Advanced Reactor Safeguards & Security

Advanced Delay Technologies

Prepared for
US Department of Energy

Andrew Thompson and James Youchison

Sandia National Laboratories

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Advanced Reactor Safeguards and Security – Advanced Delay Technologies

Andrew Thompson, James Youchison

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

Security accounts for a significant operating cost for the current nuclear power fleet. This report outlines best practices for reducing the cost of implementing access delay features into new construction of advanced reactors to minimize this burden as the next generation of reactor facilities is built. This report outlines several key principles for integrating and evaluating delay barriers or systems into a new construction facility and provides an overview of several technologies that have been proposed to increase the access delay times associated with the physical protection system in nuclear reactor facilities.

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EXECUTIVE SUMMARY

As a new generation of reactors is developed, reducing the cost of physical security without impacting the required system effectiveness will help to make new reactors economical. This report discusses several access delay technologies available to help improve the overall effectiveness of the physical security system. These technologies include both passive and active delay elements, as well as guidance on best practices related to security by design principles.

Technologies discussed include additive construction with a focus on 3D-printed concretes, obscurants, foams, dispensable liquids, less-lethal systems, and lethal systems. The benefits and drawbacks of each of these types of delay systems are discussed. In general, some active delay or denial systems can be effective when properly integrated into a physical security system, but care should be taken to look at the potential ongoing costs as well as the additional risks that these systems can introduce. Passive barriers are also discussed, and in many cases significant savings can be likely be found through optimization of more traditional barriers.

While these technologies can be effective ways to increase delay, evaluation of the system and integration into the facility design are the most critical steps to keeping the cost of the physical protection system down over the lifespan of the reactor. Security experts should be engaged early in the design phase and security should play a role in facility design. Modeling and simulation should be used to generate data supporting cost/benefit evaluations related to design decisions. Care should be taken to design the facility with an eye to the future to ensure that upgrades, maintenance, and expandability are all considered in the design phase.

The following list outlines the key takeaways from this report:

- Utilize Security by Design principles to integrate security elements and access delay systems into the design at early stages.
    - Engage security professionals while the design is still fluid and can be easily modified, as small changes to the facility layout can greatly improve security.
    - Adding security in at later design phases or retrofitting security systems after initial construction is significantly more expensive and less effective.
- Use modeling and simulation tools during early design phases to evaluate different configurations of security elements to optimize cost to benefit and ensure security requirements are being met.
- Utilize delay in depth principles to make efficient delay systems.
    - Multiple barriers requiring different tools and methods to breach can add significant delay time and increase the required adversary knowledge and skillset.
    - If active delay systems are used, consider the consequences of a system failure.
        - This possibility can be mitigated with independent and redundant active delay systems or with robust passive barriers.

- 3D printed concrete is a promising construction method for reducing costs, but it is still in the early stages and requires testing prior to implementation as an access delay barrier.
    - Additional challenges such as building codes, widely varying print media, and costs associated with early adoption should be evaluated if 3D printed concrete is considered for a design.
    - As 3D printed concrete becomes more widely adopted, there may be significant cost savings for mass production or modular fabrication of reactor facilities.
- A range of active delay and denial systems including obscurants, foams, dispensable liquids, less-lethal systems, and lethal systems could be utilized to increase delay.
    - Active systems are most effective when paired with passive barriers to increase task times.
    - Active systems require command-and-control equipment that can be a significant initial investment and that will require budgeting for ongoing maintenance and upgrades as the system ages.
    - When considering active delay systems, include flexible infrastructure such as power and communications in the design to allow for flexibility if a system or component reaches end-of-life.
    - Utilize test data along with modeling and simulation to evaluate the benefit of active delay systems.
    - These systems are most reliable when controlled from an on-site location to reduce the chance of the connection being interrupted or disconnected.

ACRONYMS AND TERMS

Acronym/Term	Definition
ARSS	Advanced Reactor Safeguards and Security
PPS	Physical protection system
SBD	Security by Design
ADS	Active delay system
3DPC	Three-dimensional printed concreted
C2	Command and control
ROWS	Remotely operated weapon system
PPE	Personal protective equipment
3SBD	Safety, Security, and Safeguards by Design
LWRS	Light Water Reactor Sustainability
UAS	Unmanned aerial system
UAV	Unmanned aerial vehicle
CUAS	Counter unmanned aerial system
NRC	Nuclear Regulatory Commission

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1. OVERVIEW

The Advanced Reactor Safeguards and Security (ARSS) program was developed to aid in reducing safeguards and security costs, solving regulatory challenges, and providing best practices for developing modern physical protection systems (PPS) for the deployment of new advanced reactor designs.

The advanced delay technologies project within the ARSS program was developed to help provide guidance on new or less utilized access delay technologies to assist manufacturers and future operators of 4th generation reactors in reducing the overall cost of access delay systems at a facility without degrading the performance. The goal of this report is to provide information to the industry on some of these technologies and guidance on how to evaluate the cost/benefit of each of them when designing a new facility. Security-by-design (SBD) is a core principle of this work. Integrating security into the design phase can greatly reduce the associated costs compared to attempting to add it at the end or performing a retrofit after the facility is constructed and this integration likely will be the most impactful step in minimizing costs related to the PPS. Taking advantage of modern physical protection system tools during the design phase to optimize the access delay system will provide significant cost reductions both for construction as well as ongoing maintenance. Forward thinking about how to protect against new and emerging threats will also provide flexibility for the system for future upgrades if required.

Reducing the cost burden of security will help to make Gen IV nuclear reactors more economically viable and ultimately help to reduce the reliance on petrochemical energy as well as to reduce reliance on foreign interests for energy production.

2. TECHNOLOGIES

There have been many advances across a wide range of disciplines since the last large push to construct new nuclear power reactors in the United States. These advances range from emerging technologies that are still in their infancy like additive construction to a range of active delay systems (ADS) and even improved modeling and simulation tools. All these options provide an opportunity to implement security by design practices in order to develop cost-efficient access delay systems to help reduce both the construction and operating expenses of new construction reactors.

This section will focus on introducing technologies that have the potential to reduce the cost of access delay systems as part of the PPS within nuclear reactor facilities. While each of these technologies can be another tool in the toolbox, none of them are a silver bullet. Each technology has benefits and drawbacks and each of them must be used in coordination with the rest of a well-designed PPS.

Modeling and simulation tools will help to provide the basis for optimizing the access delay barriers to provide the delay needed for the rest of the PPS to function and should be the foundation of any design. These modeling and simulation tools should be implemented early in the design phase so that the facility itself can be optimized to support the PPS in addition to other design considerations. Similarly, testing of proposed technologies in each application should be performed early to identify the ones that provide the most delay. Passive barrier delay times can typically be estimated for traditional materials, but the delay times provided by active delay systems can vary significantly depending on application and should be tested to ensure they provide the intended effects. Passive barriers that stray from typical reinforced concrete construction may require testing as well. Security by design principles can greatly reduce the cost and increase the effectiveness of delay barriers by designing the facilities to support security rather than trying to add security in once the design has already been developed. These early simulation efforts can also help to evaluate the sensitivity of system performance, which in turn can provide feedback on where to improve the system to make it more robust.

2.1. Additive Construction

Additive construction methods, including three-dimensional printed concrete (3DPC), have been an area of study across many industries recently. There are aspects of the technology that show promise for reducing the cost of concrete construction, but it has had limited commercial implementation to date. Additive construction, and 3DPC in particular, provides several opportunities for access delay including adjusting the wall structure to focus additional delay as needed, creating hollow concrete shells or forms to aid in composite wall construction, and allowing for novel geometries that may be more blast resistant. Additionally, sensing capabilities can be easily incorporated for increased situational awareness and structural health monitoring. To date there is little to no publicly published data about 3DPC or other additive construction methods in access delay applications, so many of these potential benefits are not yet backed by data that the authors are aware of.

While the 3DPC industry is rapidly developing, there are still hurdles to overcome. Challenges such as scalability, building code approvals, integration of 3DPC walls with other structural members, modifications to the structure, use case change of the structure, and print media supply chains are still being addressed. It is likely these technologies will be improved with time, but early engagement on these options will be critical for any advanced reactor being designed today that would like to implement 3DPC during construction.

From literature review and case studies, the reported reduction in construction cost ranges from 30–50% when compared to traditional methods. This reduction is due to the elimination of formwork material and labor costs. Formwork material cost accounts for up to 30%, while the manual labor accounts for 20% of the total cost of the concrete structure [1]. Depending on the complexity of the structure, the cost associated with formwork can be reduced further with 3DPC. The cost reduction associated with construction time is driven by the reduction in labor hours [2].

One company claims a 50–80% reduction of unskilled labor, 50–80% reduction in construction time, and a 90% reduction in material loss, resulting in a reduction of cost by more than 50% [3].

Current industry leaders quote raw material in a range from $19–$35 per square foot. However, it should be noted that this quote does not include costs associated with transportation of hardware and materials, labor needed to set up and run the machines, or renting and running the machine. Once all the hidden costs are realized the actual cost ranges from $168–$330 per square foot. Weng et al. estimated the cost of 3DCP materials to be 123 USD/m^2 [4]. García de Soto et al. estimated that the total printing cost (labor + material + equipment) is 1418 USD/m^3 for a straight concrete wall of 4.39 m^3 print volume when using a robotic arm printer [5]. 3DPC is typically used for wall fabrication, but there are additional costs to complete the structure, such as installation of roofs. Foundations are cheaper to produce through traditional means.

There is significant variation on pricing, depending on the concrete mix, equipment, overhead, geometry, and purpose of the structure. For example, a foundation wall measuring 20 meters wide, 0.305 meter thick, and 4 meters tall was reported to cost $40 per cubic meter [1]. While companies like COBOD, 1 Print Infrastructure, Diamond Age 3D, ICON, and Apis Cor Inc quoted a cost of $330 per square foot, $168 per square foot, $26.70–$85.57 per square foot, $25–$80 per square foot, and $275 per square foot, respectively [6].

Another area 3DPC claims to reduce cost is construction time. A 219.3 m^2 villa structure would be constructed in about 32 days utilizing 3DPC, a 400 m^2 two-story villa in 45 days [5]. The largest two-story 3DPC structure with a total area of 640 m^2 was completed in 500 hours of machine time; the machine worked eight hours a day over 63 days. A one-story home measuring 38 m^2 was printed in 24 hours of machine time, over the course of 3 days [7].

While these studies do show that there are potential cost reductions, they also do not often cover all the included costs. Many of the studies focus solely on the labor and material costs, but do not address the additional costs, such as logistical costs of transportation of the printing equipment and print media. For concrete printers that rely on proprietary mixtures, transportation costs can be extremely high compared to locally sourced materials. Some manufacturers are putting an emphasis on developing methods for using locally sourced concrete. Similarly, transportation costs may be able to be heavily reduced when this technology is used to manufacture a large number of structures in a small area. All these considerations should be taken into account when considering whether 3D printed concrete could provide a cost savings for the construction of reactors.

3DPC has the potential of reducing these costs but is still in the early phases. There are only a few companies that would be able to support a large-scale effort. 3DPC will have the largest impact on highly complex and unique structures that would require a large amount of labor and formwork. While the technology shows great promise, it is still under development and needs to overcome some major hurdles. From an access delay perspective, the breach and blast resistance of 3DPC is unknown and performance should be tested prior to implementation. An additional challenge is that there is a wide range of materials with different physical properties being used by various companies, and the performance of one may not be equivalent to another. Due to the technology still being under development, it has not been widely adopted in industry and is currently more costly than traditional construction methods. Once the technology matures and proprietary concrete mix can be purchased at lower price points or printing can be done with locally sourced materials, it has the possibility to replace some traditional methods. Until then, 3DPC will not have a significant economic impact to the construction industry.

Benefits:

- Tailorable designs that provide delay to key areas while minimizing material needed in others.
- 3DPC forms for composite walls designed to increase protection against a range of potential insults.
- Complex structure geometry may allow for better shedding of blast loads (ongoing area of research).

Concerns

- Unproven to date in security applications.
  - Little to no publicly published research on this topic.
- Still in early phases of deployment, and true cost of implementation is likely still high.
  - May be opportunity for cost reduction in mass production or modular fabrication.
  - Proprietary media used with some 3DPC printers may be costly to deliver to site depending on location.
    - Local material might not be suitable for use in a specific machine.
  - Transportation and setup of printer.
  - Still developing common methods for integrating 3DPC walls into the remainder of structures (attaching roof, etc.)

    - Will improve with time if technology becomes more widely adopted.

- Building code considerations
    - Not currently permitted in most building codes, requiring a significant test effort to perform the testing needed to get approval; this concern could also be reduced as time moves forward with approved construction.
- Building use case change and modifications
    - Making even minor modifications to a structure would be more difficult and costly compared to modifications made in a traditional non-concrete structure.

2.2. Active Delay Systems

Active delay systems (ADSs) are another option for slowing an adversary. Active delay systems are deployable barriers, materials, etc., which can increase the task time for an adversary. These systems typically require a command-and-control (C2) system that is used to activate the access delay elements in case of an attack. These C2 systems are frequently one of the downsides of active delay systems, as long-term support of a specific platform is not always guaranteed, and hardware and software updates and maintenance can prove to be a non-trivial cost. There is also a risk that the platform may go entirely out of support and have to be replaced to maintain system effectiveness. The active delay systems also must be inspected and tested regularly to ensure all portions of the system continue to function. The costs of maintenance, training, testing, and updating the equipment all need to be budgeted for and kept up to date.

Installation of ADSs cover a wide range of costs but are most cost effectively installed when the infrastructure is designed as part of the facility. Retrofits of the communication and power needed can be extremely high cost in a facility that is already built, and even more so in one that is already operational. In addition to the infrastructure, the C2 system itself can also be high cost. A good C2 system will have been thoroughly tested to meet high reliability standards, which in turn drives the cost of the final product up.

Active delay systems work best when paired with passive delay systems. The ADSs will complicate the task of defeating the passive barrier, forcing an adversary to work on that task even longer. ADSs typically do not provide significant increases in delay time unless they are paired with passive barriers.

One significant concern with active delay is the effect it might have on physical security system performance if it fails to activate. There are a range of scenarios where this failure could happen from poor maintenance to an unexpected hardware failure or even an insider disabling the system. The overall PPS needs to be designed in such a way that the active barrier system has redundancies or is not explicitly required to meet a minimum acceptable protection level. Line monitoring is helpful for preventing an insider from disabling an active delay system by cutting the cables, and having two-person controls for enabling or disabling high consequence ADS elements can help to minimize some of these risks.

Similarly, there can be cybersecurity risks that exist with active delay systems as well. The potential of disabling the system exists, but so does activating it at inopportune times. This action could be done as part of another larger attack, or even just done as a nuisance. This risk can be reduced by utilizing an air-gapped system to prevent remote attacks and following best practices for securing the hardware and network. There has been wide interest in utilizing wireless security system components in new designs to reduce infrastructure costs. Wireless systems increase the risk of both an adversary being able to take control of the system as well as a denial of service or jamming style attack. Strong encryption, jam resistant technologies, and system monitoring should be implemented if wireless technologies are implemented, but hard-wired systems that are not connected to external networks are preferred for high security implementations. Another factor to consider with wireless implementations is the speed of innovation in the space. Many wireless devices are only officially supported for a few years and cease to get firmware updates to ensure identified vulnerabilities in the wireless implementation are patched. As a result, an initial installation of a wireless system may seem like an appealing way to minimize initial investment, but costs over the lifespan should be considered accounting for more rapid hardware refresh cycles and more aggressive maintenance and firmware updates due to the broader attack surface that wireless provides an adversary.

System analysis with active delay systems can also be more challenging than analysis with passive barriers. Active delay systems have the potential of not deploying when needed, so the sensitivity of the system to an individual component failure should be considered. It can be challenging to evaluate the reliability of an active delay system, which increases uncertainty in system effectiveness analysis. The potential of a system failing can be reduced by having multiple independent systems, but that also increases the associated costs.

- Command-and-control systems required for many active delay systems can be a high-cost initial investment and require ongoing maintenance and upgrade costs for the lifespan of the reactor.
    - Human-in-the-loop based C2 systems can also have significant training and staffing costs.
- Efficiency is largely dependent on implementation.
    - Many active delay systems provide minimal delay on their own and typically rely on synergistic effects with passive delay elements for the highest efficacy.
- Active delay is less reliable than passive delay.
    - If an active system fails to function, the remaining delay systems need to still provide enough delay to maintain overall system effectiveness.
    - It can be challenging to determine a realistic probability of an ADS failure for running full system evaluation.
    - Having multiple independent and redundant ADSs can help to minimize this risk.
- Active delay systems open insider and cyber threat concerns.

    - An air-gapped local system is recommended to minimize the chances of the system being disabled or overtaken via connectivity.
    - Two-person control is recommended for any active systems that could have a significant effect on overall security or result in a costly activation (particularly if it could have other effects on the plant such as a shut-down).
- Supply chain can be inconsistent for active systems, particularly over long lifespans.
    - Power plants have long life cycles, resulting in a high chance of companies that support the systems going out of business, hardware or software becoming obsolete, or even for the materials used to no longer be available. Plans should be in place for how to address these situations if active delay systems are utilized.
    - Unavailability of a component can require cascading upgrades and potentially costly compensatory measures while the system is upgraded.
- Maintenance and testing can vary depending on the ADS used.
    - Some materials have limited shelf life and will need to be switched out regularly, resulting in material and labor costs.
    - Testing systems that release materials and require clean-up can be challenging to fully test to ensure reliable operation.

2.2.1. Obscurants

Visual obscurants like smokes and fogs can be used to increase the complexity of tasks that require clear sight. Tasks that require an adversary to identify a specific part of a complex structure, to navigate a crowded space, or to see features like a combination lock dial are examples of uses where visual obscurants can be effective. In simple tasks, it is typically less effective.

Installation of smokes and obscurant systems can range widely in cost depending on the volume to obscure and the type of obscurant selected. The most common commercial obscurants on the market are foggers like those used at concerts. These devices are widely marketed as anti-burglar systems and use fog bases such as propylene glycol. One of the downsides to these systems is that the heating system either must be constantly on to deploy in the shortest time possible or will have some ramp-up time to get to heat before it will produce a fog. Additionally, there can be maintenance to ensure that the system has not had any leaks and that the heating elements are clean, as buildup can cause issues. One of the main benefits to foggers is that while they will still leave a film of whatever base material is used to generate the fog, this residue is often easier to clean up and less harmful than some of the compounds generated by other smoke generators.

Another obscurant option is pyrotechnic smoke. Pyrotechnic smokes use a combustion reaction to quickly generate smokes. An example of these devices is smoke grenades. The combustion reaction can generate compounds and particulates that can be harmful if inhaled and that can be corrosive/reactive with other materials.

Irritants like CS or OC can be added to obscurants to increase their effectiveness against poorly prepared adversaries. Personal protective equipment (PPE) can be effective in limiting the effects of irritants but creates challenging working conditions and increases the likelihood that an adversary makes a mistake allowing the irritant to bypass PPE. These irritants typically increase the difficulty of cleanup and can cause lingering effects in a facility until the cleanup is complete. Irritants also carry the risk of being more likely to cause respiratory problems and discomfort for staff who may be in the area when the system is triggered, whether intentionally or accidentally. Some irritant effects can linger after the initial release and could require PPE for cleanup.

Aqueous foam can also be used as an obscurant but will be discussed in more detail in the foams section.

The level of automation in an obscurant system will be tied to the potential consequences of a dispersal. A fogger deployed in a room without any critical equipment or electronics and generally consisting of smooth surfaces that will be easy to clean could be automatically triggered since the effects of an unintended dispersal are low risk. If irritants are used or if cleanup could pose safety risks or significant financial impacts, then it may be preferable to have a human-in-the-loop C2 system to decrease the likelihood of an unintended activation. As an example, smokes or fogs in a contaminated area would create radioactive waste from the cleanup, leading to both a potential impact on safety as well as significant financial burdens.

Both effectiveness and cost of an active obscurant system are highly dependent on the system selected and the implementation in a facility. Installation costs will include a C2 system, infrastructure such as low voltage or fiber communications, and power. As with all active systems, system reliability is important and should be considered when analyzing system effectiveness. Redundant and independent systems can reduce the potential impacts of a single system failure if the obscurant is deemed necessary to meet performance goals.

Considerations with smokes and fogs include system maintenance and testing, cleanup following a dispersal, time to obscure, and potential health effects on staff in case of exposure to the obscurant.

- Low to moderate cost for installation; cleanup costs after a system discharge can be costly depending on the selected materials and location.
- Moderate to high effectiveness when coupled with other complex tasks or tasks that are greatly impaired by lack of vision; limited effectiveness when coupled with simple tasks.
- Smokes can often be toxic and/or difficult to clean.
- Fogs are effective and typically less harmful but often have other challenges.
    - Some models require the heater element to be always on due to slow heating.
    - Buildup can form on heating element, reducing effectiveness.
- Irritants can be added but increase hazards of inadvertent dispersal.

    - Irritants are extremely effective against an unprepared adversary but can largely be mitigated by a knowledgeable adversary.
    - Some irritants are accepted as generally safe but have potential to cause issues in people with pre-existing respiratory conditions.
    - Potential to be disabled by insider or by an adversary.
- Obscurants do have potential to impact response forces as well, whether simply by limiting visibility or by being affected by irritants.
    - Personal protective equipment can reduce effects, but that consideration is true for an adversary as well.

2.2.2. Foams

Dispensable foams have proven to be effective delay systems through past testing efforts. The two main categories of dispensable foams are aqueous foam and sticky foam. The purpose of aqueous foam is to fill a volume with foam to hamper visibility and motion. Sticky foam is typically deployed in an area where other tasks have to be completed.

Aqueous foam systems are widely used for fire suppression and may be able to serve a dual purpose in some applications. Without being paired with other tasks, aqueous foams are not especially effective. Aqueous foam dispensers can be installed in areas that would have minimal negative effects in the case of an unintended dispersal. More care should be taken when installing them in contaminated areas that could pose the risk of a dispersal spreading contamination.

Sticky foams are best dispersed onto targets or barriers that the adversary will have to defeat to gain access to their target. Sticky foam is a viscous, sticky material that expands when dispensed to cover a larger area. It also has high tenacity, sticking to adversaries or tools that come into contact with it, making it difficult to stretch and pull away. Sticky foam is extremely effective but does come with some drawbacks to weigh.

Sticky foam carries a risk of suffocation if it gets on a person's face, so inadvertent dispersal in an area that members of the workforce are in can pose a hazard. Cleanup is challenging, particularly if any of the foam gets into cracks or crevices in the areas that it was dispensed. Sticky foam also has the potential to separate if not mixed regularly, so some additional maintenance is required. For sticky foam, it is recommended to use an extremely high reliability C2 system to minimize the chances of an unintended dispersal due to the dangers of exposure to staff as well as the significant cost and effort associated with cleaning.

Rigid foams are foams that are dispensed as a liquid or mixture of liquids and react to set into a rigid porous material. While many rigid foams may not cure quickly enough to fully set up if used as an ADS, even while they are not fully set the foams can provide delay. Like sticky foam, they can provide some obscuration of a target and can often be sticky, slippery, or generally difficult to work with. Some foams do have the potential to cause noxious off-gassing, and some can also undergo exothermic reactions, causing temperatures that would be difficult to work in without PPE but also could pose safety concerns to staff in an inadvertent release.

- **Sticky foams**
  - Low to moderate effectiveness by itself; highly effective when paired with tasks that require high dexterity, changing tools, etc.
  - Provides obscuration, makes small tasks such as switching tools more difficult, and slows movement.
  - Cleanup after a dispersal can be challenging and time consuming.
  - May need research and development efforts to identify new readily available candidate materials.
  - Should be dispensed in locations that will not affect response force movements.
- **Rigid foams**
  - Rigid foams may not fully set depending on the amount of time in the scenario but can still provide delay before curing.
  - Some rigid foams may off-gas noxious fumes that could make for more challenging working conditions for an adversary but also pose safety concerns.
  - Some rigid foams react exothermically during curing and can produce a significant amount of heat.
- **Aqueous foams**
  - Aqueous foams provide minimal delay by themselves.
  - Using aqueous foam in conjunction with other tasks that require visibility, fine dexterity, or navigation can significantly increase complexity of those tasks.
  - Cleanup after a dispersal is typically straightforward but could carry risk of spreading contamination if used in a contaminated area.

2.2.3. Dispensable Liquids

Dispensable liquids are another technology that has been investigated in the past. These materials include friction reducing or slippery liquids and sticky liquids. These options are typically minimally effective against adversaries with knowledge of the system but can be effective against unprepared adversaries. Slippery liquids focus on making mobility as well has high dexterity tasks more difficult. Sticky liquids are most effective at making tasks like changing tools more challenging. One of the major downsides to dispensable liquids is that cleanup can be challenging. Cleanup concerns can be reduced by creating areas that would be easy to clean, but clear areas are also where these materials may be the least effective. Areas like stairwells with additional delay features are an example of where there could be an advantage to dispensable liquids.

Slippery liquids are intended to make it difficult for an adversary to get traction, either in movement or in a task. Examples include deploying it in an area like a stairwell where an adversary might need to slow down to make sure they don't slip and injure themselves, or sprayed onto a rounded knob that requires significant torque to turn. Most of these applications will require significant cleanup and can be largely mitigated by an adversary knowledgeable in the system by bringing tools to overcome the limitations.

Sticky liquids aim to provide the same benefits as sticky foams. Sticky liquids don't tend to be as effective as the foams, as they don't fill a volume, making them easier for an adversary to mitigate or avoid. It still has similar downsides, but it is less likely to block airways. This factor does make it safer for staff in the event of an inadvertent release, but at the cost of it being less effective.

- **Friction reducing liquids**
  - Slippery liquids can make tasks challenging, particularly tasks requiring maneuvering challenging terrain (stairs, slopes, tight spaces) or tasks that require a strong grip (actuating valves, turning knobs, etc.).
  - A prepared adversary is likely to be able to overcome this obstacle, but in some scenarios, there may be a significant benefit.
  - Cleanup can be challenging depending on dispersal location.

- **Sticky liquids**
  - Provides limited effects similar to sticky foam but without the volume filling benefits.
  - Less likely to impair breathing than sticky foam.
  - May be useful in some limited cases where an adversary is likely to have to interact with specific equipment to achieve their goals.
    - Less beneficial when attempting to cover a broad area.

2.2.4. Less-lethal Technologies

Less-lethal delay technologies are tools developed to use as part of a force escalation chain. The main purpose of less-lethal technologies is to provide a way to dissuade an adversary from continuing their actions without using lethal force. Less-lethal technologies are most often used in crowd control or as an intermediate step in force escalation to attempt to resolve a situation without utilizing lethal force. In addition to a response force using less-lethal technologies, they can be implemented on remotely operated weapons systems (ROWS) or in stationary emplacements covering a general area.

Less-lethal delay technologies can include bean bag rounds, rubber bullets, sting balls, or pepper balls. Most are designed to deliver an impact as deterrence but are designed to be unlikely to be lethal. Some have secondary effects like pepper balls that also deliver an irritant. Despite the intent to not be lethal, there is still potential for them to cause a fatal injury.

Because these technologies are designed to deliver less energy with the intent of doing less harm, they have limited effectiveness against a prepared adversary. A minimal amount of armor or shielding can severely limit how effective these weapons are. While this protection does limit effectiveness, it does also drive an adversary to carry the additional weight to counteract them and can slow down other tasks since some focus has to be taken to protect against these weapons.

Less-lethal technologies are generally not effective outside of crowd control or unprepared adversaries. Typically, these types of tools are not going to be cost effective for adding delay but are more useful in helping to gauge and adversary's intent, helping to inform further force escalation. It is more likely that these technologies would prove effective as part of a response force's options of engaging an adversary whose intent is not yet clear, with the possibility of deescalating an event before lethal means are used.

One area that remotely operated systems with less-lethal technologies could provide benefit is to use robots or drones outfitted with less-lethal systems to approach and gauge the intent of an adversary while allowing response force to remain in a safe location. The systems could be used to communicate with an individual in an unauthorized area and then to escalate to less-lethal technologies such as pepper balls to attempt to dissuade the adversary from moving forward. This option would not provide appreciable delay for traditional system effectiveness calculations but could provide situational aware and additional tools that could be useful in real world situations.

- Less-lethal technologies encompass a wide range of tools including bean bag rounds, rubber bullets, sting balls, pepper balls, and electroshock weapons.
- Remotely operated less-lethal systems are typically expensive.
- It is difficult to cover a wide area.
- Less-lethal systems are typically most effective early in a scenario.
    - Late into a scenario an adversary has likely demonstrated enough determination to advance despite less-lethal engagement.
- Well-protected guards with handheld less-lethal systems are likely more effective for early deterrence.
- May be some opportunity for mobile remote-operated systems to be used to assess, communicate with, and utilize less-lethal technologies if needed against individuals that may pose a threat.
- Modeling the effect of less-lethal systems on system performance can be challenging since it is difficult to quantify their ability to deter further action from a determined adversary.

2.2.5. Lethal Technologies

Lethal active delay systems have been widely discussed as a way to reduce the number of response forces needed at a site. Lethal technologies include any system that when activated has a high likelihood of killing individuals in the area. These systems allow for a responder to engage an adversary without putting themselves at risk and allow a small number of responders to control multiple systems. This force multiplication is very attractive when looking for methods to reduce recurring security costs.

Installation costs for lethal technologies are often very high. Ongoing costs for lethal technologies include the maintenance for the system, training for the responders, and frequent testing to ensure the system is still working as intended. Despite these high costs, when used properly these technologies are one of the most impactful options to reduce the number of responders needed.

One potential concern with lethal systems is employee safety. When these systems are installed, workers must have confidence that the system will not trigger and injure or kill an employee. This confidence typically includes having a human-in-the-loop for the decision to activate the system as well as visual indicator that the system is in a safe state that workers in the area can verify. Other features, such as an alarm and mandatory wait before the system is fully armed, can aid in safety but do have the potential of preventing the system from functioning in the case of a real attack.

These systems perform best when installed in a choke point that an adversary is highly likely to pass through. This placement minimizes the area they need to cover, reduces the range of motion required, and reduces the speed and tracking accuracy needed. In some cases, fixed systems can be used to provide denial coverage over an area.

Several different styles of lethal systems could be implemented at a facility to provide denial options for a response force. A remotely operated weapon system (ROWS) is one option, which allows an operator to control a robotic weapon to engage an adversary. Alternately, weapon systems can be mounted in fixed locations covering a specific area near a target and activated as an adversary passes through the area.

Due to the potential consequences of an unintended or malicious use of the system, there can be more scrutiny toward evaluating the safety of lethal denial systems from both regulators and facility staff responsible for accepting the risk associated with an inadvertent activation. Lethal systems will carry legal implications that should be addressed early in the process. If lethal denial systems are of interest, early engagement with the appropriate regulatory agencies is highly encouraged.

- ROWS
    - These systems are high cost and effectiveness varies widely depending on implementation.
    - On-site control is recommended.

    - Off-site controls carry the risk of loss of connectivity and can create a larger attack surface for adversaries.
- Two-person control is highly recommended.
- ROWS are most effective late in the pathway where an adversary will be forced to enter the line of fire to access a target.
    - While a facility can be designed to increase the likelihood an adversary will take a path that will allow engagement by a ROWS, consider alternate paths that could avoid it and ensure balanced delay is implemented.
- Pair with a passive delay barrier to ensure operators have sufficient time to engage the adversary.
- Cost of maintenance can be high.
- Long-term hardware and software support of advanced systems can carry high uncertainty.
- Investigations into mobile remote-operated systems are ongoing, but in the current state these systems likely bring more uncertainty than benefit.
- Consider what is in the line of fire for ROWS and ensure that no critical equipment can be damaged.

2.3. Efficient Traditional Barriers

One of the most cost-efficient ways of increasing delay is to include security considerations into the design phase as early as possible. While there are many delay technologies that can aid in developing a robust system, the process of designing a facility with security in mind tends to be one of the most effective methods for balancing cost and performance. The technologies listed in this report can be elements of that design that help to provide a more robust system, but designing the facility to support these technologies will provide significant cost savings regardless of the technology used, including more traditional passive barriers. Adding security into a completed design or one that has been developed far enough to be inflexible to changes carries both cost burden as well as more challenging protection strategies that can introduce weak points. Retrofitting existing facilities is even more costly.

2.3.1. Security By Design

A significant portion of the current reactor fleet in the United States was built decades ago, and a large portion of the cost associated with security comes from the effects of multiple security upgrades over that lifespan. This legacy creates a patchwork of systems that are not as well integrated as those where it was inherently designed to support both the current security needs, as well as infrastructure to provide for future maintenance and replacement of components.

As an example of designing delay into a reactor facility, portions of the facility that rarely need human access can be placed in hardened areas and these areas can utilize a concrete plug or large concrete blocks that require heavy machinery to move to limit access. Alternately, they can be outfitted with heavy vault doors that would be cumbersome for day-to-day use but that are acceptable for infrequent access. If high-risk targets for theft or sabotage can be separated in a way that lessens the impact of any one of them being compromised, consider making multiple security boundaries to separate them to increase the time needed for an adversary to access more than one. This separation may lessen the potential impact of even a partially successful adversary attack and would additionally increase the amount of knowledge and time that an adversary would need.

A security engineer familiar with the regulations as well as general security concepts should be included in the facility design at an early stage when design changes are relatively low impact. As the design begins to mature, modeling and simulation tools can be used to evaluate different configurations and systems to identify what will provide the highest delay for the lowest cost. The ARSS program also provides an opportunity to engage with national labs as independent third parties to provide feedback on design concepts.

This concept of security by design ties into the ARSS goal to move towards Safety, Security, and Safeguards by Design (3SBD). The intent of 3SBD is to ensure that safety, security, and safeguards considerations are included early in the design phase to integrate them as much as possible into the reactor design, as well as to consider the interfaces between each.

2.3.2. Advanced Modeling and Simulation

The general progression of technology also opens some opportunities not just for the delay barriers themselves, but also for improving analysis. System modeling and simulation tools provide a strong opportunity to evaluate and optimize barrier systems using methods like Monte Carlo analysis. As part of the Light Water Reactor Sustainability (LWRS) program, Sandia National Labs investigated statistical methods to improve how delay timelines are developed as part of the Risk-Informed Timeline Analysis project. This work focused on moving delay timelines from static events with determinate timelines to utilizing Bayesian statistical methods to develop distributions for task times. This method, combined with modeling and simulation tools, provides a more complete understanding of the access delay system and its interactions with the rest of a physical security system.

Modeling and simulation also allow the full system response to be considered. Physical protection systems rely on a balance between detection, delay, and response. Earlier detection or a stronger response can allow for reduced delay. One proposed method of reducing staffing costs is to utilize off-site response. This method may be a feasible path but would require a significant amount of delay that would be costly to implement. Modeling and simulation using realistic values can help to inform if this method would be a feasible path. The amount of delay required may be cost prohibitive.

Historically delay timelines have relied on data that was a point source for a given task. To defeat a given door with a given tool would be assigned a discrete time. In practice, the amount of time it takes to breach a given barrier is a statistical distribution of times. Some simple tasks will have very little variance, while more complex ones will also have wider distributions. For example, defeating a chain-link fence is a relatively quick task without too many variables that would affect the time significantly. This invariability likely would result in a very narrow distribution of times. A more complex task. such as breaching a thick, heavily reinforced concrete wall, is likely to have a wider distribution of task times and a higher probability of some kind of critical failure that would prevent adversary progression. Current methods do not account for these issues and typically assume that an adversary always performs at the absolute peak performance. This assumption is a good method for ensuring that there is conservatism in the analysis, but also has the potential to highlight short but unrealistic paths more than longer but much higher success rate paths. Treating these times as distributions accounts for differing adversary experience levels, events such as tool failures, and other factors that result in differing times.

Using these distribution-based timelines allows for a more complete understanding of the level of risk of a given pathway. The traditional methods tend to result in a focus on the shortest timelines, but in many cases these paths require many high-risk tasks to occur flawlessly in a row. This outcome is statistically unlikely, and an adversary is more likely to focus on a path that has the highest likelihood of success. Despite it being an unlikely path, it still contributes to the full distribution and allows for a more complete understanding of what investments buy down the most overall risk rather than fixating on short but unlikely pathways.

Statistical tools like these, combined with more traditional physical protection system modeling and simulation tools, also allow sensitivity studies to be performed to provide additional evidence into how robust the system is to potential degradation or failure. This information can be useful for ensuring that the system is robust to small changes either in the system itself (such as a failed component) or to evolving adversary capabilities.

One drawback to moving towards distributions of times for tasks rather than individual times is that it requires more data to generate those probabilities. For tasks like running or defeating a chain-link fence, it is possible to perform enough tests to get statistical distributions. For more substantial barriers, it can be cost prohibitive. To address the minimal data, the risk-informed methods use Bayesian methods that provide a statistically defensible way to incorporate both subject matter expert judgement from multiple sources and data. These methods will rely on the subject matter experts providing their judgement, as well as additional peer review to ensure that a third party agrees with the evaluations.

The second challenge with this approach is that it varies from the traditional methods of evaluating system effectiveness. There is a strong case for acceptance of these methods, provided there is a demonstration that the statistical methods and data used are well-grounded. Nearly every other portion of the security system utilizes probabilities for evaluation, so it is logical that delay analysis should also evolve to represent the best methods available. This evolution will require agreement from regulators, so if these methods are of interest early engagement on the topic will be needed. Even absent formal recognition of these methods by regulators, they are still useful tools that can be used to identify areas of concern that can then be addressed before regulatory reviews.

2.3.3. Passive Barrier Design

Utilizing security by design and modeling and simulation tools can help to make traditional passive barriers more cost effective. Guiding facility design using SBD principles and utilizing modeling and simulation tools can help to identify the critical points to protect and help to optimize delay strategies on those paths. This analysis can greatly reduce the amount of reinforced concrete or barrier materials needed to provide the delay required. Composite walls can also provide significant delay against many tools including explosives. A basic composite wall design is to add a spall plate to the rear face of the concrete wall. This addition will prevent concrete from spalling off the back face and increase the amount of explosive or the number of shots needed to make a clean breach. More advanced walls could utilize foam or air gaps to reduce the shock transmission through the wall or other features to make breaching with various tools more challenging. While these methods are more expensive than reinforced concrete, depending on facility design there may be opportunities to utilize this type of construction in key locations while maintaining more traditional construction methods for lower consequence portions of the facility.

Another option for some facilities, particularly smaller reactors, is to create underground facilities. This option can be accomplished either by constructing the facility below grade or by covering a facility with overburden after initial construction. While this change can be an expensive initial investment, it may offset other security costs over the lifespan of a reactor. Underground facilities provide significant delay times as well as excellent performance against blast when designed correctly. This improvement could open opportunities to use a smaller footprint for the site while still meeting the security requirements. With a smaller footprint comes less perimeter to maintain and a potential reduction in the number of staff required to operate and maintain the site.

- Designing facilities with security in mind can add significant delay with relatively low-cost increase.
- Tailoring facility design to include more substantial walls in key locations may reduce overall security costs by providing more delay.
- Concrete with heavy rebar and spall plates can add significant delay even against explosives.
- Doors or walls can be designed with layers requiring a variety of tools to cut them (steel, concrete, redwood for thermal resistance, etc.).
- Focus delay close to the targets with defined areas to engage an adversary for maximum benefit.
- Design the system to minimize working space around critical elements when feasible.
  - This design may not be possible in areas where clear working space is a safety requirement to allow for maintenance.
  - Easier to design into the system when planned early than to retrofit.

2.4. Counter-UAS

Unmanned aircraft systems (UASs) have become another area of focus recently due to the boom in consumer drones along with the heightened awareness from their use in conflicts around the globe. In 2019 the Nuclear Regulatory Commission (NRC) released an unclassified executive summary outlining the conclusions from a classified study addressing the potential threat. The executive summary stated that the study "determined that nuclear power plants and Category I fuel cycle facilities do not have any risk-significant vulnerabilities that could be exploited using UAVs and result in radiological sabotage, theft of special nuclear material (SNM), or substantial diversion of SNM" [8].

As new reactor facility designs are developed, there should be an awareness to ensure that designs do not introduce new potential vulnerabilities related to UASs. Additionally, significant research and development is being put into counter-UAS (CUAS) systems. Capabilities of these systems vary widely and include everything from detection systems for awareness to systems intended to actively engage drones. Cost and effectiveness of these systems vary widely, and systems should be evaluated prior to adoption to ensure the capabilities and limitations of the system are well understood.

2.4.1. Design for Expansion

When designing a facility, it may be beneficial to include some flexibility for future changes in security posture. This approach can be challenging for passive delay systems, but straightforward for providing installed fiber or other communication lines and potentially power to locations that active delay systems could be installed in the future. World events or emerging threats can drive shifts in the security posture necessary to protect nuclear power reactors. Designing additional capability to increase security into a facility can greatly reduce the costs associated with any future upgrades to meet these demands. The CUAS systems mentioned in the previous section are a good example. While there is potential for them to not be a requirement at the time of construction, having fiber and power either pre-run or empty conduit installed in preparation of a future run may be relatively low-cost during construction and save a significant amount of money should they ever become a required element of the security system. Doing this preparation widely throughout the facility can aid not just in active delay systems, but also for other physical protection system elements like sensors, or even just for typical operations or reactor upgrades in the future. Having fiber in place will also reduce the need for wireless systems that can create new attack surfaces as discussed in section 2.2.

2.5. Integrated Sensors

Integrated sensors in barriers typically will not provide a significant increase in the calculated system effectiveness, as the detection occurs after the barrier is already being attacked. What these integrated sensor systems do provide is an increase in situational awareness that could help protective forces respond appropriately to an event. This awareness would provide indications when various key barriers have been defeated by an adversary, helping response to better understand the adversary's intent, current progress, and an idea of their level of capability based on how quickly various barriers have been breached. This data can help to inform the level of action that is most appropriate to stop a potential threat.

- Technologies such as tailored fiber placement (TFP) or tailored wire placement (TWP) can integrate sensing into a barrier. While continuously monitoring an input, a loss of signal would indicate that an adversary is attacking.
    - These technologies are typically break-screen sensors utilizing wire or fiber optic, fixed or adhered to a surface, or encapsulated within a composite panel fixed or adhered to a surface.
- Integrated sensors could also be applied to 3D printed structures as well. By integrating the sensors during the printing process, one can apply sensors throughout the structure. These sensors have potential to be used both for structural health monitoring and intrusion detection.
- Integrated detection will not increase delay but can help with situational awareness and to identify when key barriers have been breached to better inform response strategies.

3. OVERALL RECOMMENDATIONS

- Integrating security principles into facility design through Security by Design can greatly reduce security system cost when compared to retrofitting.
- Experienced security professionals should be engaged on the project early and should provide design input at all stages of development.
- Design the facility with security in mind and with delay in depth principles.
    - Multiple barriers that require different techniques to defeat quickly force a higher level of adversary knowledge and experience for success.
        - Multiple barriers also help to provide a response force more insight on adversary intent prior to engaging.
    - Delay in depth helps reduce the risk of failures or vulnerabilities from having as much of an effect on overall system effectiveness.
    - Balanced delay across the facility helps to ensure that for any path an adversary might take that the system provides sufficient delay.
- Active delay systems are typically most effective when used along with passive delay systems.
    - Smokes and fogs should be used when there are tasks that would be complicated by inhibiting vision.
    - Foams can be used to complicate a task, particularly sticky foams.
        - Utilize foams to increase the complexity of a task and select the type of foam that will best fit a use case (aqueous foam may be good in a stairwell to make navigation more challenging, while sticky foam may be used close to a target to complicate defeating robust delay features near the target).
    - Dispensable liquids, such as friction reducing liquids, can provide some delay against unprepared adversaries, but may be limited in effectiveness if an adversary has enough prior information about the system.
    - Remotely operated weapons systems can provide significant benefits if correctly integrated into a system design.
        - Less-lethal technologies are mostly effective against undetermined or unprepared adversaries. The best use case for these systems would be external to a facility to help determine intent, but the cost of covering large areas makes this approach somewhat impractical.
        - Similarly, lethal ROWS are best placed near the targets at predetermined areas that an adversary will have to access to succeed in their task. Pairing a ROWS with a passive delay barrier will force the adversary to be in a predictable spot for enough time to engage. This location should be far enough into the facility that protective force will be prepared to activate the lethal denial system.

    - Design with an eye to the future.
        - Make maintenance, upgrades, and replacements of portions of the system as efficient as possible.
        - Consider new and emerging threats.
            - Plan any installed infrastructure for future replacements or system expansion.
            - Utilize non-proprietary systems when possible.
            - Maintain an inventory of replacement hardware to minimize the duration of any outages and limit the time compensatory measures are necessary.
            - Perform routine maintenance and testing to ensure system functions reliably.
- 3DPC shows potential for developing very effective barrier systems, but there is limited data at the time of publishing this report to provide evidence. Additionally, cost of 3DPC will remain high until there is wider adoption in industry.
    - If 3DPC is going to be utilized in security applications, testing should be performed to determine how effective it is against a range of threats.
    - Building codes are currently restrictive and approvals are typically expensive even for the limited residential use cases that are generally allowed today.
    - There is uncertainty on how the structures will age.
    - There is uncertainty on 3DPC's performance against a variety of threats.
    - Developing and printing a single facility is currently a high-cost endeavor, and the most significant cost savings will likely be found if a significant number of identical facilities are going to be built.
- Exterior delay features, such as chain-link fences or perimeter walls, typically offer a minimal amount of delay, and the cost to build these barriers with significant delay is prohibitively expensive.
- While not discussed in detail in this document, vehicle barriers with proper standoff are one of the most critical aspects of a physical protection system.
- Perform what-if/sensitivity analysis of the physical protection system with and without various elements of the delay system to determine the most cost effective and robust implementations of access delay systems.
    - It is challenging to develop a generic cost-benefit analysis for each technology because how it is integrated with the rest of the system will play a significant role.

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