Advanced Reactor Security-by-Design with AVERT® Physical Security (AVERT-PS) Modeling and Simulation

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ABSTRACT

The variety of envisioned advanced reactor designs, site configurations, and deployment locations presents facility and site designers with a wide range of new security considerations. While there are many new challenges in addressing these considerations, there are unique opportunities for security advancements through Security-by-Design (SeBD) of these new facilities and sites. Advancements in more effective and efficient security can be made while also advancing safety and safeguards through an integrated analysis of requirements and holistic solutions development. Developing these solutions depends upon subject matter expertise with access to, and proficiency in, advanced analysis tools. Future regulatory approaches to advanced reactor security are likely to be more performance-based. Advanced modeling and simulation tools will enable applicants to demonstrate required security system performance effectiveness for a variety of site configurations and deployment locations. The ability to rapidly evaluate the impact of facility and site design concepts and changes on security system performance is aided by modeling and simulation tools. Analysis tools developed by physical protection subject matter experts at Sandia National Laboratories (SNL) such as PathTrace© and Scribe3D© can help with identifying security risks and vulnerabilities as well as opportunities for initial design improvements. This initial work can inform and enable detailed, site-specific modeling and simulation analysis efforts in commercial tools. Here we describe the application of the AVERT® Physical Security (AVERT-PS) modeling and simulation software from ARES Security Corporation (ARES) to a generic Small Modular Reactor (SMR) model developed by SNL with initial security analysis done by using PathTrace© and Scribe3D©, described in SAND2021-0768, U.S. Domestic Small Modular Reactor Security by Design. The work focuses on the process for importing and configuring the model in AVERT-PS for subsequent analysis of active delay features and variations of on-site security and off-site response force levels, timeliness, and capacities for sabotage scenarios with the capability of AVERT-PS to enable rapid update and testing of security system designs and evaluate the resulting performance impacts.

INTRODUCTION

The Ken and Mary Alice Lindquist Department of Nuclear Engineering in the College of Engineering at The Pennsylvania State University offers a nuclear security option in its nuclear engineering master's program designed to educate and train the next generation of nuclear security experts. Available both in resident at University Park and online via Penn State World Campus, the nuclear security program at Penn State combines the technical, societal, and policy aspects of nuclear security with experience using state-of-the-art technologies, including the AVERT® Physical Security (AVERT-PS) modeling and simulation tool for hands-on security system design experience in a virtual environment. ARES Security Corporation (ARES) provides their AVERT-PS software to Penn State as part of the ARES commitment to supporting the education of tomorrow's leaders through their AVERT 4 Universities (A4U) program. With an intuitive user interface, AVERT-PS can quickly create a realistic 3D Digital Twin model of a facility that includes interior and exterior features or structures, access points and entrances, natural features, and the placement and configuration of all aspects of the physical protection system (PPS) and threat. AVERT-PS model parameters can be easily adjusted to test proposed design or threat changes enabling rapid testing with enhanced reporting and analysis tools.

Here we summarize the results of two culminating research projects for the Penn State World Campus Master of Engineering (M.Eng.) in Nuclear Engineering degree applying AVERT-PS to an advanced reactor, the integral-Pressurized Water Reactor (iPWR) Small Modular Reactor (SMR) generic model facility developed by Sandia National Laboratories (SNL) described in "U.S. Domestic Small Modular Reactor Security by Design" (SAND2021-0768). Here we explore some of the unique security design challenges of the envisioned new designs and deployments for advanced reactors, validating a portion of the SNL work through the use of AVERT-PS (version 8.6.3.1 Build 4 with Data Library 3.3), in particular the impact on PPS performance of various off-site response delay times; and we explore other variables such as the number of off-site responders and their relative skill levels in comparison to threat adversaries. The work was completed by the authors in two stages: in the first stage Calvin Luzum performed the initial model configuration and testing with Fletcher Boone continuing the work in the second stage by refining the configuration and testing additional design elements; Matthew Zerphy served as faculty advisor and assisted with initial model configuration and testing.

3D MODEL IMPORT AND CONFIGURATION IN AVERT-PS

SNL provided the generic Small Modular Reactor (SMR) model described in SAND2021-0768 for use in graduate student research in a demonstration of how to take an initial security assessment and system design using the PathTrace© and Scribe3D© tools available from SNL followed by an investment in more detailed design and scenario testing using commercial tools such as AVERT-PS. AVERT-PS supports the COLLADA file format (.dae file extension), and SNL provided the "iPWR_SMRv3_combined.dae" file for import into AVERT-PS. The authors are novice modelers and did not seek the assistance of experts in order to demonstrate that with only introductory skills, users could rapidly import and configure a workable model in AVERT-PS for more detailed PPS "what-if" analyses.

The initial file provided could not be imported into AVERT-PS. To troubleshoot, the file was imported into Blender (Long-term Support, LTS, Release 2.93.4) where it was discovered that the model contained many features used in Scribe3D© which were not recognizable by AVERT-PS. These extra model features were removed, and some additional work was done in Blender to add a plane with a large cutout around the basement-level portion of the reactor building to provide surrounding terrain around the SMR site. After exporting from Blender in .dae format, the file was successfully uploaded into AVERT-PS. Figure 1 shows the initial model in Blender on the left with the updated model on the right.

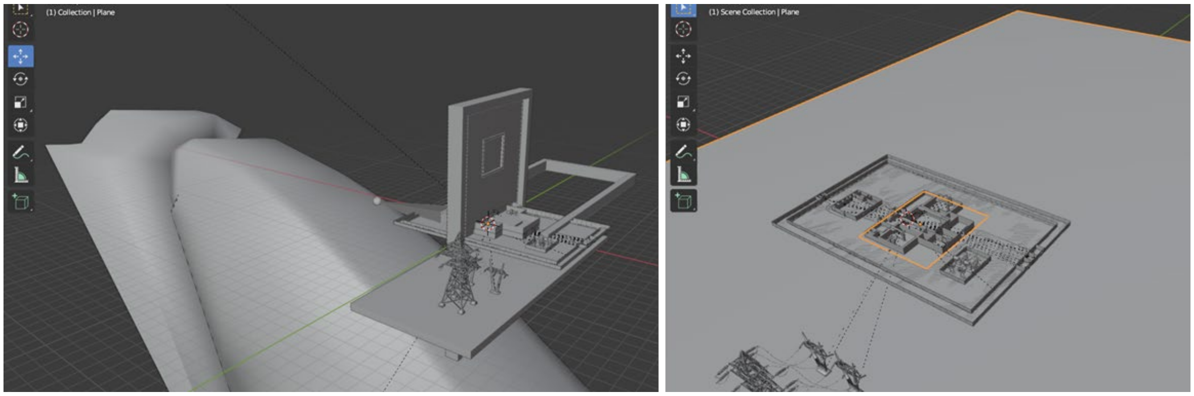

Figure 1. iPWR_SMRv3_combined.dae in Blender before and after editing.

Reviewing the model in AVERT-PS showed that some features were comprised of large, singular nodes which prevented a detailed application of features necessary to characterize the facility. Work in Blender allowed for the separation of nodes into discrete features such as walls, floors, roofs, and ceilings so that they could be assigned specific terrains or barrier patterns in AVERT-PS.

The model was tested in AVERT-PS by adding a single agent (guard or adversary) with a variety of paths to test movement throughout the site. It was quickly identified that the model did not support agent movement into and around the various buildings and rooms, which indicated a potential problem with the Navigation Mesh, or navmesh, a mesh of triangles covering all navigable regions to form a navigational node network used to path agents in a model. The "Navmesh Border" diagnostics analysis in AVERT-PS was used to investigate and showed (in blue voxels and yellow highlighted lines) discontinuities and "islands" in key locations, particularly in several doorways and landings. The problem was resolved by increasing the navmesh granularity for floor and ground type terrains within the AVERT-PS Library Editor with results shown in Figure 2.

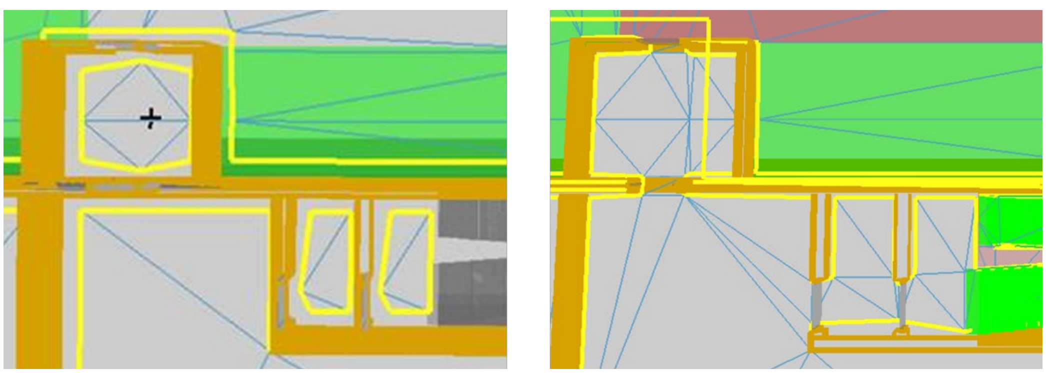

Figure 2. Disappearance of discontinuities (left) in AVERT-PS following terrain granularity adjustment (right).

<u>Configuring Model Node Physical Attributes</u>

The SMR site is surrounded by an outer and inner fence, interior to which there is an administration building, the reactor building, and a switchyard. The reactor building consists of one above-grade level and two below-grade levels. The above-grade level is comprised of nuclear and non-nuclear receiving areas, a spent fuel packaging area, turbine rooms, and auxiliary spaces. The below-grade levels house battery/generator spaces, passive safety injection tank (PSIT) rooms, and a reactor compartment with four iPWR modules and a spent fuel pool.

All physical nodes in the model were assigned a terrain or a barrier pattern in AVERT-PS to define the physical parameters of those nodes. Fences, gates, vehicle control devices, and doors were assigned no terrain, with applicable barrier patterns assigned (e.g., "Fence: Chain-Link|Outriggers") during PPS configuration. Except as otherwise noted, the remaining physical nodes for walls were assigned a "Building" terrain, which is impassible by agents; floors were assigned appropriate floor terrains to enable agent motion; roofs, stairs, tanks, and equipment were assigned the eponymous terrains; and exterior ground level nodes were assigned grass, gravel, and road terrains. The generic iPWR SMR model in the AVERT-PS Site Map wireframe view is shown in Figure 3.

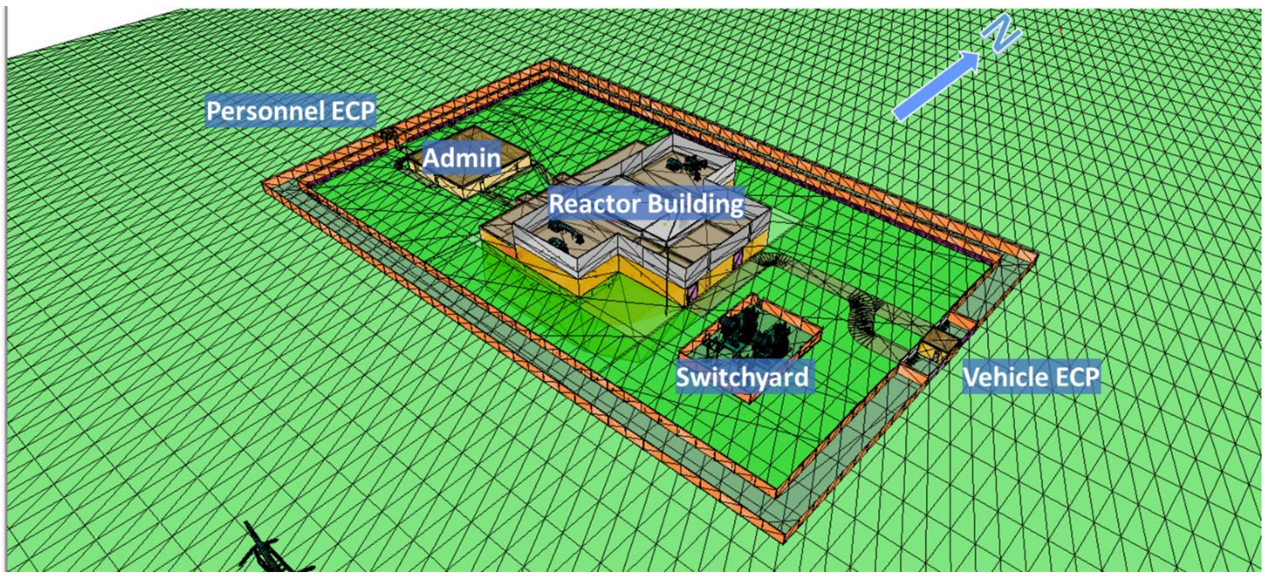

Figure 3. AVERT-PS model following successful upload (major features and North direction indicated).

Configuring the Design Basis Threat (DBT)

The Design Basis Threat (DBT) for this analysis was the SAND2021-0768 maximum threat of 8 attackers in two teams of four configured with the same equipment in the AVERT-PS Adversaries menu of the Scenario Editor panel; details are provided in Table 1. During the first stage of work, a single target of an iPWR module accessible via the basement level was used; in the second stage, the number of adversary objectives was increased to four objectives consistent with SAND2021-0768: the reactor core, the switchyard, and both the PSIT and battery/generator rooms. Objective completion times were set for each of the four objectives per SAND2021-0768: 300 seconds for both the switchyard and battery/generator room, 480 seconds for the PSIT room, and 1440 seconds for the sabotage of the reactor compartment.

The adversaries were set in AVERT-PS to approach the SMR site and move to the targets/ objectives as quickly as possible, with no concern for avoiding detection or the guard force (the "Fastest" Strategy setting). The DBT adversaries are assumed to have some weapons and combat training. The overarching goal of the adversaries is to sabotage all four objectives in the SMR facility to cause a radiological incident. The adversaries approach the facility on foot from two directions (one team of four starts to the north, the other to the east).

Threat Summary	
Size	8 attackers evenly divided into 2 teams
Weapons/Explosives	• Each team member armed with a 9mm pistol • 1 member (nominal leader) armed with a 7.62mm assault rifle • 1 member armed with a 7.62mm machine gun • 2 members each armed with a 7.62mm assault rifle and 2 breaching explosives
Tools/Equipment	Body armor and hand tools
Transportation	On foot
Knowledge	Assumed knowledgeable of facility layout, target location, and security system
Technical Skills	Military or military-style training, demolition, general engineering, operational security

Table 1. Summary Description of Threat

Configuring the Baseline PPS

The SMR site is surrounded by an outer and inner fence (8' height with outriggers) separated by an isolation zone configured with a perimeter intrusion detection and assessment system (PIDAS) with additional detection measures including outward-facing thermal cameras mounted in the fence lines and optical cameras installed around both entry points. There are also two optical cameras mounted outside of the administrative building and four mounted outside the reactor building. In total these detection measures provide 360-degree coverage of the surrounding area and facility grounds. Entry to the site is via gates at two entry control points (ECPs), one for personnel and one for vehicles on the opposite side of the site. When not in use, the vehicle ECP maintains the gates shut with vehicle bollards raised. The personnel ECP is equipped with a portal metal detector, a portal explosives detector, and an x-ray machine. Site access is controlled through proximity cards with associated person identification numbers (PINs) and biometric hand scanners for the reactor building. The central alarm station (CAS), originally in the administration building, was moved to a room in the below-grade level of the reactor building. The reactor building contains several passive infrared sensors and surveillance cameras, and each door is equipped with a balanced magnetic switch. All of these PPS items were available for easy selection and configuration via the Barriers and Detectors menus in the Scenario Editor tool in AVERT-PS.

The security force is comprised of both on-site guards and off-site responders. Off-site responders are held to the west of the site within an opaque barrier ("Debug: RF Team Barrier") that was created in the Library Editor. This barrier was a copy of the existing "Debug: Impassible Barrier" modified to enable the Platform of the "4WD: Armored" vehicle assigned to each response force team to traverse the barrier, P(traversal)=1, at the assigned time (e.g., 1.8E3 mean, in seconds, for a 30-minute off-site response time). The barrier prevents interaction until a user-defined response time is reached in the simulation, at which point the off-site responders proceed to the personnel ECP. The on-site guard force consists of five guards, two of whom man the personnel ECP with the other three posted in the CAS. The personnel ECP is continuously manned with two personnel; the vehicle ECP is unmanned and shutdown to external access except during refueling operations. Two guards in the CAS are CAS operators who are overseen by the CAS supervisor. In the baseline PPS, on-site guards are under-equipped and in lower numbers than the DBT so they remain at their posts, calling for and awaiting off-site responders. The "enhanced" on-site posture permits some guards to move with the intent to neutralize adversaries. The number, location, equipment, and actions of the on-site guard force and the off-site response force in the event of an attack is summarized in Table 2. Other than the timed response barrier, all items and attributes were easily available for selection in the Guards menu of the Scenario Editor in AVERT-PS.

Security Force Summary		
On-Site Guard Force	Number	5 on-site security guards
	Weapons/Equipment	Baseline: each guard armed with 9mm pistols, handcuffs, radio Enhanced: each guard additionally equipped with a 5.56mm assault rifle
	Location	• 2 guards at personnel ECP • 3 guards, including a supervisor, in the CAS
	Response	Baseline: all guards remain posted Enhanced: all guards respond with the intent to neutralize adversaries, except 1 guard remains in CAS to continue to coordinate response actions
Off-Site Response Force	Number	10 off-site response force personnel
	Weapons/Equipment	Each armed with a 5.56mm assault rifle, 9mm pistol, handcuffs, and radio
	Location	Off-site with ability to arrive within 30 minutes (default, other times explored)
	Response	Upon arrival on site, all responders proceed to neutralize adversaries

Table 2. Summary Description of On-Site and Off-Site Secuirty Force

BASELINE PPS UPGRADES AND PERFORMANCE

In the first stage of this study, the SMR model in AVERT-PS was updated in accordance with upgrades 1 through 4 and the facility safety and security upgrade documented in SAND2021-0768, as closely as possible. For upgrade 1 (Mantraps, Visual Obscurants, and Slippery Agents) visual obscurants were an existing Barrier pattern in the AVERT-PS Data Library; however, other items were modeled by substituting and/or modifying other patterns or creating new ones in the Library Editor. Stairwell mantraps were simulated by setting the stairwell door nodes to be both steel doors and turnstiles to limit the number of people who could proceed at a time. Slippery agents were simulated by creating a separate "On Foot Adversary" Platform to apply to adversary agents and creating a new barrier pattern for a slippery agent that only affected adversary feet. For upgrade 2 (Hardened Overhead Doors and Mantrap), a concrete vehicle barrier pattern was applied to the overhead door nodes while a mantrap identical to that from upgrade 1 was applied to the entrance on the west side of the reactor building and in the basement level of the reactor building. For upgrade 3 (Active Delays and Extended Detection Range), visual obscurants and slippery agents were applied as described in upgrade 1 to additional areas as in SAND2021-0768. For extending the detection range, two detection capabilities were added: thermal, infrared surveillance cameras on top of the exterior fence facing outward with ground radar detection around the site providing detection capability 150m past the exterior fence. Upgrade 4 (Interior Reactor Building Walls) modeling was limited by the reactor building walls in the model being comprised of only two nodes: one for the interior walls and one for the exterior walls, thus all interior walls were upgraded rather than only the area surrounding the iPWR modules. Previously these reinforced concrete walls were set in AVERT-PS to have a terrain of "Building," which is impenetrable. Setting the terrain of the below-grade walls to "No terrain" with a barrier "Wall: 36-48" Concrete|Mesh" gave adversaries the ability to breach if it resulted in a faster path. The final upgrade in the first stage work (Additional Safety and Security) included additional reactor building ingress and egress points, expanded use of visual obscurants and slippery agents, and moving the CAS and its operators from the admin building to a room adjacent to the control room in the basement level of the reactor building.

ADDITIONAL PPS UPGRADES AND PERFORMANCE

The second stage work of this study built on the first to further align the AVERT-PS model with the configuration described in SAND2021-0768 and explore some new PPS design changes, taking advantage of the ability to rapidly update PPS configurations in AVERT-PS. In addition to the "baseline," the impact of an "enhanced" on-site security posture was investigated along with manipulating three different variables to determine the effects on PPS performance: 1) the number of responders in the off-site response force, 2) off-site response time (including no response), and 3) the combat skill level of the off-site responders.

It is likely that off-site responders would not be employees of the SMR owner/operator and could be from a variety of external organizations such as local law enforcement agencies (LLEAs) comprised of a variety of different team sizes, equipment, and training depending upon the SMR deployment location. This study included an "enhanced" on-site guard configuration to investigate the impact of different on-site operating posture and equipment on overall PPS effectiveness given a variety of off-site response parameters. The expectation is that an enhanced on-site physical security posture might still allow for acceptable PPS performance in the event that the off-site response force is less effective than anticipated. The changes from the baseline to enhanced on-site PPS are designed to be relatively low cost: 1) equipping the on-site guards with 5.56mm rifles in addition to 9mm pistols, 2) having four of the five members of the security force move to neutralize the attackers upon detection (the CAS supervisor remains posted).

Initial Results were obtained using the standard response force parameters noted in Table 2 above for both the baseline on-site PPS and the enhanced on-site PPS; results can be seen in the "30-minutes" rows of Table 3. The AVERT-PS Simulation Editor was set to 5 Attack Plans with 10 Attacks per Plan. "Worst P(e)" is the lowest probability of PPS effectiveness out of the attack plans, and "% Damage" is the average percentage of the four objectives that the adversaries were able to successfully complete across all fifty attacks. (The "Objective Value" was left at the default value of "1" with "Win Criteria" left blank and defaulting to a value of "4" meaning that all four objectives must be achieved in an attack in order for the PPS to be considered ineffective.) Finally, "Average time" refers to the average time that elapsed during each attack before either the adversaries completed all four sabotage objectives or all adversaries were neutralized. The initial results for the baseline on-site guard posture are consistent with those of SAND2021-0768.

<u>Varying Response Time</u>

As in SAND2021-0768, 30-minute and 60-minute response times we evaluated; this study also explored 15-minute and 45-minute response times as well as no off-site response. All other security force inputs remained as shown in Table 2. The different response times were set by altering the "Traversal Time" parameters for the "Debug: RF Team Barrier" in the AVERT-PS library. The results demonstrate the need for a credible off-site response. It is notable that the average time for the baseline no-response (the average time needed for adversaries to complete all objectives absent off-site response or interruption by on-site guards) is similar to the time in SAND2021-0768 with the sequential attack strategy. The P(e) for the baseline 15-minute response case is a result of responders arriving while adversaries are outside the reactor building and able to engage responders at range and without cover. The enhanced on-site PPS condition performed as well or better in all five cases and reduced the fluctuation of worst-case P(e) across the response-time conditions. ("% Damage" is at least 25.0% in all cases because the adversaries always reach the switchyard and sabotage it before being interrupted and neutralized.)

Off-Site Response time	Condition	Worst P(e)	% Damage	Average time (hh:mm:ss)
15 minutes	Baseline	60%	39.5%	39:12
	Enhanced	90%	27.0%	20:27
30 minutes	Baseline	90%	30.5%	39:33
	Enhanced	90%	26.5%	33:45
45 minutes	Baseline	80%	34.5%	54:18
	Enhanced	100%	25.5%	48:12
60 minutes	Baseline	70%	34.5%	1:08:22
	Enhanced	100%	25.0%	1:01:57
No Off-Site Response	Baseline	0%	100.0%	1:45:52
	Enhanced	10%	79.0%	1:31:12

Table 3. PPS Performance for Various Off-Site Response Times for Baseline and Enhanced On-Site Security

Varying the Number of Off-Site Responders

While SAND2021-0768 investigated the impact of changing the number of adversaries, we investigated the impact of various numbers of off-site responders (12, 10, 8, and 6) using the default 30-minute response time. All other security force inputs shown in Table 2 remained the same. Changes were made in AVERT-PS by changing the number of guards in each team of responders: 6, 5, 4, and 3 in each team of responders. The AVERT-PS simulation results in Table 4 show a significant decrease in PPS performance below 10 off-site responders; however, the enhanced on-site posture mitigates the impact of a smaller off-site response force.

Off-Site Response time	Condition	Worst P(e)	% Damage	Average time (hh:mm:ss)
12 Responders	Baseline	90%	27.0%	35:08
	Enhanced	100%	25.0%	31:38
10 Responders	Baseline	90%	30.5%	39:33
	Enhanced	90%	26.5%	33:45
8 Responders	Baseline	60%	45.0%	58:56
	Enhanced	90%	29.5%	39:12
6 Responders	Baseline	40%	66.0%	1:22:15
	Enhanced	70%	38.8%	53:57

Table 4. PPS Performance for Various Off-Site Response Force Sizes in Baseline and Enhanced On-Site Security

Varying Off-Site Responder Combat Skill Level

SAND2021-0768 and all other analysis in this study assumed guards and adversaries have equal training, skills, and proficiency. The AVERT-PS Reference Manual describes the default combat skill level value of 1.0 as "trained personnel" while a value of 0.5 would be an untrained "person off the street." Also, AVERT-PS combat skill levels are relative when using the same weapon (an agent set to 1.0 would have twice the skill as an agent set to 0.5 using the exact same weapon). Only the combat skill level of the off-site responders was changed; all other response force parameters are at the baseline values in Table 2, and no changes were made to on-site guards or adversaries. The inconclusive results shown in Table 5 could indicate that weapons proficiency is not important in this scenario where responders are encountering the adversaries at extremely close ranges inside the reactor building, possibly where training level could be less impactful. More investigation is warranted. Again, the enhanced on-site security posture out-performed the baseline condition and did not decrease effectiveness as responder combat skill level decreased.

Combat Skill	Condition	Worst P(e)	% Damage	Average time (hh:mm:ss)
1.0	Baseline	90%	30.5%	39:33
	Enhanced	90%	26.5%	33:45
0.75	Baseline	80%	31.0%	38:40
	Enhanced	100%	25.0%	31:40
0.5	Baseline	80%	30.0%	37:29
	Enhanced	100%	25.5%	33:28

Table 5. PPS Performance for Various Off-Site Response Force Skill Levels in Comparison to Attackers

CONCLUSION

Managing security costs is essential for the economic viability of advanced reactor deployments and will likely include some reliance on off-site response. Building on the work of SAND2021-0768 using AVERT-PS, this study shows that a small but well-quipped and trained ("enhanced") on-site guard force can help ensure PPS effectiveness for a range of off-site response capabilities and variations (numbers, skill level, and timeliness). The impetus for initiating this study and continuing benefits include:

- Understand the steps and considerations for transitioning a model from an initial study using SNL tools to commercial tools such as AVERT-PS for continuing analysis with the capability to rapidly test a variety of new PPS and threat configurations for a variety of advanced reactor deployment scenarios.
- Develop a model for use and demonstration across the spectrum of available tools (PathTrace©, Scribe3D©, and AVERT-PS) for use in education and training to accomplish nuclear security learning objectives and show how these tools can be used for successive levels of investment along the progression from initial design to complete and dynamic modeling of design tradeoffs. Penn State will begin using the generic iPWR SMR model, in addition to the small hardened-facility and a generic large light-water reactor (LLWR) site training models provided by ARES, in nuclear security program curriculum to build capacity in understanding and using modeling tools for SeBD of advanced reactors.
- Provide insights into areas for future research to improve advanced reactor SeBD concepts, tools, and practices.

Areas for future work to improve the iPWR SMR model in AVERT-PS and to continue using the model for advanced reactor SeBD research include:

- Perform AVERT-PS simulations with an increased number of attack plans and numbers of attacks per plan to generate larger data sets for statistical analysis to further distinguish the effects of variable manipulations considered in this study and future work.

- Analyze the impact on "% Damage" for attacks in which the two adversary teams remain split and proceed on opposite sequences of objectives (rather than converging on the same initial objective and proceeding with the same objective attack sequence).
- Investigate different adversary attack strategies in AVERT-PS (e.g., avoiding detection, avoiding firepower, or a combination of factors) on PPS performance.
- Explore a range of security force response postures to include on-site guard strategies other than "Neutralize" and the application of Advanced Behaviors in AVERT-PS along with interior and exterior defensive fighting positions to determine if there are additional design considerations that could further improve PPS performance while also reducing the number of on-site guards and extending off-site response times.
- Adjust AVERT-PS Library parameters to ensure alignment with parameters used in SAND2021-0768 to enable more effective comparison between analyses.
- Review and refine the model with expert modeling assistance to identify and correct any remaining agent movement problems and enable the application of more specific terrains and barriers.

ACKNOWLEDGEMENTS

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