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Sandia National Laboratories

Security by Design Economics Analysis for Advanced Reactors and Small Modular Reactors

Project Interim Report for FY2021

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ABSTRACT

Advanced Reactor and Small Modular Reactor (AR/SMR) designs have the potential to provide clean, reliable baseload energy. Ensuring the capability to deploy these reactors in an economically viable fashion is of interest to industry.

A large portion of the expected operating costs of AR/SMRs involves the security of the plant. Security by Design (SeBD) is the practice of including features in the design and construction of the site, with the intent to decrease the operating costs related to security. Quantifying the increase or decrease in the overall lifetime cost to the plant as a result of SeBD is of paramount importance in understanding the disadvantages and benefits of such activities.

The National Nuclear Security Administration's (NNSA) Office of International Nuclear Security (INS) is funding the development of a methodology whereby the capital expenses and operating expenses, as well as the physical security effectiveness, of SeBD can be quantified for AR/SMRs.

This report is an interim report on the progress of the work performed by Sandia National Laboratories (SNL), Idaho National Laboratory, and Oak Ridge National Laboratory (ORNL). It is the second annual report on this work.

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EXECUTIVE SUMMARY

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
10 CFR 73	Title 10, Part 73 of the Code of Federal Regulations
AR	Advanced Reactor
BEA	Battelle Energy Alliance
CAPEX	Capital Expenditures
CFA	Cash Flow Analysis
CFR	Code of Federal Regulations
CNP	Civilian Nuclear Program
CRADA	Cooperative Research and Development Agreement
DBT	Design-basis Threat
DOE	Department of Energy
DOE-NE	DOE Office of Nuclear Energy
ECCS	Emergency Core Cooling System
EUCG	Electric Utility Cost Group
FOM	Figure of Merit
FY	Fiscal Year
GAIN	Gateway for Accelerated Innovation in Nuclear
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory

Abbreviation	Definition
INS	Office of International Nuclear Security
iPWR	Integral Pressurized Water Reactor
IRR	Internal Rate of Return
kW	Kilowatts
kWe	Kilowatts Electric
LCOE	Levelized Cost of Energy
LVO-SeBD	Levelized Value of Security by Design
LWR	Light Water Reactor
MWe	Megawatts Electric
MWh	Megawatt Hour
MWth	Megawatts Thermal
NDA	Non-Disclosure Agreement
NEI	Nuclear Energy Initiative
NGO	Non-Governmental Organizations
NNSA	National Nuclear Security Administration
NPP	Nuclear Power Plant
NPV	Net Present Value
NRC	US Nuclear Regulatory Commission
NRIC	National Reactor Innovation Center

Abbreviation	Definition
NUREG	Nuclear Regulatory Commission Issuance
OPEX	Operating Expenditures
ORNL	Oak Ridge National Laboratory
P_I	Probability of Interruption
P_N	Probability of Neutralization
PIDAS	Perimeter Intrusion Detection and Assessment System
PNNL	Pacific Northwest National Laboratory
PPS	Physical Protection System
PRA	Probabilistic Risk Assessment
PS	Physical Security performance
PSmin	Minimum allowable value of PS
PWR	Pressurized Water Reactor
ROI	Return on Investment
SBD	Safeguards by Design
SeBD	Security by Design
SeBDE	Security by Design Economics
SMR	Small Modular Reactor
SNL	Sandia National Laboratories
USNRC	United States Nuclear Regulatory Commission

1. INTRODUCTION

1.1. Scope/objective

The National Nuclear Security Administration's (NNSA) Office of International Nuclear Security (INS) has funded Sandia National Laboratories (SNL), the Idaho National Laboratory (INL), and the Oak Ridge National Laboratory (ORNL) to investigate options to help industry meet their needs related to assessing the benefits and drawbacks of Security by Design (SeBD) for Small Modular Reactors (SMRs) and Advanced Reactors (ARs). The three laboratories are developing a methodology for assessing the financial benefits and/or disadvantages of including SeBD features in an AR/SMR design. The assessment of financial benefits and disadvantages will lead to a method to compare the financial performance of proposed scenarios for integration of security with the operational design of the nuclear power system.

This report describes the status of the work at the end of the second funding period – Fiscal Year (FY) 2021. Included in this work is an example demonstration of how the methodology would be applied. The numbers used and the design of the reactor facility are all hypothetical.

2. BACKGROUND

2.1. Economics of current US commercial fleet

A report published by INL [1] presents a study of the costs of physical security at U.S. commercial nuclear power plants. The cost data was obtained from the Electric Utility Cost Group (EUCG), which is a group of energy companies from around the world participating with the objective of sharing information to help individual companies improve their operating, maintenance, and construction performance [2]. The cost data comprises of four parts: 1. Labor cost, 2. Service cost, 3. Material cost, and 4. Others. Due to proprietary nature of the cost data, dollar values of the cost are not published here.

Figure 1 shows the evolution over the last twenty years of the percentage contribution of the four costs towards the total cost of physical security at U.S. commercial nuclear power plants (NPPs) [1]. It is interesting to note the rapid increase in the contribution from labor cost since year 2008, indicating the shift of physical security posture towards labor-intensive approach. Labor costs account for more than 60% of the total physical security budget, and its contribution continues to rise.

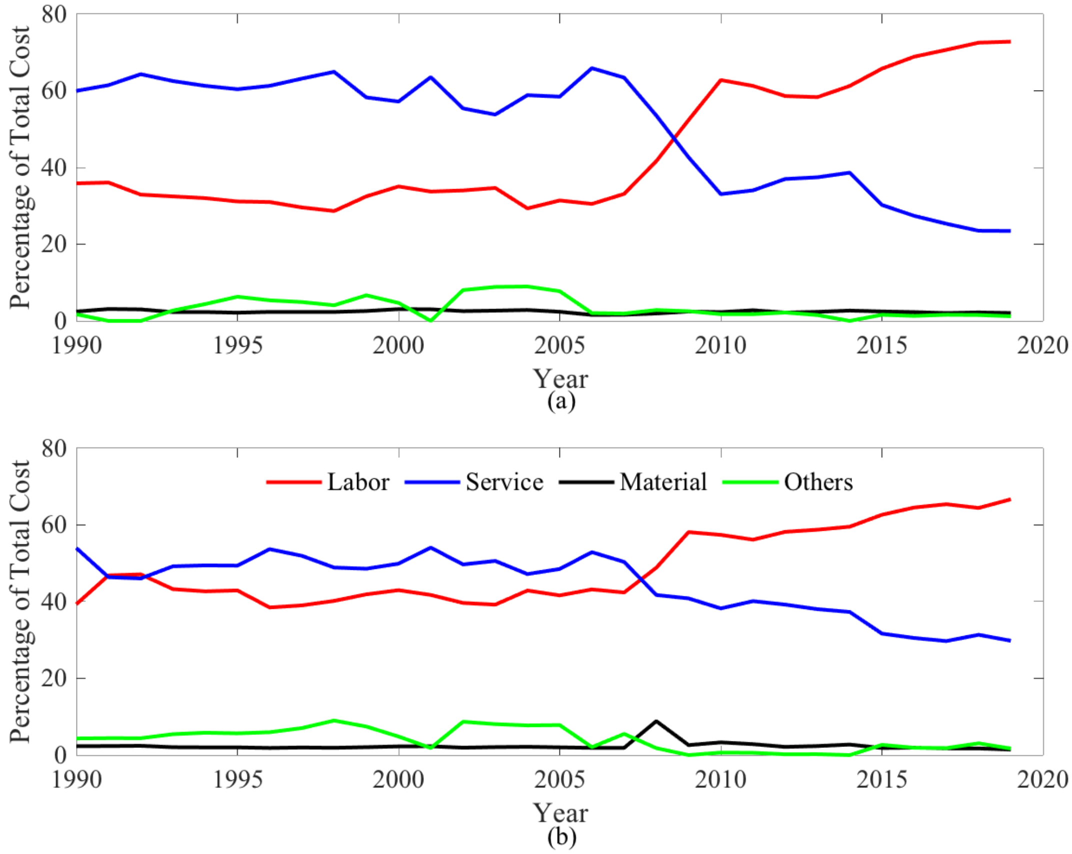

Figure 1. Evolution from 1990 to 2019 of percentage of total cost for the four types of physical security costs: Labor, Service, Material and Others at (a) Single Unit NPPs and (b) Dual Unit NPPs. Notice the continued increase in contribution of labor costs since 2008. [1, 2].

The labor-intensive approach to address the radiological sabotage and theft has come at a very high cost for the nuclear power industry that is extremely difficult to sustain in the current state of the nation's electricity generation environment, particularly in consideration of the recent and announced plant shutdowns the nation has continued to see over the past several years. If commercial nuclear power generation is to be sustained within the United States, an optimized plant physical security posture is needed that will reduce conservatisms in that posture and potentially reduce security costs for the nuclear industry while meeting the requirements of Title 10, Part 73 of the Code of Federal Regulations (10 CFR 73) [3].

2.2. Physical security performance assessment

The security assessment is a comprehensive examination of the physical security posture of a plant that may serve as technical bases for evaluating an applicant's security program during the licensing phase, or to assess the effectiveness of an existing posture. The primary purpose of the assessment is to ensure that the physical protection system of a nuclear facility provides high assurance of protection against the design-basis threat (DBT), as prescribed in 10 CFR 73.55 [3].

The Nuclear Power Plant Security Assessment Guide NUREG/CR-7145 [4] published by the US NRC provides detailed guidance for the format and content of a security assessment at nuclear power plants. The guidance document is widely used to optimize physical security during the design phase, and in planning and executing changes and upgrades of physical protection systems at existing sites. The guidance document provides a detailed methodology for performing assessment of physical security system effectiveness. Figure 2 shows the four-step security assessment process described in NUREG/CR-7145 [4].

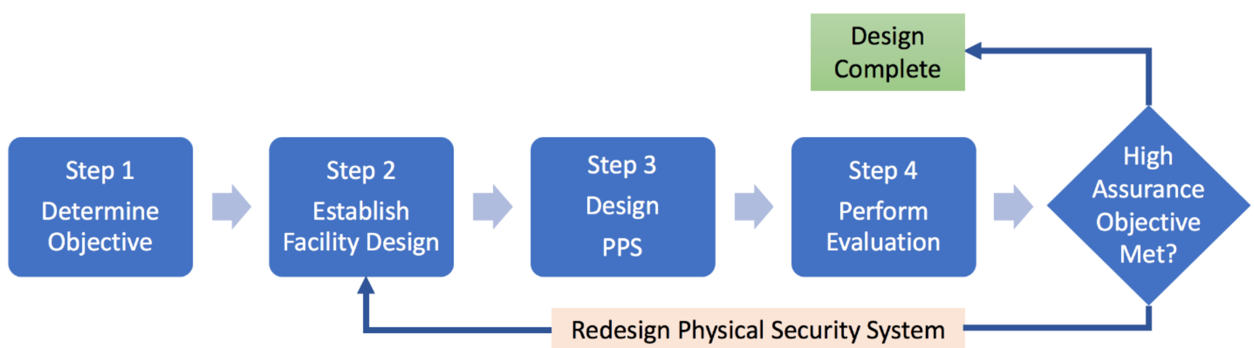

Figure 2. The security assessment process described in NUREG/CR-7145 [4].

Determine Objective: The objective of physical security system is to protect the plant from radiological sabotage and prevent theft as defined by the NRC [5]. The US NRC provides a standard set of scenarios associated with the Design Basis Threat (DBT) that defines the characteristics of the adversary force such as force size, equipment, weapons, and tactics [5]. For a given standard DBT scenario there can be several overall scenarios based on variability in target sets, entry and exit points (for theft only), and other plant specific characteristics.

Establish Facility Design: Target set analysis is performed to establish the reactor facility design that must be protected by the physical security system. A radiological sabotage target set is the combination of equipment or operator actions which, if prevented from performing their intended safety function or prevented from being accomplished, would likely result in significant core damage [5].

Design Physical Protection System: The physical protection system at a nuclear power plant is a combination of equipment, people, and procedures with the combined aim of protecting the plant assets. This step characterizes the different elements of the physical protection system (PPS) such as: detection, delay and response system, perimeter intrusion detection and assessment system (PIDAS), weapons, number of armed responders, number of patrolling officers, and strategic location of physical protection system.

Perform Evaluation: The physical security performance evaluation of step 4 is performed in three broad steps:

1. Apply NRC developed scenarios and evaluate PPS

Analyze scenarios to ensure adversary actions are within DBT capabilities and credible

Analyze scenarios to ensure barrier delay times and protective force actions are credible

For a specific scenario, the adversary and responder timelines are developed. The adversary timeline provides a direct and quantifiable assessment of the different elements of the physical protection system for a given DBT.

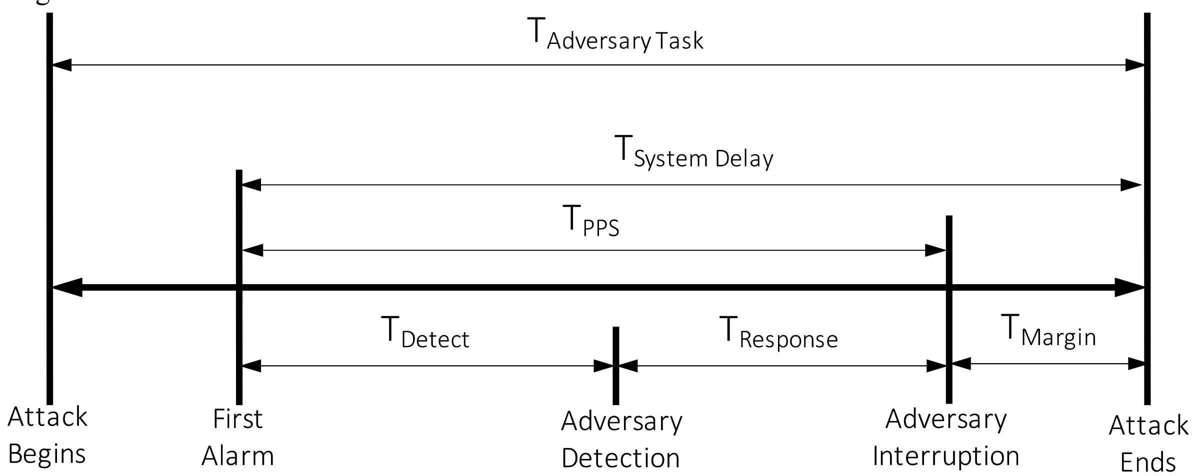

Figure 3. The timelines associated with an attack scenario.

Figure 3 shows an illustration of the timeline associated with an attack scenario. The $T_{Adversary\ Task}$ defines the time it takes the adversary to successfully accomplish the attack. This time can be estimated in a drill or mock scenario but is not known in a real attack scenario. The timeline truly begins at the instance of first alarm for the attack, from the first alarm to the successful detection of the adversary is the time to detection, T_{Detect}. Following the detection, the responders get in action in order to neutralize the attack, the timeline for responders to successfully interrupt or neutralize the attack is $T_{Response}$, which can reflect how effective the response team is in successful interruption or neutralization of the attack. The sum of T_{Detect} and $T_{Response}$ is T_{PPS}. T_{PPS} influences the probability of the PPS interrupting adversaries in a timely manner, after which the adversaries must be neutralized. NUREG/CR-7145 [4] defines the overall effectiveness of the physical security system as a probability:

$$P_E = P_I \times P_N$$

where P_E is the probability of overall effectiveness, P_I is the probability of interruption of the adversary, and P_N is the probability of neutralization of the adversary given their timely interruption. Detailed discussion on fundamentals of the probabilities and their estimation can be found in [6].

2.3. Moving toward economic optimization of physical security in advanced reactors

The long-term goal of the current effort is to provide a tool that allows vendors, utilities, and other interested entities to determine the optimal level of security to be designed into the nuclear facility. For the purpose of this work, the optimization is performed over a combination of physical security effectiveness and economic performance of the proposed facility. Since this work is done in the design phase, the cost projections being used are uncertain. These uncertainties can be accounted for with the use of distributions around the projected means or with sensitivity analyses. In this report, only the mean values are used. This work does not purport to be the final version for optimization. It is a first effort in a path toward economic optimization for security by design. This report discusses an ongoing project that has thus far created an SeBD Economics Tool. This subsection outlines how this tool can be utilized to aid AR developers, utilities, and other interested parties perform an integrated analysis of security effectiveness and economics

The SeBD Economics Tool has been created to assist AR developers in assessing cost reduction opportunities for plant security in a systematic and holistic manner. The tool allows AR developers, as well as the DOE and national laboratory analysts, to compare the net financial impacts of alternative security strategies with their expected effectiveness against adversaries. The tool clarifies the key trade-offs between security effectiveness and economic metrics for AR developers to consider early in their plant design process.

Trade-offs between security effectiveness and economic metrics can be illustrated by a Pareto efficient frontier. This conceptual framework draws on the work of the economist Vilfredo Pareto in the early twentieth century to optimize decision-making across multiple objectives [7]. Figure 4 illustrates hypothetical security posture alternatives for a nuclear plant as circles labeled with letters. The height of the circles along the vertical axis represents their security effectiveness, and the distance of the circles along the horizontal axis represents their net present value. The red horizontal line represents the minimal security requirement that the nuclear plant must meet (i.e., the floor for compliance). The figure is purely hypothetical and does not reflect security posture alternatives described elsewhere in this report.

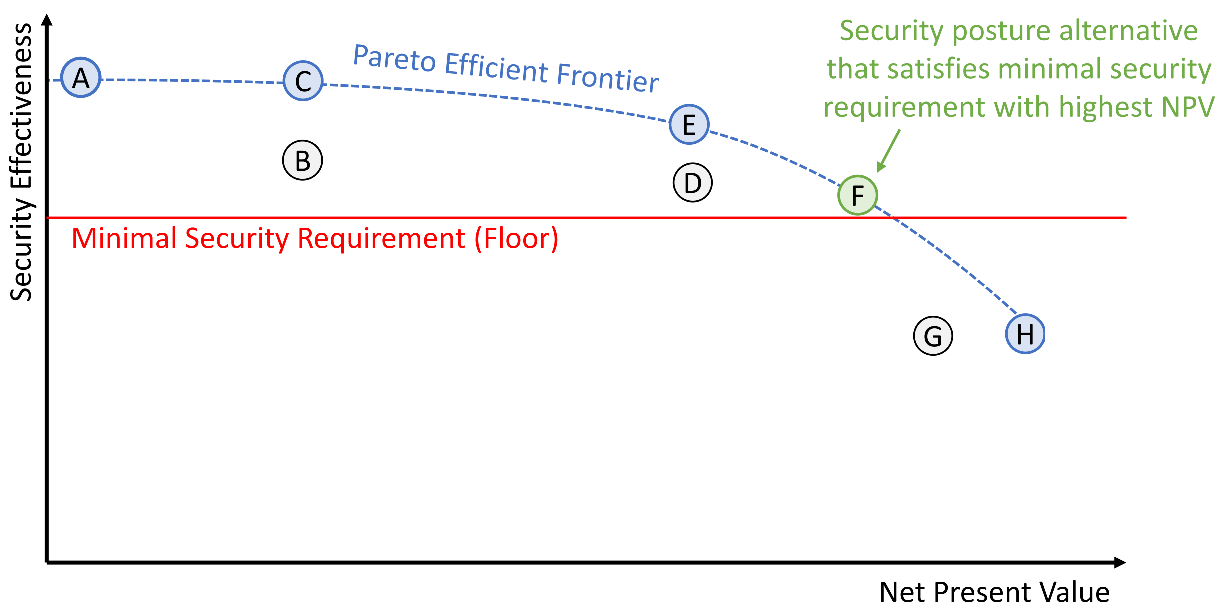

Figure 4. Hypothetical Trade-offs Between Security Effectiveness and Net Present Value with Pareto Efficient Frontier

In the upper left of the figure, alternative A would provide high security effectiveness, but its net present value is low (implying large costs). Alternatives B and C have higher NPV than A, and C is superior to B because C's security effectiveness is higher. Similarly, alternatives D and E have higher NPV than previous alternatives, and E is superior to D. Alternative F satisfies the minimal security requirement and has higher NPV than all the previous alternatives. Alternatives G and H have even higher NPV than F, but they fail to meet the minimal security requirement. The set of alternatives with the highest security effectiveness for any level of NPV constitute the Pareto efficient frontier. Other alternatives (B, D, and G) should not be selected because they are inferior to alternatives along the Pareto efficient frontier in terms of effectiveness or NPV. The best alternative to select is F because it maximizes NPV while satisfying the minimal security requirement (assuming the goal is not simply to maximize effectiveness, in which case A would be selected even though its NPV is lowest).

The SeBD Economics Tool enables AR developers to satisfy security requirements while maximizing NPV by comparing posture alternatives analogously with Figure 4. Developers can identify any number of possible alternatives, specify parameters regarding effectiveness and costs, and select the optimal strategies to incorporate into their AR designs using the tool.

The integrated assessment of effectiveness and economics also aligns with guidance from the World Institute for Nuclear Security in its recent report titled *Optimising the Efficiency of Nuclear Security* [8]. Figure 5, reproduced from *Optimising the Efficiency of Nuclear Security* [8], is similar to Figure 4. Hypothetical Trade-offs Between Security Effectiveness and Net Present Value with Pareto Efficient Frontierin displaying security effectiveness on the vertical axis and efficiency, which relates closely to costs and NPV, on the horizontal axis. Joint optimization of these two dimensions aims to maximize a metric that is a function of both effectiveness and efficiency, as denoted by the star in the green quadrant in the upper right of Figure 5. This may mean maximizing efficiency while maintaining effectiveness above a given threshold, but there may be other combinations that meet the needs of the user of the tool.

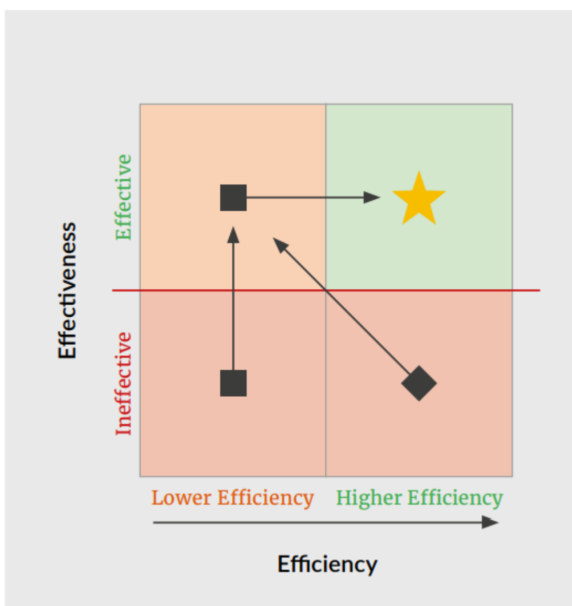

Figure 5. Joint optimization of nuclear security effectiveness and efficiency from WINS (2021b)

The SeBD Economics Tool complements capital and operating cost estimation for ARs with G4ECONS, which was developed by the Generation IV International Forum's Economic Modeling

Working Group [9]. G4ECONS is a spreadsheet model that produces representative costs for a wide range of reactor types, output capacities, and fuel parameters. The SeBD Economics Tool focuses on the capital and operating costs of security posture alternatives, which can be combined with broader cost estimates from G4ECONS or other approaches to produce total cost metrics, such as the Levelized Cost of Electricity (LCOE).

2.4. Importance of SeBD economics for advanced reactors

AR developers must incorporate cost reduction strategies early in their design processes to ensure the eventual market viability of their plants. The need for economic optimization in SeBD is underscored by the following references.

- The *Security-by-Design Handbook* issued by Sandia National Laboratory [10] notes that "[i]mplementation of SeBD practices is very important to having a cost effective and efficient protection system design for nuclear facilities" (p. 22). SeBD and economic assessments should occur early in advanced reactor design processes because "security requirements are typically less costly and easier to incorporate [at this early stage]" to "avoid expensive retrofits and expansions" after plant construction (p. 18). The *Handbook* points out that "[c]ost-benefit and life-cycle cost analyses can be performed to determine the trade-offs between capital costs for intrinsic security design features vs. lifetime operating costs" (p. 66). The SeBD Economics Tool assists AR developers in assessing these trade-offs between capital investments and operating cost savings.

- The Nuclear Energy Institute has highlighted the value of economic optimization for AR security in white papers and submittals to the Nuclear Regulatory Commission in the context of physical security requirements. NEI (2012) states that "[r]obust development and deployment of SMRs in the US hinges on cost and risk certainty. Establishing the appropriate security staffing, without compromising nuclear safety and security, is a necessary component in demonstrating the economic viability for SMRs" [11]. Like the SNL *Security-by-Design Handbook*, NEI (2012) notes that "[a]lthough there may be additional initial costs for development of such systems, these costs are expected to be offset by minimizing security related O&M costs through reduced on-site security staffing." NEI (2016) puts additional emphasis on the need for cost reduction in AR security strategies by asserting that "[c]ompliance with § 73.55 requirements [which were originally established for large light-water reactors] will diminish the cost competitiveness of AR technologies, thus hindering their development and deployment" [12].

- In its recent *Handbook on the Design of Physical Protection Systems for Nuclear Material and Nuclear Facilities* [13], the International Atomic Energy Agency (2021) also encourages nuclear developers to "determin[e] how best to combine physical protection measures such as physical barriers, sensors, procedures, video surveillance, communication devices and response into a PPS [physical protection system] that can satisfy the protection requirements, taking into account other considerations, such as initial and lifecycle costs of the PPS…" The IAEA *Handbook* further underscores the need to incorporate optimal security-by-design features "as early as possible in the facility lifetime," because this will likely "lead to more effective and efficient security measures that are more easily sustained or adapted. Adding security measures to a facility after it has been designed and built can result in long term reliance on less cost effective protection measures." IAEA (2018) [14] provides additional background information on physical protection systems and describes alternative measures to consider integrating in designs.

- The Electric Power Research Institute expresses similar points to the preceding references in its *Assessment of Potential Applications for Advanced Security Technologies at Nuclear Power Plants* [15]. It notes that the "costs associated with the security systems and security staff will continue to challenge the economics of both small modular reactors and ARs. New technologies may allow plants to implement other security measures that are as effective in protecting a nuclear plant as the currently used technologies but are less costly and present less potential concern for neighboring communities. By investing in new technologies to augment tasks typically performed by staff, plants can better optimize their staff and control costs while maintaining the security and safety of the site."

- The World Institute on Nuclear Security provides detailed guidance on SeBD, alternative measures, and economic optimization in WINS [8, 16, 17, 18].

In addition to weighing the effectiveness and economics of security posture alternatives, as summarized in the list above, AR developers may need to consider the attractiveness of their fuel and other nuclear materials as targets. Some new nuclear plants have similar fuel enrichments, usage rates (i.e., burn-up), and waste storage systems to existing light-water reactors, but other concepts deviate from the current fleet in various ways. These differences could place some ARs in other categories of material accounting and control for nuclear facilities. Light-water reactors with 10 kg or more of ^{235}U up to 10% enrichment are in Category III. Tighter requirements apply to facilities in Category II with 10 kg or more of ^{235}U up to 20% enrichment, and the tightest requirements apply to facilities in Category I with 5 kg or more of ^{235}U above 20% enrichment or 2 kg or more of plutonium [19, 14 (p. 27), 20 (p. 20), 10 (p. 129)]. Examples of studies addressing the potential security needs of advanced nuclear plants based on their fuels and materials include Bathke et al. (2012) [21], Bays et al. (2021) [22], Cheng (2019) [23], Generation IV International Forum (2009 and 2011) [24, 25], Hill et al. (2020) [26], Holcomb et al. (2020) [27], Kovacic et al. (2021) [28], and Lyman (2021) [29]. If certain AR designs would need to comply with tighter security requirements than existing light-water reactors, close assessment of security posture alternatives with the SeBD Economics Tool could be even more useful for optimizing complex security decisions for ARs.

2.5. Importance of SeBD economics from a market perspective

Review of market conditions and financial performance for existing nuclear plants provides further motivation for thoroughly evaluating security posture alternatives with the SeBD Economics Tool. As a result of low wholesale electricity prices in recent years due to abundant natural gas supply, increasing renewables penetration, and additional factors, many nuclear plants in the United States have lower revenues than costs, leading in some cases to retirements [30, 31, 32, 33]. Figure 6, reproduced from Szilard et al. [32], shows that the majority of nuclear units had negative net revenues.

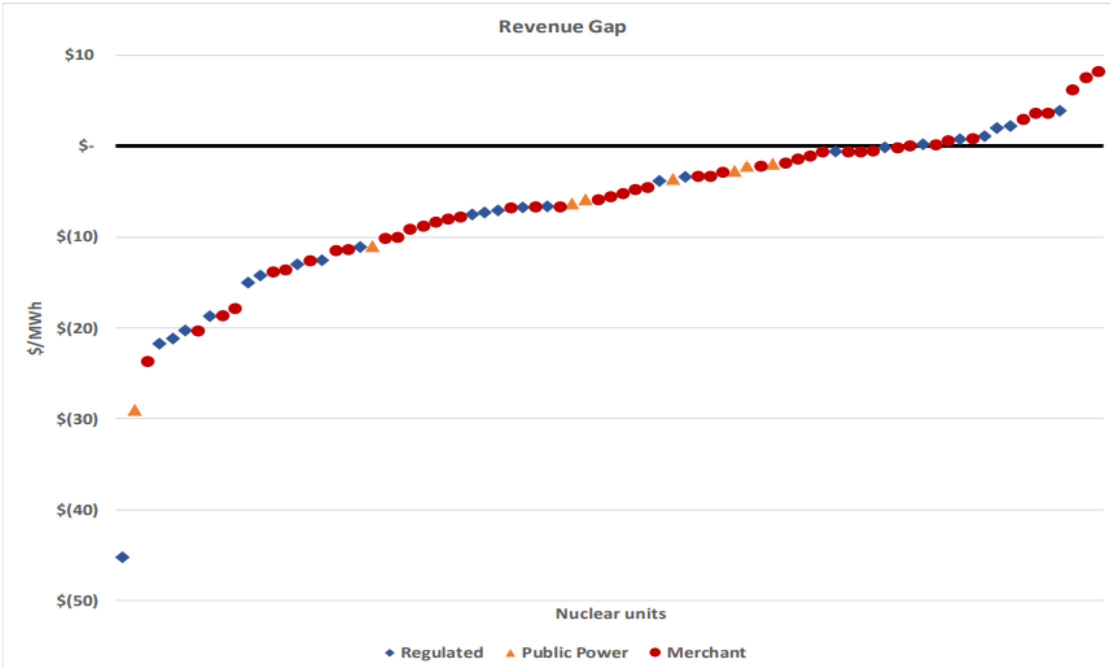

Figure 6. U.S. Nuclear Unit Revenue Gap from Szilard et al. (2017)

The nuclear industry is pursuing many strategies to reduce costs and enhance product value in light of these market pressures. NEI indicates that average operating costs across the existing fleet have dropped 24% from 2012 ($24.41/MWh) to 2019 ($18.55/MWh). However, the decrease in operating costs is not enough to make most plants profitable, as can be seen in Figure 6. U.S. Nuclear Unit Revenue Gap from Szilard et al. (2017) The MIT report titled *The Future of Nuclear Energy in a Carbon-Constrained World* [34] outlines numerous approaches to minimize capital and operating costs for new nuclear deployments while meeting safety and security requirements. Analyses by the national laboratories regarding physical security, such as Yadav et al. (2019) [35] and Yadav and Burli (2020) [36], also assist with identifying the most promising options. ARs can use the SeBD Economics Tool to ensure that their physical security costs, in combination with capital costs and other operating costs, would lead to viable market deployments.

3. METHODOLOGY AND RESULTS

3.1. Development of scenarios

In the current effort focused on physical security economics of ARs, it is important to learn from the economics of the current fleet which has experienced prohibitively large increases in costs associated with physical security, with labor costs being an important contributor to this increase. The high labor cost in physical security can be attributed to the large number of armed guards at a nuclear power plant. The performance assessment of physical security of AR is focused on understanding the impact of number of armed guards on the performance of the physical security posture of a plant.

This work leveraged the models of physical security postures of a hypothetical SMR facility modeled in PATHTRACE computer software developed by SNL [37]. The major elements of the model of SMR facility are: four nuclear reactors in a reactor building, two control room buildings, four turbine buildings, security building, and four cooling areas [37]. The four reactors are natural circulation integral Pressurized Water Reactors (iPWR) that are able to produce 140 MWth or 49 MWe from each reactor module [37]. Details of the modeled facility are available in [37].

The PPS of this facility is designed to protect against sabotage of four target locations: 1. Reactor cores, 2. Spent fuel pool (SFP), 3. Emergency power banks, and 4. Emergency core cooling (ECC) system. The PPS design comprises of a chain-link fence and an entry control point around the limited access area. The entry control point into the site's protected area is equipped with x-ray detection for contraband items. The protected area is protected by a perimeter intrusion detection and assessment system (PIDAS) which consists of two chain-link fences separated by a 40-foot isolation zone containing complementary sensing in the form of buried vibration cables and bistatic microwave detectors. The PIDAS is also equipped with cameras with proper video assessment that capture and record 5 seconds before an alarm was initiated and 5 seconds after an alarm was initiated [37]. The areas inside the PA are under constant surveillance via pan-tilt zoom cameras. Entrances to all the buildings are armed with balanced magnetic switches and keycard access or keycard and PIN access. Passive infrared curtain sensors are installed in vital areas such as reactor buildings, fresh fuel rooms, and control rooms [37].

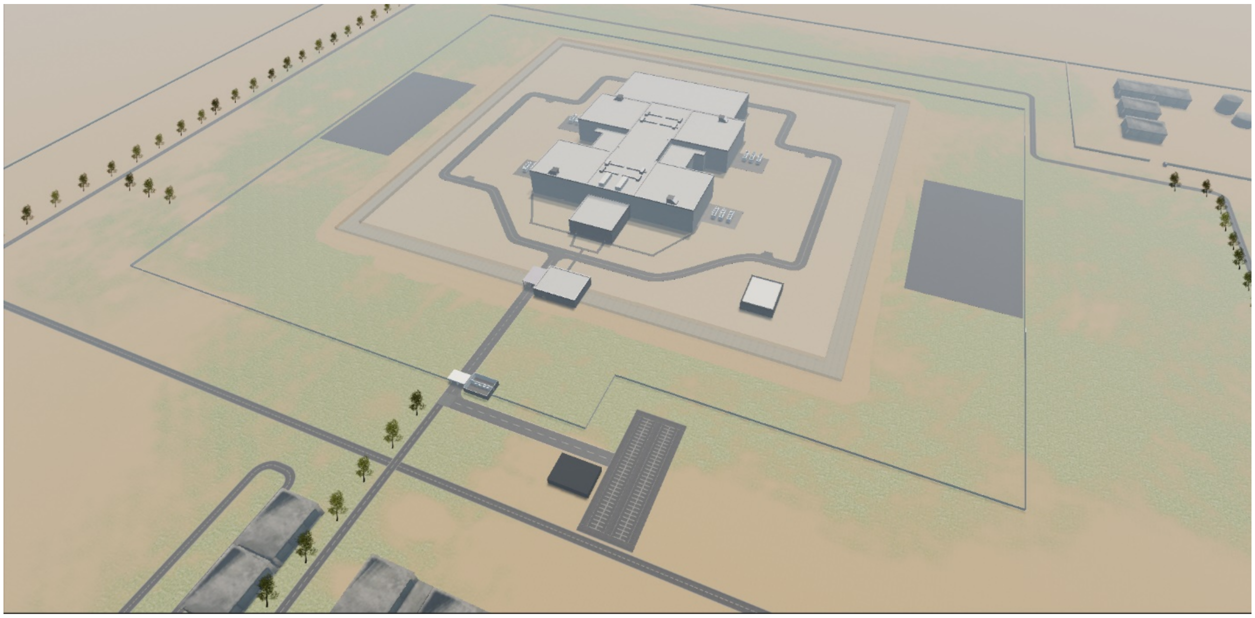

Figure 7. Layout of SMR facility modeled in PATHTRACE [37].

The adversary attack scenario is modeled to simulate an attack on the targets by two adversary teams. The first team travels from outside the perimeter fence directly to the central alarm station (CAS) and the second team from the perimeter fence to the non-nuclear receiving building. The first team makes a forced entry into the CAS building, from where they penetrate the below-grade reactor floor and place a charge on the reactor core [37]. The second adversary team penetrates the above-grade wall to force entry into the non-nuclear receiving building and then proceeds to penetrate the above-grade wall of the reactor building, where the adversaries place a charge on the emergency core cooling system (ECCS) water tank.

The PPS of the facility can detect either adversary team at several points along their paths towards their respective targets. The response force initiates the response at the onset of first alarm, with the objective of interrupting the adversaries. The attack scenario can end with two possible outcomes, 1. The responders are successful in interrupting all adversaries and stopping the sabotage, or 2. The adversaries are successful in completing the sabotage. The simulation of this attack scenario results in the P_I values for a given response posture.

3.2. G4ECONS

The Generation 4 Excel-based Calculation of Nuclear Systems (G4ECONS) model was developed for the Economic Modeling and Working Group (EMWG) of the Generation IV International Forum [37]. Version 3.0 of the G4ECONS model and user manual was released to the EMWG in late April of 2018 [39]. The G4ECONS model was designed to provide a point estimate of the levelized, unit energy cost (LUEC) and capital cost for comparing among AR concepts. The G4ECONS flow diagram and key cost accounts are shown in Figure 8.

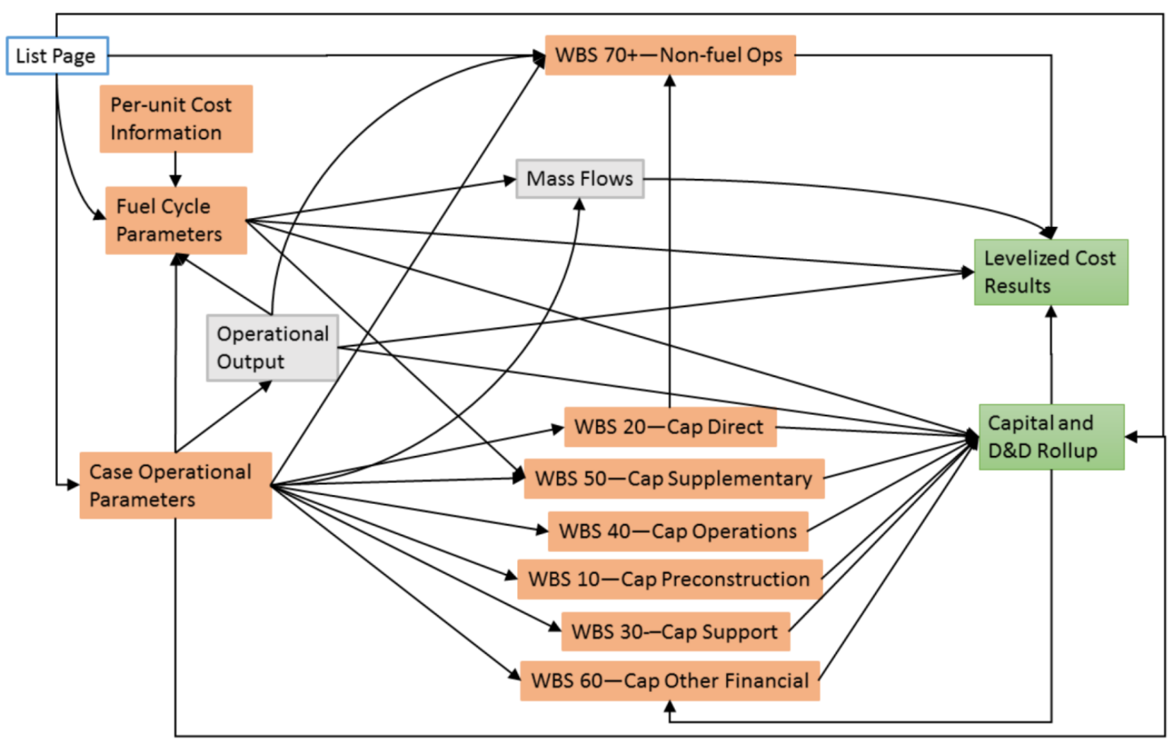

Figure 8. G4ECONDS Model Version 3 Flow Diagram, from Ref. [39]

G4ECONS has been used in several LWR and AR cost comparison studies [40, 41, 42, 43]. It has also been benchmarked against other economics tools such as NE-COST [44].

For this project, the goal is to assess the cost and effectiveness for various security postures. In terms of security costs, although not explicitly defined, these are primarily contained within the *WBS 20 – Cap Direct*, and *WBS 70+ – Non-fuel Ops* accounts. Within these accounts, security costs are contained in subaccounts *21--Buildings, Structures, and Improvements on Site,* and *71 + 72--On-site Staffing Cost (Non-Management + Management)*.

3.3. PWR 3 (SMR) reference case

For the purposes of evaluating the cost and effectiveness for various security posturers, a reference design is established. This reference design case in G4ECONS is the *PWR 3 (SMR)* reactor. Table **1** shows some of the key case operational parameters.

Table 1. PWR 3 Case Operational Parameters

Reactor Type Name	PWR 3
Plant Thermal Power, MWt	300
Plant Thermal Efficiency, %	33.33
Plant Electrical Power, MWe	100
Plant Capacity Factor, %	90
Fuel Burnup, GWtd/MHIHM	40
Specific Power, MWt/MTHM	33
Number of Cycles, #	3
Plant Lifetime, years	40
Construction Time, years	3
Total Lumped Capitalized Costs Including First Core	\$500M (or \$5000/kWe)
Operations (WBS 70+)	\$8.02M/year
Total Levelized Unit Electric Cost (LUEC), mills/MWeh	61.53

The values and parameters listed in Table 1 are assumptions and do not reflect a particular design. These values are simply provided for establishing a baseline case for estimating the effectiveness and security cost associated with different postures. For example, an SMR is expected to have a smaller facility footprint than a large LWR and could potentially be effectively protected with fewer systems and guards. However, the security cost could potentially account for a higher fraction of the total LUEC.

One important note is that for the purposes of this project, it is assumed that the capital and operational costs reported in Table 1 does not include security costs, which will be added to the accounts previously mentioned to establish a new estimate for the different security posture. Ideally, these case operational parameters would be supplied by the vendor or owner/operator of interest to achieve a more realistic estimate of security costs relative to the total plant economics.

3.4. Security cost scenario estimates

Five SeBD cost scenarios were evaluated to estimate the total security-related capital. For each of these scenarios, PathTrace was used to estimate the number of guards needed for 14 different response times. The number of guards then determined the relative operational costs. The 5 scenarios combined with the 14 different levels of security guard force created a total of 70 security postures. The different cost accounts being evaluated for each scenario are listed in Table 2. **Security Cost Account Assumptions**

Table 2. Security Cost Account Assumptions

Account	Description	Cost Assumption Value
211--Fence	Total cost for inner security fence	$1,537,894
212--Badge Readers	Total cost for badge readers for an SMR	$25,000
213--X-ray	Total cost for X-ray machines	$55,000
214--BMS	Total cost for Balanced Magnetic Switches	$25,000
215--PIDAS	Total cost for Perimeter Intrusion Detection and Assessment System around air cooled condensers	$833,661
216--Vibration Cables	Total cost for vibration cables, alarms, and lights	$27,477,034
711--Guards	Total cost for 1 guard shift (5 FTEs)	$450,000
712--Electronics O&M	Total cost for security electronics O&M	10% of the total security electronics cost

The total costs listed in Table 2 are estimated from security design assumptions related to items such as the cost of walls, fence, cables, etc. per linear-foot and the length or area of such equipment. The security cost scenarios definitions, which are based on the equipment, is shown below in Table 3, where X in the G4ECONS cost account column denotes the value listed in Table 2 is present for that scenario #ID.

Table 3. Security Posture Scenario Definitions

#ID	211	212	213	214	215	216	712 ($)
1	X	X					$2,500
2	X	X	X				$8,000
3	X	X	X	X			$10,500
4	X	X	X	X	X		$93,866
5	X	X	X	X	X	X	$2,844,070

3.5. CFA methodology

Sandia was responsible for developing a cash flow analysis (CFA) for this interlaboratory project to analyze the SeBD scenarios introduced in Table 3. The results from this analysis are presented in terms of net present value (NPV) and internal rate of return (IRR) vs. the probability of interruption (P_I). The overall goal of this project is to quantify the tradeoffs associated with higher levels of physical protection (enhanced security design), the need for security personnel, and the probability of interruption.

Cash flow analyses are a common methodology for calculating the NPV and IRR of a stream of annual revenues and costs. Future revenues and costs are discounted to reflect time value of money considerations. In general, projects should have a positive NPV in order to move forward. Crucial to the NPV calculation is the assumption about the discount rate, *r*. Higher discount rates devalue future costs and benefits. Corporations and other for-profit entities will usually require discount rates in the 8%-15% range. For a project with an *r* = 10%, a positive NPV implies that the forecasted rate of return (ROR) on the project is higher than 10%. Another measure routinely used to rank projects is the IRR. The IRR is, by definition, that r associated with an NPV = 0. If a project has an estimated IRR = 18%, then that same project would have an NPV of 18% for an assumed *r* = 18%.

The main economic considerations categories included in this CFA include:

- Revenues associated with the sale of electricity or from any incentives, such as capacity credits. The base assumption for this model were market tariff rates of 90 $/MWh and additional capacity credits of $20/MWh.
- Amortized capital cost payments associated with the construction of a 100 MWe SMR reactor with an estimated capital cost of $5000/kWe. Key financing decisions include:
  - Six-year construction period and a 30 year economic lifetime for the facility
  - 50%/%50% debt/equity financing split.
  - Debt and equity financing rates specific to scenario choice
    - ORNL assumes debt/equity/financing rates of 5%.
    - MIT assumes debt/equity/financing rates of 8%/12%/8%.
  - Federal corporate tax rate of 21%
  - State tax rate of 2.5%
  - Modified accelerated cost recovery (MACR) depreciation method

- Operating and Maintenance costs, including variable, fixed, and fuel costs.
    - Fixed O&M include expected annual operating and maintenance costs including any security costs. For this model, the security costs were kept separate from other costs in order to target the tradeoffs between increased presence of security personnel and the probability of interruption (P_I).
    - Variable O&M is based on an MIT study estimate of the average variable O&M cost for a new facility ($/MWh).
    - Fuel costs of 0.8 $/MMBtu.
    - The CFA includes annual growth rates of 2% for fixed O&M and 1% for variable O&M.

3.6. The scenarios

The CFA calculates the NPV and IRR for five scenarios, each of which contains differing levels of physical security attributes, as described elsewhere in this document. Each of the five scenarios includes an estimated capital cost. All electronic estimates include a fixed O&M cost component (10% of electronic costs). For each of the five scenarios, we consider 14 levels of security guard configurations, ranging from zero to 10 full time guards. Each full-time guard requires five full time equivalents (FTE) to fully staff a facility. We assume an average annual cost $90,000 per guard (fully loaded).

PathTrace was used to estimate the P_I for each of the 70 possible cases (five scenarios, with 14 levels of guards each).

3.7. Cash flow analysis results

The results show the tradeoffs associated with various levels of enhanced security, level of guards, and the P_I. The results are highly sensitive to the financing assumptions. Using the lower cost of capital assumptions of ORNL lead to more favorable results. In all of the figures, we include a line indicating a P_I of 90%, as an indicative minimum threshold for regulators or other decision makers.

Using the ORNL financing assumptions, the NPV is positive for all scenarios, Figure 9. Of those scenarios above the P_I=90% line, the least cost option would be scenario 3c, which has 2 guards on site at all times, in addition to the added physical security. The IRRs range from 10.3% to 12.1%, Figure 10.

Scenario 3c has a P_I of 0.93, an NPV of $367.9 million, an IRR of 12.0%. Adding additional guards decreases the NPV and IRR. The P_I does not increase until there are 6 guards on site at all times, Scenario 3i, which has an NPV of $343.8 million and an IRR of 11.6%. Based on this initial analysis, it does not make sense to add additional physical security measures beyond those of Scenario 3.

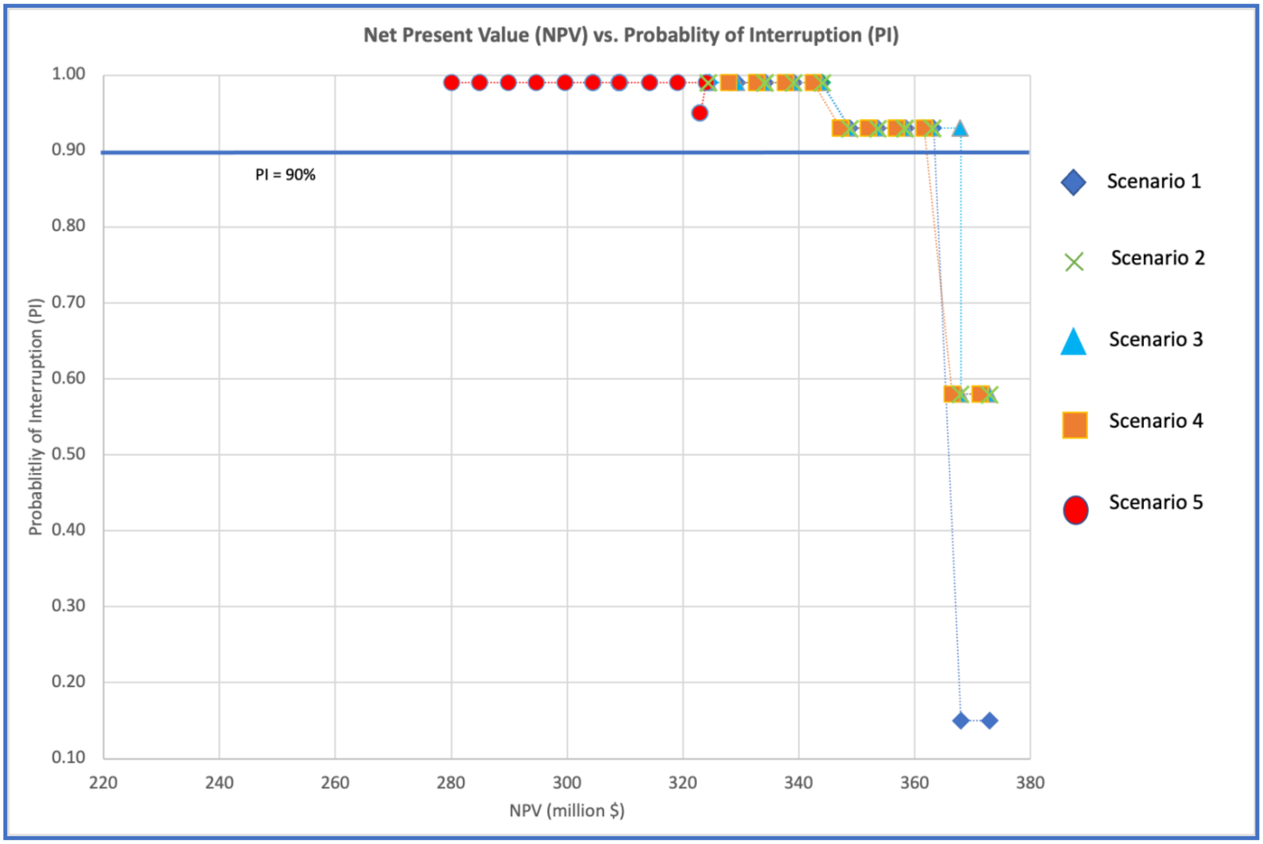

Figure 9. NPV vs. P_I: ORNL Financing Assumptions

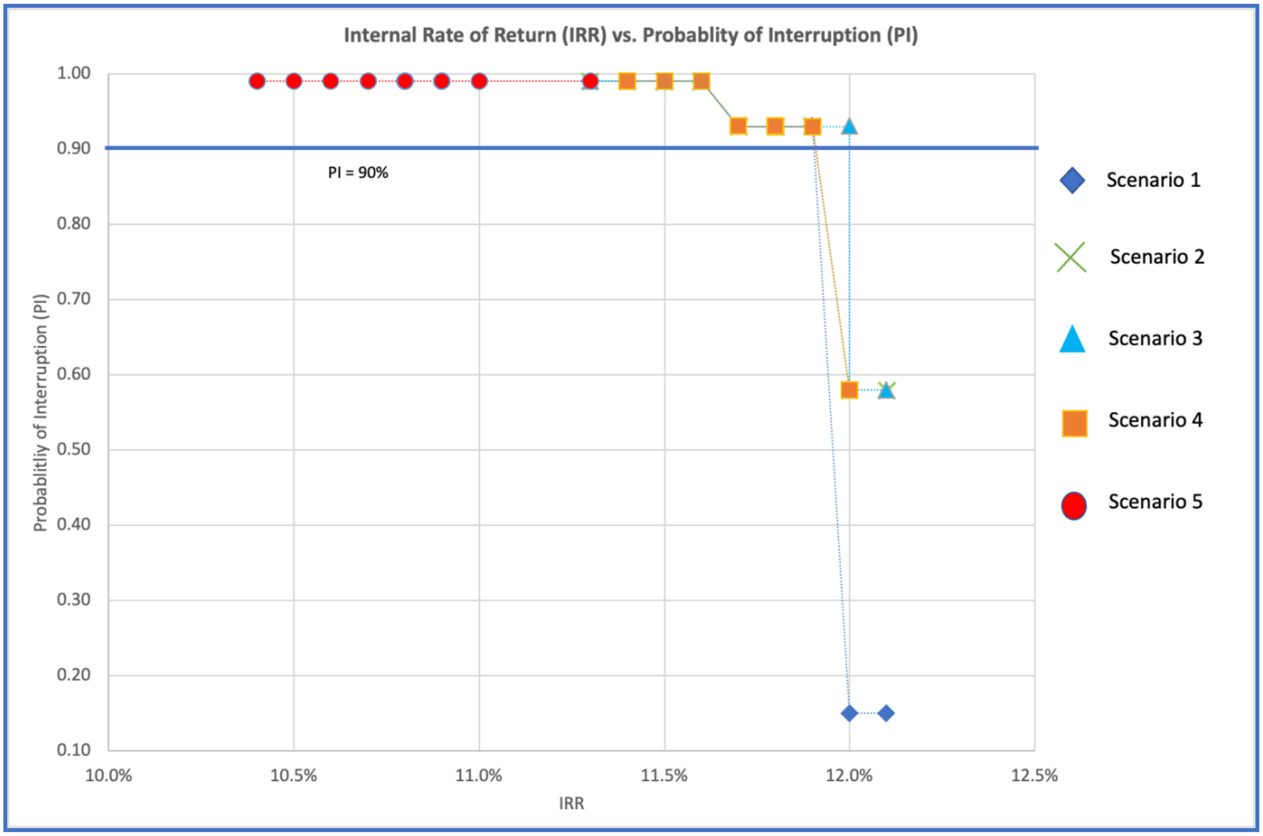

Figure 10. IRR vs. P_I: ORNL Financing Assumptions

Using the MIT financing assumptions results in significantly lower NPV and IRR estimates, Figure 11 and Figure 12. In contrast to the results using the ORNL financing assumptions, the NPV is negative for all scenarios using the MIT assumptions of 8% cost of debt financing and 12% cost of equity financing. The IRRs range from 8.8% to 10.7%, Figure 12. Investors typically have a minimum rate of return (ROR) requirement. For a required ROR of 12%, none of these scenarios are viable without government subsidies.

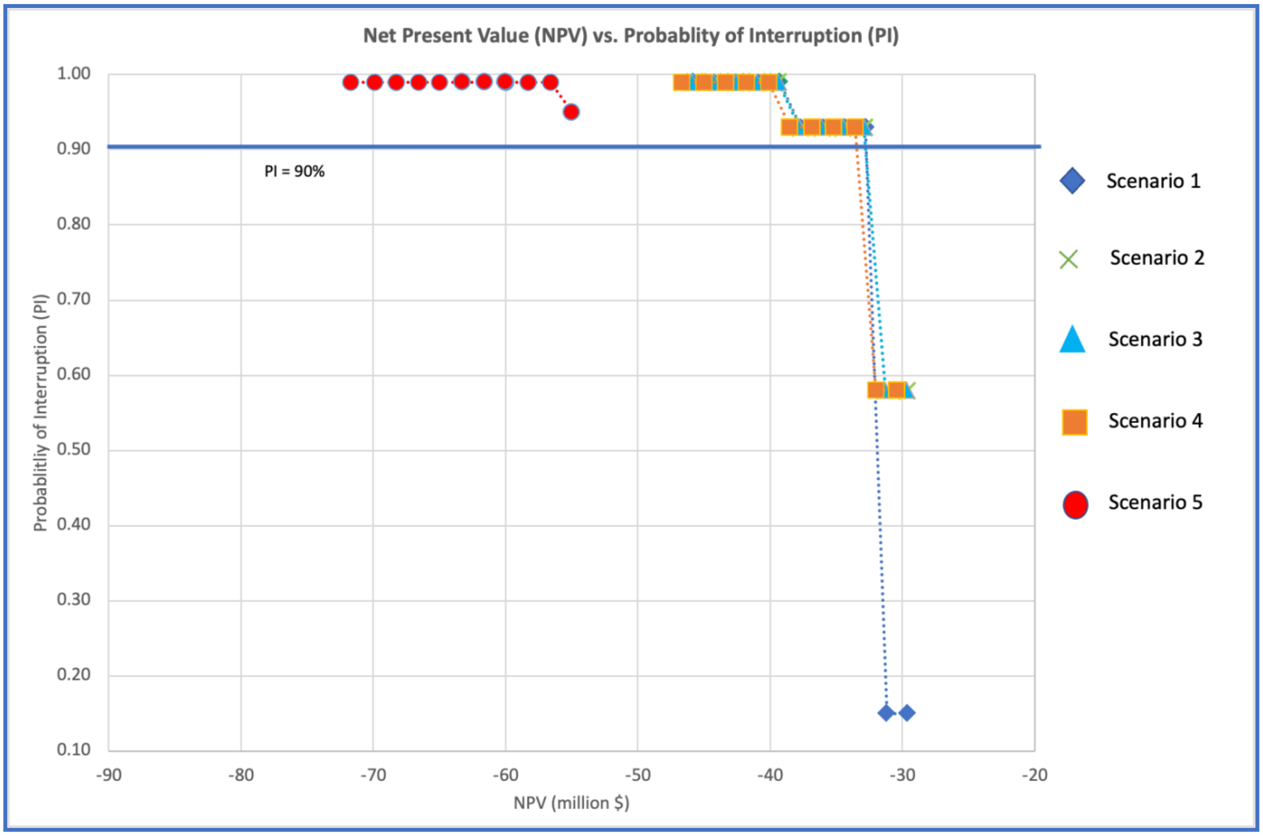

Figure 11. NPV VS. P_I: MIT Financing Assumptions

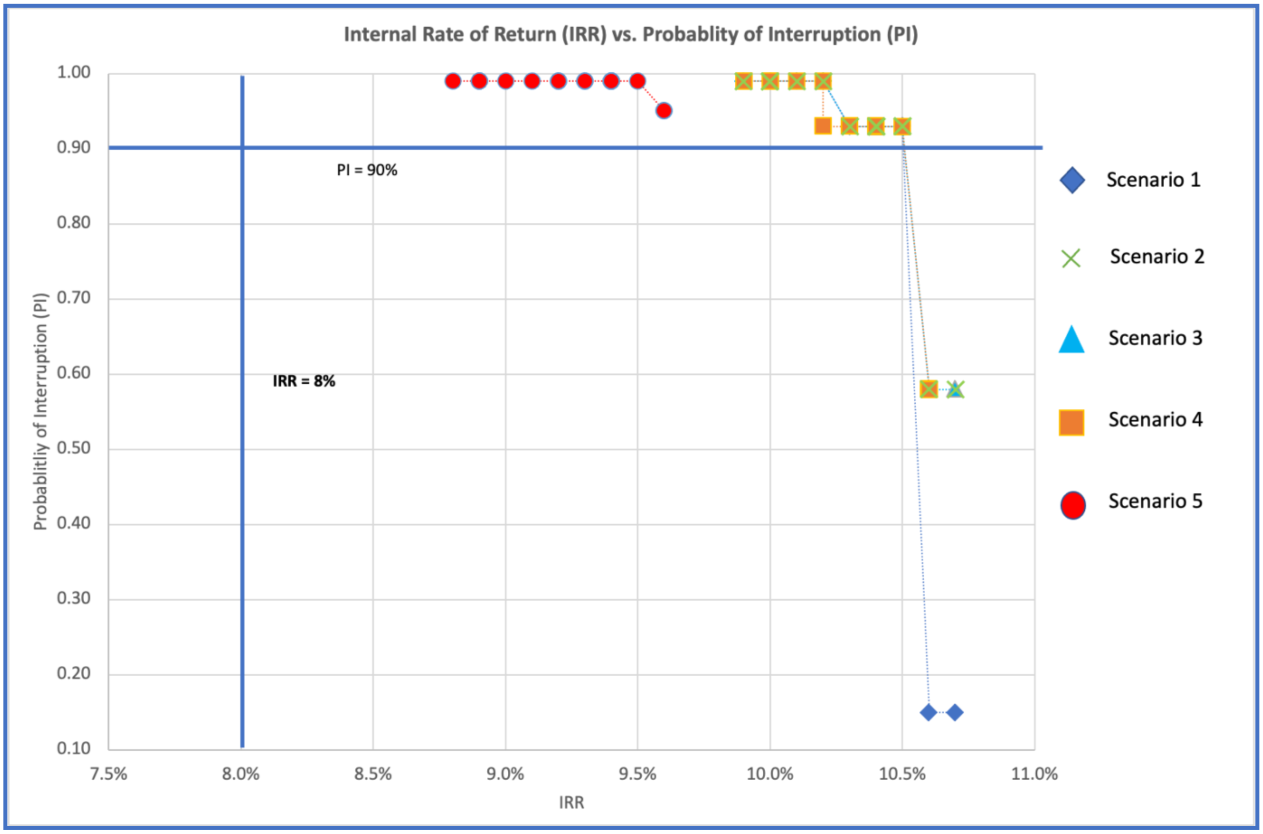

Figure 12. IRR vs. P_I: MIT Financing Assumptions

4. CONCLUSIONS AND NEXT STEPS

This effort has demonstrated that it is possible to perform a joint security/economics assessment of a nuclear facility. The results indicate that the use of pre-existing security metrics is possible and that standard economics methods can be incorporated. This is promising because it means that the terminology and analyses can be directly ported to use in the field today.

Notwithstanding the success of this effort to date, there are two further efforts that should be undertaken. The first effort that needs to be completed is a pilot study of this methodology in collaboration with an industry partner. One example of this would be to work with an AR/SMR vendor to assess the cost and/or benefit of designing security into their product.

A second effort that should be pursued is the development of the methodology into a user-friendly code that can be utilized by interested industry and/or government partners. The resulting code should be a merger of the CFA code presented in this report and one or more security assessment tools (e.g., PathTrace, Dante, or Avert). In the long term, this should be an ongoing effort until the use of this methodology is a standard for the industry.

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