# Model-Based Nuclear Systems Engineering (MBNSE): A Design Framework for Small Modular Reactors under Evolving Safety Regulatory Requirements

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## 1. Introduction

In response to the complexity of accommodating the diverse technical characteristics of SMRs and advanced reactors within a licensing system designed for large light water reactors, the United States has been reforming its regulatory framework. Developed under the Nuclear Energy Innovation and Modernization Act (NEIMA), the final 10 CFR Part 53 rule establishes a technology-inclusive, risk-informed, and performance-based licensing framework [1]. In parallel, the ADVANCE Act and Executive Order 14300 have driven reforms to the licensing system, including shorter review schedules, a regulatory framework for microreactors and the management of design changes during construction and operation. Recently, 10 CFR Part 57 was proposed to support the repeated, large-scale deployment of microreactors and other reactors with comparable risk profiles [2]. As shown in Figure 1, U.S. nuclear regulation continues to move toward multiple licensing pathways that reflect the technical characteristics and deployment modes of each reactor.

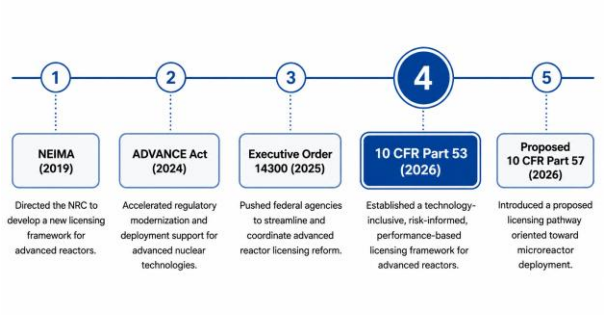



Figure 1. Evolution of the U.S. licensing framework for advanced reactors

Likewise, Korea has implemented a regulatory system based on large pressurized water reactors under the Nuclear Safety Act and its technical standards. The existing standards are applied to SMRs, and conformity and alternative criteria for features specific to each design are reviewed on a case-by-case basis. However, as SMR designs have evolved to incorporate passive safety systems, multi-module operation, factory fabrication, and non-light-water technologies, the limitations of relying solely on the existing regulatory framework have become increasingly apparent. In response, the Nuclear Safety and Security Commission announced the Roadmap for Establishing the SMR Regulatory Framework (2026–2030) [3]. The goal is to develop a regulatory framework that covers diverse reactor types and applications by expanding risk-informed, performance-based evaluations beyond existing rule-based conformity checks. The increased use of pre-application reviews and early regulatory engagement allows regulatory issues to be addressed before design finalization. Consequently, design maturation and regulatory review increasingly overlap, and design changes driven by review findings can recur during the design process.

These changes not only require new licensing procedures, but also a different approach to managing the relationship between regulatory requirements and reactor design.

Nuclear power plant design has traditionally translated regulatory requirements and top-level design bases into functions and design requirements for structures, systems, and components (SSCs), which are then verified through discipline-specific design and safety analysis. The information produced in this process is recorded in the deliverables of each discipline and design stage, such as design basis documents, P&IDs, equipment specifications, and safety analysis reports, and licensing reviews and quality assurance audits are likewise conducted on these documents. As a result, the information describing even a single system or component ends up dispersed across many documents by design stage and discipline.

Figure 2(a) illustrates this dispersed structure. The relationships between the documents are defined by cross-references at the document level, rather than being explicitly defined or maintained at the level of individual design information elements. Consequently, in order to confirm the origin of a given piece of design information and its relationship to other design and analysis information, it is necessary to search the relevant documents and databases individually.

This fragmentation becomes a more serious problem when designs change. Even a minor change to a regulatory requirement or design parameter can propagate through system configurations, equipment specifications, interfaces, safety analyses, and verification results.

Current configuration management procedures control the approval of changes and the revision of affected documents. However, identifying the scope of a change still requires manual review by responsible engineers. What is needed beyond the management of individual documents is a design information system that maintains the relationships among regulatory requirements, safety functions, SSCs, design parameters, analyses, and verification results within a single, consistent structure. This motivates the transition from document-centric to model-centric information management, as illustrated in

Figure 2(b). Model-based systems engineering (MBSE) manages this information as one connected model and traces the effects of changes. This approach effectively secures the consistency and traceability of SMR design in this environment.

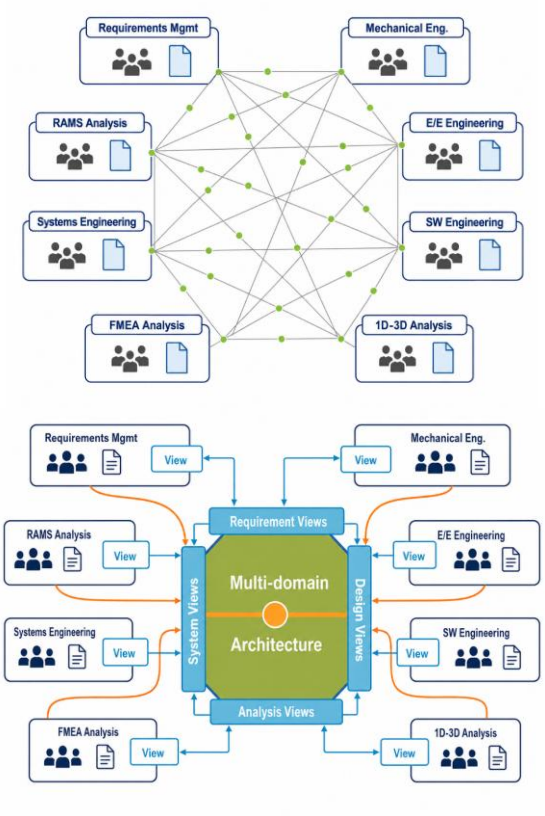



Figure 2. Fragmented design information in document-centric management (a, top) and integrated management centered on the system model (b, bottom)

## 2. Model-Based Systems Engineering and Its Extension to the Nuclear Field

### *2.1. Concept and Industrial Applications of Model-Based Systems Engineering*

The International Council on Systems Engineering (INCOSE) defines MBSE as the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities, beginning in the conceptual design phase and continuing throughout development and later life cycle phases [4]. MBSE differs from the document-centric approach in that it explicitly represents relationships among requirements, functions, structure, interfaces, and verification information in a system model, and it links and manages related design information around that model. SysML (Systems Modeling Language) is the representative standard modeling language developed to express system requirements, structure, behavior, and their relationships [5].

These characteristics respond directly to the traceability and change impact problems described in the previous section. In a document-centric environment, determining which functions and SSCs implement a requirement and which analyses or tests verify it requires comparing relevant documents one by one. In MBSE, however, these relationships are explicitly represented in the system model, and related design information is linked and managed around it. This allows traceability from requirements to verification to be visualized in diagrams and traceability matrices. Additionally, the elements affected by a change can be immediately identified.

Thus, the essential advantage of MBSE is that end-to-end traceability and change impact analysis are not reconstructed retrospectively by collating documents. Instead, relationships among design information are structured and maintained throughout the design process and can be visually confirmed. MBSE and the associated digital engineering practices have matured primarily in aerospace and defense. NASA and the U.S. Department of Defense manage requirements and interfaces from mission needs down to systems and components as models linked to analysis and test activities [6,7], and the DoD Digital Engineering Strategy in particular set the direction of treating continuously maintained models and data as the authoritative source of truth [8].

In avionics, model-based development and verification are addressed by DO-331, the Model-Based Development and Verification Supplement to DO-178C and DO-278A [9]. Common to these fields is that models serve as core engineering artifacts connecting requirements, design, and verification information.

Adopting MBSE does not mean consolidating all design information into one model or software tool. Complex system development employs many tools in addition to the system model, such as computer-aided design (CAD), physics analysis codes, requirements management tools, and test databases. The practical goal of MBSE is not to replace these tools with one, but rather to connect the information produced by each through a common system architecture and traceability relationships, creating a coherent design information system. This perspective is especially important when MBSE is applied to the nuclear field. Recent studies have also explored MBSE adoption and change impact analysis in nuclear engineering [10,11], motivating the nuclear-specific extension proposed in this paper.

### *2.2. Definition and Features of Model-Based Nuclear Systems Engineering (MBNSE)*

The general principles of MBSE also apply to nuclear design, but specific conditions related to nuclear design and licensing must be considered. This paper defines Model-Based Nuclear Systems Engineering (MBNSE) as a framework that specializes MBSE for nuclear design, licensing, and engineering processes to reflect these conditions. At its core, MBNSE defines both the structure connecting design information and the operations and state behavior acting on that information within the system model, so that users can manage both how design information is connected and how it should respond when changes occur. Specifically, MBNSE has the following five features, each addressing a condition specific to the nuclear field, as shown in Figure 3.

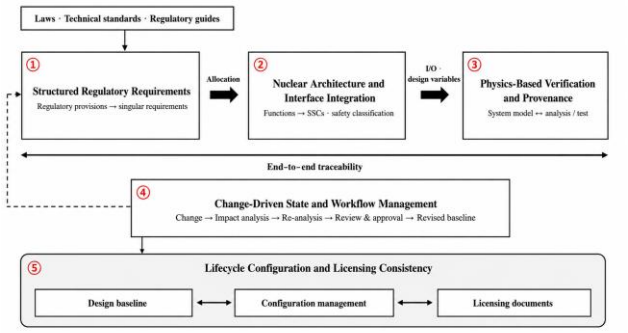



Figure 3. Overall structure of the MBNSE framework and its five features

The first feature involves managing regulatory requirements derived from laws and technical standards, as well as owner requirements, and incorporating them as core inputs to the requirements structure. In the nuclear field, laws, technical standards, regulatory guides, and license conditions form the core of the design basis, and conformity with them must be maintained not only through design but through construction, operation, and design changes. In practice, however, a single regulatory provision often encompasses its scope of application, conditions, required actions, and acceptance criteria. This makes direct allocation to a system model difficult. Therefore, regulatory text is decomposed into manageable, independent requirements (singular requirements), each of which must be assigned necessary regulatory attributes, such as source, applicable items, safety class, and seismic category. This establishes traceability from regulatory documents and requirements through safety functions and SSCs to verification evidence and allows the design areas affected by a requirement change to be identified through the model.

The second feature involves connecting the SSC classification schemes particular to nuclear plants, such as safety class, quality class, seismic category, and Class 1E electrical classification, with the system architecture and interface information. Beyond recording which functions and SSCs each requirement is allocated to, the material, energy, and information exchanged between systems and the associated design parameters are managed as explicit interfaces. These interfaces express the relationship between regulatory requirements and the physical design structure. They also express the paths along which changes propagate between systems.

The third feature is connecting the physics-based analyses and test information that serve as verification evidence for safety requirements to the system model. Whether a reactor safety function is satisfied cannot be judged from the logical structure of the system alone because it must be demonstrated by analyses and tests of the actual physical phenomena, including core neutronics, thermal-hydraulic behavior, and structural integrity. For example, representing in the system model that a particular SSC performs core cooling during an accident is not sufficient; thermal-hydraulic analysis must confirm that safety parameters, such as peak cladding temperature and critical heat flux ratio, meet the acceptance criteria.

Therefore, the inputs, outputs, and design parameter relationships between the system architecture and the physics-based analysis models are connected explicitly. An input generation capability that produces analysis inputs from the system model supports the conversion process. In nuclear safety analysis, the reliability of a result depends not only on its value, but also on the analysis code and version used, the input conditions and assumptions, and the verification status. Thus, the link between a requirement and an analysis result must include this provenance.

The fourth feature defines operational behavior for design information. Structured design information and traceability detail what is connected and how. However, in an evolving regulatory environment, it is equally important to define how the design information system responds when a requirement changes. While conventional MBSE focuses on representing relationships among requirements, functions, structures, and verification information, MBNSE takes it a step further by explicitly managing design information and the subsequent engineering activities.

When a design parameter is modified, the verification evidence of every analysis that used the parameter as an input transitions from a "valid" state to a "review required" state. This triggers the necessary review and, where required, reanalysis and approval activities have to follow. The evidence only returns to a valid state and enters the new design baseline when any required reanalysis satisfies the acceptance criteria and an engineer with approval authority completes the review. The performer, timing, inputs, and rationale of each operation are recorded in the change history to preserve traceability of change decisions. Thus, responding to change is governed by rules embedded in the model rather than by an implicit process that depends on individual experience and procedures.

The final feature is maintaining this design information and the results of engineering activities consistently across the design life cycle and connecting them to configuration management and licensing documents. Because the final licensing deliverables of the nuclear industry are still submitted and reviewed as safety analysis reports and design documents, MBNSE does not aim to replace or eliminate documents with models. Instead, the system architecture, design parameters, analysis bases, verification status, and structured requirements are managed as the authoritative source of truth. These are kept consistent with the licensing documents so that the required documents can be generated and updated from this source. Additionally, it supports document revisions and licensing responses that follow design changes.

Thus, MBNSE extends the general chain from requirements to functions, structure, and verification. It does so by incorporating structured regulatory requirements, the safety classifications and interfaces specific to nuclear plants, and physics-based verification

evidence with provenance. MBNSE also includes operations and state behavior for design information, as well as licensing and life cycle configuration management. The result is a nuclear-specific design framework that manages end-to-end traceability from regulatory requirements to the actual design and its verification evidence together with the activities that respond to change.

### *2.3. Requirements Allocation across Levels and Interface Management*

The design inputs of a nuclear system derive from many sources, including owner requirements, laws and regulatory standards, codes and standards, and the concept of operations. Upper-level requirements are not simply copied to lower levels. Rather, they are developed through decomposition, derivation, refinement, and functional identification. They are also categorized as functional or performance requirements that can be implemented at each design level. The singular requirements are the starting point of this development. Each is assigned its source and scope, and the required functions are gradually allocated to design elements at the plant, system, and component levels, forming traceability from top-level requirements to the actual design.

Among these levels, system-level requirements must be consolidated into consistent design inputs for the detailed design process. The functional specification is the core information set for this purpose. As shown in Figure 4, the functional specification combines upper-level plant objectives, safety and operational functions, intersystem interface conditions, and applicable codes, standards, and regulatory requirements. This combination defines the functions, performance, interfaces, and verification requirements of a system, providing a single design input baseline.

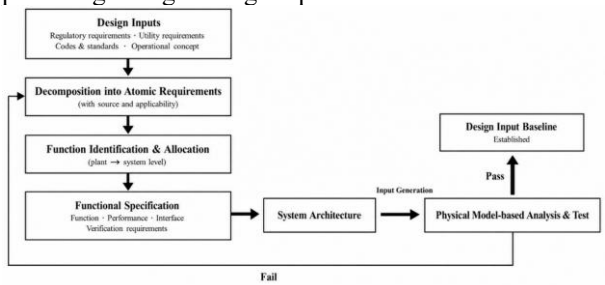



Figure 4. Requirements development from singular requirements to the design input baseline

The vertical axis is the development of requirements from the plant level through systems to components. The horizontal axis is the interface between systems and between components. Interface engineering defines the conditions and boundaries of material, energy, and information exchanged between systems or design domains. It also manages the effects that changes in one system have on connected systems under normal, transient, and accident conditions.

The steam generator is an example of a representative interface where the reactor coolant system meets the secondary feedwater and steam systems. Variables at this interface, such as feedwater flow and temperature, as well as steam pressure and flow, constrain the design conditions of both systems simultaneously. A change in these values affects primary-side heat removal performance and secondary system design.

This requirements structure is not fixed once established. It is updated and refined through iteration as feedback from the system architecture, detailed design, and safety analysis and test results is incorporated. The combination of vertical requirements development across levels and horizontal interface connections between systems becomes the basic information structure for tracing derived requirements, related functions and SSCs, interfaces, and verification evidence whenever a requirement changes.

### *2.4. Reference Ontology for Guiding Model Construction*

It does not scale to have a small group of systems engineering specialists build and maintain a plant-level MBNSE model for every system. Expertise on each system's functions, design conditions, and analysis bases resides with the discipline engineers responsible for each system, so building the model requires their participation. Therefore, the systems engineering organization defines an initial baseline model that covers plant architecture, requirements allocation across levels, system boundaries, major interfaces, and common modeling rules. Then, each discipline engineer elaborates the design information for their own domain based on this model. However, these engineers are often unfamiliar with nuclear system modeling, so a common reference is needed to guide model construction. This reference would allow them to structure design information under the same semantics and modeling rules.

Existing work in systems engineering and the nuclear field offers common semantics and reusable model structures to draw on. Representative examples are NASA JPL's IMCE, which links SysML models with OWL ontologies [12], INCOSE's pattern-based systems engineering, which uses a common metamodel and reusable system patterns [13], and IAEA guidance on applying ontologies and semantic technologies to nuclear knowledge management [14].

This study proposes a common reference ontology for the nuclear domain, informed by the IAEA guidance, and links it with the MBNSE information structure, including requirements, functions, SSCs, interfaces, design parameters, analyses, and verification evidence [14]. Reusable templates and validation rules for building system models are combined with this so that discipline engineers can build their design information within a common structure.

As shown in Figure 5, the reference ontology defines the meaning of design information concepts and the relationships among them. The modeling templates guide the functions, requirements, design parameters,

interfaces, and verification information that each discipline engineer must provide. The validation rules check for missing or conflicting mandatory attributes and relationships so that the information built for each system keeps the common structure. Through role-based views organized around upper-level requirements, related SSCs, and interfaces relevant to their work, discipline engineers can enter and review design information. Consequently, they can participate in model construction without having to understand SysML syntax or detailed modeling rules. Interfaces shared by several systems are managed jointly by the discipline engineers of those systems and the systems engineering organization, keeping the system models and the plant-level architecture consistent.

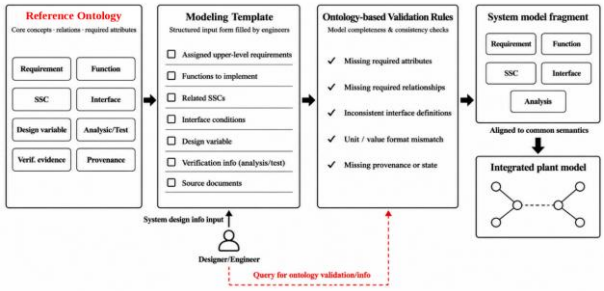



Figure 5. System model construction guided by the reference ontology, modeling templates, and validation rules

This structure provides the basis for discipline engineers and artificial intelligence to build the MBNSE model collaboratively. A language model uses ontology and modeling rules to determine what information it needs from the engineer. It identifies the requirements, functions, design conditions, and verification evidence in the engineer's responses and related design documents. Then, it proposes these as candidate model elements.

To realize this human-AI collaboration, this study considers a dual retrieval-augmented generation (Dual RAG) structure, shown in Figure 6, that searches an ontology-structured plant model graph and the regulatory and design source text separately. Model graph retrieval provides upper-level requirements, adjacent systems, interfaces, related SSCs, and existing verification evidence connected to the system being built. Source document retrieval provides underlying text from laws, regulatory guides, design basis documents, and analysis reports. As design information accumulates for each system, the plant model graph expands progressively. This allows the design knowledge of discipline engineers to be accumulated under the common semantics. It also allows the requirements development across levels and the intersystem interfaces to be connected into a plant-scale MBNSE model.

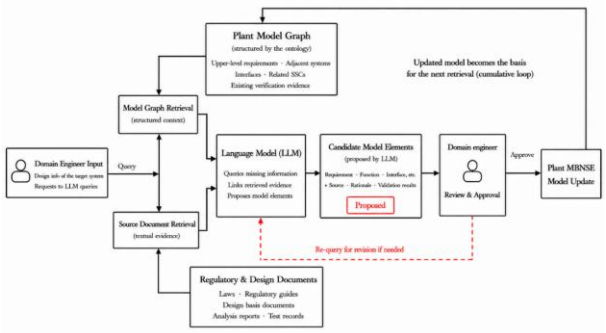



Figure 6. Dual RAG collaboration structure combining plant model graph retrieval and source document retrieval

## 3. Conclusions

The SMR licensing frameworks in the United States and Korea are shifting towards parallel licensing pathways and concurrent design and review. This makes responding to changes in requirements during the engineering phase a routine task. Document-centric management disperses design information across documents by discipline, making it difficult to trace regulatory requirements to design and verification evidence, as well as identify the impact of changes. This paper proposes Model-Based Nuclear Systems Engineering (MBNSE) as an approach to managing design information in this evolving regulatory environment.

MBNSE breaks down regulatory requirements into singular requirements allocated across the plant, system, and component levels. It links SSC classifications specific to nuclear plants and intersystem interfaces to the requirements structure. Additionally, it connects physics analyses that verify safety requirements to the system model, along with their provenance. Defining operations on design information and their state behavior incorporates both end-to-end traceability from regulatory requirements to verification evidence and the rules for responding to requirement changes. An MBNSE model can be built at plant scale by combining the reference ontology, modeling templates, validation rules, and role-based views with Dual RAG human-AI collaboration.

This framework is designed to identify the design areas and verification targets affected by a requirement or design parameter change through the model's traceability and state transition rules. It is also intended to support the systematic triggering of the necessary reanalysis and review activities. Design information managed as an authoritative source of truth can support the generation and updating of licensing documents, thereby maintaining consistency between design and licensing information. Common semantics and role-based views lower the barrier for discipline engineers to participate, enabling the framework to evolve into an organization-wide, sustainable design information management system.

## 4. Future Work

This study presented the information structure and construction method of MBNSE at the framework level.

Application to an actual system and further elaboration of the ontology and operational definitions are still needed. Future research will proceed in three stages.

The first stage is a pilot model of the power conversion system, chosen because it has fewer regulatory constraints than safety systems. The requirements will be broken down into singular requirements and assigned to functions and SSCs. The interfaces with adjacent systems, such as the steam generator, will be defined. Verification evidence from heat balance and performance analyses will be linked with its provenance. This will confirm that a traceability matrix can be generated from the actual design information.

The second stage is a Dual RAG prototype that uses the pilot model as its knowledge base. By combining plant model graph retrieval and source document retrieval, the prototype will propose candidate requirements, functions, design conditions, and verification evidence. It will then be evaluated based on the accuracy of its proposals, its agreement with the source text, and the modeling effort it reduces.

The third stage involves applying regulatory change scenarios, such as a revised technical standard or modified design parameter, to verify the behavior of change impact analysis, state transitions, reanalysis triggering, and design baseline updates. This process will refine the semantic framework, templates, and validation rules. Then, the validated structure will be extended to additional systems, expanding the MBNSE model to plant scale.

**Acknowledgements**

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