EMRALD-Based Evaluation of Passive Delay in a Defense-in-Depth Physical Protection System for Deployable Microreactors

Young Jin Go, Jeong Ik Lee*
Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea
** Corresponding author: jeongiklee@kaist.ac.kr*

***Keywords :** Microreactor, Physical Protection System (PPS), EMRALD, Passive Delay

1. Introduction

Microreactors are compact nuclear reactors characterized by factory fabrication, transportability, and self-adjusting operation. These characteristics enable deployment in remote or infrastructure-constrained locations while reducing onsite construction and operator requirements [1]. Compared with conventional large nuclear power plants, microreactors operate with smaller site footprints, limited permanent infrastructure, reduced onsite personnel, and site-dependent response capabilities. These deployment and operational features therefore create different design conditions for the physical protection system (PPS).



Fig. 1. Representative deployable microreactor concept: Westinghouse eVinci [2]

Physical protection is an essential element of nuclear security for protecting nuclear material and nuclear facilities against unauthorized removal, sabotage, and other malicious acts. A physical protection system is designed against a defined threat. The Nuclear Regulatory Commission (NRC) defines the design basis threat (DBT) as "a set of adversary characteristics established by the Commission as the basis for the design of the licensee's security systems" [3]. The International Atomic Energy Agency (IAEA) similarly recommends that physical protection measures be developed on the basis of a threat assessment or DBT, together with the application of a graded approach and defence-in-depth [4]. Within this threat-based framework, a PPS integrates detection, delay, and response functions to protect identified targets against the defined threat.

Building on these physical protection principles, this study applies Sandia's SeBD/DEPO methodology to a hypothetical deployable microreactor. Event Modeling Risk Assessment using Linked Diagrams (EMRALD) is utilized to model adversary progression and the PPS response as a time and probability dependent event sequence. A representative external adversary path from the site boundary to a protected target was constructed, and stochastic PPS configurations with and without an additional passive barrier were evaluated. The objective of this study is to assess the contribution of passive delay to the PPS system and to provide a basis for a defence-in-depth design approach incorporating modular passive protection.

2. Methodology

2.1. Security-by-Design and DEPO Methodology

Sandia National Laboratories has applied the Security-by-Design (SeBD) concept to microreactor facility design by integrating security requirements from the design stage rather than treating physical protection as a later addition. For SMR applications, Sandia adopted the Design Evaluation Process Outline (DEPO) as a systems-engineering methodology for PPS development and subsequently applied it as a guiding methodology to a hypothetical microreactor facility [5], [6].

DEPO provides a structured process for designing and evaluating physical protection systems by defining protection requirements, characterizing the facility and threat environment, developing the PPS, and assessing its effectiveness. The methodology is organized into three major steps: Define PPS Requirements, Design/Characterize the PPS, and Evaluate the PPS, as illustrated in Fig. 2.

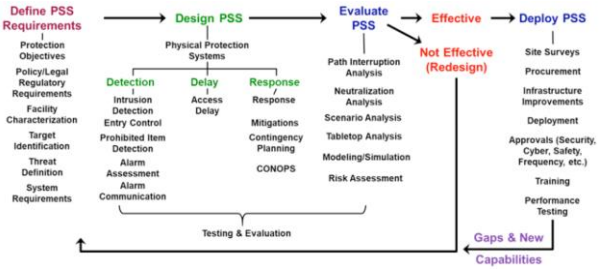


Fig. 2. DEPO methodology framework for PPS [5]

2.2. EMRALD-Based Physical Protection Model

The time-dependent behavior of the PPS was modeled using Event Modeling Risk Assessment using Linked Diagrams (EMRALD). EMRALD is a dynamic

risk assessment tool developed to represent time-dependent events and interactions among system components using linked state-based diagrams [7]. A 2023 INL study extended EMRALD for physical-security analysis of advanced/small modular reactors (A/SMRs), providing generic templates for physical barriers, intrusion sensors, physical areas, and safety actions that can be used to construct and modify attack scenarios [8]. The template data were developed for training purposes rather than to represent an actual reactor facility and can be modified by users for a specific analysis.

Based on the physical-protection concepts described in the Sandia microreactor studies and the INL generic physical-security model, a hypothetical adversary intrusion path was constructed, as shown in Fig. 3. The path represents sequential adversary progression from the perimeter fence to the protected target through successive exterior and interior protection layers.

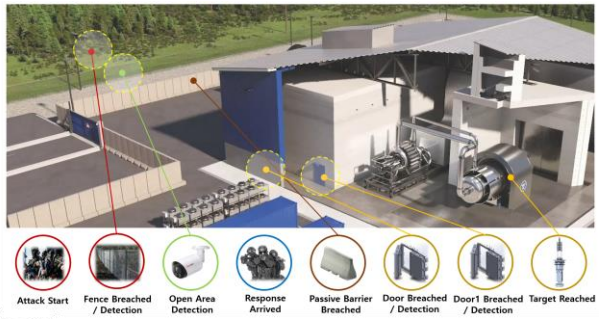


Fig. 3. Hypothetical microreactor physical protection layout and adversary progression path

Detection opportunities were assigned to the perimeter fence, open area, reactor-building door, and hardened inner door. At the fence and door locations, a successful detection was treated as a confirmed detection and initiated the response sequence. For the open-area layer, alarm generation and alarm assessment were represented separately. An open-area alarm was credited as a confirmed detection only after successful assessment. The passive barrier was modeled as a delay element without an additional detection function.



Fig. 4. EMRALD state-transition model for adversary progression, detection, response, and engagement

Adversary progression was represented as a sequential state-transition process from attack initiation to target access. Following a confirmed detection, onsite response mobilization proceeded in parallel with continued adversary progression. When the response force arrived, a single engagement opportunity was evaluated using a prescribed conditional neutralization probability. Successful neutralization terminated the attack sequence, whereas an unsuccessful engagement allowed the adversary to continue toward the protected target.

The quantitative input parameters assigned to the principal EMRALD events are summarized in Table 1. The input parameters for the simulation were derived from open-source empirical datasets available on Idaho National Laboratory. Fixed values were used for short traversal events, whereas penetration, alarm-assessment, and reponse-arrival times were represented using normal distributions with specified bounds. Detection and engagement outcomes were modeled using prescribed probabilities. The same parameter set was applied to both configurations, except for the additional passive-barrier penetration event included only in the passive-barrier case.

Table 1: Input parameters for the EMRALD PPS model

Process		Parameter	Value
Fence	Barrier	Penetration time	N (10, 288; [0, 1800]) s
	Sensor	Detection probability	P = 0.8
Open area	Traversal	Traversal time	12 s
	Detection	Alarm probability	P = 0.6
	Alarm	Assessment time	N (26.7, 33.7; [3,380]) s
Passive barrier		Penetration time	N (14, 4.8; [3, 30]) min
Reactor Building	Barrier (Door)	Penetration time	N (14, 4.8; [3, 30]) min
	Sensor	Detection probability	P = 0.6
	Traversal	Traversal Time	24 s
Hardened Room	Barrier (Door1)	Penetration time	N (14, 4.8; [3, 30]) min
	Sensor	Detection probability	P = 0.5
	Traversal	Traversal time	6 s
Response	Mobilization	Response arrival time	N (70, 7; [0, 120]) s
	Engagement	Neutralization probability	P = 0.5

Note: N (μ, σ;[L,U]) denotes a normal distribution with mean μ, standard deviation σ, and lower and upper bounds L and U, respectively. Barrier penetration parameters were based on the generic EMRALD physical-security templates [8].

Fixed traversal times and probability distributions for penetration, alarm assessment, response arrival, and engagement were assigned to the corresponding

EMRALD events. The same detection, response, and engagement assumptions were retained in both configurations so that the effect of the additional passive delay element could be evaluated independently.

2.3. Analysis Cases and Evaluation Metrics

Two stochastic PPS configurations were analyzed to quantify the effect of the additional passive barrier. The baseline case represented the adversary path without the passive barrier, whereas the passive-barrier case included an additional delay element between the open area and the reactor-building door. All other detection, response, and engagement assumptions were kept identical between the two cases. Each configuration was evaluated using 10,000 Monte Carlo simulations.

The principal evaluation metrics were response-arrival probability, attack-neutralization probability, target-access probability and time, and engagement location. Target-access time was evaluated for simulation runs in which the adversary reached the protected target. The results of the two configurations were then compared to quantify the temporal effect of the additional passive delay.

3. Results and Discussion

3.1 Overall EMRALD Simulation Results

A total of 10,000 Monte Carlo simulations were performed for each of the baseline and passive-barrier configurations. The simulations evaluated adversary progression from attack initiation to either attack neutralization or target access, together with the associated detection, response, and engagement processes. The principal simulation results are summarized in Table 1. The mean target-access time increased from 30.67 min in the baseline configuration to 44.78 min with the passive barrier, while the response-arrival and attack-neutralization probabilities remained similar between the two configurations.

Table 1: Key EMRALD simulation results for the baseline and passive-barrier configurations

Metric	Baseline	PB
Response arrival probability	96.9 %	97.0%
Attack neutralization probability	48.93%	48.72 %
Target access probability	51.07 %	51.28 %
Mean target-access time (min)	30.67	44.78
SD of target access time (min)	7.29	8.85
Mean reactor building door breach time (min)	16.14	30.35
Dominant engagement location	Door	Passive barrier
Fraction of engagements at dominant location	95.0 %	95.1 %

3.2. Effects of Additional Passive Delay

The primary effect of the additional passive barrier was an increase in adversary progression time. The mean target-access time increased from 30.67 min in the baseline configuration to 44.78 min in the passive-barrier configuration, corresponding to an additional delay of approximately 14.11 min. A similar temporal shift was observed in the reactor-building door breach time, which increased from 16.14 to 30.35 min. The standard deviation of the target-access time increased from 7.29 to 8.85 min, reflecting the additional stochastic penetration process introduced by the passive barrier.

A more distinct change was observed in the location of response engagement. In the baseline configuration, approximately 95.0% of engagements occurred at the reactor-building door. With the additional passive barrier, approximately 95.1% of engagements occurred at the passive barrier instead. The additional delay element therefore shifted the dominant engagement location from the reactor-building entrance to an outer protection layer. In the present model, the prolonged penetration time at the passive barrier provided sufficient time for the response force to arrive while the adversary remained at that layer.

In contrast, the overall response-arrival and attack-neutralization probabilities remained nearly unchanged. The response-arrival probabilities were 96.9% and 97% for the baseline and passive-barrier configurations, respectively, while the corresponding attack-neutralization probabilities were 48.93% and 48.72%. This similarity results from the common detection and response assumptions applied to both configurations and the prescribed conditional neutralization probability of 50%. Thus, within the present model, the additional passive barrier primarily changed when and where engagement occurred, rather than the probability of successful neutralization.

4. Conclusions and Future Work

This study developed a hypothetical deployable-microreactor PPS based on the SeBD/DEPO methodology and modeled adversary progression, detection, response, and engagement using EMRALD. The baseline and passive-barrier configurations were evaluated through 10,000 Monte Carlo simulations. The addition of the passive barrier increased the mean target-access time from 30.67 to 44.78 min, corresponding to approximately 14.11 min of additional adversary delay. This result quantitatively demonstrates the temporal contribution of an additional delay layer within a defence-in-depth PPS and shows that passive protection can increase the time available for response before target access.

The passive barrier also affected the location of response engagement. This result indicates that the location and delay characteristics of protection layers can influence where the response force encounters the adversary. Such engagement-critical locations may therefore be considered when coordinating surveillance, alarm assessment, and response resources within a layered PPS.

In contrast, the response-arrival and attack-neutralization probabilities remained nearly unchanged between the two configurations. This behavior is consistent with the use of identical detection and response assumptions and a prescribed conditional neutralization probability in both cases. Therefore, the passive barrier primarily affected adversary progression and engagement location rather than the detection or neutralization probabilities themselves. Further improvement of the PPS can be investigated by extending detection to more remote protection layers and by explicitly considering detection timing and alarm-assessment time, thereby increasing the time available for response.

Future work will focus on three extensions of the present model. First, the adversary model will be expanded to include multiple attack scenarios with different intrusion paths, threat types, and threat intensities. Specifically, the adversary model will be specified by introducing tactical engagement scenarios, such as gunfight dynamics, and evaluating the impact of varying attack team sizes. Second, the response model will be refined to represent engagement at identified critical points, mobilization of external response forces, and variations in neutralization probability. Third, the PPS configuration will be extended from simple fence and reactor-building protection to a multilayer passive protection system incorporating sacrificial barriers, blast-resistant doors, and other delay elements that the adversary must penetrate or overcome. These extensions will enable the present hypothetical model to evolve toward a threat-informed, multilayer physical protection model for deployable microreactors.

REFERENCES

[1] U.S. Department of Energy, What is a Nuclear Microreactor?, Office of Nuclear Energy, https://www.energy.gov/ne/articles/what-nuclear-microreactor.

[2] Westinghouse Electric Company, eVinci Microreactor, https://westinghousenuclear.com/innovation/evinci-microreactor/.

[3] U.S. Nuclear Regulatory Commission, Design Basis Threat (DBT) Frequently Asked Questions, https://www.nrc.gov/security/faq-dbtfr.

[4] International Atomic Energy Agency, Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5), IAEA Nuclear Security Series No. 13, Vienna, 2011.

[5] A. Evans, C. Byrum, D. Stanford, E. Sandt, and T. Goolsby, Physical Protection Recommendations for Small Modular Reactor Facilities, Sandia National Laboratories, SAND2021-15712, 2021.

[6] A. Evans, A. Neef, B. Stromberg, and C. Evans, U.S. Domestic Microreactor Security-by-Design, Sandia National Laboratories, SAND2021-13779 R, 2021.

[7] Idaho National Laboratory, EMRALD Documentation: Demo Project, https://emrald-docs.inl.gov/Modeling/demoProject.html.

[8] R. Christian, C. P. Chwasz, M. A. Ziccarelli, S. Zhang, S. R. Prescot, V. Yadav, S. W. St Germain, D. Grabaskas, and M. D. Bucknor, Methodology and Tool for the Physical Security Analysis of Micro and Advanced Reactors, Idaho National Laboratory and Argonne National Laboratory, August 2023.