

# Multi-Module Risk Assessments: Overview of EPRI’s Multi-Unit Framework and Multi-Module Plant Designs

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**Abstract:** This paper reviews EPRI’s multi-unit risk assessment framework [1] in the context of emerging multi-module nuclear plant designs. It evaluates current regulatory definitions and various design considerations that influence the modeling of risk for tightly coupled modules. Findings indicate that while existing frameworks remain broadly applicable, unique design elements and configurations, such as shared structures, shared systems, and remote control rooms, require further research to ensure robust safety evaluations.

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## 1. INTRODUCTION

As nuclear technologies evolve towards small modular reactors (SMRs), the term “multi-module” has gained prominence. Although the term “modular” is often used to describe the construction philosophy of such designs, the risk assessments for these designs must consider whether a plant with multiple modules is fundamentally different from current “multi-unit” or “multi-reactor” plants, such that the risk assessment characteristics and/or considerations are also fundamentally different.

In the United States, the Nuclear Regulatory Commission (NRC) offers some guidance on multi-module risk. The “Multi-Module Risk: NRC Draft Technical Guidance” [2] provides the following:

*“A nuclear power module is a nuclear power reactor and its associated safety and control features. A multi-module nuclear power station, or nuclear power plant, is one that is composed of multiple nuclear power modules wherein: a) each module can be safely operated independent of other modules, and b) all modules are located within a common building structure such that a module can be physically impacted by events occurring at another module due to proximity and lack of a physical barrier providing separation.”*

The definition provided by the NRC seems to center on the “tight coupling” of modules within a common structure. Many commercial nuclear power plants are also located at multi-unit sites; these sites have various degrees of coupling between each unit/reactor. Some have common structures and systems, while others have structures that are directly connected but not shared. Other multi-unit configurations are simply multiple single-unit plants located within proximity to one another; these are considered examples of loose coupling. Understanding the nature of the coupling between multiple units/reactors is of critical importance when performing a multi-unit risk assessment.

EPRI’s “Framework for Assessing Multi-Unit Risk to Support Risk-Informed Decision-Making: General Framework and Application-Specific Refinements” [1] (referred to as the EPRI framework), along with the International Atomic Energy Agency’s (IAEA) Safety Report No. 96, “Technical Approach to Probabilistic Safety Assessment for Multiple Reactor Units,” [3] and Safety Report No. 110, “Multi-Unit Probabilistic Safety Assessment” [4], serve as a technical foundation for the performance of multi-unit (multi-reactor) risk assessments.

When discussing the assessment of multi-unit risk, it is essential to recall its definition: **the risk that hazards impact multiple co-located reactors, resulting in multiple accident sequences (that is, accidents involving two or more reactors within the same timeframe)**. Multi-unit risk represents a distinct risk metric (beyond the single-unit risk metrics already addressed in current PRAs or PSAs) that aims to yield different risk insights than current single-unit assessments. While single-unit assessments may consider the impact of one unit on another, the common assumption is to consider one accident sequence at a time (single-unit core damage, single-unit release).

## 2. LITERATURE REVIEW

As a starting point, the following literature review identifies pertinent references relating to the term “module.”

### 2.1 United States Code of Federal Regulations

The United States Code of Federal Regulations (CFR), Title 10, “Energy”, is comprised of four volumes. The first and second volumes (Parts 1–199) are found in Chapter I, “Nuclear Regulatory Commission.” In 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants” [5], the term “modular design” is defined as:

*“...a nuclear power station that consists of two or more essentially identical nuclear reactors (modules) and each module is a separate nuclear reactor capable of being operated independent of the state of completion or operating condition of any other module co-located on the same site, even though the nuclear power station may have some shared or common systems.”*

Appendix G to 10 CFR Part 52, “Design Certification Rule for NuScale” [6] discusses a “nuclear power unit” as:

*“...applied to this certified design, means a nuclear power module and associated equipment necessary for electric power generation and includes those structures, systems, and components required to provide reasonable assurance the facility can be operated without undue risk to the health and safety of the public.”*

Appendix G also provides a table on the “Minimum Requirements per Shift for On-site Staffing of NuScale Power Plants by Operators and Senior Operators Licensed Under 10 CFR Part 55.” In general, staffing requirements are defined by the number of operating units, which is considered synonymous with the number of operating modules.

10 CFR Part 170, “Fees for Facilities, Materials, Import and Export Licenses, and Other Regulatory Services under the Atomic Energy Act of 1954, as Amended,” [7] provides the following information per Section 170.3:

*“Small modular reactor (SMR) for the purposes of calculating fees, means the class of power reactors having a licensed thermal power rating less than or equal to 1,000 MWt per module. This rating is based on the thermal power equivalent of an SMR with an electrical power generating capacity of 300 MWe or less per module. Small modular reactor site (SMR site) is the geographically bounded location of one or more SMRs and a basis on which SMR fees are calculated.”*

Based on this review within the United States, the term “modular” appears to be applied broadly to any design featuring multiple modules/units/reactors, where each module can be operated independently of the others. This would apply to any operating site with the same design units, with each unit designed to operate independently. The only reference to “SMR” is in Part 170, defining the fee structure.

## **2.2 NRC Draft Technical Guidance**

The NRC’s draft technical guidance [2] provides a discussion of multi-module risk. For example, the terms “multi-module,” “multi-unit,” and “station” are discussed. This draft guidance document was written for the purpose of proposing criteria for Chapter 19 of the NRC’s standard review plan (SRP) [8], which states:

*“Design-Specific PRA (Procedures Specific to Integral Pressurized Water Reactors)*

- 1. For small, modular integral pressurized water reactor designs, the staff reviews the results and description of the applicant’s risk assessment for a single reactor module; and, if the applicant is seeking approval of an application for a plant containing multiple modules, the staff reviews the applicant’s assessment of risk from accidents that could affect multiple modules to ensure appropriate treatment of important insights related to multi-module design and operation.”*

Based on this guidance, the NRC will verify that an applicant has performed the following review:

- “i. Used a systematic process to identify accident sequences, including significant human errors, that lead to multiple module core damages or large releases and described them in the application.*
- ii. Selected alternative features, operational strategies, and design options to prevent these sequences from occurring and demonstrated that these accident sequences are not significant contributors to risk. These operational strategies should also provide reasonable assurance that there is sufficient ability to mitigate multiple core damage accidents.”*

The guidance also provides the following definition of a multi-module nuclear power station:

*“One that is composed of multiple nuclear power modules wherein: a) each module can be safely operated independent of other modules, and b) all modules are located within a common building structure such that a module can be physically impacted by events occurring at another module due to proximity and lack of a physical barrier providing separation.”*

It is interesting to note that this definition could apply to “large” or “small” reactors, with size (for example, small and larger) describing the reactor’s power output. For example, the Canada Deuterium Uranium (CANDU) design features four units/reactors that could meet this definition of a multi-module system. However, distinctions noted between multi-unit risk and multi-module risk seem to focus on “small” reactors within a common building or structure. Such distinctions include:

- Multi-unit plants have unit-specific licensed operators (that is, a team of operators for each reactor). Some multi-module designs have considered using one (or a few) operators to control multiple modules (that is, one team of operators for multiple reactors).
- Typically, multi-unit plants are designed to reduce the potential for one unit to impact other units. The sharing of systems or structures in a multi-module design could result in an accident in one module impacting other modules.

The guidance also notes the difference between “station” and “site,” specifically noting that 10 CFR uses the term “station” to describe multiple units at one location. In contrast, “site” is used to describe the “actual physical, environmental, and demographic features” of a location. 10 CFR Part 52, Section 1 [5] provides the following definition of site characteristics:

*“Site characteristics are the actual physical, environmental, and demographic features of a site. Site characteristics are specified in an early site permit or in a final safety analysis report for a combined license.”*

While the distinction between a station and a site is interesting, it does not seem to impact the development of a multi-module risk assessment.

### **2.3 IAEA Small Modular Reactors Regulators’ Forum**

The IAEA Small Modular Reactors Regulators’ Forum addressed the difference between multi-unit and multi-module in several reports [9, 10, 11]. The SMR Forum focuses on the design differences between multi-unit and multi-module plant designs, and not specifically on the elements of a risk assessment. The items identified by this forum address issues and challenges related to the development of overall site-level risk assessments and performance metrics, as well as the absence of acceptance criteria or accepted guidance for multi-unit risk metrics. An Appendix dedicated specifically to risk assessments addresses some of the challenges with multi-unit risk (with no differentiation between unit and module). These challenges are consistent with those previously identified in the EPRI framework [1].

The IAEA’s “Small Modular Reactors Regulators’ Forum Working Group on Design and Safety Analysis, Phase 2 Report” [10] provides a common position on terminology and definitions related to modular designs, and notes that this term is not well defined. In general, this term is used to denote both modular

design approaches and/or modular construction approaches. The IAEA's description of modular reactors suggests that such designs focus on locating multiple reactors in close proximity to each other and allow for the addition of reactors over time. This definition speaks to the ability to scale up or add independently operated identical nuclear reactors over time at the same site, within close proximity to each other, and potentially utilizing shared structures, systems, and components (SSCs).

The IAEA's "Small Modular Reactors Regulators' Forum, Pilot Project Report: Considering the Application of a Graded Approach, Defense-in-Depth and Emergency Planning Zone Size for Small Modular Reactors, SMRRF" [11] identifies differences between multi-unit and multi-module, specifically considering that current regulations typically address multiple units, not multiple modules. Based on the limited design information available for new reactors, the IAEA working group cannot confirm that a multi-unit design is equivalent to a multi-module design.

These IAEA reports note that modular designs may introduce novel safety considerations, including common cause failures (CCF), hazard analysis, and human reliability, among others. Although the reports state that existing multi-unit requirements are appropriate (in general), it notes that future modular designs may require additional considerations.

## **2.4 VTT Technical Research**

The Valtion Teknillinen Tutkimuslaitos (VTT) Technical Research Centre in Finland has also investigated the differences between multi-unit and multi-module risk assessments [12]. The 2021 VTT research report is based on a review of documents from the IAEA, the University of Maryland, and the Idaho National Laboratory. This research does not identify any fatal flaws or limitations to the expansion of PRA or PSA tools and techniques for modeling multi-module scenarios. This research concludes that there are elements of multi-module risk assessments that differ from those of multi-unit assessments. Possible differences could include risk metrics, plant operating state(s) (POS), initiating events, and dependent failures (human and common cause). This research also notes that passive system operation and reliability are likely to differ from current operating experience and will require additional considerations. Modeling challenges include increased complexity associated with multiple modules, potential for larger CCF groups, increased POS combinations, and more complex fault tree and event tree logic.

While these items are understood and factual, such issues do not differentiate between a module and a unit. That is, complexity arises from evaluating multiple elements and tighter coupling, but a clear distinction between units or modules is not necessarily evident. This arises from the number of elements to consider when evaluating the risk of multiple reactors and multiple concurrent accident sequences.

## **2.5 Technical Requirements for Licensing Advanced Non-Light Water Reactors**

Although not specific to multi-module risk, the Nuclear Energy Institute (NEI) has developed technical report 18-04, "Modernization of Technical Requirements for Licensing of Advanced Non-Light Water Reactors – Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development" [13]. NEI 18-04, Table 3-1 interprets multi-module as follows:

*"[a] nuclear power plant, which may include one or more reactor modules."*

The NEI report discusses risk frequencies in a “per plant-year” context, indicating the application of single-unit metric for multi-module sites.

For the PRA/PSA elements, NEI 18-04 leverages the ASME/ANS PRA Standard for Non-Light Water Reactors [14], which explicitly addresses multi-unit considerations with reference to multi-reactor plants, without differentiation between units and modules.

### **3. RISK ASSESSMENT CONSIDERATIONS**

Research performed by EPRI and documented in a 2025 white paper titled “Multi-Module Risk Assessments: A Review of EPRI’s Multi-Unit Risk Assessment Framework and Multi-Modular Nuclear Plant Designs” [15] performed a review of proposed advanced nuclear technologies and provides the following observations:

- Many multi-module designs utilize individual modules that are arranged as fully separated units, such that a reactor module could be considered equal to a reactor unit.
- In several instances, the multi-module design appears to be similar to current “dual-unit” sites. That is, similar to sites with two independent (or mostly independent) reactor units.
- Some multi-module designs utilize an integrated reactor building that can house two or more reactor units. In general, the sharing of buildings and structures could allow for adverse conditions from one reactor to impact other reactors. This could result in multi-module impacts that are different from those within the scope of current multi-unit frameworks.
- In several instances, multiple reactors are expected to be operated from a shared control room. Some advanced designs propose using remote control technologies, enabling continuous monitoring and shutdown capabilities from a centralized or regional control center. This approach could potentially reduce the size of the on-site workforce. While shared control rooms are already common practice, remote operation introduces new considerations that differ from those associated with traditional multi-unit configurations.
- Several multi-module designs are being considered for hydrogen production or used to support non-electrical production. Except for the hydrogen hazard (or other case-specific hazards), multi-module considerations do not appear to be unique or different from current multi-unit risk assessments.
- In general, the term module is used to describe scalability, which is consistent with the IAEA’s definition for modular reactors [12], and their ability to scale up or add reactors over time.

In general, these findings agree with the current EPRI framework [1] and other multi-unit risk assessment frameworks. For unique or novel design considerations (for example, the use of a remote control room), additional research and guidance are required.

In addition to the EPRI white paper discussed above, EPRI's 2025 report titled "Advanced Nuclear Technology: Application of EPRI Framework for Multi-Reactor Risk Analysis to Advanced Reactors" [16] examines the applicability of the EPRI multi-unit framework to "multi-reactor" (considered to be synonymous with multi-unit and multi-module) risk assessments for advanced reactors and sites with mixed reactor technologies. This research again shows that the major steps outlined in EPRI's multi-unit framework are generally applicable to a variety of multi-reactor configurations. The EPRI report also identifies potential expansions of the framework to address unique issues such as those already identified in this paper.

Although the focus of this research was on the assessment of multi-unit risk, insights from this research, and the insights gained from the performance of such risk assessments, could be used to inform the design, procedures, training, and plant operations when managing multi-module risk.

The following sections review the EPRI framework in the context of multi-module designs.

### **3.1 Ground Rules and Assumptions**

One fundamental premise of EPRI's framework is that a technically adequate single-unit PRA/PSA is often available as a starting point for developing a multi-unit risk assessment. It is recognized that for a multi-module design with inherent coupling between units, this assumption may not be realistic, and a specific multi-module risk assessment may need to be developed that does not rely on a single-unit model. This consideration is not new. In fact, this is one lesson learned from the experience of CANDU plants operating within Canada [17].

### **3.2 Initial Site Assessment**

EPRI's framework discusses the coupling between units at a site. In this context, multi-module designs exhibit the attributes of coupling with the following additional considerations:

- Some designs utilize a single-unit concept that can be expanded "modularly" without a significant degree of coupling between the modules. This configuration is consistent with loose coupling between units.
- Some designs envision independent units/modules hosted in a common structure or building, but still with a one-to-one ratio between the reactor and the power conversion unit (PCU) and a one-to-one ratio between the reactor and engineered safety systems. This configuration is consistent with tight coupling between units, similar to some CANDU designs [17] that also share structures (containment, turbine building) across multiple units.
- Some designs envision configurations with a shared PCU for multiple reactors. This configuration is different from those envisioned in the EPRI framework.
- Some designs locate multiple reactors in a single reactor building or pool. This configuration is different from those envisioned in the EPRI framework. Still, it may be similar to some CANDU designs [17], where multiple reactors share a vacuum building and containment envelope.

### 3.3 External Hazards Assessment

The EPRI framework emphasizes the modeling of external hazards as directed by the ASME/ANS PRA Standard [18]. For advanced reactor designs with applications beyond power generation (for example, hydrogen production), the EPRI framework remains applicable; however, more emphasis is warranted on assessing hazards associated with any cogeneration production facilities. This is not necessarily a multi-unit/module specific issue, but it is noted for awareness and completeness.

### 3.4 Multi-Unit Risk Structure and Screening

EPRI's framework discusses the combination of sources in a multi-unit risk assessment in the context of POS combinations. While the overall context remains applicable to advanced reactor designs, additional (new) POS may be appropriate depending on the operation strategy envisioned by the specific design. Several advanced reactor designs – specifically, microreactors – envision a configuration in which an entire reactor module is installed and operated, then swapped out at the end of its life for a new module. The “spent” module(s) will remain at the site for a period of time to cool down.

### 3.5 Multi-Unit Human Reliability Analysis

EPRI's framework discusses the challenges of realistically modeling HRA dependencies across units in a shared control room. This includes the challenges of modeling command-and-control dependencies. Several multi-module designs suggest transitioning to a common control room. Remote control room configurations are also being considered, which indicates that more than one site could be controlled from a single location/control room. While this is obviously a scenario with no precedent or regulatory approval, the use of a remote control room suggests additional considerations are needed to appropriately model the human reliability dependencies between units/modules, including:

- The applicability of current methodologies for assessing performance shaping factors like stress and clarity of indications when/if the same workstation may be used to control multiple units/modules/sites.
- The treatment of communications and the interface between remote and local operators.
- The command-and-control evolution and timing following an accident scenario.

## 4. CONCLUSION

When performing a multi-unit/module/reactor risk assessment (that is, evaluating the risk that hazards impact multiple co-located reactors, resulting in multiple accidents within the same timeframe), the definition and potential differences between a unit and a module are important considerations. Based on the review presented in this paper, to date, no major gaps in risk assessment frameworks, technology, or guidance have been identified regarding the distinction between multi-unit and multi-module approaches. Current information related to the definition of small multi-module designs suggests that:

- A **small** reactor has a thermal power rating far less than that of current operating commercial reactors. It stands to reason that the risk to public health and safety from such a reactor will also be less than that of current operating commercial reactors. For that reason, a multi-module risk

assessment may identify new and valuable risk insights associated with longer mission times, for which repair and replacement may be credited, and for which additional risk assessment techniques (for example, a spent fuel pool risk assessment) may become more common.

- A **module** is comprised of a reactor and its associated safety and control features. This may include independent electrical generation and/or cogeneration capabilities (depending on the application). Each reactor module is independent, and additional modules can be added over time. As a result, this definition is not fundamentally different from the current definition of a reactor unit, but the different applications (for example, heat generation versus electricity production) may require greater focus on specific external hazards.
- A **multi-module** configuration is comprised of multiple identical, independent, co-located reactor modules, likely within a common structure, such that the same hazard can impact multiple modules, and/or be affected by events occurring at another module due to proximity and lack of physical separation. It is this sharing of structures and lack of physical separation that introduces additional coupling mechanisms between reactor modules (for example, different or unique POS).

While current multi-unit designs have varying degrees of coupling between reactors, a multi-modular design may exhibit greater coupling due to the lack of physical separation and the general proximity of the reactors. When evaluating the risk associated with such tightly coupled reactors, evaluating commonalities and dependencies becomes especially important. This includes additional considerations for inter-unit CCF, external hazards that have common impacts across a site, and human action dependencies. Equally important is the consideration of new and novel design approaches, such as remote control rooms, passive safety systems, and reduced dependency on human actions during an accident sequence.

Currently, the frameworks, technologies, and guidance available for developing multi-unit risk assessments are considered well-suited for assessing multi-modular configurations.

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