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Technical Methodology to Demonstrate the Separation of Nuclear Facilities from Adjacent Facilities

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ABSTRACT

This report defines a technology- and regulator-neutral methodology to demonstrate separation of a nuclear facility from adjacent facilities. In this sense, “separation” is defined to be a structured approach to the design and licensing of a nuclear facility that appropriately addresses quality requirements in adjacent facilities, including the appropriate design, technical, and regulatory footprint between the nuclear and adjacent facilities. This could result in support for expanded missions for nuclear energy beyond traditional electricity generation roles, as well as increased efficiencies and flexibility in terms of design and operations.

This report provides the methodology to demonstrate separation, guidance on how to develop reactor technology for utilization in separated facilities, and guidance on verifying and maintaining separation.

Future work will focus on application of this methodology within specific regulatory jurisdictions, test cases of application of the methodology, and ways to realize potential resource allocation efficiencies during construction, operations, and maintenance.

Keywords

Adjacent facility
Design envelope
Nuclear facility
Separation

EXECUTIVE SUMMARY

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Product Title: Technical Methodology to Demonstrate the Separation of Nuclear Facilities from Adjacent Facilities

Primary Audience: Architect/engineers, reactor original equipment manufacturers (OEMs), nuclear facility owners/operators, and nuclear regulators

Secondary Audience: Plant constructors, investors, and local regulators

KEY RESEARCH QUESTION

This report evaluates how the development of a technology- and regulator-neutral methodology that considers the separation of a nuclear facility (NF) from adjacent facilities (AFs) may be used to establish a more efficient approach to the design and operation of nuclear facilities. In this sense, "separation" is defined to be a structured approach to the design and licensing of an NF that appropriately addresses quality requirements in AFs, including the appropriate design, technical, and regulatory footprint between the NF and AF. In this context, "separation" is intended to mean a structured approach to the design and licensing of an NF that appropriately addresses quality requirements in AFs and minimizes the need for regulatory oversight of AFs.

RESEARCH OVERVIEW

Research consisted of a literature review and outreach to industry subject matter experts (SMEs) for contribution to the development of the methodology. A technical advisory group consisting of industry stakeholders and SMEs was consulted for input and review of the content in this report.

KEY FINDINGS

- The team developed a technology- and regulator-neutral methodology that considers separation between the NF and any AFs, indicating that such an approach could provide an enabling approach for NF design going forward, particularly in support of non-electric grid missions.
- Demonstration of separation can be based on a technology- and regulatory-neutral set of criteria, as opposed to prescribed requirements or design solutions.
- Separation ultimately needs to be demonstrated on a site-specific basis. However, reactor technology can be developed and standardized to support this demonstration.

- While demonstration of separation does not require submission to the regulator of detailed information for facilities outside of the NF boundary, maintaining separation requires initial and ongoing verification of systems and structures in AFs that can impact the NF, to the extent that an appropriate regulatory footprint can be maintained.

WHY THIS MATTERS

Establishing a more efficient approach to the design and operation of nuclear facilities can help streamline NF design going forward, particularly in support of non-electric grid missions. Doing so with a robust technical, programmatic, and regulatory basis has the potential to reduce barriers to the expanded application of advanced NFs in multiple areas.

HOW TO APPLY RESULTS

The methodology presented in this report can be applied during the design, licensing, construction, operations, and maintenance of new nuclear energy plant projects.

LEARNING AND ENGAGEMENT OPPORTUNITIES

Users of this report may contact EPRI for further information regarding this report.

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DEFINITIONS

Nuclear facility (NF): Any facility that contains at least one nuclear reactor.

Adjacent facility (AF): Any facility outside the boundary of the NF (but functionally related to the NF) that can impact the NF due to NF transients initiated by systems interfacing to the AF and external hazards originated from the AF.

Nuclear facility boundary: The physical, functional, and programmatic boundary that delineates the scope between the NF and AFs.

Nuclear facility design envelope: The set of technical parameters at the NF boundary that is used as input for the safety assessment of the NF. This includes parameters for interfacing systems and external hazards.

Nuclear quality requirements: These are the requirements imposed on the design, procurement, testing, installation, operations, and maintenance of structures, systems, and components (SSCs) due to the function that the SSC provides with regard to demonstrating compliance to nuclear regulatory requirements for the NF. These may include technical requirements, such as seismic requirements, or process requirements, such as design, procurement, testing, or quality assurance requirements.

Regulatory limits: Regulatory limits include all applicable radiological and nuclear safety limits defined by the regulator. These may include dose limits, effluent release limits, fuel damage limits, and offsite release limits. The scope of this methodology is focused on nuclear regulatory limits, but the same process could consider other limits (e.g., chemical hazards).

Safety assessment: The set of qualitative and quantitative analyses required to demonstrate that regulatory limits are met.

ACRONYMS AND ABBREVIATIONS

AF	adjacent facility
BOP	balance of plant
DC	Design Certification
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
GDA	Generic Design Assessment
GQA	Graded Quality Assurance
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
NEI	Nuclear Energy Institute
NF	nuclear facility
NRC	Nuclear Regulatory Commission
NSSS	nuclear steam supply system
O&M	operations and maintenance
OEM	original equipment manufacturer
P&ID	piping and instrumentation diagram
PRA	Probabilistic Risk Assessment
QA	Quality Assurance

SDA	Standard Design Approval
SSCs	structures, systems, and components
VDR	Vendor Design Review

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1 INTRODUCTION

Nuclear energy is reliable, dispatchable, carbon free, and has a high energy density. Its primary output is heat, which can be utilized for a number of energy applications including electricity, process heat, district heating, district cooling, and desalination. As a result, it offers many advantages in a future sustainable energy system.

Currently, there are a number of challenges to the use of nuclear energy to support future energy markets. These include high capital costs, high operations and maintenance (O&M) costs, and barriers to utilizing nuclear energy in non-electric applications. However, a concept that builds upon current regulatory methods and approaches with a robust technical, programmatic, and regulatory basis can address these issues if the concept of separation is explored via a structured approach to the design and licensing of a nuclear facility (NF) that appropriately addresses quality requirements in adjacent facilities (AFs). These challenges and the basis for the developed methodology are discussed in detail below.

Challenges to the Adoption of Nuclear Energy

Capital Costs

Previous EPRI research analyzed cost data for recent nuclear construction projects and found that construction of balance of plant (BOP) structures, systems, and components (SSCs) are significant contributors to the overnight cost[1] of a nuclear generating facility [1,2]. This research comparing BOP construction costs for previous nuclear power plants with other generating technologies, such as natural gas combined-cycle plants and concentrated solar power plants, determined that a primary driver for higher nuclear plant BOP construction costs is the unnecessary application of nuclear quality requirements to BOP SSCs. There are two reasons for this:

- BOP SSCs are used to demonstrate the safety case (including design basis and beyond design basis events).
- Nuclear quality requirements are applied to the BOP SSCs for consistency with the nuclear portion of the plant.

[1] Overnight cost is defined as the total cost excluding interest accrued during construction.

O&M Costs

In addition to capital costs, O&M costs are higher for nuclear plants relative to most other dispatchable generation technologies [3]. This is largely attributed to the higher staffing levels typically seen at nuclear power plants. These staffing levels are driven by:

- Activities to ensure ongoing compliance to nuclear regulatory requirements.
- The desire for high levels of plant availability.

Sufficient separation of the NF in the original NF design would reduce O&M costs by confining nuclear-safety-driven programs to the NF. This would allow a larger portion of the plant to be reliably and safely operated following fit-for-purpose, industry-standard practices for O&M, thereby reducing overall facility staffing levels.

Complexity of Non-Electric Missions

While there have been examples of non-electric uses of nuclear energy, such as district energy [4] and industrial applications [5], the majority of commercial applications of nuclear energy have been for electricity generation.

However, due to global objectives to reduce fossil fuel use, nuclear energy is being considered for many other uses, such as hydrogen production, chemical production, and desalination. These missions may be concurrent with electricity generation or may be dedicated to non-electric use. This concept could apply to existing operating plants seeking to diversify revenue streams, as well as the design and construction of new plants for dedicated purposes.

One challenge with non-electric missions is the demonstration of the safety case. In current electric utility plants, some information on the BOP is typically required to inform the safety and hazards analysis. In addition, the BOP designs are generally similar among different electric utility plants. By contrast, there is a significant variation of BOP facilities in non-electric applications. For example, a college campus may require hot water and chilled water, while a petrochemical facility may require steam and electricity. This variation would increase the burden on the review of the BOP that would typically be included in the license application.

Facility ownership presents another challenge. Many of the proposed use cases for non-electric missions involve one company that owns and operates the nuclear plant, which would then provide steam and electricity to other facilities that are owned and operated by an end user that is a different company. This separation in ownership between the NF and an adjacent facility (AF) could present challenges in providing AF design information in regulatory applications.

Use of Separation to Enable Nuclear Energy

To address these challenges, the concept of separating the NF from AFs is introduced. In this context, "separation" is defined to be a structured approach to the design and licensing of an NF that appropriately addresses quality requirements in AFs and minimizes the need for regulatory oversight of adjacent facilities to address the challenges described previously.

An Extension of Current Methods

The methodology described in this report is intended to be implementable as it is a logical extension of existing processes that are accepted for use across the world, including both deterministic and risk-informed approaches.

Deterministic approaches were used extensively in the original design and licensing of most current nuclear power plants built in the early nuclear construction period (e.g., 1960s-1980s) and utilized a functional boundary that separated "Safety-Related" SSCs from "Non-Safety-Related" SSCs, with all necessary regulatory requirements met by reliance on mostly Safety-Related SSCs (as regulations evolved, some expectations on Non-Safety-Related SSCs were also included). Figure 1 shows a conceptual example of highlighted "Safety-Related" SSCs defined at a nuclear power plant on a functional basis.

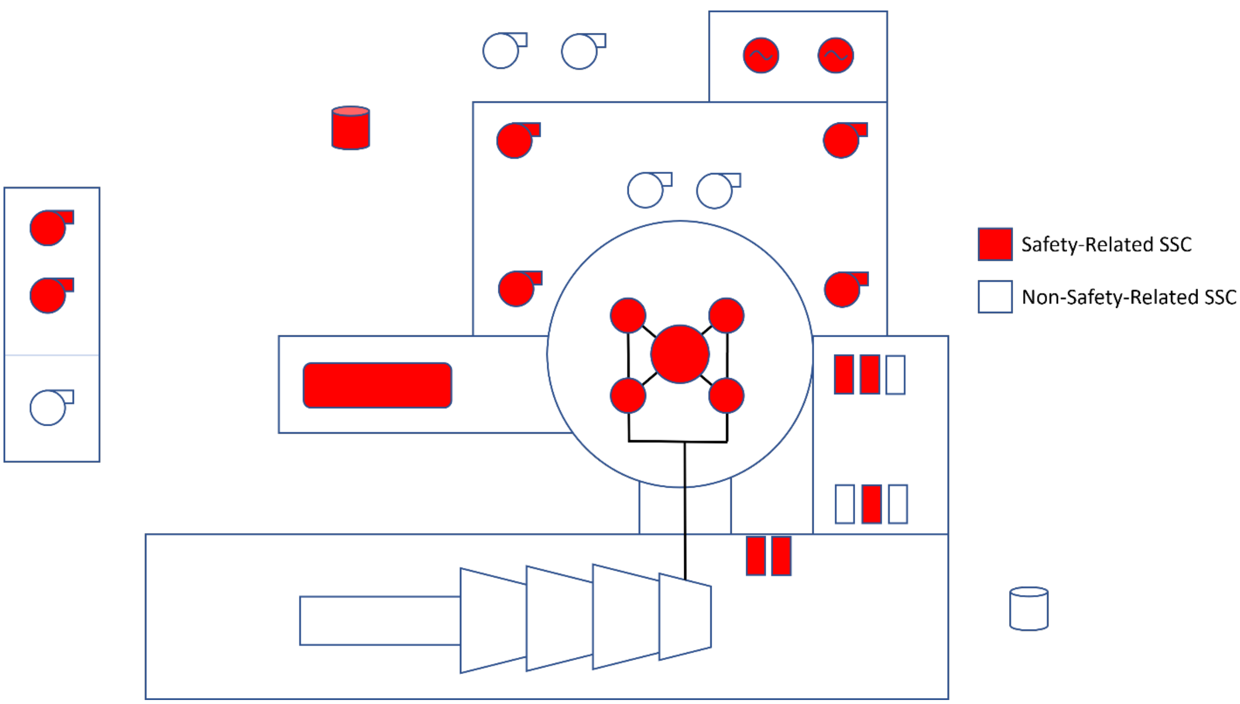

Figure 1. Concept of "Safety-Related" SSCs from a deterministic approach

Risk-informed approaches (discussed in more detail below) introduced in the 1990s and beyond provide additional information for a more refined approach to plant operations and management, capturing new insights into the most risk significant SSCs and processes, regardless of Safety-Related classification. These risk-informed approaches expand the scope of consideration to include relevant SSCs at the plant that could contribute to the safety/risk analysis, while also allowing a reduction of focus on items defined as “Safety-Related” that are not risk significant. Figure 2 shows a conceptual example that includes additional risk significant SSCs in a crosshatched pattern and reduced treatment for SSCs in a dotted pattern.

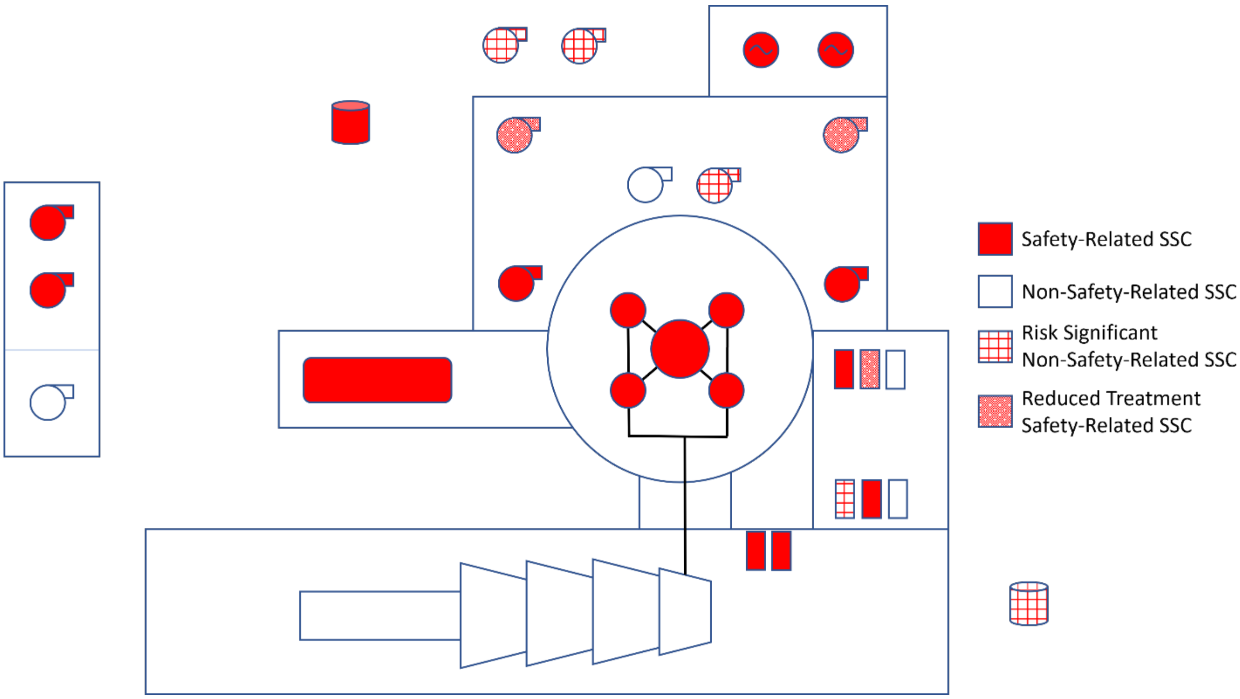

Figure 2. Concept of “Risk Significant” SSCs from a risk-informed approach

The new methodology developed in this document builds on this refined approach to promote a well-rounded, yet focused approach to demonstrate in a technical and regulatory sense that a "separated" nuclear facility meets all safety requirements during design, construction, and operation using a set of safety significant SSCs generally contained within the physically separated NF as shown conceptually by the highlighted area in Figure 3. Though not necessarily limited to advanced reactor designs, this approach can be particularly beneficial to new designs that utilize different nuclear fuel forms and rely on passive safety approaches to significantly reduce the amount of SSCs necessary to assure a high level of safety (especially during the design stage). Therefore, this new methodology is intended to be consistent with current approaches to nuclear safety employed around the world by utilizing a focus on both physical and functional separation of only those SSCs necessary to demonstrate protection of public health and safety via safe operation of the NF.

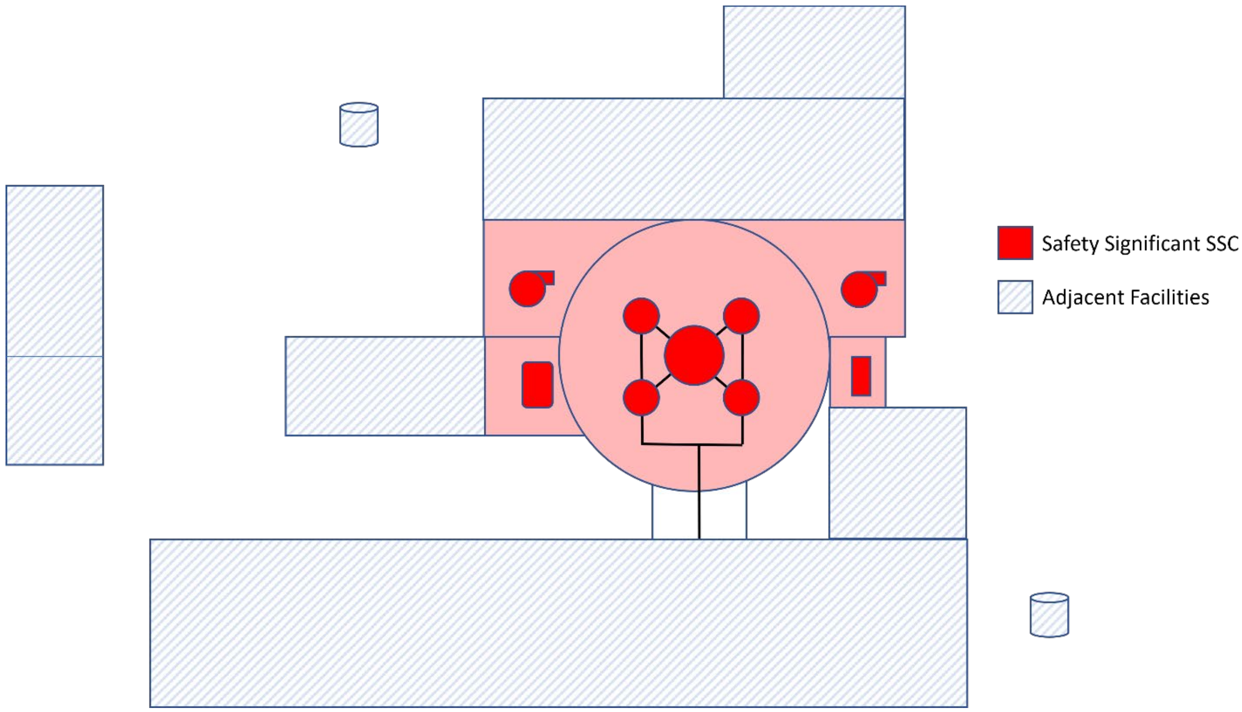

Figure 3. Concept of “Safety Significant” SSCs from a separation approach

Consistency with Current Applications

The US Nuclear Regulatory Commission (NRC) policy on the use of Probabilistic Risk Assessment (PRA) in regulatory matters [6] marked an important milestone in US nuclear regulation. An off-shoot of this policy was the development of a process that could be used, in combination with a licensee’s plant-specific PRA model, to re-evaluate components for safety significance and “grade” the quality assurance (QA) controls commensurate with these categories as described in Regulatory Guide 1.176 [7]. The goal of this process is to assure that QA programs are applied “in a matter consistent with the importance to safety of the associated plant equipment.” The regulatory guide provides the NRC’s expectations for a Graded Quality Assurance (GQA) Program which involves an assessment of the technical adequacy of the plant’s PRA model and a four-step process to implement GQA, the major elements of which are:

1. Definition of the changes to the QA program,
2. Performance of the engineering analysis to establish the safety significance of SSCs,
3. Definition of an implementation and monitoring program, and
4. Submittal of the license amendment.

Experience implementing GQA programs led the NRC to conduct rule making which resulted in 10 CFR 50.69 [8], along with an industry-developed and NRC-endorsed categorization guide [9,10].

As the NRC was implementing this process to enable GQA programs, a major international movement was underway to enhance product quality. This movement started in the mid-1980s and ultimately resulted in the issuance of the international standard ISO-9001-2000, "Quality Management Systems." As nuclear industry vendors implemented ISO-9001 in their broader businesses, it was logical to ask whether an ISO-9001 system provided adequate assurance of quality in nuclear applications. The NRC Staff compared ISO-9001 as it had been implemented by French and Canadian regulators and other regulated industries (such as aerospace) against 10 CFR 50, Appendix B implementation. The NRC Staff found that, although these entities had embraced ISO-9001 to a degree, they had augmented ISO-9001's requirements in a number of areas including design, development, manufacture, assembly, reliability, servicing, and regulatory compliance. A similar set of differences had been identified by the International Atomic Energy Agency (IAEA) [11]. The NRC Staff's conclusion was that supplemental guidance was necessary for quality programs developed under ISO-9001 to be consistent with quality expectations in the nuclear industry [12].

The worldwide nuclear industry had also embarked on efforts to systematize an approach to risk-informing the design of advanced reactors. Because these efforts focus on the design of new reactors as opposed to support of the existing fleet, they incorporate safety assessment methods that can be used prior to the design being mature enough to fully support a PRA model. The US [13] and international [14, 15] guidance documents incorporate such "pre-PRA" safety assessment methods, including hazard and operability assessments and failure modes and effects analysis, for use in initial development of system requirements for safety. These methods are recognized by both deterministic [16] and probabilistic safety assessment standards [17] and previous EPRI research has placed these methods within a systematic framework for developing the safety case for an advanced reactor system design [18].

This wide range of PRA and "Pre-PRA" safety assessment methods generally support the concepts of nuclear industry's initial efforts to create GQA programs. Such consistency is evident in the criteria established in Regulatory Guide 1.176[2] for evaluating a potential license modification, which when looked at generically may involve:

- Use of the system engineering process to identify required functions and systems to accomplish those functions.
- Conduct of an industry standard safety assessment.
- Combination of the above with engineering judgement, to identify a preliminary set of initiating events and the SSCs that are important for preventing or mitigating those events.
- Conduct of an independent review of the above technical analysis.

[2] Though Regulatory Guide 1.176 was officially withdrawn, these concepts are consistent with the newer guidance that superseded it, such as in Regulatory Guide 1.201.

- Use of the results to identify those systems that are safety-related, those that are non-safety related, and any potential interfaces between the two.
- Consideration of non-safety-related systems, which after review for potentially important-to-safety interfaces, would be candidates for handling with fit-for-purpose QA systems to be assessed by the reactor designer.

Therefore, this separation methodology is designed to be consistent with existing regulatory processes and analysis methods which have demonstrated success in improving the efficient regulation and operation of the nuclear industry.

The Separation Concept

Currently, many reactor original equipment manufacturers (OEMs) are pursuing varying degrees of separation in their designs. Each reactor OEM is adopting a technology-specific approach to demonstrating separation, and there is no single accepted approach to demonstrating separation. Furthermore, some regulators have acknowledged the idea of separation, especially for advanced reactors, but uncertainty remains surrounding specific requirements for separation.

To address the need and current state of the industry, this report provides a technology- and regulator-neutral methodology to demonstrate separation of NFs and AFs. While this report focuses on separation in design, additional strategies should be employed during project execution and O&M to realize the full potential economic benefits of separation.

The basic concept of separation proposed in this report is the following:

- Divide a facility into a nuclear portion (that is, NF) and a non-nuclear portion (that is, AFs) with a clear physical, functional, and programmatic boundary between the two.
- Identify the interfacing systems and external hazards that can affect the NF.
- Define the parameters for the interfacing systems and external hazards at the NF boundary in the NF design envelope.
- Demonstrate the safety case using the NF and the NF design envelope, including verification of key separation criteria.

Verification of the NF design envelope is then managed separately from the demonstration of the safety case—first during construction of the facility, and then during O&M. Figure 4 illustrates this concept.

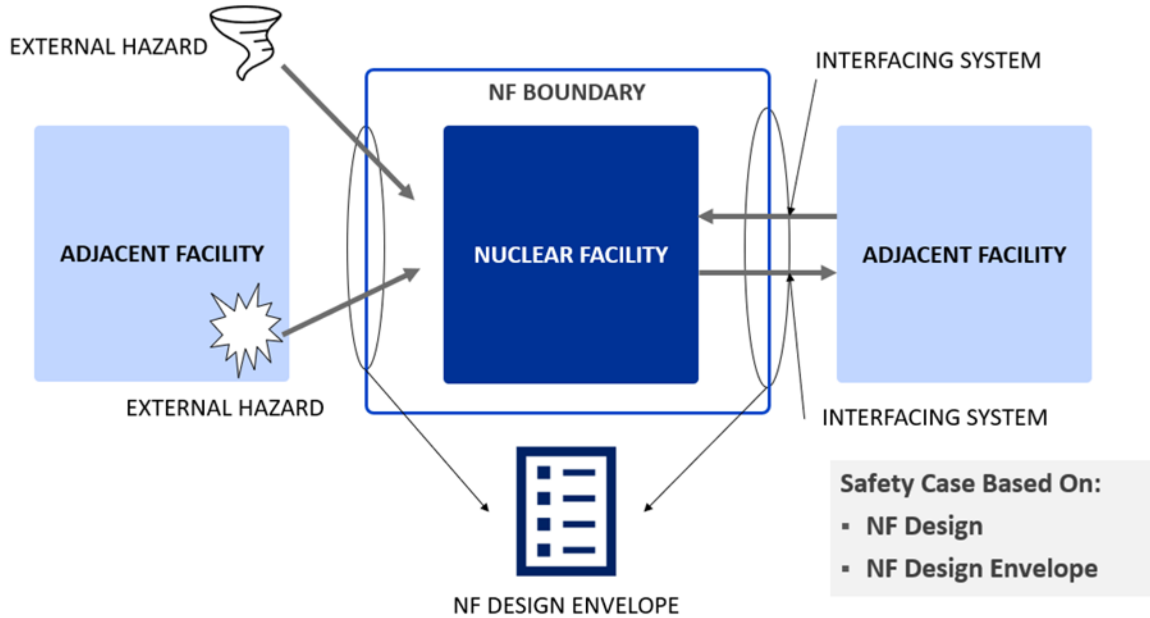

Figure 4. Concept for separating an NF from AFs

2 SEPARATION METHODOLOGY

Overview

This section provides a methodology to demonstrate separation in the design of a nuclear plant for a given site. To provide the broadest applicability to various industries, the methodology is both regulator- and technology-neutral for both the NF and AF. Figure 5 presents an overview of the methodology.

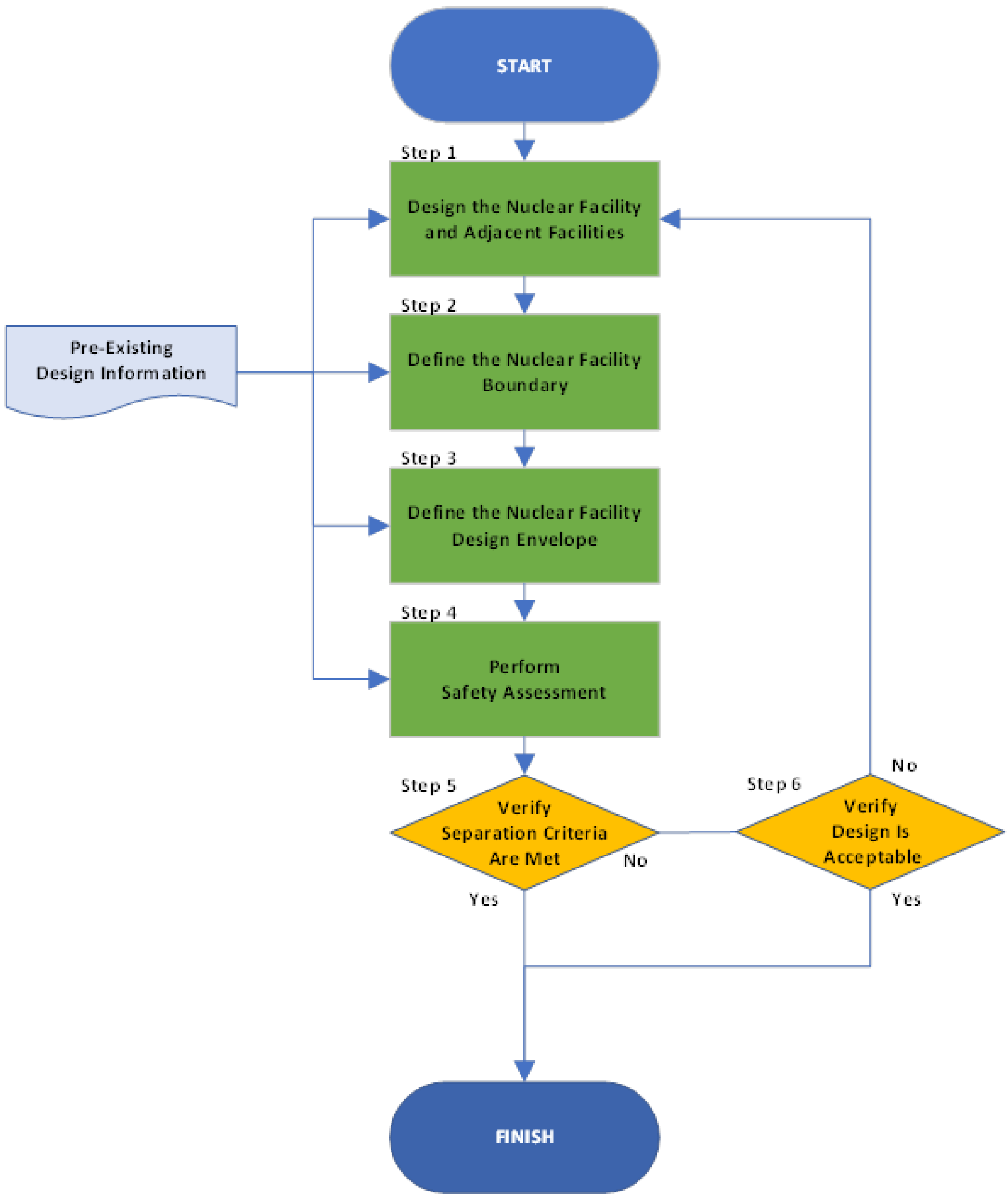

Figure 5. Methodology to demonstrate separation of an NF from AFs

Implementation Through Facility Design Process

The separation criteria (defined in Step 5) should be considered early in the design process to efficiently achieve the desired degree of separation, while also meeting regulatory requirements and business objectives. As such, the methodology shown in Figure 5 should be applied iteratively as the design matures. Table 1 provides guidance on the expected level of detail for each step of the methodology as the design progresses from site and technology selection through conceptual, preliminary, and detailed designs, as well as construction.

Table 1. Application of the separation methodology to the site-specific design process

Separation Step	Separation Step Description	Site and Technology Selection	Conceptual Design	Preliminary Design	Detailed Design	Construction
1	Design the NF and AFs	Pre-conceptual design	Conceptual design	Preliminary design	Detailed design	As-built design
2	Define the NF boundary	Initial NF boundary	Updated NF boundary	Updated NF boundary	Final NF boundary	As-built NF boundary
3	Define the NF design envelope		Initial NF design envelope	Updated NF design envelope	Final NF design envelope	As-built NF design envelope
4	Perform safety assessment		Initial safety assessment	Updated safety assessment	Final safety assessment	As-built safety assessment
5	Verify separation criteria are met		Initial verification	Updated verification	Final verification	As-built verification
6	Verify design is acceptable		Initial verification	Updated verification	Final verification	As-built verification

Final demonstration of separation must be made for a given site-specific design. However, the separation methodology can also be adapted to develop reactor technology for pre-approval that is “separation-ready,” independent of a site. Whatever elements of the methodology that are incorporated into a reactor technology (e.g., NF and/or AF design, NF boundary definition, NF design envelope, safety assessment, etc.) can then be applied to a project at a specific site (see Figure 5). This is discussed further in Section 3.

Process Steps

Step 1 - Design the Nuclear Facility and Adjacent Facilities

The first step of the methodology is to develop the design for the NF and AFs. It is important to consider the separation criteria early and iteratively during the design process so that the goals of separation are more likely to be met.

When performing the design, there are various design techniques that can be utilized to aid in the demonstration of separation. These techniques are summarized below.

The methods discussed below may add capital and O&M costs, which could reduce or eliminate the cost savings of separation. The designer should consider these tradeoffs when selecting these methods.

Isolation

Isolation is a technique that eliminates impact on the NF from an event originating from the AF. Isolation is commonly used for electrical decoupling in electrical and instrumentation and control (I&C) systems. Techniques include the use of isolation transformers, shunt circuits, or fiber optic converters. Isolation techniques for mechanical systems may be possible but are not commonly used.

Isolation can also be applied to prevent external hazards from impacting the NF. One example is using seismic isolation to decouple NF structural response from ground motion. Another technique is using physical barriers, such as a wall to prevent missile hazards from affecting the NF.

Transient Decoupling

Transient decoupling is a technique that reduces the speed of the impact of transients propagating from the AFs to the NF. Reducing the speed of the NF response may increase the ability of the design to demonstrate that applicable regulatory limits are met. One example of time lag equipment currently proposed in advanced reactor designs is a thermal storage tank between the NF and AFs that could reduce the speed of reactivity insertion events due to overcooling transients.

Radiological Material Isolation

To meet the separation criteria, the NF design must ultimately be able to maintain the release of radiological material within regulatory limits. Two approaches are commonly used to isolate radiological material: intermediate loops, and isolation systems.

An intermediate loop placed within the NF can create a buffer for material egress between a system containing radiological material and an interfacing AF system. Intermediate loops can reduce the risk of egress events by preventing a single failure of an interfacing component from introducing radiological material into an AF system.

Another approach is the use of radiation detection and isolation SSCs. This could preclude the use of an intermediate loop by providing the ability to isolate the NF from the AFs upon detection of the potential to exceed radiological limits.

Construction Considerations

If separation has been achieved as defined in this document, different methods of project execution could lead to reduced capital costs for new nuclear builds. one example is the construction of the NF and AFs by separate engineering, procurement, and construction (EPC) firms. This approach can use separate access points to reduce security measures during construction and designate separate material laydown areas to facilitate the separate management of NF materials from AF materials. The NF and AF designs should consider the construction strategy to fully obtain these potential benefits.

O&M Considerations

The plant design significantly impacts the subsequent ability to reduce O&M costs due to separation. Therefore, the concept for plant operations should be defined concurrently with the design. This includes automation philosophy, desired controls, and maintenance strategies. These topics influence design choices such as the I&C architecture. These design choices can significantly impact the demonstration of separation.

For example, utilizing an integrated I&C system across the NF and AFs may support the intended concept of operations, but may create additional challenges with demonstrating separation. In contrast, independent I&C systems with a minimum number of hard-wired signals would greatly reduce the burden of demonstrating separation.

In addition to operations, the designer should consider security in the design and its impact on separation. Factors affecting physical security include the facility layout, security barriers, access points, and physical security procedures to potentially reduce the overall footprint of the protected area. Cybersecurity factors influence design decisions on I&C architecture and remote system access.

Step 2 - Define the Nuclear Facility Boundary

An NF physical, functional, and programmatic boundary must be established to define the scope of the NF and to develop the NF design envelope. The NF design envelope serves as the basis of the safety assessment and ensures the separation criteria are met.

Determine Placement of the NF Boundary

The first step is to determine the placement of the NF boundary. The following items should be considered when placing the NF boundary.

Optimize SSCs Placed Within the NF Boundary

The first consideration is to try to optimize the scope of SSCs placed within the NF boundary. There are two competing objectives with this consideration:

- Reducing the scope of the NF, which minimizes the number of SSCs within the NF boundary.
- Fully meeting separation criteria, which may require inclusion of more SSCs within the NF boundary in order to meet regulatory limits.

This optimization is dependent on the specific reactor design and overall project objectives. For example, conventional pressurized water reactors may draw the boundary between the nuclear island and the turbine island. In contrast, a boiling water reactor design may utilize an NF boundary to include both the nuclear island and turbine island, due to radiation being normally present in the steam system and turbine generator.

In advanced reactor designs, the use of intermediate loops could enable greater flexibility in defining the NF boundary, as more or less equipment within the intermediate system could be included within the NF. In some cases, including more equipment could facilitate achieving the separation criteria and thereby demonstrating that regulatory requirements are met.

Figure 6 provides a simplified example of potential NF boundary locations with a design that uses an intermediate heat transfer loop and thermal storage tanks. The dashed red line to the left indicates one potential NF boundary location that excludes the thermal storage tanks from the NF. The dashed orange line to the right indicates another potential NF boundary location that includes the thermal storage tanks in the NF.

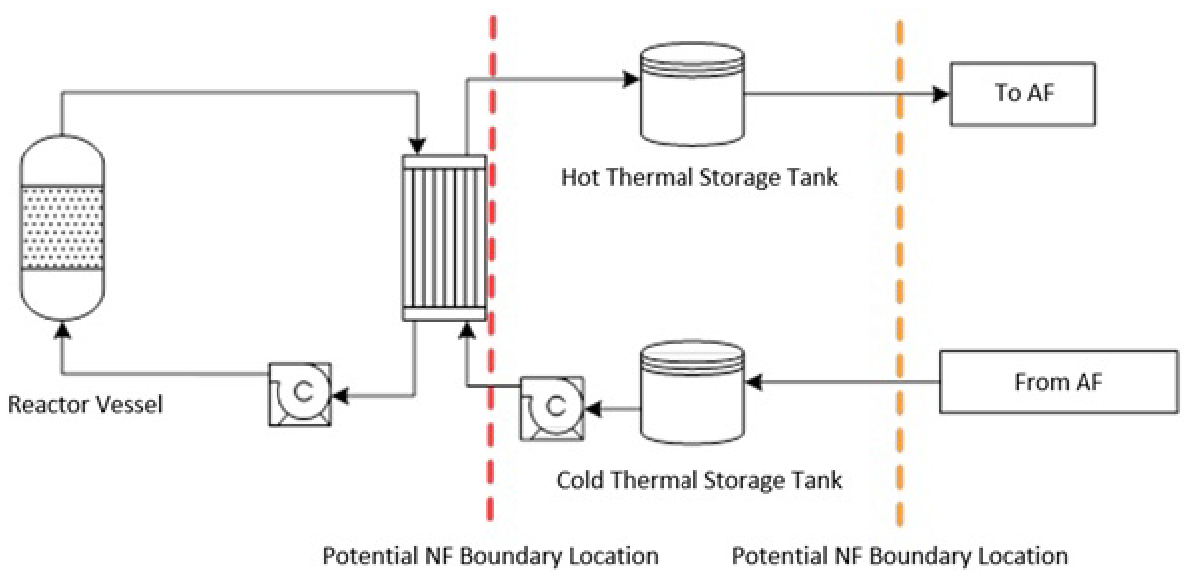

Figure 6. Potential NF boundary locations for designs using intermediate loops

Provide a Consistent and Logical Boundary

For simplicity and ease of understanding the NF boundary during design, construction, operations, and maintenance, establishing the NF boundary in a logical, consistent manner is recommended. For example, in Figure 6, including one thermal storage tank in the NF and excluding the other tank would not be logically consistent.

Multi-Unit NFs

For multi-unit NFs, the NF boundary may either be drawn around one unit or multiple units, depending on whether a single unit can achieve separation criteria on its own. This is significantly influenced by the nature and amount of system/component sharing between modules.

Figure 7 and Figure 8 show examples of potential scenarios involving multiple units. Figure 7 illustrates use of multiple units that share a common spent fuel pool. In this case, encompassing all the units and the spent fuel pool within the NF is simpler. Figure 8 shows individual standalone units—each with their own spent fuel pool. Use of the approach shown in Figure 8 requires inclusion of external hazards initiated from adjacent NFs within the NF design envelope.

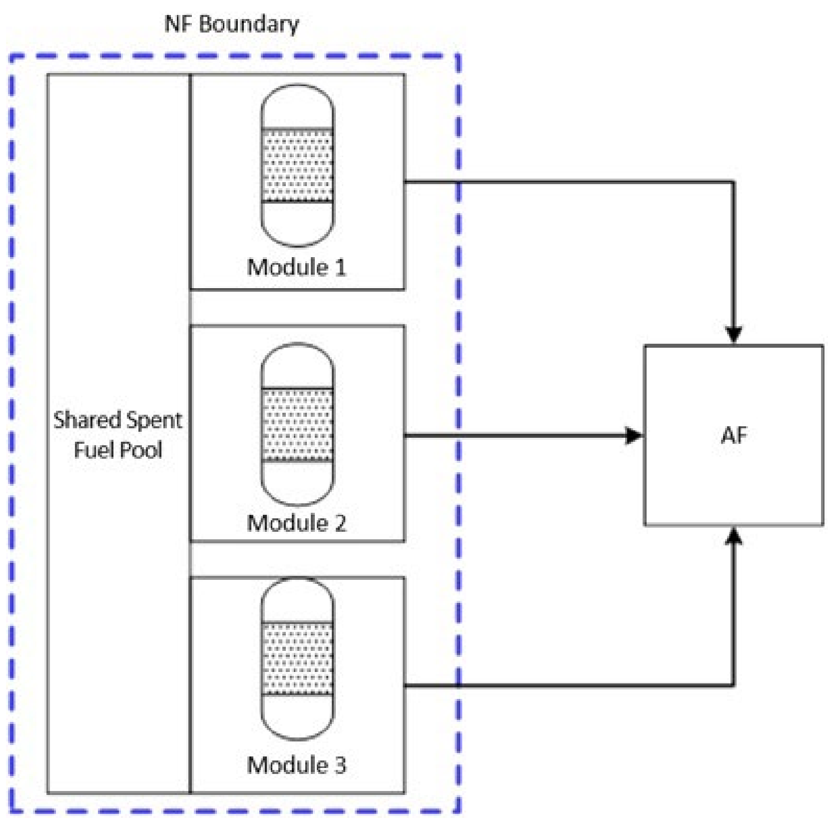

Figure 7. Example of multi-module deployments with a single NF boundary

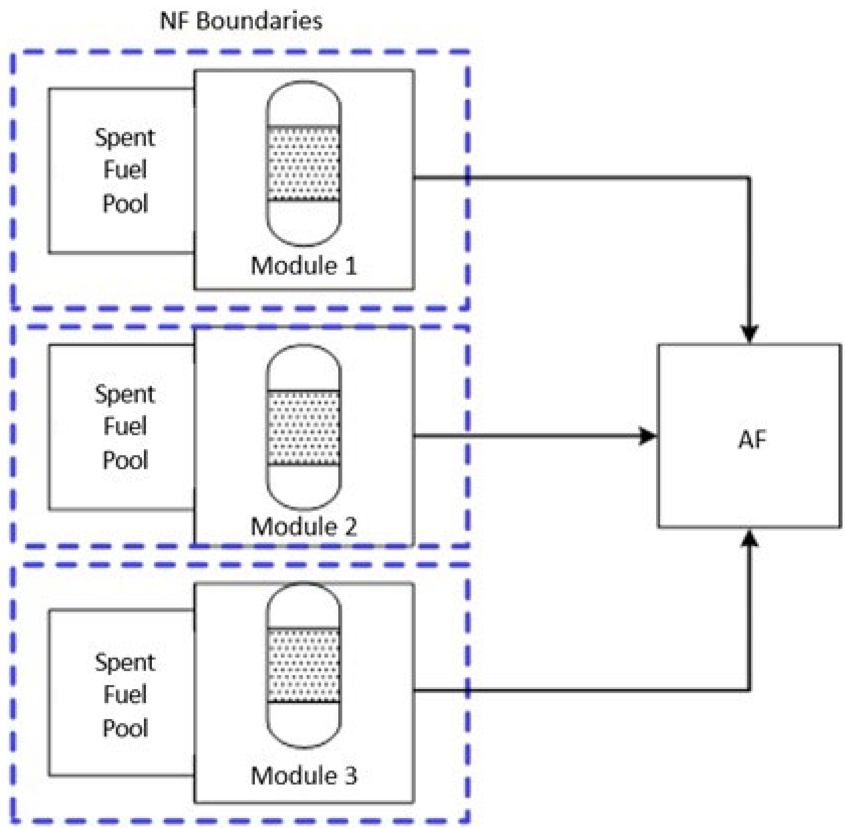

Figure 8. Example of multi-module deployments with multiple NF boundaries

Security

Aligning the NF boundary with security boundaries (e.g., protected area) may enable improved separation during construction and operations. However, while the primary objective in defining the NF boundary is to achieve the separation criteria, considerations for security as addressed in Step 1 can be considered.

Documenting the NF Boundary

To document the NF boundary, all physical boundaries should be identified in physical plan drawings, and all system boundaries should be identified in all design drawings, especially for interfacing systems. Examples of how the boundaries are identified varies by design phase and typical engineering deliverable, as summarized below:

- Conceptual design
  - System boundaries
    - Process flow diagrams
  - Physical boundaries
    - Site plan drawings

- Preliminary design
  - System boundaries
    - Piping and instrumentation diagrams (P&IDs)
    - Single line drawings
    - Control system architecture drawings
  - Physical boundaries
    - General arrangement drawings
- Detailed design
  - System boundaries
    - Isometrics/piping plans
    - Wiring diagrams

Step 3 - Define the Nuclear Facility Design Envelope

The NF design envelope contains bounding parameters for conditions at system interface points along the NF boundary and bounding parameters for external hazards. These parameters provide inputs to the NF safety assessment, which must demonstrate that regulatory limits are met under all such conditions. Guidance for documenting NF design envelope parameters for interfacing systems and external hazards is discussed below.

Interfacing Systems

All interfacing systems crossing the NF boundary shall be identified. For each interfacing system, sufficient information shall be provided so that the safety assessment can be performed using only design information regarding the NF and the parameters in the NF design envelope. This information should include the following:

- Mechanical systems
  - Design parameters (e.g., pressure, flow, temperature)
  - Failure modes (e.g., loss of flow, overpressure)
  - If necessary, characterization of the frequency of the failure modes
- Electrical Systems
  - Design parameters (e.g., voltage, current, frequency)
  - Failure modes (e.g., loss of power)
  - If necessary, characterization of the frequency of the failure modes

- I&C Systems
  - Interfacing signals (e.g., turbine trip, thermal storage tank level)
  - Failure modes (e.g., loss of signal)
  - If necessary, characterization of the frequency of the failure modes

Characterization of the frequency of a particular failure mode may be required based on the regulatory framework utilized and the impact of the failure mode on the safety of the NF. This report does not specify methods of characterizing the failure mode frequency. However, the methods used may include a specific limit (e.g., less than 0.01 events per reactor critical year) or a predefined range (e.g., anticipated operational occurrence). Regardless of the approach used, the methods used should not require detailed information for systems outside the NF boundary.

Examples of envelope parameters for each type of interface are provided below. The specific parameters needed for each interface vary depending on the design and safety assessment methodology. The values below are not inclusive of all potential failure modes and are provided for demonstration purposes only. They represent an assumed NF interfacing with a traditional steam cycle AF for which the boundary is drawn at the exit/entry points to the steam generator.

- Mechanical: feedwater system
  - Design parameters
    - Maximum flow: 1 million lb/hr (450,000 kg/hr)
    - Minimum flow: 0 lb/hr (0 kg/hr)
    - Maximum pressure: 600 psig (4100 kPa)
    - Minimum pressure: 0 psig (0 kPa)
    - Maximum temperature: 500°F (260°C)
    - Minimum temperature: 32°F (0°C)
  - Failure modes
    - Loss of feedwater
  - Failure mode frequency
    - Loss of feedwater: anticipated operational occurrence
- Electrical: 480 volts AC distribution system
  - Design parameters
    - Power: 1000 MVA
    - Voltage: 480 VAC

    - Frequency: 60 Hz
  - Failure modes
    - Loss of power
  - Failure mode frequency
    - Loss of power: 0.03 events per reactor critical year
- I&C: plant control system
  - Design parameters
    - Signal: salt tank level
  - Failure modes
    - Loss of signal
  - Failure mode frequency
    - Loss of signal: 0.001 events per reactor critical year

External Hazards

The NF design envelope shall also define external hazard events that can impact the NF. The list of external hazards shall include the following:

- Events that originate outside both the NF and AFs. These events are essentially the list of traditional external hazards for nuclear power plants. Examples would include seismic events, tornadoes, and seiches.
- Events that propagate from inside the AF(s) that are induced by events external to the NF and AF(s). An example is a seismic event that causes an AF structure to fail with consequences that cross the NF boundary.
- Events that originate inside the AF(s). These could include turbine blade missile hazards or hydrogen explosions.

Each external hazard event shall identify bounding limits for hazard magnitude, and if necessary, event initiating frequency. The specific parameters needed for each external hazard event vary depending on the AF and NF designs, site details, safety analyses, and regulatory requirements. An example of envelope parameters for an external hazard is provided below. Values below are for demonstration purposes only.

- External event: explosive hazard
  - Peak overpressure: 1.0 psi (7 kPa) at the NF boundary

Step 4 - Perform Safety Assessment

The purpose of the safety assessment is to demonstrate that applicable regulatory limits are met given the NF design and the bounding parameters in the NF design envelope. The following steps should be performed:

- Select the regulatory framework to be used. This includes the following:
  - Determine the country in which the facility will be licensed.
  - If multiple frameworks are available within a given country, select the framework to be used.[3]
- Determine the applicable regulatory limits.
- Determine the required analyses to be performed. This may include a deterministic safety analysis, a probabilistic safety analysis, or both.
- Determine the initiating events and hazards to be analyzed. This may be defined by the regulatory framework or determined via a hazards analysis. The following shall be considered.
  - Initiating events
    - NF internal system failures (e.g., loss of coolant accident)
    - NF boundary interfacing system failure (e.g., loss of feedwater)
  - Hazards
    - Internal hazards (e.g., internal flooding)
    - External hazards from outside the AF(s) (e.g., seismic)
    - External hazards from the AF(s) (e.g., explosive hazard)
- Perform the analyses in accordance with the regulatory framework and governing industry practices.

Step 5 - Verify Separation Criteria Are Met

In this step, the separation criteria are evaluated. If the separation criteria are met, then the process is complete. If not, then the design is evaluated to determine if it is acceptable in step 6.

[3] For example, in the United States, an applicant can utilize a more traditional deterministic approach or a more risk informed approach utilizing Nuclear Energy Institute (NEI) 18-04.

Criterion 1

For normal conditions, the amount of radiation and radiological material crossing the NF boundary shall be maintained within regulatory limits.

To meet this criterion, the NF design must ensure that any potential exposure to radiation or radiological material during normal conditions is controlled within acceptable limits at the NF boundary. This eliminates the need for AF SSCs to meet nuclear quality requirements for control of radiation and radionuclides, and eliminates the need for the regulator to review those SSCs.

Criterion 2

For abnormal and accident conditions, the safety assessment shall demonstrate that all applicable regulatory limits are met with the following constraints:

- The safety assessment is based on the parameters defined in the NF design envelope.
- Only NF SSCs and NF operator actions can be credited in the safety assessment.

Meeting this criterion eliminates the need for nuclear quality requirements to be applied for SSCs outside the NF, and minimizes the need for regulatory oversight of the AFs. Specifically, oversight can be limited to inspection that the verification of the NF design envelope has been performed.

Step 6 - Verify Design Is Acceptable

If the separation criteria defined in step 5 are not met, then the following evaluation shall be performed:

The design is considered acceptable when the following are criteria are met, even if separation criteria are not fully met:

- Are all regulatory limits met?
- Does the design meet overall project goals, including capital cost, O&M cost, project risk, and use of the facility?

If both criteria are met, then the design can be considered complete. The specific areas of non-compliance to the separation criteria shall be noted and addressed in the license application.

If the design is not acceptable, then return to step 1 to modify the NF design, AF design, or NF design envelope as appropriate.

Use of Pre-Existing Design Information

The methodology outlined in Figure 5 recognizes the potential use of pre-existing design information. The decision to utilize pre-existing design information results from the desire to utilize one or more of the following in the project:

- One or more existing NFs
- One or more existing AFs
- A pre-approved reactor design

Considerations of these options are discussed below.

Existing NFs

In this case, an existing NF is intended to be integrated with a new AF or an existing AF that will be modified. An example of this case is the repurposing of an existing nuclear plant to add hydrogen production.

The following steps should be followed for this case:

- Develop a solid baseline of the existing NF design, NF design envelope, and safety assessment.[4]
- Determine if the project objectives can be met with the existing NF design, NF design envelope, and safety assessment.
- If project objectives can be met, then no further evaluation is required. The AF design can proceed with the existing NF design envelope providing bounding parameters for the AF.
- If project objectives cannot be met with the existing NF design or NF design envelope, there are two options:
  - Modify NF design envelope. This option maintains the existing NF design and simply modifies the NF design envelope.
  - Modify NF design and NF design envelope. This option requires modification to the NF, which increases project cost and complexity.

[4] An existing facility may have a design and safety evaluation, but not an NF design envelope. Changing the licensing basis of the existing facility to be based on separation is beyond the scope of this report.

Existing AF

In this case, an existing AF is intended to be integrated with a new NF or an existing NF that will be modified. One example is adding a nuclear-powered steam source for an existing chemical plant.

The following steps should be followed for this case:

- Develop a solid baseline of the existing AF design.
- Develop a list of potential reactor technology options to be considered for the NF.
- Determine if the project objectives can be met with the existing AF design and potential reactor technologies.
- If project objectives can be met, then no further evaluation is required. The NF design and NF design envelope can be developed based on the existing AF.
- If project objectives cannot be met, then modify the AF design as necessary to achieve the desired amount of separation with the intended reactor technologies.

Pre-Approved Reactor Design

In many countries, there are mechanisms to develop pre-approved reactor designs to simplify site-specific licensing activities. This could accelerate development of the site-specific design by leveraging prior design and licensing work. Examples utilizing pre-approved reactor designs include a Standard Design Approval (SDA) or a Design Certification (DC) in the United States, Pre-Licensing Vendor Design Review (VDR) in Canada, and the Generic Design Assessment (GDA) in the UK.

The scope of the pre-approved reactor design may vary to include, for example, only the nuclear steam supply system (NSSS), the NF, or both the NF and AFs.

The designer needs to understand early in the project the scope and licensing history for a pre-approved reactor design and whether the reactor was designed for separation in accordance with this methodology, or whether the design can accommodate the principles of this methodology. In particular, the existence of information related to the NF design envelope should be identified. Prior design information should be utilized as appropriate to meet overall project objectives.

3 DEVELOPMENT OF REACTOR DESIGNS WITH SEPARATION FOR PRE-APPROVAL

In many countries, regulatory processes allow a standard reactor design to be developed and pre-approved prior to the application of that reactor to a particular site. This process may provide several advantages, including reduced regulatory review burden, reduced project schedule, and reduced project costs.

It is recommended that reactor designers utilize the principles of this methodology when developing standardized designs for pre-approval. This reduces the burden of integrating the pre-approved reactor design into the demonstration of separation for a given site. Table 2 provides guidance on adjustments to utilize this methodology for the development of a standard design for pre-approval.

Table 2. Methodology adjustments for development of reactor designs for pre-approval

Separation Step	Separation Step Description	Adjustments
1	Design the NF and AFs	Design only the scope desired (e.g., portion(s) of the NF, complete NF, NF and AF).
2	Define the NF boundary	Define per the desired scope.
3	Define the NF design envelope	Make assumptions for the NF design envelope parameters outside the NF that are not known based on intended market/sites. These create bounding parameters for the site. Clearly delineate which external hazards have and have not been considered.
4	Perform safety assessment	Perform the assessment against the scope of the NF design and NF design envelope defined
5	Verify separation criteria are met	Verify to the extent possible given the scope of the NF design
6	Verify design is acceptable	Verify to the extent possible given the scope of the NF design

4 MAINTAINING SEPARATION

Once separation has been established during design and verified during construction, separation needs to be maintained over the long term during O&M of the facility.

The NF design and NF design envelope shall be controlled using design features such as protective trips, and administrative controls such as configuration management programs for both design and licensing documentation.

The AF shall be periodically verified to be within the bounding parameters defined in the NF design envelope. The frequency of the verification should be based on the potential for changes within the AF.

5 CONCLUSION

Summary

An approach that considers separation of facilities within a structured approach to the design and licensing of a nuclear facility is proposed here with the intent of addressing quality requirements in adjacent facilities and establishing an efficient footprint for regulatory oversight of adjacent facilities. Separation has the potential to significantly improve the economics of nuclear energy and enable the expansion and diverse application of nuclear energy while ensuring compliance to nuclear regulatory limits.

This report provides a generic methodology to achieve separation in design. To achieve the desired degree of separation and realize its potential economic benefits, the desired outcomes and criteria for separation discussed in this report should be considered from the earliest stages of design.

This report also provides guidance on how to apply the methodology during the development of reactor designs for pre-approval. In addition, this report provides guidance on maintaining separation during O&M.

Recommendations for Future Work

The guidance in this report is intended to be technology- and regulator-neutral. Regulator engagement on this topic is essential to establish specific details of employing separation in the design and license application process.

It is recommended that this methodology be tailored for a specific regulatory framework to optimize its usefulness. The tailored methodology should be presented to the regulator and then follow the country-specific regulatory pathway for review and approval.

Additionally, this document focuses primarily on providing a methodology for separation in design to enable reductions in capital and O&M costs via the application of appropriate quality requirements. However, specific strategies will need to be developed to achieve the potential cost savings during construction and operations. It is recommended that additional studies be performed to develop these strategies.

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