U.S. Domestic Pebble Bed Reactor: Security-by-Design

Prepared for
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ABSTRACT

U.S. nuclear power facilities face increasing challenges in meeting dynamic security requirements caused by evolving and expanding threats while keeping cost reasonable to make nuclear energy competitive. The past approach has often included implementing security features after a facility has been designed and without attention to optimization, which can lead to cost overruns. Incorporating security in the design process can provide robust, cost-effective, and sufficient physical protection systems. The purpose of this work is both to develop a framework for the integration of security into the design phase of High Temperature Gas Reactors (HTGRs) that utilize pebble-based fuels and increase the use of modeling and simulation tools to optimize the design of physical protection systems. Specifically, this effort focuses on integrating security into the design phase of a model HTGR that meets current Nuclear Regulatory Commission (NRC) physical protection requirements and providing advanced solutions to improve physical protection and decrease costs. A suite of tools, including SCRIBE3D©, PATHTRACE© and Blender© were used to model a hypothetical, generic domestic HTGR facility. Physical protection elements such as sensors, cameras, barriers, and guard forces were added to the model based on best practices for physical protection systems. Multiple outsider sabotage scenarios were examined with four-to-eight adversaries to determine security metrics. The results of this work will influence physical protection system designs and facility designs for U.S. domestic HTGRs. This work will also demonstrate how a series of experimental and modeling capabilities across the Department of Energy (DOE) Complex can impact the design of and complete Safeguards and Security by Design (SSBD) for SMRs. The conclusions and recommendations in this document may be applicable to all SMR designs.

ACKNOWLEDGEMENTS

The team would like to acknowledge the many subject matter experts who contributed their expertise to the development of this hypothetical facility, the design of the security system and the analysis of the security system.

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EXECUTIVE SUMMARY

This report analyzes the design of a hypothetical pebble bed reactor (PBR) facility and the physical protection system for a PBR facility. The design and analysis focus on designing a PBR facility with a small footprint and physical protection system to allow for cost-effective deployment of PBRs domestically. This study focuses on identifying methodologies and design decisions impactful for PBR vendors for deploying cost-effective and secure PBR facilities.

Based on numerous High Temperature Gas Cooled Reactors (HTGRs),[1] a representative HTGR reactor model and site layout were created assuming four reactors and four turbines for electricity production[2]. Each reactor is located in a separate building. Key reactor components such as the fuel pebbles, moderators and reflectors, control rods and other core internals are housed within a confinement structure. The confinement structure allows for possible venting in the very unlikely case of radiological effluent release from the fuel. The following are a list of key components of the representative HTGR reactors:

1. Each reactor core produces 360 MWth with an efficiency of 42% for a power output of 150 MWe
2. The core is fueled by TRI-structural ISOtropic (TRISO) particle fuel pebbles with an enrichment of 8.5% (i.e., equilibrium core)
3. The TRISO fuel particle[3] includes a uranium, carbon, and oxygen fuel matrix kernel of approximately 500 micrometers in diameter[4] embedded in multiple layers of containment in order to physically protect the fuel and prevent the escape of fission products. This makes the fuel robust and resistant to high temperatures for extended periods of time while maintaining fission product retention. Outside of the fuel kernel is porous carbon for fission gas accumulation. Following this is an inner pyrolytic carbon layer, a structural silicon carbide layer, and finally an outer layer of pyrolytic carbon.[5] Each pebble consists of approximately 15,000 coated fuel particles in a graphite matrix with a 5 mm buffer which makes up the 6 cm diameter pebble.[6]
4. Each core has 420,000 pebbles[7] in circulation at any given time.

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[1] For numerous examples of high-temperature gas-cooled small modular reactors in the open source, see: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 135-194.

[2] "Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS)." International Atomic Energy Agency. 2020

[3] Department of Energy Office of Nuclear Energy, "TRISO Particles: The Most Robust Nuclear Fuel on Earth," July 9, 2019, retrieved January 14, 2021, https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth#:~:text=TRISO%20stands%20for%20TRi%2Dstructural,release%20of%20radioactive%20fission%20products.

[4] Similar to the PBMR®-400 from Pebble Bed Modular Reactor SOC Ltd in South Africa. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, p. 164.

[5] Paul Demkowicz, Ph.D., "TRISO Fuel: Design, Manufacturing, and Performance," Idaho National Laboratory, NRC HTGR Training, July 16-17, 2019.

[6] Similar to the PBMR®-400 from Pebble Bed Modular Reactor SOC Ltd in South Africa. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, p. 164.

[7] Similar to the HTR-PM from Tsinghua University, ChinaSee: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 137-140.

5. Pebbles are offloaded once they reach the target burnup (i.e., 90 GWd per ton). Refueling occurs online with continuous addition and removal of pebbles. Pebbles pass through the reactor until they reach a tube and flow through a measurement system to measure burnup. Once the pebble reaches the target burnup, it is sent to a spent fuel container. If the burnup is not met, it is pneumatically sent back up to the top of the core for another pass.
6. Primary cooling is conducted by forced circulation from a helium circulator[8]
7. Core reactivity is controlled by boron carbide (i.e., B_4C) control rods and small absorber spheres[9].

Figure 1 shows the hypothetical facility.

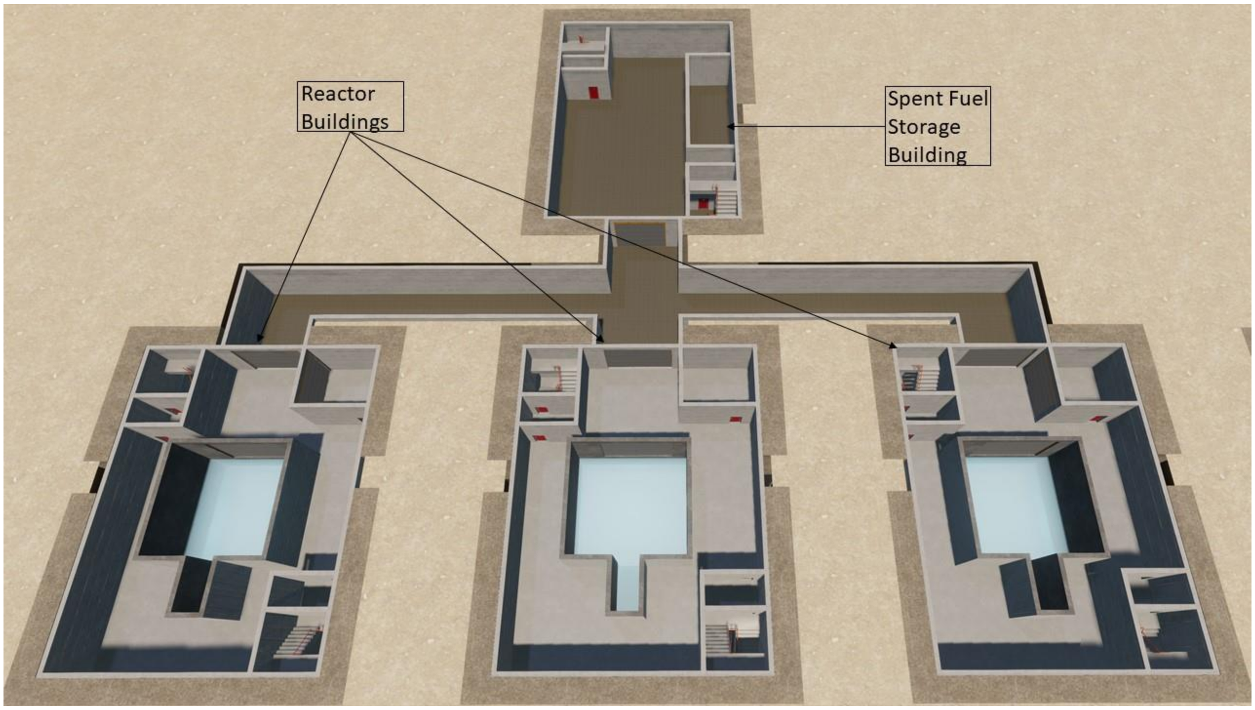

Figure 1 Hypothetical Facility Layout

For this design and analysis, the facility and physical protection system were designed to allow for an offsite response force time of 30-minutes and 60-minutes. For this analysis sabotage of nuclear material or facility is core damage (i.e. loss of pebble integrity) or radiological release from the facility.

In the design of this facility, underground siting was considered to increase adversary task time, active delay features were implemented to multiply adversary task times and the overall adversary task time, and extended detection to detect malicious acts earlier and improve the effectiveness of the physical protection system. Additional upgrades include hardening and reinforcing doors with steel lining to increase adversary task times, mantraps to increase delay time, and reinforced wall

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[8] C. F. McDonald and M. K. Nichols, "Helium Circulator Design Considerations for Modular High Temperature Gas-Cooled Reactor Plant," GA Technologies, Inc., San Diego, California, GA Project 6300, December 1986, https://inis.iaea.org/collection/NCLCollectionStore/_Public/19/005/19005804.pdf.

[9] Similar to Urenco's U-Batter from the United Kingdom. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 293-296.

thickness to increase adversary task time. The use of path analysis tools and force-on-force modeling simulations were used to determine the probability of interruption and the probability of neutralization using traditional methodologies. The baseline PPS design was based on current Nuclear Regulatory Commission (NRC) regulations, with some exceptions made for the consideration of reduced on-site response force numbers by the small modular reactor community.

Figure 2 shows system effectiveness of the physical protection system for defending against sabotage against a PBR reactor and spent fuel canisters for a 30-minute and 60-minute response force time. In this analysis, successful sabotage was considered when the adversary was able to place a breaching charge onto one of the reactors or the spent fuel canisters in the spent fuel building. This was considered successful sabotage to avoid sensitives associated to reactor sabotage consequences.

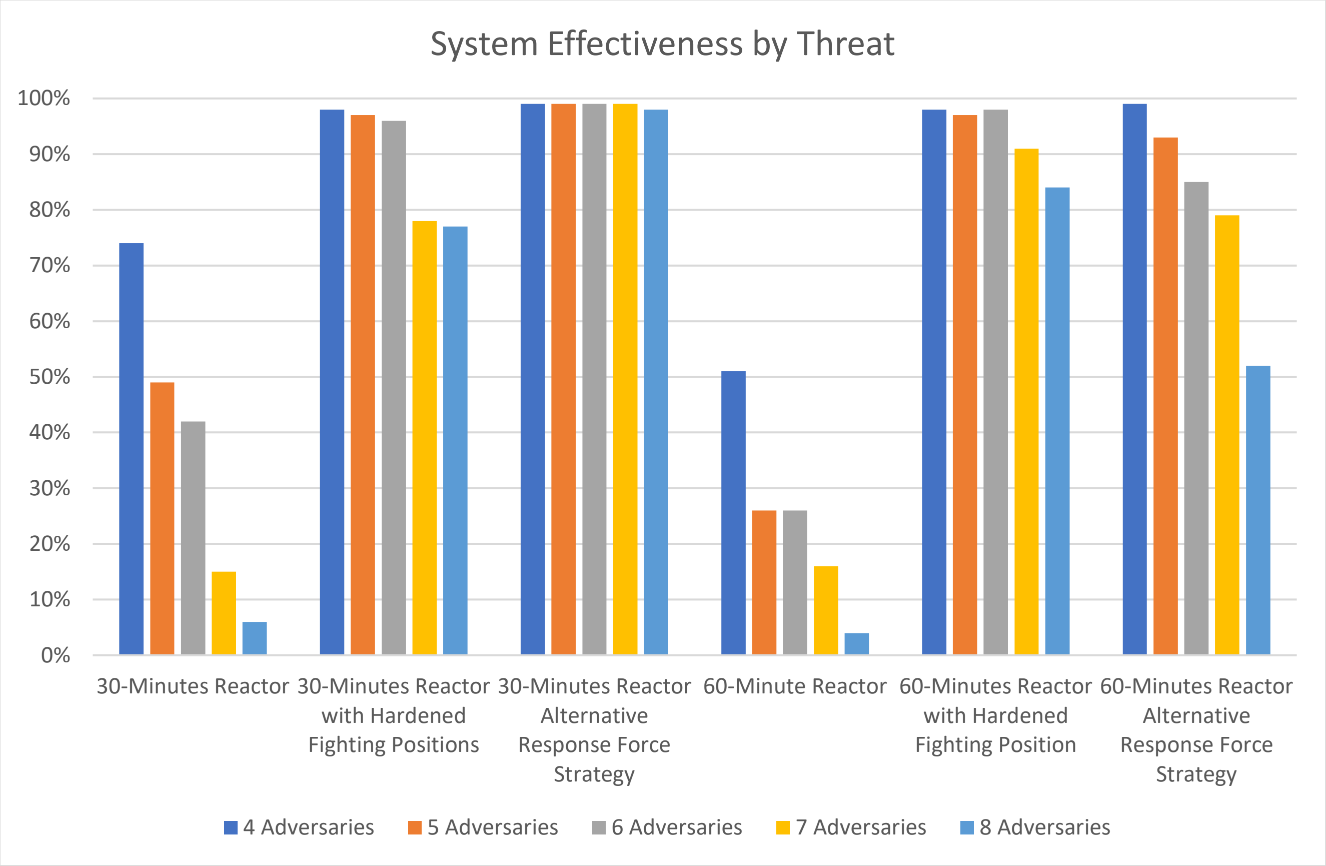

Figure 2 System Effectiveness of The Physical Protection System

As can be seen in the figure above, the system effectiveness for both targets is higher for a 30-minute response force time than for a 60-minute response force. This decrease in system effectiveness is largely due to decreases in probabilities of neutralization as response force time increases. As the response force time increases, the adversary force can harden themselves in the facility and increase the effectiveness in which they can engage with the response force. Improving response force tactics, planning, and procedures for entering the facility and engaging with an adversary force may improve the probabilities of neutralization and therefore system effectiveness. It can also be seen that the system effectiveness is much higher for spent fuel canisters than for reactors. The primary reason for this is due to the open space in the spent fuel storage building and increased barriers to increase delay time and improve the system effectiveness of the physical protection system. The open space allows the response force to effectively neutralize an adversary force as compared to the confined space in the reactor buildings. Additionally, alternative response force strategies such as the use of hardened fighting positions and alternative response force routes into the facility were analyzed. This allows for a comparison of different response force strategies and the impact that these strategies have on the effectiveness of the physical protection system. These alternative response force strategies impact and improve the effectiveness of the physical protection system.

PBR facility designers should consider decreasing the response force time to the site as much as possible to provide an effective physical protection system. This analysis identified that shorter response force times can lead to more effective physical protection systems for PBR facilities.

Facility designers should develop trainings and exercises for response force members that ensure proper tactics, contingency plans and compensatory measures are put in place to ensure the effectiveness of response provided by the response force. Sites should consider the use of extended detection technologies to detect malicious acts earlier and allow for the response force to arrive earlier and engage the adversary before they penetrate deeper into the PBR facility. PBR designers should consider the use of active delay features that can multiply adversary task time and improve the probability of interruption and therefore the system effectiveness of the physical protection system. PBR facilities should also consider designs where reactors and spent fuel are placed below-grade to increase the adversary task time and improve the effectiveness of the physical protection system. Details of these recommendations, implementation and analysis can be found through the remainder of this report.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ASD	Adversary sequence diagram
BAS	Backup alarm station
BMS	Balanced magnetic switch
CAS	Central Alarm Station
CFR	Code of Federal Regulations
CCTV	Closed circuit television
CDP	Critical detection point
CVCT	Chemical volume control tank
DBA	Design basis accident
DBT	Design basis threat
DEPO	Design and evaluation process outline
DMA	Deliberate motion algorithm
DOE	Department of Energy
ECCS	Emergency core cooling system
ECP	Entry control point
FRB	Fuel Receiving Building
HTGR	High Temperature Gas Cooled Reactors
iPWR	Integral-Pressurized Water Reactor
KIA	Killed in action
LAA	Limited access area
LEU	Low-enriched uranium
LLEA	Local law enforcement agency
LOCA	Loss of coolant accident
LWSMR	Light Water Small Modular Reactor
LWR	Light water reactor
MVP	Most vulnerable path
NRC	Nuclear Regulatory Commission
NEIMA	Nuclear Energy Innovation and Modernization Act
OCA	Owner-Controlled Area
PA	Protected area

Abbreviation	Definition
PBSMRF	Pebble Bed Small Modular Reactor Facility
P_D	Probability of Detection
P_E	Probability of Effectiveness
P_I	Probability of Interruption
PIDAS	Perimeter intrusion detection and assessment system
PIN	Personal Identification Number
P_N	Probability of Neutralization
PPB	Power production building
PPS	Physical Protection System
PSIT	Passive safety injection tank
RF	Response force
RFT	Response force time
RPV	Reactor pressure vessel
RWMT	Residual water makeup tanks
SFSC	Spent Fuel Storage Canister
SMR	Small Modular Reactor
SMRF	Small modular reactor facility
SNL	Sandia National Laboratories
SNM	Special Nuclear Materials
SSBD	Safeguards and Security by Design
TRISO	TRI-structural ISOtropic
UPS	Uninterruptible power supply
URC	Unacceptable radiological consequence
VA	Vital area

1. INTRODUCTION

Domestic nuclear facilities face stringent requirements for security, particularly for nuclear power generating facilities, including advanced small modular reactors (SMRs). This analysis focuses on the United States domestic regulatory structure from the Nuclear Regulatory Commission (NRC) perspective. Nuclear power plant facilities must meet these stringent regulatory requirements for physical protection due to the threat posed by theft and sabotage of nuclear material. This places nuclear power at a significant disadvantage compared to other energy sources since it requires more upfront, operational, and maintenance costs in physical protection systems (PPS) and protective force personnel.

Some SMR vendors claim that due to the robust passive safety features of the nuclear reactors, an onsite security force is not necessary. By only using offsite local law enforcement, operational costs may be significantly reduced. Furthermore, future nuclear facilities will need to incorporate Safeguards and Security by Design (SSBD) to optimize the performance of the PPS within reasonable cost constraints while meeting stakeholder objectives. Historically, the design of nuclear facilities has been retrofitted to accomplish the performance objectives of safeguards and security[10]. Incorporating these factors into the design phase of the facility can significantly decrease implementation and operational costs throughout the facility's lifetime. As part of this design process, it is important to assess the vulnerabilities of the facility through modeling and simulation to identify potential technological and engineering solutions to address those vulnerabilities before the facility is built.

In this report, this design process is demonstrated by identifying a hypothetical design basis threat (DBT) along with employing path and scenario analysis to identify weaknesses in a hypothetical facility's PPS.

The PBR facility described in this report is hypothetical. To avoid potential sensitivities, various individual characteristics of open source planned PBR facilities were selected and/or slightly modified for the hypothetical model[2].

The report documents the reactor, design of the facility, operations, and PPS. The goal of the analysis is to establish an effective physical security system, including an offsite local law enforcement agency (LLEA) as the facility's response force. The modeling and simulation effort describes the process to develop a physical security system using the security-by-design process, including an offsite response force.

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[10] Garcia, M.L. 2008. Design and Evaluation of Physical Protection Systems, 2nd edition, Sandia National Laboratories.

2. REGULATORY CONSIDERATIONS FOR ADVANCED REACTOR DEPLOYMENT

The U.S. Code of Federal Regulations (CFR) Title 10, "Energy" includes Chapter I Parts 1-199 applicable to the NRC. The NRC also publishes regulatory guides to aid in the implementation of these regulations. The following parts of 10 CFR are most applicable to the security and safeguards of special nuclear material:[11]

- Part 11 - Criteria and Procedures for Determining Eligibility for Access to or Control Over Special Nuclear Material
    - Establishes requirements for access to special nuclear materials (SNM)[12]
- Part 25 - Access Authorization for Licensee Personnel
    - Procedures for access authorization to classified information[13]
- Part 26 - Fitness for Duty
    - Requirements for fitness-for-duty programs of nuclear power reactor licensees[14]
- Part 73 - Physical Protection of Plants and Materials
    - Requirements for physical protection systems of plants and special nuclear material in transit and at fixed sites[15]
- Part 74 - Material Control and Accounting of Special Nuclear Material
    - Requirements for control and accounting of SNM at fixed sites and in transit[16]
- Part 95 - Facility Security Clearance and Safeguards of National Security Information and Restricted Data

The NRC has many ongoing activities for near-term, mid-term and long-term to prepare for review and licensing of the next generation reactors. The NRC has been directed by Congress under the Nuclear Energy Innovation and Modernization Act (NEIMA) to establish a technology-inclusive regulatory framework for advanced reactor use by 2027.[17] There are two major activities which relate to physical security rulemaking: Alternative Physical Security Requirements for Advanced Reactors, NRC-2017-0227 and the Part 53 Framework.

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[11] Nuclear Regulatory Commission, "Regulations, Guidance, and Communications," accessed October 9, 2020, https://www.nrc.gov/security/domestic/reg-guide.html.

[12] Nuclear Regulatory Commission, "Part 11 – Criteria and Procedures for Determining Eligibility for Access to or Control Over Special Nuclear Material," page last reviewed/updated September 15, 2020, accessed October 9, 2020, https://www.nrc.gov/reading-rm/doc-collections/cfr/part011/full-text.html.

[13] Nuclear Regulatory Commission, "Part 25 – Access Authorization," page last reviewed/updated September 15, 2020, accessed October 9, 2020, https://www.nrc.gov/reading-rm/doc-collections/cfr/part025/full-text.html.

[14] Nuclear Regulatory Commission, "Part 26 – Fitness for Duty Programs," page last reviewed/updated September 15, 2020, accessed October 9, 2020, https://www.nrc.gov/reading-rm/doc-collections/cfr/part026/full-text.html.

[15] Nuclear Regulatory Commission, "Part 73 – Physical Protection of Plants and Materials," page last reviewed/updated September 15, 2020, accessed October 9, 2020, https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/full-text.html.

[16] Nuclear Regulatory Commission, "Part 74 – Material Control and Accounting of Special Nuclear Material," page last reviewed/updated September 15, 2020, accessed October 9, 2020,

[17] "Advanced Reactor Details", Nuclear Regulatory Commission, Accessed July 19, 2021, https://www.nrc.gov/reactors/new-reactors/advanced/details.html.

2.1. NRC-2017-0227 – Alternative Physical Security Requirements for Advanced Reactors

The 2018 document SECY-18-0076 "Options and Recommendation for Physical Security for Advanced Reactors" evaluated alternatives for physical security for advanced reactors.[18] As an outcome of SECY-18-0076, the NRC proposed a rulemaking effort to establish new alternative physical security regulations for SMRs and advanced reactors to protect against radiological sabotage.[19] This evolved into NRC-2017-0227 limited-scope rulemaking which proposes amending physical security requirements for small modular reactors and other advanced reactor designs commensurate with the risk to the public health and safety. If the licensee can meet certain performance-based eligibility criteria, then the licensee would be eligible for certain voluntary alternative requirements.[20] Specific sections assessed for alternatives include 10 CFR 73.55 "Requirements for Physical Protection of Licensed Activities in Nuclear Power Reactors against Radiological Sabotage," which defines requirements to protect against the design basis threat of radiological sabotage. The NRC is requesting comment on a proposed rule changing current regulations to give more flexibility to SMRs and other advanced nuclear technologies by developing dedicated physical security requirements to reduce the burden on licensees to request for exemptions.[21] This proposed rule aims to keep the requirements of 73.55 to protect against radiological sabotage of the DBT but set out additional guidance for advanced reactors which can establish a performance-based approach for meeting these requirements.

The NRC is proposing to amend the 73.55 security requirements based on three performance metrics. If any individual criterion is met the revised requirements would be applicable and the licensee would be able to follow the performance-based alternative approach:[22,23] [Note that these criteria, as with content involved within the entirety of the rulemaking activities, are draft and therefore subject to change.]

8. "The radiological consequences from a hypothetical, unmitigated event involving the loss of engineered systems for decay heat removal and possible breaches in physical structures surrounding the reactor, spent fuel, and other inventories of radioactive materials result in offsite doses below the reference values defined in §§ 50.34(a)(1)(ii)(D) and 52.79(a)(1)(vi) of this chapter."

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[18] SECY-18-0076, "Options and Recommendation for Physical Security for Advanced Reactors," dated August 1, 2018, (ADAMS Accession No. ML18170A051).

[19] SECY-18-0076, Nuclear Regulatory Commission, Margaret M. Doane, Options and Recommendation for Physical Security for Advanced Reactors," August 1, 2018, https://www.nrc.gov/docs/ML1805/ML18052B032.pdf.

[20] Planned Rulemaking Activities – Rule, "Alternative Physical Security Requirements for Advanced Reactors," NRC-2017-0227, https://www.nrc.gov/reading-rm/doc-collections/rulemaking-ruleforum/active/ruledetails.html?id=76.

[21] Physical Security for Advanced Reactors," A Proposed Rule by the Nuclear Regulatory Commission on 07/16/2019, accessed October 13, 2020, Document Citation: 84 FR 33861, Page: 33861-33864, Agency/Docket Number: Docket No. NRC-2017-0227, RIN: 3150-AK19, Document Number: 2019-15008, https://www.federalregister.gov/documents/2019/07/16/2019-15008/physical-security-for-advanced-reactors.

[22] Please see NRC Markup of NEI-20-05 Draft B Comments on "Methodological Approach and Considerations for a Technical Analysis to Demonstrate Compliance with the Performance Criteria of 10 CFR 73.55(a)(7)", NRC-2017-0227-0027, March 8, 2021. Note that these criteria, as with the entirety of the rulemaking activities, are draft and therefore subject to change.

[23] World Institute for Nuclear Security and Nuclear Threat Initiative, "Security of Advanced Reactors," August 2020, ISBN: 978-3-903191-75-4.

9. "The plant features necessary to mitigate an event and maintain offsite doses below the reference values in §§ 50.34(a)(1)(ii)(D) and 52.79(a)(1)(vi) of this chapter cannot reasonably be compromised by an adversary as defined by the design basis threat for radiological sabotage."
10. "Plant features include inherent reactor characteristics combined with engineered safety and security features that allow for facility recovery and mitigation strategy implementation if a target set is compromised, destroyed, or rendered nonfunctional, such that offsite radiological consequences are maintained below the reference values defined in §§ 50.34(a)(1)(ii)(D) and 52.79(a)(1)(vi) of this chapter."

If any of these eligibility criteria are satisfied, the licensee is eligible for the application of several voluntary performance-based alternatives specified in 73.55(s) which prescriptive requirements within 73.55 (b), (e), (i), and (k). Specifically, the proposed change calls out (but is not limited to):[24] [For full descriptions of the proposed alternatives, be sure to follow the rulemaking activities at Regulations.gov under docket ID: NRC-2017-0227]

- Licensee may rely on local law enforcement to perform the interdiction and neutralization requirements
  - This relieves a licensee of 73.55(k)(5)(ii) minimum number of armed responders
  - Relieves of other requirements in 73.55(k)(3-7) and (k)(8)(ii)
- Relieved of 73.55(e)(9)(v) and 73.55(i)(4)(iii) requiring that the secondary alarm station, including if offsite, be designated and protected as a vital area
  - Sites must still have two onsite alarm stations per 73.55(i)(2), but a designated secondary alarm station may be offsite. It is not required to be a vital area, nor is its associated secondary power supply required to be.

The licensee must perform and submit a site-specific analysis of how their design satisfies the security requirements and performance criteria.

2.2. Part 53 – Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors

This rule is intended to be used by advanced reactor applicants by December 31, 2027. It is in addition to but also in coordination with the limited-scope rulemaking NRC-2017-0227. Rulemaking documents and preliminary proposed rule language can be found under Regulations.gov under document ID NRC-2019-0062. As part of this, proposed language is in development for a technology-inclusive performance-based program which allows for a risk-informed graded approach to physical security, cyber security, and information security, as well as fitness for duty programs and access authorization. The proposed 53.830 Security Program in Subpart F requires the implementation of a physical protection program which 1) protects special nuclear material according to Parts 73 and 37, and 2) protects against radiological sabotage per requirements within 73.55 or the proposed 73.100 unless the following is satisfied:[25]

"The radiological consequences from a hypothetical, unmitigated event involving the loss of engineered systems for decay heat removal and possible breaches in physical structures surrounding

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[24] Revised Preliminary Proposed Rule Language, Posted by the Nuclear Regulatory Commission on Sep 13, 2020, NRC-2017-0227-0023.

[25] Nuclear Regulatory Commission June 10, 2021, Public Meeting Presentation, "Part 53 Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors Rulemaking – Subpart F and 10 CFR Part 73 Emergency Preparedness and Security."

the reactor, spent fuel, and other inventories of radioactive materials result in offsite doses below the values in §§ 53.210(b)(1) and (2)."[26]

This proposed language relieves the applicant from protecting against the DBT of radiological sabotage if the licensee can perform an analysis demonstrating compliance with the criteria. If the criteria are not met, the licensee would have to protect against the DBT with a physical protection program and demonstrate that it meets current performance and prescriptive requirements in 73.55 or the newly proposed 73.100. The proposed section of 73.100 outlines a novel framework to meet general objectives and performance requirements and provides optimal flexibility to protect the plant against the DBT.

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[26] "Section 53.210(b)(1): 25 rem (250 mSv) total effective dose equivalent (TEDE) at any point on the boundary of the exclusion area for any 2-hour period following. Section 53.210(b)(2): 25 rem TEDE at outer boundary of the low population zone." Quoted directly from June 10, 2021 NRC Public Meeting Presentation, "Part 53 Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors Rulemaking – Subpart F and 10 CFR Part 73 Emergency Preparedness and Security."

3. HYPOTHETICAL SMALL MODULAR REACTOR SITE

The hypothetical high-temperature gas reactor pebble bed small modular reactor facility (PBSMRF) developed for this design and analysis encompasses features and capabilities of multiple U.S. domestic SMRs currently in development. This provides a framework for the design and analysis to capture SSBD for domestic SMR applications. The hypothetical SMR facility in this study is located 15 miles outside of Portland, Oregon, in an area with a population of approximately 650,000 people.

3.1. Site Description

3.1.1. *Climate*

The region surrounding the facility has a moderate, wet climate. Its summers are warm and dry, and its winters are cool and wet. The warm season starts in June and lasts until September with an average daily high temperature above 76°F.[27] The cold season is between November and February and has an average daily high temperature below 52°F.[1] As temperatures rarely exceed 95°F, the temperature should not affect any passive infrared technologies. The region generally has a low level of humidity[1] but receives an average of 43 inches of rain and three inches of snow per year.[28] This level of precipitation may induce noise in sensors and cause the degradation of security elements (mold/rust/mineral deposits/electrical shorts). Portland is cloudy about 60% of the time and foggy about 34% of the time.[29] This may impact assessment via electronic means or visual inspection by patrols or response forces.

3.1.2. *Local Wildlife*

Oregon has a large variety of wildlife that may affect day-to-day operations at a nuclear facility. These include multiple species of deer, elk, antelope, and moose.[30] These animals are not intimidated by fences and can jump up to seven or eight feet.[31,32] While these animals are not a danger to nuclear materials they may impact staff movement, disrupt operations, and set off nuisance alarms. The Pacific Northwest is also home to black bears and multiple species of foxes.[4] Bears[33] and foxes[34] can climb fences or tunnel underneath them, which may cause nuisance alarms and, in the case of bears, significantly impact operations and the safety of staff. Oregon is also home to many species of large birds including the Trumpeter Swan[35], which may exceed 30 lbs., wild turkeys that may weigh as much as 30 lbs., and the American White Pelican, which while weighing only 14 lbs., can have a wingspan of over nine feet. These birds may induce nuisance alarms as they move throughout the property, including on motion detectors and fence vibration sensors.

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[27] https://weatherspark.com/y/757/Average-Weather-in-Portland-Oregon-United-States-Year-Round

[28] https://www.bestplaces.net/climate/city/oregon/portland

[29] https://www.currentresults.com/Weather/US/cloud-fog-city-annual.php

[30] https://myodfw.com/wildlife-viewing/species/hoofed-mammals

[31] https://www.adn.com/uncategorized/article/alaska-mansions-fence-kills-another-moose-fourth-three-years/2012/07/20/

[32] https://pss.uvm.edu/ppp/articles/deerfences.html

[33] https://www.youtube.com/watch?v=daQ_O8mHm8Y

[34] https://www.wildlifeonline.me.uk/articles/view/red-fox-deterrence

[35] https://myodfw.com/wildlife-viewing/species/trumpeter-swan

3.2. PBSMRF Buildings

The site consists of four primary building structures and two separate entry control points (ECPs).

- Office Building – The office building has one above-grade floor and one below-grade floor. The above-ground floor contains the office spaces that can be used by site personnel. The below-grade floor houses the Central Alarm Station (CAS) and the reactor control room.
  - The office building is 40’ wide by 57’ long
- Switchyard – This fenced in area is where the switching substation is located. This substation allows for offsite power to be connected to the site and the power produced by the PBSMRF to be transmitted to the local electrical grid.
- Three Reactor Buildings – Each reactor is housed within its own reactor building. The reactor building consists of one above-grade floor and two-below grade floors.
  - The reactor building is 40’ wide by 57’ long
- Three Power Production Buildings – The Power Production Building (PPB) consists of one above-grade floor and one below-grade floor. The above-grade floor houses the turbine and diesel generators, the below-grade floor houses battery banks.
  - The power production building is 72’ long by 70’ wide
- Fuel Receiving Building (FRB) – The fuel receiving building has one above-grade floor and one below-grade floor. The below-grade floor houses fresh and spent fuel. The below grade has connecting hallways to each reactor building to move fresh and spent fuel.
  - The FRB is 67’ long by 36’ wide

3.3. Reactor Description

Based on numerous HTGRs, [36] the site operates three reactors and three turbines for electricity production. Each reactor is located in a separate building. Key reactor components such as the fuel pebbles, moderators and reflectors, control rods and other core internals are housed within a confinement structure. The confinement structure allows for possible venting in the very unlikely case of radiological effluent release from the fuel. The following are a list of key components of the HTGR reactors:

- Each reactor core produces 360 MWth with an efficiency of 42% for a power output of 150 MWe
- The core is fueled by TRI-structural ISOtropic (TRISO) particle fuel pebbles with an enrichment of 8.5% (i.e., equilibrium core)
- The TRISO fuel particle[37] includes a uranium, carbon, and oxygen fuel matrix kernel of approximately 500 micrometers in diameter[38] embedded in multiple layers of containment in order to physically protect the fuel and prevent the escape of fission products. This makes the

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[36] For numerous examples of high-temperature gas-cooled small modular reactors in the open source, see: “Advances in Small Modular Reactor Technology Developments,” A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 135-194.

[37] Department of Energy Office of Nuclear Energy, “TRISO Particles: The Most Robust Nuclear Fuel on Earth,” July 9, 2019, retrieved January 14, 2021, https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth#:~:text=TRISO%20stands%20for%20TRi%2Dstructural,release%20of%20radioactive%20fission%20products.

[38] Similar to the PBMR®-400 from Pebble Bed Modular Reactor SOC Ltd in South Africa. See: “Advances in Small Modular Reactor Technology Developments,” A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, p. 164.

fuel robust and resistant to high temperatures for extended periods of time while maintaining fission product retention. Outside of the fuel kernel is porous carbon for fission gas accumulation. Following this is an inner pyrolytic carbon layer, a structural silicon carbide layer, and finally an outer layer of pyrolytic carbon.[39] Each pebble consists of approximately 15,000 coated fuel particles in a graphite matrix with a 5 mm buffer which makes up the 6 cm diameter pebble.[40]

- Each core has 420,000 pebbles[41] in circulation at any given time.
- Pebbles are offloaded once they reach the target burnup (i.e., 90 GWd per ton). Refueling occurs online with continuous addition and removal of pebbles. Pebbles pass through the reactor until they reach a tube and flow through a measurement system to measure burnup. Once the pebble reaches the target burnup, it is sent to a spent fuel container. If the burnup is not met, it is pneumatically sent back up to the top of the core for another pass.
- Primary cooling is conducted by forced circulation from a helium circulator[42]
- Core reactivity is controlled by boron carbide (i.e., B_4C) control rods and small absorber spheres[43]

The reactors are cooled through the forced circulation of helium gas and the transfer of this heat to a steam generator.[44] The core is moderated by graphite within the pebbles, a centralized graphite column, and an outer core reflector, making this a thermal reactor powered by mostly thermal neutrons.[45] The reactor pressure vessel (RPV) contains primary system components including control rods, fuel pebbles, graphite central column, and graphite reflector. The primary helium coolant pressure inside the reactor is maintained by a compressor that keeps the helium at a constant 7MPa.[46] Primary circulation is conducted by a forced helium circulator/blower and via a compressor external to the vessel. Each reactor utilizes one helical-coil steam generator in a countercurrent flow to transition heat from the helium to the water to convert into superheated steam. The superheated steam exiting from the steam generator is transferred to a high-pressure turbine, followed by two

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[39] Paul Demkowicz, Ph.D., "TRISO Fuel: Design, Manufacturing, and Performance," Idaho National Laboratory, NRC HTGR Training, July 16-17, 2019.

[40] Similar to the PBMR®-400 from Pebble Bed Modular Reactor SOC Ltd in South Africa. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, p. 164.

[41] Similar to the HTR-PM from Tsinghua University, ChinaSee: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 137-140.

[42] C. F. McDonald and M. K. Nichols, "Helium Circulator Design Considerations for Modular High Temperature Gas-Cooled Reactor Plant," GA Technologies, Inc., San Diego, California, GA Project 6300, December 1986, https://inis.iaea.org/collection/NCLCollectionStore/_Public/19/005/19005804.pdf.

[43] Similar to Urenco's U-Batter from the United Kingdom. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 293-296.

[44] Similar to the HTMR100 from STL Nuclear in South Africa. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 171-174.

[45] Annular core with central graphite column similar to the PBMR®-400. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 163-166.

[46] Similar to the HTR-PM from Tsinghua University, China. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 137-140.

low-pressure turbines. There is one turbine series per reactor core, making a total of three turbine series on site. The steam and any letdown water are collected and sent to dry-cooling towers to condense the steam-water mixture into liquid. The liquid water is then pumped back to the steam generator for heating. The condenser is ultimately cooled by the environmental air.

Each reactor pressure vessel is approximately 30-m (98.4-ft) tall and 6-m (19.7-ft) in diameter. The RPV sits within a confinement structure. The confinement structure is made of 1-m (3.3-ft) reinforced concrete and contains venting mechanisms[47] that allow for the potential venting of steam. Each reactor is housed in its own confinement structure. The RPV is partially located below-grade with the reactor core being below-grade. The confinement buildings are only expected to be accessed during maintenance, delivery of new fuel or removal of spent fuel, domestic safeguards inspections as needed by the , or when security inspections are needed. The site has one onsite control room for all three reactors that is always staffed by two control room operators. The site does not have a traditional spent fuel pool; however each reactor is equipped with spent fuel storage canisters (SFSC).[48] Once a tank is filled it can be moved to an interim storage facility located onsite. All SFSCs are located below grade

3.4. Safety During Abnormal & Emergency Conditions

Due to the neutronic and physical characteristics of the fuel, the PBSMRF is inherently safe and can tolerate accident scenarios of up to 1600°C without radiological release. .[49] The reactor will remain in a safe condition indefinitely following a loss of power or coolant event. Decay heat can be dispensed indefinitely passively through a reactor decay heat removal system. If a loss of power causes a loss of forced cooling, negative temperature feedback will shut down the nuclear reaction. Control rods and spheres will also insert into the core, providing redundancy to completely shut down the reaction until power restoration. Decay heat in the fuel will be conducted and radiated out without the fuel temperature exceeding limits indefinitely.

While a loss of helium coolant from the primary loop would not cause an issue due to cooling characteristics, it is possible that the ingress of water or air may cause chemical issues and oxidation of the graphite. A small amount of water or air entering the reactor core can be tolerated for 24 hours without concern.[50] After this time some intervention is needed. High-quality, nuclear-grade

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[47] IAEA, "Advances in Small Modular Reactor Technology Developments," Vienna, 2020, p. 170.

[48] Similar to the PBMR®-400 from Pebble Bed Modular Reactor SOC Ltd in South Africa. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 163-166.

[49] The passive safety characteristics of pebble-bed fuel is documented in many open-source publications. See:

Ph.G. Tipping, "Key elements and principles of nuclear power plant life management (PLiM) for current and long-term operation," Editor(s): Philip G. Tipping, In Woodhead Publishing Series in Energy, *Understanding and Mitigating Ageing in Nuclear Power Plants*, Woodhead Publishing, 2010, p. 50.

PBMR®-400 from Pebble Bed Modular Reactor SOC Ltd in South Africa. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, pp. 163-166, as well as the HTR-PM from Tsinghua University, China, on pp. 137-140.

[50] Similar to the HTR-PM from Tsinghua University, China. See: "Advances in Small Modular Reactor Technology Developments," A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2020 Edition, Vienna Austria, September 2020, p. 139.

graphite also limits the oxidation and amount of combustion.[51] It is not expected that water ingress into the primary system would cause a sufficient reactivity spike or temperature increase which would cause significant fuel degradation.[52]

In case of a loss of water coolant from the secondary loop, passive cooling via radiation and natural convection away from the reactor pressure vessel would be sufficient to cool the core without radiological release indefinitely.

One primary and one backup emergency diesel generator are provided for each reactor core in the plant. The diesel generators are located on the first below-grade floor of each reactor PPB. While not necessary for safe cooling of the reactor during loss of power, the diesel generators can provide emergency power for physical security-related equipment, safety-related instrumentation, and control, including reactor sensors such as humidity or air sensors for chemical control, and communications equipment. As long as one diesel generator is functioning for each core, the generators can provide power to security and sensing equipment for 168 hours (i.e., 7 continuous days). Battery banks are located above-grade in the first floor of the PPB and can provide 72 hours of power for the same equipment.

3.5. Advanced SMR Facility Operations

This model was developed in response to the trends from the SMR community with decreased operational and security personnel on site. Two reactor operators (e.g., one operator and one shift supervisor) will be located within the control room which is in the basement of the office building. One control room operator can safely operate all three reactors at one time. In emergency situations, reactor operations can be conducted from a remote location. The CAS is located onsite with two security officers located onsite. The Backup Alarm Station (BAS) is at the same location as the offsite control room. The base case facility design can be seen below. Figure 3 shows the overall site layout. The site is surrounded by an owner-controlled area (OCA) with a perimeter of one-quarter of a mile from the reactors inside of the reactor building. Access is controlled in the owner-controlled area via an automated access control system. The protected area (PA) boundary is secured by one unarmed guard who verifies the automated access control system. All boundary areas are equipped with vehicle entrances and exits. The site does not allow for private vehicles to enter through the OCA boundary. This site design was developed based on reducing security system installation and operation cost, while providing effective physical security system effectiveness. These security layers will increase the access control points needed to gain access within the facility, increase detection and delay areas to provide an effective physical security system, and potentially decrease cost by not having a traditional Perimeter Intrusion Detection and Assessment System (PIDAS). Literature reviews and subject matter expert discussions were held to determine the feasibility of this design[5,6]. Figure 3 shows the site layout.

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[51] CCN 225061, SUBJECT: Contract No. DE-AC07-051D 14517 - Next Generation Nuclear Plant Project Nuclear - Modular High Temperature Gas-cooled Reactor Safety Basis and Approach - NRC Project #0748, September 6, 2011, INL/EXT- 11-22708, "Modular HTGR Safety Basis and Approach.", August 2011.

[52] Zhang, ZY & Dong, Yujie & Scherer, Winfried. (2005). Assessment of Water Ingress Accidents in a Modular High-Temperature Gas-Cooled Reactor. Nuclear technology. Vol. 149, pp. 253-264.

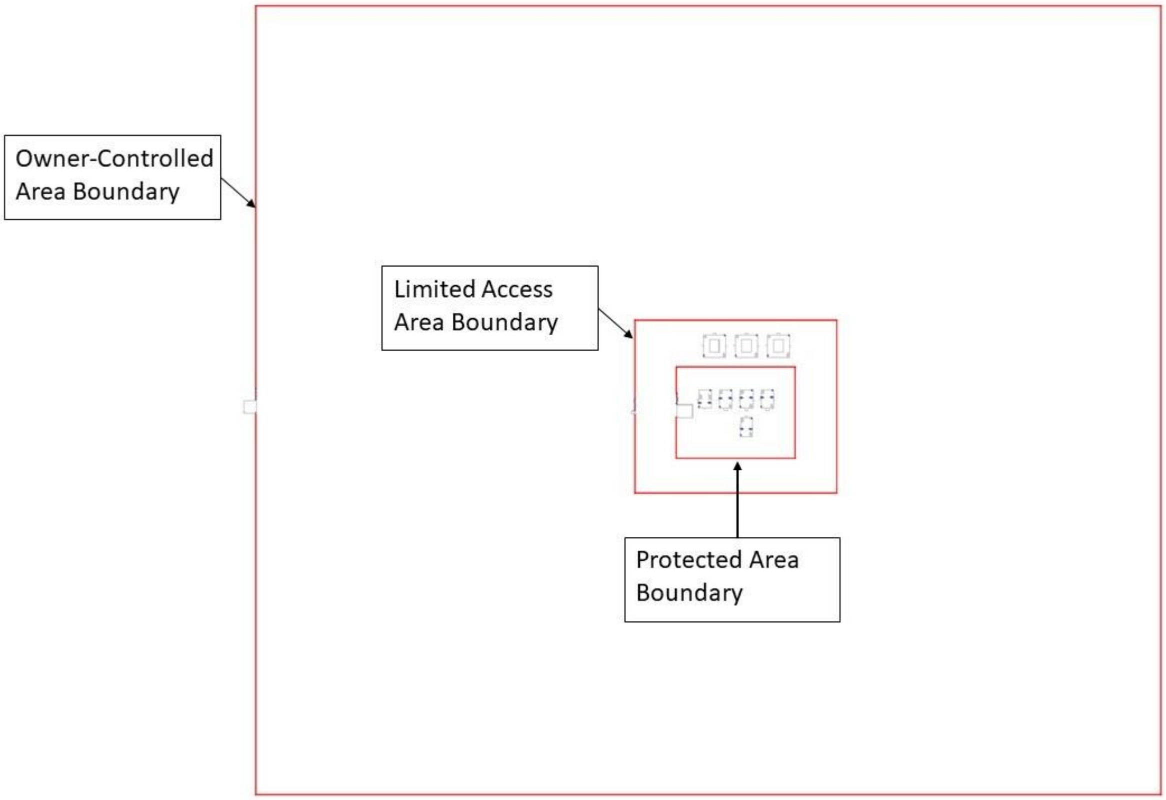

Figure 3 Site Layout

Figure 4 shows a detailed description of the site. The site consists of three turbine buildings inside of the OCA boundary. The OCA is equipped with an ECP building. Inside of the PA boundary, the site has an office building (houses CAS and control room), three reactor buildings and a spent fuel storage (SFS) building.

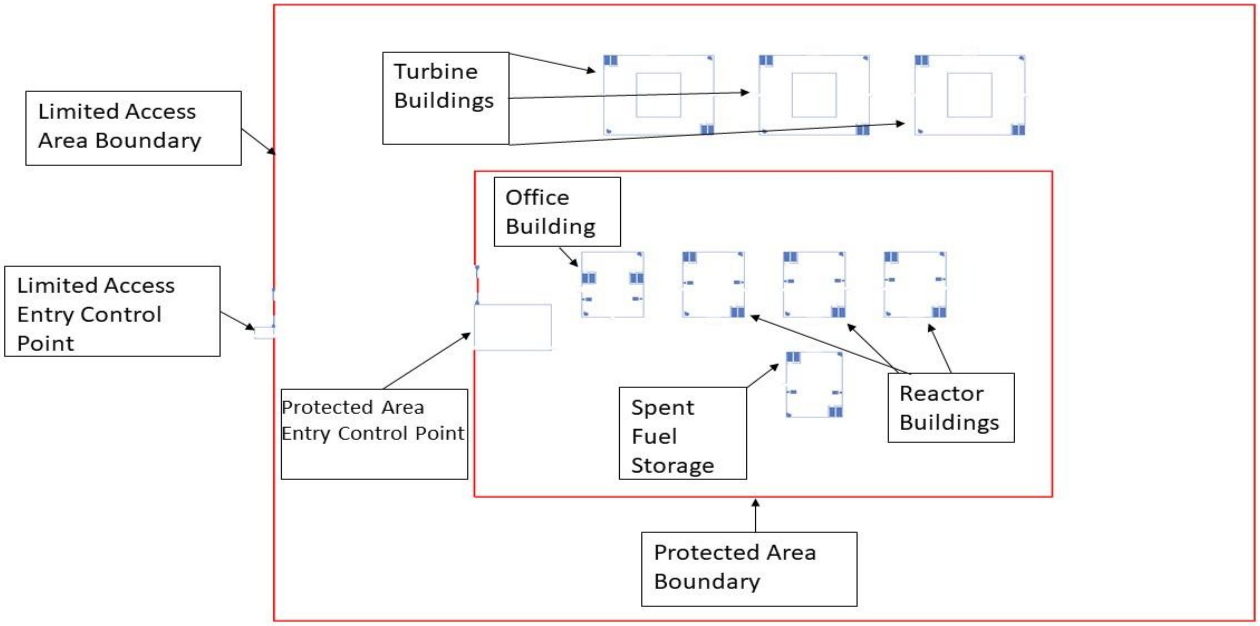

Figure 4 Owner-Controlled Area and Protected Area

Figure 5 shows the first basement level of the facility. Spent fuel can be moved in a canister from the reactor buildings to the SFS building which allows for long-term storage of the spent fuel. The diesel generators are located on this floor.

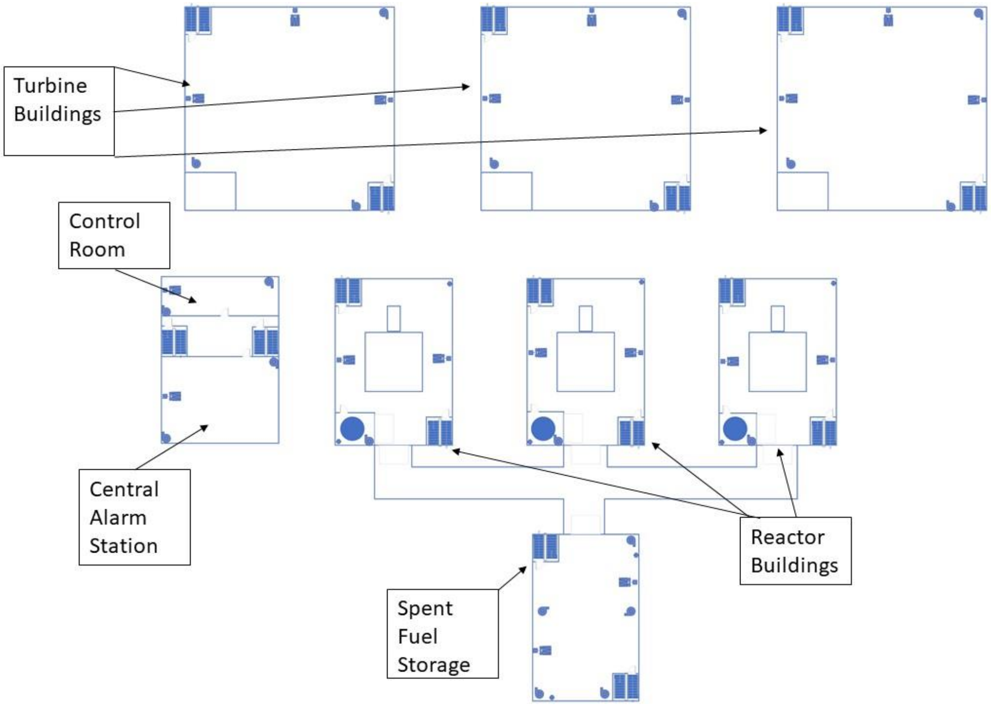

Figure 5 Basement One

Figure 6 shows the second basement. The facility reactors are primarily housed on this floor.

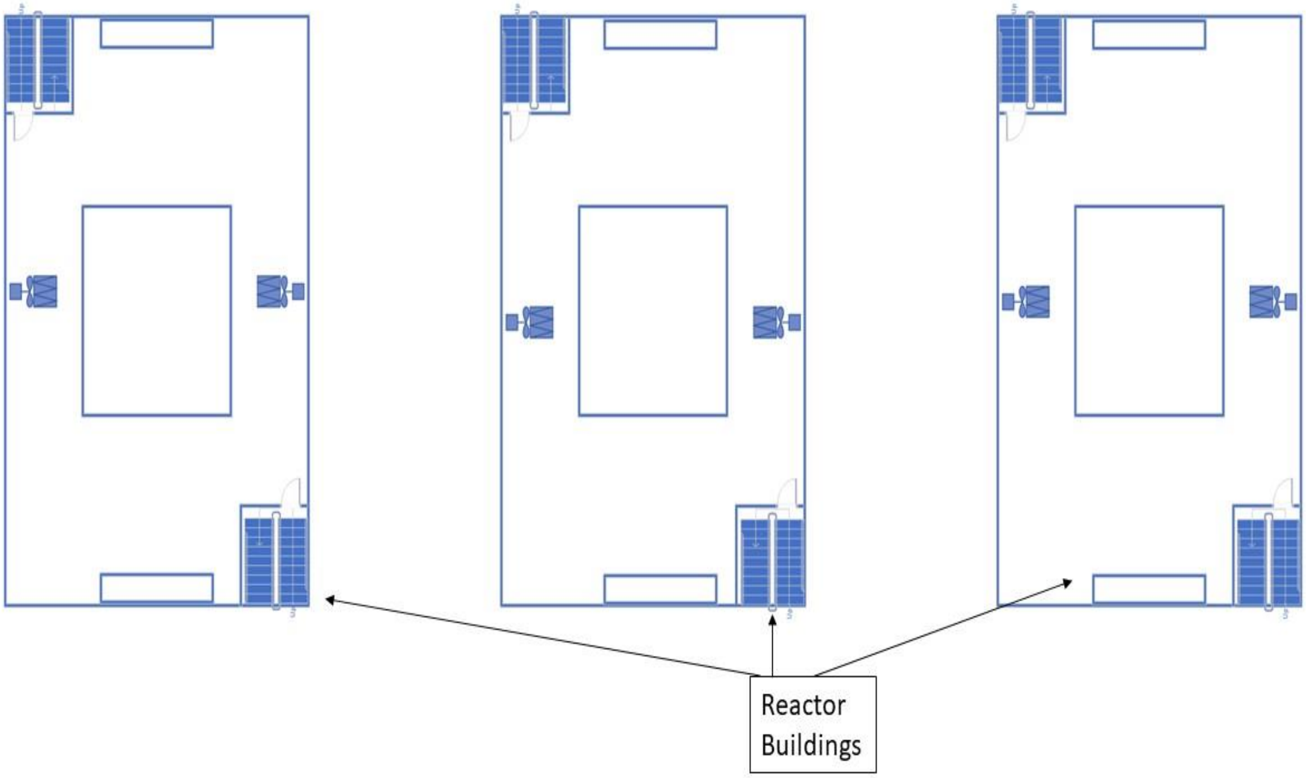

Figure 6 Basement Two

4. OVERVIEW OF VULNERABILITY ASSESSMENT

The evaluation of an existing or proposed physical protection system (PPS) requires a methodical approach that measures the ability of the security system to meet defined protection objectives. Without this kind of careful assessment, valuable resources might be wasted on unnecessary protection or, worse yet, fail to provide adequate protection of material against a theft or sabotage attack by the defined threat. The vulnerability assessment (VA) methodology was developed to implement performance-based physical security concepts at nuclear sites and facilities.

4.1. Modeling Tools

4.1.1. PathTrace©

PathTrace© is a path analysis tool that is used to analyze all facility paths adversaries may take to achieve their goal. This tool was used in this analysis to determine the P_I using a hypothetical PPS.

To determine the potential adversary paths, the software identifies multiple pathways adversaries may take. Specifically, the tool develops three paths:

- The quickest adversary path, where decreasing the task time is prioritized over decreasing the probability of detection
- The stealthiest path, where decreasing the probability of detection is prioritized over decreasing the task time
- The most vulnerable path (MVP), where the path is optimized considering the probabilities of detection, adversary task time, and response timelines

4.1.2. Blender

Blender[53] is a free and open source 3D creation suite that is widely used throughout the 3D modeling community. It supports the entirety of the 3D pipeline and is designed to create efficient, highly detailed 3D models that can be ingested by any engine. The Blender toolset enables the creation of detailed, to-scale models of facilities, vehicles, and equipment that can be used for visualization, analysis, and training. The team used Blender to create the facility 3D model for this project.

4.1.3. Scribe3D© – Tabletop Recorder and Automated Tabletop Data Tool

Scribe3D© is a 3D tabletop recording and scenario visualization software created by Sandia National Laboratories (SNL). It was developed for use by other national laboratories, government organizations, and international partners using the Unity[54] game engine, which has been used for a number of other training and analysis tools within the DOE complex. Unity is a commercial game engine built for developers and non-developers to create a wide variety of games and applications. It features a fully customizable framework and set of development tools.

Scribe3D© is used to create, record, and play back scenarios developed during tabletop exercises or as a planning tool for performance testing, force-on-force, and other security analysis-related applications. The capabilities offered by Scribe 3D© can help open discussions and capture their results, visualize consequences, collect data, and record events, as well as help make decisions while

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[53] Blender Foundation, available at www.blender.org/about/ (2019).

[54] Unity Technologies, available at unity3d.com/unity (2019).

users develop scenarios. Data can be viewed in 2D or 3D and be played back in real-time or at various speeds. Transcript reports are automatically generated from the recorded data. The automated functions of Scribe3D© enable recorded scenarios to be run in a Monte Carlo fashion to collect large quantities of data for analysis purposes after initial scenarios are defined in the traditional tabletop exercise.

4.2. System Effectiveness Analysis Assumptions

The vulnerability assessment process uses the following assumptions:

- Pathways are determined using tabletop analysis and SME judgement
- Target areas and operational states are all accurately identified
- Adversary acts are planned and executed at a time that provides maximum opportunity for success for the adversary
- Facility security features function as-designed, and RF respond as-defined
- Appropriate threat attributes and capabilities are identified
- When data are limited or missing and the analyst must rely on subjective expert opinion, the analysis is conducted conservatively, with the advantage weighted toward the adversary
- Adversaries and response force are assumed to be equal with regard to training and combat ability
- Adversaries are willing to die to achieve their mission
- Only sabotage scenarios are analyzed
- RF strategy is denial only

5. HYPOTHETICAL SMR PHYSICAL PROTECTION SYSTEM

5.1. PPS Design Process

In the physical protection world, the Design and Evaluation Process Outline (DEPO)[1] has been used for several decades for the design of a PPS. The DEPO process is shown in Figure 7. The process begins by defining the PPS requirements, which involves defining regulatory requirements, characterizing the facility, identifying targets, and identifying the threat. From there, the PPS is designed with appropriate elements for detection, delay, and response. Then various tools are used to evaluate the PPS, including both path analysis and performance testing. These tools have increasingly moved toward single-analyst modeling capabilities. Based on performance and identified gaps or vulnerabilities, the PPS will be redesigned. In this effort, the traditional DEPO approach was altered for the implementation of the security-by-design process. For this analysis, the first step was defining the PPS requirements. This includes identifying the regulatory requirements, characterizing the facility, identifying targets, and identifying the implementation of the design basis threat. Once the requirements were defined, initial safety and operational considerations were reviewed. The PPS was then initially designed to fit the requirements as well as the safety and operational considerations. The PPS was evaluated using path analysis and force-on-force analysis to determine overall system effectiveness. Once the system is assessed, safety and operations are considered, and the system is continually redesigned and evaluated until an effective PPS is implemented that creates the least impact to facility and safety and operations[10].

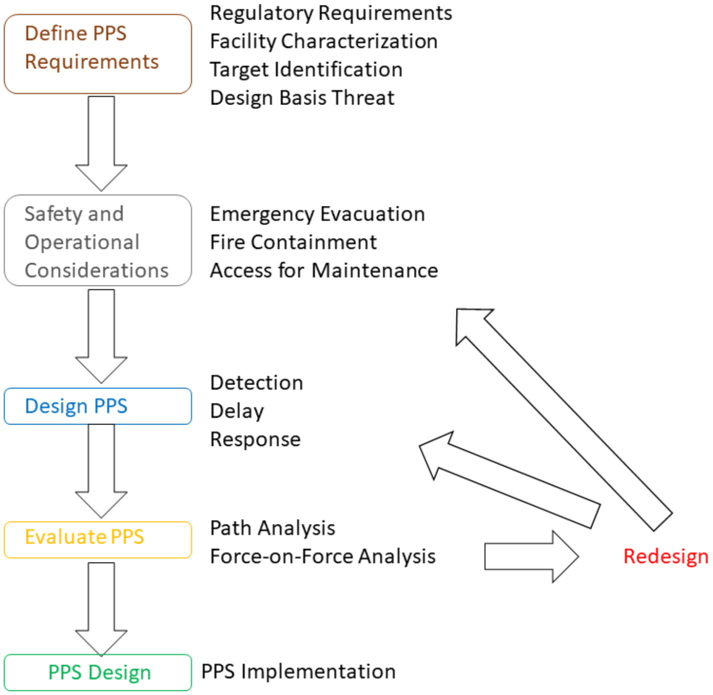

Figure 7 Security-by-Design DEPO Process

Analysis will be conducted using current Nuclear Regulatory Commission (NRC) practices for physical protection and current technologies; a separate analysis will be conducted using advanced technologies and practices. This method will provide insights regarding the effectiveness of current practices and the possible effectiveness of using more advanced concepts and technologies.

The base case used for the analysis includes the implementation of an Exclusion Area (EA) that functions as a limited access area (LAA), a protected area (PA), and vital areas (VA) according to current NRC Recommendations found in NRC 10 Code of Federal Regulations Part 73 (10 CFR 73). This methodology will evaluate the PPS effectiveness of current 10 CFR 73 regulations for SMRs under proposed operating conditions and methods. As part of the analyzing the efficacy of these regulations, minimal guards and response force sizes will be present.

5.1.1. Initial Physical Protection System Design

Error! Reference source not found. illustrates the exterior physical protection system. The facility design contains three security layers. The first layer being the owner-controlled area boundary. For this facility design this boundary is a chain-link fence with a vehicle access control point. This security boundary is made to control access to the site as well for a novel detection and assessment technology to extend detection out to the owner-controlled area boundary. Deliberate motion tracking systems will be placed to detect adversary movement or action out to the owner-controlled access area. This allows for the site to notify the response force earlier of a nuclear security event

Vehicle barriers have been placed around the Limited Access Area (LAA) Boundary according to potential adversary vehicles as specified in the Design Basis Threat (DBT). The fence line is protected by a fence disturbance sensor. The Protected Area (PA) Boundary is protected by a fence disturbance sensor as well as bistatic microwave sensors inside the perimeter of the PA. This allows for multiple layers of detection at the perimeter of the facility. A closed-circuit television (CCTV) system exists inside of the LAA and PA to assess the activation of alarms and begin the assessment process.

Access to the site can only occur through three entry points at the owner-controlled area boundary, the LAA boundary, and the PA boundary. The vehicle entrances at the LAA and PA boundary are only operational during times of fuel shipment at all other times these vehicle entries are closed. Each boundary has a personnel entry. The owner-controlled boundary is manned only during operational hours, the LAA boundary is manned 24/7 by one unarmed guard and the PA boundary is manned 24/7 by two guards. At the PA boundary, Pedestrians must pass through a metal detector, an explosives detection portal, and have their on-person items sent through an x-ray machine. Once through contraband detection, pedestrians are granted access with a proximity card and the entering of a personal identification number (PIN). When receiving new reactor fuel or equipment to the site, the facility is notified ahead of time and the vehicle entry point is manned by two guards. The hydraulic vehicle barriers are maintained in a raised position when operational and only lowered one at a time as an authorized vehicle passes through as follows:

1. The driver and all other vehicle passengers must stop at the access point at the outer gate.
2. One of the guards at the access point steps out of the guardhouse and verifies the driver's and any passengers' credentials, as well as the shipment authorization forms.
3. The passengers and driver then exit the vehicle process through the personnel entrance in the same manner as described above.
4. During this time, one of the guards at the vehicle access point visually inspects the vehicle for contraband and explosives.
5. Once validated and granted access, the driver and any passengers return to the vehicle.
6. The hydraulic barrier is lowered by the second guard and the gate opened by the first guard, and the vehicle passes through.
7. The gate is closed, the vehicle barrier is raised, and the process repeats.

6. TARGET IDENTIFICATION

The analysis focused on adversary attacks of three target locations. These target locations focus on direct sabotage of nuclear material. Due to the inherent safety features and complexity of these safety features only direct sabotage scenarios were considered in this analysis. Table 1 shows the sabotage targets that were used.

For the purposes of this analysis, a direct sabotage attack on the below locations is postulated to result in an Unacceptable Radiological Consequence (URC) event.

Table 1 Sabotage Targets

Location	Building Area	Form of Material	Amount of Material On-site (% Enrichment)	Total Isotope Amounts	Level of Radiation
Reactor Building 1	Reactor	TRISO pebbles	3,780 kg U (8.5% U-235)	321 kg U-235	High
Reactor Building 1	Spent Fuel Canister	TRISO pebbles	1,890 kg U (8.5% U-235)	161 kg U-235	High
Reactor Building 2	Reactor	TRISO pebbles	3,780 kg U (8.5% U-235)	321 kg U-235	High
Reactor Building 2	Spent Fuel Canister	TRISO pebbles	1,890 kg U (8.5% U-235)	161 kg U-235	High
Reactor Building 3	Reactor	TRISO pebbles	3,780 kg U (8.5% U-235)	321 kg U-235	High
Reactor Building 3	Spent Fuel Canister	TRISO pebbles	1,890 kg U (8.5% U-235)	161 kg U-235	High
Spent Fuel Storage Building	Below-Grade Storage	TRISO Pebbles	5,760 kg U (8.5% U-235)	482 kg U-235	High

7. RESPONSE FORCE

National requirements are used as a first step to define the response force roles and responsibilities. In an actual design, the roles and responsibilities will be based on the facility's design and site requirements.

The site will have two onsite guards to conduct personnel and package searches into the facility. The site will also have two guards in the CAS, with one shift commander present to relieve CAS operators. These guard decisions were based on the premise of reducing onsite guard members to decrease operational cost. Guards are equipped as follows:

Handguns with approximately 45 rounds of 9-mm ammunition

- Batons
- Pepper spray
- Handcuffs with keys
- Handheld radios

The response force members are required to complete certification and training on selected weaponry and equipment that may be necessary for use in the event of an adversary attack. Weaponry and equipment for the response force members includes:

- Handguns with approximately 45 rounds of 9-mm ammunition
- Access to shoulder-fired weapons (e.g. 9-mm H&K MP-5s and 5.56-mm type rifles)
- Batons
- Pepper spray
- Handcuffs with keys
- Handheld radios

7.1. Response Force Assumptions

Due to the uncertainty in future SMR security designs and regulations, the analysis will focus on a PPS that does not use onsite armed response force personnel. Based on this assumption, no armed responders are on site. Response force times of 30 minutes and 60 minutes were assessed.

8. THREAT ASSUMPTIONS AND CHARACTERIZATION

The concept of the DBT is used to establish the threat to which the PPS of a facility is designed against. For this study (a notional facility with a notional threat) a DBT will not be used. Rather, the section below will characterize the threat spectrum used for the security study. In this vulnerability assessment, the number of adversaries were varied from four to eight. It is assumed that a passive, nonviolent insider is providing facility knowledge for the outsider threat group.

8.1. The Vulnerability Assessment Process

The evaluation of an existing or proposed PPS requires a methodical approach that measures the ability of the security system to meet defined protection objectives. Without this kind of careful assessment, valuable resources might be wasted on unnecessary protection or, worse yet, fail to provide adequate protection of material against a theft attack by the defined threat. The Vulnerability Assessment (VA) methodology was developed to implement performance-based physical security concepts at nuclear sites and facilities.

The measure of overall security effectiveness is described as system effectiveness and expressed as a probability (P_E). P_E is determined using two terms: the probability of interruption (P_I) and the probability of neutralization (P_N). Analysis techniques are based on the use of adversary paths, which assume that a sequence of adversary actions is required to complete an attack on an asset. It is important to note that P_E will vary with the threat. As the threat capability increases, performance of individual security elements or the system will decrease.

Interruption is defined as the probability of arrival by the security force at a deployed location to halt adversary progress. Interruption may lead to the initiation of a combat event; however, it does not mean the task has been literally interrupted, simply that security forces have arrived before completion of the adversary task.

Neutralization is defined as the defeat of the adversaries by the security forces in a combat engagement or by other means. P_N is a measure of the likelihood that the security force will be successful in overpowering or defeating the adversary, given interruption. This defeat could take many forms; it could mean the adversaries are rendered task-incapable because a vital vehicle is disabled, or key personnel are neutralized. It could mean that all adversaries are neutralized. Neutralization is simply the ability of the security force to prevent the adversary from completing its mission.

These probabilities are treated as independent variables when the defined threat:

1. Selects a path that exploits vulnerabilities in the system, and
2. Is willing to use violence against the security forces.

In this case, the effectiveness of the system (P_E) against violent adversaries, expressed as the probability of interrupting and neutralizing the adversaries, is calculated by the following formula:

$$P_E = P_I x P_N$$

It is important to stress the conditional probability. Interruption (P_I) is meaningless without neutralization (P_N). If a system has a very high probability of interruption but lacks the firepower to respond to the given threat, the system fails. Conversely, if the system lacks the timely detection to get responders to the fight, it does not matter how well staffed and armed the response is.

8.2. Threat Assumptions and Characterization

The DBT assumed for this analysis is based on information from the 10 Code of Federal Regulations Part 73.1 (i.e., 10 CFR 73.1) see Table 2. The adversary team members were assumed to have the following characteristics:

- A determined violent external assault
    - Attack by stealth or deceptive actions
    - Operate in groups through a single-entry point
    - multiple groups attacking through multiple entries
- Military training and skills, willing to kill or be killed, enough knowledge to identify specific equipment or locations necessary for a successful attack
- Active or passive insider
- Land or water vehicles, which could be used for transporting personnel and their hand-carried equipment to the proximity of VAs
- Land vehicle bomb assault, which may be coordinated with an external assault
- Cyber attack
- Able to perform any of the tasks needed to steal or sabotage critical assets
- Armed with a 7.62 mm rifle or 7.62 mm belt-fed machine-guns (2), a pistol, ammunition, grenades, satchel charges containing bulk high explosives, not to exceed 10 kg total, detonators, bolt cutters, and miscellaneous other tools[55]
- Each able to carry a man-portable total load,29.5 kg [65 lb.]
- Adversary run speeds are assumed to be 3 m/s

For all scenarios, it was assumed each attack would start when the adversaries verified that no response force element (e.g., roving patrol) was within visual range of the initial breach. They would also avoid hardened and manned response positions if possible. See Table 2.

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[55] 10 Code of Federal Regulations Part 73 "Physical Protection of Plants and Materials." https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/full-text.html

Table 2 Outsider High-Level Threat Assessment Used for Analysis

High-Level Terrorist Threat		
Motivation		Ideological; cause public terror (regionally and internally)
Goals		Theft and/or sabotage of nuclear materials/items
Capabilities and Attributes	Numbers	4/5/6/7/8 may divide into two or more teams
	Weapons	7.62mm(assault rifles), 7.62mm MGs (machine guns), RPG (rocket propelled grenade), sniper rifles, hand grenades
	Explosives	Improvised explosive device (IED), shape charges, vehicle bomb, suicide vest/backpack, commercial and military explosives (assume adversary carries sufficient amounts to complete objective)
	Tools	Night vision devices, hand tools, power tools, bridging/breaching equipment, chains, ladders, ropes, cutting torches, radios, fake/stolen identification, stolen/purchased uniforms and insignias
	Weight Limit	20 kg (45 lb) per person
	Transportation	Foot, bicycle, motorcycle, automobile (truck, car, off-road), all-terrain vehicles, boat (rubber zodiac, small boat, fishing craft)
	Knowledge • Facility • Security System • Operations	Assume full knowledge of facility layout and target locations, security system (people, equipment/technology, and procedures), and mission-critical operations, functions, and processes
	Technical Skills	Military training, demolition, information technology, general and site-specific engineering
	Funding	High – regional and international support
	Insider Collusion	Planning, local cell structure, safe-havens, sympathetic population, logistics, money
	Support Structure	One passive insider (providing information only)

9. PATH ANALYSIS AND FACILITY UPGRADES

The analysis focused on developing a physical protection system that creates an effective probability of interruption (PI) for the entire site that implements an offsite response force. PathTrace© was used to identify potential outsider adversary pathways that could be used to commit a sabotage act at the PBR facility. The first portion of the analysis centered on designing a security system with a PI of 95% or greater for a response time of 30-minutes. The second portion of the analysis centered on increasing to a 60-minute response time with a PI of 95% or greater.

9.1. Base Case Facility and Physical Protection System

When using an offsite response force, previous analysis has shown that implementing building designs and physical protection systems that allow for early detection and assessment, and increased delay time to increase the adversary task time[56] . For this case and all subsequent upgrade cases, the most vulnerable path (MVP) was assessed. Upgrades to the facility design and PPS are based on the MVP. The goal of the design and analysis was to reach a PI of 95% or higher for all targets. In this scenario, the adversary breaches through the protected area boundary fence, breaches through the roll-up doors that enter the reactor building, use the stairwells to proceed below-grade, and then the adversaries attempt to sabotage the reactors. Figure 8 depicts this adversary path.

Figure 8 Base Case Path to All Targets

As can be seen in Table 3 on the next page, the base case facility design and physical protection system does not allow for an effective physical protection system since the probability of

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[56] Evans, A.S., Parks, M.J., Horowitz, S., Gilbert, L., Whalen, R. "U.S. Domestic Small Modular Reactor Security by Design." Sandia National Laboratories. SAND2021-0768. March 2021.

interruption is zero at all target locations. A P_I of 0% would effectively lead to a system effectiveness (P_E) of 0%. The probability of interruption is zero in this case because the adversary can complete their act of sabotage at any of the targets before the response force can arrive onsite to interrupt them. Therefore, further upgrades were needed.

Table 3 Base Case Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	1061	99	0	1800
Spent Fuel Canister 1	593	99	0	1800
Reactor 2	1068	99	0	1800
Spent Fuel Canister 2	598	99	0	1800
Reactor 3	1073	99	0	1800
Spent Fuel Canister 3	603	99	0	1800
Below-Grade Canister Storage	578	99	0	1800

9.2. Upgrade One – Active Delay (Obscurants and Slippery Agents)

9.2.1. Active Delay Features – Obscurants and Slippery agents

In order to achieve additional levels of delay, active (i.e., non-lethal) delay agents will be added to the PPS design. Active delay agents are those that must be deployed via a CAS action in ~~or~~ order to impede adversary progress. They function in concert with passive delay features in that they multiply delay times by making normal breaching techniques much harder to accomplish. These delay multiplication factors have been tested and documented with international partners in an open forum and are thus unclassified. Two less intrusive active delay features are obscurants and slippery agents.

9.2.1.1. Active Delay – Obscurants

Obscurants work by removing or limiting the adversary's vision, forcing the adversary to complete a breaching task by feel only. A common obscurant is pyrotechnic smoke fired from a commercial security fogger, which can fill a small space in seconds and can be controlled and deployed by a CAS operator.

9.2.1.2. Active Delay – Slippery Agents

Slippery agents can be deployed in confined spaces to make it much harder to interact with tools or surfaces or even to stand up and move. However, when active delay features are most powerful are when they are combined. For example, if an adversary is attempting to breach a door using a charge, they enter a mantrap filled with smoke, and are immediately doused with an incredibly slippery liquid. They must feel around to find the door, attach a slippery charge to a slippery surface, and retreat across the slippery floor to detonate it. If at any time they drop a necessary tool, it becomes much harder to find, because they cannot see. In training exercises, it was observed that these features have the following delay multiplication factors, see Table 4 Column 3 shows how a 30-second delay feature can become a 76 second delay feature by adding active delay to it[57].

Table 4 Delay Multiplication Factors

Active Delay Type	Delay Multiplication Factor	Example Delay time (s)
Baseline	1	30
Obscurant	1.66	49.8
Slippery Agent	1.55	46.5
Combined Obscurant and Slippery Agent	2.54	76.2

It is assumed that upon assessed detection of an adversary attack, the CAS operator will activate the obscurant features, limiting all visuals within certain areas (to be described below). The slippery agent will be deployed strategically as soon as adversaries enter key locations, to lengthen breach time. The locations of these active delay barriers were placed in locations to increase the adversary task time of reaching targets within the facility.

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[57] Sandia National Laboratories Determining Delay Multiplication Factors Exercise (SAND2006-4605P)

Figure 9 shows these active delay features that were applied to stairwells in which the adversary force would have to use to enter the below-grade floors and gain access to target areas.

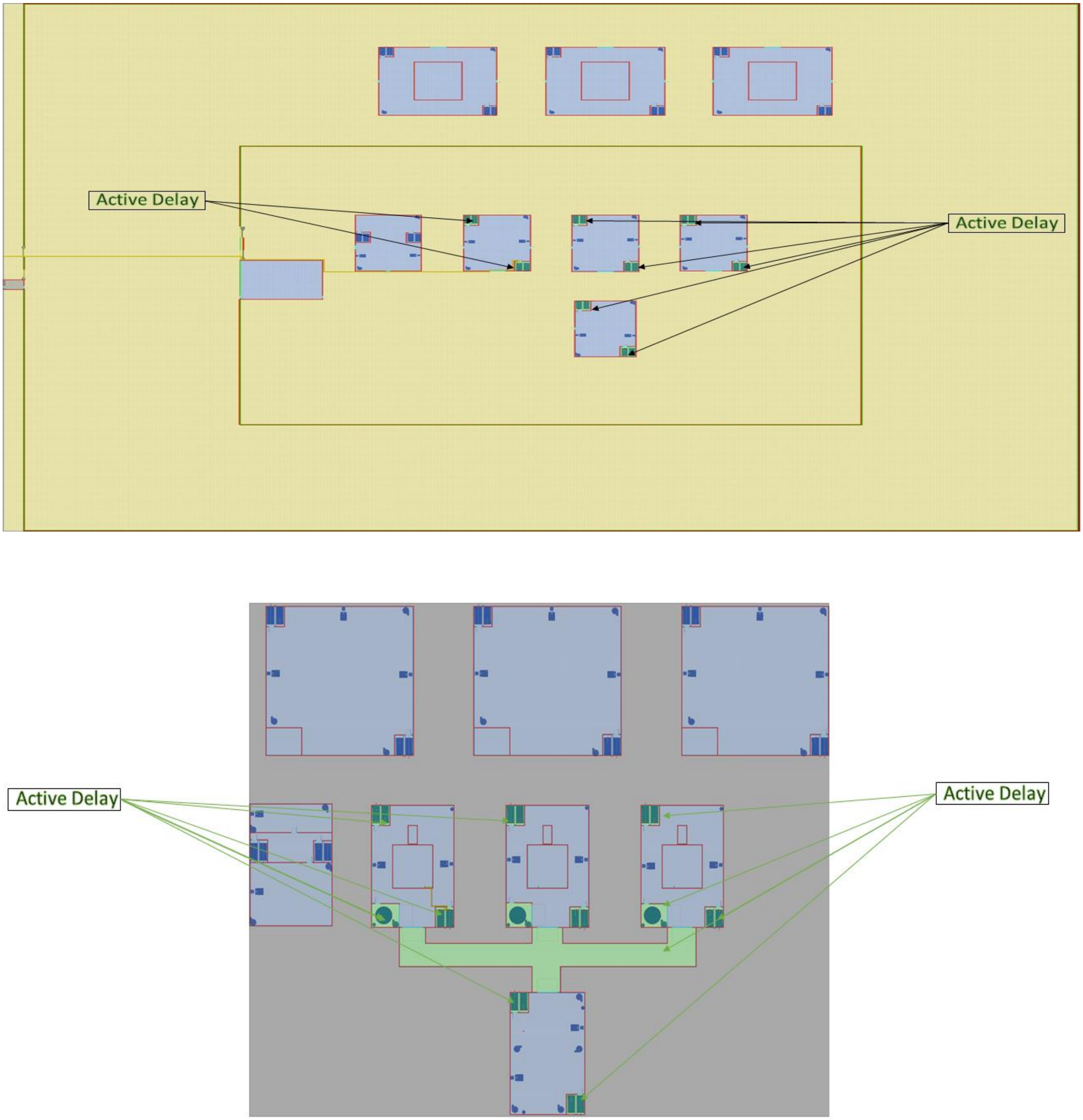


Figure 9 Active Delay, above-grade (top) and below-grade (bottom)

The adversary force took the same pathway as in the base case. The effects of this upgrade are shown in Table 5.

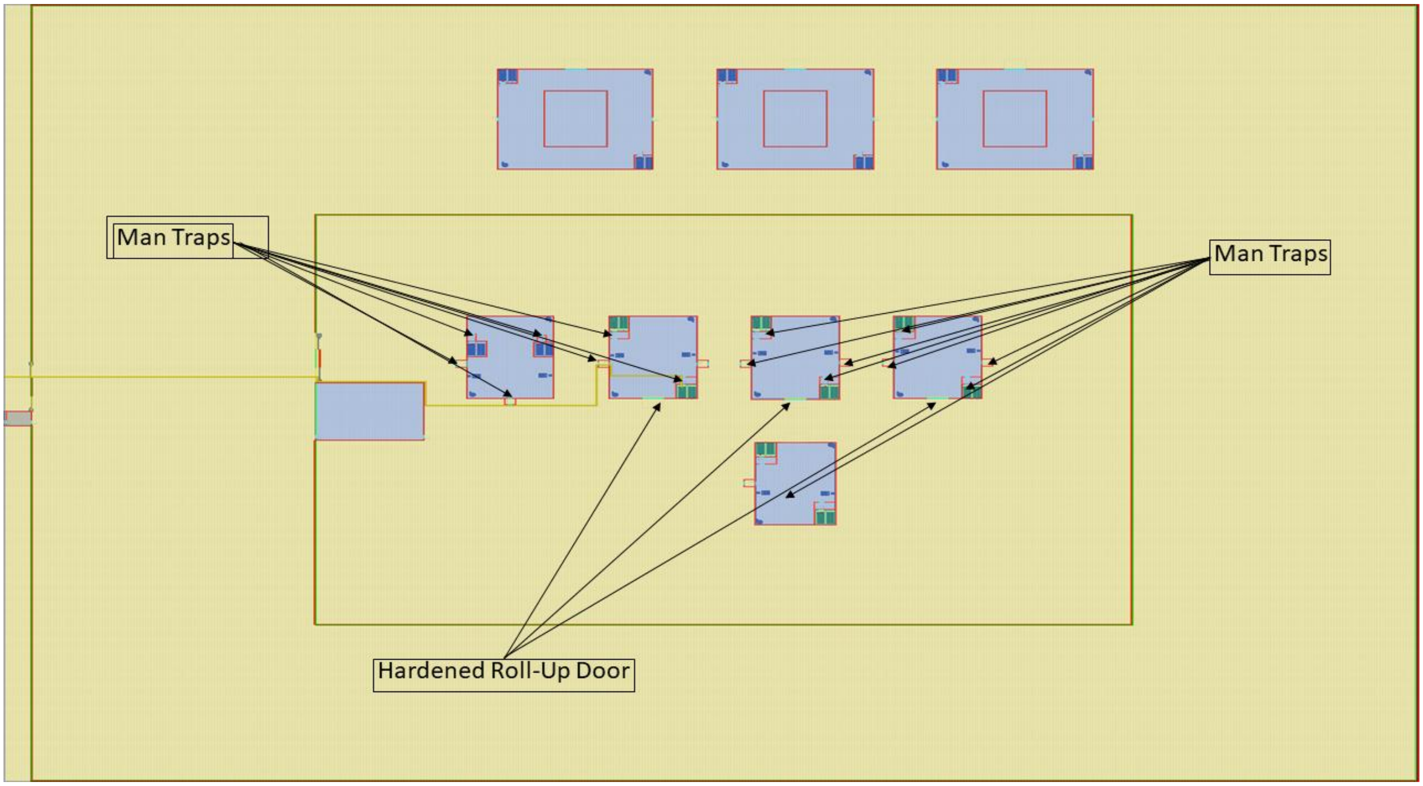
Table 5 Upgrade One Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	1086	99	0	1800
Spent Fuel Canister 1	618	99	0	1800
Reactor 2	1093	99	0	1800
Spent Fuel Canister 2	623	99	0	1800
Reactor 3	1099	99	0	1800
Spent Fuel Canister 3	628	99	0	1800
Below-Grade Canister Storage	613	99	0	1800

Upgrade package one increased the adversary task time to each target. However, the increase in task time did not increase the P_I. Again, because the adversary total task time is much less than the response time the probability of interruption remains zero. Therefore, further upgrades were necessary.

9.3. Upgrade Two – Active Delay, Mantraps and Reinforced Roll-Up Doors

In this upgrade, mantraps were applied to above-grade door entrances, stairwell entrances above-grade and below-grade, and added active delay features int the room where storage canisters are held for each reactor and in the hallway connecting the reactor buildings to the spent fuel storage building. Mantraps in this design are doorways that protect an inner doorway. The outer door is equipped with access control devices as is the inner door. This mantrap allows for alarm station operators to lock both doors and not allow access controls to enable entrance. This increases the adversary task time and helps to reduce effects caused by an insider providing access control credentials to an external adversary force. An additional upgrade included hardened roll-up doors. Moveable concrete barriers were placed behind roll-up doors to increase the time it takes an adversary to penetrate through roll-up doors. Figure 10 shows these upgrades.



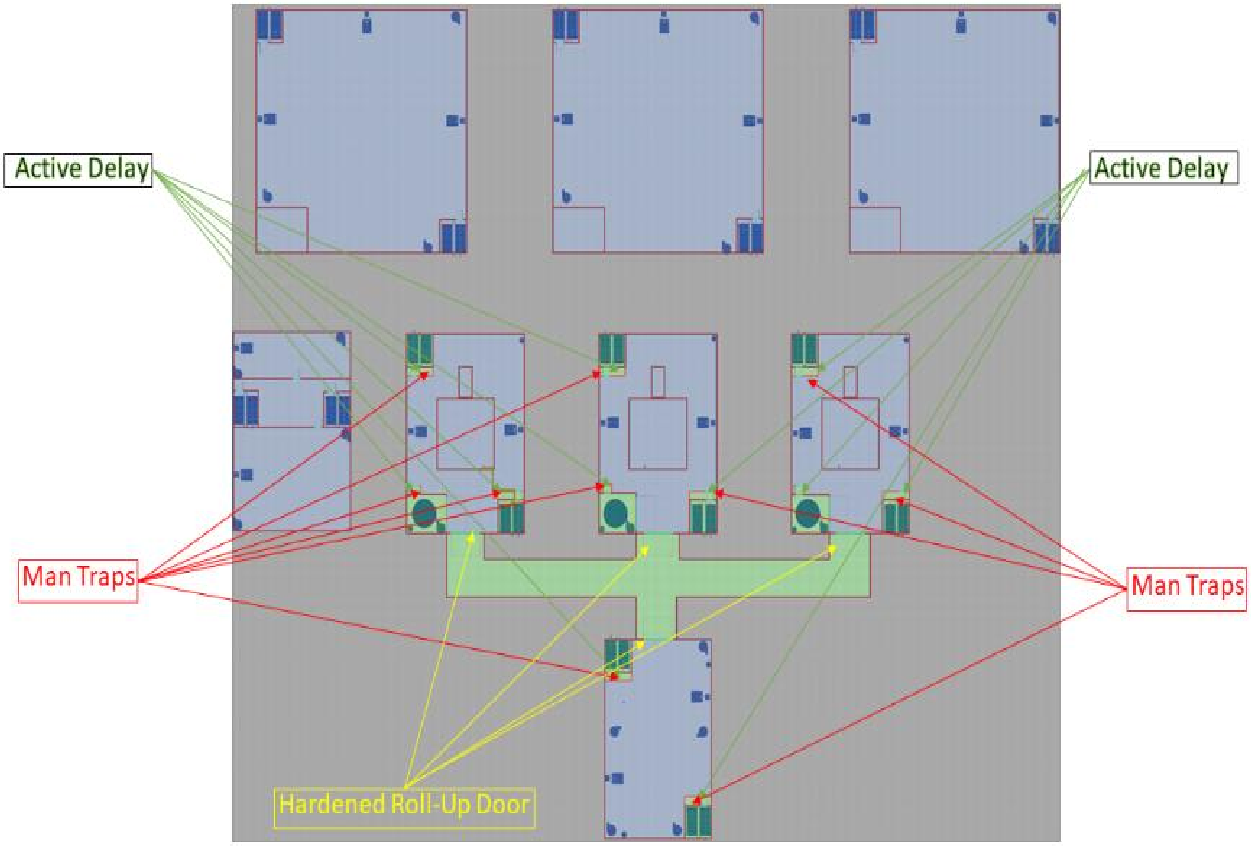


Figure 10 Man Traps, Active Delay and Hardened Roll-Up Doors

The effects of these upgrades can be seen in the Table 6.

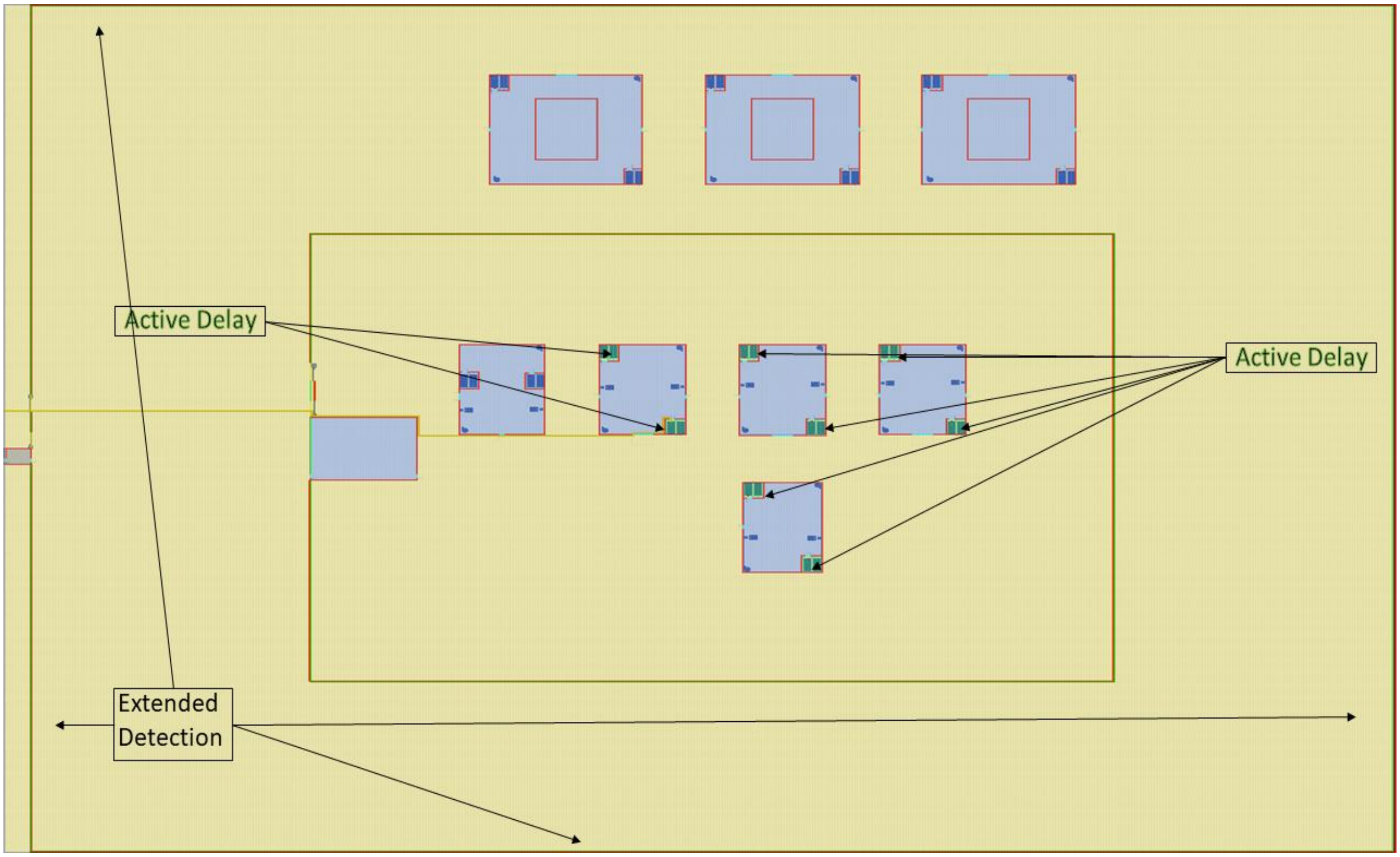
Table 6 Upgrade Two Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	1165	99	0	1800
Spent Fuel Canister 1	721	99	0	1800
Reactor 2	1171	99	0	1800
Spent Fuel Canister 2	727	99	0	1800
Reactor 3	1177	99	0	1800
Spent Fuel Canister 3	723	99	0	1800
Below-Grade Canister Storage	690	99	0	1800

As can be seen, the adversary task time increased but is still much less than the response force time. This caused the probability of interruption to remain zero and require further upgrades.

9.4. Upgrade Three – Hardened Canister Room Doors, Active Delay in Mantraps, and Extended Detection

To increase the delay time to the storage canisters inside of the reactor buildings hardened doors were placed in front of the doors into the canister storage room doors. These doors are like the reinforced doors implemented in upgrade two for the roll-up doors. Active delay systems were also placed in the above-grade man traps to increase the adversary task time. The use of extended detection was also implemented in this design. Using a combination of radar and video motion detection that reaches far beyond the facility perimeter, the deliberate motion algorithm (DMA) can decipher motion moving toward the facility, while minimizing nuisance alarms from weather or traffic in the area. It is assumed that detection begins at the owner-controlled area of the facility. This in effect allows the RF to muster and get into position even sooner on the timeline. Additionally, extended detection technologies were applied. Extended detection such as deliberate motion algorithms can be applied to detect adversary motion outside of the facility protected area. the deliberate motion algorithm (DMA) can decipher motion moving toward the facility, while minimizing nuisance alarms from weather or traffic in the area. It is assumed that detection begins between 200 and 300 meters from the walls of the facility. Figure 11 shows these upgrades.



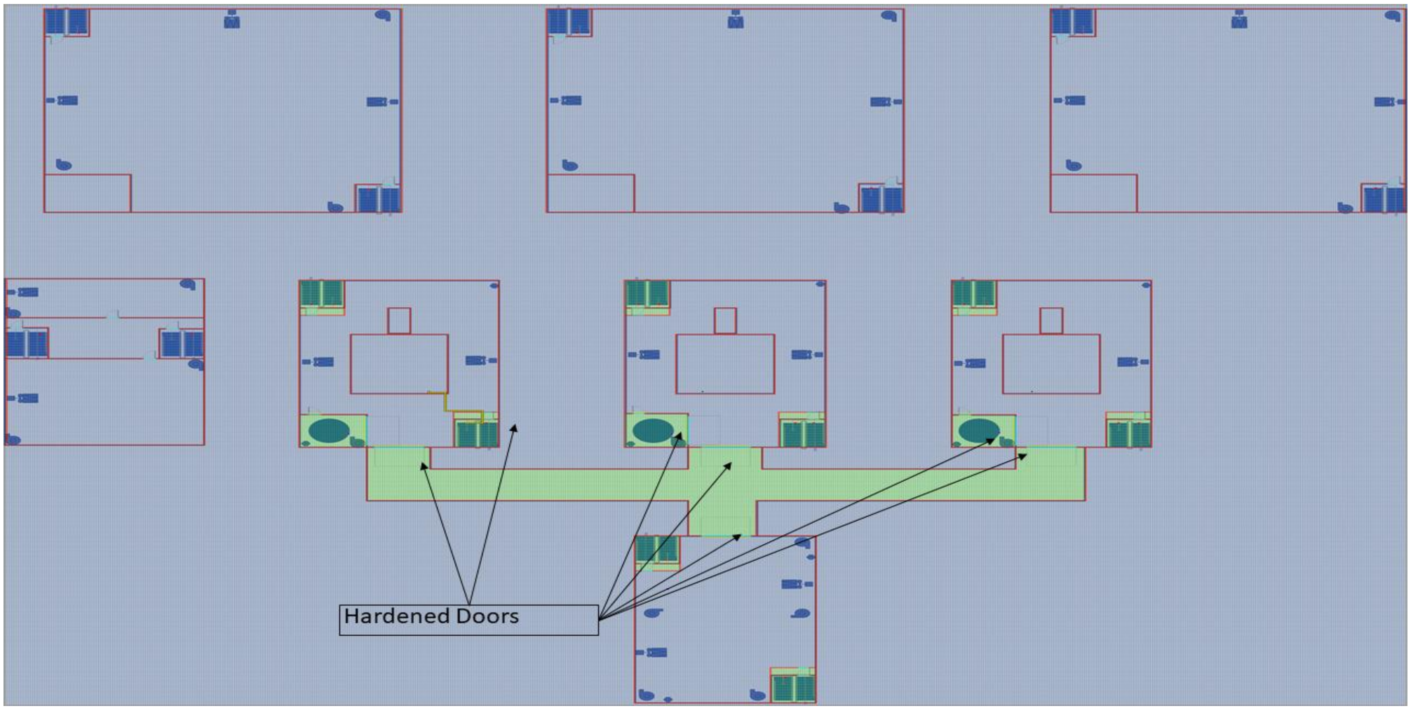


Figure 11 Active delay and hardened doors

The effects of these upgrades can be seen in the Table 7.

Table 7 Upgrade Three Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	1183	99	0	1800
Spent Fuel Canister 1	1186	99	0	1800
Reactor 2	1189	99	0	1800
Spent Fuel Canister 2	1191	99	0	1800
Reactor 3	1195	99	0	1800
Spent Fuel Canister 3	1196	99	0	1800
Below-Grade Canister Storage	692	99	0	1800

These upgrades caused increase in adversary task time to all target locations. However, these changes did not increase the adversary task time to be longer than the response force time. Therefore, further upgrades were implemented.

9.5. Upgrade Four – Hardened Spent Fuel Storage Entry Door and Increased Stairway Wall Thickness

To increase the delay time of the adversaries from reaching the spent fuel storage area below ground the entry door from the stairwell was reinforced with a concrete barrier similar to those in upgrades two and three. Adversaries were also penetrating the spent fuel storage area through the stairwell wall so the wall thickness around the exit of the stairwell was increased to increase adversary task time. These upgrades can be seen in Figure 12 below.

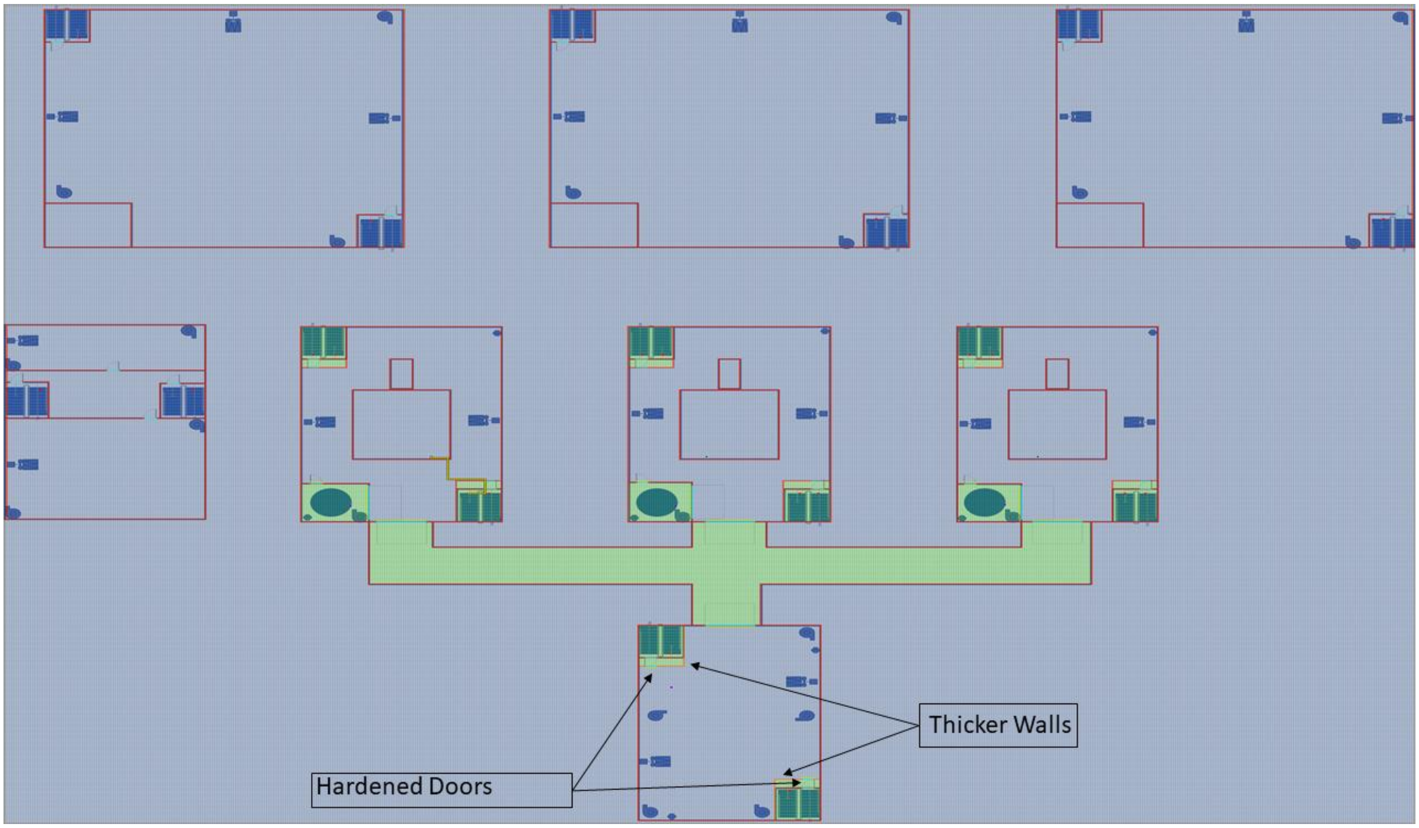


Figure 12 Thick walls and hardened doors (below-grade)

The effects of these upgrades can be seen in Table 8.

Table 8 Upgrade Four Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	1183	99	0	1800
Spent Fuel Canister 1	1186	99	0	1800
Reactor 2	1189	99	0	1800
Spent Fuel Canister 2	1191	99	0	1800

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 3	1195	99	0	1800
Spent Fuel Canister 3	1196	99	0	1800
Below-Grade Canister Storage	1172	99	0	1800

These upgrades drastically increased the adversary task time to reach the spent fuel canisters in the below-grade storage areas for spent fuel canisters. However, this increase in task time was not longer than the response time and therefore, further upgrades were needed.

9.6. Upgrade Five – Active Delay in Spent Fuel Storage Building

To increase the task time in the below-grade spent fuel canister storage area, active delay features (slippery agents and obscurants) were placed in the underground room. This active delay is meant to act as a multiplier for the adversaries as the enter the storage area. These active delay features and their location can be seen in Figure 13 below.

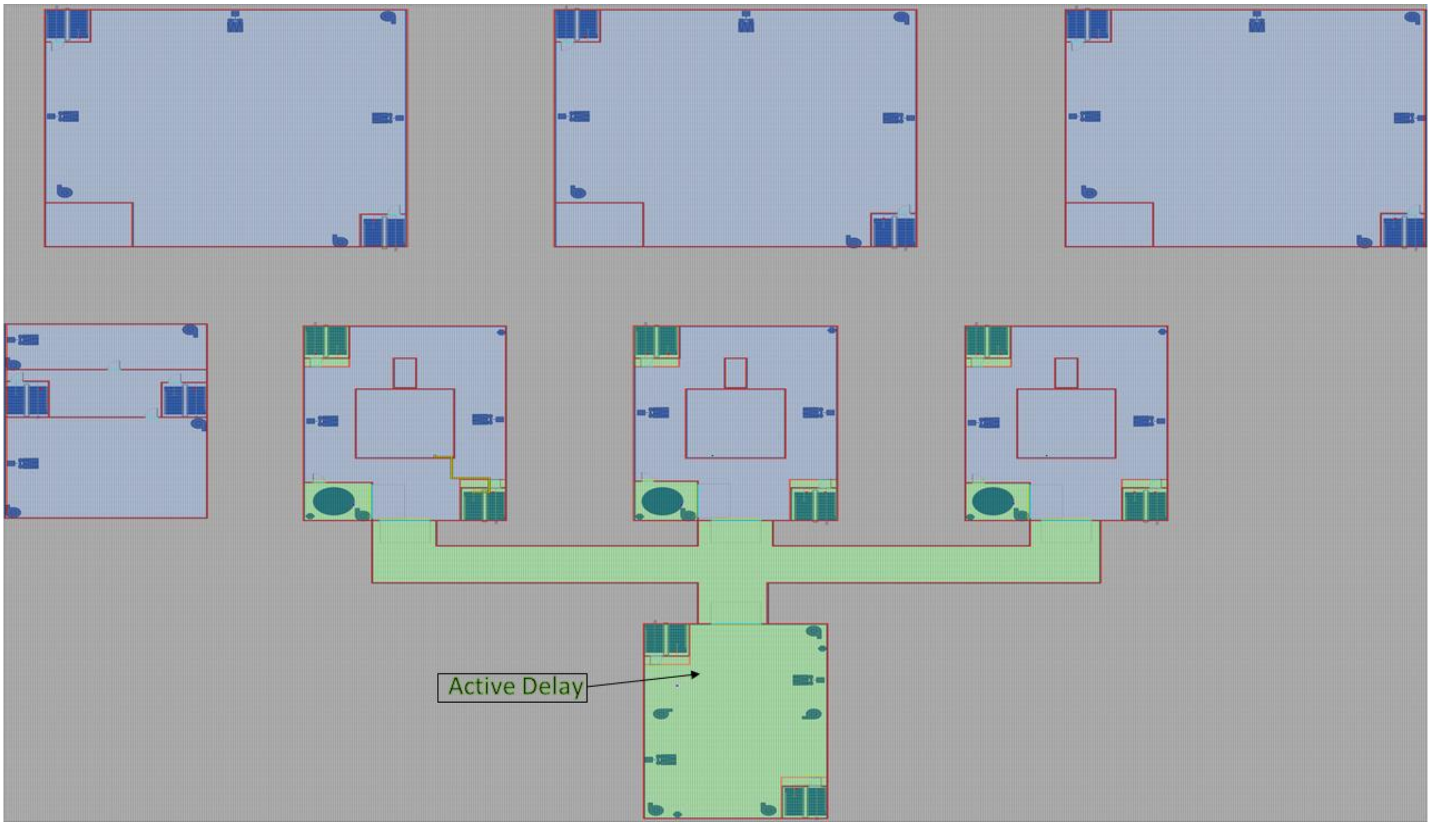


Figure 13 Active delay in the below-grade canister storage area

The effects of this upgrade can be seen in Table 9.

Table 9 Upgrade Five Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	1183	99	0	1800
Spent Fuel Canister 1	1186	99	0	1800
Reactor 2	1189	99	0	1800
Spent Fuel Canister 2	1191	99	0	1800
Reactor 3	1195	99	0	1800
Spent Fuel Canister 3	1196	99	0	1800
Below-Grade Canister Storage	1594	99	0	1800

These upgrades increased the overall adversary task time but did not extend the adversary task time longer than the response time. Therefore, further upgrades were necessary.

9.7. Upgrade Six – Increased Wall Thickness Around Reactors and Reinforced Doorway into Below-Grade Canister Storage Area

The next upgrade in the design was aimed at increasing the adversary task time to sabotage the reactors onsite. The reactors were placed inside of a thicker wall that would cause the adversaries to first breach the wall surrounding the reactors and then conduct an act of sabotage. This upgrade can be seen in Figure 14 below.

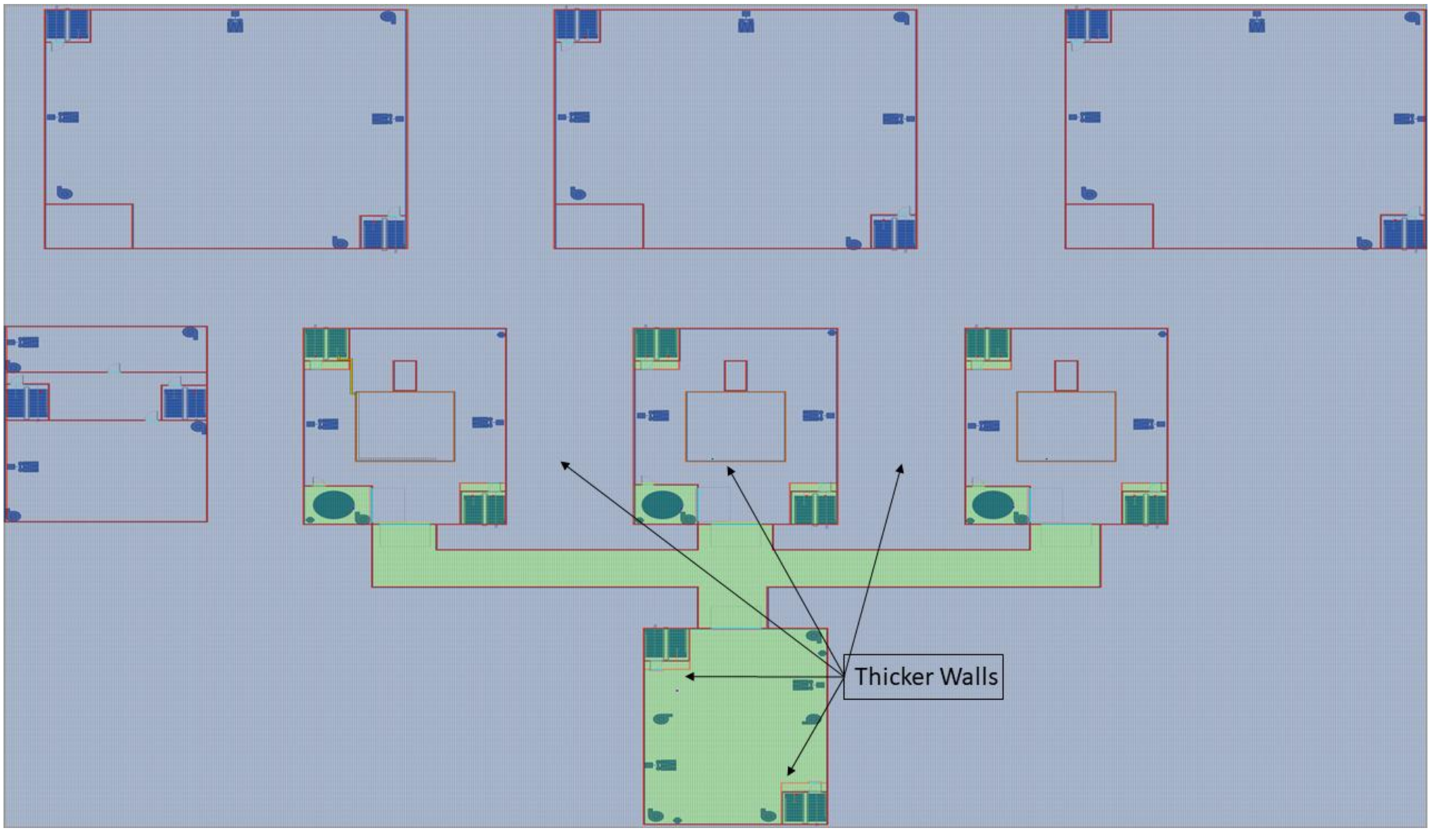


Figure 14 Thicker walls around reactors

The effects of this upgrade can be seen in Table 10.

Table 10 Upgrade Six Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	3013	99	99	1800
Spent Fuel Canister 1	1186	99	0	1800
Reactor 2	3021	99	99	1800
Spent Fuel Canister 2	1191	99	0	1800
Reactor 3	3026	99	99	1800
Spent Fuel Canister 3	1196	99	0	1800
Below-Grade Canister Storage	1594	99	0	1800

This upgrade proved to be very effective in increasing the adversary task time to achieve sabotage at any of the three reactors. The thicker wall around the reactors increased the probability of interruption to 99%. The effect of this upgrade is primarily due to the cumulative effect of the previous upgrades as well. Upgrades one through five allow for a balanced physical protection system that increases the adversary task time along all of the pathways into the facility. This creates a robust physical protection system that improves the probability of interruption. This is a high value which is beneficial for increasing the overall security system effectiveness. However, the task times were still too short to provide a probability of interruption for the storage canisters inside of the reactor buildings and the below-grade canister storage areas. The task time for the storage canister area did not increase because the adversaries chose to enter the below-grade canister storage area via the reactor buildings to decrease the probability of detection and delay times and therefore this upgrade provided no change to the below-grade canister storage area task time.

9.8. Upgrade Seven - Increased Wall Thickness Around Canister Rooms and Active Delay in Reactor Buildings

The next upgrade focused on increasing the delay time needed for an adversary to gain access to the spent fuel canisters inside of the reactor building. This upgrade increased the wall thickness around the canister rooms to the same level as those around the reactors themselves. An additional upgrade was to include active delay elements inside of the reactor buildings. These upgrades can be visualized in Figure 15 below.

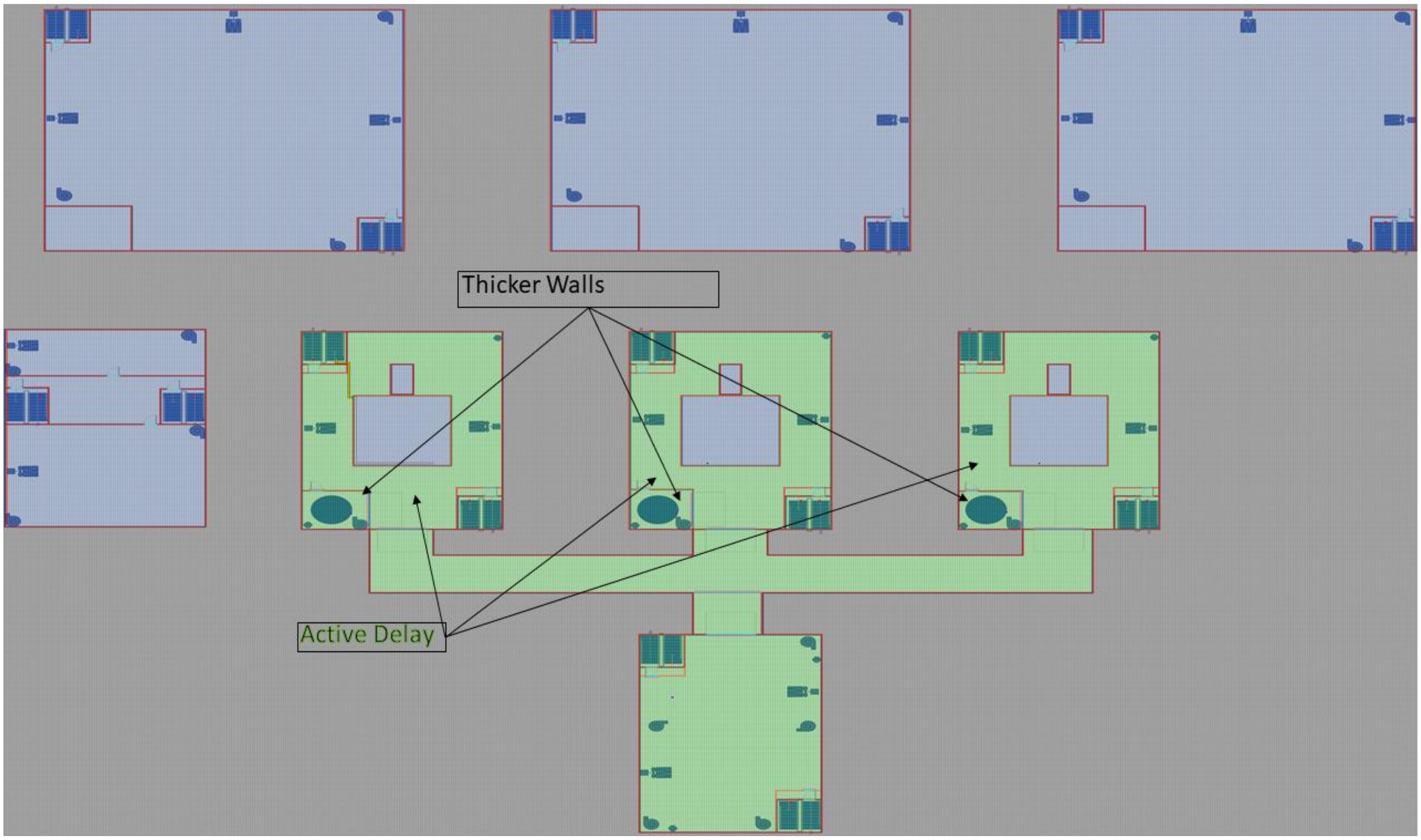


Figure 15 Active delay and thicker walls

The effects of this upgrade can be seen in Table 11.

Table 11 Upgrade Seven Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	3013	99	99	1800
Spent Fuel Canister 1	2385	99	99	1800
Reactor 2	3021	99	99	1800
Spent Fuel Canister 2	2375	99	99	1800
Reactor 3	3026	99	99	1800
Spent Fuel Canister 3	2397	99	99	1800
Below-Grade Canister Storage	1663	99	0	1800

As can be seen from the table above, these upgrades greatly increased the adversary task time of reaching the spent fuel canisters. However, the probability of interruption was not high for the spent fuel canisters below-grade due to the lower adversary task time. Therefore, further upgrades were necessary.

9.9. Upgrade Eight – Below-Grade Reinforced High-Bay Door

To deter adversaries from entering the below-grade canister storage area from the reactor buildings through the connecting hallway, a second high-bay door and a reinforced high-bay door were placed before the entry into the below-grade canister storage area. This was meant to force adversaries to approach through the stairwells above-grade in the storage building. This upgrade can be seen in Figure 16 below.

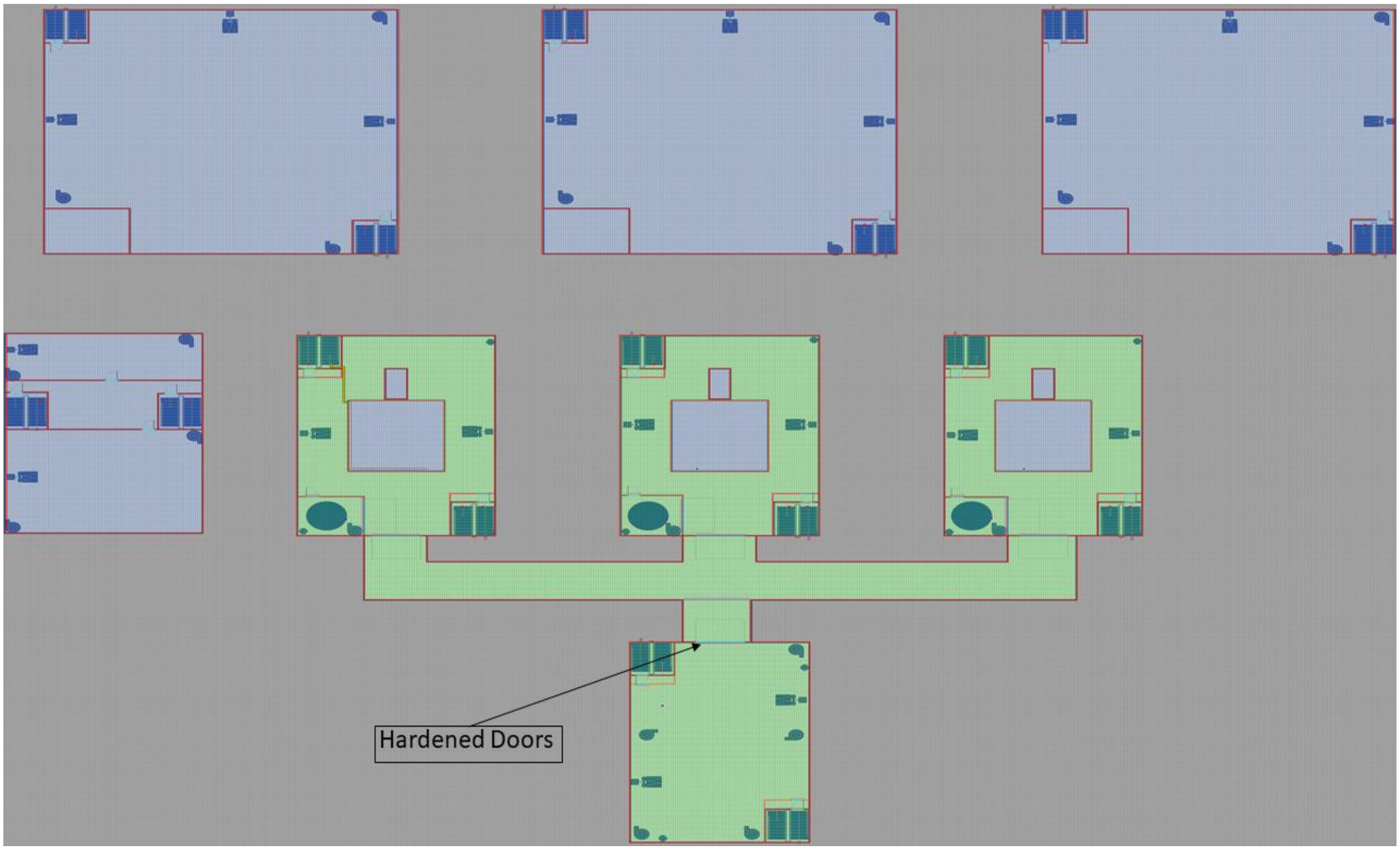


Figure 16 Hardened below-grade hallway door

The effects of this upgrade can be seen in Table 12.

Table 12 Upgrade Eight Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	3013	99	99	1800
Spent Fuel Canister 1	2385	99	99	1800
Reactor 2	3021	99	99	1800
Spent Fuel Canister 2	2375	99	99	1800
Reactor 3	3026	99	99	1800
Spent Fuel Canister 3	2397	99	99	1800
Below-Grade Canister Storage	2363	99	99	1800

As can be seen from the table above, this upgrade increased the overall adversary task time to the below-grade canister storage targets. This increase in adversary task time allowed for the probability of interruption to increase to 99%. This upgrade was the final upgrade to allow for a proper response and interruption to occur for this facility with a response time of 30-minutes.

The following sections focus on upgrades to the facility that could be implemented to allow for a 60-minute response force.

9.10. Upgrade Nine – Reactor Building Hallways and Active Delay

The first upgraded implemented to try to reach an effective probability of interruption with a 60-minute response time was to add hallways filled with active delay technologies. The purpose of this upgrade was to increase the adversary task time to reach and sabotage the reactors and spent fuel canisters below-grade in the reactor buildings. This upgrade can be seen in Figure 17 below.

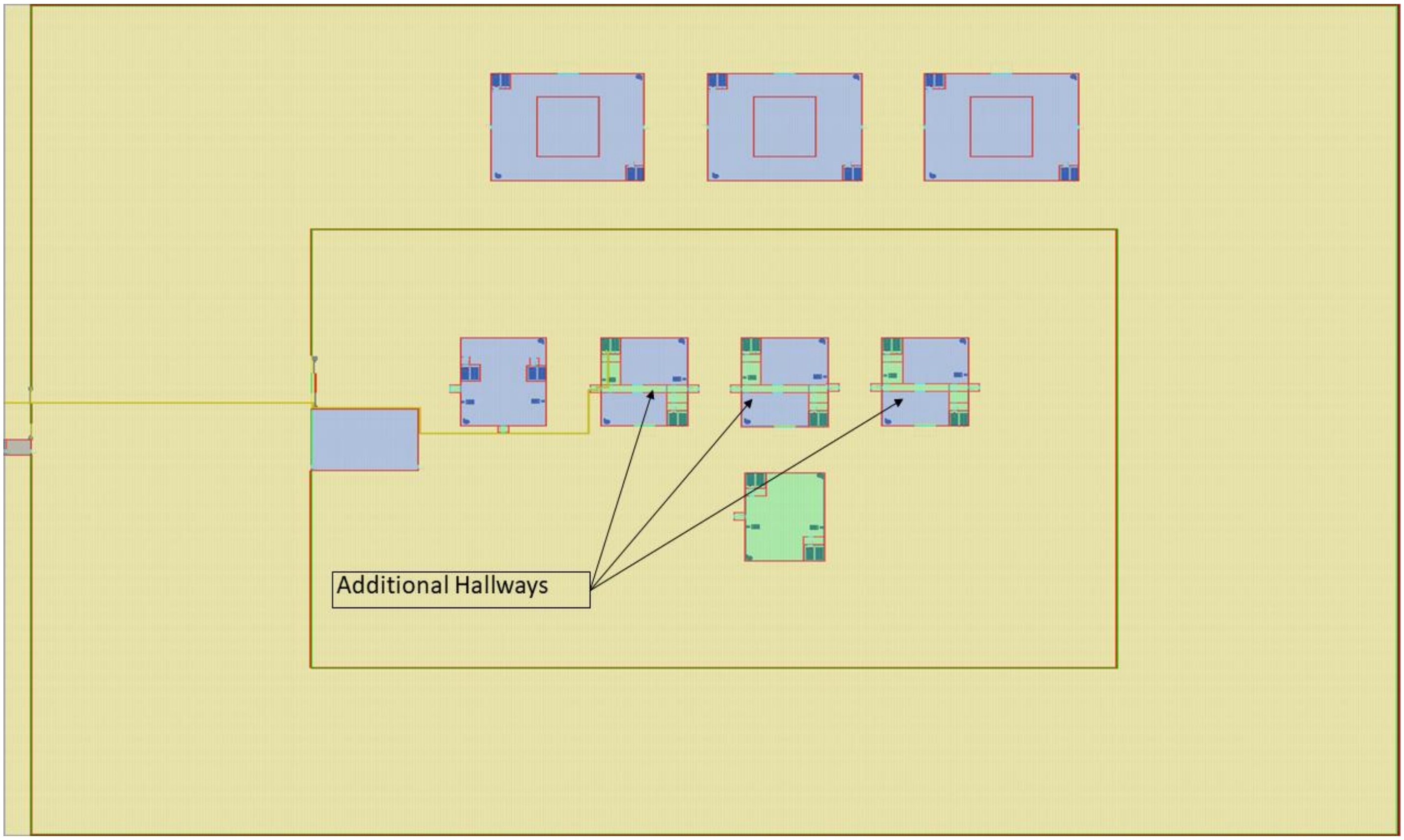


Figure 17 Additional hallways above-grade

The effects of this upgrade can be seen in Table 13.

Table 13 Upgrade Nine Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	2178	99	0	3600
Spent Fuel Canister 1	1982	99	0	3600
Reactor 2	2183	99	0	3600
Spent Fuel Canister 2	1972	99	0	3600
Reactor 3	2189	99	0	3600

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Spent Fuel Canister 3	1993	99	0	3600
Below-Grade Canister Storage	1906	99	0	3600

The adversary chose to go through the created hallways and doorways because this reduced the probability of detection before the critical detection point and decreased total task time. This upgrade provides an example of an upgrade in which the adversary chooses to use a different route into the facility that introduces a new vulnerability. New upgrades had to be developed to increase the adversary task time to all the targets again.

9.11. Upgrade Ten – Hardened Above-Grade Stairwell Entrance Doors

To increase the adversary task time, hardened doors were placed at the stairwell entrances in the reactor buildings. This upgrade was used to increase the adversary task time of gaining access to below-grade floors of the reactor building. This upgrade can be seen in Figure 18 below.

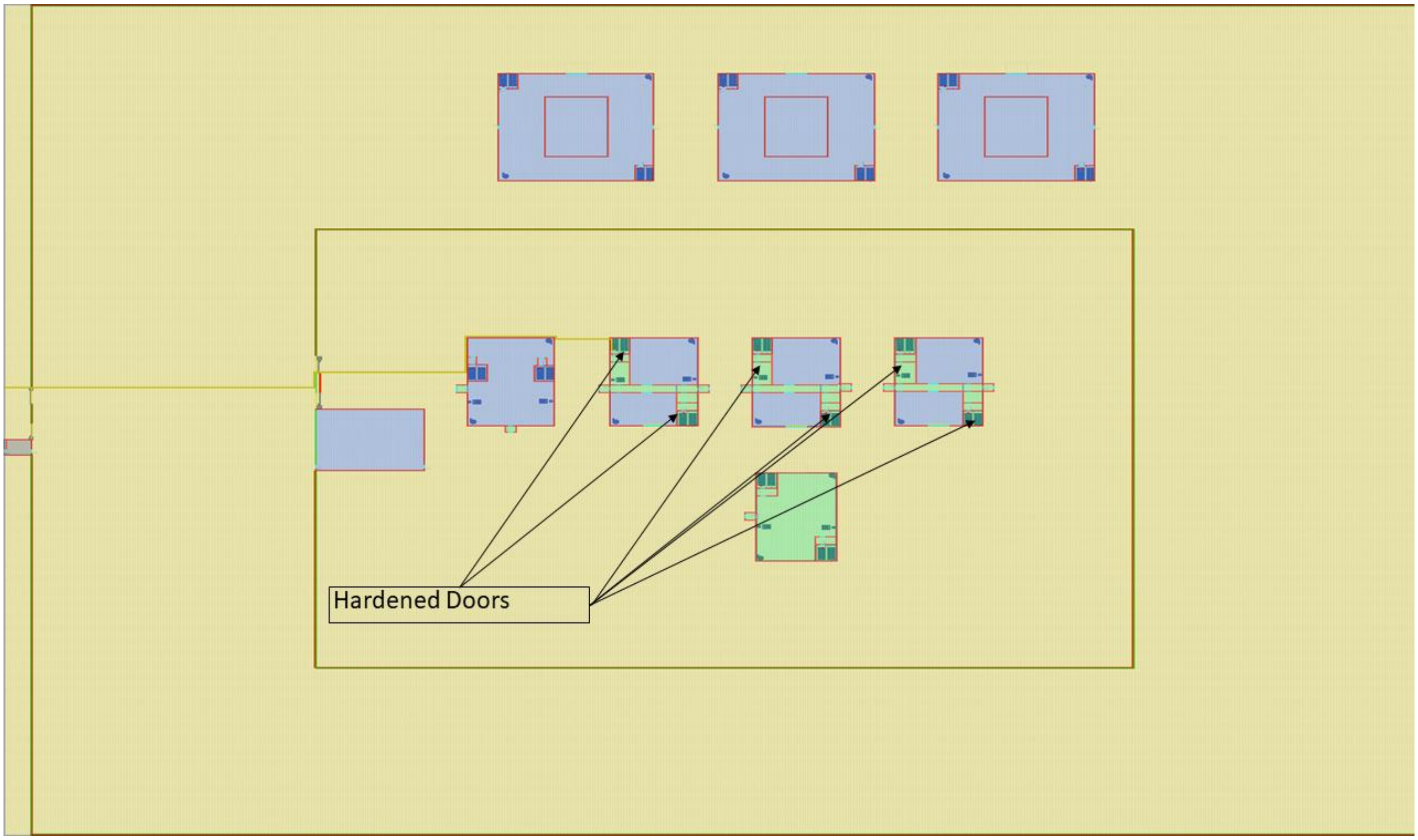


Figure 18 Hardened doors

The effects of this upgrade can be seen in the Table 14.

Table 14 Upgrade Ten Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	2974	99	0	3600
Spent Fuel Canister 1	2779	99	0	3600
Reactor 2	2979	99	0	3600
Spent Fuel Canister 2	2769	99	0	3600
Reactor 3	2984	99	0	3600
Spent Fuel Canister 3	2790	99	0	3600
Below-Grade Canister Storage	2313	99	0	3600

This upgrade did increase the overall adversary task time to each target location. Task times here still are lower than those upgrades for a 30-minute response time. This is largely due to the adversary to begin prioritizing speed and decreasing task time. Further upgrades were needed to reach an effective probability of interruption.

9.12. Upgrade Eleven – Increased Wall Thickness at Stairwells and Below-Grade Canister Storage Area

Upgrade eleven added increased wall thickness to the stairwells that go from above-grade to the below-grade areas of the reactor building. After reinforced doorways were added the adversary force would breach through the walls of the stairwell to enter the reactor building. This wall material was consistent to the thicker wall in upgrade seven. The spent fuel canister storage area was placed inside of a thicker wall, like that in upgrade 7, and had reinforced high-bay doors, like those in upgrade

eight. These upgrades can be seen in

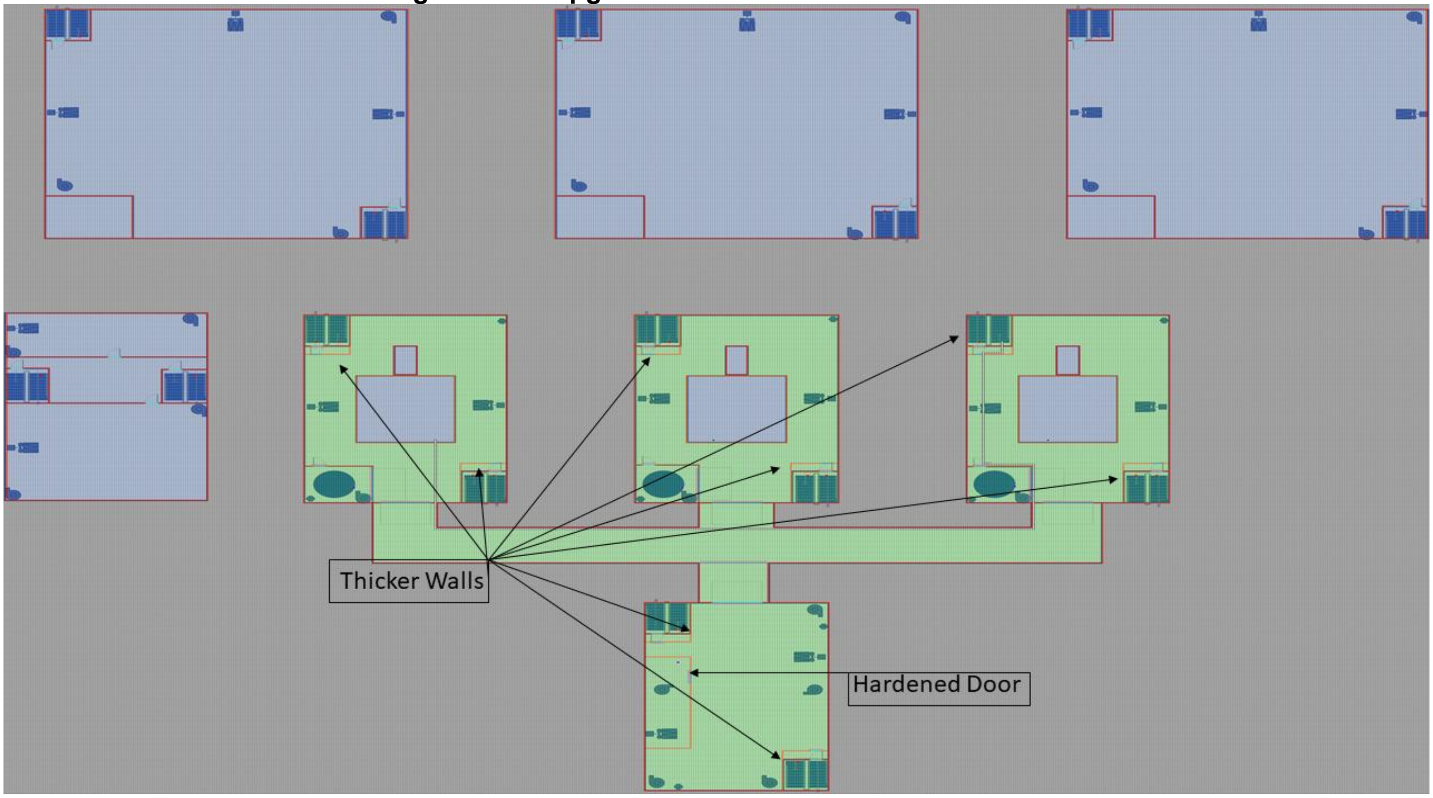
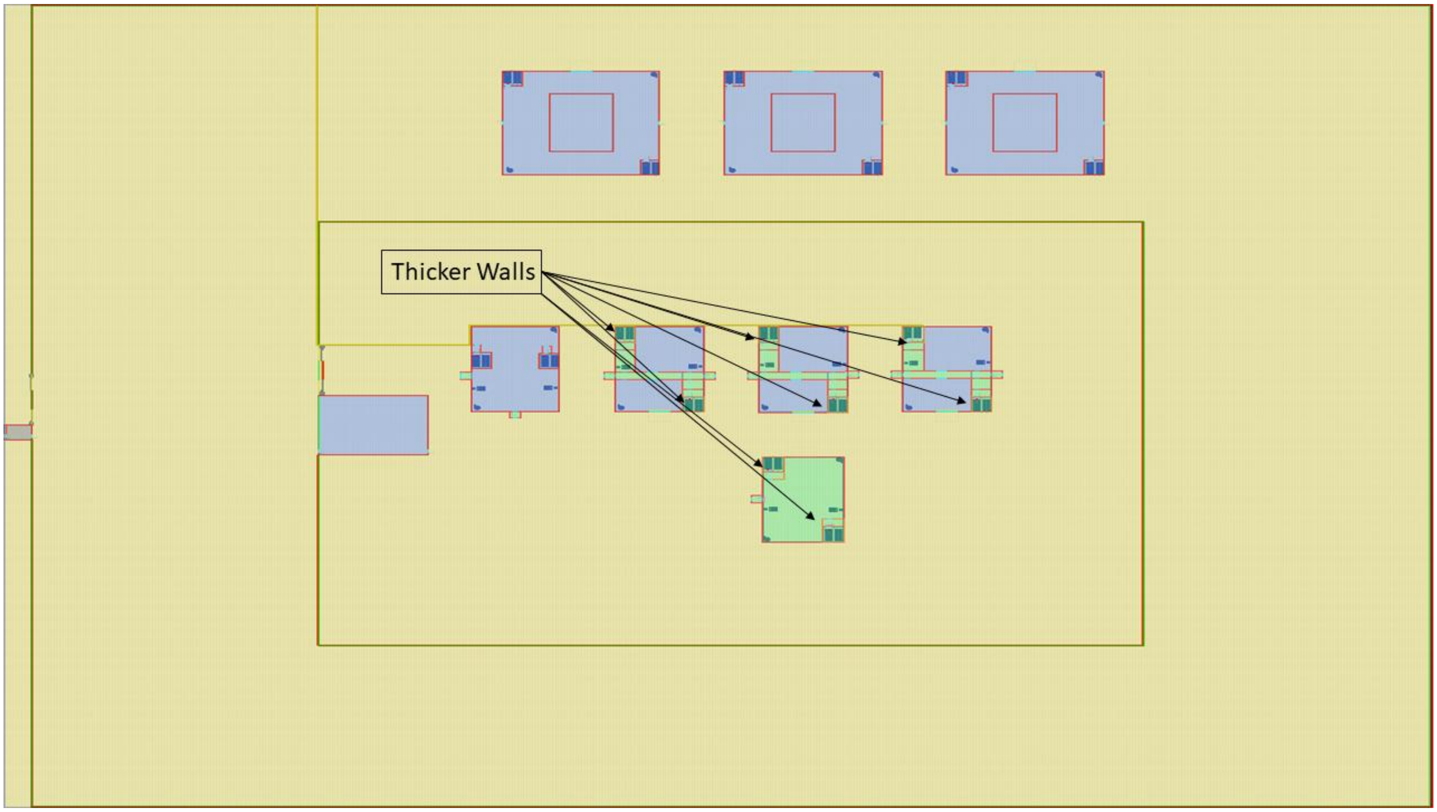


Figure 19.



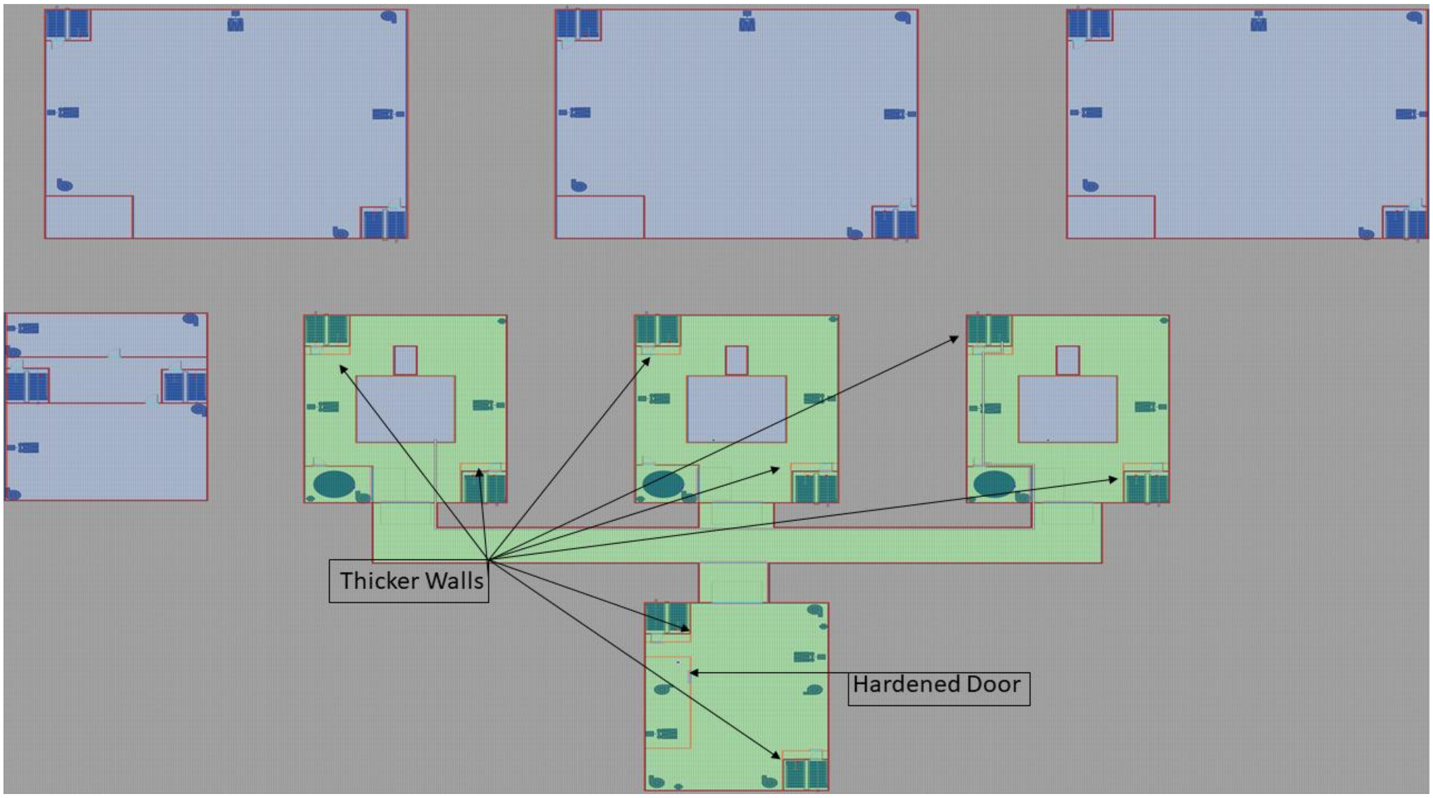


Figure 19 Increased wall thickness and below-grade storage area wall

The effects of this upgrade can be seen in Table 15.

Table 15 Upgrade Eleven Path Analysis Results

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor 1	4974	99	99	3600
Spent Fuel Canister 1	4779	99	99	3600
Reactor 2	4961	99	99	3600
Spent Fuel Canister 2	3683	99	99	3600
Reactor 3	4964	99	99	3600
Spent Fuel Canister 3	4483	99	99	3600
Below-Grade Canister Storage	4567	99	99	3600

As can be seen from the table above, the adversary task time greatly increased for all targets in this analysis. These upgrades provided increased adversary task times and provide great insights into the physical security system design for PBR facilities.

10. VULNERABILITY ANALYSIS OF FACILITY DESIGN

Vulnerability assessment results are based on analysis of the physical paths that the adversary follows to achieve its objective or a set of objectives. The protection functions of detection and delay along the paths are key factors in determining the adversary attack scenario that is most likely to succeed. There are many possible combinations of potential paths to get to a target location and sabotage specific targets; therefore, all possible adversary paths must be considered. The following steps were taken in this analysis to determine system effectiveness (and ultimately system vulnerability) and facility risk.

1. An adversary timeline was constructed and all physical protection elements in the system were identified.
2. Detection and delay values for each protection layer and path elements in the Adversary Sequence Diagram (ASD) were incorporated.
3. The most vulnerable paths (MVPs) were identified by analyzing the effectiveness of detection and delay along each possible path.
4. Scenarios of concern were developed, response timelines and effectiveness were evaluated, and system effectiveness was determined.

After completing the system effectiveness analysis, the VA team examined the paths and scenarios that had lower-than-desired system effectiveness (i.e., high vulnerability) and scenarios of interest that posed a risk to the facility. The goal was to identify the system's greatest vulnerabilities to theft so they could be mitigated.

10.1. Definition of Adversary Path

An adversary path is an ordered series of actions against a facility that, if completed, will result in a successful radiological sabotage event. Protection elements along the path potentially detect and delay the adversary so the dedicated response force can interrupt the series of events. The performance capabilities of detection, assessment, delay, and response are used in path analysis to determine the probability of interruption (P_I). Key performance measures included in estimating P_I are the probability of detection (P_D), delay time, and response force time (RFT).

10.2. Adversary Attack Scenarios

This hypothetical PBR was designed to minimize the targets. For this analysis the primary targets are reactor sabotage at Reactor 1 and sabotage of spent fuel in the spent fuel storage building. One reactor was chosen to reduce the analysis time, since the task times from previous sections for reactor sabotage at all four reactors are very similar this method was chosen to derive lessons learned and recommendations see Table 16.

Table 16 Sabotage Targets

Target	Location	Safety Related Purpose
Reactor 1	Reactor Building 1	Provides the operation of nuclear material in the reactor
Spent Fuel Storage	Spent Fuel Storage Building	Provides storage for spent fuel canisters and prevention of radiological release

For this analysis two scenarios were analyzed with varying adversary team numbers and varying response force timelines. These scenarios include the adversary team attempting acts of sabotage on the target mentioned in the table above. For successful sabotage in this analysis, the adversary force must be able to place a breaching charge on the reactor or a spent fuel canister that would cause a release of radioactive material. This analysis does not consider the consequences to this release and this was used to bound the physical protection system design.

10.2.1. Thirty-Minute Response Time

10.2.1.1. Reactor Sabotage

This scenario analyzes an adversary team breaching the facility and attempting to sabotage Reactor 1. The response force arrives at the exterior protected area boundary at the 30-minute mark and begins to recapture the site and neutralize the adversary force. In this analysis, the response force is awarded a win if the adversary is unable to sabotage the target due to attrition of adversary personnel and/or lack of required equipment to complete the necessary breaches or sabotage acts. The adversary force is afforded the win if they can complete sabotage of the reactor. This analysis assumes that all of the upgrades in the previous sections is applied (upgrades one through eleven). Table 17 identifies the probability of neutralization for conducting sabotage to Reactor 1.

Table 17 Thirty-Minute Force-on-Force Analysis Results (Reactor Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	75	49	42	15	6
Red Wins	25	51	58	85	94
Average Engagements	31	36	33	29	35
Average KIA Engagements	8	10	10	11	11
Blue Force Count	8	8	8	8	8
Average Blue Force KIA	5	6	6	7	8
Average Blue KIA in Win	3	4	4	5	6
Red Force Count	4	5	6	7	8
Average Red KIA	3	4	4	3	4
Average Red KIA in Win	2	3	3	3	3

As can be seen from the table above the number of blue force wins (i.e. the probability of neutralization) decreases as the adversary force size increases. The probability of neutralization is directly impacted by the adversary's ability to penetrate into the facility and harden their position. Since the response force time is long, the adversary is able to penetrate into the facility and use the facility design to harden their position when engagements with the adversary occurs. The use of the facility structure allows the adversary force to maintain cover and actively engage the response force to complete acts of sabotage at the facility.

Figure 20 shows the system effectiveness of the physical protection system against defending against reactor sabotage.

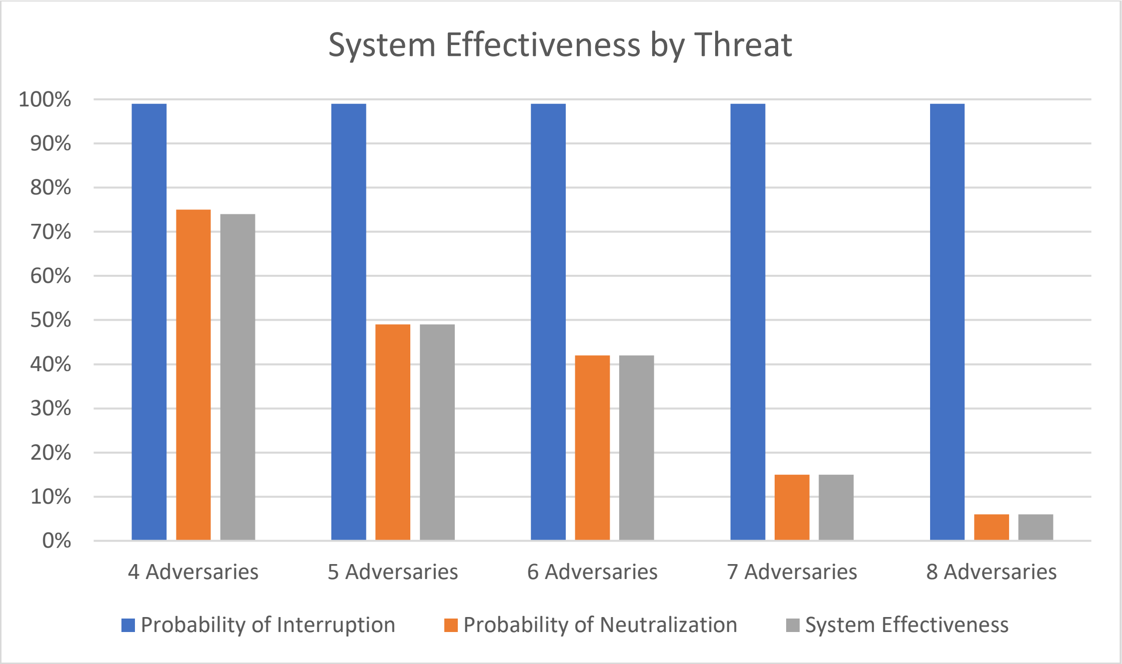


Figure 20 Thirty-Minute Response Time by System Effectiveness (Reactor Sabotage)

As can be seen in the figure above the system effectiveness is directly impacted and follows the probability of interruption. The probability of interruption is high in all cases based on the ability of the physical protection system to detect and delay the adversary force and allow for the response force to interrupt the adversary force. However, the physical protection system effectiveness decreases because of the low probability of neutralization. As the adversary number increases the system effectiveness decreases due to the shift in tactical advantage from the response force to the adversary force.

10.2.1.1.1. Hardened Fighting Position

For this analysis, a response force strategy was used where a dedicated responder was placed on the above-grade floor of each reactor building in a hardened fighting position. This hardened fighting position allows the responder to engage the adversary force as the enter the reactor building and neutralize part of the adversary force before they enter the below-grade portion of the reactor building. This allows the response force to gain an advantage when the offsite response force arrives onsite. This response posture assumes that eight offsite responders arrive onsite at thirty-minutes while one responder is in each hardened fighting position. This upgrade can be seen in the Figure 21.

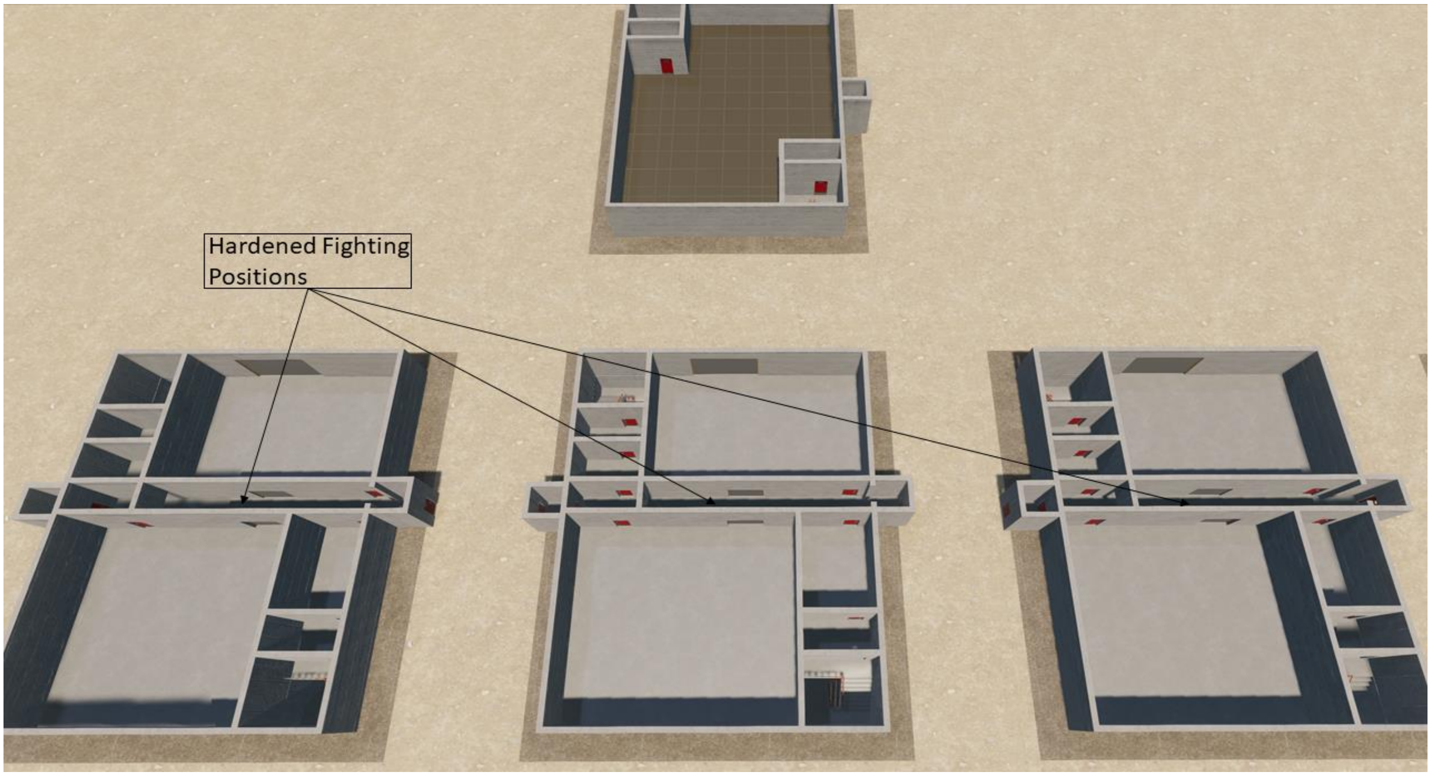


Figure 21 Hardened fighting position upgrades

Table 18 shows the impact these hardened fighting positions had on the probability of neutralization.

Table 18 Thirty-Minute Hardened Fighting Position Force-on-Force Analysis Results (Reactor Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	100	98	97	79	78
Red Wins	0	2	3	21	22
Average Engagements	28	28	33	38	36
Average KIA Engagements	7	8	10	11	12
Blue Force Count	12	12	12	12	12

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Average Blue Force KIA	3	3	4	5	5
Average Blue KIA in Win	3	3	4	4	5
Red Force Count	4	5	6	7	8
Average Red KIA	4	5	6	6	7
Average Red KIA in Win	N/A	3	3	4	5

The use of hardened fighting positions improved the probability of neutralization along all adversary force sizes. The hardened fighting position also allows for an increase in response force survivability which is a key metric to the effectiveness of a physical protection system. The impact this had on system effectiveness can be seen in the Figure 22.

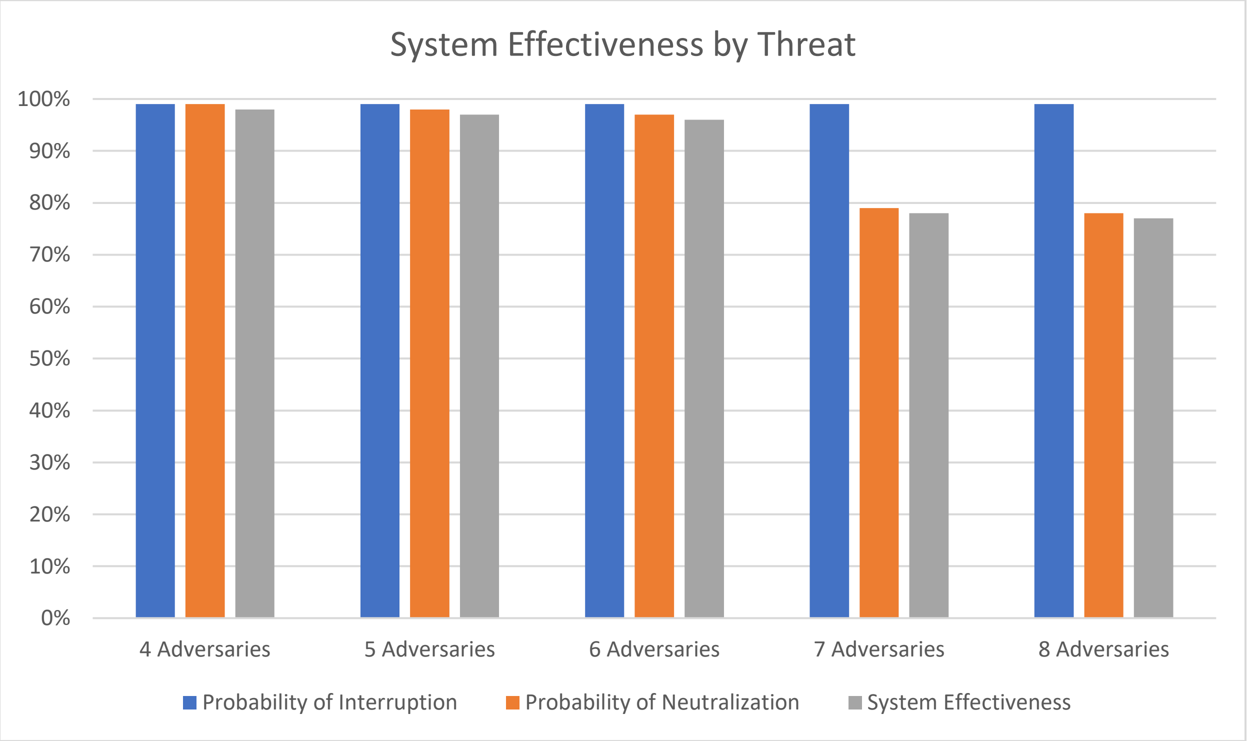
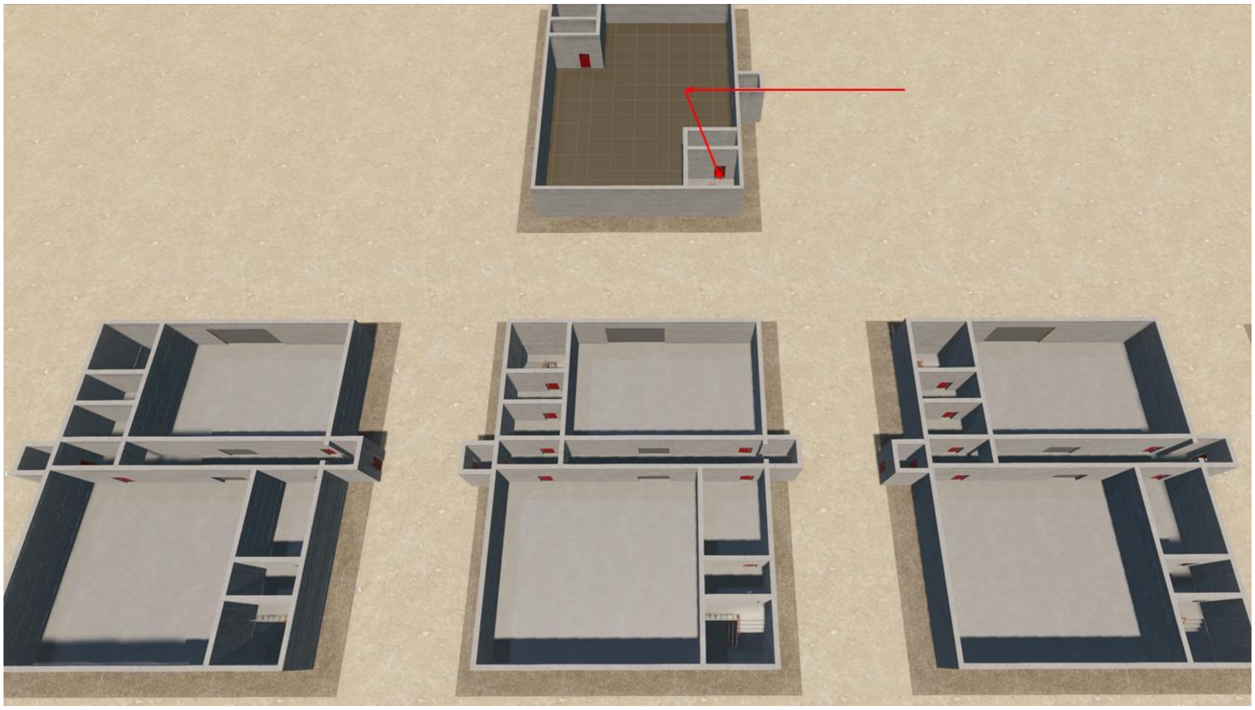


Figure 22 Thirty-Minute Hardened Fighting Position by System Effectiveness (Reactor Sabotage)

The use of hardened fighting positions improved the probability of neutralization and therefore increased the overall system effectiveness of the physical protection system. Hardened fighting positions with a dedicated onsite responder may be an effective strategy for securing a PBR facility.

10.2.1.1.2. Alternative Response Force Strategy

In this analysis, an alternative response force strategy was implemented to respond to an adversary threat. Instead of the response force entering the reactor building from the above-grade floor, the response force enters the facility from the spent fuel building and uses the underground tunnel to gain access to the below-grade floor of the reactor building. This allows the response force to gain access to the below-grade floor and protect the reactor without engaging the adversary in the stairwell of the reactor building. In addition to this change in strategy, the response force team is equipped with two mobile hardened fighting positions for the lead responders entering the building. This strategy only uses eight offsite responders. This alternative response force strategy can be seen in Figure 23.



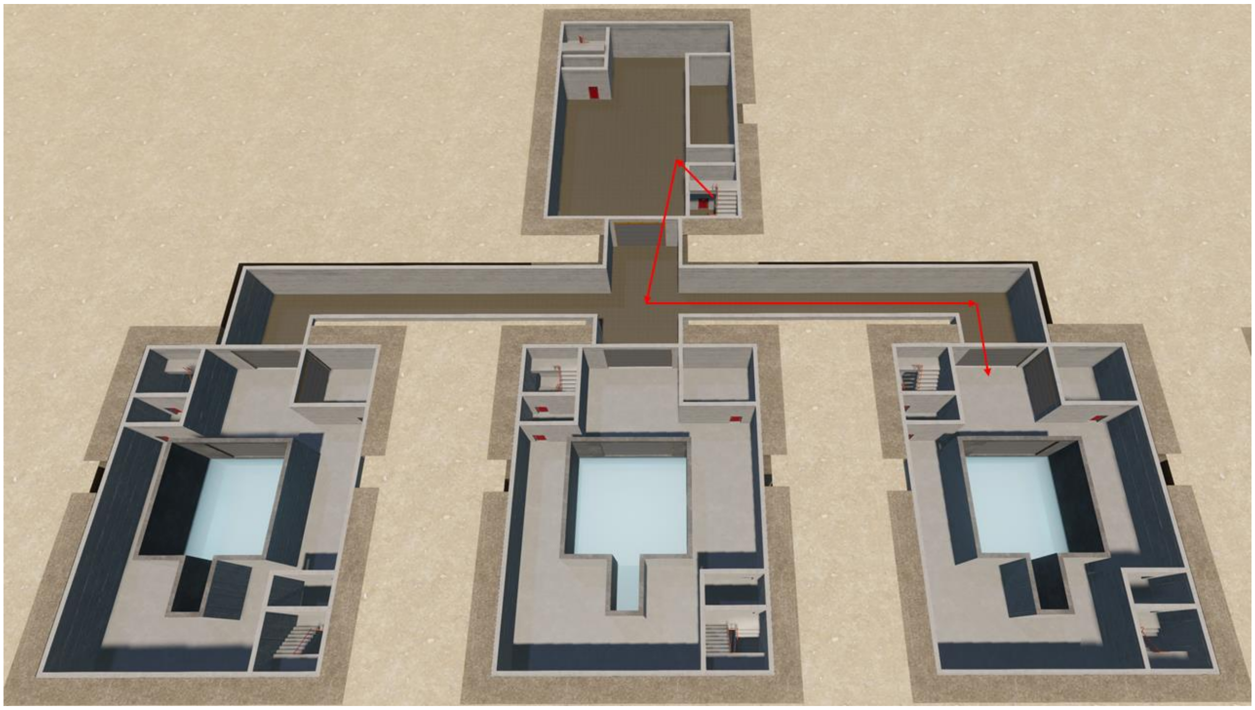


Figure 23 Alternative Response Force Strategy

The impact of this response force strategy on the probability of neutralization can be seen in Table 19.

Table 19 Thirty-Minute Alternative Response Force Strategy Force-on-Force Analysis Results (Reactor Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	100	100	100	100	99
Red Wins	0	0	0	0	2
Average Engagements	13	17	20	24	29
Average KIA Engagements	4	5	6	8	9
Blue Force Count	8	8	8	8	8
Average Blue Force KIA	0	0	0	0	1
Average Blue KIA in Win	0	0	0	0	2
Red Force Count	4	5	6	7	8

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Average Red KIA	4	5	6	7	8
Average Red KIA in Win	N/A	N/A	N/A	N/A	4

This change in response force strategy is the most effective response force strategy when paired with the upgrades to the physical protection system. This response force strategy improves the probability of neutralization and also improves response force survivability. The impact of this response force strategy on system effectiveness can be seen in Figure 24.

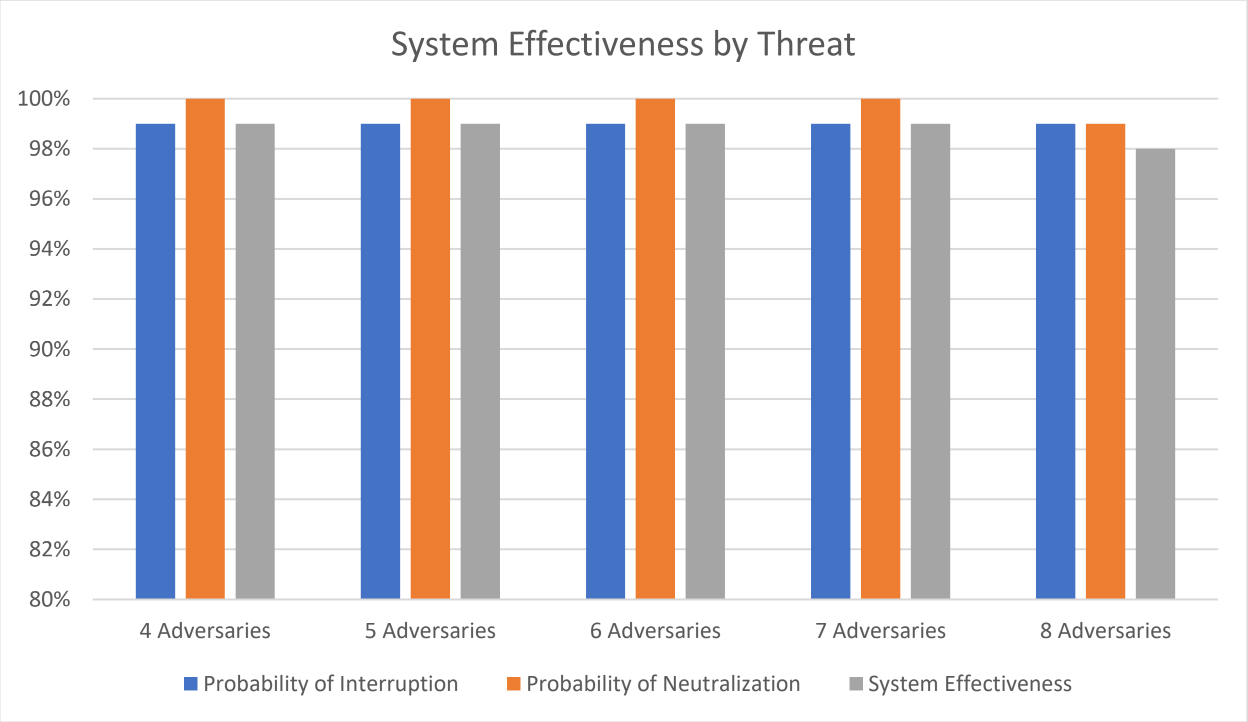


Figure 24 Thirty-Minute Alternative Response Force Strategy by System Effectiveness (Reactor Sabotage)

This analysis shows that the physical protection system must consider all aspects including detection, delay, and response forces must be considered. The use of this alternative response force strategy and the physical protection system upgrades provides a robust and effective physical protection system.

10.2.1.2. Spent Fuel Sabotage

This scenario analyzes an adversary force attempting to sabotage spent fuel canisters in the spent fuel storage building. In this analysis, the response force is awarded a win if the adversary is unable to sabotage the target due to attrition of adversary personnel and/or lack of required equipment to complete the necessary breaches or sabotage acts. The adversary force is afforded the win if they can complete sabotage spent fuel canisters. Table 20 shows probability of neutralization results for spent canister sabotage.

Table 20 Thirty-Minute Force-on-Force Analysis Results (Spent Fuel Canister Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	100	97	94	79	45
Red Wins	0	3	6	21	55
Average Engagements	14	20	25	28	31
Average KIA Engagements	5	7	9	11	12
Blue Force Count	8	8	8	8	8
Average Blue Force KIA	2	3	3	5	6
Average Blue KIA in Win	2	2	3	4	4
Red Force Count	4	5	6	7	8
Average Red KIA	4	5	6	6	6
Average Red KIA in Win	N/A	3	3	3	4

As can be seen in the table above the system effectiveness against defending against sabotage of the spent fuel canisters is higher than that for reactor sabotage. The spent fuel storage area is a much larger area than the reactor buildings and provides less cover for the adversary teams than in the reactor building. In this analysis, the response force was able to effectively engage adversaries who stayed behind to act as security because of the larger numbers the response force had in these individual engagements. Again, as the adversary force increases in size the probability of neutralization decreases. Improvements in response force tactics and training may aid to the improvement of the probability of neutralization and improve overall physical protection system effectiveness.

Figure 25 shows the system effectiveness of the physical protection system against defending against spent fuel canister sabotage.

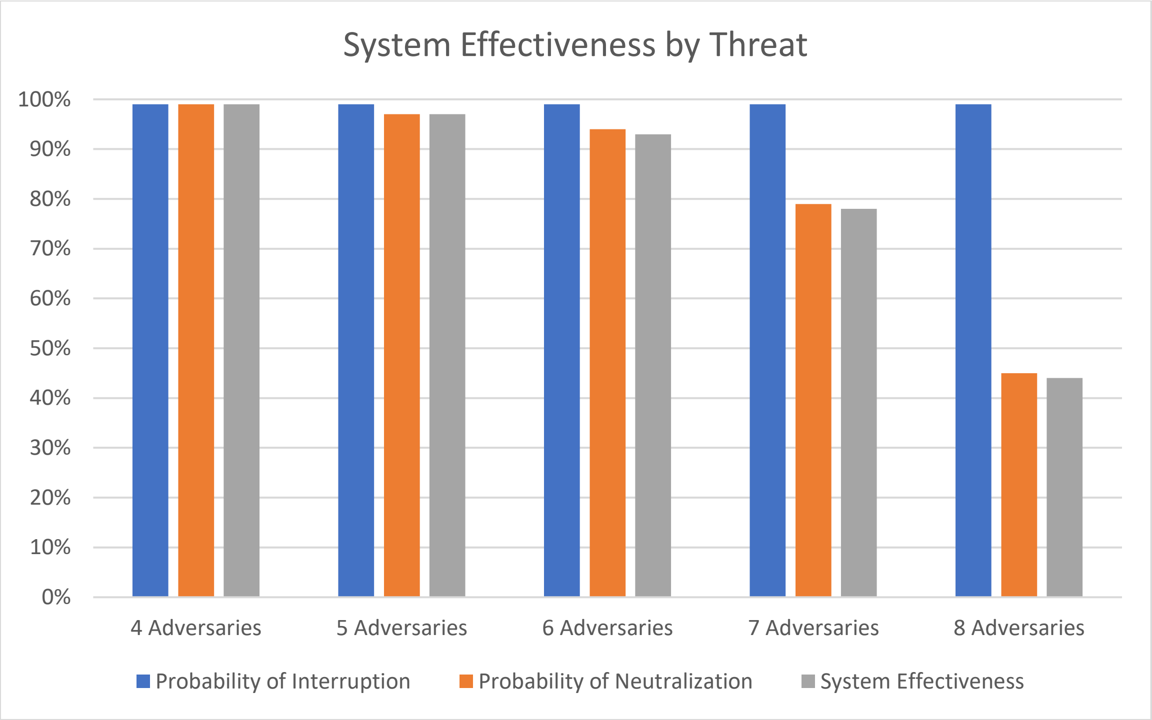


Figure 25 Thirty-Minute Response Time by System Effectiveness (Spent Fuel Canister Sabotage)

The figure above shows the system effectiveness of defending against spent fuel canister sabotage. System effectiveness follows the probability of neutralization. As the adversary force increases from 6 to 7 persons the system effectiveness decreases rapidly. This is primarily due to the positioning of the adversary force and their ability to engage with the response force. This may require additional considerations for response force tactics and planning.

10.2.2. Sixty-Minute Response Time

10.2.2.1. Reactor Sabotage

This scenario analyzes an adversary team breaching the facility and attempting to sabotage Reactor 1. The response force arrives at the exterior protected area boundary at the 60-minute mark and begins to recapture the site and neutralize the adversary force. In this analysis, the response force is awarded a win if the adversary is unable to sabotage the target due to attrition of adversary personnel and/or lack of required equipment to complete the necessary breaches or sabotage acts. The adversary force is afforded the win if they can complete sabotage of the reactor. Table 21 identifies the probability of neutralization for conducting sabotage to Reactor 1.

Table 21 Sixty-Minute Force-on-Force Analysis Results (Reactor Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	52	26	26	16	4
Red Wins	48	74	74	84	96
Average Engagements	36	37	42	40	38
Average KIA Engagements	8	9	10	10	11
Blue Force Count	8	8	8	8	8
Average Blue Force KIA	5	7	7	7	8
Average Blue KIA in Win	3	3	4	4	5
Red Force Count	4	5	6	7	8
Average Red KIA	3	3	3	3	3
Average Red KIA in Win	1	2	3	3	3

The table above shows the probability of neutralization for varying adversary forces. As the adversary force size increases, the probability of neutralization decreases. The 60-minute response force time has much lower probabilities of neutralization than for a 30-minute response force time. The primary issue is the extended time that the adversaries have before they are interrupted. The adversary force is able to harden their position more and the adversaries have penetrated further into the facility allowing for sabotage of the reactor to be achieved in many of the cases. Therefore, further tactical and planning decisions need to be considered by a site and the response force for extended response force times.

Figure 26 shows the system effectiveness of the physical protection system against defending against reactor sabotage.

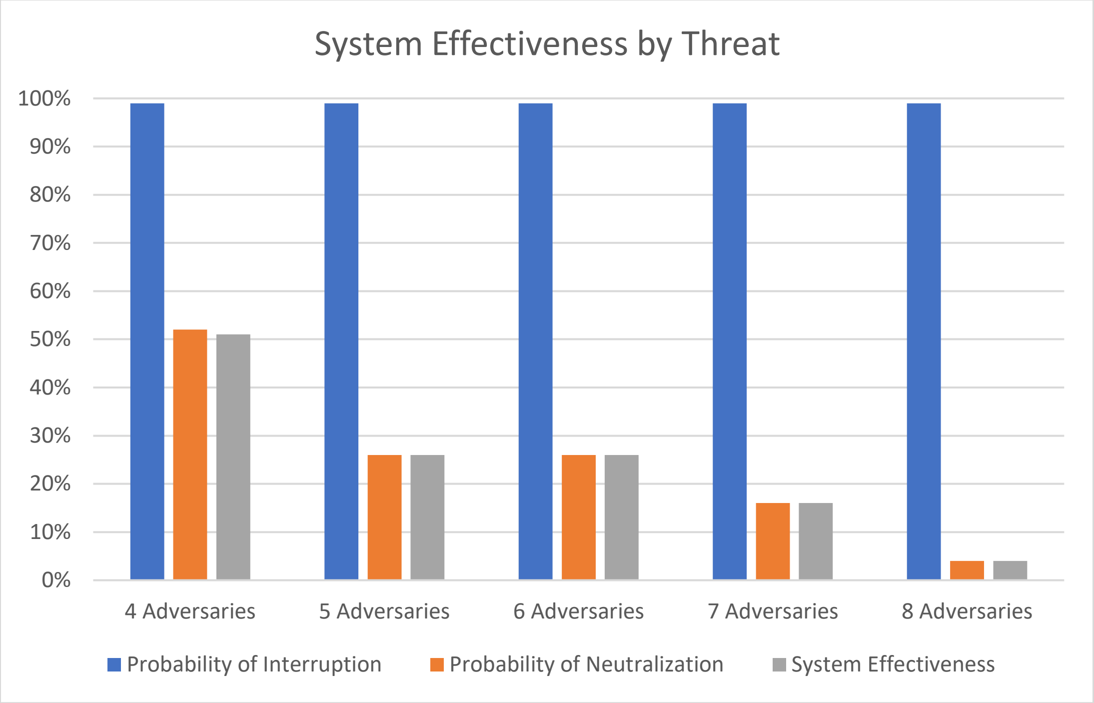


Figure 26 Sixty-Minute Response Time by System Effectiveness (Reactor Sabotage)

The figure above shows the direct role that probability of neutralization has on the effectiveness of the physical protection system. The physical protection system design allows for high probability of interruption, but the low probability of neutralization decreases the system effectiveness. Therefore, methods such as tactics and planning from the response force must be considered for improving the probability of neutralization. Other upgrades such as mobile hardened fighting positions may also improve the probability of neutralization and the system effectiveness of the physical protection system.

10.2.2.1.1. Hardened Fighting Position

This analysis uses the hardened fighting position as discussed in previous sections. This response force strategy assumes an offsite response force of eight members and onsite responders in hardened fighting positions in the above-grade floor of the reactor buildings. The impact of this upgrade on the probability of neutralization can be seen in Table 22.

Table 22 Sixty-Minute Hardened Fighting Position Force-on-Force Analysis Results (Reactor Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	99	98	99	92	85
Red Wins	1	2	1	8	15
Average Engagements	26	29	37	42	46
Average KIA Engagements	6	8	9	11	12
Blue Force Count	12	12	12	12	12
Average Blue Force KIA	2	3	3	4	5
Average Blue KIA in Win	2	2	3	4	4
Red Force Count	4	5	6	7	8
Average Red KIA	4	5	6	7	8
Average Red KIA in Win	1	2	2	4	5

The use of hardened fighting positions on the above-grade floor of the reactor building significantly improved the probability of neutralization compared to the previous analysis. This hardened fighting position allows the response force to engage the adversary force before they can all enter the below-grade floor of the reactor building. This allows the offsite response force to be more effective at engaging the adversary force once they arrive. The impact of this upgrade on system effectiveness can be seen in Figure 27.

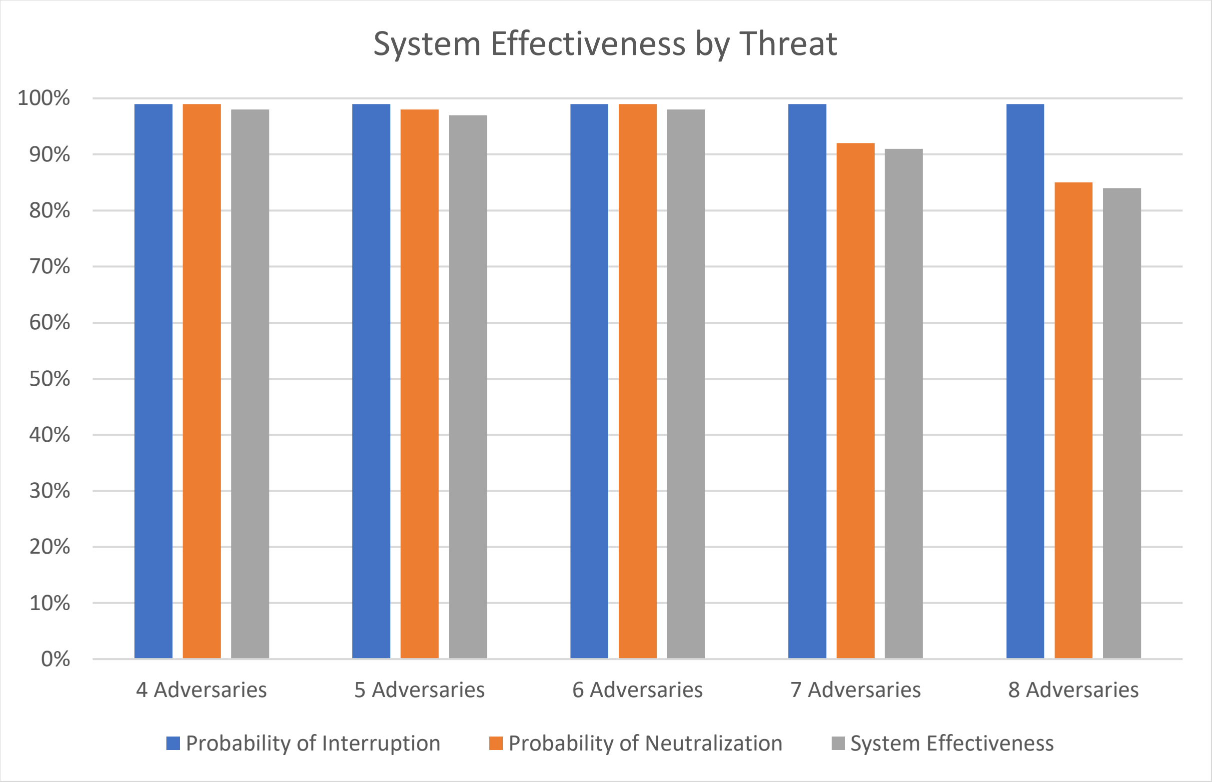


Figure 27 Sixty-Minute Hardened Fighting Position by System Effectiveness (Reactor Sabotage)

The use of hardened fighting positions improved the probability of neutralization and therefore the overall system effectiveness.

10.2.2.1.2. Alternative Response Force Strategy

In this analysis, the alternative response force strategy that was discussed in previous sections is applied for an offsite response time of sixty-minutes. This analysis assumes that no onsite response force is present. In addition, the offsite response force is equipped with two mobile hardened fighting positions. The impact of this alternative response force strategy can be seen in Table 23.

Table 23 Sixty-Minute Alternative Response Force Strategy Force-on-Force Analysis Results (Reactor Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	100	94	86	80	53
Red Wins	0	6	14	20	47
Average Engagements	15	21	24	30	34

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Average KIA Engagements	5	7	8	10	11
Blue Force Count	8	8	8	8	8
Average Blue Force KIA	1	2	2	4	5
Average Blue KIA in Win	1	1	3	3	3
Red Force Count	4	5	6	7	8
Average Red KIA	4	5	5	6	5
Average Red KIA in Win	N/A	1	2	2	2

The probability of neutralization using the alternative response force strategy is greater than the base case analysis. However, it is less than the hardened fighting position response strategy. The impact of this change on system effectiveness can be seen in Figure 28.

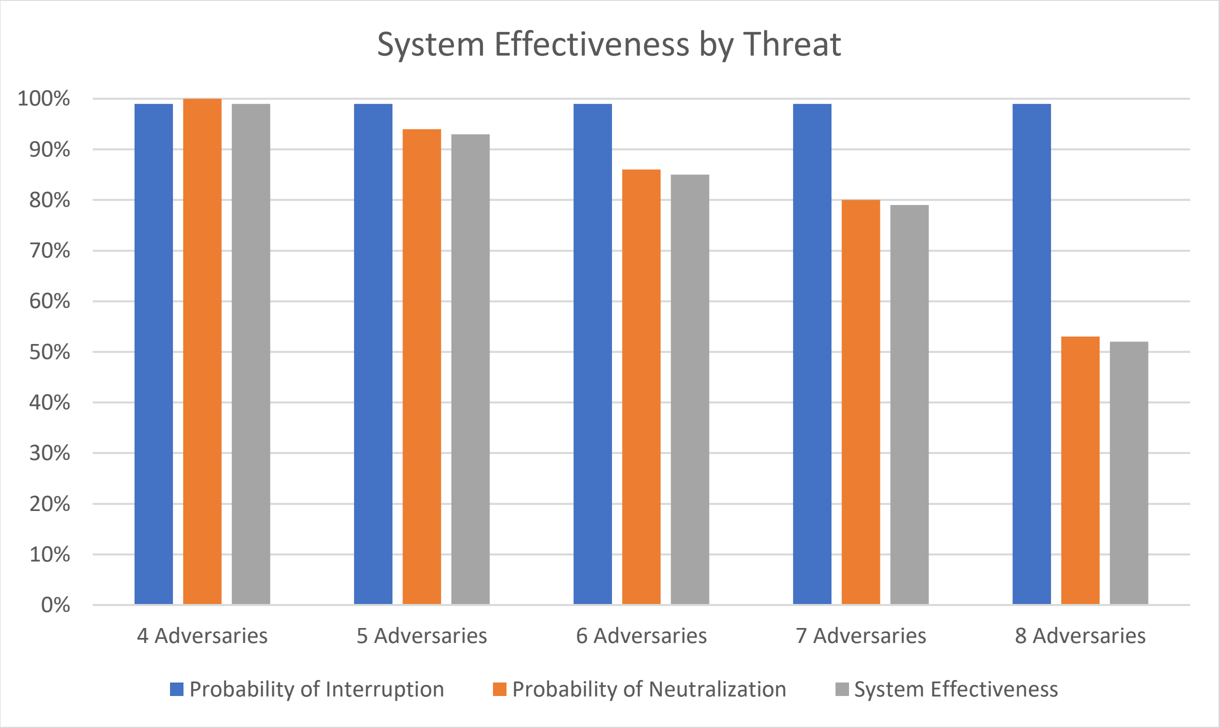


Figure 28 Sixty-Minute Alternative Response Force Strategy by System Effectiveness (Reactor Sabotage)

This approach has a lower system effectiveness than the hardened fighting position response force strategy. This is primarily because at sixty-minutes the adversary force is able to harden themselves in the below-grade floor of the reactor building. When using the hardened fighting position, the response force can neutralize some of the adversary force allowing the offsite response force to become more effective in engaging the adversary force once they arrive onsite.

10.2.2.2. Spent Fuel Sabotage

This scenario analyzes an adversary force attempting to sabotage spent fuel canisters in the spent fuel storage building. In this analysis, the response force is awarded a win if the adversary is unable to sabotage the target due to attrition of adversary personnel and/or lack of required equipment to complete the necessary breaches or sabotage acts. The adversary force is afforded the win if they can complete sabotage spent fuel canisters. Table 24 shows probability of neutralization results for spent canister sabotage.

Table 24 Sixty-Minute Force-on-Force Analysis Results (Spent Fuel Canister Sabotage)

Name	Results: 4 Adversaries	Results: 5 Adversaries	Results: 6 Adversaries	Results: 7 Adversaries	Results: 8 Adversaries
Number of Runs	100	100	100	100	100
Blue Wins	100	98	91	77	45
Red Wins	0	2	9	23	55
Average Engagements	14	18	23	27	31
Average KIA Engagements	5	7	9	11	12
Blue Force Count	8	8	8	8	8
Average Blue Force KIA	1	2	4	5	6
Average Blue KIA in Win	1	2	3	4	4
Red Force Count	4	5	6	7	8
Average Red KIA	4	5	6	6	6
Average Red KIA in Win	N/A	2	3	3	4

The table shows the probability of neutralization for defending against spent fuel sabotage in the spent fuel storage building. The probabilities of neutralization are like those of the 30-minute response force time. This shows that the physical protection system is flexible in defending against an adversary force with both a 30-minute and 60-minute response force time.

Figure 29 shows the system effectiveness of the physical protection system against defending against spent fuel canister sabotage.

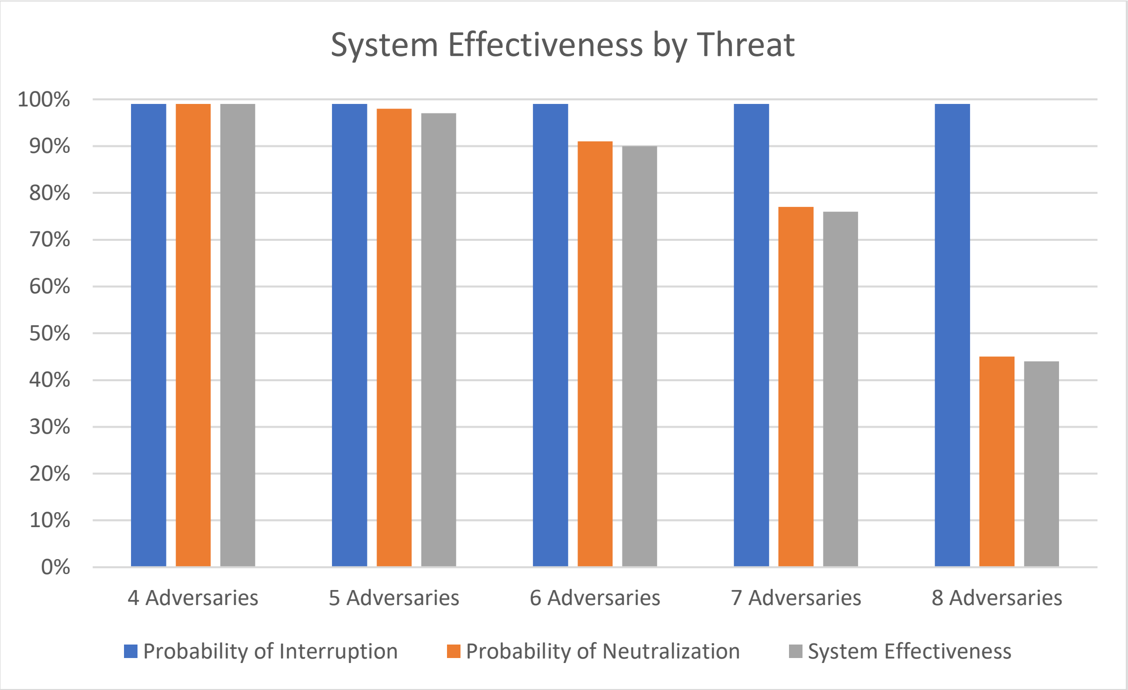


Figure 29 Sixty-Minute Response Time by System Effectiveness (Spent Fuel Canister Sabotage)

The figure above identifies the system effectiveness for defending against sabotage of spent fuel canisters in the spent fuel storage building. The system effectiveness follows the probability of neutralization. The system effectiveness of the 60-minute response is slightly less than that of the 30-minute response force time. This shows that the physical protection system designed is flexible against defending sabotage of spent fuel with varying response force times.

11. CONSIDERATIONS

The results from this analysis are useful in analyzing and designing a pebble bed reactor facility for domestic applications. This analysis proved valuable in determining facility designs and physical protection systems that can be applied to improve the system effectiveness at defending against acts of sabotage at a pebble bed reactor facility. Several aspects of facility and physical protection system design have been identified that should be considered when designing and siting a domestic pebble bed reactor facility.

11.1. Facility Considerations

This analysis shows many considerations PBR designers should have when designing a PBR facility. PBR facility layouts should be considered by these designers. The layout of the facility has impacts for both the physical protection system and the day-to-day operations of the facility. Facility designers should ensure that the facility layout is conducive to the protection of nuclear material and allow for efficient operations of the facility. This can ensure effective physical protection system designs that allow for cost-effective operations of a PBR facility. By integrating the necessary operations of a PBR facility with the design of the physical protection system, facility designers can ensure that proper access control, access delay and response can be integrated into the design.

Facility designers should also consider the siting of their facility in terms of its effect on the physical protection system. Siting the facility in locations in which the perimeter of the facility is unobstructed can allow for extended detection technologies such as DMA, LIDAR and RADAR. Extended detection beyond the protected area boundary can allow for an improved physical protection system by detecting adversaries earlier and activating the response force before the adversary reaches the protected area boundary. Siting the facility in elevated positions can also increase the adversary task time for adversaries moving and traversing the facility.

Federal, state, and local building codes may also impact the design of the facility and the physical protection system. It is important for facility designers to understand the restrictions and requirements that are necessary to design the facility. Ventilation systems, lighting, electrical boxes and pathways, and emergency ingress and egress points must be considered in the facility design. The potential adversary pathways increase with the considerations of these systems and therefore increase the complexity of designing and analyzing physical protection systems.

Facility designers must also consider siting the facility near the offsite response force providing response to the site. This analysis shows that decreasing the offsite response force time can have a direct impact on the effectiveness of the physical protection system. Placing the facility near the response force may allow for an increase in the effectiveness of the physical protection system. Siting must also consider identifying primary and secondary routes for the response force to the PBR facility. The site must consider the time it takes the response force to reach the facility and mount an effective response to neutralize the adversary force. Identifying primary and secondary routes to the facility is important to ensuring an effective response force and improving the effectiveness of the physical protection system.

11.2. Physical Protection System Considerations

Facility designers must consider the design and implementation of physical protection components into the design of their PBR facility. Including components of physical protection system components can improve the effectiveness of the physical protection systems and reduce costly retrofits to the site and physical protection system.

PBR sites should consider the use of active delay systems such as obscurants and slippery agents to multiply the task time for the adversary to complete individual tasks. Multiplying task times can increase the overall adversary task time for conducting acts of sabotage at a PBR facility. The combination of active delay features with reinforced walls, doors, doors with magnetic locks and other passive delay features can increase the overall adversary task time for achieving acts of sabotage at the facility. Active delay features may pose a risk to site personnel due to premature activation. Active delay features may come with increased operational costs for the command-and-control infrastructure of these active delay systems and features. However, these active delay features can be used to increase adversary task time as needed and improve the effectiveness of the physical protection system.

PBR facility designers may consider the ability for the CAS operators to lock facility doors both at mantraps and internal to the facility. This locking feature can increase adversary task time and help to mitigate insider threats at PBR facilities. These features can increase the adversary task time by causing adversaries to breach doorways instead of bypassing doorways.

The analysis has shown that the probability of neutralization drastically impacts the effectiveness of the physical protection system. Therefore, it is imperative that PBR facilities must have a response force with the tactical expertise, plans and procedures to effectively neutralize an adversary force. The analysis shows that the use of hardened fighting positions and alternative response force strategies can improve the probability of neutralization and therefore, system effectiveness. Response force plans and tactics must be considered when designing a physical protection system for a PBR facility. Sites must ensure that response force personnel are intimately familiar with the site, target locations, and the contingency plans for handling nuclear security events. The site should conduct regular exercises and tests to ensure the effectiveness of the response force to maintain the effectiveness of the physical protection system. Sites should also consider contingency plans if the primary route to the facility is unpassable. Weather, traffic conditions, and acts by an adversary to block routes to the facility can directly impact the time it takes the response force to arrive at the facility. The site must consider how these events may impact the response force time to the facility and how this could impact the overall effectiveness of the physical protection system.

12. CONCLUSIONS AND FUTURE WORK

The analysis in this document shows impactful methods to improve the effectiveness of physical protection systems for PBR facilities. It is important that PBR facility designers ensure that the design of the physical protection system meets NRC requirements and regulations

From this analysis, physical protection system designs must be based on the response force time to allow for an effective response to interrupt and neutralize an adversary force. Active delay features can be applied in strategic locations by PBR facilities to multiply the task time by an adversary force and increase the overall adversary task time. The increase of adversary task times may increase the effectiveness of the physical protection system and allow for secure operations of a PBR facility. PBR sites must also consider that active delay systems must be passed through by the response force once they have been activated. This can delay the response force from interrupting the adversary force and impact their ability to effectively neutralize an adversary force. Facility designers may consider providing the response force with capabilities that can aid responders in recapturing a facility and neutralizing an adversary force.

This analysis also showed that the application of technologies such as DMA, RADAR, and LIDAR may be applied to detect adversaries beyond the protected area boundary. Earlier detection can allow for the response force to be notified earlier and respond to malicious acts at a PBR facility. This analysis shows that decreased response force times can improve the effectiveness of the physical protection system.

Future work will evaluate the feasibility of using extended detection beyond the owner-controlled area to improve detection and enhance the capabilities of a physical protection system. The use of final denial systems will be analyzed for their effectiveness as part of a physical protection system and potential to reduce the number of responders onsite or offsite that are needed. Additionally, cost-effectiveness analysis will be conducted to determine the cost for various physical protection system designs.

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