarios that include both are modeled as additional states that branch off the normal states of a declared nuclear fuel cycle. In addition, safeguards for declared facilities are incorporated in the Markov chain as transitions from the proliferation pathway to a terminal detected state. Two kinds of detection activities are differentiated. One represents the regular routine inspections with certain frequency inside a facility and another represents the safeguards activity during transfer between two facilities, i.e., instantaneous inspection. Although material accountancy is the key inspection method, the effects of a combination of complementary detection means can be modeled by selecting a detection rate that represents an effective time period required to reach the state of being detected. The transition between two states in the Markov chain is characterized by a transition rate and the amount of nuclear material being siphoned off the fuel cycle by the proliferator is characterized by a diversion rate. For misuse scenarios, these parameters of the model are determined with consideration to minimize the risk of detection during normal operation. For the diversion scenarios, the parameters are determined by the goal of achieving one significant quantity of nuclear material. The parameters have to be calculated dynamically to represent reality of proliferation according to the type and amount of material to be diverted for specific diversion scenarios. A discrete rate of detection is incorporated in this modeling framework. Due to the measurement uncertainty of inspection using the material accountancy method, the detection rate changes are not continuous and are represented by step functions in time with respect to diversion rates, which are defined as the ratio of diverted material to the total material at a specific facility. These features allow for the extensive study of scenarios strategies such as distributed, concentrated, and protracted diversion.

RESULTS

Figure 1 provides a graphic representation of the Markov model for diversion scenarios at the front-end of a fuel cycle associated with an advanced light water reactor. The material flow in declared facilities and the types of states are shown in Stages I, II, …, VIII. The diverted material will be processed in clandestine facilities shown in Stage IX, X, and XI. Various states are differentiated, e.g., the normal outcome state indicates where the material is normally intended to flow in the declared system. These results assume that detection of the clandestine operations does not occur. However, as indicated in Figure 1, detection of these operations can be incorporated and computed in the model. This allows for assessment of safeguards measures (e.g., and additional protocol) beyond those for the declared facilities. The cumulative detection probabilities for the distributed diversion scenarios at the front-end of a fuel cycle are calculated using a computer program PRCALC [3] and the results are shown in Figure 2. It is assumed that there is no additional protocol related to safeguards. Thus, there is no detection in clandestine facilities as shown in Figure 2.

PRCALC can generate the pathways and Markov models automatically for different scenarios. It is also able to compute different PR measures such as the detection probability, shortest path in terms of least time or cost, and a technical difficulty index. Sensitivity studies can be done very quickly within this framework. Thus alternative input sources and assumptions can be tested for their impact. Sensitivity studies have been performed to study the impacts of additional safeguards measures and the tradeoffs between choices of shorter development time and higher failure probability.

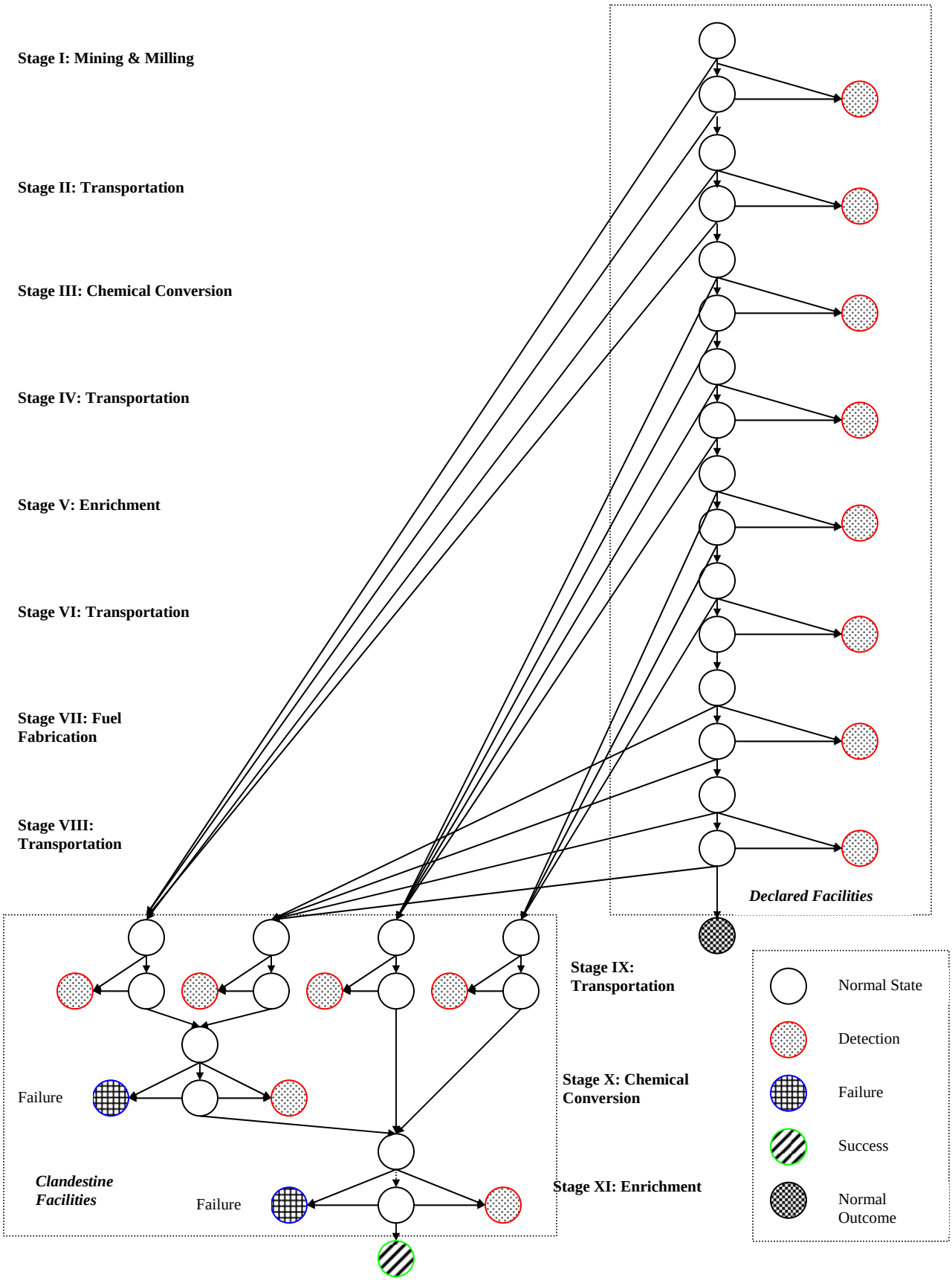

Figure 1 Markov Model for Diversion at Front-end of an ALWR Fuel Cycle

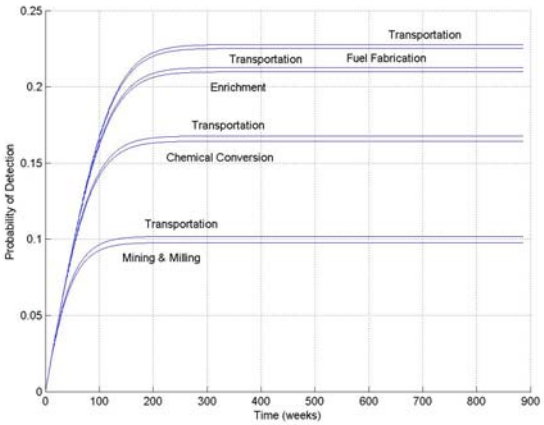

Figure 2 Detection Probability of ALWR Front-end Distributed Diversion

A systematic methodology of modeling and computing probabilistic measures for PR & PP has been proposed and implemented in this study using Markov chain techniques By taking into consideration intrinsic and extrinsic barriers to proliferation the resultant model provides valuable insights to the effort of enhancing proliferation resistance.

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