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U.S. Domestic Small Modular Reactor Security by Design

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ABSTRACT

U.S. nuclear power facilities face increasing challenges in meeting evolving security requirements caused by evolving and expanding threats while keeping cost reasonable to make nuclear energy competitive. The addition of security features after a facility has been designed and without attention to optimization (the past approach) 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 to develop a framework for the integration of security into the design phase of Small Modular Reactors (SMRs) and the use of modeling and simulation tools to optimize the design of physical protection systems. This effort will intend to integrate security into the design phase of a model SMR that meets current NRC physical protection requirements and provide 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 SMR facility. Physical protection elements such as sensors, cameras, portal monitors, barriers, and guard forces were added to the model based on best practices for physical protection systems. One outsider sabotage scenario was examined with 4-8 adversaries to determine security metrics. This work will influence physical protection system designs and facility designs for U.S. domestic SMRs. The purpose of this project is to demonstrate how a series of experimental and modeling capabilities across the Department of Energy Complex can impact the design of U.S. domestic SMRs and the complete Safeguards and Security by Design (SSBD) for SMRs.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

This report highlights the design and path analysis of a Light Water Small Modular Reactor (LWSMR). This effort included the design of a hypothetical LWSMR for conducting path analysis to determine probabilities of interruption for an offsite response force with a response time of 30 minutes. The analysis provided insight into the design considerations that must be considered when developing a LWSMR. This analysis focused on improving facility and physical protection system designs to provide an effective probability of interruption. Design choices focused on the implementation of building and physical protection system designs that improve the probability of interruption while minimizing the impact on the facility footprint and facility operations. Upgrades to the physical protection system increased the probability of interruption for an offsite response time of 30 minutes by the addition of two external facility walls, one internal facility wall inside the reactor building, hardening stairwells and entry points, and the introduction of active access delay features at stairwells and key entry points. Upgrades also included the use of advanced sensing and detection technologies that can be applied in the Exclusion Area to increase the probability of detection and the probability of interruption at this hypothetical SMR. These upgrades proved effective at increasing the probability of interruption to above 95% for an offsite response time of 30 minutes. Future work may consist of force-on-force modeling of this LWSMR to evaluate the probability of neutralization for this hypothetical facility and evaluate the system effectiveness at this hypothetical LWSMR. Additional work may consider similar analysis for various SMR designs including pebble-bed reactors and molten-salt reactors.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
PPS	Physical Protection System
SMRs	Small Modular Reactors
SSBD	Safeguards and Security by Design

1. INTRODUCTION

Nuclear facilities around the world face stringent requirements for security, particularly for nuclear power generating facilities, including planned small modular reactors (SMRs). Nuclear power plant facilities must meet 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 will not be necessary. By only using offsite local law enforcement, this significantly helps to reduce operational costs. 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 in order to accomplish the performance objectives of safeguards and security. By incorporating these factors into the design phase of the facility, this can significantly decrease implementation and operational costs throughout the facility's lifetime. As part of this design process, it is important to assess the vulnerability of the facility through modeling and simulation in order to identify potential upgrades 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.

Specifically, a hypothetical SMR facility is modeled to evaluate whether a reduced security posture is justified given the robust passive security features.

The SMR facility described in this report is hypothetical. In order to avoid potential sensitivities, various individual characteristics of planned SMR facilities were selected and/or slightly modified for the hypothetical model.

The report documents the reactor, design of the facility, operations, and physical protection system. The goal of the system is to reach an adversary timeline for sabotage of 30 minutes, which is used as a benchmark for offsite LLEA response. The initial work documented contains the process to reach 30 minutes of access delay by describing path analysis results for the base case PPS and four upgrade packages designed to lengthen the adversary timeline.

2. HYPOTHETICAL SMALL MODULAR REACTOR FACILITY

The hypothetical SMR developed for this design and analysis encompasses many features and capabilities of multiple U.S. domestic SMRs in development. This provides a framework for the design and analysis to capture SSBD for domestic SMR applications. The hypothetical SMR facility is located 15 miles outside of Portland, Oregon with a population of approximately 650,000 people.

2.1. Site Description

2.1.1. Climate

The region surrounding the facility has a moderate, wet climate. Its summers are warm and dry, and its winters are cool and wet. Its warm season starts in June and lasts until September with an average daily high temperature above 76°F.[1] The cold season is between November and February and has an average daily high temperature below 52°F.[1] As the temperatures are rarely above 95°F the temperature should not affect any passive infrared technologies. The region generally has a low level of humidity[1] but receives 43 inches of rain a year, and 3 inches of snow.[2] 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.[3] This may impact assessment via electronic means or visual inspection by patrols or response forces.

2.1.2. Local Wildlife

Oregon has a large variety of wildlife which may affect day-to-day operations at a nuclear facility. These include multiple species of deer, elk, antelope, and moose.[4] These animals are not intimidated by fences and can jump up to seven or eight feet.[5,6] While these animals don't prove 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[7] and foxes[8] can climb fences or tunnel underneath them.They 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[9] which may

[1] https://weatherspark.com/y/757/Average-Weather-in-Portland-Oregon-United-States-Year-Round
[2] https://www.bestplaces.net/climate/city/oregon/portland
[3] https://www.currentresults.com/Weather/US/cloud-fog-city-annual.php
[4] https://myodfw.com/wildlife-viewing/species/hoofed-mammals
[5] https://www.adn.com/uncategorized/article/alaska-mansions-fence-kills-another-moose-fourth-three-years/2012/07/20/
[6] https://pss.uvm.edu/ppp/articles/deerfences.html
[7] https://www.youtube.com/watch?v=daQ_O8mHm8Y
[8] https://www.wildlifeonline.me.uk/articles/view/red-fox-deterrence
[9] https://myodfw.com/wildlife-viewing/species/trumpeter-swan

exceed 30 lbs, wild turkeys which may weigh as much as 30 lbs, and the American White Pelican which while weighing only 14lbs can have a wingspan of over 9 ft. These birds may induce nuisance alarms as they move throughout the property including motion detectors and fence vibration sensors.

2.2. Reactor Description

Based on many U.S. domestic SMR designs, the reactor for this design and analysis will be an integral-Pressurized Water Reactor (iPWR). This iPWR houses the reactor core, reactor core coolant pumps, pressurizer and the steam generators inside of the reactor pressure vessel. Housing these items inside of the pressure vessel creates a smaller plant design and reduces the number of potential sabotage targets. The iPWR design also decreases the number of large connection pipes connecting to the pressure vessel, which removes the risk of a primary loop large-break loss of coolant accident (LOCA). Removing primary system large-break LOCAs can reduce the risk of sabotage at an SMR facility. The reactor is fueled by low enriched uranium (LEU) UO_2 pellets that are enriched to 4.9% U-235 for proliferation resistance. The site operates four reactor units simultaneously. The whole reactor core is replaced every 24 months via an underwater refueling system, and the spent fuel core stored onsite for 10 years in a spent fuel pool. The expected design lifetime of the plant is 60 years.

The reactors are cooled and moderated by light water with boric acid for reactivity control. The reactor pressure vessel (RPV) contains all of the primary system components, including the reactor core, control rod drive system, integral helical coil steam generators, reactor coolant pumps, and pressurizer. The primary coolant inside of the RPV is liquid borated water maintained by the pressurizer at 15 MPa. Cooling in the primary system is performed by forced circulation with 10 internal canned motor coolant pumps. The water is forced upwards through the core by the coolant pumps and flows downwards through the helical coil once-through steam generators on the way down. There are two steam generators per reactor core, which combine steam before it heads to the turbine. On the secondary side, the water and steam at an average pressure of 6 MPa is heated in the steam generator in a countercurrent flow, resulting in some superheating of the steam beyond saturation. The steam then travels to a high-pressure turbine followed by a series of low-pressure turbines. There is one high-pressure turbine per reactor core, for a total of four turbines per plant. The steam and any letdown water is collected and sent to a condenser to completely condense the steam-water mixture into liquid, then pumped back to the steam generator for heating. The condenser is cooled by the ocean for ultimate heat rejection.

Reactivity control as well as safe shutdown is mainly performed by the B_4C control rods. The Quad-Power RPV is 20 cm thick, 16 m high, and 3.5 m in inner diameter. The RPV is located within a 1.3-m thick concrete containment vessel located below-grade. The containment vessel inner height is 21 m, with a 5 m inner diameter. Containment is cooled with an integral water tank in direct contact outside of the concrete shell, which acts passively to transfer heat to a heat exchanger via natural circulation.

The entire reactor building which holds the four reactors as well as the spent fuel pool is below-grade, as is the main control room building. Both of these buildings are also seismic category I structures. The reactor building is only expected to be accessed during refueling operations or safeguards inspections, when maintenance is needed, or when security inspections are needed. The main control room onsite operates all four reactors and is staffed at all times by one operator and one shift supervisor.

The SMR is capable of passive cooling after a loss-of-onsite power design-basis accident (DBA) before fuel melting without operator action for 144 hours. Following a loss of on-site power, the reactor is automatically tripped inserting its control rods shutting down the nuclear chain reaction. In the case of a loss-of-coolant accident (LOCA), the Emergency Core Cooling System automatically initiates. The ECCS consists of Passive Safety Injection Tanks (PSITs), which inject gravity-driven water passively into the RPV following depressurization from automatic depressurization valves. Each reactor core is equipped with one PSIT located inside of the containment vessel, which can maintain 72 hours of cooling. Following this, Residual Water Makeup Tanks (RWMTs) inside of containment can provide an additional 72 hours of cooling. There is a single RWMT per reactor core. Battery banks and emergency diesel generators are used for redundant security system power. All safety systems are entirely passive.

2.3. SMR Facility Operations

To model the recent developments within the domestic and international SMR community, the site is designed with minimal operational personnel on site. Two reactor operators (one operator and one shift supervisor) will be located onsite within the main control room. One control room operator can safely operate four reactors at one time. During emergencies, operational control can be shifted from the main control room to an offsite control room located at a secure location in the operator's corporate engineering office. One central alarm station (CAS) is located onsite with two security operators. One operator can successfully assess alarm points and communicate to an offsite response force. The backup alarm station is located at the same location as the offsite control room.

2.4. SMRF Buildings

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

- Office Building

The office building has an above-grade and below-grade floor. The above-grade portion consists of office spaces that can be used for site operators and others to use. The below-grade floor consists of the CAS and the response force barracks. The CAS operators process and assess alarms, and initiate response force members to respond to alarms.

- Dry Cask Storage Area

  This fenced-in area will store spent fuel within concrete dry casks after it has cooled in the spent fuel pool for about ten years. This will not be included in the security analysis since this is beyond the scope of the current SMR study which seeks to identify plant components relevant to the primary reactor building characteristics different from existing LWRs.

- Power Production Building

  The Power Production Building (PPB) consists of one above-grade floor and two below-grade floors. The above-grade floor is 15-feet tall, and the below-grade floors are 20-feet tall.   The above grade floor consists of:

  - Two turbine and battery bank rooms (59’ x 52’6”),
  - The reactor building (77’5” x 61’3”),
  - An auxiliary building (39’ x 148’),
  - Nuclear receiving building (39’10” x “42’1”), and
  - A non-nuclear receiving building (39’10” x 42’1”).

  The PPB also houses the spent fuel pool, four reactor cores and a spent fuel processing area.

  The first below-grade floor consists of:

  - Reactor Control Room,
  - Two battery bank and diesel generator rooms,
  - Below-grade nuclear receiving building, and
  - The reactor building.

  The second below-grade floor also consists of the reactor building as well. The figures below display the site layout and buildings.

Figure 1: Above-Grade SMRF.

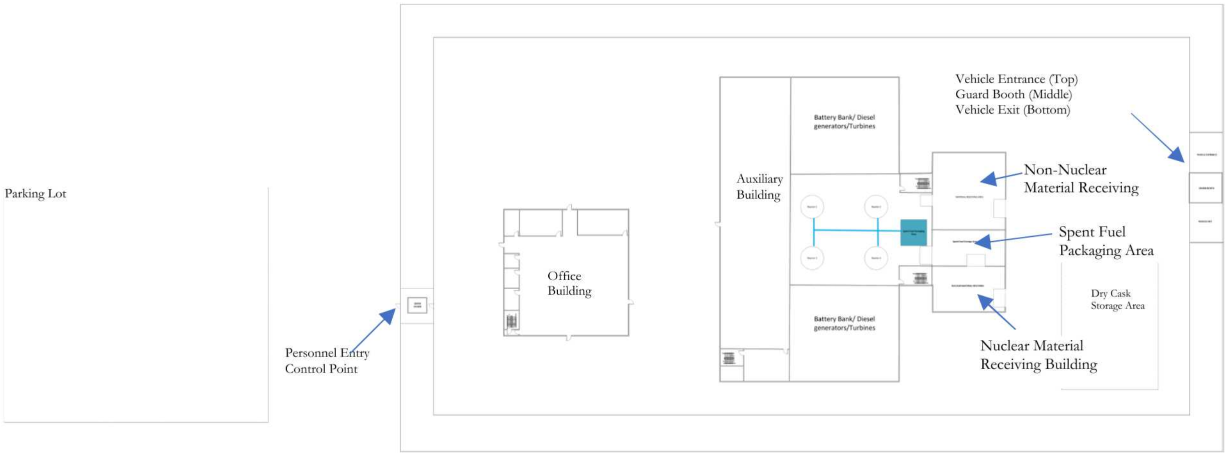

Parking Lot
Personnel Entry Control Point
Office Building
Auxiliary Building
Battery Bank/ Diesel generators/Turbines
Battery Bank/ Diesel generators/Turbines
Vehicle Entrance (Top)
Guard Booth (Middle)
Vehicle Exit (Bottom)
Non-Nuclear Material Receiving
Spent Fuel Packaging Area
Dry Cask Storage Area
Nuclear Material Receiving Building

Figure 2: First Below-Grade Floor SMRF.

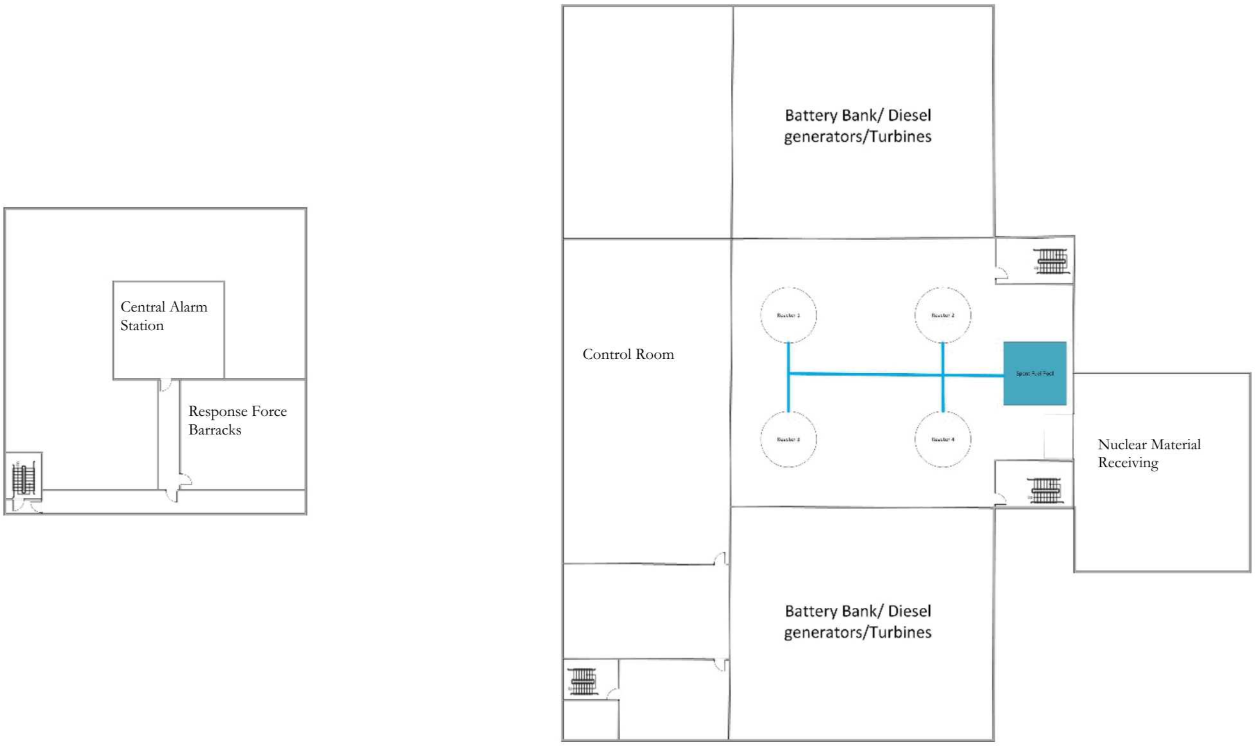
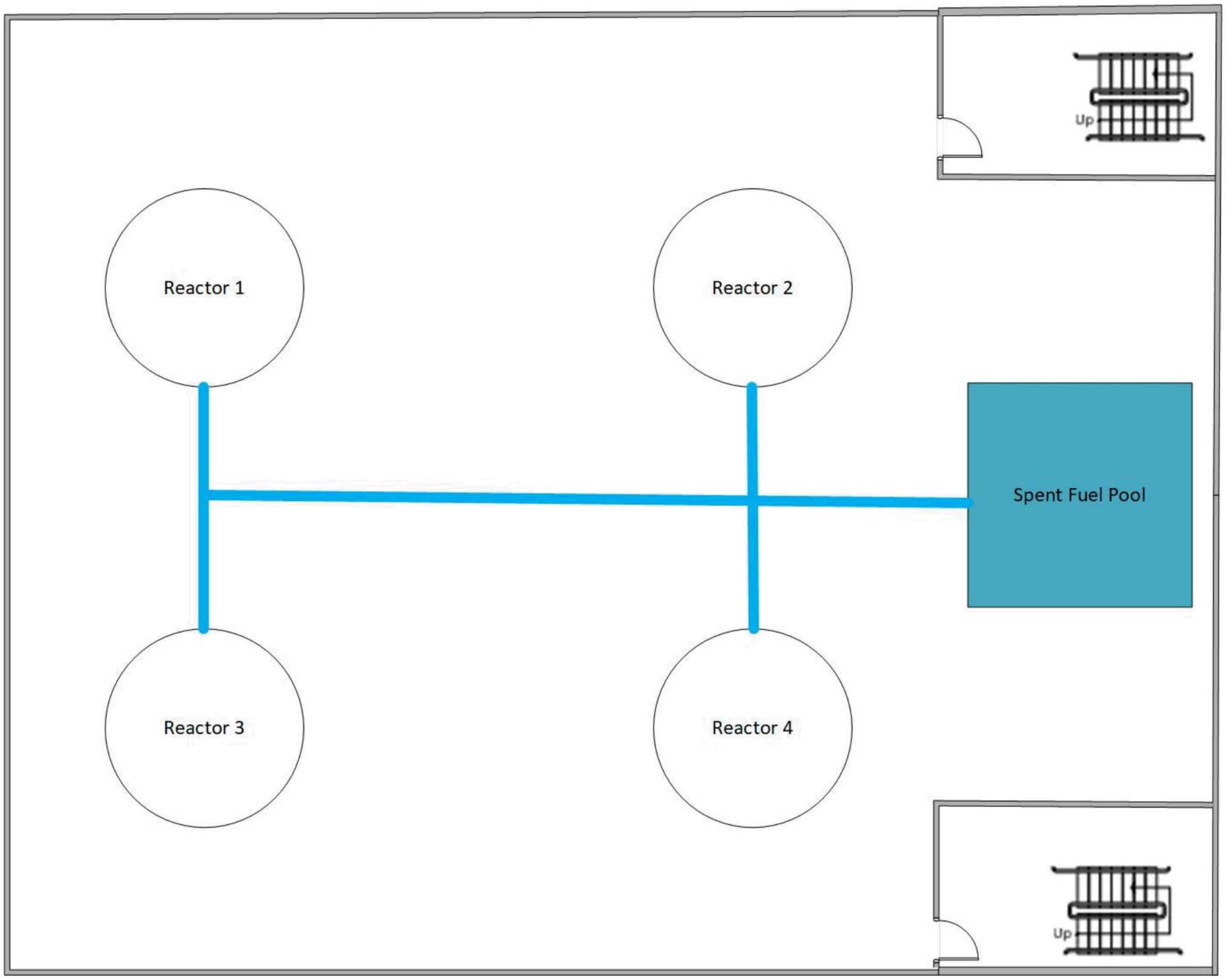


Figure 3: Second Below-Grade Floor SMRF.



3. HYPOTHETICAL SMR PHYSICAL PROTECTION SYSTEM

3.1. PPS Design Process

In the physical protection world, DEPO (Design and Evaluation Process Outline) [1] has been used for several decades for the design of a PPS. The DEPO process is shown in Figure 1. 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. One addition that has been made to the original DEPO process is to include Security by Design (SBD) recommendations. This means not just adding more guns, guards, and gates, but developing optimized PPS designs that may request changes to the facility of process design early in the design process. The PPS design will be iterated until satisfactory results (from performance tests) are obtained.

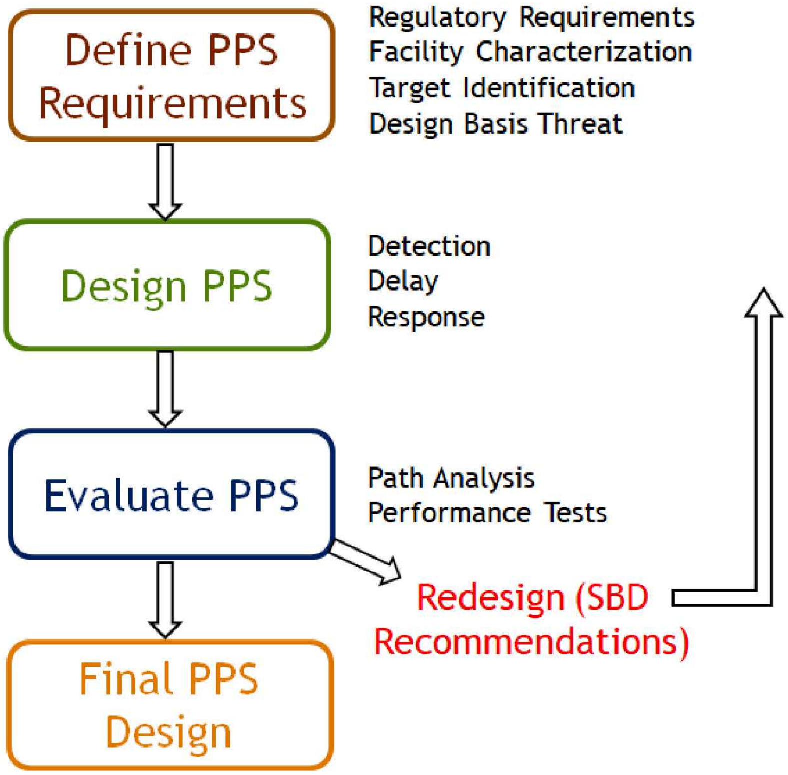


Figure 1: DEPO Process[2]

Analysis will be conducted using current Nuclear Regulatory Commission (NRC) practices for physical protection with current technologies and a separate analysis 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.

3.2. Current Practices of Small Modular Reactor Facility Physical Protection

The base case used for the analysis will include the implementation of an Exclusion Area (EA) which functions as a limited access area (LAA), 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 physical protection system effectiveness of current 10 CFR 73 regulations for SMRs under proposed operating conditions and methods. As part of the analysis of current 10 CFR 73 regulations, minimal guards and response force sizes will be present to analyze the effectiveness of these regulations.

3.2.1. Perimeter Physical Protection System Design

The site includes an EA, which is an EA area functioning as the site's limited access area. The EA encompasses an 8-foot high fence which functions as demarcation, is not manned by guards and does not contain any detection or assessment technologies. The entry point for the fence is usually unlocked during all hours. Since the EA does not include any sensing or entry control, it's presence is excluded from this analysis.

The site's protected area (PA) is controlled by a perimeter intrusion detection and assessment system (PIDAS) consisting of an outer and inner fence line (8-feet tall with outriggers), separated by an isolation zone with sensing, see Figure 4. The isolation zone consists of bistatic microwave sensing, and the inner fence has a vibration sensor. The entire isolation zone consists of closed-circuit television (CCTV) cameras for assessment from the CAS. All CCTV cameras on site are on a loop recording and automatically save 10 seconds before and after an alarm.

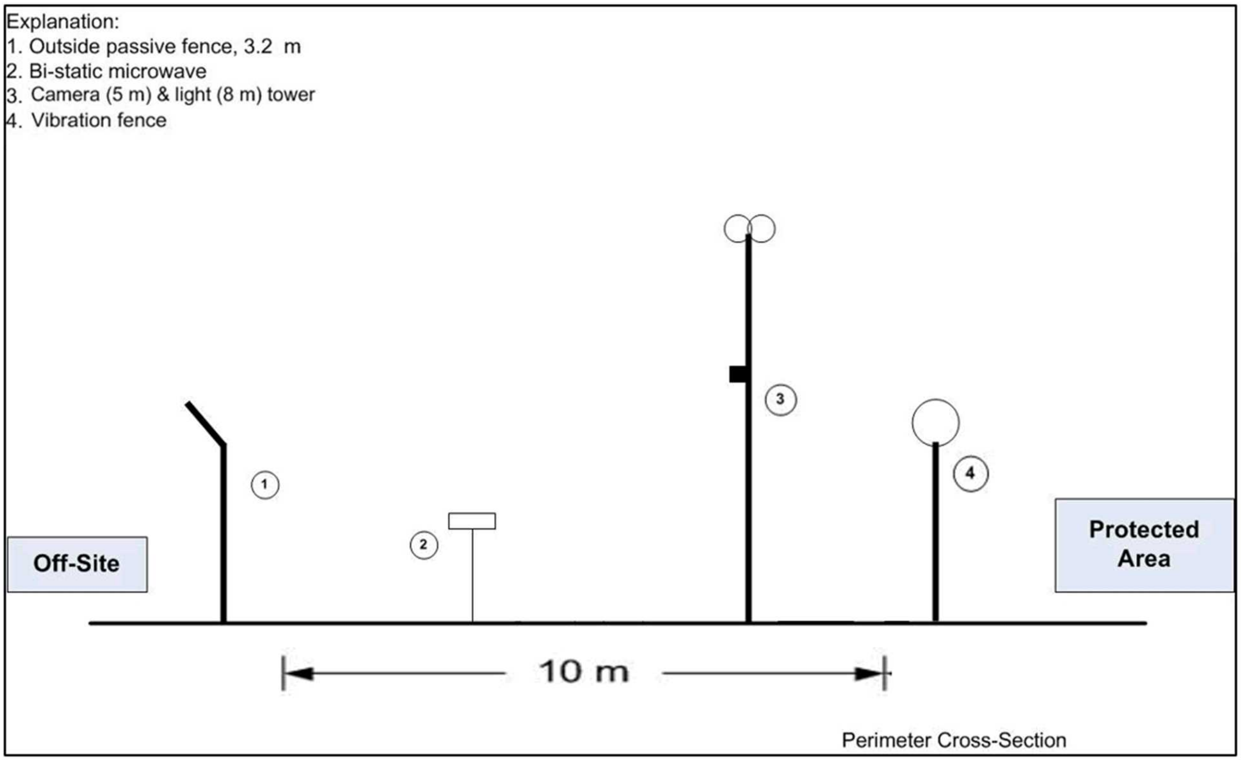


Figure 4. PIDAS Cross-section

The PA has two points of entry, one for personnel and one for vehicles, also both assessed with CCTV. The vehicle entrance is only operational during the receipt of new reactor fuel or equipment. Inner and outer hydraulic vehicle barriers are raised when the access point is not operational. The personnel entrance is manned 24/7 by two guards who perform detection of prohibited items before entering the PA. Pedestrians must pass through a metal detector, an explosives detection portal, and have their on-person items sent through a 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 vehicle access control point consists of an inner and outer gate, with vehicle barriers on the outer side of each. 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:

The driver and all other vehicle passengers must stop at the access point at the outer gate. 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. If authorized, the outer gate is opened and the inner vehicle barrier lowered by the second guard. The driver is then instructed to drive inside the gate and stop before the second vehicle barrier. The outer vehicle barrier is raised and the outer gate is closed. The passengers and driver then exit the vehicle process through the personnel entrance in the same manner as described above. During this time, one of the guards at the vehicle access point inspects the vehicle for contraband and explosives visually. Once validated and granted access, the driver and any passengers return to the vehicle. The inner hydraulic barrier is lowered by the second guard and the inner gate opened by the first guard, and the vehicle passes through. The inner gate is closed and inner vehicle barrier raised and the process repeats.

3.2.2. Internal Physical Protection System

All building entrances inside the PA are armed with balanced magnetic switches (BMSs) and all entrance doors are monitored by security cameras. Building entrances except for vital areas are secured by proximity card reader access controls. The site operates four vital areas: the reactor building, two battery bank and diesel generator rooms, and the nuclear receiving building. The vital areas are secured by two-factor authentication, using a hand geometry reader and a PIN entrance to allow access into the VAs.

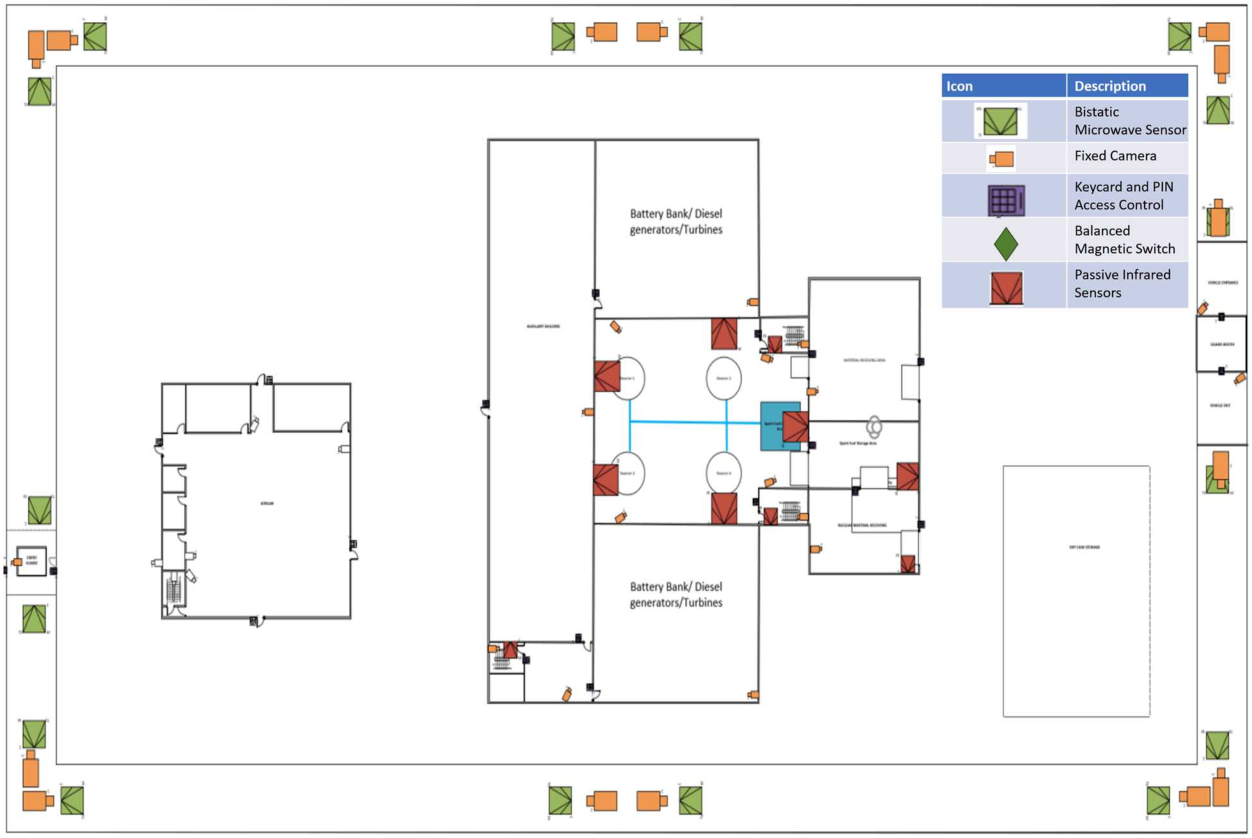
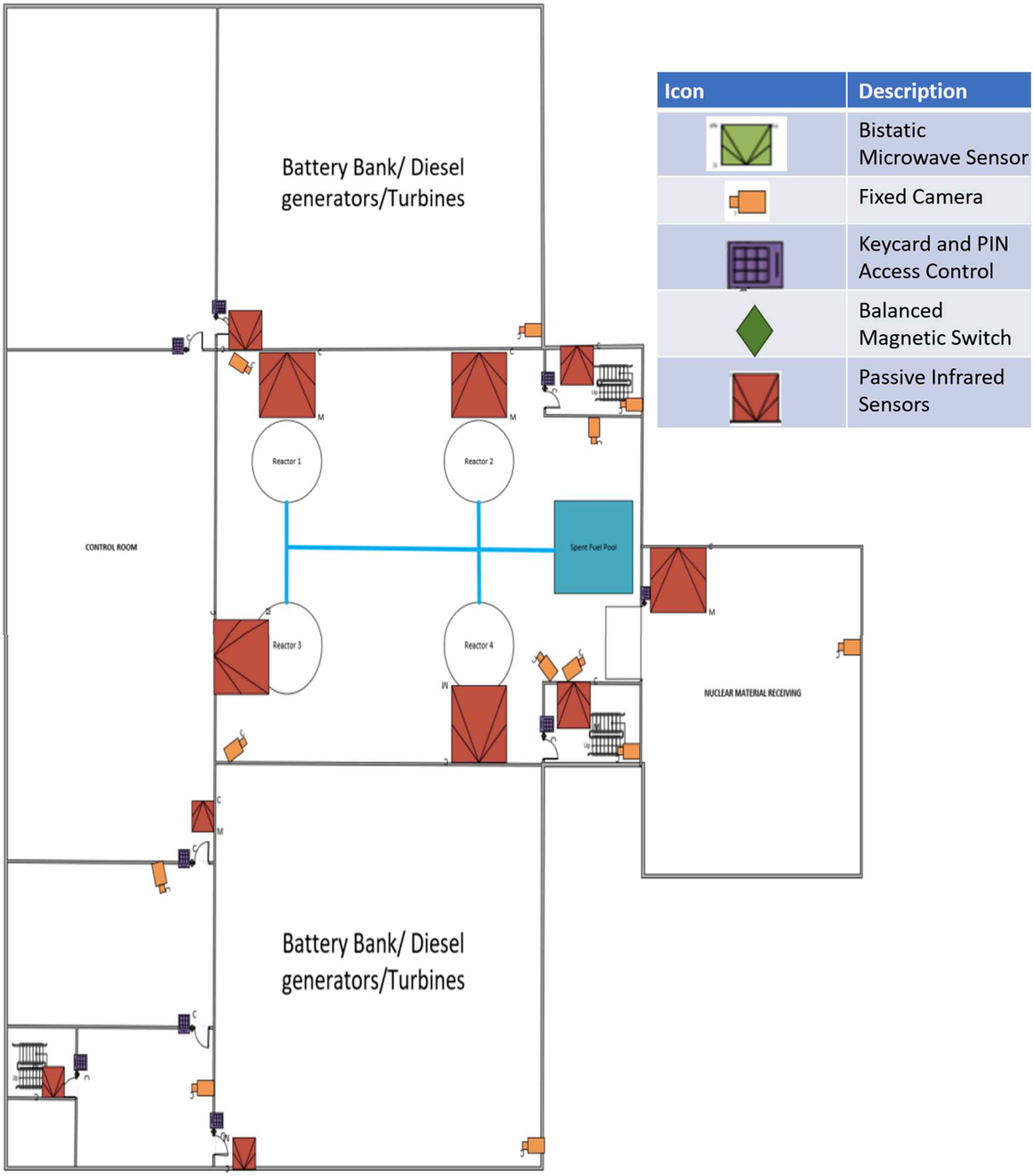

Icon
Description
Bistatic Microwave Sensor
Fixed Camera
Keycard and PIN Access Control
Balanced Magnetic Switch
Passive Infrared Sensors
Battery Bank/ Diesel generators/Turbines
Battery Bank/ Diesel generators/Turbines

Figure 5. Baseline PPS Design – Ground Floor



Battery Bank/ Diesel generators/Turbines
CONTROL ROOM
Reactor 1
Reactor 2
Spent Fuel Pool
Reactor 3
Reactor 4
NUCLEAR MATERIAL RECEIVING
Battery Bank/ Diesel generators/Turbines
Up

Icon	Description
🟩	Bistatic Microwave Sensor
🟧	Fixed Camera
▦	Keycard and PIN Access Control
◆	Balanced Magnetic Switch
🟥	Passive Infrared Sensors

Figure 6. Baseline PPS - Basement Level

4. TARGET IDENTIFICATION

The analysis will focus on adversary attacks of four target locations. These target locations will focus on direct sabotage attacks of nuclear material and indirect sabotage attacks of safety equipment at the SMR facility. The direct sabotage attacks will prioritize target locations at the reactor cores and spent fuel pools. The indirect attack scenarios will focus on attacks to the emergency battery power banks and the emergency core cooling system tanks located in the reactor building.

4.1. Direct Sabotage Targets

The hypothetical SMR operates nuclear fuel in all four reactor cores. The site also houses spent nuclear fuel within the spent fuel pool. 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.

Facility	Location	Form of Material	Amount of Material On-site (wt% enrichment)	Total Isotope Amounts	Level of Radiation
SMR Facility	Reactor Core	UO_2 pellets in rods, 17x17 rods in an assembly and 73 assemblies	13,478 kg U (4.9% U-235)	660 kg U-235	High
SMR Facility	Spent Fuel Pool	UO_2 pellets in rods, 17x17 rods in an assembly and 292 assemblies	53,192 kg U (4.9% U-235)	2,606 kg U-235	High

Transfer of fresh fuel into the reactor core requires a crane operator in the basement of the reactor building. The reactor must be shut down and radiation levels reduced to an operable amount from inside of the control room. Once the reactor is shut down, the crane operator will position the crane to pick up the fresh fuel and move the fuel into the reactor core. Only one reactor unit can be opened at one time and the crane is set to a weight limit so that no more than one reactor core can be fueled at a time.

Spent fuel is moved in a similar fashion. The reactor is shut down and the fuel is removed from the core by the crane operator. The fuel is then placed in the spent fuel pool. Only spent fuel from one reactor can be removed at a time through the weight limits set by the crane.

The third target that was considered in this analysis are the locations in which the battery banks are housed. The battery banks are used for emergency power to operate safety systems needed for the reactor in the case offsite power is lost.

5. 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 Central Alarm Station, with one shift commander present to relieve Central Alarm Station 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 to 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 i.e. 9-mm H&K MP-5s, and 5.56-mm type rifles.
- Batons.
- Pepper spray.
- Handcuffs with keys.
- Handheld radios.

5.1. Response Force Assumptions

Due to the uncertainty in future SMR security designs and regulations, the analysis will focus on the use of no onsite armed response force personnel. Based on this assumption, no armed responders are onsite[10].

[10] 10 Code of Federal Regulations 73 "Physical Protection of Plants and Materials."

. For the first phase of the analysis, the site will be designed to an he offsite response force of 30-minutes. If 30 minutes is achieved, then future work will extend this time to 60mins to account for siting in more rural locations.

6. PHYSICAL SECURITY VULNERABILITY ASSESSMENT

The concept of the design basis threat (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 4-8. It is assumed that a passive, nonviolent insider is providing facility knowledge for the outsider threat group.

6.1. The Vulnerability Assessment (VA) Process

The evaluation of an existing or proposed Physical Protection System (PPS) requires a methodical approach in which the ability of the security system to meet defined protection objectives is measured. 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 as a whole 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 that 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, then 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.

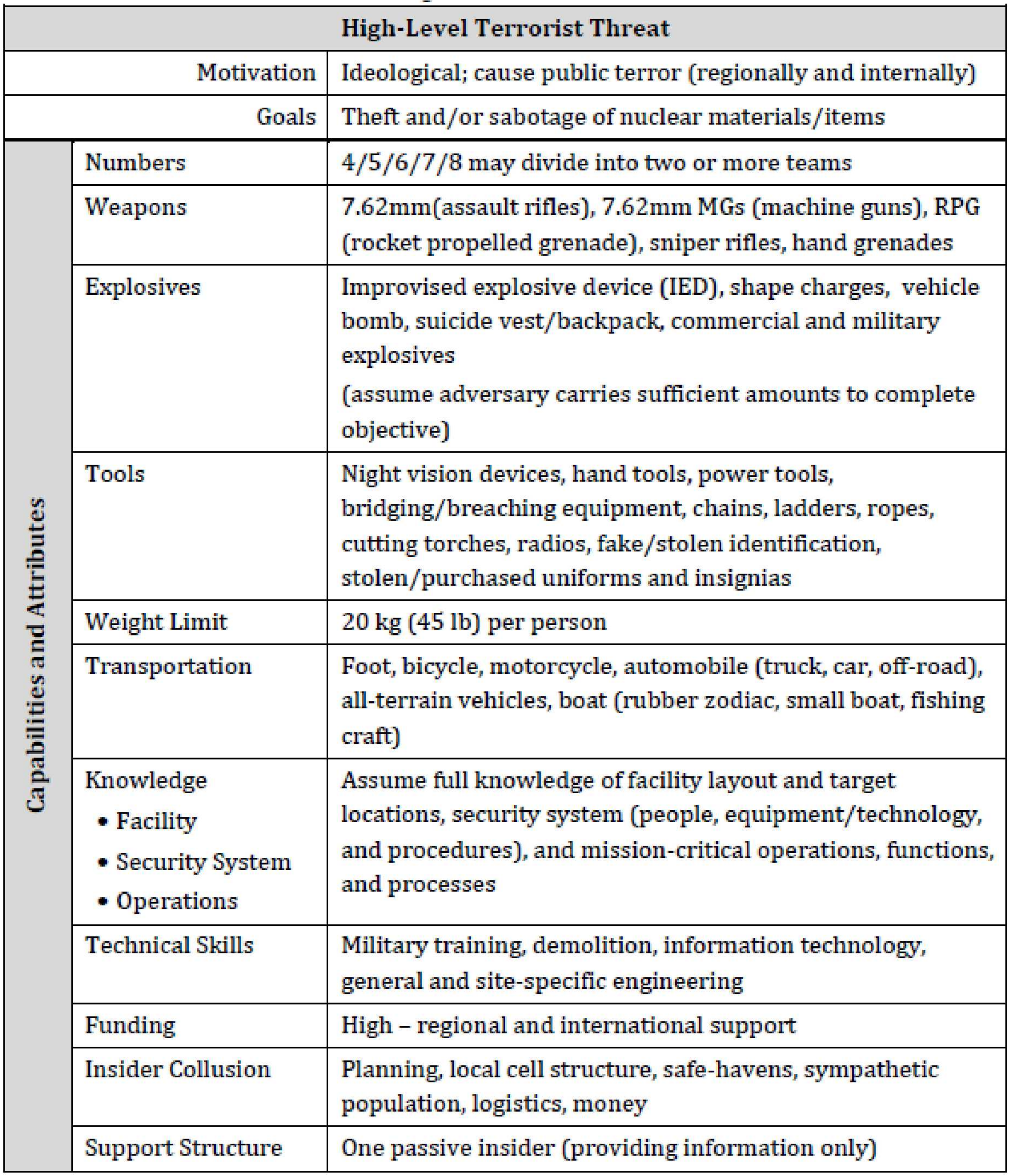
6.2. Threat Assumptions and Characterization

The adversary team members were assumed to have the following characteristics:

- Equally trained as responders.
- Able to perform any of the tasks needed to steal or sabotage critical assets.
- Armed with an 7.62mm rifle, or 7.62mm 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.
- Able to each carry a man-portable load (29.5 kg [65 lb.]).
- In scenarios involving vehicles, the adversary team has access to two four-wheel drive vehicles.
- Adversaries have the tactical capability to divide forces and coordinate attacks from multiple vectors

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.

Table 1: 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)

6.3. Modeling Tools

6.3.1. Blender

Blender [7] 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 allows for the creation of detailed, to-scale models of facilities, vehicles, and equipment that can then be used for visualization, analysis, and training. For this project, Blender was used to create the facility 3D model.

6.3.2. PathTrace © - Path Analysis Tool

PathTrace is a tool that allows a user to explore and analyze entry paths in two dimensions. Given an aerial photo or detailed drawings of the facility, the user draws barriers such as walls, fences, windows, doors, and any user created material on top of the image of the facility, specifying the amount of time it would take to breach these barriers, as well as the probability that they would be detected in doing so. The tool allows for the drawing of detection areas, which is a distinction between areas of a facility where an adversary may walk slower or be detected more easily due to the nature of existing in that area (sensors, patrols, etc..). Finally, the user may specify the kinds of tools the adversary may be carrying, and its effects on the time to defeat a barrier, as well as their probability of detection. Once the user has mapped out the entire facility, they can then analyze the entry paths into the facility with a variety of methods, given the Physical Protection System (PPS) Response Force Time (RFT) and an Adversarial Strategy. The user will receive data visually or textually representing the adversarial task time, the total probability of detection, the critical detection point, the time after the critical detection point, the probability of interruption, as well as the probability of detection, delay, and defeat time of every barrier, and detection area that the adversary has encountered. The final data allows the user to fully explore their facility and any potential vulnerabilities in a simple fashion.

6.3.3. Scribe3D© – Table Top Recorder and Automated Tabletop Data Tool

Scribe3D© is a 3D tabletop recording and scenario visualization software, created by Sandia National Laboratories. It was developed using the Unity [8] game engine for use by other National Laboratories, government organizations, and international partners. 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. Unity was used to build Scribe3D© and many other training and analysis tools within the DOE complex.

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, or other security analysis related applications. The tools 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 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© allow for 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.

7. PATH ANALYSIS AND FACILITY UPGRADES

The analysis focused on developing a physical protection system that creates an effective probability of interruption (P_I) for the entire site. The site analysis considered offsite response.

PathTrace was used to identify the potential outsider adversary pathways to commit a sabotage act at the SMRF. The first portion of the analysis focused on a dedicated onsite response force with a response time of 5 minutes. The analysis focused on identifying the P_I and improving the P_I to 95% or greater. The second analysis focused on identifying and improving the P_I to 95% or greater for an offsite response time of 30 minutes. The team focused on impactful facility design changes and implementation of physical protection technologies to improve the P_I.

7.1. Base Case Facility and Physical Protection System Design

The offsite response force analysis focused on the implementation of building designs and physical protection systems that improved the probability of detection and increasing the adversary task time that improved the P_I for the system designed for the SMRF. For this analysis the Most Vulnerable Path (MVP) will be used for path analysis and upgrading the facility layout and the physical protection system.

For the base case and all subsequent upgrades, the MVP for three targets was analyzed. Those targets are the reactor core itself, the spent fuel pool, and the battery bank. The goal of this analysis was to reach the 95% P_I threshold at 30 minutes for all three targets.

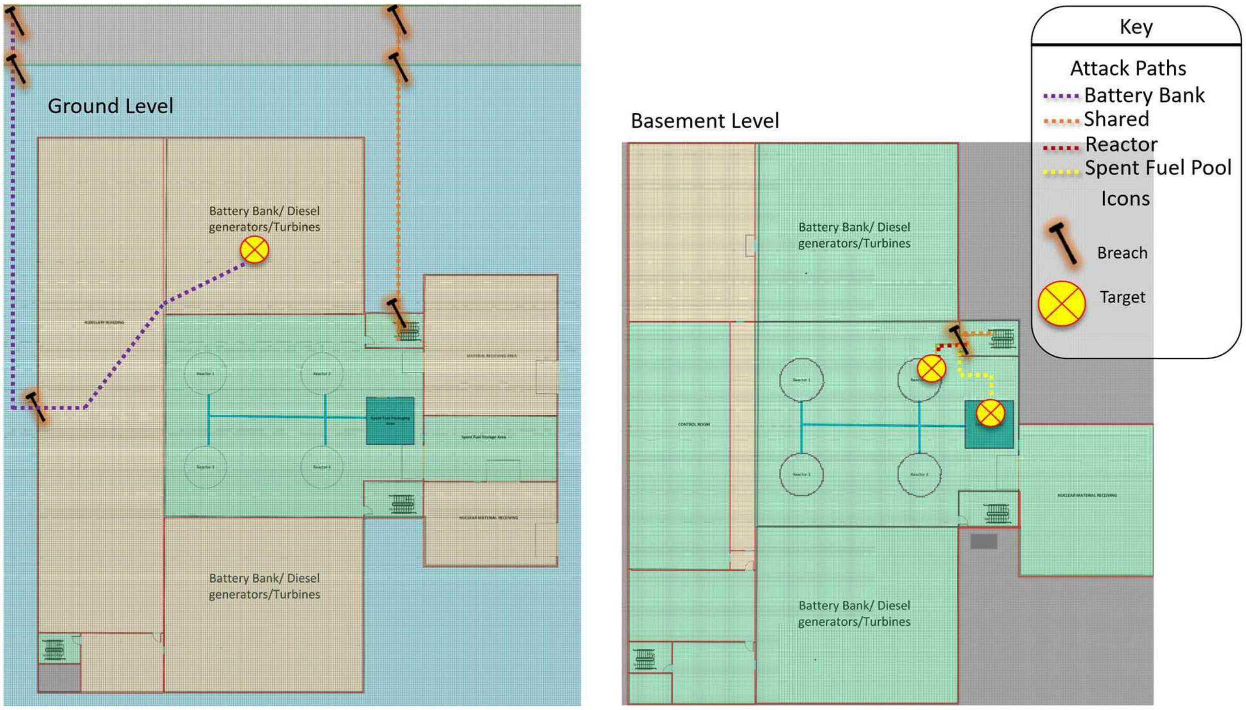

Ground Level
Battery Bank/ Diesel generators/Turbines
AUXILIARY BUILDING
Reactor 1
Reactor 2
Reactor 3
Reactor 4
Spent Fuel Packaging Area
MATERIAL RECEIVING AREA
Spent Fuel Storage Area
NUCLEAR MATERIAL RECEIVING
Battery Bank/ Diesel generators/Turbines
Basement Level
Battery Bank/ Diesel generators/Turbines
CONTROL ROOM
Reactor 1
Reactor 3
Reactor 4
NUCLEAR MATERIAL RECEIVING
Battery Bank/ Diesel generators/Turbines
Key
Attack Paths
Battery Bank
Shared
Reactor
Spent Fuel Pool
Icons
Breach
Target

Figure 7. Base Case Path to All Targets

Figure 7 shows the adversary paths to each target. For the spent fuel pool and reactor targets, the paths are largely the same (identified in orange) adversaries breach the PIDAS, move on foot to the stairwell wall, and breach it. They then move downstairs to the sabotage targets, reactor (red) and spent fuel pool (yellow). Breaching the wall allows them to avoid sensing along all the doors leading to the stairwell, and though the wall breach takes an extended amount of time, it is the more vulnerable path.

Table 2. Base Case Timeline - Reactor Sabotage

Element Crossed	**PD**	**Delay**	**At Time**	**Distance Traveled**
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.16	30	5.16
Inner Fence	0	30	35.16	0.08
Protected Area	0.02	22.69	65.16	22.69
Wall	0.75	480	87.85	0.08
Stairwell Upper	0.9	2.03	567.85	2.03
Strairwell	0.75	10	569.88	0.24
Stairwell Lower	0.9	3.65	569.88	3.65
Door	0.75	10	573.53	0.12
Reactor Area	0.9	3.88	583.53	3.88
Reactor Sabotage	0.9	900	587.41	0.12
Cumulative PD	PI		Time to Complete	Traversal Distance
0.99	0		1497.391	38.1

Table 2 shows the PathTrace data output from the base case scenario for sabotage of the reactor. Though detection probability nears 100%, the path is not timely with a 30 minute RFT. Additional upgrades will be needed to force the adversary through a longer path with additional delay.

Table 3 shows the timeline for the Battery bank sabotage attack. The adversary breaches the PIDAS, and proceed to the Aux Building, and then to the battery bank room (identified in purple in Figure 7. The path is lacking delay, and in fact most of the task time is that spent at the target on the sabotage action.

Table 3. Base Case Timeline - Battery Bank Sabotage

Element Crossed	**PD**	**Delay**	**At Time**	**Distance Traveled**
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.16	30	5.16

Inner Fence	0	30	35.16	0.08
Protected Area	0.02	30.9	65.16	30.9
Door	0.75	10	96.06	0.08
Aux Building	0.8	19.98	106.1	19.98
Door	0.75	10	126	0.08
Battery Bank Room	0.8	8.38	136	8.38
Battery Bank Sabotage	0.9	600	144.4	0.08
Cumulative PD	PI	Delay After CDP	Total Time	Traversal Distance
0.99	0	0	744.4	64.85

Table 4: Base Case Physical Protection System Path Analysis.

Target	Task Time (s)	Cumulative Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor	1497	99	0	1800
Spent Fuel Pool	1380	99	0	1800
Battery Bank	744	99	0	1800

As seen in Table 4, the P_I for the SMRF does not lead to an effective physical protection system with a 30-minute off-site response force for any target. A P_I of 0% would effectively lead to a system effectiveness (P_E) of 0%. Upgrades are necessary.

7.2. Upgrade One – Additional Exterior Walls, Stairwell Portal, Battery Bank Relocation and Active Delay (Obscurants and Slippery Agents)

7.2.1. Active Delay Features – Obscurants and Slippery agents[3]

In order to achieve additional levels of delay, active (non-lethal) active 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 multiple 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.

7.2.1.1. 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 used 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.

7.2.1.2. 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 5. Column 3 shows how a 30 second delay feature can become a 75+ feature by adding active delay to it.

Table 5. Delay Multiplication Factors

Active Delay Type	Delay Multiplication Factor	Example Delay time
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 active 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 in order to lengthen breach time.

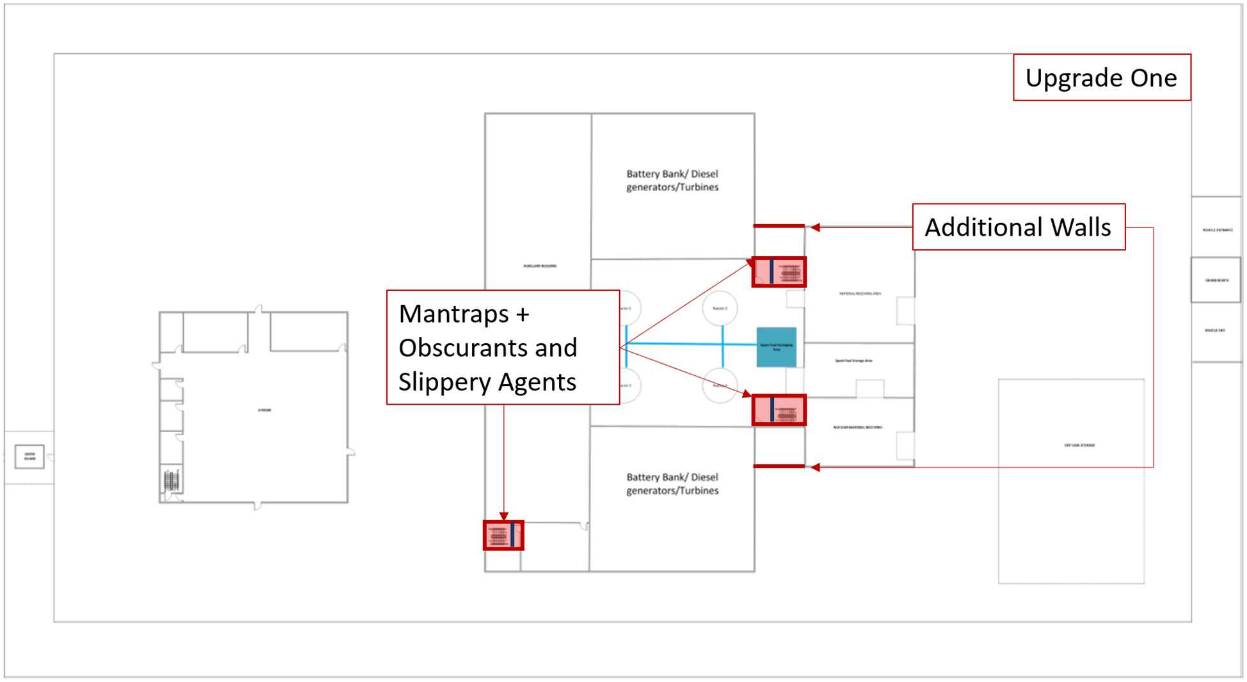

Upgrade One
Battery Bank/ Diesel generators/Turbines
Additional Walls
Mantraps + Obscurants and Slippery Agents
Battery Bank/ Diesel generators/Turbines

Figure 8. Upgrade One – Walls and Doors at Vital Stairwells, plus active delay (obscurants and slippery agents)

For base case reactor and spent fuel sabotage path, the adversary enters the protected area through the fence-line and isolation zone, proceeds to and breaches the wall into the reactor building stairwell and gains access below grade. A facility design change was implemented to add an additional wall between the non-nuclear receiving building, the nuclear receiving building and the reactor building made of the same material as the facility exterior walls. A second addition was to add a secondary door to the stairwells below grade that implemented active delay features such as obscurants and slippery agents in between the two doorways of the stairwell that lead into the below-grade reactor building floor.

Figure 9 shows the path with the wall and active delay upgrades. The reactor and spent fuel path, now takes the adversaries to through two roll-up doors, and the door into the stairwell.

Figure 9: Upgrade One – Walls and Doors at Vital Stairwells Paths, Battery Bank Basement

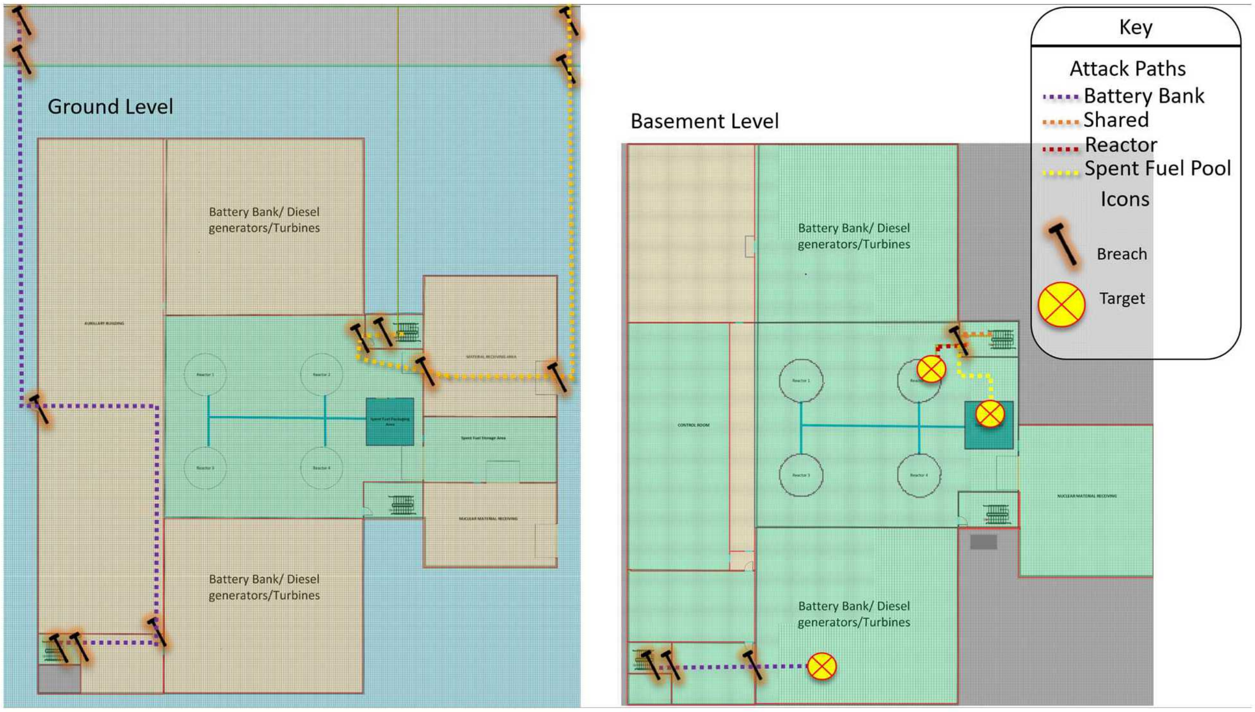

Ground Level
Battery Bank/ Diesel generators/Turbines
AUXILIARY BUILDING
Reactor 1
Reactor 2
Reactor 3
Reactor 4
Spent Fuel Packaging Area
MATERIAL RECEIVING AREA
Spent Fuel Storage Area
NUCLEAR MATERIAL RECEIVING
Battery Bank/ Diesel generators/Turbines
Basement Level
Battery Bank/ Diesel generators/Turbines
CONTROL ROOM
Reactor 1
Reactor 3
Reactor 4
NUCLEAR MATERIAL RECEIVING
Battery Bank/ Diesel generators/Turbines
Key
Attack Paths
Battery Bank
Shared
Reactor
Spent Fuel Pool
Icons
Breach
Target

Table 6 shows that this path does not add delay for reactor and spent fuel pool targets, as those breaches combined are still quicker than the initial wall breach from base case. Further upgrades are necessary for these paths.

Table 6. Upgrade 1 - Sabotage Timeline - Reactor

Element Crossed	PD	Delay	At Time	Distance Traveled
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.16	30	5.16
Inner Fence	0	30	35.16	0.08
Protected Area	0.02	27.09	65.16	27.09
Roll Up Door	0.75	60	92.25	0.08
Non-Nuclear RA	0.8	12.95	152.3	12.95
Roll Up Door	0.75	60	165.2	0.08
Upper Reactor Area	0.9	6.18	225.2	6.18
Door	0.75	10	231.4	0.08
Stairwell Mantrap	0.9	1.86	241.4	1.86
Door Upgrade 2	0.75	24.5	243.3	0.08
Upper Stairwell area	0.9	1.52	267.8	1.52
Stairwell	0.75	25.4	269.3	0.24
Lower Stairwell Area	0.9	3.65	269.3	3.65
Door	0.75	10	272.9	0.12
Lower reactor Area	0.9	3.88	282.9	3.88
Reactor Sabotage	0.9	900	286.8	0.12

Cumulative PD	PI		Total Time	Traversal Distance
0.99	0		1212	63.24

The battery bank path was extremely delay deficient. To remedy this, the battery bank was shifted to the basement floor to lengthen the attack path, and utilize all upgrades designed for the other targets. Mantraps were added in the stairwell leading to the battery banks. Table 7 shows the path timeline for sabotage of the battery banks. This upgrade package requires a great deal more delay to reach 30 mins.

Table 7. Upgrade 1 - Sabotage Timeline – Battery Bank

Element Crossed	**PD**	**Delay**	**At Time**	**Distance Traveled**
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.16	30	5.16
Inner Fence	0	30	35.16	0.08
Protected Area	0.02	30.81	65.16	30.81
Door	0.75	10	95.98	0.08
Aux Building	0.8	31.49	106	31.49
Door	0.75	10	137.5	0.08
Foyer	0.8	6.86	147.5	6.86
Door	0.75	10	154.3	0.08
Upper Stairwll	0.9	0.76	164.3	0.76
Door Upgrade 2	0.75	24.5	165.1	0.08
Mantrap Area	0.9	1.52	189.6	1.52
Stairwell	0.75	10	191.1	0.24
Lower Stairwell	0.9	0.82	191.1	0.82
Door Upgrade 2	0.75	24.5	191.9	0.12
Mantrap Area	0.9	0.82	216.4	0.82
Door	0.75	10	217.3	0.12
Hall	0.9	7.29	227.3	7.29
Battery Bank Door	0.75	10	234.6	0.12
Battery Bank Room	0.9	5.17	245.1	5.17
Battery Bank Sabotage	0.9	600	250.2	0.12
Cumulative PD	PI	Delay After CDP	Total Time	Traversal Distance
.99	0	0	860.2	92.58

The effects of this facility upgrade can be seen below in Table 8.

Table 8: Facility Upgrade One Results

Target	Task Time (s)	Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor	1212	99	0	1800
Spent Fuel Pool	1096	99	0	1800
Battery Bank	860	99	0	1800

Upgrade package one, summarized in Table 8, increased the adversary task time. However, this increase in task time did not increase the P_I. The analysis showed the probability of detection was not impacted, however an increase in delay time was needed to improve the P_I to allow the responders sufficient time to interrupt the adversary.

7.3. Upgrade Two – Hardened Roll-Up Doors, Aux Door Mantrap, Hardened mantraps at Battery Banks

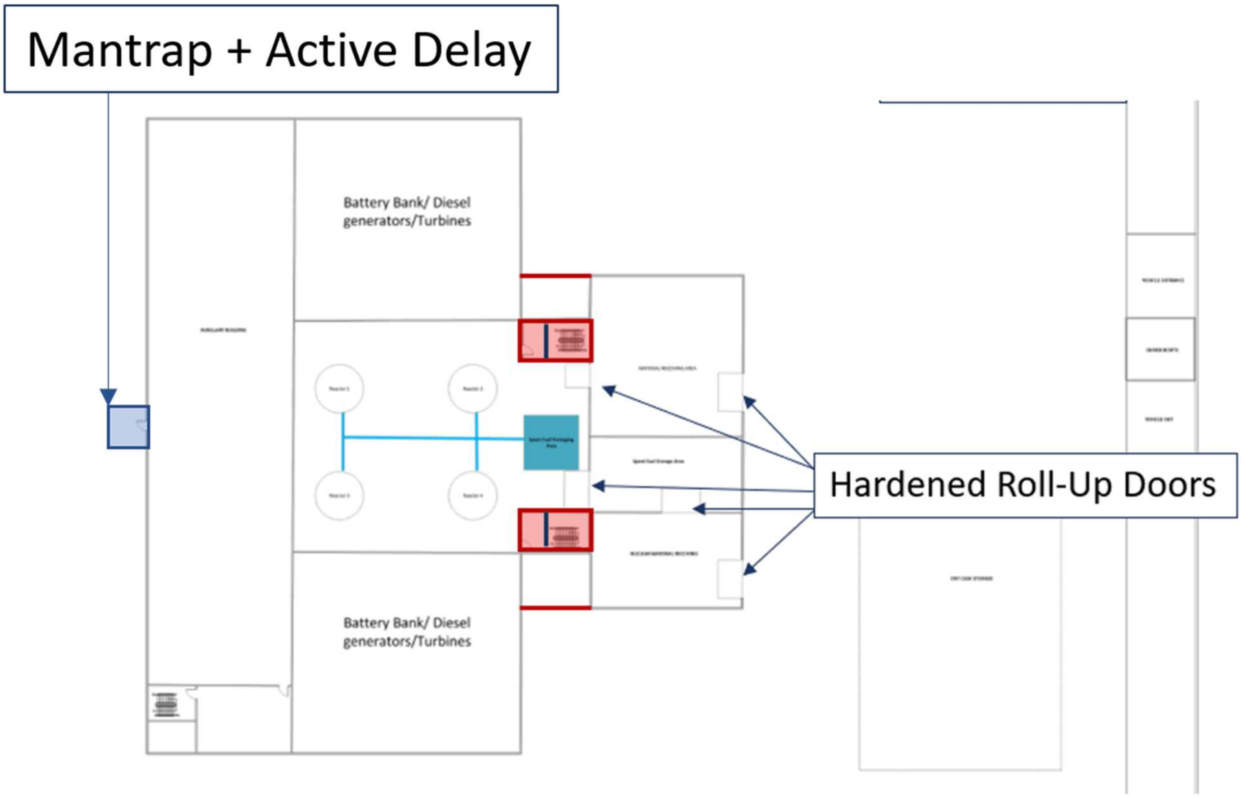

Mantrap + Active Delay
Battery Bank/ Diesel generators/Turbines
Hardened Roll-Up Doors
Battery Bank/ Diesel generators/Turbines

Figure 10. Upgrade 2 – Hardened Roll-Up Doors, Aux Mantrap

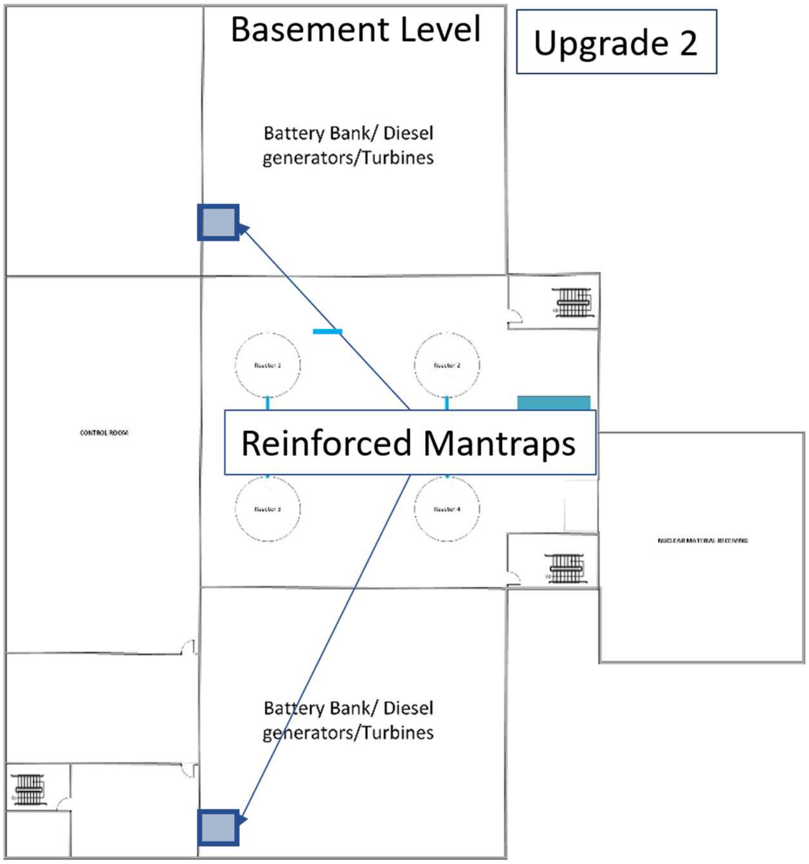

Basement Level
Upgrade 2
Battery Bank/ Diesel generators/Turbines
Reactor 1
Reactor 2
CONTROL ROOM
Reinforced Mantraps
Reactor 3
Reactor 4
NUCLEAR MATERIAL RECEIVING
Battery Bank/ Diesel generators/Turbines

Figure 11. Upgrade 2 - Hardened Mantraps at Battery Banks (Basement Level)

From the previous upgrade, for spent fuel pool and reactor targets, the adversaries enter the facility through the roll-up doors at the receiving area and then the roll-up door at the reactor building. The roll-up doors do not provide adequate delay, therefore they require upgrades. Concrete blocks on rails are placed behind the roll-up doors. These blocks would be locked in place when not in use to provide extra delay. For spent fuel and rector targets, the physical path remained the same, however delay time increased. The increase was not enough to reach 30 minutes, so additional design changes were necessary.

The paths for all targets were the same, in that the adversaries took the same routes to each respective target see Figure 9. For this reason, screenshots of the Upgrade 2 paths were not included.

Table 9. Upgrade 2 - Sabotage Timeline - Reactor

Element Crossed	**PD**	**Delay**	**At Time**	**Distance Traveled**
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.16	30	5.16
Inner Fence	0	30	35.16	0.08
Protected Area	0.02	27.09	65.16	27.09
Roll Up Door w/ Block	0.75	180	92.25	0.08
Non-Nuclear RA	0.8	12.95	272.3	12.95
Roll Up Door w/ Block	0.75	180	285.2	0.08
Upper Reactor Area	0.9	6.18	465.2	6.18
Door	0.75	10	471.4	0.08
Stairwell Mantrap	0.9	1.86	481.4	1.86
Door Upgrade 2	0.75	24.5	483.3	0.08
Upper Stairwell area	0.9	1.52	507.8	1.52
Stairwell	0.75	25.4	509.3	0.24
Lower Stairwell Area	0.9	3.65	509.3	3.65
Door	0.75	10	512.9	0.12
Lower reactor Area	0.9	3.88	522.9	3.88
Reactor Sabotage	0.9	900	526.8	0.12
Cumulative PD	PI		Total Time	Traversal Distance
0.99	0		1452	63.24

For the battery bank, shifting the location to the basement level and adding mantraps, increased delay time, but did not reach 30 minutes. Mantraps were added at the aux door entryway and at the entry doors to the battery bank rooms. In addition, a pair of concrete sliding barriers were added at the entrance to each battery bank room. Under normal operating conditions, these barriers will both be closed forming a mantrap just inside the battery bank access doors

Table 10. Upgrade 2 - Sabotage Timeline - Battery Room

Element Crossed	PD	Delay	At Time	Distance Traveled
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.16	30	5.16
Inner Fence	0	30	35.16	0.08
Protected Area	0.02	30.81	65.16	30.81
Door	0.75	10	95.98	0.08
Mantrap Area Aux Door	0.9	1.02	106	1.02
Door Upgrade 2	0.75	25.4	107	0.08
Aux Building	0.9	31.49	132.4	31.49
Door	0.75	10	163.9	0.08
Foyer	0.8	6.86	173.9	6.86
Door	0.75	10	180.7	0.08
Upper Stairwell	0.9	0.93	190.7	0.93
Door Upgrade 2	0.75	25.4	191.7	0.08
Mantrap Area	0.9	2.12	217.1	2.12
Stairwell	0.75	25.4	219.2	0.24
Lower Stairwell	0.9	1.76	219.2	1.76
Door Upgrade 2	0.75	25.4	221	0.12
Mantrap Area	0.9	0.71	246.4	0.71
Door	0.75	10	247.1	0.12
Hall	0.9	6.35	257.1	6.35
Door	0.75	10	263.4	0.12
Mantrap area	0.9	0.82	273.4	0.82
Door Upgrade 2	0.75	25.4	274.2	0.12
Inner Area	0.9	2.47	300.1	2.47
Roll Up Door With Barricade Plus Retreat	0.75	210	302.6	0.12
Hardened Inner Area	0.9	2.12	512.6	2.12
Roll Up Door With Barricade Plus Retreat	0.75	210	514.7	0.12
Battery Bank Room	0.9	0.35	724.7	0.35
Battery Bank	0.9	600	725.1	0.12
Cumulative PD	PI		Total Time	Traversal Distance
0.99	0		1350	95.26

The effect of this upgrade 2 can be seen in Table 11 below. For all targets, delay is increased but fails to reach any P_I at 30 minutes RFT.

Table 11: Facility Upgrade Two.

Target	Task Time (s)	Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor	1452	99	0	1800
Spent Fuel Pool	1335	99	0	1800
Battery Bank	1350	99	0	1800

7.4. Upgrade Three – Active Delay for Hardened Doors, Extended Detection, Active delay along battery bank path

7.4.1.1. Extended Detection – Fused Radar and Video motion detection using the Deliberate motion algorithm (DMA)[4]

Using a combination of radar and video motion detection reaching far beyond the facility perimeter, the deliberate motion algorithm (DMA) is able to decipher motion moving towards the facility, while minimizing nuisance alarms from weather or traffic in the area. Assumptions for the technology are that detection begins between 200 and 300 meters from the walls of the facility. This, in effect allows the RF to muster and get into position even sooner in the timeline.

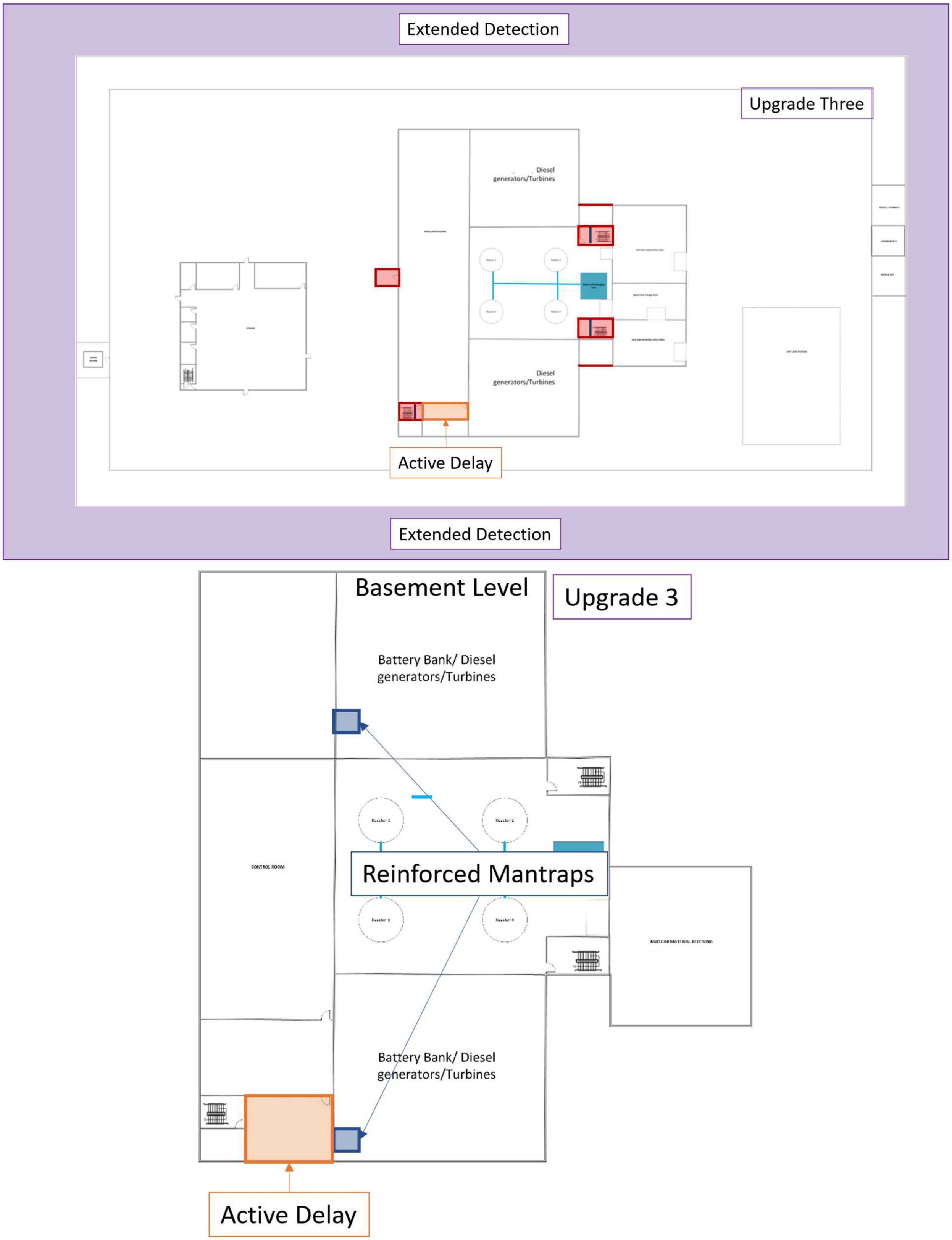

Extended Detection
Upgrade Three
Diesel generators/Turbines
Diesel generators/Turbines
Active Delay
Extended Detection
Basement Level
Upgrade 3
Battery Bank/ Diesel generators/Turbines
CONTROL ROOM
Reinforced Mantraps
NUCLEAR MATERIAL RECEIVING
Battery Bank/ Diesel generators/Turbines
Active Delay

Figure 12. Upgrade 3 - Roll-up Door Active Delay, Extended Detection, Active delay along the battery bank path

To further upgrade this system, active delay measures (slippery agents and obscurants) are placed added to hardened roll-up doors as well as along the path leading to the battery banks, see Figure 12. This upgrade is only practical on interior doors, meaning the hardened roll-up doors on the material receiving exterior walls are not upgraded. The upgrade is also applied to the hardened mantraps leading into the battery banks rooms. In addition, offsite detection capabilities using LIDAR and RADAR, and the DMA are applied to detect adversary motion in the Exclusion Area of the facility (outside of the Protected Area. By utilizing extended detection capabilities, it is assumed that the detection timeline begins 100 seconds earlier, this adds 100 seconds of delay.

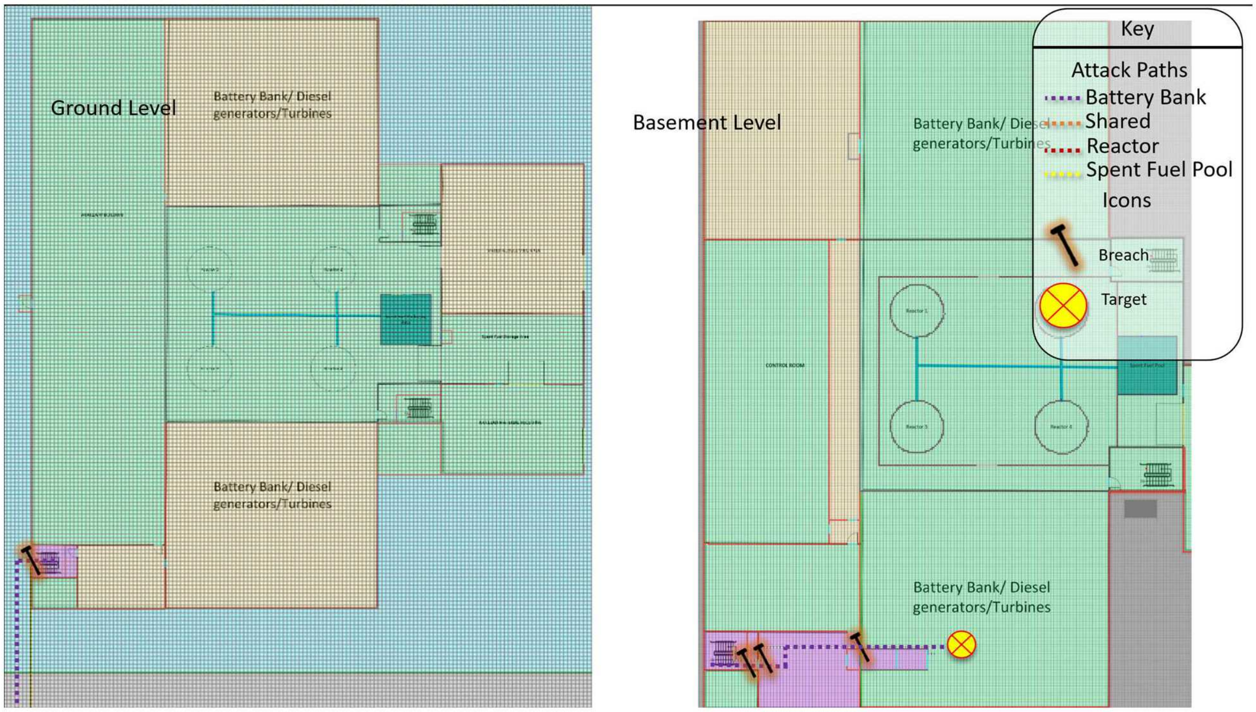
Table 12 shows the attack timeline for the reactor path.

Table 12. Upgrade 3 - Sabotage Timeline - Reactor

Element Crossed	PD	Delay	At Time	Distance Traveled
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.16	30	5.16
Inner Fence	0	30	35.16	0.08
Protected Area	0.02	27.09	65.16	27.09
Roll Up Door w/ Block	0.75	180	92.25	0.08
Non-Nuclear RA	0.8	12.95	272.3	12.95
Roll Up Door w/ Block	0.75	457	285.2	0.08
Upper Reactor Area	0.9	6.18	742.2	6.18
Door	0.75	10	748.4	0.08
Stairwell Mantrap	0.9	1.86	758.4	1.86
Door Upgrade 2	0.75	24.5	760.3	0.08
Upper Stairwell area	0.9	1.52	784.8	1.52
Stairwell	0.75	25.4	786.3	0.24
Lower Stairwell Area	0.9	3.65	786.3	3.65
Door	0.75	10	789.9	0.12
Lower reactor Area	0.9	3.88	799.9	3.88
Reactor Sabotage	0.9	900	803.8	0.12
Cumulative PD	PI		Total Time	Traversal Distance
0.99	0		1729	63.24

For the battery bank target, the active delay and hardened mantraps forced the adversary into drastic action, see Figure 13.

Table 13. Upgrade 3 Sabotage Path - Battery Bank


Ground Level
Battery Bank/ Diesel generators/Turbines
Battery Bank/ Diesel generators/Turbines
Basement Level
Battery Bank/ Diesel generators/Turbines
Battery Bank/ Diesel generators/Turbines
Key
Attack Paths
Battery Bank
Shared
Reactor
Spent Fuel Pool
Icons
Breach
Target

The path shifts and the adversary breaches the reinforced concrete wall on the exterior of the facility to gain access to the stairwell. Then, rather than braving the hardened mantrap, breaches the reinforced concrete wall into the battery bank room. These wall breaches push the timeline out to 2567 seconds, well beyond 30 minutes, see Table 14.

Table 14. Upgrade 3 - Sabotage Timeline – Battery Bank

Element Crossed	PD	Delay	At Time	Distance Traveled
Outer Fence	0	30	0	0.08
Exclusion Zone	0.9	5.93	30	5.93
Inner Fence	0	30	35.93	0.08
Protected Area	0.02	9.06	65.93	9.06
Exterior Wall	0.9	900	74.98	0.08
Stairwell Upper	0.75	4.23	975	2.12
Stairwell Upper	0.75	25.4	979.2	0.24
Stairwell Lower	0.75	3.53	979.2	1.76
Door Upgrade 2	0.75	25.4	982.8	0.12
Mantrap Area	0.75	1.41	1008	0.71
Door	0.75	10	1010	0.12
Active Delay	0.75	16.46	1020	8.23
Wall	0.9	900	1036	0.12
Battery Bank Area	0.9	5.64	1936	5.64
Battery Bank	0.9	600	1942	0.12

Cumulative PD	PI	Delay After CDP	Total Time	Traversal Distance
1	0.99	1700	2567	34.49

The effect of this upgrade can be seen below in Table 15. For reactor and spent fuel targets, delay times are now approaches 30 minutes, but falls short. A final upgrade package is necessary.

Table 15: Facility Upgrade Three.

Target	Task Time (s)	Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor	1729	99	0	1800
Spent Fuel Pool	1612	99	0	1800
Battery Bank	2567	99	99%	1800

These upgrades greatly increased the task time required for an adversary to complete acts of sabotage. However, even with the high probability of detection did not increase the probabilities of interruption along the sabotage path for the reactor and the spent fuel pool.

However, for the battery bank path, the additional active delay features added to the concrete barrier mantrap in the battery bank room and along the path leading to the room, push the timeline beyond 30 mins with a P_I of 99%.

7.5. Upgrade Four - Below-Grade Reactor Wall

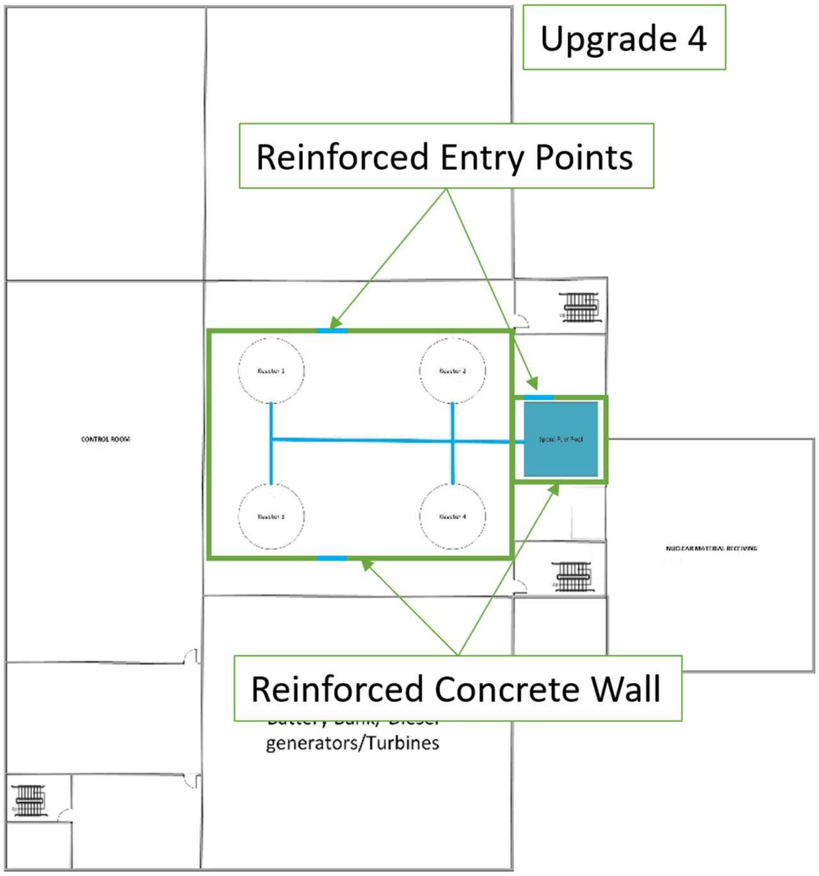


Figure 13. Below-Grade Reactor Wall

An additional upgrade was implemented, and a wall was placed in the below-grade of the reactor building to separate reactor containment structures of the reactor building. The wall was created with hardened personnel access points that allow for personnel to enter the reactor building if work or maintenance is needed. The results from this upgrade can be seen below in Table 16.

Table 16: Facility Upgrade Four.

Target	Task Time (s)	Probability of Detection (%)	Probability of Interruption (%)	Response Time (s)
Reactor	2345	99	100	1800
Spent Fuel Pool	2228	99	100	1800
Battery Bank	2567	99	100	1800

8. RESULTS AND DISCUSSION

The results from this analysis were very insightful for analyzing and designing an SMR facility for domestic applications. This analysis was insightful in determining facility designs and physical protection systems that can be applied to improve the probability of interruption and may lead to a higher physical protection system effectiveness. Through several aspects of facility and physical protection system design have been identified that should be considered when designing and siting a domestic SMR facility.

8.1. Facility Considerations

SMR facility designers must consider the effects of their building layout when designing an SMR facility. In the design of this hypothetical facility, there was a direct pathway for the adversary to breach the walls of the reactor building that directly led to a below-grade access stairwell. This design may save on initial design costs; however, security may suffer. The upgraded design choice was to implement an additional wall that increased the adversary task time. It is important in the design phase of an SMR to consider the building material that is used in the design. Building materials can have an impact on the adversary task time and their ability to achieve their objectives. Building materials that are designed with security applications can be cost-effective at improving security performance than industrial building materials.

An additional concept which can be implemented in facility designs to increase adversary task time is long hallways including several doors or other barriers. Hallways and doors require longer adversary movements to reach target locations, and doors present another barrier that the adversary must defeat in order to gain access to target locations. Extended hallways with multiple doors also create multiple areas in which facility operators can introduce physical protection system technologies such as active delay technologies, and where central alarm station operators can introduce mechanisms such as magnetic locks and door strikes that force the adversaries to breach doors or walls in order to get to target locations or retreat out of an SMR facility.

Facility siting is also important when understanding and designing SMR facilities and their physical protection systems. Use of advanced detection capabilities such as LIDAR and RADAR detection in the EA requires optimal conditions such as flat terrain with low amounts of visual obscurants. Designers may also consider siting SMR facilities in locations which present advantages to the response force. This may include placing facilities in locations where the response force would have the higher ground to force the adversaries to advance uphill. Berms may also be placed in strategic locations where they may be effective against standoff attacks.

If offsite response forces are to be used as a dedicated response force or to augment an onsite response force, siting may consider the proximity of the site to the offsite response force location. This may aid in decreasing the response time from an offsite location to the site.

8.2. Physical Protection System Considerations

SMR facility designers must consider physical protection system elements in the design phase of their facility. These elements should include access controls, intrusion detection technologies, assessment technologies, access delay (passive and active), and response force capabilities. In this analysis we focused on understanding the probabilities of interruption when using onsite and offsite response forces and the benefits and potential vulnerabilities with offsite and onsite response forces.

Physical protection systems for SMR facilities should be designed to provide adversary detection as early as possible when using both onsite and offsite response forces. For example, the use of the LIDAR and RADAR detection technologies in the EA provides early detection before traditional detection begins at the protected area boundary. This improves and initiates the response force timeline earlier than if this detection capability did not exist on the site.

Site designers may also consider the use of active delay systems onsite such as vehicle barriers at entry control points, and potentially along the protected area perimeter to mitigate the effects vehicles pose to the site. Active access delay systems also include obscurants and slippery agents that may be used as delay multipliers. These are agents that multiply the task time of an adversary to accomplish a task such as breaching a wall or gaining access through a doorway. In combination with systems such as magnetic locks or door strikes, these methods can drastically increase delay time inside of a facility and potentially halt adversary progress. However, active delay technologies such as these can also hinder the ability of response force members to respond. Therefore, site designers must consider that if these active systems are used, the response force members may need another access point to target locations to interrupt an adversary along their path to a target location. Facility designers may introduce choke points, or locations in which an adversary must pass the response force members to reach a target location. These choke points can be used to increase the response force probability of neutralizing an adversary before they can reach their target location.

Some additional considerations may include the ability for CAS operators to lock doors and entry points inside of the facility. Increased locking mechanisms and access controls should be applied to interior doors of SMR facilities. These mechanisms can increase the potential adversary task time and force adversaries to breach facility walls and barriers that may lead to an increase in the probability of interruption and therefore the system effectiveness used on a site. These locking mechanisms also increase the probability that doors within an SMR facility are locked automatically through access control systems, rather than relying on the use of guards or response force members to lock doors and entry points.

It is also important that site security personnel and response force members are intimately familiar with the site and the target locations on site. This will increase the ability of response force members to respond to adversary actions and interrupt the adversary in a timely manner. The site should also conduct regular exercises with onsite response force members or offsite response force members and correct deficiencies as soon as possible to increase the effectiveness of the response force.

The site should also consider regular full and limited-scope performance testing and operational testing of the physical protection system and its component technologies. On a site with a reduced footprint, each element is critical in implementing an effective physical protection system. These technologies must remain in an operable and functional state to ensure there are no significant vulnerabilities in the physical protection system.

9. CONCLUSION AND FUTURE WORK

Several main conclusions can be drawn from this initial analysis. Furthermore, this path analysis has led to an understanding that future work is needed to assess facility and physical protection system designs.

The hypothetical facility design for this study was a LWSMR facility that was designed to reduce its physical footprint and therefore potential construction and operational cost. A SSBD approach allows for the development of security by design in the design phase of a facility. In doing this, the site footprint can remain small and the physical protection system should be designed to minimize normal operational impact but also be effective.

Offsite response forces require a facility and physical protection system design that implements enough delay time against the adversary for the offsite response to arrive. From the analysis conducted, it can be determined that active access delay measures with multiplication effects on adversary task time can be impactful in improving the physical protection system probability of interruption by allowing offsite response sufficient time to travel to the site and interrupt the adversary's progress. However, as discussed previously, active access delay features may pose a risk to operations due to their need for consistent testing and maintenance. These systems may also impact the response force's ability to respond. The site designers should consider alternative entrance points that the response force may use to interrupt the adversary before the adversary reaches the target location.

Another important factor is the location in which an SMR facility is sited. If offsite response force members are used, the designers may consider the site location and its proximity to the offsite response force location. Designers must also consider t using natural landmark features to protect the site from potential standoff attacks and provide a strategic advantage for responders.

An important note on the current design is that it was created to maximize delay time, but currently does not consider response force ability to recapture the site. Furthermore, a 30min offsite response time may not be adequate for most locations, so an additional 60min response time will be considered.

Future work in this effort will include force-on-force simulations to determine a probability of neutralization for this hypothetical facility. This would allow for the determination of a system effectiveness for this facility and provide further security considerations for potential light water SMRs. Future analyses may be conducted for other various SMR designs, including pebble-bed reactors and molten salt reactors. These facilities have different plant designs, including safety features and operational considerations very different from light water SMRs. These considerations may affect the physical protection system effectiveness and present unique challenges that must be accounted for. This analysis effort can provide SMR designers and regulators, such as the NRC, with insights into designing and regulating various SMR designs from a physical security perspective.

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