ORNL/TM-2024/3423

Security by Design Business Case Development

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Nuclear Energy and Fuel Cycle Division

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ABBREVIATIONS

ACT	assessment calculator template
ARIS	Advanced Reactors Information System
A/SMRs	advanced small modular reactors
ASN-F	French Nuclear Safety Authority
ATM	automatic teller machine
BRE	bullet-resistant enclosure
CBRN	chemical, biological, radiological, and nuclear
CFD	computational fluid dynamics
CFR	US Code of Federal Regulations
C-NSC	Canadian Nuclear Safety Commission
COL	combined operating license
DOE	US Department of Energy
EIA	US Energy Information Administration
FOAK	first of a kind
GAO	government accounting office
IAEA	International Atomic Energy Agency
IRR	internal rate of return
ITAAC	inspections, testing, analyses, and acceptance criteria
LCOE	levelized cost of energy
LERF	large energy release frequency
LWR	light-water reactor
LWRS	LWR Sustainability [project]
NEI	Nuclear Energy Institute
NPP	nuclear power plant
NPV	net present value
NRC	US Nuclear Regulatory Commission
NSS	Nuclear Security Series
O&M	operation and maintenance
PBMR	pebble bed modular reactor
PSS	physical protection system
R&D	research and development
RO	real options
ROI	return on investment
SBD	safeguards by design
SeBD	security by design
SME	subject matter expert
SMR	small modular reactor
URC	unacceptable radiological consequence
WAAC	weighted average cost of capital
WINS	World Institute for Nuclear Security

ABSTRACT

Security-by-design (SeBD) is considered an essential component in the development of advanced / small modular reactors (A/SMRs), with the potential to minimize long-term operational costs through efficient placement and design of physical protection systems. However, without an explicit business case and guidance, true SeBD could elude developers, leading to suboptimal security solutions and impeding new nuclear deployment. This report presents a review of potential pitfalls for advanced reactor vendors and builds a business case for implementing SeBD into the quality assurance program for advanced reactor designers. This report also presents revenue stream options to a company with an SeBD program.

1. INTRODUCTION

Although security is not the main objective when building a nuclear reactor, it is a key cost component to ensure compliance within the required regulatory framework. Ensuring a secure nuclear facility is paramount to protecting public health. However, security is also a key cost component and should be optimized while meeting all regulatory requirements. When security by design (SeBD) is combined with safety and safeguards by design (SBD), this represents the general concept of S^3. If S^3 is considered early in the process as integral to nuclear plant design, then the plant's return on investment (ROI) will be increased. This report presents several hypotheses regarding SeBD and analyzes potential benefits of an integrated approach during design and deployment. The S^3 approach will ensure that security is always addressed throughout the lifecycle of the plant. The economic value of SeBD for an advanced reactor design will be modeled to predict potential benefits and to determine which entities would realize value. These results will provide justification for investing in an SeBD process as part of the plant's standard design.

1.1 DEFINING SECURITY BY DESIGN

In this document, *SeBD* is defined as follows:

> *An integrated process by which the physical protection system of a nuclear plant is intentionally integrated into the full life cycle of the facility, including planning, design, construction, operation of nuclear facilities, through a combination of analytical, physical, technological, and procedural measures. Security by design is the intentional application and integration of security with all other aspects of design and operation throughout a facility design lifecycle to improve the overall site security posture while reducing the need for costly retrofits or added security resources post-design.*

Incorporating an SeBD methodology optimizes facility features to reduce security risks while still meeting the functional design requirements. Under this definition, SeBD is implemented holistically to ensure nuclear plant security. The nuclear design vendor follows a programmatic, analytical method to align the needs of all advanced reactor stakeholders over the entire lifecycle—from design through decommissioning. As defined here, SeBD can take many forms, but the key components are as follows:

1. A formalized security design process
2. Security that is fully integrated into the plant design through processes, procedures, or automation
3. Emphasis on security design equivalent to that traditionally applied to safety, technology, licensing, and plant economics

The theoretical and likely unachievable objective of all S^3 or (3S) by design processes is to strive toward a walk-away-safe-and-secure nuclear facility: in this perfect and potentially unachievable scenario the plant must be designed to ensure that it is be placed at a site without personnel and be safe and secure. This theory follows the hierarchy of effectiveness and cost, as shown in Figure 1 below.

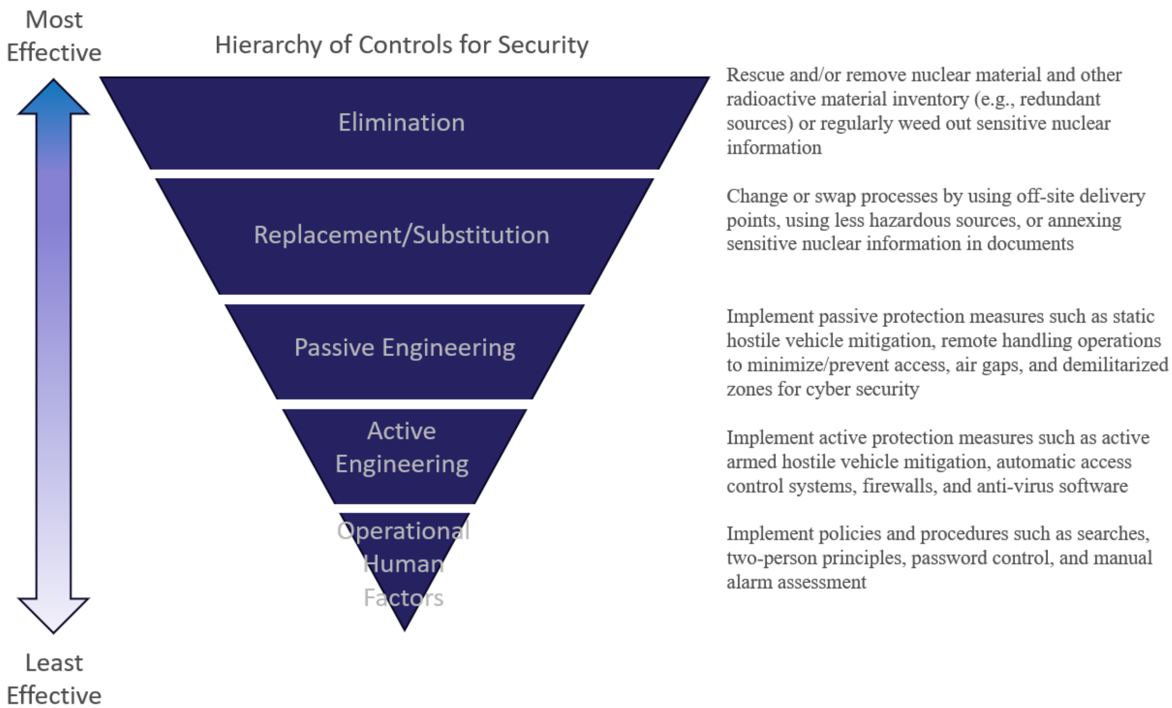

Figure 1. Hierarchy of cost and effectiveness for design (WINS 2020)

According to International Atomic Energy Agency (IAEA) Nuclear Security Series (NSS)-13, SeBD can be summarized as follows (although the term SeBD is not used in this document):

For a new nuclear facility, the site selection and design should take physical protection into account as early as possible and address the interface between physical protection, safety and nuclear material accountancy and control to avoid any conflicts and to ensure that all three elements support each other. (IAEA NSS 13, §3.28)

The general goal for all designs is (1) to eliminate unnecessary elements because the underlying reason for maintaining that element (be it security, safety or other) has been eliminated, and (2) to ensure that the different aspects of design are integrated and support each other.

The IAEA definition is also closely aligned with the Nuclear Energy Institute (NEI) response to the proposed US Nuclear Regulatory Commission (NRC) Rule, 10 Code of Federal Regulations (CFR) Part 73.52, in which a plant's requirements for physical protection can be adapted for plants in which the performance capabilities preclude radiological sabotage. An applicant could thus conduct security by design to implement the following:

1. *Uses a reactor technology that is not susceptible to significant core damage and spent fuel sabotage, or*
2. *Does not have an achievable target set, or*
3. *Has engineered safety and security features that allow for implementation of mitigation strategies to prevent significant core damage and spent fuel sabotage if a target set is compromised, destroyed, or rendered non-functional.* (NEI 2016)

The World Institute for Nuclear Security (WINS) aptly summarizes SeBD for advanced reactors as follows:

> *The world cannot afford to miss this unique opportunity to incorporate security by design into the next generation of advanced reactors. These new reactors have the potential to play a huge role in slowing climate change and reducing the risk of nuclear weapons proliferation, and we hope this guide serves as an important contribution to making the expansion of nuclear energy beneficial for ourselves and for future generations.*(Wins 2020)

2. METHODOLOGY

2.1 HYPOTHESIS

Security is ***not*** incorporated into design for any or all the following reasons:

1. Nuclear capital for research and development (R&D) is finite, so funding is spent on items that yield the highest return on investment—novel design, safety, licensing, and the business case—from which more capital can be acquired.
2. Because security tools do not integrate into the current licensing and safety paradigm for nuclear reactors, significant effort is required to fully integrate SeBD into the typical design processes.
3. Because nuclear plant designers do not pay for the built-up cost or participate in the post-construction security market, they have no reason to invest in security because they do not stand to profit from integrating security into their designs throughout the process.
4. Not designing security into the design of a new or advanced nuclear power plant (NPP) builds up a future cost that will be paid later with interest when the plant is deployed—a cost that may be greater than the initial costs would have been in an integrated setting.

Therefore, the hypothesis is that a security process that is integrated into the nuclear design process and analyzed throughout the various design phases will be more effective than delaying the security analysis until the licensing or construction phase of a project.

2.2 GOALS

The goals for this paper are divided into four areas to determine if the hypothesis provided in Section 2.1 is true or false.

1. The regulatory environment in which designers, owner/operators, and rate payer markets exist, and the standard design phases that must be completed to operate in that environment
2. The possible mismatch of incentives between designers and future customers
3. Past lessons and analysis for reactors built in the United States where data were available
4. Application of business decision-making theories and processes to nuclear SeBD

These items must be evaluated generally so that individual nuclear power plants may use proprietary information to demonstrate the benefits of adopting an SeBD method and to justify the investment. Security can be incorporated into the plant design from the initial conceptual analysis phase to the retirement phase: this will lead to overall cost reductions in the construction, operation, and retirement of the nuclear power plant. Benefits can be realized through sales, defect avoidance, rework, delivery on schedule, plant levelized cost of energy (LCOE), and lower maintenance cost.

2.3 LITERATURE REVIEW

Section 2.3.1 presents the advanced reactor framework as it appears in the market today, primarily from a US advanced reactor perspective. This section provides a high-level overview related to the international community as described primarily in IAEA documentation. Section 2.3.2 presents a view of the nuclear market as it stands today, providing a high-level overview of where the market currently resides and where it could go with the new advanced nuclear market. Section 2.3.3 presents a SME expertise review on the design stages and goals for a nuclear power plant undergoing design certification and the potential mismatch of incentives between the designer and the future owner. Section 2.3.4 gives a case study for the impacts of mismatched incentives for cyber security. Section 2.3.5 reviews past nuclear reactor construction costs based on the available data. Because advanced reactor designers plan to learn from the mistakes of the past in terms of standard delays, cost overruns, and other types of events, it is important to use this information to benchmark how overall costs are imposed on a reactor before building out the cost contributions of security and savings for SeBD. Nuclear reactors built before the 1980s did not implement the characteristics of an SeBD or safety by design approach that is now aspired to by designers and regulatory officials. Section 2.3.6 discusses the need for scalability in nuclear designs and security of those nuclear plants for deployment in multiple locations. Section 2.3.7 then presents an overview of nuclear plant operation costs as gleaned from subject matter experts (SMEs) and interviews with owners around the United States and internationally, informing the cost baseline for an operating nuclear plant, as well as the security impact to the overall costs of a plant. Models and literature for mega-projects (>$1B) or other highly complex projects can be used to determine the impact to cost when a defect is found and how it can delay construction time or add costs. For example, should the designer avoid considering security concerns for a reactor prior to construction and then be required to make costly design changes to address issues, or should the designer increase security costs to compensate? Finally, section 2.3.8 applies similar programs design around improved product designs and defect avoidance to advanced reactors SeBD process.

2.3.1 Regulatory Environment for the Advanced Reactor Market

Advanced nuclear reactors have many features which could enable new markets and opportunities for deployment. Features that could be included in the designs differ significantly from the baseload power sources seen in the world's water reactor fleet. Attributes such as enhanced passive safety, transportability, high temperature coolants, and modularized design are promoted aspects of many advanced reactor concepts. An advanced reactor's novel operational features could lead to new revenue options through load following, power storage, transportable energy production, and production of commercial heat for systems such as hydrogen, cement, coke, and other industrial production (NEI 2016). However, to date, no US advanced nuclear reactors have been commercially built, so there is uncertainty about the advertised capabilities of such reactors. Capital should be prioritized for new reactor designs that incorporate security features. However, as posited in the hypothesis in Section 2.1, priorities and economic pressures may force advanced reactor vendors to spend their limited capital on other licensing concerns. The NRC's methods for licensing new nuclear designs are summarized below. Although these methods are not representative of regulations around the world, many countries look to learn the NRC to inform their regulatory frameworks.

In the United States, multiple methods have been developed or are under development to would allow for implementation of a modular generic design. The US-based licensing approach is addressed here because advanced nuclear reactors, with their modular designs, align with US licensing processes, and the NRC has a major influence on other regulatory bodies and nuclear newcomer countries. An understanding of these two processes helps illustrate the new advanced reactor market and the modular approach to deployment around the world in which SeBD must operate. The first method is addressed in 10 CFR part 50, which allows for a two-step licensing process. Figure 2 displays this two-step licensing process which is reproduced here from the NRC (Borchardt 2008).

Figure 2. NRC diagram of 10 CFR Part 50 licensing process (Borchardt 2008).

This licensing process provides a method for designing as you go, as in an à la carte method of building and designing a nuclear reactor. It provides flexibility and does not require a certification up front for the design, but it must have adequate information for a safety analysis report. Some construction preparations can begin, but the NRC requires the owner/operator to conduct an environmental review and safety evaluations to obtain a construction permit. Once the construction is begun, the safety evaluation and environmental impact assessment can be completed and approved prior to the receipt of the operating license. Although this process is flexible, it can result in high variability between plant designs, because the process allows for changes and justifications throughout. This customer-driven design process allows customers to specify the requirements and work with the appropriate vendors/designers to facilitate the design to meet their needs.

The 10 CFR Part 52 process was developed to rectify some issues that had been experienced 10 CFR Part 50 in the United States. This new, single-step licensing process attempts to frontload development and provides generic certifications that can then be deployed throughout the United States as long as the plant designer has the appropriate justifications to receive a standard design certification, as well as the appropriate inspections, testing, analyses, and acceptance criteria (ITAAC) to prove the plant was built to meet the safety requirements agreed to in the standard design certification. This process is more aligned with the concept of modularity, in which a plant can be designed into discrete modules which have certain requirements, and the associated ITAAC can be deployed to multiple sites like products rolling off an assembly line, with minimal deviations.

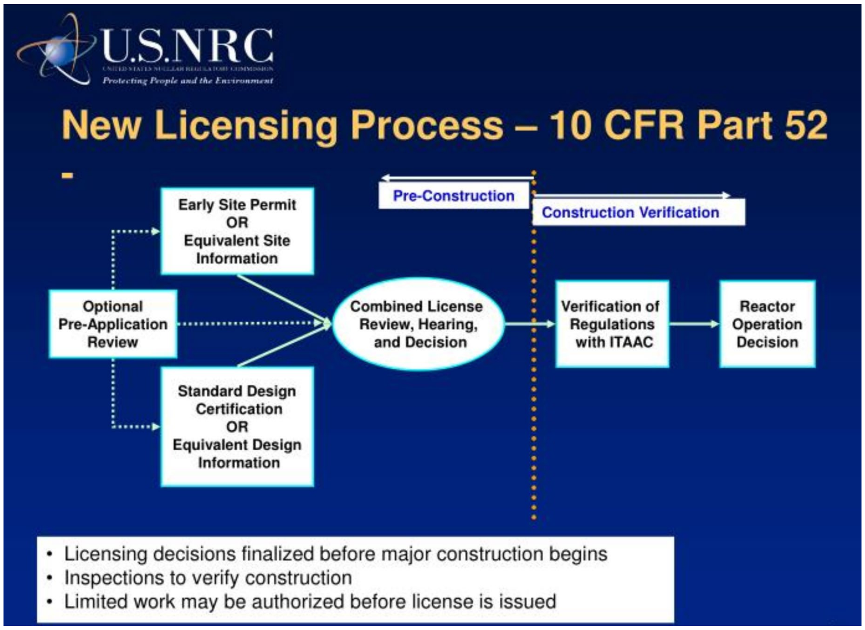

Figure 3. NRC diagram for 10 CFR Part 52 licensing process (Borchardt 2008).

A report to Congress (Rusco 2023) also compares the two processes for the different licensing methods.

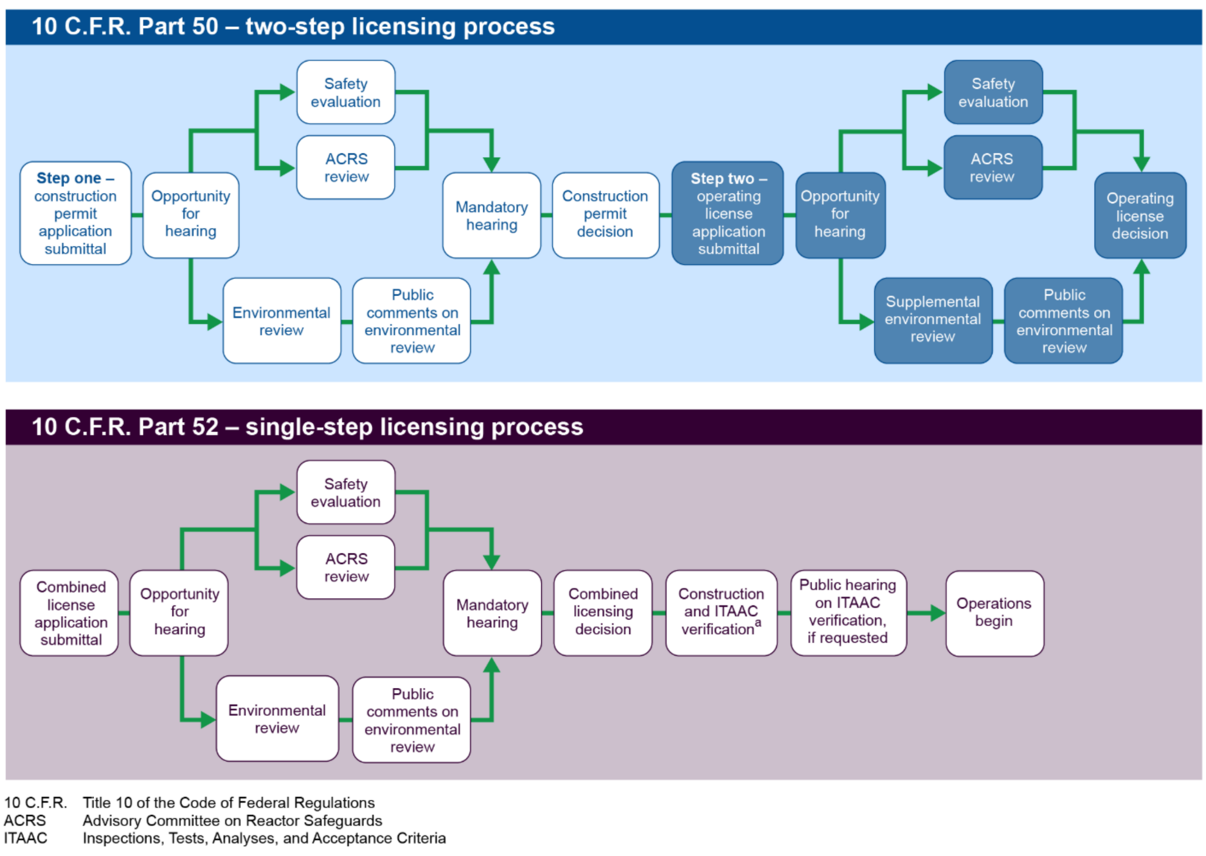

Figure 4. Illustration of the NRC licensing process (GAO 2023).

The new 10 CFR Part 52 process decouples licensing of the design from the construction and commissioning of the plant. This approach can eliminate risk from the design in the eyes of a future buyer, but the operator that must follow the plan may suffer with designs that are inadequate for operation and maintenance, of which security is a part. This leads to a possible mismatch in incentives because the vendor/designer will respond to financial pressures by working to meet the minimum requirements for licensing, causing the owner/operator to take on additional risk. For example, it is possible to justify establishing the potential for systems for security, but the final design is left to the licensee or the combined license owner. Colloquially, some security analysts have stated that they can "build a security system that protects anything." However, this ignores the question about whether it is affordable. This leads to an incentive mismatch for regulatory processes aligned with the 10 CFR Part 52 NRC two-stage licensing model. This is detailed further in sections below.

According to the IAEA Advanced Reactors Information System (ARIS) database (IAEA 2024), Third Way Database (Ahn 2022), and the Congressional Research Service February 2023 report to the US congress (Holt 2019), advanced reactors can generally be classified into 10 categories:

1. Gas-cooled reactors (including high-temperature reactors)
2. Supercritical CO_2 reactors
3. Sodium fast reactors
4. Molten salt reactors
5. Small modular reactors
6. Lead-cooled fast reactors
7. Gas-cooled fast reactors
8. Heavy water reactors
9. Advanced light-water reactors
10. Microreactors

Some of the earliest work for SeBD was conducted by Sandia National Laboratories. Their SeBD handbook establishes 12 primary principles a state must follow to implement an SeBD approach (Snell 2013). The handbook defines many principles, but its state-based licensing and regulatory approach may be implemented by a nation state. In general, this type of approach to implement top-down requirements for all plants would apply to states developing regulatory criteria, but they typically do not apply these approaches to a reactor in the design stage. Instead, plant designers focus on meeting the required regulations and the key functions from the IAEA security series for a physical protection system (PSS): deterrence, delay, detection, and response (IAEA 2021).

The overall process as laid out in the IAEA NSS follows a process similar to the NRC process for design and evaluation of PPSs.

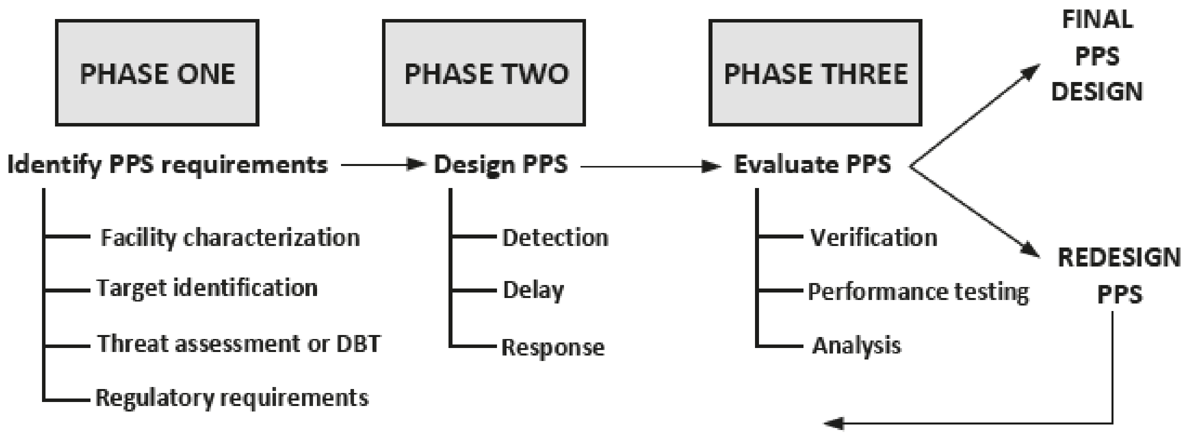

Figure 5. Process for the design and evaluation of a physical protection system (PPS) (IAEA NSS No. 40 2021).

The basic PPS framework indicates that there is a "Final PPS Design." However, the threat profile for nuclear plant changes over time, so any nuclear plant in the "Evaluate PPS" stage may need to return to the "Redesign PPS" stage, which is triggered by changes to regulatory guidance, generic safety issue publications (i.e., regulatory instructions to the license holder), or to the design basis threat (DBT). In interviews, one nuclear industry consulting company indicated that they do not typically maintain security personnel unless there is a predicted change regulation, at which point they hire staff in anticipation. The same contractor stated that they maintain safety, project management, and some other areas of expertise for consulting in the nuclear industry full time.

IAEA's definitions of SeBD used in this paper are limited primarily to Section 3.35 of NSS No. 40: "Effectively managing interfaces between safety and security is an important element of both … physical protection measures should not compromise safety and safety measures should not compromise physical protection (IAEA 2020)." Section 3.36 states, "Close interaction between physical protection and safety specialists is particularly needed in the identification of sabotage targets and protection of these locations." IAEA NSS No. 40 also includes guidance regarding defense in depth and leveraging synergies between plant safety and security (§3.38, §3.39). These guidelines present the case for using potential synergies between security and safety, but they do not explicitly state that the systems be integrated in a single protection strategy. However, these requirements could be met by implementing defense in depth and segregating safety and security systems from one another, leading to higher costs and complexity. Instead, integrating and taking credit for safety and security systems where applicable would lead to a more optimized, more affordable system. Definitions in Section 1.1 above and in the IAEA guidelines differ slightly, but they can support segregation of expertise between safety and security in which a safety team makes a design change, and the security team then re-evaluates design changes if they are found during the design change process. This issue is illustrated in Figure 5: in which there is no trigger mechanism for re-evaluation or a means of integrating changes to the plant's safety design as plant design evolves. A fully integrated process linking security and safety components together in a cost-effective manner is depicted in Figure 6.

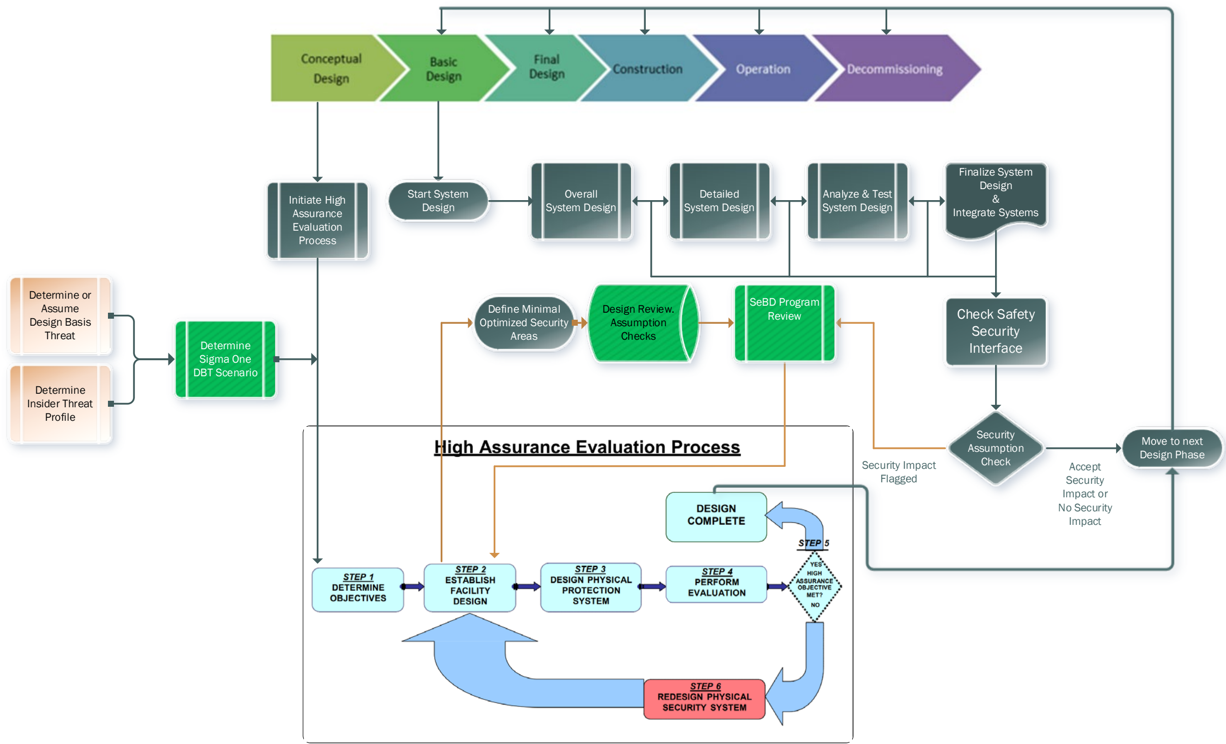

Figure 6. Potential adaptation and integration of safety and security licensing design processes.

This figure illustrates options for linking safety and security processes. Components relied upon for safety are key components of target sets. The physical protection system must protect those systems and thus the safety design of the plant. Safety and security processes must be integrated with the physical protection system design. This type of approach in a SeBD program within the NRC and IAEA frameworks will not only allow for a cost-effective method of ensuring that the advanced reactor vendor could meet the physical security requirements of a regulator, but it will also provide future revenue options. For example, this type of program can be leveraged to optimize requirements for different regulatory bodies and integrated into a quality assurance process required by regulators worldwide. It could also be developed into a security service for the nuclear industry in the future. This type of future revenue would incentivize companies to invest in this area, as discussed in sections below. It would also help to correct the potential incentive mismatch between the plant designer and the licensee. The mismatch is between the licensee's objective for a fully optimized security cost structure for the life of the plant and a designer's goal to provide adequate justification to a regulatory body that security requirements can be met once the site is commissioned. To further illustrate these options herein the various market components are presented, along with applicable market sizes in which an SeBD program can lead to the capture of market share.

2.3.2 Market Review

This market review assumes that the primary identifying factor is the use of fissionable and fissile material for power generation, so the nuclear fuel cycle will be used to gather a baseline set of market information. The standard nuclear fuel cycle diagram in Figure 7 can be used to define the various portions of the market.

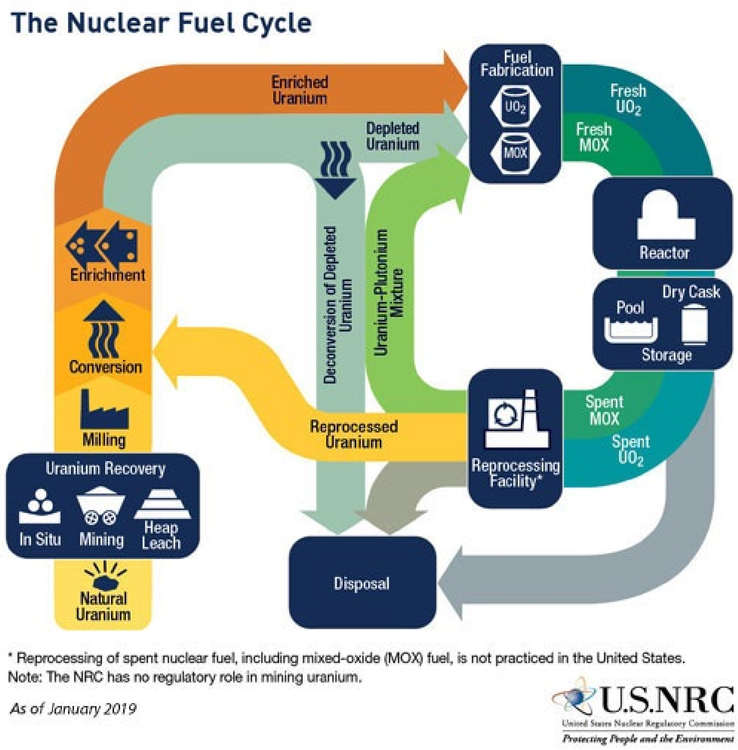

Figure 7. Nuclear fuel cycle.

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In the standard product lifecycle, four typical stages are outlined: *concept and development*, *growth*, *maturity*, and *decline*. The nuclear plant lifecycle also typically includes a retirement stage during which the savings for retirement are spent on site deconstruction and decontamination.

1. **Concept and development phase** (also known as the *market development phase*, the *R&D phase*, or the *infancy phase*): the market case is formalized and R&D is completed, but the technology has not been fully proven for the market.
2. **Growth phase:** the demand for the product increases, along with the overall market.
3. **Maturity phase**: demand softens, and multiple similar products enter the market.
4. **Decline phase**: new sales are diminishing, alternatives have developed, and the overall market may shrink, or companies may consolidate.

The retirement or decommissioning cycle of an individual nuclear plant can also be considered a separate market cycle.

As part of this analysis, the following assumptions have been made.

- The total market share and valuations within the different stages of the nuclear fuel cycle include the *nuclear premium*, which is an increase in cost for a specific component by a factor often ranging from 2 to 10.
- Most important components of that portion of the cycle are included within that specific market are therefore are included within the evaluation of that market.

The nuclear fuel / NPP market is at the maturity or decline portion of the product lifecycle, where innovation and development must step in and restart the cycle.

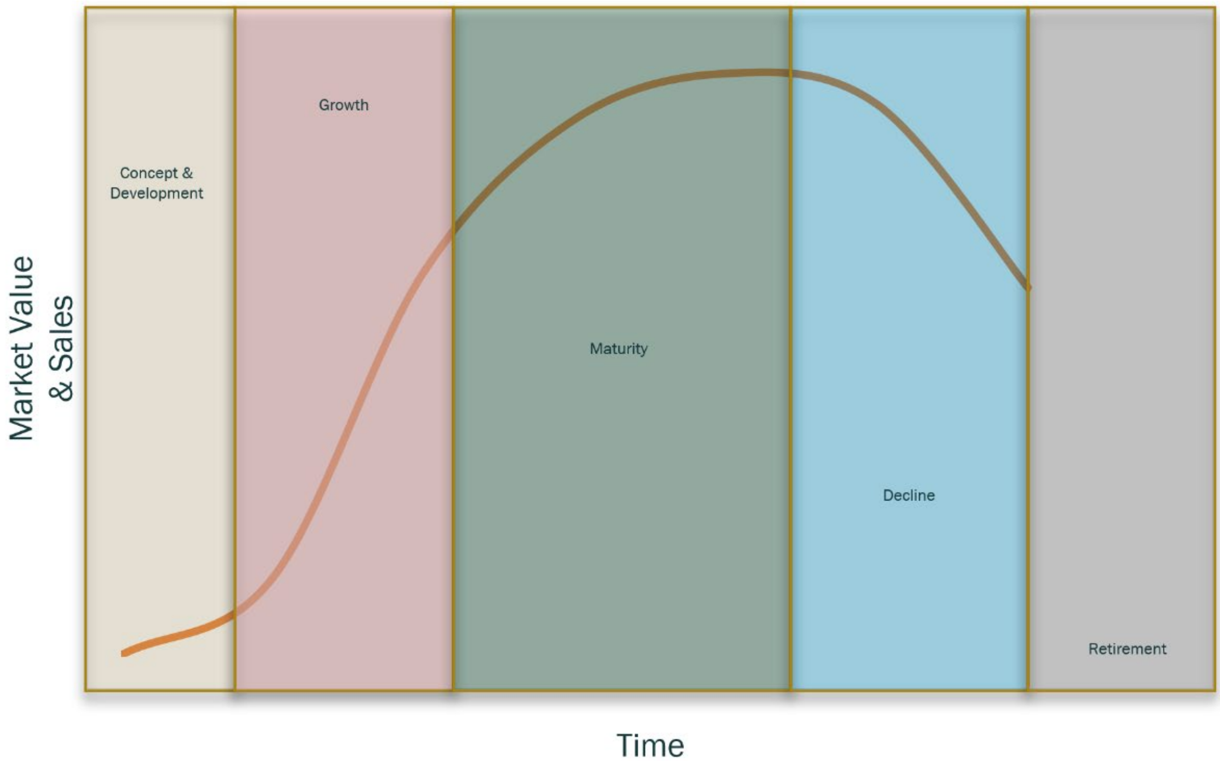


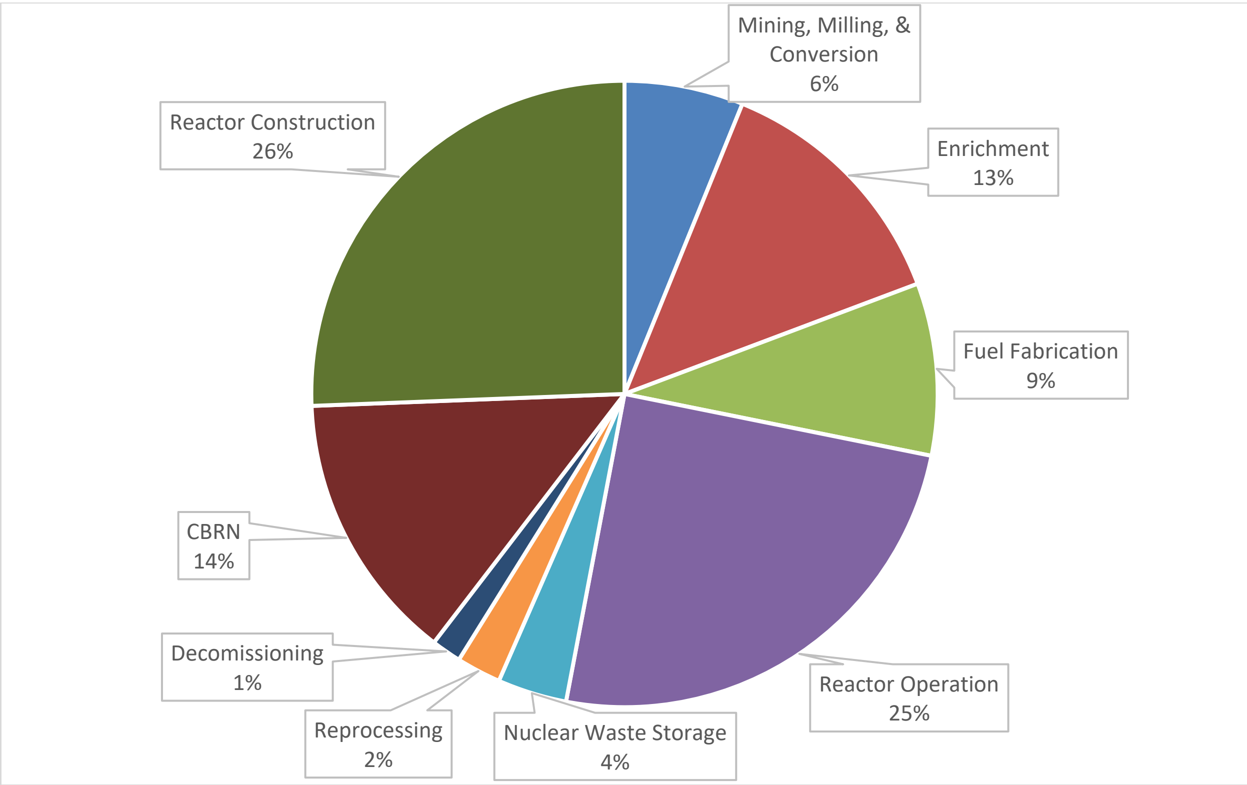
Figure 8. Illustration of the standard product lifecycle.

Over the past 15 years, the market has seen several plant retirements, and alternative energies have entered competitive markets. Thus, the current nuclear market is in the maturity or decline stage. The advanced nuclear market is geared to innovate and reset the decline stage back to the growth stage as new advanced reactor designs enter to fill the gap between necessary power production and declining nuclear power production of legacy plants. Companies are looking to capture an overall increase in energy market growth ranging between 16% to 57% at a rate of 0.5 to 1.6% per year according to the US Energy Information Administration (EIA 2023). Advanced reactors must step in with other technologies to fill that energy production gap.

A cursory examination of the present market for the nuclear fuel cycle is illustrated in Table 1, showing approximations for different segments of the nuclear fuel cycle, and Figure 9 illustrates these market size figures.

Table 1. Estimated market for nuclear fuel cycle components and the estimate year ($M)

Nuclear markets	Totals ($M)	Year	Reference
Mining, milling, and conversion	8,086.6	2023	RationalStat 2023
Enrichment	17,280.0	2022	Reports and Data 2024
Fuel fabrication	11,700.0	2022	Yahoo Finance 2024
Reactor operation	32,670.0	2022	Straits Research 2024
Nuclear waste storage	4,710.0	2021	Skyquest 2024
Reprocessing	3,030.0	2023	Market and Data Research 2024
Decommissioning	2,027.5	2023	Deloitte 2018
Chemical, biological, radiological, and nuclear (CBRN)*	18,400.0	2023	Allied 2024
Reactor construction	33,700.0	2017–2023	GM Insights 2023 IMARC Group 2023



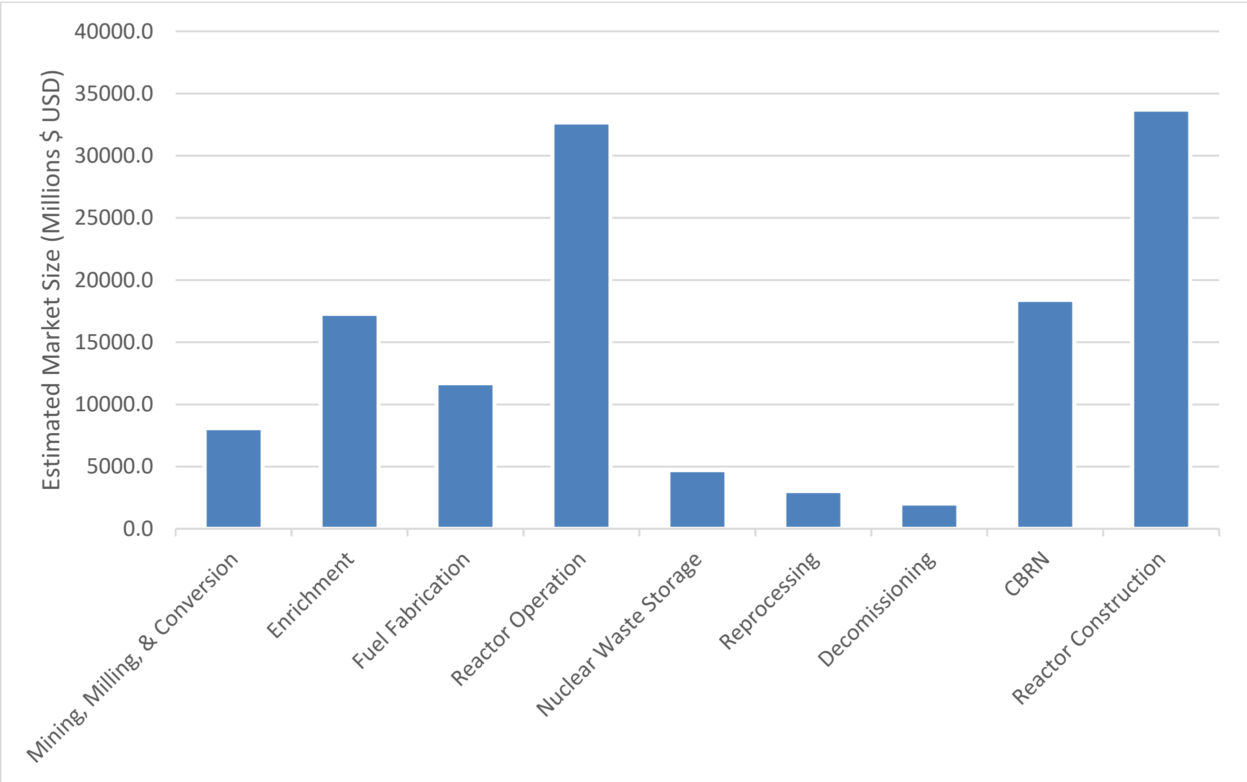


Figure 9. Total fuel cycle market.

Unfortunately, the nuclear reactor construction market varies greatly depending on the source. For example, a 2023 market analysis places the valuation at $52 B (GM Insights 2023), whereas another 2023 report specifies $7 B (IMARC Group 2023), and most other market estimates remain stable within ~5–15%. The viability of nuclear reactors is strongly influenced by when a project is started, when construction is completed, or when a project is abandoned. Figure 9 provides an average from several different sources, but the overall uncertainty in this number is high. Multiple advanced reactor vendors can capture portions of the market for an estimated $66 B (Construction + Operation), with additional market value at $12 B if the vendor provides fuel. If a designer maintains an SeBD program capable of analyzing and adapting their generic design to manage future threats, then the company provides itself with potential revenue options for the future in which an economic analysis of return on investment and the net present value of future potential cash flows can be analyzed within the various markets for growth.

2.3.3 Phases of the Nuclear Design Lifecycle and the Incentive Mismatch

IAEA NSS No. 35 G, *Security during the Lifetime of a Nuclear Facility*, gives a pre-sited design for the typical nuclear lifecycle for a plant (See Figure 10). However, there are some potential issues with this lifecycle because it is framed from the licensee owner/operator perspective vs. the vendor/designer of the plant. This report focuses on implementing SeBD during the design phase, before purchase and selection of a plant design and location. Thus, an altered generic design process flow is also included in the diagram. Although the original design process from the IAEA was created from a security perspective, it can also be applied to a safety and licensing. Note in this diagram, cessation of operation and decommissioning are grouped into the decommissioning phase, although those stages could be considered a different phase.

From the safety and licensing plant vendor/designer's perspective, the design lifecycle shown in Figure 11 is a typical representation of the lifecycle for a designed plant and is analogous to the IAEA illustration presented in Figure 10.

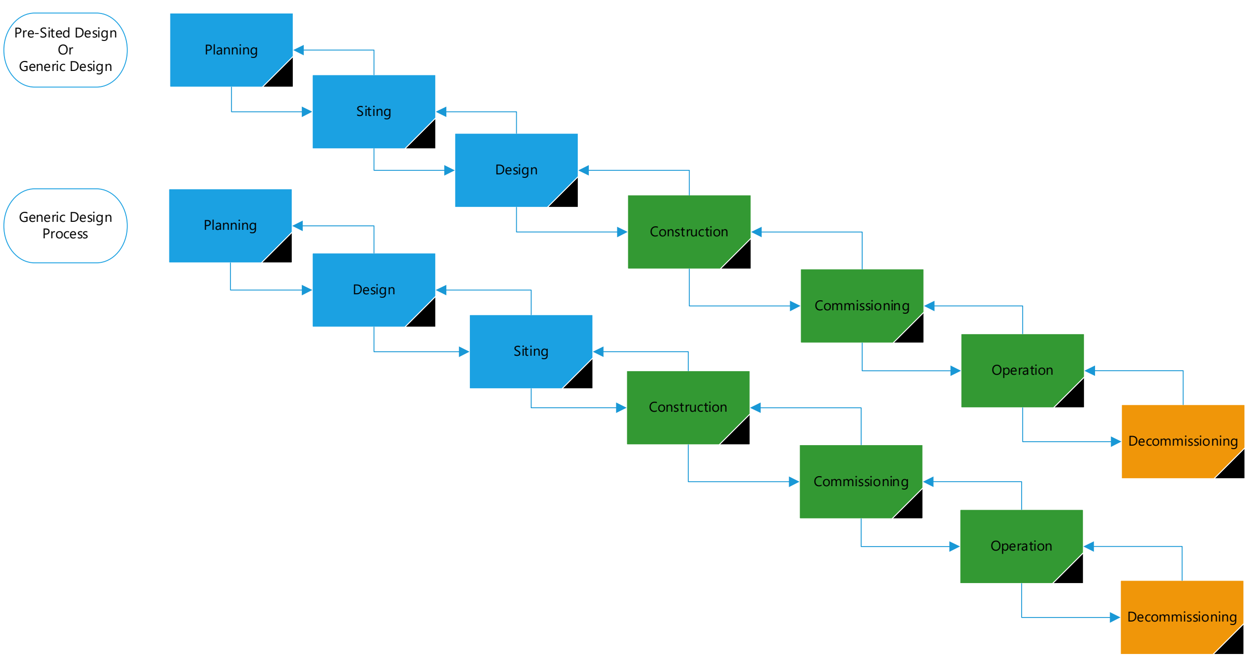


Figure 10. IAEA NSS No. 35-G process illustration for plant and security design.

Figure 12 shows several design areas and indicates the level of completion at different phases of the design and licensing processes based on past industry experience, SME input in the areas of licensing and design, and NRC SME opinions. As the digital integration of design continues to advance, these categories could merge into one system, or many categories could change, but typically, these large, general categories represent the necessary areas of scope required to obtain a generic design certification from the NRC.

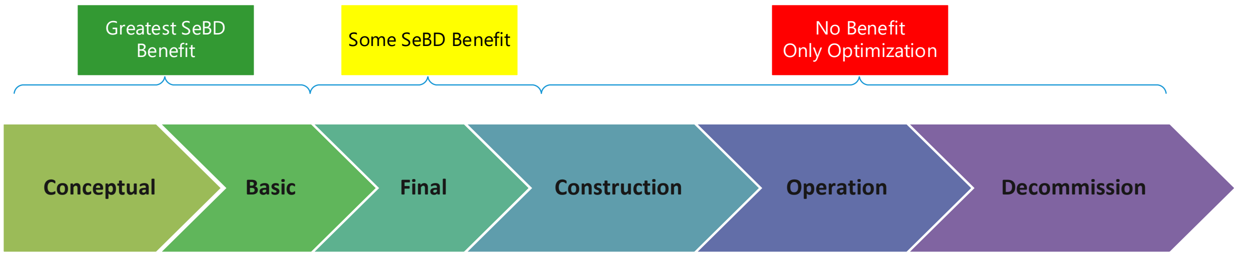


Figure 11. Plant design and operation lifecycle illustration.

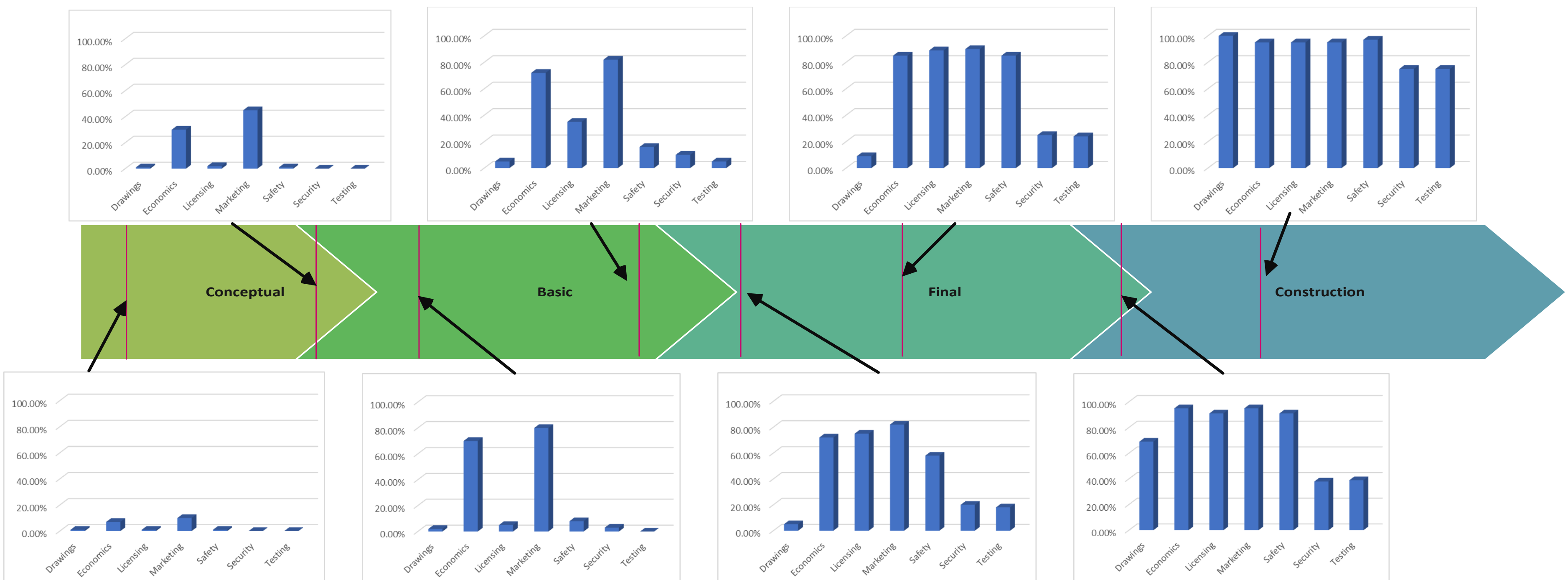


Figure 12. Percentages of completion required for NRC design approval according to plant design category.

During the planning phase, the conceptual design is developed, and regulatory bodies' required approvals are obtained before formal siting and design changes begin. During the siting phase, candidate sites are analyzed, along with factors in the nation state's requirements. Siting is a key parameter to security, whereas in the safety space, siting can often be assumed, because the systems are designed to work within a bounding operational envelope of locations and atmospheric conditions. Security posture, however, can change drastically based on a facility's proximity to site-based phenomena such as population zones, industrial centers, geological features, oceans, or rivers. Security analysis often puts a significant emphasis on the site, but the modular designs of advanced reactors or small modular reactors (SMRs) hold to a single standardized, scalable design that is independent from the site.

This difference hints at a potential incentive mismatch between a modular or standardized nuclear plant designer and a facility owner/operator when it comes to security. Some aspects of security design may be considered difficult to efficiently design until a site is determined.

The design phase is an iterative process that begins with the conceptual design, progresses through the final design and ends with a regulatory body's approval to begin construction. This process aligns with the design cycle shown in Figure 11.

During construction, the plant is built, and performance tests are conducted as systems are completed. Commissioning phase brings those systems up to operational conditions and confirms that all required criteria are met. This phase ends with the regulatory body approving the operation for the stated length of the license period.

Finally, during the operation phase, the plant produces the desired power, and the design is modified to meet the needs of the plant stakeholders until it is required to cease power production and decommission the plant. Figure 11shows these items merged into a single operation and decommissioning phase.

When considered through a business framework, the incentives between the different bodies involved in plant safety, security, and operation and maintenance are not in alignment. On the one hand, the plant designer has an incentive to conduct the minimal amount of security designs to meet the burden of proof to the regulatory body that a plant, should it be constructed, will be able to meet the necessary security requirements. On the other hand, the owner and operator want this to be a fully integrated and optimized process that minimizes the cost of security over the entire plant lifecycle. Thus, the customer has a need for optimized security in plant design with a minimal approach to target sets and vital areas while optimizing the "deter, detect, delay, and response" aspects of physical security. In the early design process, if a decision is made that expands target sets, expands radiological areas, decreases the protected area, or increases the source terms at the facility's boundary, then these engineering changes can have lasting consequences for the life of the plant. Analyzing the process step by step helps indicate where the incentives of the plant designer and the owner operator can lead to suboptimal choices in design.

The Planning and Conceptual Design Phase

In this phase, the designer's primary goal is to garner further interest. To do this a novel concept or market niche has to have been identified, so the nuclear vendor can propose a new design to fill a potential market niche. This phase includes some engineering, but it typically has a simple set of goals focused on obtaining enough funding to continue the design. If the basic design does not produce enough capital investment to fund further engineering, then the company will necessarily abandon the project. Thus, the designer will lay out the business plan, propose the novel concept (modular, simple, $/kWh, etc.), define the plant's basic performance characteristics (P-V diagrams, MWe, MWth, etc.), and establish basic safety concepts (passive safety, defense-in-depth, etc.) and will apply these concepts to obtain additional capital to move to the next phase in the process.

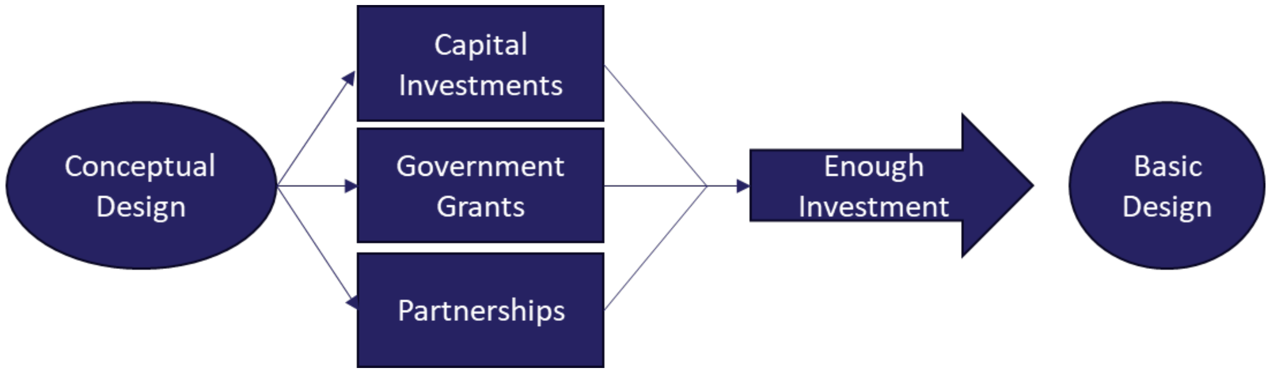


Figure 13. Conceptual design goals.

As a part of this study, it is important to track where the money comes from and where the money is spent. Worldwide venture capital investment according to CNBC (CNBC 2022) for fusion and fission energy is shown in Table 2.

Table 2. Worldwide venture capital investment in nuclear fission and fusion energy

Year	Total	Number of deals	Price/deal
2020	$168.9 B	12,884	$13 M/deal
2021	$341.0 B	18,027	$19 M/deal
2022	$219.7 B	14,032	$16 M/deal

Local investment in the United States for a small subset of reactor designers as presented by crunchbase.com is shown in Table 3.

Table 3. Investment amounts received by selected nuclear vendors as of 2024 (Crunchbase.com 2024)

Company	Investment amount
TerraPower	$758.6 M
NuScale Power	$469.6 M
X-energy	$285.2 M

Additional awards and grants to companies from the Advanced Reactor Demonstration Project may be reflected in these numbers but the financial reporting does not indicate if it is included. In the venture capital space, signing contracts or memoranda of understanding (MOUs) and forming partnerships allow for the concept of “piling on,” helping secure the level of investment and reducing risk so that more investors view the product as a safe investment and thus provide additional capital.

A major impetus for obtaining enough investment is based upon the company’s business plan. The company’s plan will include their objectives, the strategy target ROI, and other goals. The objective is to convince potential investors that all or a subset of the following points are credible.

Plant sales. Engineering, procurement, construction, and even partial ownership—all part of the business case definition.
Fuel sales. Contractual obligations to obtain fuel specifically from a vendor or partner with potential profit-sharing agreements in place.

Operating services to maintain plant. Contractual obligations to maintain the plant and provide engineering and maintenance services to the constructed facility.

At this phase in the process, development funds are spent in the areas where ROI, which is defined as additional funding secured relative to the initial investment, is maximized. At the end of this phase, there is enough investment so that the economic case and marketing case have been developed to the point that allows the nuclear design vendor to further the reactor development. Funding can then be applied to develop plant drawings, safety, and licensing, depending on immediate needs. This information is not available because each plant has a different set of design criteria that must be provided to investors to secure additional funding. This is one reason why partnerships are formed or capital investments are made for the research, but purchases are not expected during this phase. The expected key categories for a plant design at this stage are estimated as shown in Table 4.

Table 4. Design category percentage of completion for the conceptual design phase

Design category	Percentage to completion
Drawings	1%
Economics	25–35%
Licensing	0–5%
Marketing	35–45%
Safety	1–5%
Security	0%
Testing	0%

During this phase of the advanced reactor design, the designer is incentivized to focus on marketing the idea for future funding and will emphasize the novel concept and will work to prove that the risks associated with investing in this concept are minimal. Minimal testing is performed at this stage on the generic concept.

The prospective owner/operator will then measure the needs of their potential business market against the design to determine whether there is a potential need for this type of facility. They will compare design metrics such as power output against power market growth estimates and consider key measures such as the levelized cost of energy. They will also measure their potential risks in partnering or investing in such a design. Development risks are high at this phase, but investment provides them with greater opportunity to refine their specific requirements for safety, security, and safeguards.

Here there is very little match between the incentives of the owner/operator and reactor designer because the data needed to make an informed judgment are not yet available. However, this is also the least costly time to establish an SeBD process that will de-risk many items and will ensure that the process can be robust enough to catch potential defects in design.

Basic Design Phase

Within the design phase, the focus of a company's capital can shift from the financial/business plan to obtaining funding and partnerships for cost and risk sharing used to create detailed designs. Although there is still some necessary focus on funding mechanisms, primary requirements shift to the need for a feasible design and the data required to support that design, along with having enough information and for plant system designers to hold regulatory meetings and identify a regulatory licensing path to construction and operation. However, the design will continue to evolve significantly during this and later phases. At this point, systems are beginning to be formulated, and the plant's source term will have much less uncertainty, so security target sets can be defined based on potential radiological sabotage of structures, systems, and components (SSCs) relied upon for the health and safety of the public and for defense against reaching a defined unacceptable radiological consequence (URC) as defined by IAEA.

Whether the prospective company is well established or a startup, reactor development funds are finite, and progress must be made to obtain additional funding or revenue partnerships while developing the design and licensing basis. The company must also have the basic performance capabilities to support the plant. These factors can lead to restricted options for possible siting locations and may affect definition of the site boundary and the associated radiological consequences for safety and security. Figure 14 illustrates some of the key goals to be met in order to move to the next phase.

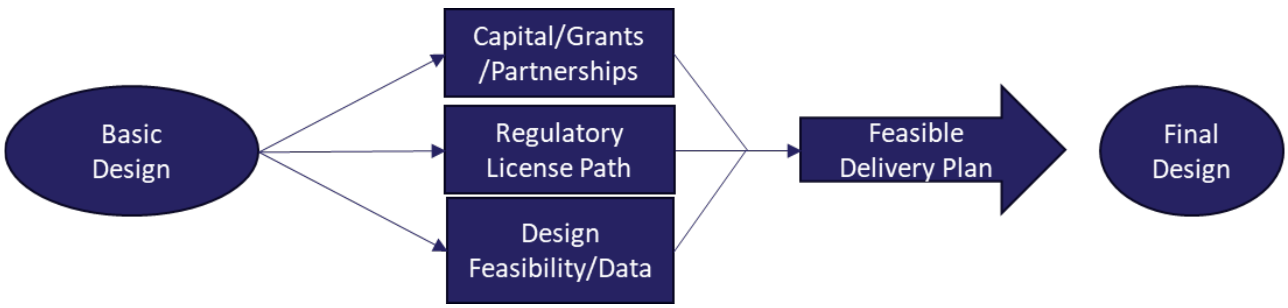


Figure 14. Basic design goals.

During this phase, the plant physical protection design could be considered infeasible for all desired applications or potential sites. However, it is possible to define the necessary requirements, equipment, and optimal layout of the plant for a general or example site. The restrictions, integration points, and assumptions must be defined, and when the safety layout of the plant violates or negates those assumptions, then the security scope must be expanded. However, in this phase, most nuclear companies do not invest in security designs. To reach the final design phase, a typical advanced reactor vendor will have achieved the percentages-to-completion shown in Table 5.

Table 5. Basic design phase completion estimates

Design category	Percentage to completion
Drawings	5–10%
Economics	60–70%
Licensing	25–35%
Marketing	70–80%
Safety	10–15%
Security	5–10%
Testing	2–5%

At this phase, the advanced reactor designer is incentivized to maintain enough funding to begin licensing the various methods and components they want to use in their plant. Significant economic objectives include prioritizing the designs of key components, building a licensable safety case, improving economics and marketing to keep the company operating, defining a viable regulatory path for approval, and obtaining some key approvals for fundamental safety case components and methods. These objectives must be prioritized by a company with limited funding sources.

The owner/operator at this phase wants to see a viable licensing path, a market analysis showing the reactor output that meets customer needs, and the cost to produce that power (including security costs) allows for the power to be sold at a reasonable price and profit. The designer should also have the appropriate quality control and managerial processes in place to control integration of the system into a large, complex project. If these items are established, then the purchase or funding of such a concept is a lower risk to prospective the owner/operator.

Here the owner/operator and advanced reactor vendor have several different incentives. The vendor focuses on reducing overall risk and marketing their plant, but they have very little interest in adapting a design for a specific customer's needs beyond that of potentially obtaining a contract or order. Instead, they optimize the design for multiple markets and spend their finite cash on the key items that will serve to de-risk their design. Their main focus when de-risking their design is regulatory approval or customer purchase. In nearly all markets, obtaining regulatory approval is a key moment at which the probability of future sales rises dramatically.

Final Design Phase

During the final design phase, the regulator's questions are answered, final topical and methodology reports are submitted and approved, and the final case for a competitive advantage or business case is formed. Topical reports can cost millions of dollars in both development and regulatory review and provide a competitive advantage by illustrating that the vendor has a licensed methodology associated with their plant design. Figure 15 illustrates the key goals that should be met before moving on to the construction phase.

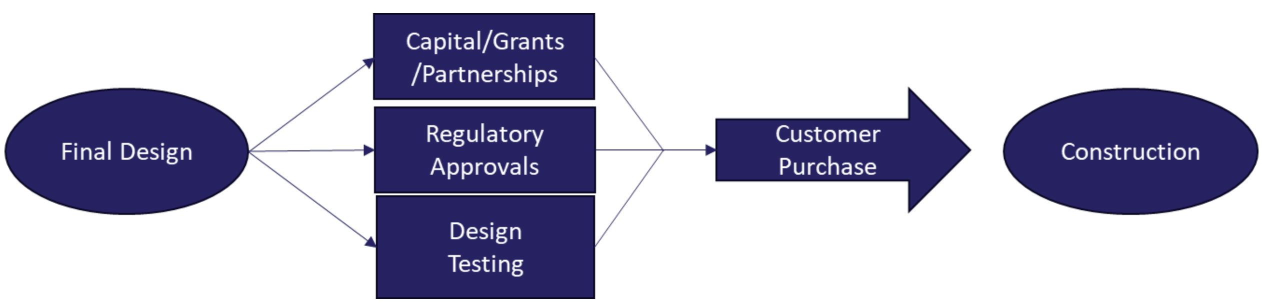


Figure 15. Final design goals.

At this stage, the advanced reactor designer must meet the minimum requirements for moving forward to sales and construction. To do this, each licensing requirement must be met. If a generic design certification from a regulatory body is desired, then only those key items deemed necessary for that approval will be part of the application process. To complete the reactor design, a plant may receive a generic approval after only having completed the completion percentages in key design categories shown in Table 6.

Table 6. Final design phase completion estimate.

Design category	Percentage to completion
Drawings	10–15%
Economics	70–80%

Licensing	75–85%
Marketing	80–85%
Safety	75–80%
Security	15–20%
Testing	15–20%

At this phase, the advanced reactor designer is incentivized and under pressure to receive the various regulatory approvals to begin construction. If a generic design process is being followed, then the designer must prove that the facility meets the safety, security, and safeguard measures necessary to construct the plant. Having limited funds to complete this process means that there are economic pressures affecting the selection of what must completed. Designers complete the minimum work necessary to obtain regulatory approvals. These approvals can serve as a de-risking incentive for investors and customers to "pile in," providing funding and sales to the designer in response to reduced risk of investment as signified by regulatory approvals. In this phase, safety and licensing are prioritized because they are key components for receiving approvals, future funding, and sales, whereas security and detailed testing are not prioritized unless regulatory authorities deem it necessary.

The owner/operator at this phase wants to obtain approvals for the safety case from the regulatory body so they can assume that the risk level for purchasing the plant is reduced. Although the owner/operator is more likely to invest in an approved design, they also must consider the price and future operational and maintenance for the entire life of the plant. Therefore, they pressure the designer to ensure that such considerations are in place. Having an appropriate quality assurance system helps and is often required by a regulator, but also having established processes to ensure that quality, maintainability, scalability, and costs stay within expected bounds is important. Many customers look at systems such as a strong design change process, ITAAC, simplified safety designs, quality control (such as Six Sigma, a business process designed to implement failure rates in the an order of magnitude less than typical nuclear safety requirements) strong audit ability for customers, and an SeBD program to ensure that the constructed plant will meet the customer's long-term quality and cost effectiveness goals.

The designer and owner/operator in this phase, again, do not have aligned incentives. The designer wishes to receive approval and investment/sales, and the owner/operator wants to have designs that are 100% complete and all operational and maintenance costs optimized for the life of the plant. As discussed below, security design can be implemented in almost any facility, but if it not designed well at this phase, higher costs will be passed down to the owner/operator for the life of the plant. An SeBD program should capture these long-term goals, maintain costs, and provide adequate assurance to the regulatory authority that a security system can be implemented to prevent sabotage and theft while providing assurances to the owner/operator that it is optimized for cost effectiveness.

Construction Phase

During this phase of the plant almost if not all the security by design measures for the plant are gone. At this phase the focus is on program planning, procurement, staged security, schedule, and safety. Figure 16 illustrates the key goals that should be met to move to the operational phase of the plant lifecycle.

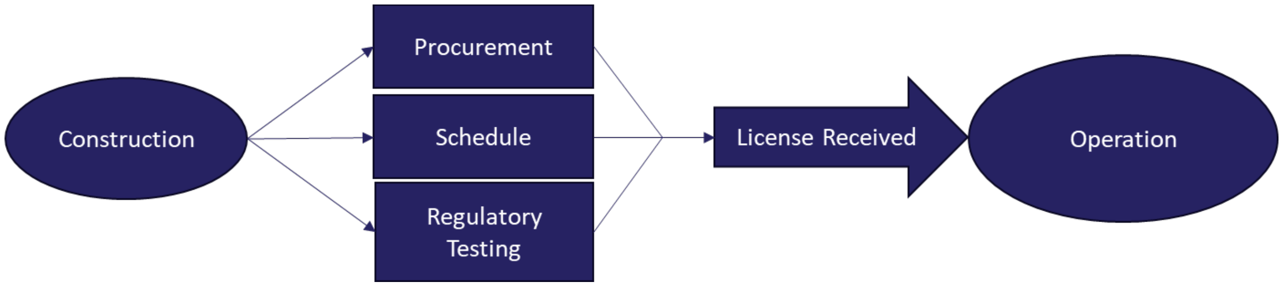


Figure 16. Construction goals.

During construction, the advanced reactor vendor will work to complete the necessary drawings, systems integration, most of the design change documents, many as-built justifications for parts that differ, and testing and licensing of final parts. Testing may be limited to defining the final set of tests for the plant. Then the vendor will work to advance all of the completion percentages to 100%. Additionally, during operation, when critical safety equipment is delivered, the equipment must meet higher security protocols than a typical security site, with sanitized establishment of security around the equipment until it is ready to be installed. When fuel delivery is scheduled, the security necessary for having special nuclear material on site must be present. Testing is the dual responsibility of the owner/operator and the vendor and must be performed prior to each key phase leading up to operation. The vendor has a limit to the amount of testing to be accomplished, and there are certain confidential security items that the vendor may not be allowed to review to ensure the security of a specific site. Once the plant is prepared to go critical and begin providing power to the grid, all testing must be met according to the regulators' review and the plant can commence operation. At this point, although the advanced reactor operator may not have reached 100% for the design, the plant has been found to meet the necessary requirements, and each category reaches 100%.

Table 7. Construction phase completion estimates

Design category	Percentage to completion
Drawings	95–100%
Economics	90–100%
Licensing	85–95%
Marketing	95–100%
Safety	95–100%
Security	75–85%
Testing	75–85%

The advanced reactor vendor in this phase wants to meet schedule deadlines, procure components that meet requirements at the maximum profit possible, minimize contractual issues (lawsuits), maximize cash flow to avoid bankruptcy, meet regulations, meet customer requirements and expectations clearly, and minimize design changes.

The owner/operator wants to meet schedule deadlines, pay for components that meet requirements at minimum cost, minimize contractual issues (lawsuits), meet regulations, minimize security costs, communicate expectations and requirements clearly, and minimize design changes.

If security planning has not be conducted in detail at this point and scalability has not been built into construction planning, then issues will arise. As discussed further below, delays can lead to staging issues for safety-related equipment and drives the need to secure those items on or off site because of security constraints. Security planning must be completed before fuel arrives, so it is necessary to be able to scale up to that level and having a plan. At this phase, if a system is found to not meet the effectiveness necessary or if it does not function as required, then it may have to be replaced, resulting in added costs and schedule delays.

Operation Phase

In the typical security model, all SeBD process savings are excluded from this phase, and cost shifts completely to the customer, who must now operate the facility and take responsibility for security. The vendor's revenue streams now shift to fuel, maintenance, engineering, and customer support until other vendors step in to offer their competitive services. At this phase, the industry offloads the full CBRN security market to other industries. The nuclear fuel market at this phase provides $18 B, whereas the fuel market size is $11B. The industry relies heavily on plant layout and design, which is held by the vendor and offloaded to the owner via the purchase. An SeBD for operating a nuclear plant could be offered elsewhere, but most nuclear vendors have limited or no scope in this market. Figure 17 illustrates the key goals that will be met before moving onto the decommissioning phase.

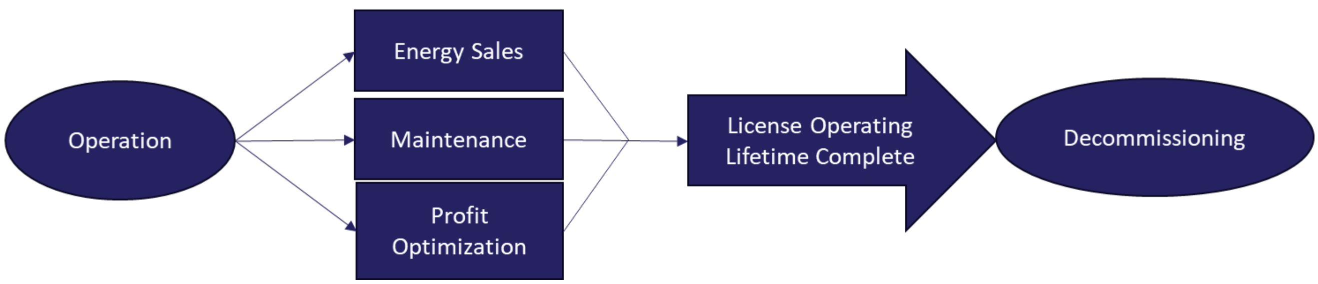


Figure 17. Operating goals.

The advanced reactor designer's incentives are to maintain revenue streams from the plant for services, engineering, procurement/supply, upgrades, and fuel. Vendors do not typically maintain a security presence in this space, even though they hold the safety analysis of record and maintain contracts for maintenance, operation, and sales. A detailed systems integration model or a digital twin of a plant may be maintained by the designer and could easily serve as the basis for security and safety upgrades. The plant designer could maintain the digital twin or other simulation models because they hold the plant's initial design of record and maintain a security contract. As noted in Section 2.3.1, the target sets are determined through the safety analysis held by the designer, so it follows that the contract and revenue streams could be extended to maintain plant security in line with the safety analysis. This would only be possible through implementation of an SeBD process. If there is no security analysis associated with the plant design, or if the security effort was minimized in the early design phases, then other security companies will likely hold the analysis of record for the target sets and security design and could more readily take advantage of the potential revenue stream. In conclusion, the vendor's goal is to charge the highest possible premium for services and to maintain long term- contracts that may not be in the interest of the plant owner/operator.

The owner/operator of the plant has competing goals to minimize the cost of services, engineering, procurement/supply, upgrades, and fuel, whereas the advanced reactor designer wishes to maximize these costs. Additionally, the owner/operator wants to be capable of bidding out to more cost-effective service providers if necessary to save on operational costs. Thus, to maximize profit, the owner/operator will strive to charge market rates for power while maximizing profit.

Decommissioning Phase

The goal at this phase is to transition all special nuclear material as soon as possible from the reactor and temporary storage areas to more permeant areas or disposition sites to shrink the footprint of the radioactive portion of the plant to be as small as possible. A scaled approach to security and reduction of security force is a concern during this phase because the cost for a non-operating nuclear plant becomes an issue if the security force must remain at the same level as that required for an operating plant with no revenue from the operations. Figure 18 illustrates the key goals that will be met prior to a regulatory body releasing the license and the plant land moving to greenfield status.

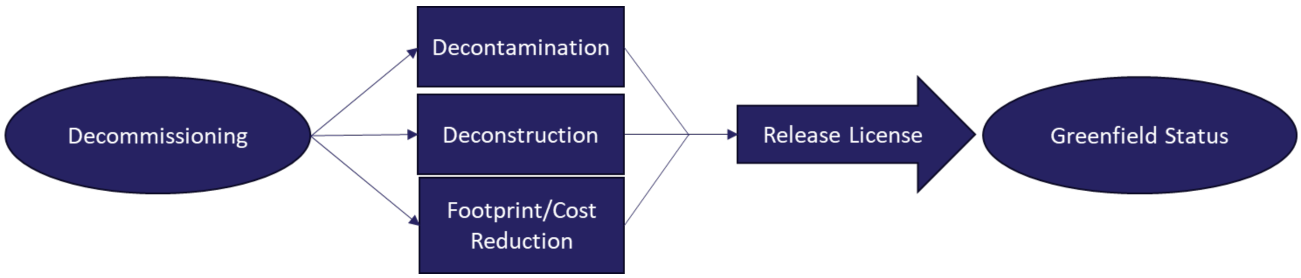


Figure 18. Decommissioning goals.

During this phase, the advanced reactor designer may be incentivized to maintain a decommissioning service contract and provide the necessary information to safely and efficiently decommission the site. The designer may wish to charge a premium for this service because they designed and assisted in operating the plant and thus can provide the service better than other potential vendors.

However, the owner/operator wants to shrink the footprint of the plant as quickly as possible and store any radioactive waste offsite or in the most compact area possible. When the site is no longer generating revenue, the pressure for economic selection is focused on speed and reduced cost of those doing the decommissioning. The owner/operator will work to minimize the cost at this phase as much as possible and will shrink the security force. At stage, holding the safety analysis of record has little value, and the advanced reactor design may hold less pricing power in the areas of safety, security, and safeguards unless the owner/operator maintains an operating presence and there is sufficient goodwill between companies. Otherwise, the lowest bidder in this phase may be a primary driving force and could ultimately win contracts for this work.

Example Case

As an example of this progress, the pebble bed modular reactor (PBMR) design illustrates the transitions between these phases, as seen in publications developed throughout the process. The PBMR design was a government-funded project and thus was required to report and publish many items in public sources, unlike most privately owned companies. Some of the earliest papers for the concept were published around in 2002 and 2003 (Koster 2003) and covers basic operational bounds in thermodynamic cycle selection, temperature, and entropy calculations. In 2005, the reactor, fuel, and renderings of the nuclear island were laid out, along with the facility layout (Matzner 2004). Also, in 2005 papers were published giving the detailed physics, systems analysis, core kinetics, and thermal hydraulics, as well as some testing of those predictions (Reitsmaa 2005). In 2008, detailed results and test plans were published for pebble bed packing, thus indicating that test facilities had been built and data analyzed (Rousseau 2008). At this point, the design could be updated based on the results. Publications followed on safety analysis, validation of code sets, computational fluid dynamics (CFD) results, and further testing, and the application of those results to safety analysis and operation (Dudley 2008, Janse van Rensburg 2011, Acir 2012, Boer 2017). In 2010, the government abandoned the concept, but it continued in a private form via some of the researchers going to work for companies such as X-energy and developing publications. Projects and publications continue but design documentation is now mostly proprietary as private companies are engaging with regulators and potential operators and deployment sites. In 2019, a mechanistic source term white paper was delivered to the NRC, and over the next three years probabilistic risk analysis, principal design criteria, training programs, security templates, and emergency planning, and many others publications were submitted for pebble bed designs (NRC 2024).

The Potential for Incentive Mismatch

As described earlier, there are many possible incentive mismatches in security that must be rectified. Implementing an early-stage SeBD program for an advanced nuclear reactor design will incur costs that initially may not appear to be an opportunity for a vendor/designer to benefit from sales; the overall prospect of investment may seem to be an area of diminishing returns. The need for the owner/operator's involvement in security, the modular multilateral aspect (deployable to many nations), the regulatory route for a generic design certification, and limited financing are all economic selective pressures that could drive a deferral of design responsibility for security. These factors can lead to ineffective and costly upgrades to the security posture that must then be maintained, with associated cost incurred for the 60+ year lifetime of a plant.

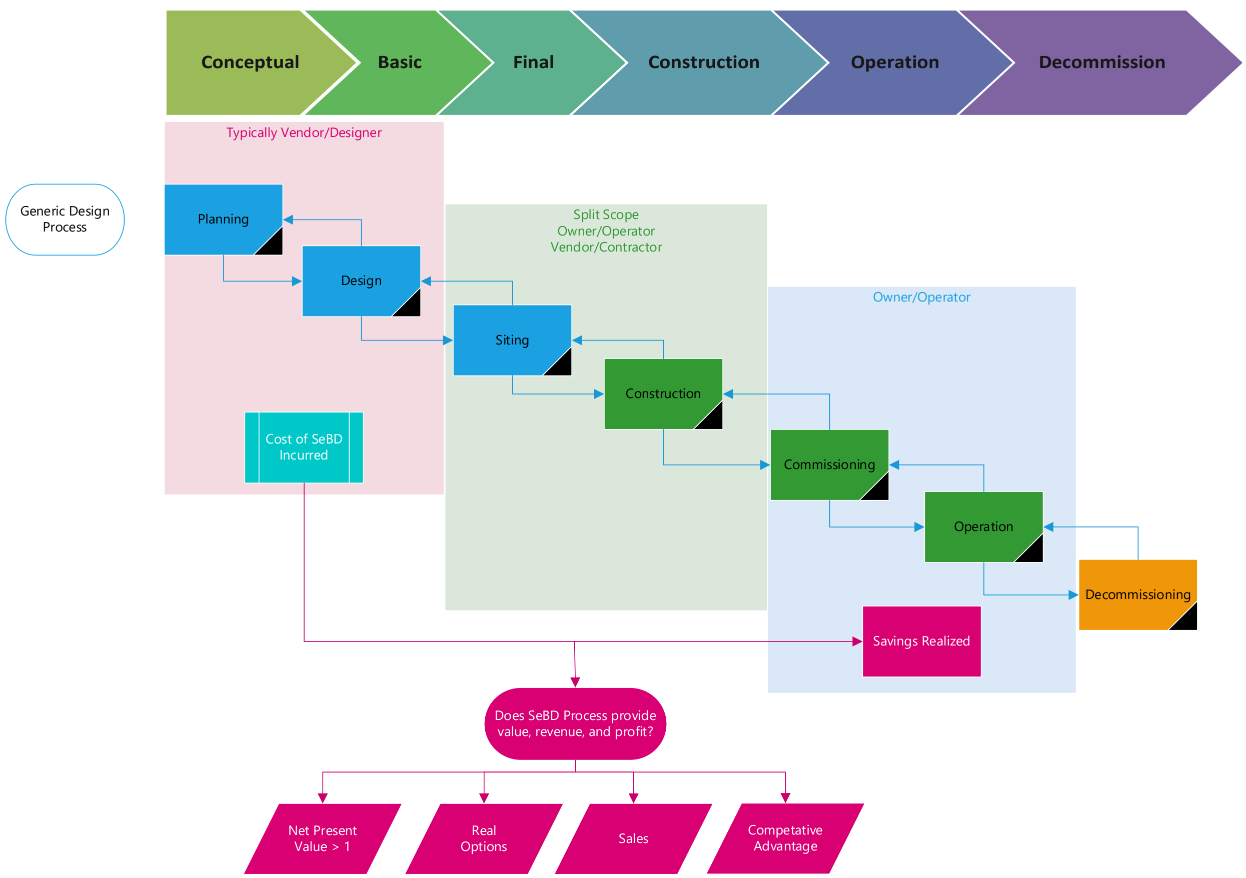


Figure 19. Illustration of the potential incentive mismatch between the final plant owner and the plant designer/vendor.

The regulatory environments can differ dramatically between countries, and the market for advanced reactor design and delivery is a high risk with potentially only medium ROI in the nuclear fuel cycle. Thus, systems must be implemented to allow companies to capture multiple long-life streams of market share associated with the delivery of a NPP commissioning. Further discussion of a potential economic model for SeBD is provided in Section 3.

Similar programs, business cases, and past power plant operations will be analyzed to provide a more complete picture of where an SeBD process can be advantageous and can provide the necessary cost/benefit returns to garner a company's investment. For example, when a vendor/designer implements an SeBD process, the following items become available.

- Security services maintenance sales
- Digital twin and operational maintenance
- Security and safety integration market competitive advantage
- Access to the CBRN security market
- A real options approach to analyzing an SeBD program

To present a full picture, lessons learned from previous cases with similar impacts can be reviewed. The first discussion related to incentive mismatches and responsibilities being separated between multiple companies is focused on cyber security and is discussed in the next section.

2.3.4 Cyber Security SeBD Case and Comparisons across Nuclear

SeBD for nuclear power systems has not been fully implemented; furthermore, the potential benefits of SeBD are also not fully quantified. These principally qualitative benefits, paired with the known challenges of working within regulations and within known workflows, creates an inertia to implementing novel ideas which are not guaranteed to provide significant benefits. The three primary organizational bodies for the nuclear power industry are the regulator, the vendor, and the owner/operator. The regulator is tasked with ensuring regulations provide proper levels of safety and security, and they are also tasked with enforcing the regulations. The vendor (and associated contractors) designs and constructs an NPP for the owner/operators. The vendor must follow regulations, which can result in significantly higher costs if exemptions or special requests are made. It is even possible for the vendor to not optimize possible cost savings if the regulators have approved a design as-is due to changes being more costly in time and capital. Finally, the owner/operators are responsible for the operations of the NPP and for generating energy for the licensed application (e.g., electricity or process heat).

The costs of electricity are thus affected by the costs of both the initial cost of capital and the ongoing costs from fuel costs, staffing, maintenance, security, and so on. Because of the expected long lifecycles of NPPs, it is conceivable that significant reductions in ongoing costs or operation and maintenance (O&M) costs could significantly benefit the owner/operators. However, if the reduction in O&M cost is not enough to offset the initial capital cost, then it may not be considered feasible to invest in SeBD. Therefore, the ways in which SeBD can reduce the cost of producing electricity with NPPs is an important area of research.

Lessons Learned: Cybersecurity

The principles of SeBD have been applied to cybersecurity for a longer period than to physical security. Cybersecurity also generally has a shorter development lifecycle than physical security and can inform development of SeBD. Additionally, one of the possible solutions presented to reduce the O&M of NPPs is to reduce the number of personnel on site. A downside to this approach is that extensive cybersecurity would be required to confront new vectors of attack. Therefore, it is even more crucial to understand and implement the lessons learned from cybersecurity to ensure that nuclear SeBD is successful.

One such lesson is to consider misaligned incentives and how they can negatively affect security. It has been proposed that incentives can be modeled as a system with inputs and feedback (Lenchik 2016). When incentives were misaligned, it was found that the feedback forms a reinforcement of negative behavior which ultimately reduces security and increases cost incurred when an incident occurs. One example is automatic teller machine (ATM) fraud that affected consumers as a result of vulnerabilities within the ATM systems. Because of regulations, the banks in the United States were held responsible for proving that fraud did not occur or that the bank was not at fault. This resulted in an investment from the bank to prevent further fraud by increasing the security of the ATM so they would not be responsible for the costs associated with continued fraud. Thus, the regulation forced the bank to have a reinforcing feedback loop to implement increased security to mitigate fiducial risk to the bank, and by extension, its customers. Conversely, the banks in the United Kingdom were not subject to regulation that declared the banks responsible for proving they were not responsible. Instead, the banks forced the customers to attempt to prove they were frauded. Because the bank had the ability to fix their ATMs and knew how their system functioned, it was not easy for the customers to prove fraud or to improve their experience with the bank. Therefore, a negative reinforcement was developed because of the bank's lack of incentive to improve security if they were not affected. The outcome of this dichotomy was that banks in the United States had reduced costs associated with fraud compared to the banks in the United Kingdom. The lessons learned from this example and others indicates that SeBD can reduce costs and ensuring that security providers have the proper incentives to properly secure their customers can reduce the costs to both parties.

A second lesson to consider comes from the hidden nature of information related to security. Akerlof defined a classic case for hidden information as the "market for lemons" (G. A. Akerlof 1978). Essentially, the customer, without knowledge of what is good and what is bad, can end up paying more for a worse product because of the knowledge hidden from them by the seller. Furthermore, the security market has been considered worse than a lemons market because even the seller may not even truly know how good their security product is (Anderson 2007). In part because of these concerns, SeBD could be applied by the vendor to reduce the cost to the owner/operators while providing the best possible security design if given the correct incentives to do so. With sufficient SeBD, the vendor and owner/operators could also be better informed on how their security system is and could be better prepared to address future security concerns.

Possible Solutions and Concerns

This section discusses a non-exhaustive list of solutions and concerns related to physical security based on the challenges faced in cybersecurity. Four areas of discussion are presented, along with some possible solutions and concerns. The four areas are information asymmetry, misaligned incentives, regulations, and certifications.

A possible solution for information asymmetry is for owner/operators to better understand the system they are purchasing. This could include having a security expert assess the system for its value and competitiveness. This helps identify lemons in the market by relying on expert opinion. Possible concerns are that vendors and experts do not always know about or agree on the effectiveness of a security system. In a limited market, the vendor has leverage because of the wide availability of security designs. Without the properly aligned incentives, the optimal security system may not be the same for the vendor vs. the owner/operator.

Incentives can be aligned through vendors and owner/operators sharing liability and SeBD. Liability sharing can also encourage the use of SeBD as an objective to reduce long-term for both parties. Furthermore, the vendor would be incentivized to provide an effective solution to mitigate their possible liability when compared to a suboptimal solution that could have earned them more money without the addition of the shared liability. Positive incentives include increased profits or reduced costs for both parties involved. Vendors could provide long-term service contracts to provide intermittent system upgrades to reduce cost and risk. This would also allow for the continued profit incentive of a service contract, which coincides and reinforces the incentive of shared liability if implemented. Misaligned incentives can lead to inefficiency and reduced profit, as well as inefficiency within a regulated economy such as nuclear power. Without the proper incentives, the vendor does not work to provide superior quality because only the costs and profits are considered. Therefore, a race to the minimum required system is inevitable, stifling innovation, future planning, and scalability to prevent cost to the owner/operator. Positive outcomes of SeBD should be encouraged through offering positive incentives to vendors and the owner/operators. This can result in increased profit or reduced liability for the vendor and a security system that fits the budget and provides optimal security to owner/operators.

Existing regulations could be overhauled to be more informative, more consistent, and more relevant to current and possible future demands for nuclear power. Because nuclear power and security are highly regulated, the regulations can profoundly affect financial decisions. Regulations can also help encourage all parties to have aligned incentives, but incentives must be identified, along with their anticipated effects create on affected parties. Furthermore, the possible and negative effects must also be considered. The existing regulatory environment may be insufficient for handling modern or future nuclear power and nuclear security challenges. Regulatory solutions often lag behind the industry and can be shortsighted or so narrowly focused that they can be ineffective or even cause harm to the industry. Finally, attempts to avoid regulation can make the regulations less effective because enforcement becomes more of a challenge.

The lag of regulations in an industry can often result in an industry establishing regulations through certifications. Because certifications are a type of regulation, many of the pros and cons of regulations apply. Furthermore, certifications can be established to help owner/operators be better informed about the security system they are sold. At a minimum, certifications must meet the requirements for defeating the design basis threat. Certifications can provide knowledge of features above and beyond that provided in the requirements. Features could be selected based on the needs or preferences of the owner/operators. Beyond the similar concerns shared with regulations, one main concern is that some may attempt to obtain certifications without properly meeting the requirements. This devalues the certifications because most who try to obtain certifications do not meet the requirements.

2.3.5 Past NPP Construction Review

Analysis of past construction of NPPs shows several interesting trends based on available data. This section does not include excessive detail regarding the causes of cost overruns and delays, but it does present an assessment of general trends in the data. Construction costs for light-water reactors (LWRs) in the United States are summarized in a report commissioned by the US Department of Energy (DOE) in 1986 (EIA 1986). Data from this report show the ever-increasing trend of nuclear reactors being deployed within the United States, as shown in the Figure 20. It should be noted that different reports often report slightly different values. All costs are adjusted for inflation to 2020 dollars.

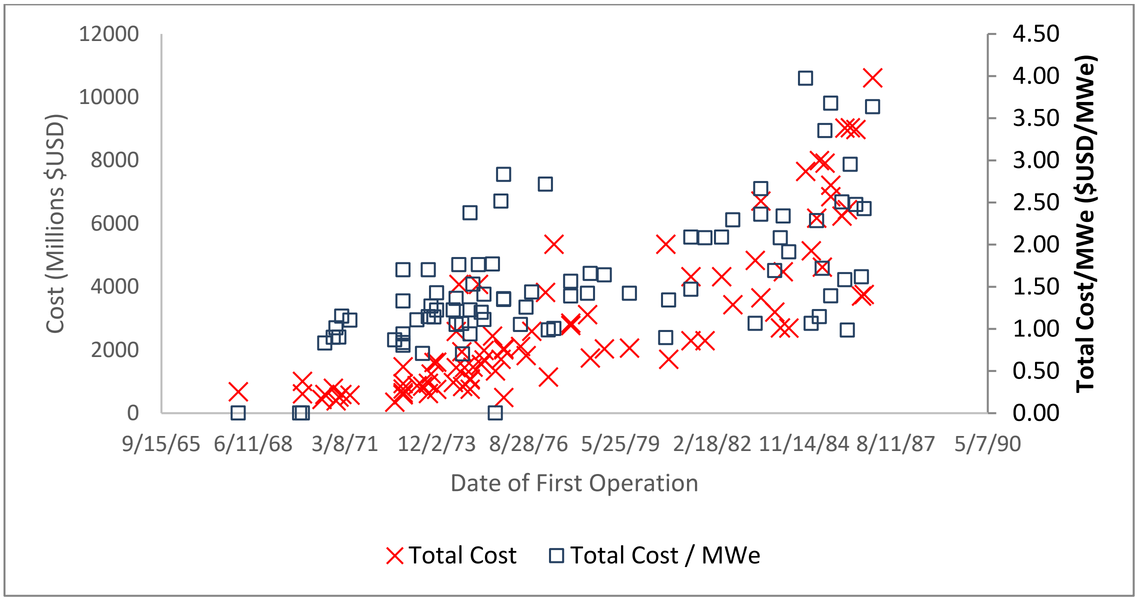


Figure 20. Comparison of total cost of a nuclear plant (primary axis) vs. the date it was commissioned (secondary axis) that normalizes the cost to the net summer MWe capacity in 2020 USD.

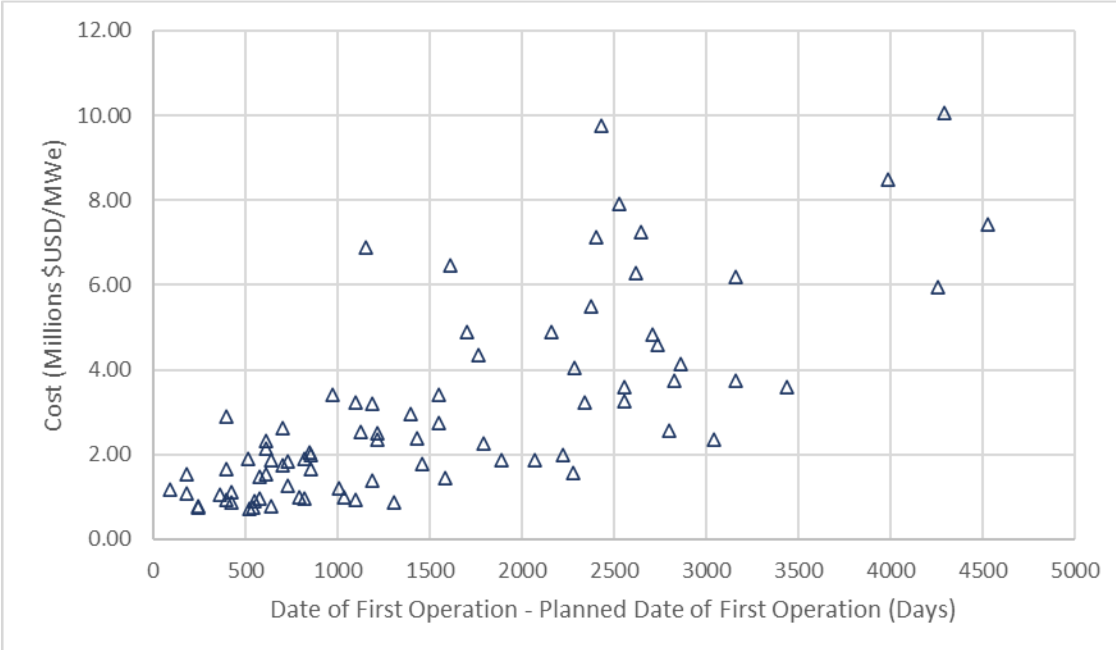


Figure 21. Cost of a US-built nuclear facility vs. the overall delay of completion in days.

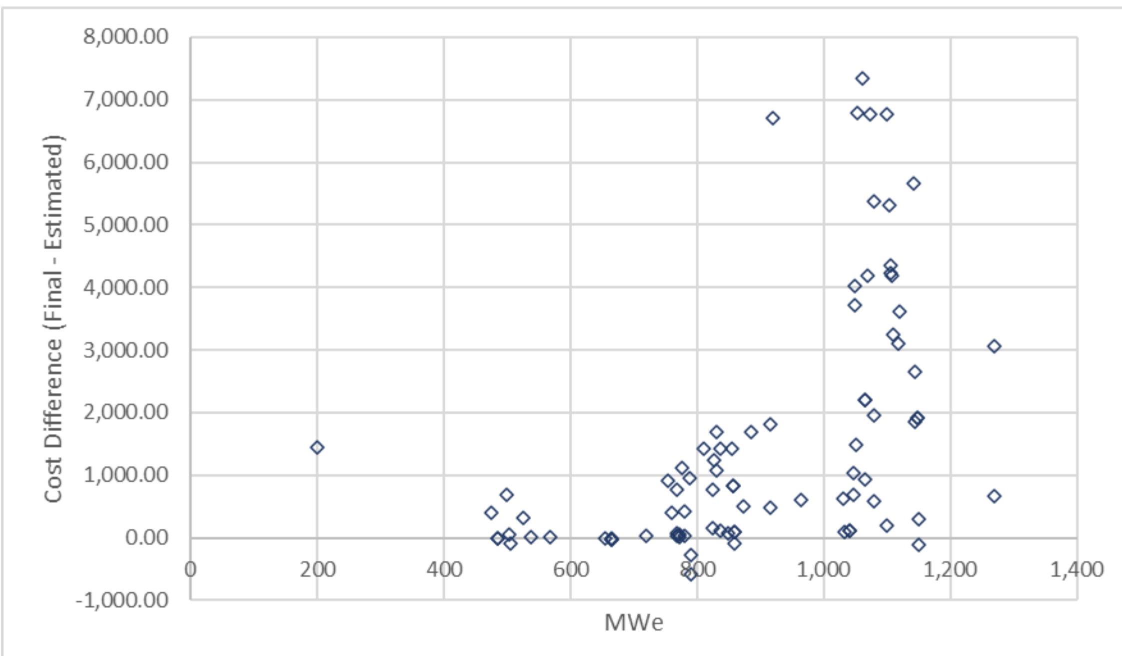


Figure 22. Estimated cost difference vs. the total net summer capacity of the plant in MWe.

Although a further look into the plants constructed in the United States from 1965 through the 1980s has highly variable issues that can be applied for each plant, a high-level comparison shows an increasing trend in delays and costs of nuclear reactors while with progressively higher MWe outputs, as seen in Figure 21. Thus, a standard loose trend of increasing costs can be seen tracking with a larger, potentially more complex plant. However, with this type of general analysis, the outliers and differences in plant designs can be lost easily in the trend. For example, Ft. Saint Vrain (a high-temperature gas-cooled reactor) showed low MWe output with a cost difference beyond the general trend. This is primarily because it is a first-of-a-kind (FOAK) commercial reactor developed after Peach Bottom was constructed. Ft. Saint Vrain had significant issues with water ingress into the reactor's helium system. Although a detailed analysis of past reactors is not the purpose of this paper, this background helps illustrate some of the trends seen in advanced nuclear reactor design today.

The overall goal of many Generation III+ and advanced reactors is to alter this trend of increasing size, cost, and delays in the United States and in the world at large. Figure 22 illustrates that as the plants approached 1,000 MWe output, the variableness of cost in the data scatter dramatically. Thus, the concept of smaller, modular, and standardized reactors could be developed using this data to capture lower cost, shorter delays, and medium power areas of these plots. However, any correlations drawn based on the data presented above are subjective and do not represent strong correlations in nuclear plant construction (as in the Ft. Saint Vrain reactor example earlier).

Additionally, these plants represent larger scale megaprojects (greater than 1 billion dollars),but these projects could shrink to a value of over $12 B for a Gen III+ LWR (ANS 2022) down to $9 B for a FOAK multi-pack SMR.

The modularity of NPPs and the methods of vendors designing and potentially licensing a nuclear reactor prior to purchase can lead to the inevitable, most expensive portion of added costs to a construction project—design changes. "Even in well-managed projects, the design changes can directly impact the cost in a range from 2.1% to 21.5% of total construction costs" (Aslam 2019). Although security requirements are specified in nuclear reactor regulations, they are not the primary intention of the vendor. In fact, as stated in Section 2.3.3, potential incentive mismatches between a designer and an owner/operator that can lead to a "race to the bottom" or a "delay cost till necessary" approach. In these two approaches, the vendor applies only minimal effort, equipment cost, and licensing rigor to obtain approvals to construct or make a plant sale as long as the cost is borne by the vendor. In a reversal, if the cost is borne by the owner/operator, then there is a cash flow incentive during construction that may lead to the vendor not purchasing the most economical component. A higher price for the component may yield a higher percentage in profit on that equipment if there is no fixed price or cost sharing requirement in place.

Review of plant designs approved by the NRC show that several regulatory requirements are reserved for the combined operating license (COL) holder (NuScale 2020). Although statements like these within generic licensing documents do not indicate that only a limited analysis was conducted, it does indicate that potential routing of design electronics equipment, backup power, and other security-related equipment is susceptible to design changes dictated by external forces during construction because these designs may not be completed at the time of construction (Aslam 2019). Gathered results from case studies and surveys from multiple papers and hundreds of datapoints and concluded that design changes, requirement changes, and scope creep were some of the highest contributors to cost overruns and delays, as would be expected. However, one key conclusion is the creation of a method for a complete design management approach to handle and communicate efficiently between the sources of those design changes, as shown in Figure 23.

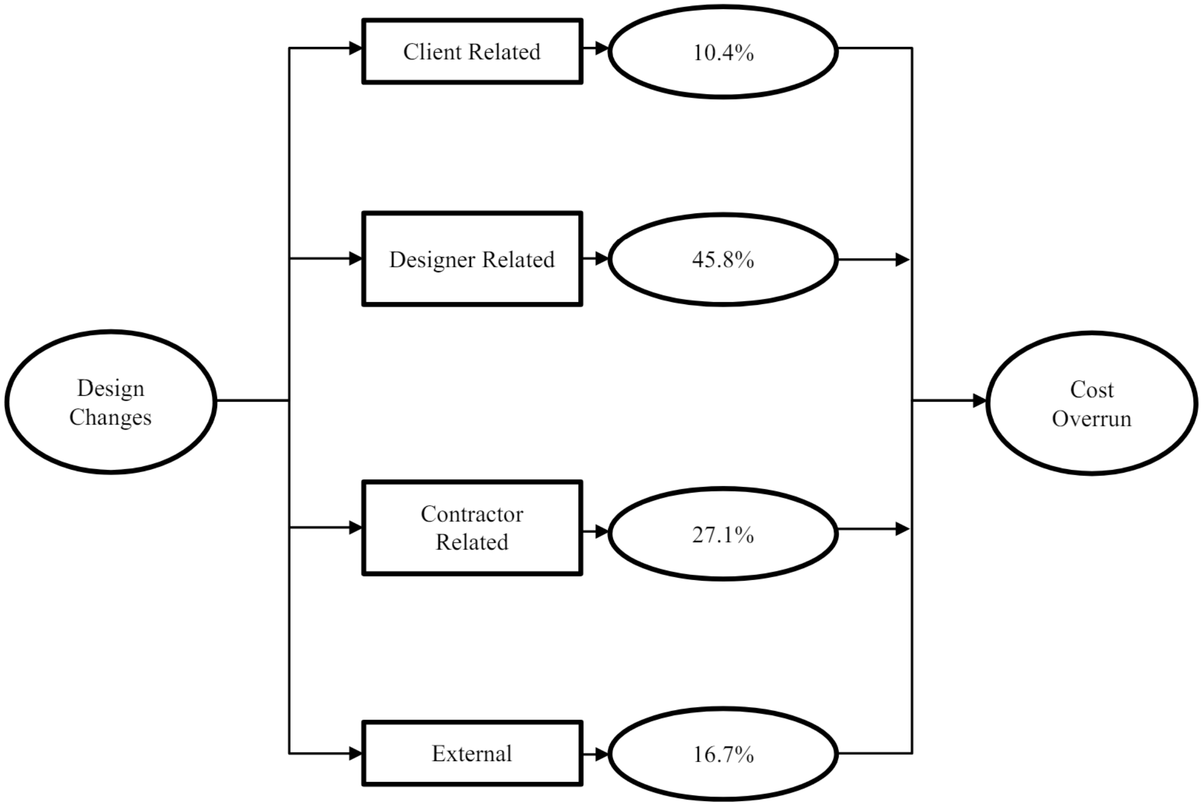


Figure 23. Summary of design change sources (Aslam 2019).

A nuclear reactor construction project is by definition a megaproject(i.e., those generally costing over $1 B). If the values given in Figure 23, are assumed, then 45.8% of the total design changes will be designer related.. Contractor-related issues may also be the designer's responsibility because the designers may be selecting and/or managing construction contracts. Thus, the designer may be liable for up to 72.9 % of reactor design change cost overruns. The average past construction project overruns are 98% (Aslam 2019) in the United States, excluding the latest FOAK plants built at Vogtle. The DOE-commissioned report released in 1986 shows an average overrun of 93% average overrun (EIA 1986) when the initial cost estimate is compared to the final cost estimate at commissioning. If these calculations are correct and a project were to cost $1 B, this would indicate a potential liability of $1.44 B. If a conservatively low 1% of these design change alterations are related to security, then it can be concluded that $14 M in liability is avoidable through implementation of an SeBD design program. This does not include the engineering design and construction implementation costs associated with repairing the security defect.

$$\$1\text{ B} \times 1.98 \times .729 = \$1.44\text{ B}$$

The generic, modular design concept provides challenges and advantages to handling these illustrative design change areas. Mainly, if the interface requirements between systems are well defined and documented, then changes within a specific module could avoid further construction costs. Discussions held with SMEs at operating and recently constructed nuclear plants indicate the common nature of delays related to shifting requirements, equipment not working and having to be removed, site acceptance testing failures, and design changes that were necessary to handle construction issues that impacted security. In such scenarios, security was involved. For instance, delays to install security equipment or safety-related equipment meant that these materials required storage instead of being installed in a timely manner, so they had to be secured in an area to prevent sabotage to key safety components. The abandoned V.C. Summer project reported (Summer 2016) that delays led to a lack of space for staging of equipment, leading to further project delays. In these events, it was necessary for security to scale up and scale down when certain pieces of equipment arrived and were installed, thus leading to additional costs to secure equipment.

To solve such issues, the designer, operator, and contractor must communicate thoroughly throughout the design lifecycle. However, many plants are under-designed, and there are no detailed relationships with customers abroad prior to high levels of design being completed. Therefore, it is difficult or impossible for future foreign customers who may be new to nuclear energy and dealing with developing regulations to maintain a partnership during the design process. Thus, the system for implementing SeBD must be the focus, and it must be adaptable and scalable. Such a system would be comparable to a standard quality management system typically required within a nuclear regulatory framework. The management of such a system would enable a nuclear provider to provide O&M programs not just for the safety design of the plant, but also for security maintenance of the plant—all while providing a high-quality methodology for entrance into the CBRN security market.

2.3.6 Flexibility: Scalable Design and Statistical Distributions of Requirements

An essential part of lifecycle economics of SeBD can be derived through adding design flexibility. A major work in design flexibility (De Neufville 2011) details how challenges of generating long-lasting value in large-scale and complex engineered projects can be addressed. Ideally the system will specify what is required and when it is required. A quote capturing the conceptual differences is that robust design (static) is a passive way to deal with uncertainty; flexible design is the active way to deal with uncertainty. The impossibility of defining all the requirements a priori (uncertainty) drives the need to adopt an adaptable design in which flexibility empowers lifecycle cost savings. However, this design must have a strong foundation and must include the fundamentals for safety (defense in depth, passive safety, etc.) and security detection, delay and response. Therefore, it is extremely important to having security designers influencing the design from the beginning. There is also the need to understand and identify when standard methods are inadequate for dealing with rapid change. An intelligent design process will anticipate many possible futures with a wide range of possibilities and will lean on statistical methods for understanding the risks/rewards. Past case studies (De Neufville 2011) have demonstrated increases of up to 80 percent of the expected value of complex projects through flexibility in design. The flexible design process is as follows:

1. Recognize the major project uncertainties likely to be encountered. Where might flexibility help?
2. Identify the specific parts of the system that can best be used to address these uncertainties.
3. Evaluate flexible design alternatives and incorporate them into the design.
4. Plan for implementation of the chosen flexibilities for cases in which the timing and circumstances of the implementations will be made and determine who will be responsible for them.

Flexibility in design has a major impact on levelized cost of energy methods of analysis. The ability for security to be dispatched and to adapt to future needs will require a Monte Carlo–based approach for understanding the cost savings potential. Implementation of this approach requires the uncertainties to be quantified as probability distributions. These distributions are used to create a mathematical/statistical model which can be used to forecast various future scenarios, thus accounting for the randomness and variability of the overall system.

2.3.7 Nuclear Power Plant Operation and Maintenance Costs

Cost to a generating nuclear plant can be divided into three basic categories: fuel, capital, and operations (McCallum 2023). Fuel costs are the basic inputs to the nuclear reactor. In terms of LWRs, this expense fluctuates based on the acquisition and enrichment of uranium; these are typically the two main driving costs associated with fuel. Other driving costs for fuel are items such as fuel services, engineering, manufacturing, and various smaller items such as burnable poisons. These expenses are typically incurred for ⅓ of the core every 18 to 24 months, depending on the type of reload cycle. Advanced reactors, however, can have a widely varying fuel form and reload schedule and thus present new challenges when estimating their fuel costs.

Capital costs are defined by the capital investment to repair, replace, or upgrade the plant's current equipment. Items such as upper head replacement and steam generator replacement are obvious items that fit into this category; however, security upgrades, and even the increase of a plant to a higher power level, could be considered in this capital investment category. Additionally, the accounting practices of the plant must include certain purchases into either the operation category or the capital investment category of a plant's operation and maintenance budget. Therefore, comparing reactors could be difficult because of different acceptable accounting practices.

Operating costs include the personnel and equipment costs necessary to operate the plant on a day-to-day basis. "Operating costs include categories such as licensing, security, maintenance and human resources" (McCallum, Julianne. 2023). because they are associated with the scale of electricity production. Labor fits into this category as part of engineering O&M. Training, equipment, surge labor for reloads, contractors, and other items are typically placed in this category, along with several materials and services. There could be some overlap with the capital costs because equipment and material, as well as engineering, can be a portion of both categories, making it difficult at times to compare plants, because some may include capital cost within some O&M budgets, and others may not. As part of this project, various NRC-licensed plants were contacted to determine the budget ranges and investments necessary and to confirm previous information gathered through the US-based LWR Sustainability (LWRS) project.

> *A nuclear power plant can incur nearly $600 million in O&M related expenditures on an annual basis, of which security related O&M can account for over $34 million (approximately 6%). Payroll and overtime subcategories of O&M costs are typically the two most significant costs from a physical security standpoint. As a result, reduction in manpower at a nuclear power plant can translate into a sizeable cost savings on an O&M budget.* (Burli 2020)

The survey results from plants that held discussions verify these numbers. A single unit plant would incur a typical O&M budget ranging between $22 and 25 M per year vs. a plant with two or more units that would cost between $30 and 35 M per year. Additionally, several plants included capital costs—not typically accounted for within the O&M budgets—of approximately $5 to 10 M per 5 years for upgrades, system replacements, and costs incurred to replace equipment that may be out of date.

Based on SME opinions and interviews with current and former security managers and operators, several points are provided below:

- Operators realize economies of scale because security forces typically protect the footprint of the reactor, so having a slightly larger footprint for a second reactor does not double security cost.
- Single plant operators relate costs of a single guard post as $500 K.
- Bullet-resistant enclosures (BREs) and upgrades can cost up to $2.6 M per installation or replacement.
- Security analysis and engineering typically costs from $200K to $500K per contract to conduct.

- Single unit security costs are $22–27 M per year.
- Dual unit security costs are $25–35 M per year.
- Large portions of nuclear security costs are labor that ranges sometimes as high as 50% of the total security costs.

These numbers and solicited SME opinion were combined with the NEI data regarding the plants currently in operation to illustrate some basic trends between security costs and the available plant data (NEI 2024). It should be noted that more detailed cost figures would be necessary to draw more detailed conclusions. The general trends from the NEI data are presented in the Figure 24 and Figure 25 .

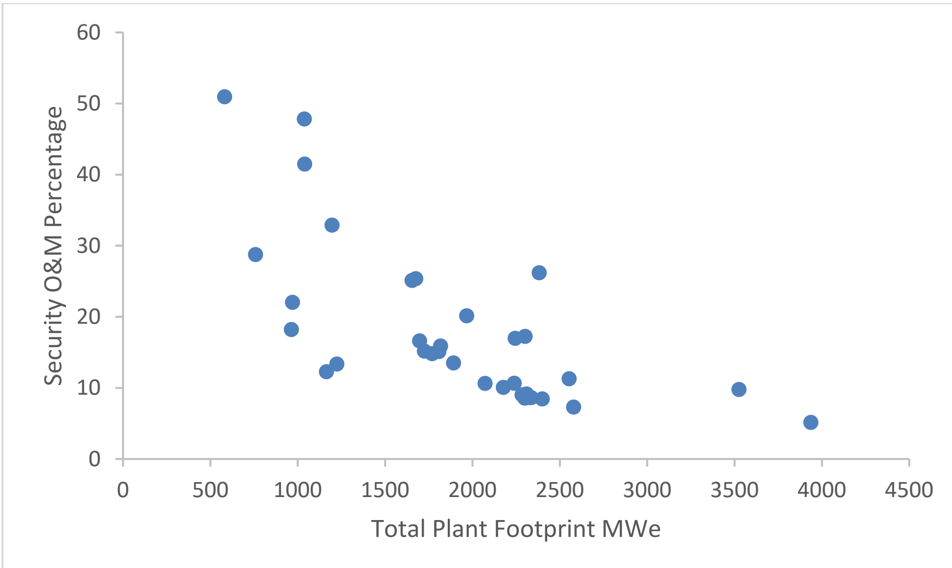


Figure 24. Estimated percentage of security cost of total O&M for plants based on average NEI cost data (NEI 2024).

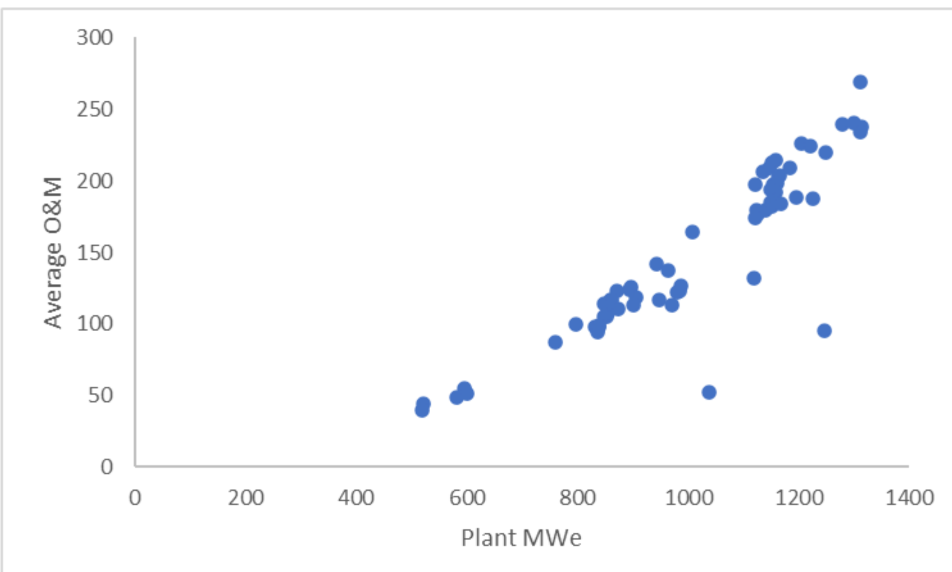


Figure 25. Estimated O&M costs for pressurized water reactors operating nuclear reactors in the United States (NEI 2024).

It can be concluded that as the plant scales up, the security costs remain level because plant maintain similar protection levels, despite the differences in total power output. However, combining the above estimates with those presented in Figure 22 shows that there is a tradeoff because as plants approach 1,000 MWe, there is a significant amount of uncertainty in the final price of the reactor. However, as MWe output decreases, there is a risk of requiring a level of security like that of a larger plant, so the O&M cost can become dominated by the security costs. For microreactors, placement of a single security guard could negate the profitability of that reactor and thus place a high premium on implementation of a SeBD program in that company. This optimization problem must handle each vendor by each site, but as the size of the reactor shrinks, it becomes of much greater importance to right-size the security force. Therefore, an SeBD program should be a must for smaller output plants to ensure a viable reactor design and security force.

2.3.8 Literature Review Results as Applied to Advanced Reactors

Design of a nuclear reactor as illustrated in Section 2.3.3 is a highly iterative process that requires a rigorous quality assurance process well beyond that found in most industries. Design of high quality, low risk of failure systems with defense-in-depth features to protect the health and safety of the public must be in line with the stated goals of the NRC, the Canadian Nuclear Safety Commission (C-NSC), and the French Nuclear Safety Authority (ASN-F).

> *The NRC's mission is to license and regulate the Nation's civilian use of radioactive materials, to provide reasonable assurance of adequate protection of public health and safety, to promote the common defense and security, and to protect the environment.(NRC).*
>
> *We regulate the use of nuclear energy and materials to protect health, safety, security and the environment. We also implement Canada's international commitments on the peaceful use of nuclear energy, and disseminate objective scientific, technical and regulatory information to the public. - Canadian Nuclear Safety Commission (C-NSC).*
>
> *Regulating nuclear safety and radiation protection in order to protect workers, patients, the public and the environment from the risks involved in nuclear activities. It also contributes to informing the citizens Autorite De Surete Nucleare French Nuclear Safety Authority (ASN-F).*

In DG-1061, the NRC proposes two subsidiary objectives to the quality health objectives: core damage frequency (with a value of 1×10^{-4} per reactor year), and LERF (with a value of 1×10^{-5} per reactor year) for purposes of examining proposed changes to the current licensing bases (CLBs) of individual plants. The probabilities and defects in design are comparable to the goals of Six Sigma to achieve a high quality, with only 3.4 defects per million opportunities (3.4×10^{-6}). Thus, looking at the projected profitability of an SeBD program could relate to similar quality assurance programs and the defect savings and services they offer, such as Six Sigma.

Kwak and Anbari (2006) outline the needs and obstacles for implementing a Six-Sigma approach (a business process designed to implement failure rates an order of magnitude less than nuclear reactor's LERF). One key goal is to investigate the impacts of Six Sigma implementation with early investment and design thoroughly with the proper process and toolsets and standard review gateways for technology development of a product. SeBD as defined in Section 1.1 presents an analogous process in which investment is made early in security and the design is optimized, tested, and measured for scalability. This approach is the same in terms of Six Sigma. A Six Sigma approach as defined by Kwak shows reported benefits varying from reduction in defects by 150× to savings of $2–15 billion at General Electric and Dupont. Additional savings are also illustrated, as well as increases in on-time deliveries of products and improvement of operations by 500%. Key factors in realizing these savings as illustrated by Kwak and Anbari are implementing of SeBD in the early design phase of a nuclear plant, maintaining involvement, and realizing final savings, as shown in Figure 26.

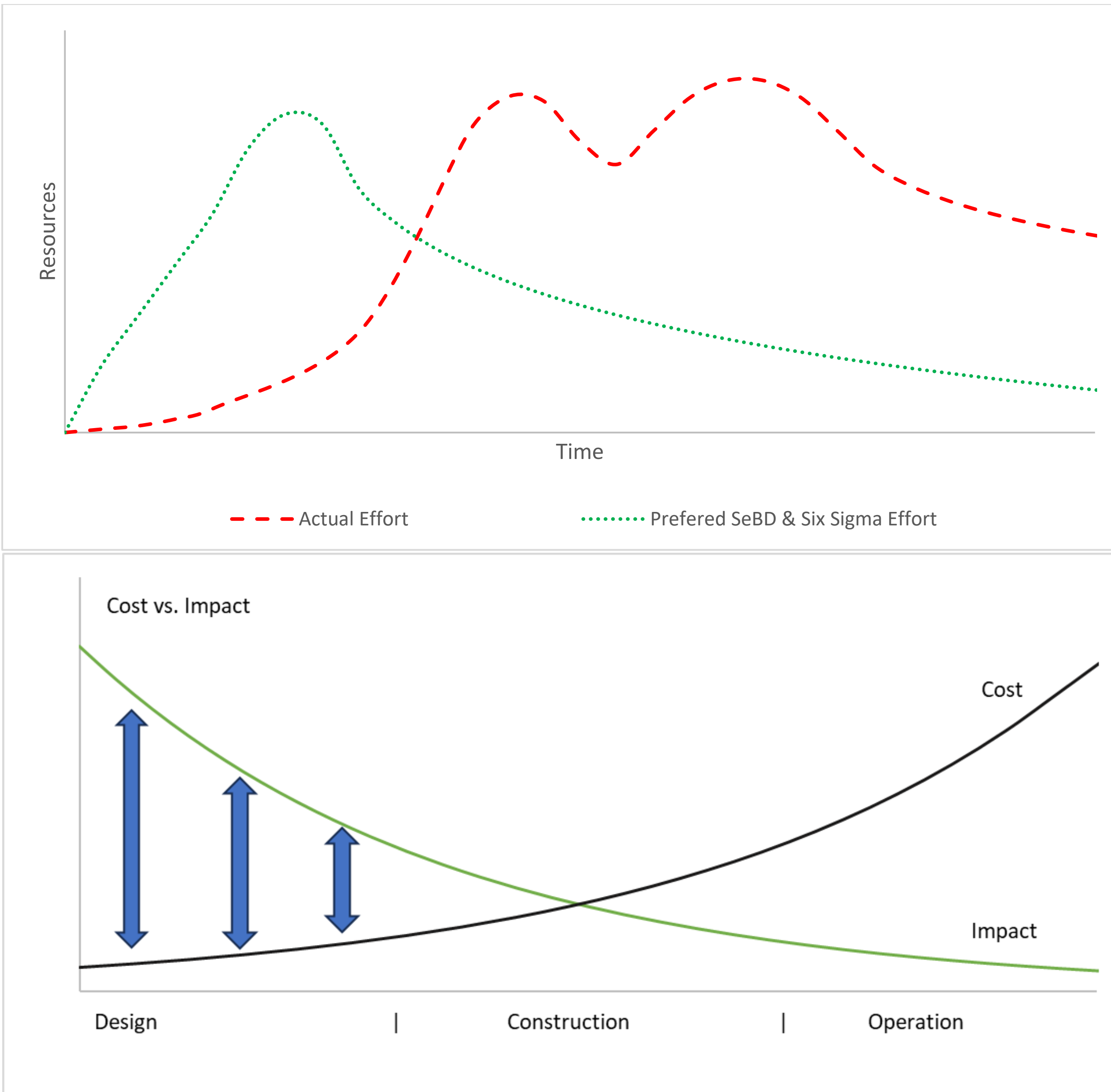


Figure 26. Illustration of SeBD and Six Sigma effort and opportunity and cost to fix defects or implement effective security.

However, as discussed in Section 2.3.3, it is not clear who realizes those savings. The real answer is both: however, the primary issue is the perception of those savings and if they appear to be abstract or if they are accounted for in the business case for the SeBD program. For the vendor and designer, the savings appear in terms of sales that can be interpreted as occurring despite any security designs implemented in the plant, as well as savings realized during construction because of reduced delays that would have been included in an SeBD program when analyzing the scaling of security during construction. Therefore, for the vendor, these savings can be abstract and more difficult to quantify. Section 3.1.4 develops some concepts for security managers to utilize to justify investments and savings. For the owner, these are key inputs into their ability to sustain the plant and maintain a lean workforce.

The cost to establish an SeBD program vs. the savings depends on the size of the company, the effort needed to inject an SeBD culture into a company, and the ability to maintain the processes and culture involved. These factors are similar to those required to implement a Six Sigma culture and processes into a company and to ensure that it is maintained. However, the primary difference between the two is that a Six Sigma training regime within a company, while costing as much as hundreds of thousands of dollars per year, has applicability to all products produced by a nuclear company, ranging from nuclear fuel to the design and implementation of the reactor vessel, whereas security primarily impacts the licensee. Because Six Sigma's application primarily to mass manufacturing the processes does not perfectly lend itself to application to something like a SeBD program, the principles may still be applied. Because a Six Sigma approach attempts to capture the customer's input, these two types of programs are parallel in their approach to implement an NPP quality assurance and security program. Ultimately it will be necessary for the advanced reactor vendor to determine the best way to ensure quality and defect reduction through their quality assurance program. Whether it is through a SeBD approach that has parallel processes to a Six Sigma approach or different approach, the value in investing early in development of such a program to benefit the advanced reactor designer and the ultimate owner of the plant.

3. ADVANCED REACTOR SEBD COST MODEL DEVELOPMENT

A review of the literature and past construction efforts for NPPs indicates that taking an LCOE, net present value (NPV), or return on investment (ROI) approach may not be sufficient for evaluating the true effectiveness of implementing an SeBD program. The regulatory environment and different countries' regulatory bodies point to the need for flexibility, all while attempting to cut costs by having a standard design. The previous sections discuss past and current literature at length and define some examples of why an SeBD program is necessary for an advanced reactor vendor. The regulatory environment allows for a disconnect between the owner/operator and the advanced reactor vendor, as detailed in Sections 2.3.1 and 2.3.3, but they must operate in a competitive market as laid out in Section 2.3.2. Keeping potential profit markets open to investment until the last possible time is an effective management tool, and an SeBD program allows for analysis of various profit center options to remain open while meeting regulatory requirements and customer expectations and reducing risk to future construction. Not having an SeBD program in place allows for mismatched incentives and the opening of a "market for lemons," as discussed in a case study in Section 2.3.4. Finally, an analysis of past reactor operations (Section 2.3.5), cases for scalable designs (Section 2.3.6), and the operational expenditures of current reactors (Section 2.3.7) are reviewed to apply the concept of an SeBD process to similar business processes (Section 2.3.8)

The effectiveness of a security system design for a specific location can be evaluated, and a cost–benefit NPV can be conducted. Optimization can be implemented, but the general concept of SeBD as an effective cost savings method has several factors that must be analyzed and considered. These issues include the following:

1. Regulatory differences
2. Market capture and participation
3. Plant designer/owner incentive mismatch.
4. Effective use of limited capital
5. Past nuclear power plant delays and overruns
6. Flexibility and scalability in an ever-changing security environment

Thus, it is necessary to view SeBD as a process similar to other cost savings investment programs used in heavy construction, engineering and procurement, and high-quality markets.

For an SeBD program to be viewed positively from a business perspective, justifications must be made for investment, and the investment in general must contribute to one or all of the following seven factors presented in Figure 27.

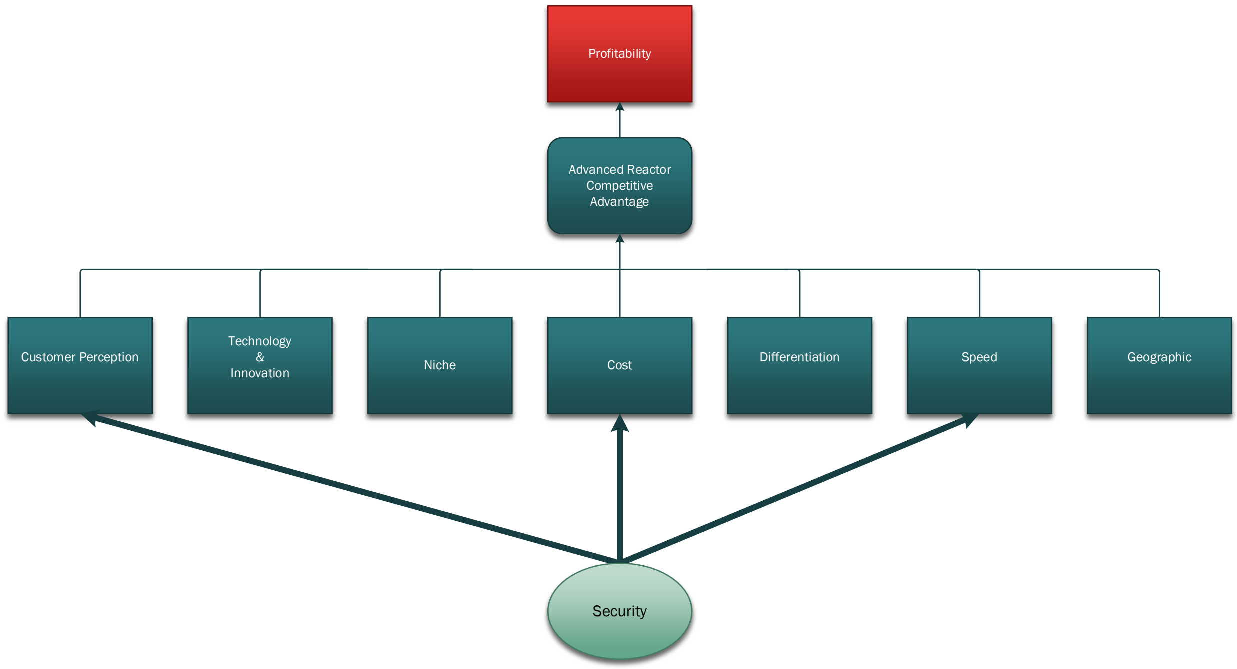


Figure 27. Company advantages that lead to a market competitive advantage.

The model for realizing cost savings is based on the vendor/designer being the holder of record for all the details of the design. Thus, the vendor/designer and integrate safety and security from the start to meet the necessary items that lead to a competitive advantage and company profitability while delivering a valuable service that can be maintained as a profit center for the life of a nuclear reactor. An illustration of the potential profit options made available by having and maintaining an SeBD program are illustrated in Figure 28.

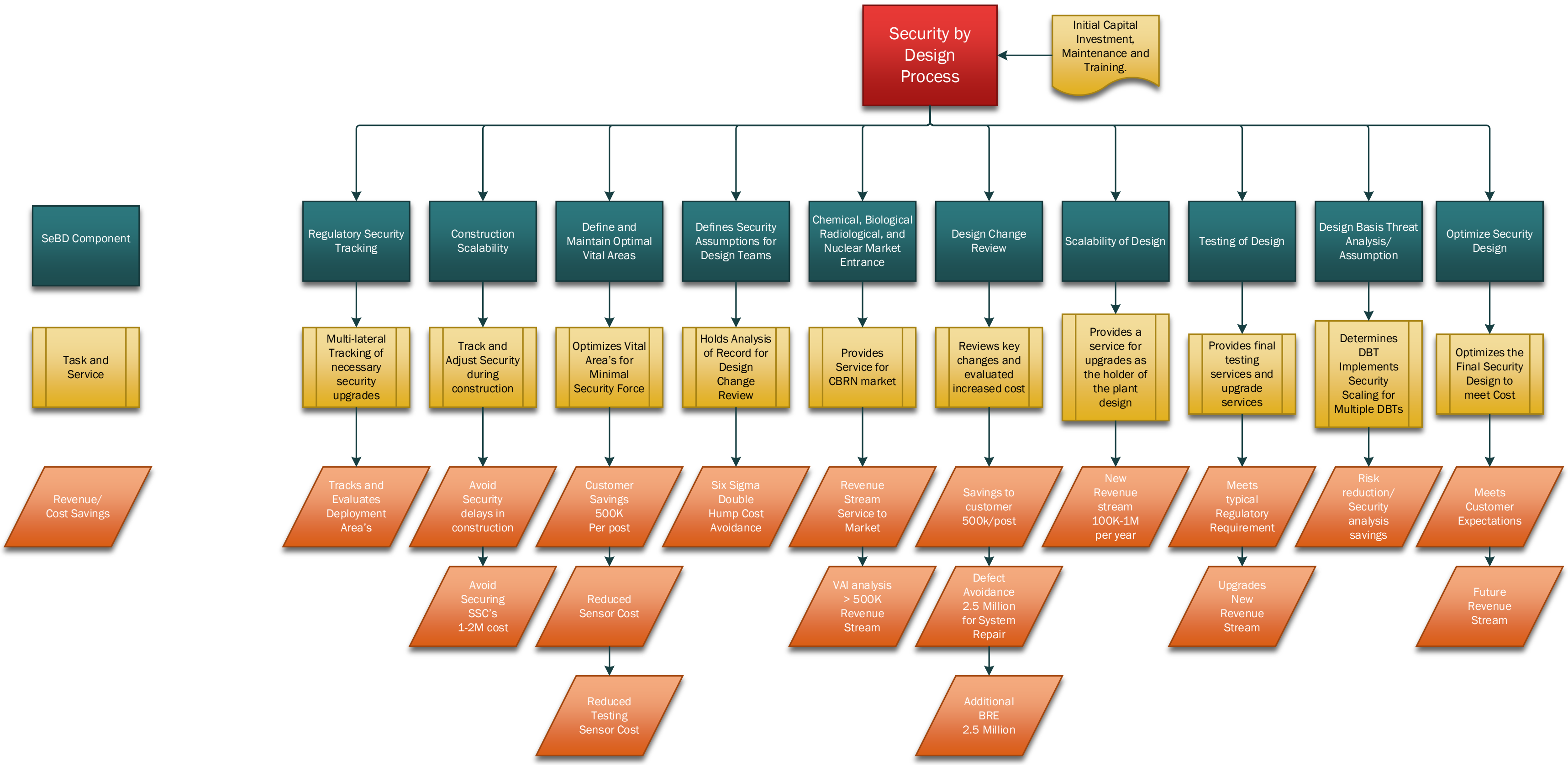


Figure 28. Proposed SeBD process implementation model.

This general model is designed to illustrate the benefits to a SeBD program, and the optional profit centers afforded to a company by this type of program. The initial decision may be to meet regulatory burdens placed on the nuclear industry, but there is a large market in future contracts opened up through this program. When the new digital twin modeling that may become part of the new advanced reactor landscape is realized, having an SeBD program that holds the analysis of record as the digital twin is upgraded can lead to services and savings for an end customer.

The standard business approach to decision making would be to perform an NPV calculation with this model and analyze whether to invest in an SeBD program as part of a standard prescriptive quality assurance process. An SeBD program lead must prove that a slight increase in training and qualification is necessary and justify a maintenance cost similar to that required for a Six Sigma program at a company. This approach yields long-term savings and future profitability options. If the program is set up properly, then the cost avoidance and ability to offer services or require a contract obligation for security services in the future would allow a positive NPV to be calculated, depending on the specific inputs of the company. Section 3.1 establishes the process for investment decision making for SeBD.

3.1 INVESTMENT DECISION-MAKING METHOD FOR SECURITY BY DESIGN

3.1.1 Investment Decision-Making Background

Many organizations that are determining whether to take on an investment in their infrastructure will perform an investment decision-making exercise. There are numerous methodologies available to determine whether an investment will return the cost required for execution, as detailed in the following sections.

In novel sectors/markets like R&D, innovation projects, and A/SMRs, the inputs to a typical investment decision-making exercise are likely based on subject matter expertise and insight rather than empirical data. In this case, it is critical that the investment decision-making analyst identify and maintain the assumptions used to determine assessment inputs.

The investment decision-making exercise is used to identify major risks, assumptions, initial and recurring costs, cost savings, expected cash flows, and the expected financial return for the organization. As market data become available, uncertainties and risks within the investment decision-making model can be refined to make the analysis more accurate. However, the absence of empirical data should not mitigate the use of the assessment with proper identification and management of key assumptions. The process of investment decision making is as much about risk identification and justification of assumptions as it is about the final value. When an investment decision-making tool is used, the output could be reviewed by numerous parties within and external to the organization. Although the results will be reviewed, the inputs to the results are a primary concern to reviewers and will likely be studied in detail.

This section provides the organization’s security leadership with the understanding and tools to build an organization-specific assessment of the financial benefit or cost of implementing an SeBD program.

This effort would be organizationally dependent on which investment tool to implement. The NPV Assessment Calculator presented in Section 3.1.4 includes calculation of each assessment method described in this report.

3.1.2 Choice of Investment Decision-Making Method

Numerous means are available to determine the net benefit of an investment. This report discusses the primary means that can be used to assess investments and provides justification for using the NPV method.

This report considers NPV, profitability index, internal rate of return (IRR), payback period, and ROI investment decision-making methods. The remainder of this section provides a brief description of each method and discusses pros and cons for their use.

3.1.2.1 Net Present Value

The NPV is an investment decision-making tool that uses discounted cash flows (the concept that money now is worth more than money in the future) to assess an initial investment (Fernando 2024). The NPV relies on a discount rate which can combine the organization's weighted average cost of capital (WACC) with additional risk metrics. This discount rate is applied to future cash inflows and outflows to determine the present value of total earnings. As uncertainty increases, so does the discount rate value, thus decreasing the present value of the future earnings.

The NPV results are a present value of cash flow that, if positive, shows a net benefit or return on the investment. The NPV formula is shown in Eq. (1) (Fernando 2024). The more positive the NPV, the higher the benefit of the project. The NPV is not normalized against the initial investment.

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{1}$$

The NPV benefits from the ability to assess potential projects against one other to better prioritize spending. Additionally, the NPV requires detailed assessments of cash inflows and cash outflows throughout the life of the project. Therefore, inputs to the NPV can be used on other analyses such as IRR, ROI, profitability index, and payback period. An additional NPV benefit is that the analysis is ubiquitous in financial modeling. When security leadership uses the NPV method, it is likely to align with organizational financial assessments.

The NPV is strongly influenced by the choice of discount rate from the analyst. This can lead to grossly inaccurate results, so the choice of discount must be justified and documented well. Additionally, the NPV becomes less accurate the further in the future that the assessment occurs. With A/SMR deployment timelines, this may be difficult to resolve. Sensitivity analyses—in which the analyst chooses to alter key variables (discount rate, periods of revenue, costs, etc.) to identify those which have the greatest impact on results—provide useful insights to the analyst when the NPV is considered over many years.

3.1.2.2 Profitability Index

The profitability index is a ratio between the present value of future cashflows and the initial cost of the investment (Chen 2024). The profitability index uses the same inputs as the NPV, but it is a ratio instead of a dollar metric. The formula for profitability index is provided in Eq. (2) (Chen 2024).

$$Profitability\ Index = \frac{Present\ Value\ of\ Future\ Cashflows}{Initial\ Investment} \tag{2}$$

The primary benefit of the profitability index is its ability to normalize various projects against their required inputs. The profitability index also has benefits similar to those of the NPV.

One disadvantage to the profitability index is that it does not account for project size (Chen 2024). On its own, this could result in the profitability index prioritizing high margin small projects, which may not be in the organization's best long-term interest.

3.1.2.3 Internal Rate of Return (IRR)

The IRR is a discount rate that makes the net present value equal to 0 (Fernando, Internal Rate of Return (IRR): Formula and Examples 2024). The IRR is compared against the organization's WACC to determine if the investment is beneficial. If the IRR is greater than the WACC or greater than the cost of borrowing money, then the investment is seen as profitable. The formula for IRR is shown in Eq. (3) (Fernando, Internal Rate of Return (IRR): Formula and Examples 2024).

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0, \tag{3}$$

where

C_t = net cash inflow during the period t,
C_0 = total initial investment costs,
IRR = the internal rate of return,
t = the current time period, and
T = the total number of time periods.

IRR uses concepts similar to those of the NPV and therefore shows similar benefits and drawbacks (Fernando, Internal Rate of Return (IRR): Formula and Examples 2024). The IRR does not require the analyst to determine and justify a discount rate, which simplifies the analysis. However, the lack of a justification of a discount rate can lead to a gap in risk identification.

As with NPV, IRR should be used with sensitivity analyses to develop insights into the key assumptions. Sensitivity analyses, in which the analyst chooses to alter key variables (discount rate, periods of revenue, costs, etc.) (Fernando, Internal Rate of Return (IRR): Formula and Examples 2024). to identify those with the greatest impact on results, and they provide useful insights to the analyst when the NPV is considered over many years.

The IRR calculation is included with the NPV calculator documented in Section 3.1.4.

3.1.2.4 Return on Investment (ROI)

ROI is a simple calculation used to determine how much money the organization has made normalized over the investment (Beattie 2024). The ROI considers the total amount of money made against the amount of the initial cost of the investment. The formula for ROI is presented in Eq (4) (Beattie 2024).

$$ROI = \frac{Current\ Value\ of\ Investment - Cost\ of\ Investment}{Cost\ of\ Investment} \tag{4}$$

The benefits of using ROI are the simplicity of the formula and the ease with which the outputs can be combined with other investment decision-making metrics to provide a holistic view of the investment's performance.

The current value of the investment is the value of the cashflow at the time when the cashflow occurred. Therefore, ROI does not account for the time value of money and should be considered primarily for short duration projects (Beattie 2024).

The ROI calculation is included with the NPV calculator documented in Section 3.1.4.

3.1.2.5 Payback Period

The payback period is the amount of time required for an investment to become profitable (Kagan 2024). The organization will have some amount of time before the revenue streams and net cash inflow can account for the initial investment. A simple calculation is used to determine in which time period the cumulative cash flow is first at zero for the project.

This analysis is beneficial in its simplicity. It is also a key input to investment decision making because some organizations have a formal or informal required payback period (Kagan 2024).

The payback period does not account for the time value of money and can result in heavily skewed results (Kagan 2024).

The payback period calculation is included with the NPV calculator documented in Section 3.1.4.

3.1.3 Process for Determining Net Present Value of a Project

The NPV calculation has four critical inputs: the time period, the discount rate, cash inflows, and cash outflows. This section discusses each of these critical inputs and describes how they can be calculated using the NPV calculator presented in Section 3.1.4

3.1.3.1 Time Period

The time period value is the time over which the analysis occurs. Typically, the analyst defines each time period as one year. The analysis can cover up to 20 years of cashflow.

3.1.3.2 Discount Rate

The discount rate of the net present value calculation is a means to adjust the future cashflows to the present value of money. The discount rate can include rates of return from capital markets, as well as risk of project success. The discount rate effectively normalizes projects across multiple sectors to compare them for investment decision making. Discount rates that are adjusted for risky investments must have a documented justification for their value. Discount rates are typically available from within the organization's finance department and can be expected to range between 7 and 25%.

The analyst should start with any discount rate available from their organization's finance team, such as the weighted average cost of capital (WACC), and then add percentage points based on the risks associated with the investment, the likelihood of returns, or any other risks believed to exist with security by design.

3.1.3.3 Cash Inflows

SeBD programs can expect three primary cash inflows. The first is based on the reduction of risk of security defects and the rework to remedy them.

This line item represents the offset of cost from utilizing an SeBD program. In this calculation, the offset or reduction of cost can be viewed as a cash inflow and is included as such. This calculation accumulates the cost savings from reduction in rework, reduction in regulatory requests for additional information, and construction, if applicable. The analyst should identify all anticipated areas of reduction of rework or offset of costs throughout the organization's role in the project. For example, if the analyst expects more efficient regulatory engagements, then fewer design changes should be included in the cost reduction section.

The second cash inflow is the additional cashflow from earlier sales of reactors. The NPV assessment is time dependent and is based on the discount rate already determined. The basis of this calculation is that cash inflow now is worth more than the same cash inflow later. This calculation determines the change in the present value of the earlier purchase, and it weights the cashflow based on expected licensee decision making. If the earlier sales of reactors are expected as a result of the execution of a formal SeBD program, then this sheet should be populated. The expectation here is that an organization that manages security design early in the process will meet regulatory demand, audit, inspection, and licensing requirements while also lowering overall operational costs. This schedule and cost savings will provide the impetus for the licensee to purchase the reactor sooner.

The third cash inflow is that of additional sales of reactors. If additional sales of reactors are expected as a result of the execution of a formal SeBD program, then this sheet should be populated. The expectation here is that an organization that manages security design early in the process will meet regulatory demand, audit, inspection, and licensing requirements while also lowering the overall operational costs of their reactor. This schedule and cost savings will provide the impetus for the licensees to purchase additional reactors and/or more licensees to purchase the reactor.

3.1.3.4 Cash Outflows

Four primary cash outflows or costs associated with SeBD program implementation are identified. The first is the cost of developing the SeBD program. SeBD should be a formal process defined within the organization. Depending on the auditability, the organizational culture, applicable regulatory positions, and other attributes, program development will have an associated cost. This cost is the initial investment the company must make, and it occurs in Period 0. Items to include in this cost are the development of the procedure, including labor hours, costs to develop training, administrative costs to roll out the program to resources, and others.

The second cash outflow is the cost of maintaining the SeBD program documentation. SeBD should be a formal process defined within the organization. Depending on the auditability, the organizational culture, applicable regulatory positions, and other attributes, program maintenance will have an associated cost. This cost is the yearly maintenance required to perform self-assessments, revise documentation based on lessons learned or the corrective action program, update training, and other administrative tasks.

The third cash outflow is the cost of additional labor from implementing the SeBD program documentation. The formal SeBD program will demand additional labor hours from key design groups. The security organization will perform more analyses and reviews throughout the design process, and in doing so, design alterations and labor hours from other sub-organizations will be required. This cash outflow is a means to capture that additional cost.

The fourth cash outflow is the cost of purchase and maintenance of software used specifically for the SeBD program. This will be considered as software not required for any other security analysis and will be only for SeBD.

3.1.3.5 Result

The primary calculation deemed most useful in this report is the NPV calculation. The NPVs ability to consider risk and time value of money and to produce the other investment decision making results warrants its choice as the primary investment decision-making method.

3.1.4 NPV Assessment Calculator Template

Attachment 1 of this report is an NPV assessment calculator template (ACT). The macro-enabled Excel file consists of multiple sheets and formulas to make building an NPV assessment straightforward. The following sections describe how to use the NPV ACT in support of building a business case for an SeBD program within an organization. The NPV ACT is limited to 20 years of future values, so the NPV assessment may not perform well past that time.

3.1.4.1 Navigation through the Template

The NPV ACT includes an "NPV Analysis" sheet which is the starting point for data entry, where the results of the analysis reside. The "NPV Analysis" sheet contains in-document hyperlinks for easy navigation to data entry sheets. Use the hyperlinks by single left clicking them. Each data entry sheet also has a hyperlink to return the analyst to the "NPV Analysis" page.

Cash Inflows	0
Reduction in Security-based Rework	$ -
Early Sales	$ -
Additional Sales	$ -
Other	$ -
Cash Inflow	$ -
Present Value (PV) of Cash Inflow	$ -
Cumulative PV Cash Inflow	$ -

Figure 29. NPV analysis (examples of hyperlinks are inside the red box).

Additionally, the analyst can use the worksheet tabs at the bottom of the Excel window to navigate throughout the document.

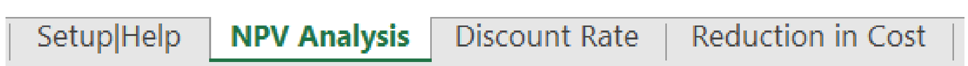


Figure 30. Example of worksheet tabs.

Some worksheets contain pivot tables for combining data. They can be unhidden, but the analyst should limit interaction with these sheets because they are a core attribute to the calculation and do not require direct analyst input.

3.1.4.2 Help

The NPV ACT has a help menu in the "Setup|Help" worksheet. The help menu is divided into two parts. The first is the Quick Start Guide, which provides a summary of the information in this Section. The second part is a guide for inserting and deleting rows.

3.1.4.3 Data Entry

NPV analyses require significant amounts of data. The data are both numerical, like costs and percentages, and written word, like justifications and comments. The NPV ACT contains data entry fields for both of those types of data. This section discusses the process to populate the data within the NPV ACT. As described above, the "NPV Analysis" worksheet is the starting point of the analysis. When beginning the assessment, the user should start in that sheet. The "NPV Analysis" worksheet should be reviewed from the top down.

Discount Rate

The first item to populate is the discount rate. Use the hyperlink "Discount Rate" to navigate to the discount rate data entry sheet or select the tab "Discount Rate" at the bottom of the page. The discount rate sheet is divided into four sections. The first is a description of the discount rate and its use; the second is an instruction guide on entering data, and the third and fourth are data entry fields.

The analyst should only alter information or values within orange tinted cells. Gray and white cells are not locked or protected, but they should not be altered.

In the "Discount Rate" sheet, the analyst is required to assess risks and provide justification as to why those risks are high, medium, or low. The justification field is more important to the analysis than the choice of risk value.

Use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

Revenue, Cash Inflows

The next item to populate is revenue or cash inflows. These represent the positive value the organization will receive from building an SeBD program. There are three primary cash inflows from an SeBD program: cost reduction, early sales, and additional sales. Each of these inflows is described in detail in Section 3.1.3.3. Entering the data for these cash inflows is the next step in the NPV assessment.

Navigate to the cost reduction sheet via the hyperlink on the "NPV Analysis" sheet or use the "Reduction in Cost" tab at the bottom of the page. This sheet is divided into three parts. Part 1 is a general description of this cash inflow stream, Part 2 includes instructions for populating the data, and Part 3 includes the data entry fields. The analyst should read Parts 1 and 2 and enter the specific data in each orange cell in Part 3. The "Cost Reduction Justification" field is critical to the analysis, so this review and should not be overlooked. Once all data entry is complete, the analyst should use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

Navigate to the early sales sheet via the hyperlink on the "NPV Analysis" sheet or use the "Early Sales" tab at the bottom of the page. This sheet is divided into three parts. Part 1 is a general description of this cash inflow stream, Part 2 includes instructions for populating the data, and Part 3 includes the data entry fields. The analyst should read Parts 1 and 2 and enter the specific data in each orange cell in Part 3. The "Justification and Comments" field is critical to the analysis and review and should not be overlooked. Once all data entry is complete, the analyst should use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

Navigate to the additional sales sheet via the hyperlink on the "NPV Analysis" sheet or use the "Additional Sales" tab at the bottom of the page. This sheet is divided into three parts. Part 1 is a general description of this cash inflow stream, Part 2 includes instructions for populating the data, and Part 3 includes the data entry fields. The analyst should read Parts 1 and 2 and enter the specific data in each orange cell in Part 3. The "Justification and Comments" field is critical to the analysis and review and should not be overlooked. Once all data entry is complete, the analyst should use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

There is also an "Other" cash inflow used to include any additional cash inflow streams the analyst would like. This cash inflow is entered directly in the "NPV Analysis" sheet, or this can reference the outputs from another sheet which could be added by the analyst.

Costs, Cash Outflows

The next item to populate is costs or cash outflows. These represent the negative value the organization will incur from building an SeBD program. There are four primary cash outflows from an SeBD program: cost of program development, cost of program maintenance, cost of additional labor, and cost of software purchase and maintenance. Each of these outflows is described in detail within Section 3.1.3.4. Entering the data for these cash inflows is the next step in the NPV assessment.

Navigate to the program development cost sheet via the hyperlink on the "NPV Analysis" sheet or use the "SeBD Program Dev." tab at the bottom of the page. This sheet is divided into three parts. Part 1 is a general description of this cash inflow stream, Part 2 includes instructions for populating the data, and Part 3 includes the data entry fields. The analyst should read Parts 1 and 2 and enter the specific data in each orange cell in Part 3. The analyst should be cautious to avoid overwriting the formula within the gray box. The "Justification/Comments" field is critical to the analysis and review and should not be overlooked. Once all data entry is complete, the analyst should use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

Navigate to the program maintenance cost sheet via the hyperlink on the "NPV Analysis" sheet or use the "SeBD Program Maintenance" tab at the bottom of the page. This sheet is divided into three parts. Part 1 is a general description of this cash inflow stream, Part 2 includes instructions for populating the data, and Part 3 includes the data entry fields. The analyst should read Parts 1 and 2 and enter the specific data in each orange cell in Part 3. The analyst should be cautious to avoid overwriting the formula within the gray box. Once all data entry is complete, the analyst should use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

Navigate to the program maintenance cost sheet via the hyperlink on the "NPV Analysis" sheet or use the "SeBD Addtl Labor" tab at the bottom of the page. This sheet is divided into three parts. Part 1 is a general description of this cash inflow stream, Part 2 includes instructions for populating the data, and Part 3 includes the data entry fields. The analyst should read Parts 1 and 2 and enter the specific data in each orange cell in Part 3. The analyst should be cautious to avoid overwriting the formula within the gray box. Once all data entry is complete, the analyst should use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

Navigate to the program maintenance cost sheet via the hyperlink on the "NPV Analysis" sheet or use the "Software Maintenance" tab at the bottom of the page. This sheet is divided into three parts. Part 1 is a general description of this cash inflow stream, Part 2 includes instructions for populating the data, and Part 3 includes the data entry fields. The analyst should read Parts 1 and 2 and enter the specific data in each orange cell in Part 3. The analyst should be cautious to avoid overwriting the formula within the gray box. Once all data entry is complete, the analyst should use the "NPV Analysis" hyperlink to navigate back to the NPV analysis page or click on the "NPV Analysis" tab on the bottom of the page.

There is also an “Other” cash inflow where the analyst can include any additional cash inflow streams the analyst would like. This cash inflow is entered directly in the “NPV Analysis” sheet, or this can reference the outputs from another sheet, which could be added by the analyst.

3.1.4.4 Formulas

The NPV ACT is preloaded and programmed with formulas that support the format of the tool. The analyst has complete freedom to alter any formula or program within the NPV ACT, but in doing so, the interlinked formulas, spreadsheets, or navigation may critically fail.

3.1.4.5 Results

There are two primary results from the NPV ACT. The first is the results section on the “NPV Analysis” sheet. These results include the NPV of the investment, the profitability index, the internal rate of return, the payback period, and the return on investment. These are all useful insights for determining the value of an SeBD program.

The next result is the data and justification produced. The data are available for further sensitivity studies, other financial assessments, and metric following for the program. The justifications and comments are available to aid in documentation of the assessment, sensitivity studies, and review.

Each of these results can be used to build charts and graphs for use when working with executive leadership to build a financial justification for SeBD implementation.

Finally, the analyst will gain key relationships internal to the organization while building the inputs to the NPV ACT. This is a “soft” result, but it will assist in bringing the SeBD program and value to other sub-organizations within the organization.

3.1.4.6 Use and Alterations

The NPV ACT results should be reviewed and verified for accuracy with organizational finance experts and leadership before finalizing. The analyst should review the spreadsheet with key stakeholders to verify required inputs and align outputs. If the financial analysts require different results, then the analyst should not put extra effort into building these assessments or entering the data.

As mentioned above, the NPV ACT is completely open to change and alteration. This provides the analyst flexibility in modeling, but there is a risk of unintended alteration. It is critical that the analyst primarily alter only orange fields and follow instructions for inserting and deleting rows. With knowledge in visual basic for applications (VBA) and Excel formula use, the analyst can feel free to further develop the sheet to their specific needs.

4. CONCLUSIONS

The results of this paper illustrate that a relatively small investment in an SeBD process can save millions of dollars for the owner/operator over the 40 to 100 years of operation in the back end of the nuclear fuel cycle–all while creating additional profit options for the vendor. Regulation has begun to emphasize a 3S (safety, security, and safeguards-by-design) focus, so advanced reactor vendors should adapt. Changes in regulations around the world will greatly impact the security of a facility and its ability to deploy in another region. Applying an SeBD process into the quality assurance system supports defect avoidance, creates a salable customer product (because the vendor holds the safety vital area identification data), provides maintenance contract availability for future revenue, and creates the ability to scale security designs to meet changing regulations in countries around the world. Because modularity is key for most designs, this scalable approach is necessary. Performing one-off analysis of each region when before attempting to make sales in a market will be costly, will occur late in the design process, and can lead to delays during construction. Not enabling the ability to scale with construction could lead to increased security needs for storage of safety equipment prior to installation that increases construction security costs by millions of dollars.

The market shows that there is an applicable and comparably large market for CBRN security within a utility and that the right amount of investment could maintain competitive services in that market for the life of the plant and thus show an applicable ROI for the implementation of such a program. Past NPP construction shows that the delays in construction can cause massive spikes in price and cost overruns: in the United States alone there was an estimated 93% increase on average for the LWR plants built in the 20th century. Most of those increases were caused by design changes in construction and are estimated to be the result of designer changes, which can make them potentially liable for the costs and delays. Interviews with individuals in charge of nuclear security at new construction projects also indicated that site testing of security equipment, if not properly vetted by the vendor prior to procurement, could lead to millions of dollars in losses resulting from removal and replacement of such equipment.

The LCOE for NPPs remains high in a difficult energy market, where renewable penetration continues to drive higher efficiencies in O&M costs at a plant, including security (Abou-Jaoude 2023). Comparisons between a Six Sigma design process and the savings realized through its implementation parallels if not exemplifies the types of savings that can be realized in such an endeavor. Thus, the implementation of an SeBD process is in the best interest of the vendor, customer, and state and should be implemented if an advanced reactor designer is looking to deploy a standard or site-specific design. Finally, the security environment must react to new security threats in a faster, and more profound manner as time progresses, and the general trends have been to apply manpower to such issues. The vendor holding the digital twin, the building integration model, and the safety design holds the key to analyzing for novel threats and can charge for the analysis instead of defaulting to the CBRN market for the analysis.

Based on these observations, an SeBD program will lead to savings in cost and schedule while raising the effectiveness and profitability of a company that makes the initial investment.

5. FUTURE WORK

This document presents the general framework for an SeBD process and provides a justification for why such a program is worth the investment. The details of this program are left to the ultimate owner of the program to determine, but suggestions are provided to be included in the quality assurance program, and a system similar to a defect avoidance quality program is warranted—something parallel to a Six Sigma approach to security. Furthermore, an additional measure that would increase the validity of such a model would be to take a real options (RO) approach to setting up an SeBD program.

An RO approach encourages decision makers to create opportunities by answering several main questions (Martins 2013).

- What are the future alternative actions?
- When should we choose between these actions to maximize value, based on evolution of key variables?
- How much is the right to choose an alternative worth at a given time.

This approach allows decision makers to build models that determine whether specific business decisions are likely to lead to a positive NPV and to determine the last possible time to make those decisions. That delay time can be considered of value, because it allows a company to watch how the market is shaping to determine if an investment decision is warranted. The inputs also follow the Black-Scholes-Merton Model used in financial options markets, which further aligns those in the decision-making process to justify to financial organizations the investment in such a program in terms that financial investment institutions will understand: NPV and RO.

In the future, it would be necessary and prudent to invest in gathering more detailed data from partners to define a better NPV and RO calculations and to develop simple toolsets that can show how a base SeBD program at a company can lead to long-term savings, services, and optimization of security forces for NPPs.

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