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Securing Small Modular Reactors in Urban Environments

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SECURING SMALL MODULAR REACTORS IN URBAN ENVIRONMENTS

Sandia National Laboratories

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ABSTRACT

Current small modular reactor (SMR) deployment use cases consider both rural and urban deployments, depending on the operational in-country needs for clean and reliable sources of energy. Many studies have been conducted analyzing security in rural and remote deployment locations, but this study looks at the physical security implications of an SMR placed in an urban environment and its uses for electricity production, district heating, and process heating.

SMRs used for electricity production, district heating, and process heating may be key sources of both energy infrastructure and commercial infrastructure within a city and a State. As a result, long-term shutdowns could have a serious impact on a State's overall energy or commercial production. Therefore, operators may consider further security applications to protect an SMR plant from physical attacks against both radiological sabotage and sabotage acts that could result in the SMR facility being offline for a significant amount of time.

In this study, the team designed and analyzed a physical protection system (PPS) for securing an urban SMR facility against acts of radiological sabotage and sabotage acts that could disrupt the facility's long-term operation. Additionally, this work analyzed the nuanced security issues related to siting an SMR near an urban environment (versus in a rural environment). The result of these analyses includes recommendations for PPSs for urban SMR facilities used for energy production, district heating, and process heating.

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

Term	Definition
BBRE	blast and ballistic rated enclosure
CAS	central alarm station
CCTV	closed-circuit television
DBT	design basis threat
DMA	deliberate motion analytics
ECP	entry control point
EPZ	emergency planning zone
IDS	intrusion detection system
LAA	limited access area
LLWR	large light water reactor
NAR	nuisance alarm rate
OCA	owner-controlled area
PA	protected area
PIDAS	perimeter intrusion detection and assessment system
PPS	physical protection system
ROE	rules of engagement
SME	subject matter expert
SMR	small modular reactor
UAS	uncrewed aircraft system
VBED	vehicle-borne explosive device
VBS	vehicle barrier system

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EXECUTIVE SUMMARY

The use of small modular reactors (SMRs) in an urban environment could enhance an ongoing effort to combat climate change. However, there are challenges regarding securing urban SMRs. A significant concern is the close proximity to outsider threats and other threats that may not impact rural SMR deployments. In an urban environment, considerations should be made for other buildings and structures that could provide an advantage to an adversary team such as height for engaging a response force, nearby locations for conducting surveillance, and methods for engaging or delaying an offsite response force. Urban environments also present challenges that rural environments may face, such as an increased occurrence of protests and petty crimes. Additionally, urban environments may limit the impact or ability to conduct extended detection around the perimeter of an SMR facility.

A physical protection system (PPS) was designed using both the deliberate motion analytics (DMA) algorithm and an onsite response force to mitigate an act of sabotage to radiological targets and acts of sabotage to energy security targets that allow for electricity production, district heating, process heating or any combination of these uses cases. To design and analyze the effectiveness of the PPS, a hypothetical SMR facility was used. This hypothetical SMR facility can be seen in Figure E 1.

Figure E 1. Hypothetical SMR Facility

The design considered five armed responders located in blast and ballistic rated enclosure (BBRE) towers placed on top of various buildings at the site. A group of subject matter experts (SMEs) was used to develop credible adversary attack scenarios to the facility and then to identify appropriate locations for the BBRE towers to be placed to ensure protection against acts of sabotage against radiological targets and energy security targets at the facility.

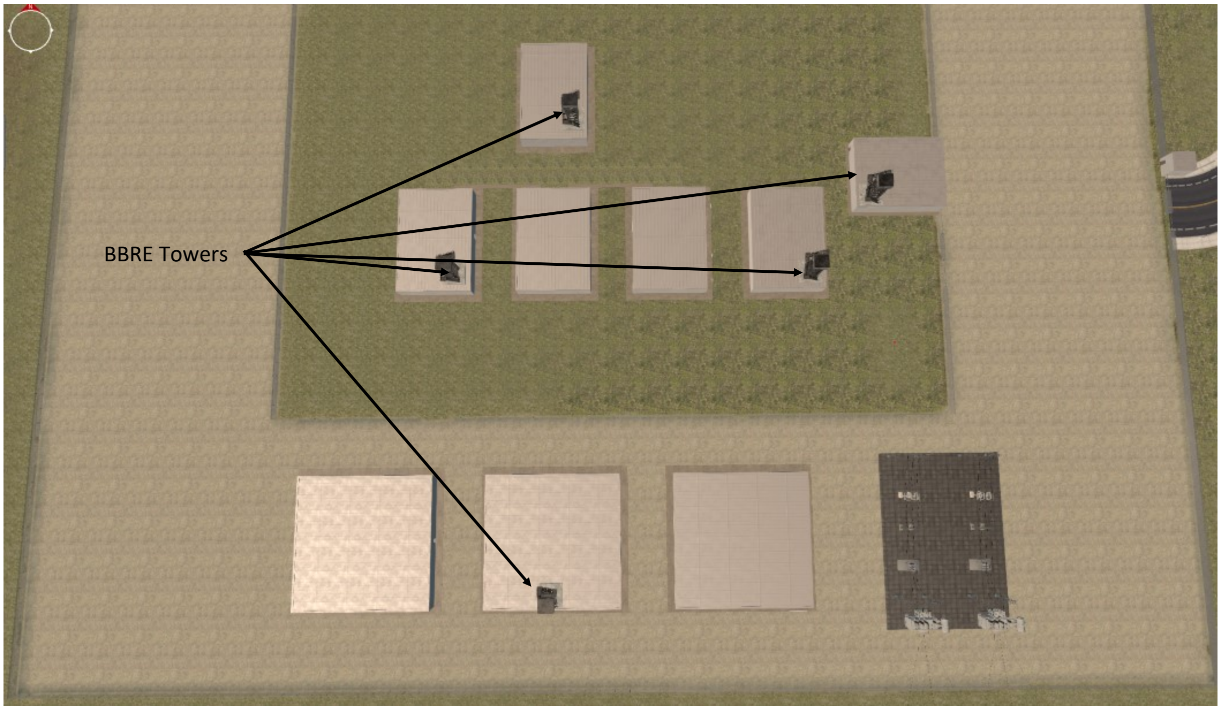

Figure E 2. BBRE Tower Placement

Six credible adversary attack scenarios were analyzed where the adversaries targeted radiological targets (i.e., reactors or reactor safety systems in the reactor buildings) or energy security targets (i.e., energy conversion systems in the turbine buildings). Table E 1 shows results from one of the six scenarios analyzed. The results of the analysis show the PPS design was effective at neutralizing adversary attacks on radiological targets or energy security targets.

Table E 1. Adversary Attack Scenario PPS Results

Number of Adversaries	Number of Responders Involved	Number of Engagements
8	2	1
7	2	1
6	2	1
5	2	1
4	2	1

Additionally, this report considers how an urban SMR facility may use efforts such as extended detection or increased delay measures to allow for an offsite response force to be used to protect both radiological and energy security targets. This report also provides recommendations for designing PPSs in urban environments and methods to counter the challenges of operating a PPS in an urban environment.

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1. INTRODUCTION

The use of small modular reactors (SMRs) in an urban environment could enhance an ongoing effort to combat climate change. However, there are challenges regarding securing urban SMRs. A significant concern is the close proximity to outsider threats and other threats that may not impact rural SMR deployments. In an urban environment, considerations should be made for other buildings and structures that could provide an advantage to an adversary team such as height for engaging a response force, nearby locations for conducting surveillance, and methods for engaging or delaying an offsite response force. Urban environments also present challenges that rural environments may face, such as an increased occurrence of protests and petty crimes. Additionally, urban environments may limit the impact or ability to conduct extended detection around the perimeter of an SMR facility.

If SMRs are used for multiple purposes such as district heating, process heating, and energy production, it may be in the best interest of the operator to consider protecting these energy conversion processes as well as traditional (i.e., radiological) targets. These additional use cases for SMRs present great economic advantage and provide for the overall well-being of the population. For example, an SMR used to provide electricity and district heating for an urban environment may be critical for the health and safety of at-risk individuals during heat waves or colder weather. If the SMR is the primary source of this energy generation, the loss of the SMR may result in a higher economic loss and societal loss, even if the reactor is not lost due to radiological sabotage. Therefore, this study attempts to leverage the physical protection system (PPS) designed to defend against acts of radiological sabotage to also protect the energy conversion to electrical generation or for heating purposes. This study acknowledges the need for operators to reduce the overall operating costs of an SMR facility, including security. Therefore, this study attempts to leverage a necessary PPS that also protects the energy conversion systems needed to realize the potential of SMRs.

This study also considers various response force strategies, to include an onsite response force and an offsite response force. Both onsite and offsite response strategies may be applied for SMR facilities in urban environments. Additionally, this study will evaluate how detection, delay, and response can be used to secure an urban SMR that can be used for energy production, district heating, and process heating. Analysis on the PPS strategies proposed includes path analysis using PathTrace and tabletop exercises using Scribe3D.

1.1. CHALLENGES FOR OPERATING A PPS IN AN URBAN ENVIRONMENT

Due to their smaller footprint, SMRs may be a prime candidate for placement near an urban environment compared to traditional large light water reactors (LLWRs). Considering the use of SMRs for additional applications such as district heating or process heating, these urban placements may allow for larger economic viability to transfer heating to urban environments. There are many considerations that must be made when designing or operating a PPS in an urban environment. These considerations include, but are not limited to:

1. Potential increased frequency of protests
2. Potential increase of petty crime
3. Planned standoff distances and encroachment of the city around a facility

4. Adversaries' use of the urban environment

1.1.1. Potential Frequency of Protests

The first consideration is the potential frequency of protests that may be seen at an urban SMR deployment compared to a rural SMR deployment. The increase for the frequency of protests may be due to the proximity of people with anti-nuclear sentiment protesting a nuclear facility located near their urban environment. This should not be taken lightly by vendors and potential operators of SMR facilities in urban environments. The increased frequency of protests may pose issues to both operations and security of the SMR. Protestors may block roadways used for personnel, material , or equipment arriving at the facility. Protestors blocking roadways into the facility may also pose an unintended risk for security operations at the facility. For example, many protests are planned and public knowledge; an adversary team may use this to their advantage. If an offsite response force is used, the roadblocks and protestors may increase the time it takes for the response force to arrive and interrupt an adversary force. If an onsite response force is used, the protests may present a distraction and additional people to consider if an engagement has to occur between the onsite response force and the adversary force. One method for reducing the burden on operators is to create a designated protest space outside of the limited access area (LAA) where protestors can protest. Facility designers should consider where this location may be to best ensure the protection of the facility and ensure protestors are not in the way of a potential engagement between the response force and an adversary force. Figure 1 highlights where a designated protest area may be located. The location of this protest area is outside of the LAA and not near the immediate roadway for personnel arriving at the facility. This location is also at a distance away from the potential radiological and energy security targets at the facility.

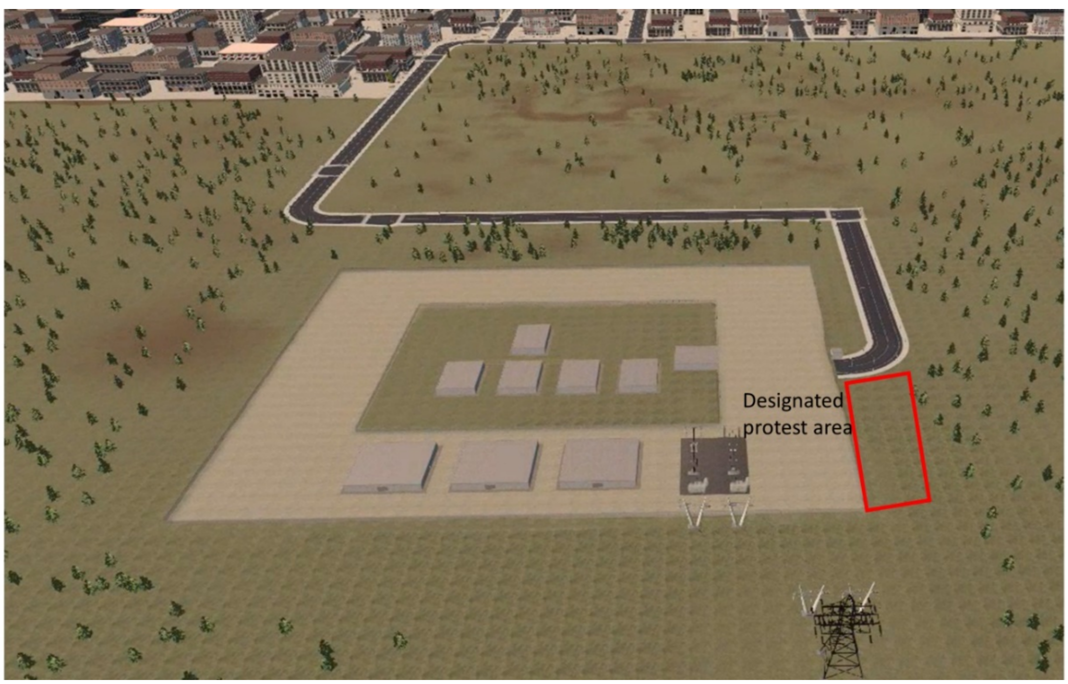

Figure 1. Designated Protest Area

1.1.2. Potential Increase in Petty Crime

The second consideration is the potential increase in petty crime that may occur at an urban SMR facility. Urban centers and suburban areas tend to have higher crime rates per capita than in rural environments[1]. The increased crime rates may pose a risk to an SMR placed in an urban environment. As the facility is built, the public will become aware of the overall cost of the facility and the potential amounts of material in the facility that could be stolen and sold (i.e., copper piping, wiring). Because of this increased risk of petty theft and violent and nonviolent crimes, it should be considered how the PPS will interact with and mitigate these risks. For example, petty criminals may not understand the risk of attempting to steal from a nuclear power facility and may ignore posted warning signs. The operator and the competent authority must have a well-developed, practiced, and implemented use-of-force continuum and policy to ensure the protection of the facility against acts theft. Facilities should also ensure that all critical aspects, such as copper wiring and other necessary equipment, are protected to ensure the safe and secure operation of the facility.

1.1.3. Urban Sprawl and Standoff Distances

The third consideration is the spread of the urban environment toward the facility and how this may impact planned standoff distances. Cities, urban areas, and their surrounding areas have tended to expand further and further out from the city center in recent years. The expansion of these cities and urban areas may present long-term issues to SMRs in urban environments. Traditional LLWRs have been designed to have large standoff distances away from urban environments and other personnel. Standoff distances not only impact the design of vehicle barrier systems (VBSs), but also adversary fire or adversaries gaining a height advantage over the facility to engage the response force. There may not be anything that the facility can do to prevent the encroachment of the urban environment close to the SMR facility. However, operators of an urban SMR should consider how this encroachment may impact the facility in the long-term.

1.1.4. Adversary Use of Urban Environment

The fourth consideration is how the adversaries may use the urban environment to their advantage. This could involve the adversaries using taller buildings around the facility to both engage personnel and for surveillance and reconnaissance, and using the urban environment to delay an offsite response force. By using taller buildings located around the facility, adversaries may be able to engage any security personnel onsite from a distance and vantage point that increases their ability to neutralize the response force. The second advantage is that the urban environment may provide additional opportunities to conduct reconnaissance and surveillance of the facility from an advantageous location.. Additionally, an urban environment may provide the adversaries the ability to delay the arrival of an offsite response force by creating diversion scenarios in the urban environment, such as causing an accident or other ways to block roads or create distractions.

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[1] https://ovc.ojp.gov/sites/g/files/xyckuh226/files/ncvrw2018/info_flyers/fact_sheets/2018NCVRW_UrbanRural_508_QC.pdf

2. HYPOTHETICAL FACILITY DESCRIPTION

The hypothetical SMR facility is located approximately 0.5 km from the edge of the urban city. This facility was sited at this location due to its proximity to the urban environment to reduce the overall cost to supply district heating. For the purpose of this study, the siting location was chosen to discuss the potential security considerations accompanying an urban environment deployment. This location does not include analysis of emergency planning zones (EPZs) and other safety, legal, and regulatory considerations. Figure 2 shows how this SMR facility was sited in an urban environment.

Figure 2. SMR Facility in an Urban Environment

The site consists of an outer fence that defines the LAA, also called the owner-controlled area (OCA). Within the LAA, there is an entry control point (ECP) and three turbine buildings. The ECP at the LAA is responsible for processing all individuals and personnel into the LAA. The site design does not allow for private vehicle parking inside of the LAA due to the location of the switchyard and turbine building. Inside the LLA is another inner fence line, which defines the protected area (PA). Within the PA, there are five buildings, which consist of three reactor buildings, one central alarm station (CAS) and control room building, and a spent fuel storage building. Figure 3 provides an overview of the site layout.

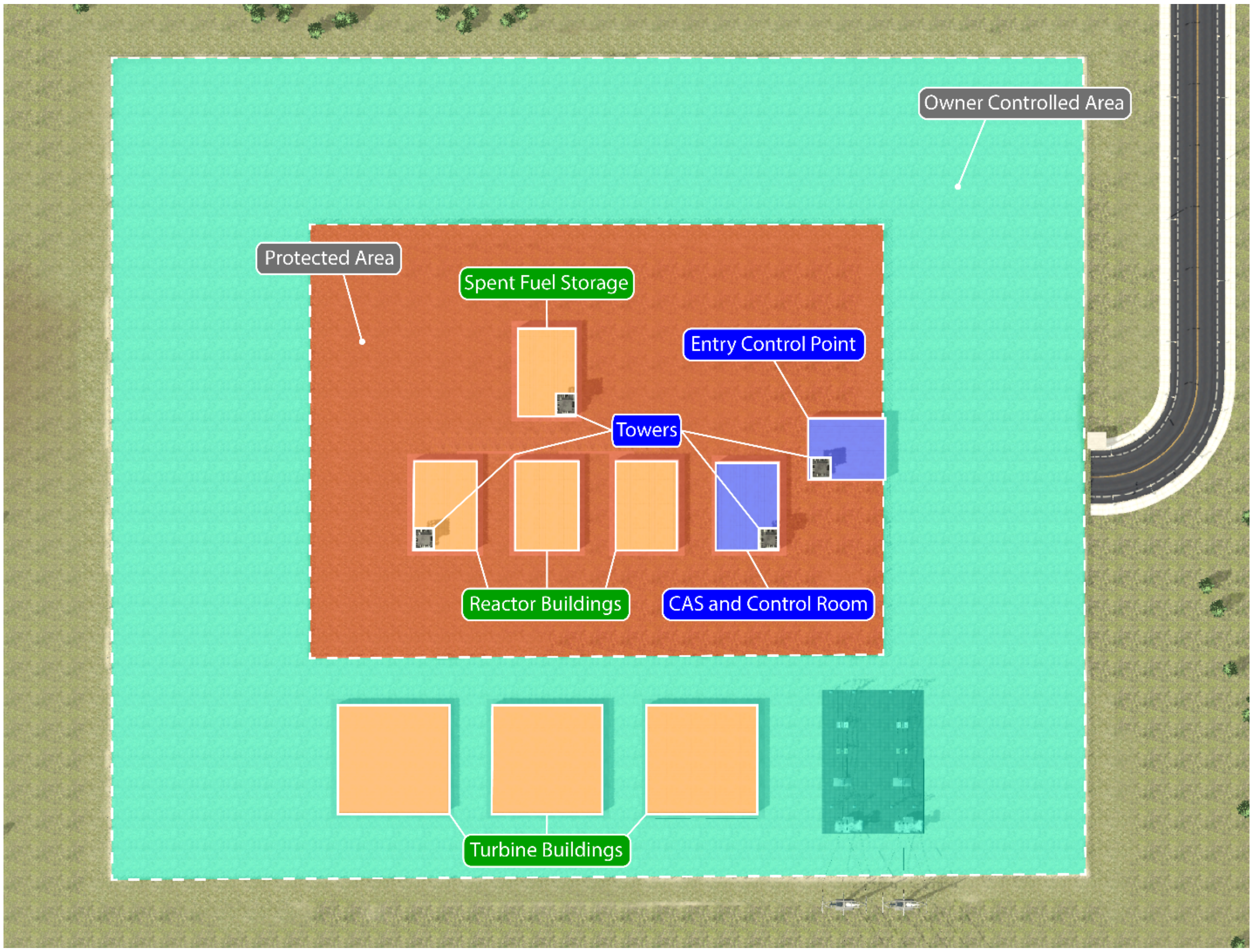

Figure 3. SMR Site Design Layout[2]

2.1. HYPOTHETICAL FACILITY BUILDINGS

As discussed previously, inside the LAA, there are three turbine buildings and the switchyard. The turbine buildings in this analysis are intended for energy production as well as energy conversion, to be used in district heating and process heating. In this example, inside of the turbine building would be the condenser for the SMR. Higher temperature water would exit from the turbine and flow to a pumping station that could then pump this warmer water to substations within the urban environment to be used for district heating. Figure 6 shows how district heating would be conducted using an SMR.

[2] The facility used was developed by the DOE-NE's Advanced Reactor Safeguards and Security Program and modified for this project. "U.S. Domestic Pebble Bed Reactor: Security-by-Design." Alan Evans, et. al. Sandia National Laboratories. SAND2021-13122 R. October 2021. US Department of Energy Advanced Reactor Safeguards and Security Program.

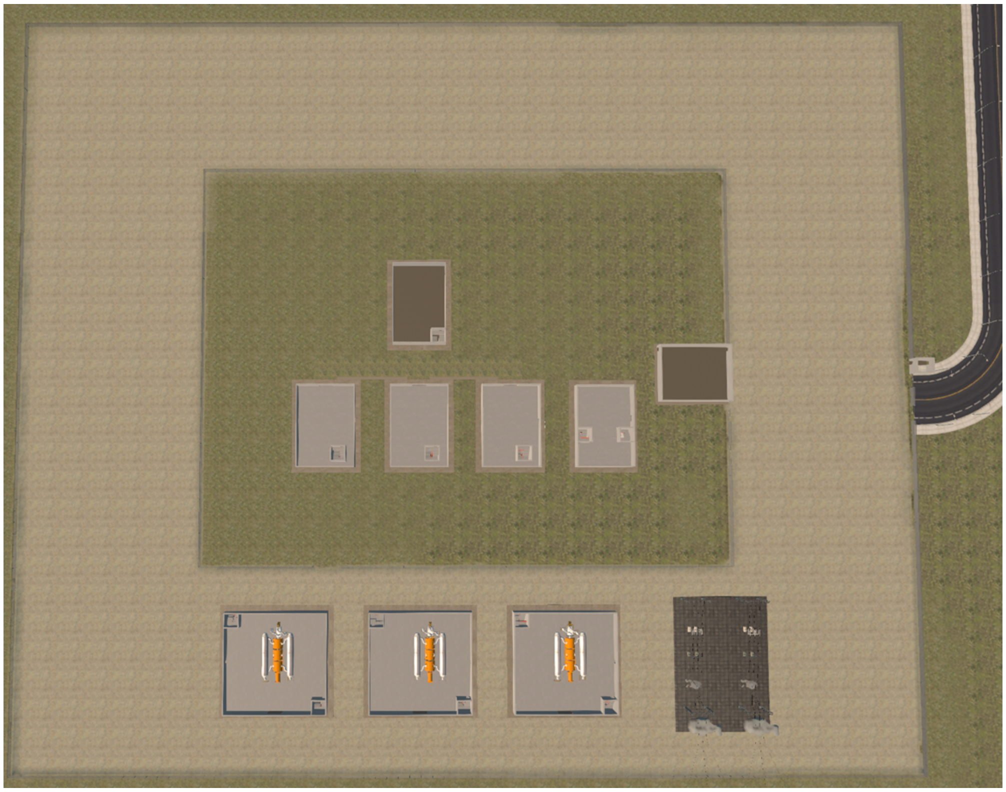

Figure 4. Hypothetical Facility Above-Grade Floor

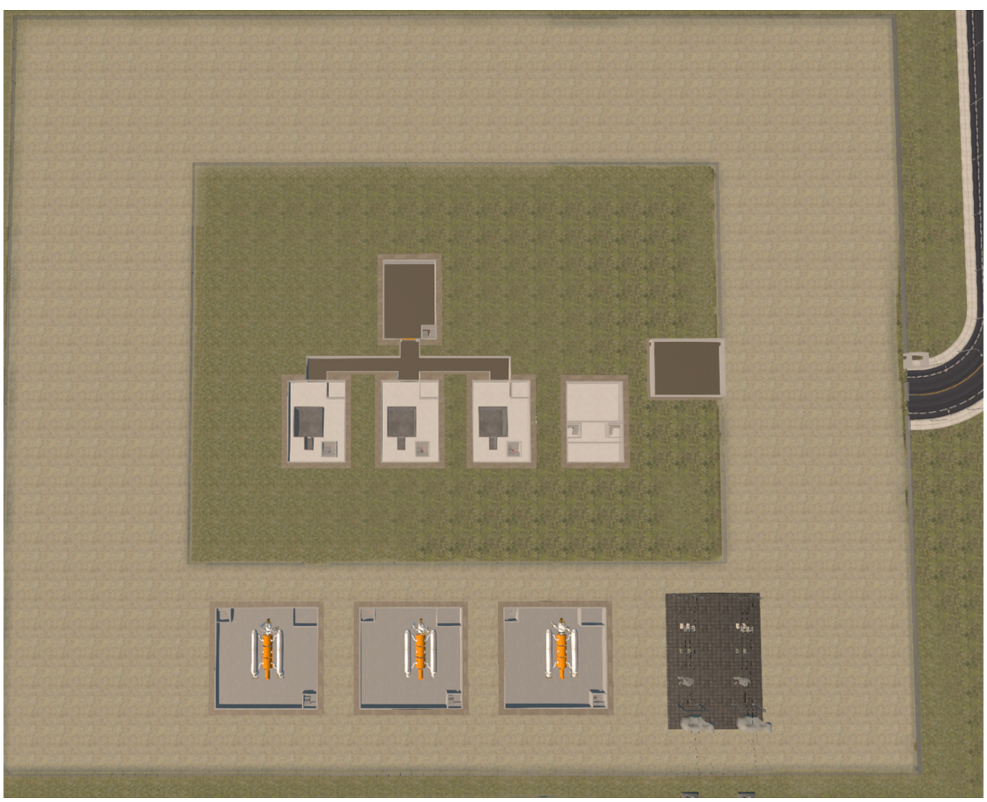

Figure 5. Hypothetical Facility Below-Grade Floor

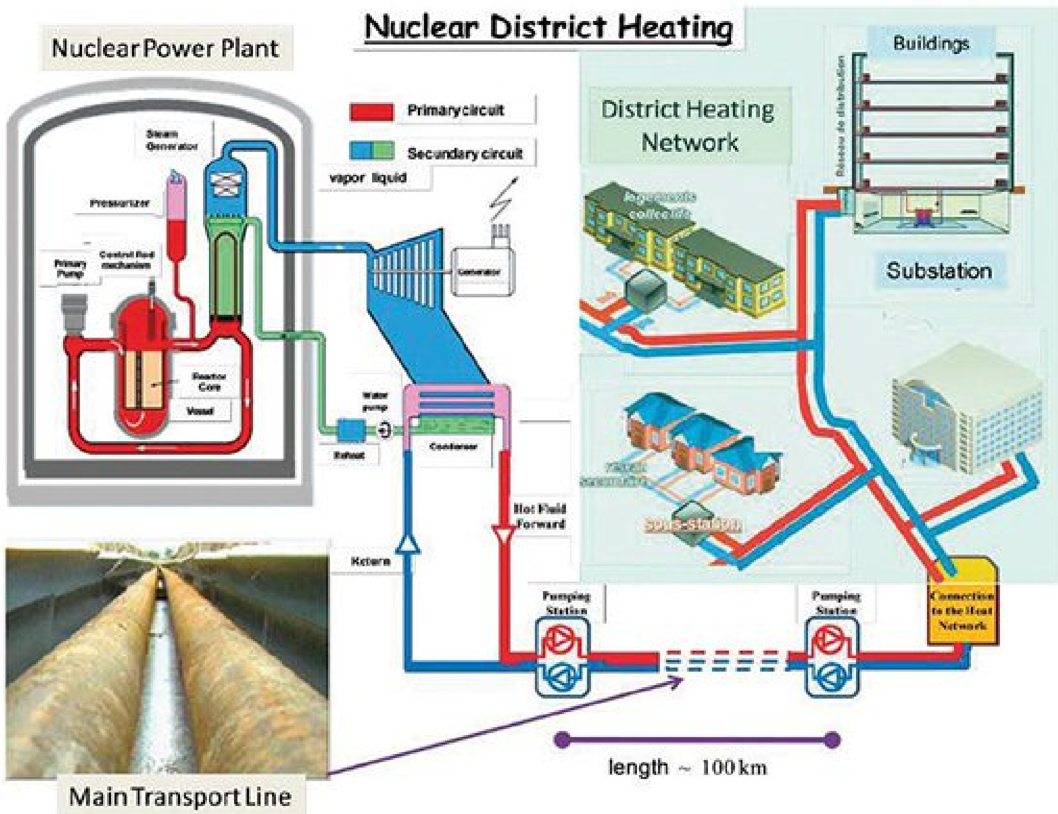

Figure 6. District Heating Example[3]

As discussed in Section 1, this paper considers the energy production portions of the hypothetical SMR as potential targets that need to be protected. These locations or items within the facility are called "energy security targets." Inside the LAA, there are four target locations considered: the three turbine buildings and the switchyard.

Inside the PA, there are three reactor buildings, a spent fuel storage building, the building for the CAS and control room, and the PA ECP. The three reactor buildings house three reactors all located below-grade. The spent fuel storage building stores spent fuel in canisters. All spent fuel is stored below-grade. The CAS and control room building is located below-grade. In this analysis, the sabotage targets the inside of the PA to include the three reactors in the reactor buildings and the spent fuel canisters in the spent fuel building.

[3] https://www.powermag.com/district-heating-supply-from-nuclear-power-plants/

3. PHYSICAL PROTECTION SYSTEM DESIGN

One of the key elements to this work is designing a PPS that is effective at defending against both radiological sabotage and sabotage of the energy production portion of the facility. Additionally, one consideration is the cost of expanding the PPS design to protect energy production, whether for electricity production, district heating, or process heating. In this effort, we aim to design a PPS that is both robust and cost-effective.

3.1. INTRUSION DETECTION SYSTEM

Traditionally, robust intrusion detection systems (IDSs) around nuclear facilities have been designed in the form of a perimeter intrusion detection and assessment system (PIDAS). A PIDAS has been traditionally applied around the PA of a facility and not the LAA. The reason for this is both cost and performance. LAAs tend to be much larger than a PA and therefore require more sensors and fence lines to create a robust IDS. A visual depiction of an example PIDAS can be seen in Figure 7.

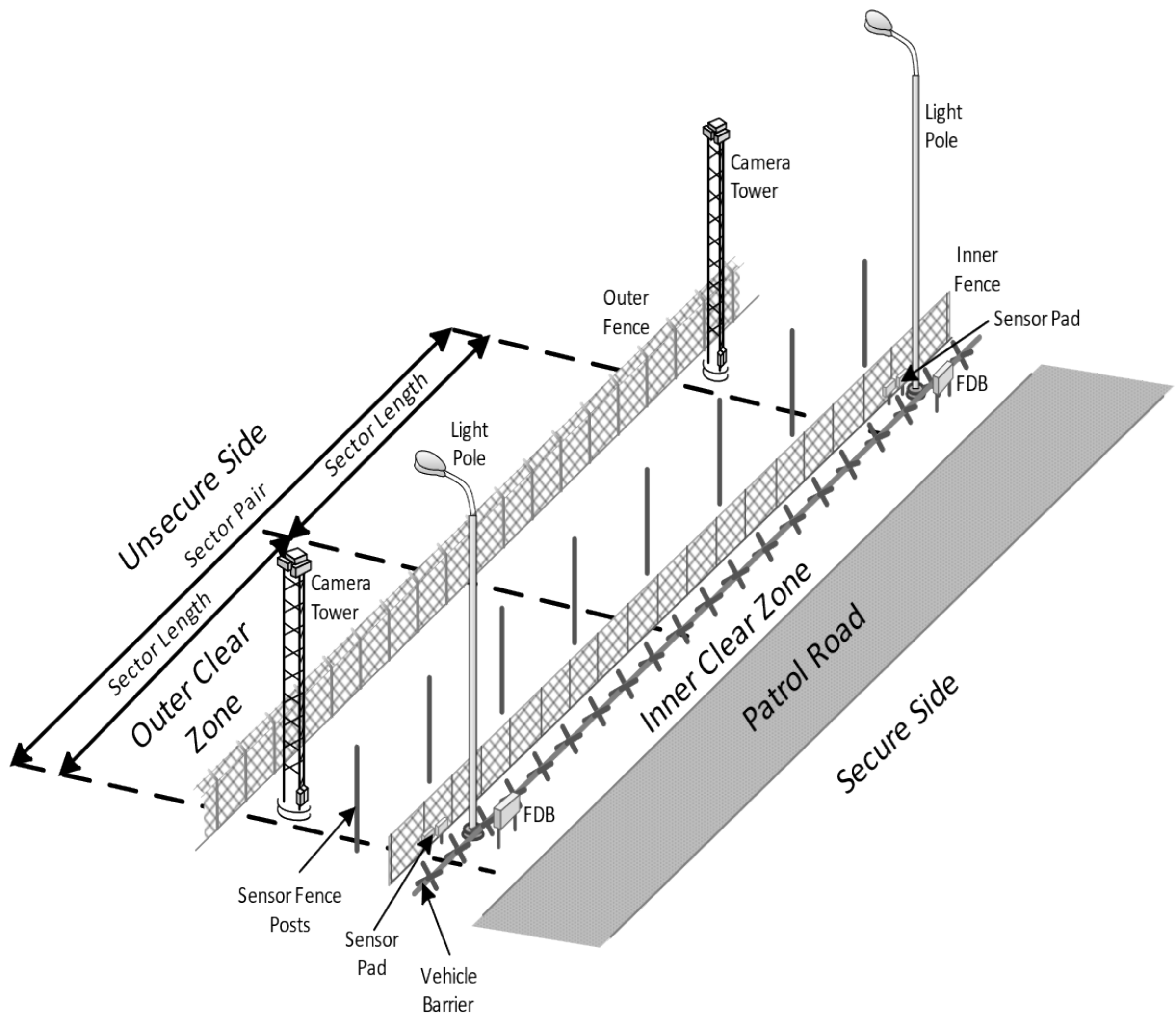

Figure 7. PIDAS Example[4]

Designing and developing a PIDAS can be a costly endeavor for an SMR vendor and a costly part of the PPS to maintain and ensure it is effective by the operator and end user. The PIDAS has an unsecure side and a secure side. Traditionally, the secure side boundary is the PA boundary. The PIDAS is separated by two fence lines and has an isolation zone between the PA fence line and the outer fence line. The outer fence line is the nuisance fence. The nuisance fence ensures that nuisances are kept out of the isolation zone and reduce the nuisance alarm rate (NAR) of the IDS. Traditionally, the isolation zone is secured by at least two different sensors and closed-circuit television cameras (CCTVs). The sensors and cameras are divided up into sectors and overlap is provided by the sensors and the cameras to provide adequate sensing and assessment in each sector and ensure continuous detection and assessment around the perimeter of the facility.

[4] "Advanced PIDAS Design Workshop." Sandia National Laboratories, SAND2024-05626PE

When evaluating the design of the hypothetical facility, the PIDAS would have to expand to the LAA to ensure that the turbine buildings are protected by an IDS. This may increase the costs to deploy the PPS and increase the long-term operation and maintenance costs. However, this would be an important aspect in ensuring the protection of both radiological and energy security targets. The first benefit of extending the PIDAS to the LAA in this scenario is it provides detection earlier than at the traditional PA boundary. Extending the PIDAS would allow for the earlier detection of an adversary, which improves the probability that the PPS response force can interrupt the adversary force, both for an onsite and offsite response force. The second benefit is that it provides detection around the turbine buildings and can allow for a quicker response to the turbine buildings and the energy production equipment that may be stored in the buildings.

3.1.1. *Emerging Technology for Intrusion Detection Systems*

The design of the IDS system for this hypothetical facility considers the use of an emerging technology called deliberate motion analytics (DMA) to allow for the detection of an adversary at the LAA. DMA is a multiple intelligence fusion algorithm for intrusion detection and tracking using a distributed, multi-layer tracking and classification algorithm. DMA's motion pattern recognition algorithms have demonstrated the ability to identify potential intruders inside and outside of the perimeter, issuing alarms against tracks with the correct motion features while filtering out background noise and non-threatening tracks from weather, foliage, and traffic.

Effective utilization of DMA enables individual sensor settings to be set at very high sensitive detection thresholds, increasing the probability of sensing a stealthy intruder. Because individual sensors can be set to a high detection sensitivity, the individual sensors will generate numerous nuisance alarms. However, fusing complementary sensors allows for the potential to eliminate nuisance alarms. Test results to date have shown that the DMA algorithm is capable of effectively filtering out hundreds of thousands of nuisance alarms per day from individual sensors, yielding no nuisance alarms over a period of 1–7 days. DMA has successfully demonstrated the fusion of complementary sensors, including:

1. Radar and video analytics
2. Radar and thermal radar
3. Video analytics and a buried line sensor[5]

DMA is a newer technology that may be implemented at an SMR facility to reduce the overall number of security technologies and infrastructure needed to form a perimeter IDS. As can be seen from Figure 8, a DMA perimeter IDS may allow for less infrastructure and a reduced amount of trenching and cabling.

[5] Alan Evans, John L. Russell & Benjamin B. Cipiti (2023) New Security Concepts for Advanced Reactors, Nuclear Science and Engineering, 197:sup1, S70-S79, DOI: 10.1080/00295639.2022.2112134

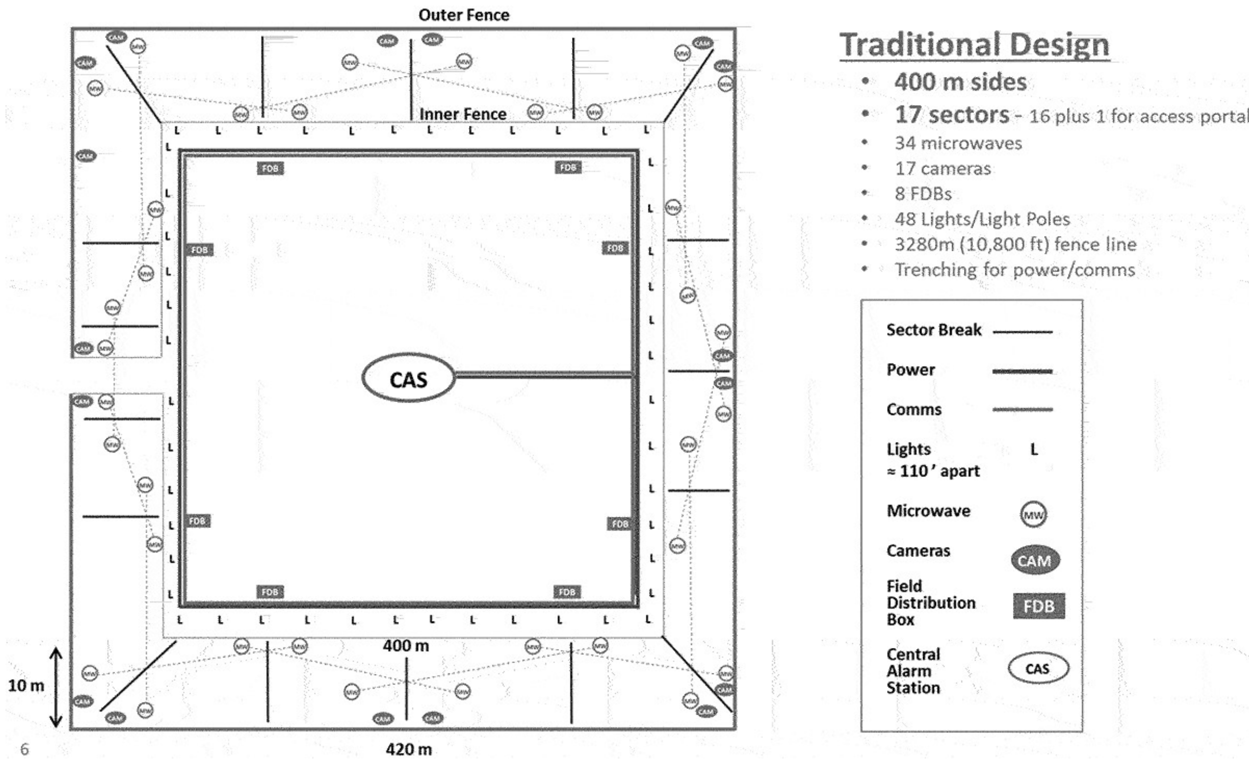

Figure 8. Example of DMA for Single Unit Site

In this hypothetical design, DMA stations are placed on two of the turbine buildings, the spent fuel building, two of the reactor buildings, and the PA ECP building. DMA deployed for this hypothetical facility considers the use of radar and video analytics. The location of the DMA stations was chosen to provide continuous coverage around the facility. Based on the facility design, multiple DMA stations are needed to ensure that the radar emitted is not blocked by buildings and does not allow for gaps around the perimeter. The DMA setup allows for detection just inside the LAA perimeter fence line. DMA can allow for extended detection beyond the LAA, but as discussed previously, due to potential nuisance alarm sources in an urban environment, the DMA was set to be within the LAA perimeter boundary.

Figure 9. DMA Placement

3.2. DELAY FEATURES

The facility initially was designed with minimal delay features for the use of an onsite response force. The delay features included security doors at all door entrances into the reactor buildings, turbine buildings, spent fuel building and the CAS and control room building. One of the reasons for small amounts of delay features is that using an onsite response force does not require as many delay features if the response force is placed into fixed positions along credible adversary pathways to target locations. If the onsite response force is designed to move from one position to an interrupting position, then more delay barriers may be needed. Additionally, if an offsite response force is used, more substantial delay barriers may need to be included in the overall plant design.

The second aspect of delay built into the facility is placing the potential targets (radiological and energy security) below-grade. Below-grade placement of the targets allows for an increase in delay barriers and delay features to be added into the overall design. Delay features can be designed into the building entrances, the stairwell entrances, the stairwells, or any elevator systems used to move people or equipment below-grade. Additionally, below-grade siting of targets may increase the inherent protection against large explosives in vehicles or add additional protection against advanced threats such as drones or uncrewed aircraft systems (UAS).

In this design, a continuous VBS surrounds the facility at the LAA boundary. The VBS is designed to prevent vehicles from penetrating into the facility and delivering adversaries closer to target locations or detonating vehicle-borne explosive devices (VBEDs) near target locations or near security and plant personnel. The VBS is designed to prevent the design basis threat (DBT) vehicle from penetrating into the facility and detonating VBEDs to cause damage to the reactors, spent fuel storage, or energy security targets. It is important that vendors and operators consider the size of the vehicle in the DBT and the amount of explosives the vehicle can carry when designing the VBS.

3.3. RESPONSE STRATEGY

The primary response strategy analyzed in this report considers an onsite response force placed in strategic BBRE towers.

There are 5 BBRE towers located throughout the site; these BBRE towers are designed to be 40 feet tall. BBRE Tower 1 was designed to be placed on top of the PA ECP. This allows for overwatch of vehicle and personnel entrance and provides line-of-sight over the majority of the facility, but specifically allows for greater protection from attacks that originate from the north, as seen in Figure 10.

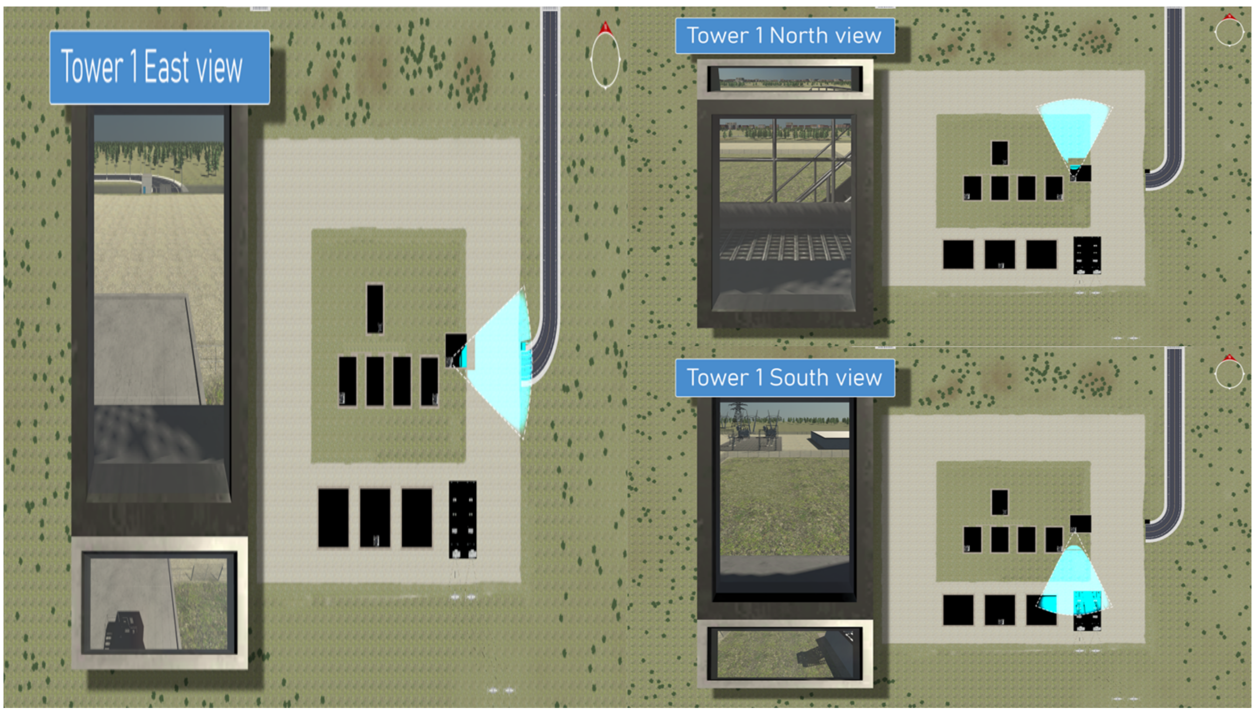

Figure 10. BBRE Tower 1 Field-of-View

BBRE Tower 2 is located on top of the CAS, as seen in Figure 11. This allows for protection of the CAS as well as line-of-sight along the south side of all reactor buildings. This position has limited line-of-sight south of the turbine buildings, but aids in engagements that originate from the north and west. Additionally, this BBRE tower has line-of-sight to the switchyard and can provide overwatch and surveillance of the switchyard.

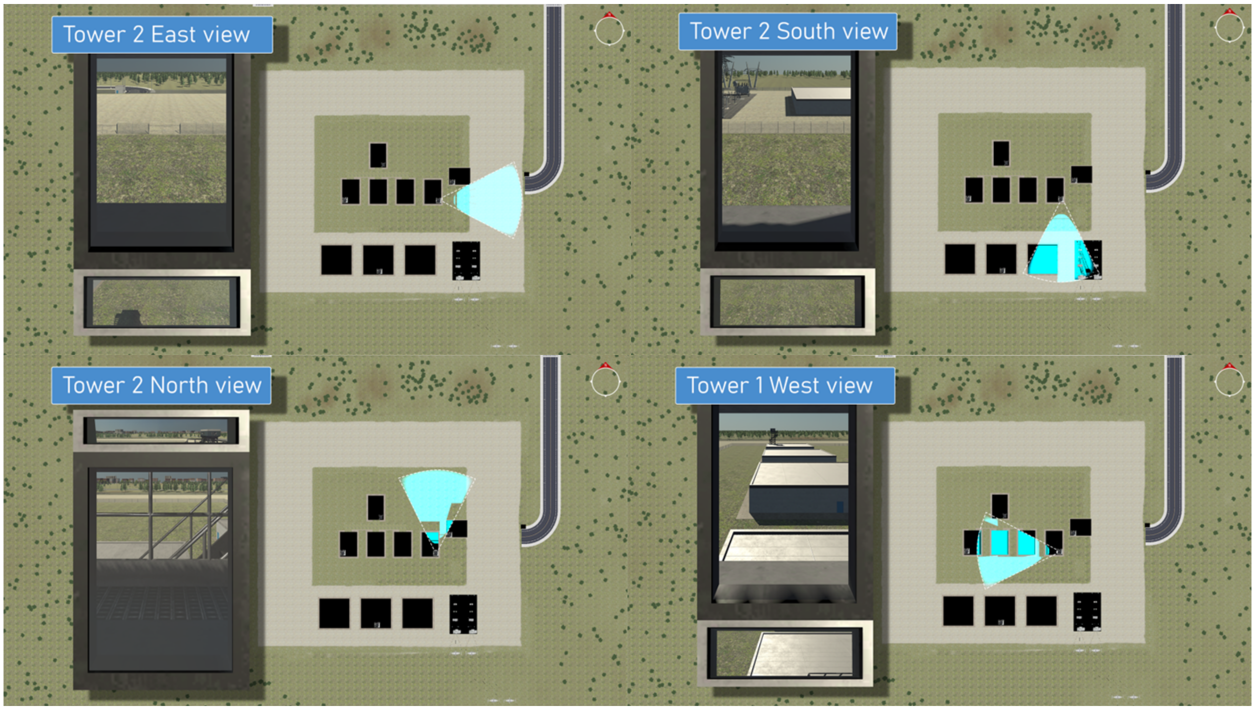

Figure 11. BBRE Tower 2 Field-of-View

BBRE Tower 3 is located on top of the spent fuel storage. This offers line-of-sight over the entire north side of the LAA and PA but has proven advantageous in tabletop simulations of attacks that originate from the south and west due to the height of the tower. The fields of-view from this BBRE tower can be seen in Figure 12.

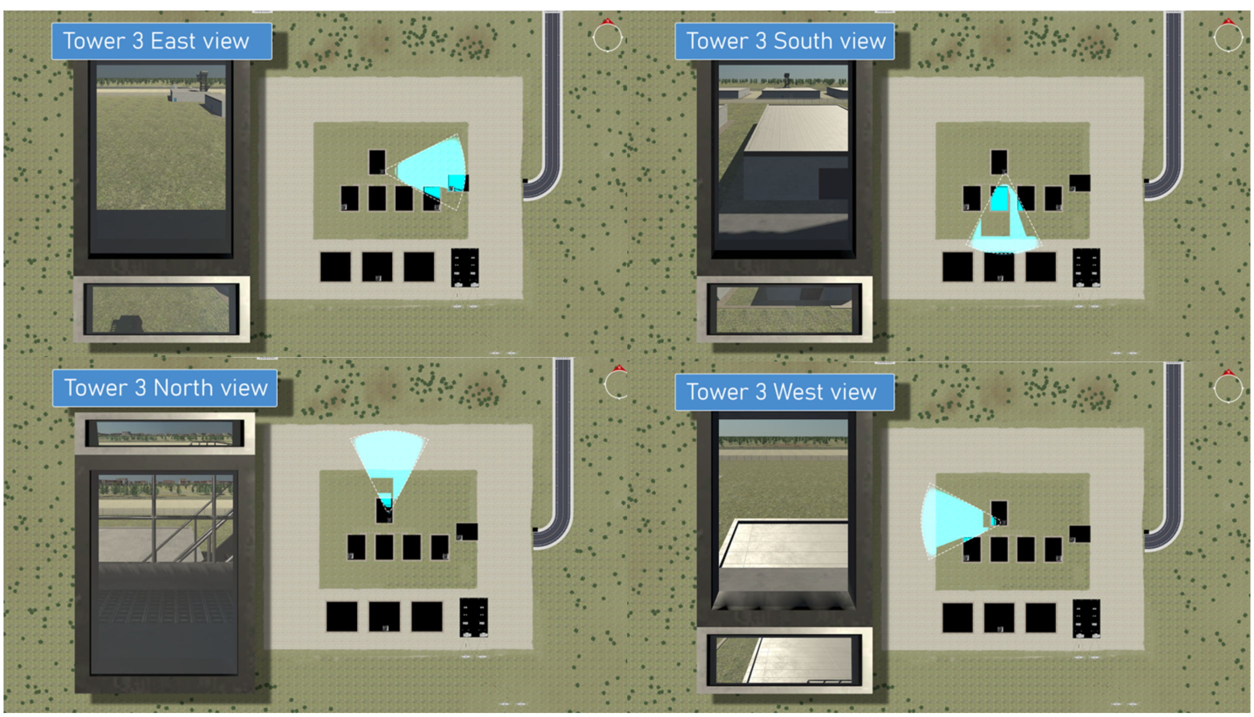

Figure 12. BBRE Tower 3 Field-of-View

BBRE Tower 4 is located on top of the east reactor building, as seen in Figure 13. This allows for line-of-sight over the east part of the LAA and it aids most in engagements that originate from the east and south, but has limited view of the front of the turbine buildings.

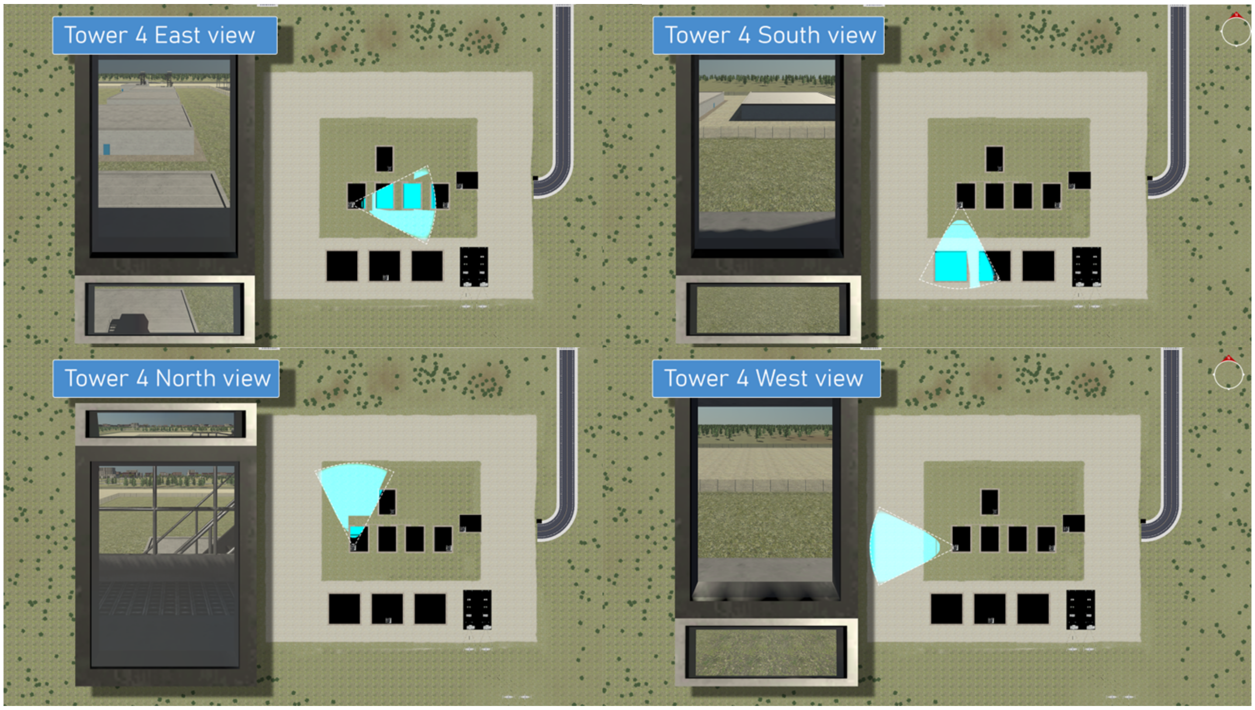

Figure 13. BBRE Tower 4 Field-of-View

BBRE Tower 5 was added to protect the south side of the turbine buildings. This tower is located on top of the middle turbine building. This allows for a clear line-of-sight to the southern part of the LAA, but also can aid in engagements from the west and east. This fields-of-view from this BBRE tower can be seen in Figure 14.

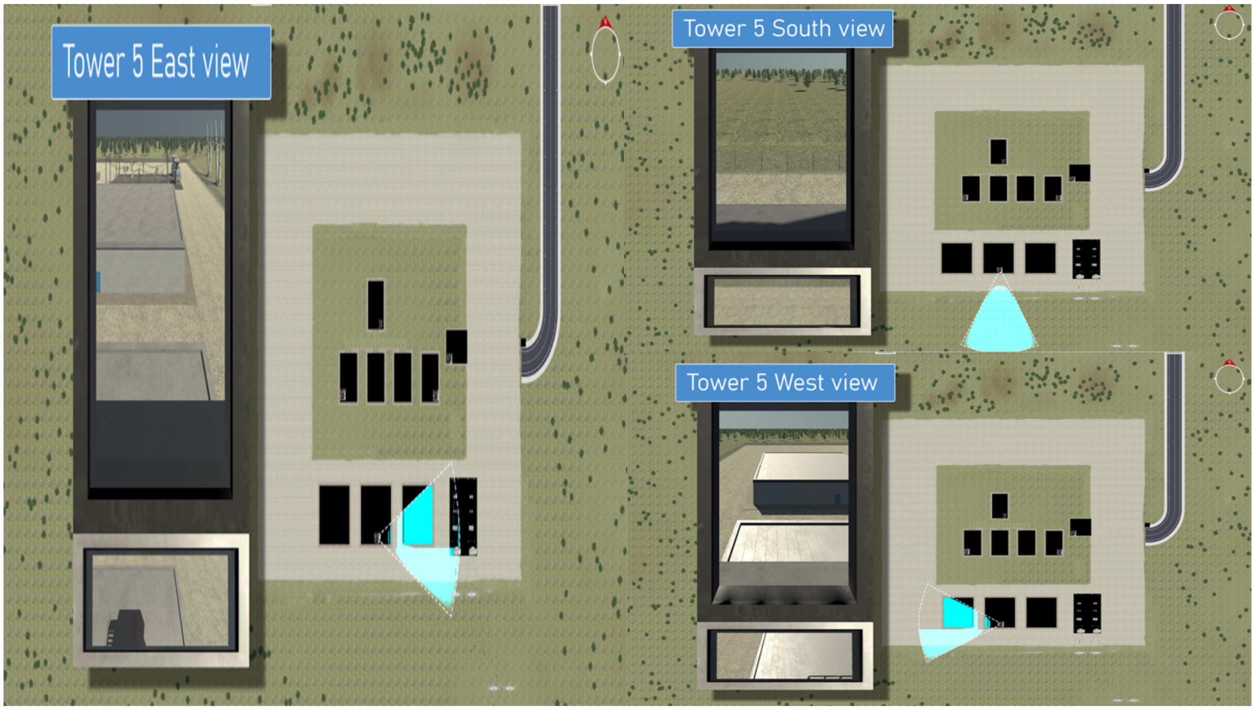

Figure 14. BBRE Tower 5 Field-of-View

It should be noted this response strategy was chosen based on discussions with subject matter experts (SMEs) with many years of experience securing nuclear facilities and leading response teams at nuclear facilities. By increasing the number of targets at the facility in multiple different buildings, the overall response design was aimed at developing a strategy where overlapping fields-of-fire from a response force could interrupt and neutralize an adversary force. One of the major considerations in this design was the overall reduction of costs. To reduce costs, these BBRE tower positions were chosen to minimize the total number of responders needed and increase the overall effectiveness of the PPS. Finally, in tabletop exercises and discussions with SMEs, this strategy was also chosen because of the loss of advantage to the response force that would be seen when the adversaries entered buildings with targets. If the adversary was able to enter the buildings, the response force would be forced to pursue them, and the adversary team could more easily hold the response force from interrupting and neutralizing the adversary force.

3.4. INITIAL FACILITY CHANGES TO INCREASE PPS EFFECTIVENESS

A facility change was made to the overall design before any analysis of the PPS design was conducted. Initially, the exterior door and roll-up door on the turbine buildings were originally designed to face south, as shown in Figure 15. This allowed for attackers to easily access these doors with minimal engagement from the response force in BBRE towers (originally without the fifth BBRE tower).

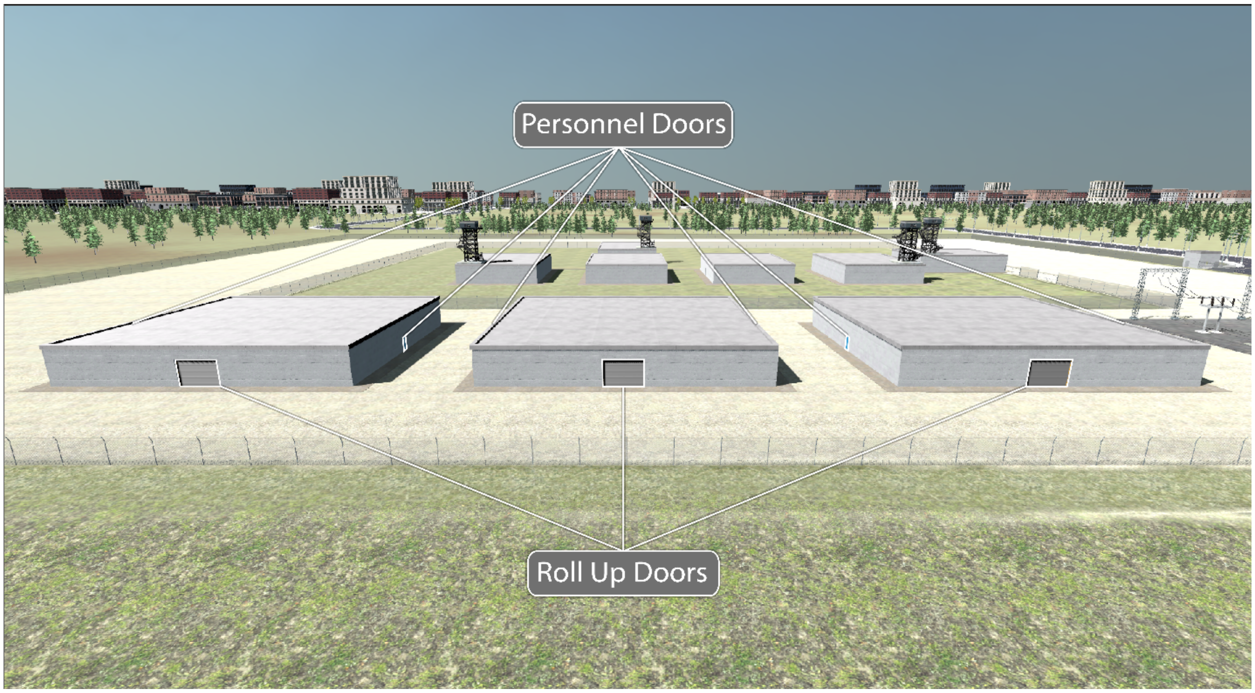

Figure 15. Original Door Placement

All doors at the facility, including personnel and roll-up doors, were moved to face the interior of the plant rather than the south of the plant. The reason for this is to create a more advantageous pathway for the response force to be effective. By moving the doors to face the interior part of the facility, BBRE Towers 1 through 4 can all view these doors. This change was also made because the doors into the reactor buildings and the turbine buildings have a much shorter delay time than the reinforced concrete walls surrounding the door; this allowed adversaries quick entry into the building without having to use explosive capabilities. By forcing the adversary to the middle of the PA, the response force can focus fields-of-fire to the adversaries and if the adversaries choose to breach the south walls of the turbine buildings, they can be engaged by BBRE Tower 5 while exposed and trying to perform a complex explosive breach on the exterior walls into the turbine building. Figure 16 shows the change of door placements facing the interior PA.

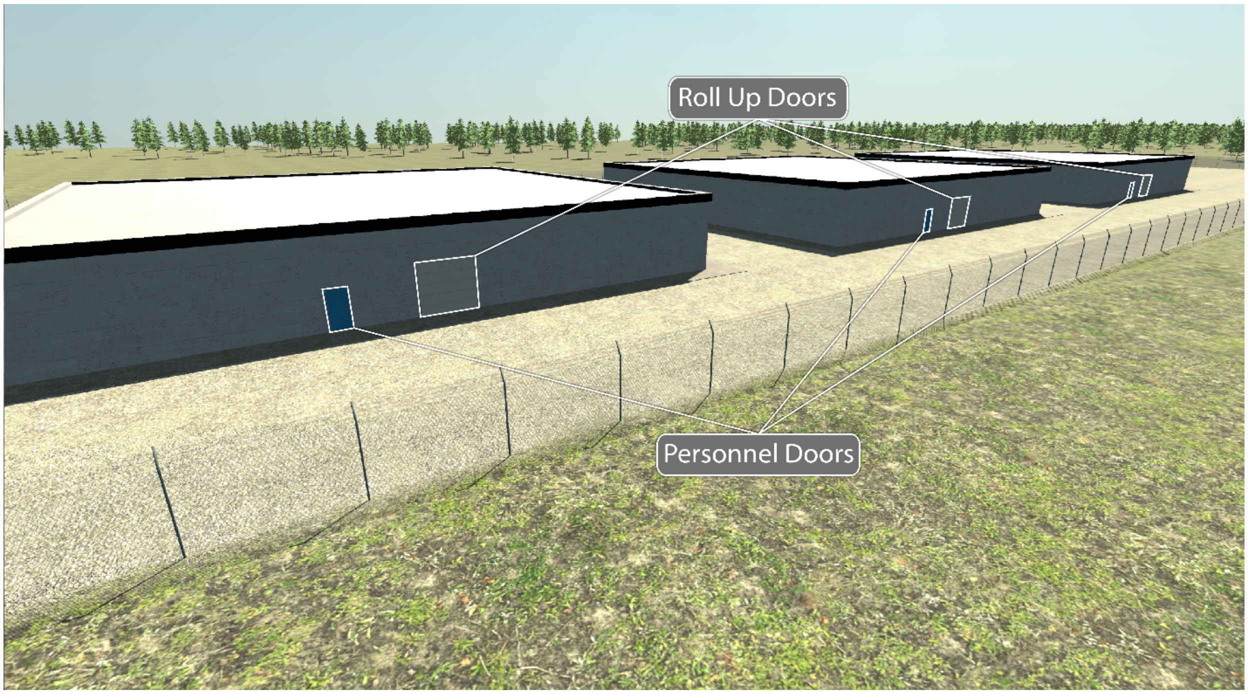

Figure 16. New Door Placement

4. PPS EVALUATIONS

To evaluate the PPS designed for this hypothetical SMR, tabletop exercises were conducted using SMEs to develop facility adversary attack plans with the highest likelihood of success. These SMEs have decades of experience working at NPPs in the U.S. and at Department of Energy facilities, and are experienced in providing armed response, physical protection, and adversary attack planning at domestic nuclear facilities. Six distinct adversary scenarios were identified and developed for this hypothetical SMR.

Each of the 6 scenarios was analyzed using Scribe3D© (Scribe). Scribe is a Sandia National Laboratories-developed scenario and tabletop exercise visualization tool (not a combat simulation or probability of neutralization tool). For each scenario, a range of 4–8 adversaries was used and a total cumulative probability of neutralization was calculated from the tabletops conducted. Each engagement (i.e., where the adversary and response force had an opportunity to engage) was simulated 1,000 times to ensure a statistically significant number of engagements to determine the effectiveness of the response force and the response strategy. These engagements were based on whether the adversary and response force had line-of-sight of each other and assuming the rules of engagement (ROEs) had been met. The ROEs were determined to be met when the adversaries breached the LAA fence line with weapons.

4.1. SCENARIO SUMMARIES

4.1.1. Scenario One

In scenario one, the adversaries attack from the south side of the facility and move to the reactor buildings. The results listed in Table 1 demonstrate that a high probability of neutralization is achieved. In addition, the adversaries were neutralized before they reached/entered the inner fence area. The primary reason for the high probabilities of neutralization is the change in the door location and the overlapping fields-of-fire provided by the response force along the adversary pathway to the reactor buildings. The SMEs who developed the attack scenarios considered this a credible adversary pathway due to the cover and concealment provided by the turbine buildings on the south side of the facility. The biggest factor in the effectiveness of this scenario is BBRE Tower 5, which can engage many of the adversaries before they move to the PA fence line. The scenario resulted in multiple engagements, and an increased number of engagements based on the size of the adversary force. During the scenario, the response force was not able to win all engagements (the neutralization of all adversaries), but because of the overlapping fields-of-fire and multiple responders the PPS was ultimately successful at defending against the full range of adversaries.

Table 1. Scenario One Analysis Results

Number of Adversaries	Number of Responders Involved	Number of Engagements
8	5	4
7	5	3
6	5	2
5	5	2
4	5	2

4.1.2. Scenario Two

In scenario two, the adversaries perform a split attack, where one group attacks from the south and one attacks from the north in equal numbers. The BBRE placements allow multiple responders to engage the adversaries attacking from both the north and south. By having multiple fields-of-fire on the approaching groups, the response force is able to neutralize many of the adversaries before they reach the PA fence. BBRE Towers 3 and 5 were able to effectively engage and neutralize adversaries from the south and BBRE Towers 1, 2, and 4 were able to effectively neutralize adversaries from the north. Additionally, the large open terrain on the north side of the facility provided an additional advantage to the response force engaging adversaries from the north. In this scenario the split action by the adversary team provides an advantage to the response force and divides the number of adversaries. Smaller adversary group numbers in this scenario all the response force to be more effective. As can be seen from the table below, the overall number of engagements is lower than the from scenario one. This is because the response force has an advantageous position in these scenarios.

Table 2. Scenario Two Analysis Results

Number of Adversaries	Number of Responders Involved	Number of Engagements
8	5	3
7	5	3
6	5	2
5	5	2
4	5	2

4.1.3. Scenario Three

In scenario three, the adversaries originate their attack from north. All BBRE towers have a line-of-sight to the attacking force from the north and can engage the adversaries. Due to the open space and multiple protected fields-of-fire, the response force can neutralize all adversaries regardless of group size before they reach the reactor buildings. Table 3 highlights the results from this tabletop exercise. As can be seen from the table below there is only one engagement per adversary group size. This is the result of the positions of the responders and the uncovered terrain that the adversaries have to cross to reach the target location.

Table 3. Scenario Three Analysis Results

Number of Adversaries	Number of Responders Involved	Number of Engagements
8	4	1
7	4	1
6	4	1
5	4	1
4	4	1

4.1.4. Scenario Four

In scenario four, the adversaries originate their attack from the west, near the turbine building. Only BBRE Towers 4 and 5 have clear line-of-sight to the adversaries entering from this area of the facility. BBRE Towers 1, 2, and 3 have obstructed line-of-sight due to the other BBRE towers or buildings on site. Even with this hindrance, Towers 4 and 5 can defeat the adversaries with a high probability of neutralization, as seen in Table 4. In this scenario the two response towers are able to effectively visualize the adversaries and engage. The uncovered terrain that the adversaries must cross also allows the responders to engage adversaries from positions of cover and this advantage leads to one effective engagement for the response force.

Table 4. Scenario Four Analysis Results

Number of Adversaries	Number of Responders Involved	Number of Engagements
8	2	1
7	2	1
6	2	1
5	2	1
4	2	1

4.1.5. Scenario Five

In scenario five, the adversaries originate an attack from the south side of the facility and attack the middle turbine building. As stated earlier, the high bay door would have been an easy access point for the adversaries and would not have allowed the response towers to engage with them. To avoid this problem, the high bay door as well as the personnel entry door were moved to face the reactor buildings, which grants the response towers line-of-sight and forces the adversaries to engage with the response towers to gain access into the turbine buildings. The results of this scenario can be seen in Table 5. In this scenario there are multiple engagements as the adversaries are able to make it to the skin of the turbine buildings providing them some form of cover from the response force. Overall, the PPS is effective against all adversary group sizes.

Table 5. Scenario Five Analysis Results

Number of Adversaries	Number of Responders Involved	Number of Engagements
8	4	3
7	3	3
6	3	2
5	3	2
4	3	2

4.1.6. Scenario Six

In scenario six, the adversaries originate an attack from the south side of the facility and attack a turbine building. Unlike scenario five, the tabletop exercises forced the adversaries to attack the exterior wall that faces the south. This reinforced the need for a fifth BBRE tower located on the middle turbine building. The addition of the BBRE tower forces adversaries to engage with the BBRE tower before being able to breach the wall; in each scenario, the BBRE tower played a critical role in in the effectiveness of the response strategy. This is shown in Table 6. The addition of this BBRE tower ensured the PPS is effective against all adversary scenarios. In addition, this BBRE tower played an effective role in many other scenarios ensuring the PPS effectiveness for all adversary attack scenarios.

Table 6. Scenario Six Analysis Results

Number of Adversaries	Number of Responders Involved	Number of Engagements
8	1	2
7	1	2
6	1	2

Number of Adversaries	Number of Responders Involved	Number of Engagements
5	1	2
4	1	2

4.2. EVALUATING EXTENDED AND EARLY DETECTION IN URBAN ENVIRONMENTS

Many SMR vendors and utilities are interested in using extended detection technologies to detect adversaries earlier and potentially increase the response force's time to interrupt and neutralize an adversary. There are a variety of methods to achieve this, including DMA. Extended detection may provide additional time when applied outside of the LAA or PA fence line. Using the PathTrace tool, the team conducted a path analysis to identify the increase in the total adversary task time resulting from early detection, based on adversary distance and traversal time. Table 7 provides a summary of these results.

Table 7. PathTrace Analysis Shows Increases Adversary Task Times Increasing with Early Detection

Distance of Early Detection Perimeter (m)	Total Adversary Task Time (s)		
	Vehicle (20 m/s)	Walking (1 m/s)	Running (3 m/s)
100	5	100	33.3
200	10	200	66.7
300	15	300	100
400	20	400	133.3
500	25	500	166.7
600	30	600	200
700	35	700	233.3
800	40	800	266.7
900	45	900	300
1000	50	1000	333.3

As shown in Table 7, if the facility terrain is not engineered to slow down people or vehicles, the increase in adversary task time is limited to the range of the extended detection and how the adversary is moving up to the facility. If extended detection technologies are pushed to 1,000 meters, the adversary task time increases significantly for each adversary mode of transport.

Another consideration when using an extended detection technology is where it could be most impactful. In an urban environment, the facility and PPS will have to consider normal vehicle traffic and persons that may be present within the area on a regular basis, as extended detection technologies may cause a large number of alarms as a result of normal activity within the detection range. This large number of alarms may become too burdensome for an alarm station operator, and as a result, negatively impact the effectiveness of this detection technology.

To increase the effectiveness of this type of detection in an urban environment, SMR facilities may consider a larger LAA or PA, as well as engineering features into the terrain that increase the time to cross areas with extended detection. By extending the LAA or controlled area of an SMR facility, extended detection technologies may not alarm as often, which could result in a more manageable amount of nuisance alarms. Engineering features such as ditches, rocky terrain, or uneven terrain up to the facility perimeter add to the delay time and can slow people and vehicles down, thereby increasing the total time to reach the facility.

5. SITE DESIGN LAYOUT – OFFSITE RESPONSE

Considering an event for which onsite response is not a possibility, site changes would have to be made to achieve a time of thirty minutes in total delay time to allow offsite response personnel to arrive. The PathTrace tool was used to examine the necessary changes to allow an offsite response force to arrive and interrupt the adversaries before they arrive at the target location in 30 minutes (1,800 seconds). The seven different design changes to the original site design are summarized below.

5.1. FIRST DESIGN ITERATION

We removed the inner fence line that defined the PA in exchange for a PIDAS. This then created the whole site as a PA and increased delay time. The initial decrease in delay time was achieved by having detection further out and accounting for the delay time to move from the outer fence line to the reactor building. This would require the PA ECP to be moved to where the current LAA ECP is located to conduct prohibited item searches and allow entry to the PA.

5.2. SECOND DESIGN ITERATION

Personnel traps were installed on the reactor and CAS buildings, the turbine building doors, and the roll-up doors. The personnel trap requires authorized individuals to enter an accepted access control credential at the outer door, proceed to the inner door, then enter into a space between the outer door and inner door (see Figure 16). The inner door can only be opened once the accepted credentials (i.e., badge and PIN) are entered and the CAS operator verifies the individual matches the picture on the badge presented through the use of CCTV cameras in the trap.

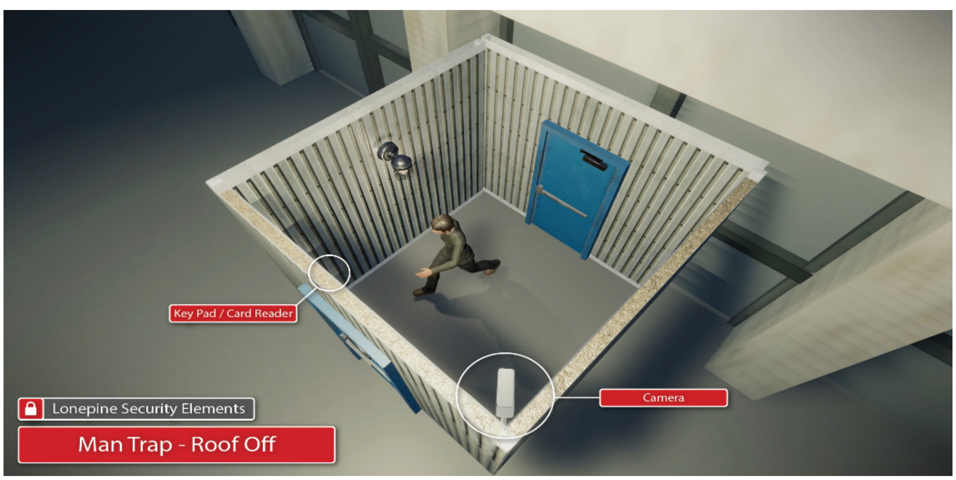

Figure 17. Personnel Trap Example

5.3. THIRD DESIGN ITERATION

More focus was put onto the turbine buildings. The outside walls were upgraded from 1-foot-thick reinforced concrete walls to 2-foot-thick reinforced concrete walls, which increased delay time. PathTrace indicated that an adversary pathway through the wall was deemed less detectable and quicker than going through the personnel traps. Lastly, personnel traps were installed in the doors to access the stairwells leading below-grade in each reactor building.

5.4. FOURTH DESIGN ITERATION

The only design change was the installation of reinforced active delay doors in the reactor buildings. These reinforced doors are controlled by the CAS operator and are left open during normal operation. During a security event (i.e., a credible alarm is reported to the CAS), the doors can be actively shut over the existing doors to the stairwells. These reinforced doors were applied to all doors leading below-grade in the reactor buildings. This created more delay for adversaries attempting to reach and sabotage the reactors.

5.5. FIFTH DESIGN ITERATION

The adversaries were forced to go through doorways (to simulate a credible attack scenario) instead of going through the walls. The reactor building walls were increased in thickness from 1-foot-thick reinforced concrete to 2-foot-thick reinforced concrete to increase adversary attack time. This then forced the adversaries to attack through the spent fuel building, located to the north of the reactor buildings. This forced the adversaries to go through the roll-up doors that connect the lower levels of the reactor and spent fuel buildings. This change not only increased adversary task time but increased overall probability of detection.

5.6. SIXTH DESIGN ITERATION

In the turbine buildings, we increased the adversary task time by moving the target area of the turbine to the bottom floor of the building, which creates a longer and more delayed path towards the turbine itself. To address the adversaries going through the spent fuel building to enter the reactor buildings, the outer walls of the building building were changed to be 2-foot-thick reinforced concrete walls and personnel traps were added to all exterior doors entering the spent fuel building.

5.7. SEVENTH DESIGN ITERATION

We added personnel traps to the staircase doors with reinforced active delay doors in order to increase adversary task time in the turbine building. This forced the adversaries through two doors and helped create a task time of 1800 seconds or more for all six targets.

The original site design offered the least amount of delay time but would still be effective with an onsite response force. As seen in Table 8, there is not enough delay in any of the site designs for an offsite response force to arrive in time to interrupt the adversary.

Table 8. PathTrace Analysis of Security Design and Delay Time to Target

Design Upgrade Iterations	Target: West Turbine Building	Target: Middle Turbine Building	Target: East Turbine Building	Target: West Reactor	Target: Middle Reactor	Target: East Reactor
	Delay Time (s)					
0	50	592	591	822	769	816
1	631	636	642	830	781	828
2	638	636	649	899	843	896
3	1298	1596	1609	932	876	930
4	1598	1596	1609	1750	1694	1741
5	1124	1128	1134	2438	2105	2519
6	1505	1438	1417	2780	2784	2772
7	1913	1846	1826	2780	2784	2772

In addition to the upgrade iterations discussed above, pairing these upgrade iterations with a form of reliable extended detection may increase the overall adversary task time. All upgrades should consider the performance, costs, and overall impact to the effectiveness of the PPS. Urban operators of SMRs should also consider that the times we analyzed are based on a response force being able to arrive at an interruption point 30 minutes after being dispatched. Thirty minutes may not always be achievable. An offsite response force may arrive at the site, have to debrief and prepare for the upcoming situation, and then proceed to interrupt and neutralize the adversary force. This may increase the overall time it takes for the response force to be able to interrupt the adversary force and should be considered when conducting any path analysis and design upgrades to allow for an offsite response force.

6. CONCLUSIONS AND RECOMMENDATIONS

Many conclusions and recommendations can be drawn from this work to inform both vendors and operators considering an SMR deployment in an urban environment that may be used for electricity production, district heating, process heating, or any combination. Many of the results and recommendations should be applied based on the strategy that can be deployed under the regulations that exist in country.

6.1. URBAN ENVIRONMENT CONSIDERATIONS

Urban environments present different challenges than traditional LLWR deployments or SMRs being deployed in rural environments. These urban environment challenges include increased potentials for protests and petty crimes as well as the likelihood that the urban and suburban areas will move closer to the facility as the urban areas grow. Additionally, considerations should be made for how adversaries may use the urban environment to their advantage when attacking an SMR facility.

To counter potential protests at the facility, facility operators should consider having a designated protest area that is designed to not interfere with operations or security personnel. Facility operators should develop security plans and contingency plans to ensure adequate security when protests do occur. These plans should consider how the site PPS will respond to incursions by protestors and have detailed plans for coordinating with local law enforcement agencies to respond to large protests.

Urban SMR facility operators should also consider how an adversary may use the urban environment around the SMR facility to their advantage to attack the SMR facility. Adversaries may use the height of surrounding buildings (if close enough) as a position to be able to engage personnel onsite at the SMR. This position would give them an advantage in an engagement with the response force. Large buildings near an SMR facility may also provide an advantageous location for the adversary to perform surveillance and reconnaissance of the facility and gain knowledge to attack the facility most effectively. Finally, adversaries may use the normal day-to-day rhythms to cause delays for an offsite response force to arrive and respond to a security event at an urban SMR facility. These events could be to disrupt the arrival of response forces by causing a vehicle accident or other incidents that could delay the offsite response force from arriving.

6.2. ELECTRICITY PRODUCTION, DISTRICT HEATING, AND PROCESS HEATING CONSIDERATIONS

Facility operators considering the wide use cases of SMR technologies may wish to protect their investments by ensuring the security of radiological targets and energy security targets at their facility. In the past, this may have been a costly endeavor to protect so many targets in various locations around the facility. This report and the associated analysis show protecting the targets may be possible and cost-effective if included in the security-by-design process; security can be retrofitted around additional targets later in the facility’s lifetime.

One recommendation that is if the equipment used for electricity production, district heating, and process heating is to be secured similar to that of radiological targets, they should not be treated as separate systems. By treating energy security targets and radiological targets as separate, the overall cost for the security system may be greater than if the system was designed to adequately protect both. In this analysis, the protection of energy security and radiological targets was seen to be one PPS design and designed to meet high performance requirements to protect all targets. By conducting this design and analysis before the plant is constructed or enters final design phase, the most cost-effective solution can be developed. Additionally, this allows for modifications to the facility to be made that will not lead to large costs, compared to if these changes are made during construction or modifications are needed after construction. For example, by moving door locations to advantageous positions, the site design can be optimized to improve security and facilitate operations before final design is completed. Moving doors and plugging old doors may be a costly upgrade once the facility has been built.

6.3. RESPONSE FORCE

While use of response forces at nuclear facilities in urban environments is not new, there are unique challenges that should be considered for response forces at large SMR deployments in urban environments. As discussed, at SMR facilities there are significant amounts of plant capital equipment and potential radiological targets present. If offsite response forces are used, a detailed analysis and agreement must be developed to determine the time it takes for the response force to arrive at the facility, as well as how long it takes the response force to effectively interrupt and neutralize an adversary force. These response times may be long, depending on the type of response force assigned to the facility. For example, if the response force is local law enforcement who have day jobs as well, response time may be longer than if response is assigned to law enforcement whose only responsibility is to respond to the SMR facility.

Although this study analyzed a response force strategy considering BBRE towers, there are many other options to implement an effective onsite response force. These methods can include an onsite response force that can be mobile and respond to adversary incursions and interrupt the adversary force at target locations. This will require a detailed response plan, training, and analysis to ensure the response force can effectively interrupt an adversary force. Another method is considering the use of BBREs that are not on towers but built into the actual plant buildings and elevated. These would not require towers but would require the building structures to be designed to support the BBREs. Additionally, these designs may allow for the BBREs to be able to engage both externally and internally and provide a defense-in-depth approach to the response force strategy.

Additionally, depending on the location of the urban SMR and the daily amount of foot and vehicle traffic around the facility, strict rules of engagement may be needed to limit unintended and adverse consequences to persons or vehicles outside the SMR facility. Finally, an SMR in an urban environment may be prone to more anti-nuclear protests or other protests than SMRs in rural environments. The SMR facility, guard force, and response force should develop a coordinated plan for handling protests. The plans should consider approaches for various types of protests (i.e., violent or non-violent), the number of protesters (i.e., hundreds or thousands), and identify the mitigations and contingencies to limit the impact on operations and security at the SMR facility.