Risk-Informed SSC Categorization for an Innovative SMR under NEI 00-04 (10 CFR 50.69)

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ABSTRACT

Innovative small modular reactors (i-SMRs) may incorporate extensive passive safety features, modular plant layouts, shared systems, and interdependent module configurations. When defense-in-depth is maintained while quality assurance and management levels are expected to be commensurate with safety significance, a deterministic safety classification scheme alone may not adequately represent the actual safety contribution of structures, systems, and components (SSCs). This study proposes a risk-informed SSC categorization methodology for an innovative SMR under development, based on NEI 00-04, the implementation guideline for 10 CFR 50.69.

The proposed methodology consists of eight steps: (1) collection of input information and review of PRA technical adequacy, (2) engineering evaluation, (3) risk significance evaluation, (4) defense-in-depth (DiD) evaluation, (5) preliminary functional categorization, (6) sensitivity analyses, (7) integrated decision panel (IDP) review, and (8) final categorization and documentation. Final categorization is determined through the integrated consideration of risk significance, defense-in-depth, sensitivity analyses, and engineering judgment by the IDP.

Keywords: *Innovative SMR; NEI 00-04; 10 CFR 50.69; RISC-1–4; Risk-informed; SSC categorization; IDP; PRA*

1 INTRODUCTION

Small modular reactors (SMRs) have attracted attention as a next-generation nuclear energy concept because of their compact size, modular construction, and deployment flexibility. In particular, innovative SMRs are intended to achieve both safety and constructability through the extensive use of passive safety features, system simplification, and modular design. However, these design characteristics may make it difficult for a conventional deterministic safety classification scheme, originally developed for large light-water reactors, to adequately represent the actual risk contribution of SSCs and the proportionality of management requirements.

Traditionally, safety classification in nuclear power plants has been established primarily on the basis of prevention and mitigation functions for design basis accidents (DBAs). Accordingly, requirements for quality assurance, inspection, testing, environmental qualification, and seismic design have been determined. While this approach is effective in ensuring consistency and conservatism in design, it may impose the same level of special treatment on a broad range of equipment regardless of its actual risk contribution. Therefore, a risk-informed approach is needed so that limited design and operational resources can be focused on SSCs of greater safety significance.

The most systematic regulatory and technical basis for such an approach is the integrated framework consisting of 10 CFR 50.69, Regulatory Guides 1.174, 1.200, and 1.201, together with NEI 00-04 [1-5]. This framework maintains the fundamental deterministic design basis while introducing PRA and engineering judgment to evaluate SSC safety significance and to apply differentiated treatment levels accordingly.

However, when this framework is applied to an innovative SMR under development, additional considerations become necessary. At the current design stage, the plant design may not yet be fully finalized, operational and maintenance data are not available, and PRA scope and data maturity may remain limited. In addition, passive components, shared systems, inter-module dependencies, and common-cause failures may require interpretations beyond those used in conventional large reactor applications. Therefore, at the present stage, it is more meaningful to establish a categorization logic and documentation structure that can be progressively refined with design maturation and licensing progress than to claim a fully completed operational categorization result.

The objective of this study is to propose a risk-informed SSC categorization methodology for an innovative SMR and to describe its process, decision criteria, key considerations, and expected outputs. To this end, the paper maintains the basic philosophy of NEI 00-04, presents an eight-step categorization process suited to the design stage, and discusses an application path that can be progressively enhanced as design and licensing activities advance.

2 REGULATORY BASIS AND OVERVIEW OF THE METHODOLOGY

10 CFR 50.69 does not eliminate the conventional distinction between safety-related and non-safety-related SSCs. Rather, it provides a framework for categorizing SSCs into RISC-1 through RISC-4 according to their risk significance and for applying differentiated treatment levels based on that categorization [1]. The essence of this regulation is to maintain the basic philosophy of deterministic design while implementing a management structure that is commensurate with safety significance through the integration of PRA and engineering judgment.

The direct implementation guidance for this framework is provided by RG 1.201 [2], while the practical categorization process and decision logic are detailed in NEI 00-04 [5]. In addition, PRA technical adequacy is supported by RG 1.200 [3], and the general philosophy of plant-specific risk-informed decision-making is based on RG 1.174 [4]. The regulatory evolution leading to this framework is also consistent with the PRA policy statement and the final rulemaking history [6,7].

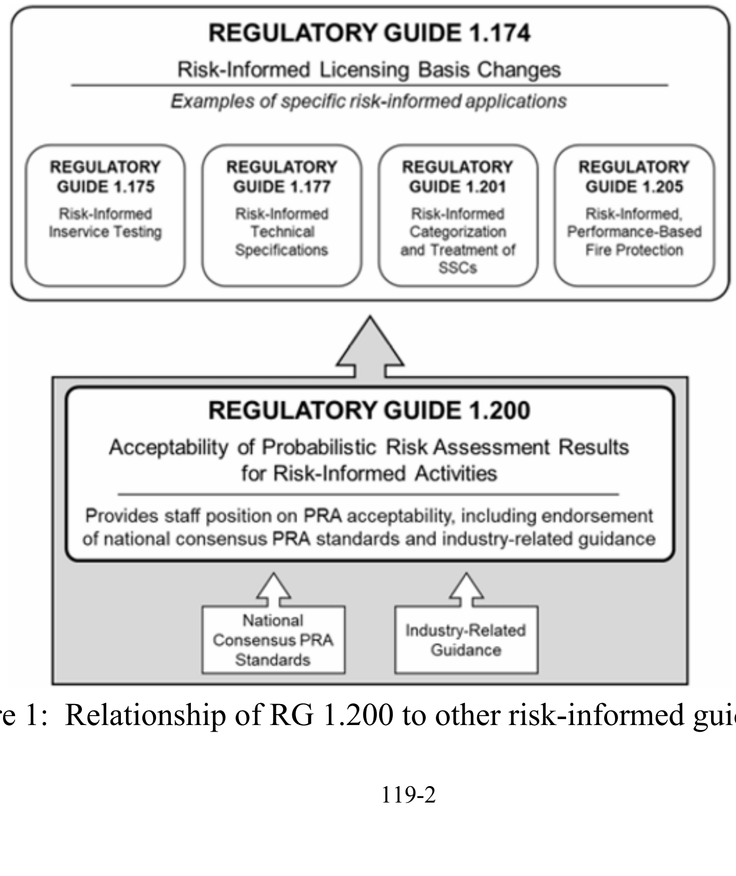

Figure 1: Relationship of RG 1.200 to other risk-informed guidance

An important feature of this methodology is that final categorization is not determined solely by PRA results. The safety significance of a function or SSC is determined through the integrated consideration of risk significance evaluation, defense-in-depth evaluation, sensitivity analyses, and IDP judgment [2,5]. Therefore, risk-informed categorization is not simply a matter of calculating importance measures, but a structured decision-making process that combines quantitative analysis, deterministic evaluation, and engineering judgment.

When this methodology is applied to an innovative SMR, its basic process and philosophy can be retained, but its application range and decision basis should be managed more explicitly. The key contribution of this study is not merely to restate an established risk-informed categorization framework, but to restructure it so that it can reflect design-stage uncertainty and SMR-specific characteristics.

3 RISK-INFORMED SSC CATEGORIZATION PROCESS

The categorization process proposed in this study consists of eight steps. The first step is the collection of plant and design input information and the review of PRA technical adequacy. At this stage, design inputs, system information, functional definitions, PRA model scope, assumptions, shared system configuration, and interfaces among modules are organized. In addition, the range over which the current PRA can be used for risk-informed activities is identified. This step defines the basis for the scope of the subsequent categorization results.

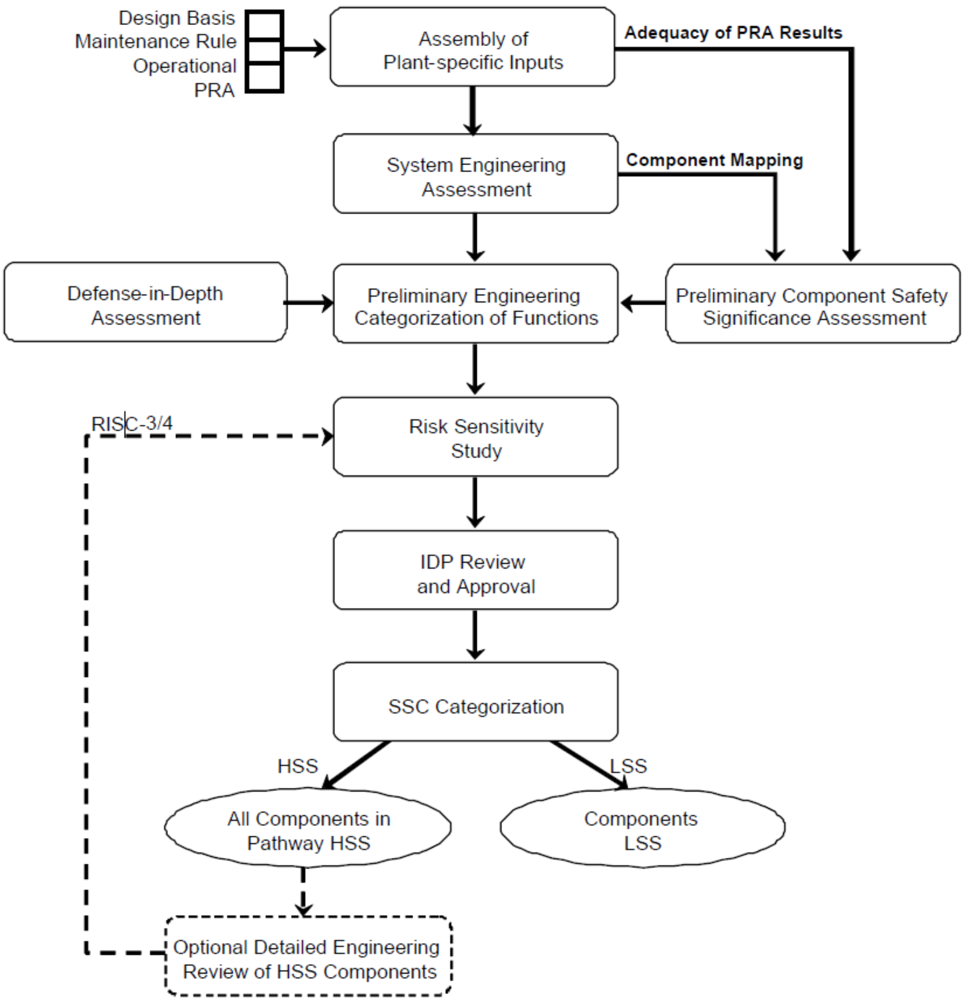

Figure 2: Overall Framework of the Proposed Risk-Informed SSC Categorization Process [5]

The second step is engineering evaluation. This step establishes system boundaries and organizes the mapping among functions, failure modes, and SSCs. In an innovative SMR, one SSC may support multiple functions, while one function may be implemented by multiple SSCs or shared systems. For this reason, a function-oriented structure is essential.

The third step is risk significance evaluation. At this stage, PRA importance measures are used to identify candidate safety-significant items. In general, measures such as RAW, F-V, and, where appropriate, CCF-related indicators may be applied [5]. However, at the design stage, these results should be interpreted as inputs for identifying candidate items and guiding further review, rather than as final deterministic decision criteria.

The fourth step is defense-in-depth evaluation. Even if a function shows low importance in quantitative PRA terms, its safety significance may remain high if it is important for the prevention of core damage, accident mitigation, containment function, or the reduction of radioactive releases. For passive components and functions with limited operational data, this step should explicitly supplement PRA results through deterministic considerations such as required safety functions, available success paths, redundancy, diversity, and design margins. The fifth step is preliminary functional categorization, in which the results of risk significance evaluation and defense-in-depth evaluation are integrated at the functional level.

The sixth step is sensitivity analysis. This step examines how conservative variations in key uncertainty factors, such as human error, common-cause failure, and maintenance unavailability, may affect the preliminary categorization result. The seventh step is IDP review. The IDP considers PRA results together with design basis requirements, defense-in-depth, functional interactions, and shared system effects, and then approves the final categorization direction. At the current stage, the IDP should include multidisciplinary expertise in system design, PRA, safety analysis, operations, and licensing so that both probabilistic and deterministic considerations can be reviewed in an integrated manner.

The final step is categorization and documentation. In this step, functions and SSCs are categorized in a controlled manner into RISC-1 through RISC-4, and the basis for the result is documented in the categorization basis report and associated traceability records. However, the final categorization at this stage represents a controlled result based on currently available design information and PRA maturity, and it is therefore subject to refinement as design details and licensing activities advance.

Table 1: Risk-Informed SSC Categorization Process

Step	Main Inputs	Main Evaluation Content	Main Outputs
1	Design and PRA inputs	Scope, PRA applicability, limitations	Input list; adequacy review
2	Functions, boundaries, SSCs	Function-failure mode-SSC mapping	Mapping table; boundaries
3	PRA model; importance measures	Candidate HSS/LSS identification	Risk significance results
4	Deterministic functions; response logic	Supplement to PRA results	DiD results
5	Results from Steps 3-4	Preliminary functional categorization	Preliminary categorization

6	HEP, CCF, unavailability assumptions	Stability and uncertainty effects	Sensitivity results
7	Integrated results	Multidisciplinary IDP judgment	IDP review records
8	Approved categorization basis	RISC-1 to RISC-4; traceability	Basis report; traceability; change link

4 KEY CONSIDERATIONS FOR APPLICATION TO AN INNOVATIVE SMR

The first major consideration in applying this methodology to an innovative SMR is the limitation of PRA scope and data maturity. At the current design stage, the plant design may not be fully fixed, operational and maintenance information is unavailable, and some operating modes, external events, and passive failure modes may not yet be fully reflected. Therefore, the categorization result should be understood not as a final operational conclusion, but as a controlled categorization basis established within the current design and analytical scope.

Second, passive components and low-probability passive failure modes require specific interpretation. Even when passive components are not explicitly prominent in the PRA model, their failure can still have a substantial effect on safety functions. Accordingly, at the design stage, the safety significance of passive components should be assessed not only through PRA importance measures but also through function mapping and defense-in-depth considerations. In particular, deterministic supplementary review is needed to confirm whether required safety functions, success paths, and design margins remain sufficient when quantitative evidence is limited.

Third, shared systems and inter-module dependencies complicate the interpretation of the risk contribution of individual SSCs. The failure of a particular SSC may affect not only a single function, but also the safety performance of multiple modules simultaneously. Therefore, shared functions, influence paths, and common support functions should be explicitly addressed during engineering evaluation and IDP review. When a plant-level multi-module PRA is not yet fully established, these effects should still be reflected through explicit influence-path identification, bounding assumptions in sensitivity analyses, and structured IDP review.

Fourth, common-cause failure and maintenance unavailability are key uncertainty factors that influence categorization stability at the design stage. In repeated modular configurations and similar environmental conditions, the possibility of simultaneous functional impairment caused by common causes may increase. Sensitivity analysis should therefore be treated not as a supplemental calculation, but as an essential structural part of the categorization process.

Fifth, in low-risk designs, the direct application of conventional relative importance measures may identify an excessive number of candidate HSS items. For this reason, importance measures should be used to identify candidate items, while final categorization should be based on a conservative integration of defense-in-depth, sensitivity analyses, and IDP review.

Table 2: Key Considerations for an Innovative SMR and Their Treatment

Key Consideration	**Meaning**	**Reflected in Step(s)**	**Treatment at the Current Stage**
Limited PRA scope and data maturity	Restricted applicability	1, 6, 7	State scope and limitations
Passive and low-probability passive failures	Possible PRA underrepresentation	2, 4, 7	Supplement by function and DiD

Shared systems and inter-module dependencies	Potential multi-module impact	2, 6, 7	Path identification; bounding review; IDP
Common-cause failure (CCF)	Repeated design/common environment effect	6, 7	Conservative sensitivity cases
Maintenance unavailability	Reduced functional availability	6	Check categorization stability
Importance measures in low-risk designs	Potential over-sensitivity	3, 6, 7	Use for screening, then integrated judgment
Design changes and model updates	Categorization basis can evolve	8	Link to traceability and change control

5 EXPECTED OUTPUTS AND PHASED APPLICATION

The direct output of this study is not a simple categorization table for a particular point in time, but a categorization basis that is defensible under the current design-stage conditions. The key outputs may be grouped into three categories. First, a categorization basis report that records the categorization logic, applicability range, assumptions, limitations, and judgment basis for each function and SSC. Second, a traceability matrix that links functions, systems, SSCs, PRA bases, deterministic safety functions, defense-in-depth judgments, and sensitivity analysis results. Third, a change-management interface that allows the existing categorization result to be reviewed consistently when design changes occur or PRA models are updated.

The practical purpose of this framework is not to implement a complete 10 CFR 50.69 treatment program at the present stage. Rather, the immediate objective is to establish a categorization logic that reflects both safety design philosophy and risk information, and to provide decision criteria and documentation structures that can support future design development and licensing interactions. As design details advance and licensing activities progress, the framework can be progressively refined through expanded PRA scope, accumulated operational and maintenance information, and design updates.

The limitations at the current stage should also be recognized. Additional refinement may be required for whole-plant multi-module risk, certain operating modes, some external events, and passive failure modes. Further work may also be needed to develop plant-specific importance criteria for low-risk designs. The value of this study, therefore, lies not in presenting a completed final categorization table, but in providing a structured technical basis that can be expanded reliably in later stages.

6 CONCLUSION

This study proposed a methodology for applying NEI 00-04-based risk-informed SSC categorization to an innovative SMR. The proposed methodology consists of input information collection, PRA adequacy review, engineering evaluation, risk significance evaluation, defense-in-depth evaluation, preliminary functional categorization, sensitivity analyses, IDP review, and final categorization and documentation. Final categorization is based not only on PRA results, but also on the integrated consideration of risk significance, defense-in-depth, sensitivity analyses, and IDP judgment.

The conclusions of this study may be summarized as follows. First, the fundamental process and philosophy of risk-informed SSC categorization developed mainly for large light-water reactors can also be applied to an innovative SMR. Second, additional considerations are required for SMR-specific features, including design-stage PRA limitations, passive components, shared systems, inter-module dependencies, common-cause failures, and the interpretation of importance measures in low-risk designs. Third, the key outcome at the present stage is not a fully completed operational categorization result, but the establishment of a categorization basis that can be progressively refined as the design matures and licensing activities advance.

Accordingly, the significance of this study does not lie in a one-time categorization result for a specific stage. Rather, it lies in providing a structured risk-informed licensing basis that can be continuously updated as the design evolves and licensing activities proceed. Future work is needed on multi-module PRA, additional operating modes and external events, passive failure modes, and plant-specific importance criteria. At the present stage, the priority is not to prematurely propose new numerical thresholds, but to establish a clear and extensible categorization process and documentation structure that can be expanded with confidence in later stages.

ACKNOWLEDGEMENT

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