**Technology Inclusive Content of Application Project**
**For Non-Light Water Reactors**

# Definition of Fundamental Safety Functions for Advanced Non-Light Water Reactors

Draft Report Revision B
Issued for Collaborative Review

Document Number
SC-16166-100 Rev A

Battelle Energy Alliance, LLC
Contract No. 221666
SOW-16166

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Amir Afzali, Next Generation Licensing and Policy Director — Date
Southern Company Services

## Disclaimer

## Abstract

Non-light water reactor (non-LWR) technologies will play a key role in meeting the world's future energy needs and will build on the foundation established by the current light water reactor (LWR) nuclear energy fleet. Given the long timeframe and significant financial investment required to mature, deploy, and optimize these technologies, an efficient and cost-effective non-LWR-licensing framework that facilitates safe and cost-effective construction and operation is a critical element for incentivizing private sector investment. The Technology Inclusive Content of Application Project (TICAP) is an important step in establishing that licensing framework. This Department of Energy (DOE) cost-shared, owner/operator-led initiative will produce guidance for developing content for specific portions of the Nuclear Regulatory Commission (NRC) license application Safety Analysis Report (SAR) for non-LWR designs.

The portions of the SAR on which this work will focus are those addressed in the Nuclear Energy Institute (NEI) publication NEI 18-04, "Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development." The TICAP guidance will help ensure completeness of information submitted to the NRC while avoiding unnecessary burden on the applicant and allowing for flexibility so that the content of the applications will be of the appropriate scope and level of detail that is commensurate with the complexity of the design being reviewed.

TICAP will generate a number of products culminating in an NEI document that will be submitted to the NRC for endorsement. The NEI document will provide guidance for key elements of the content of an advanced reactor license application. This report contains a set of fundamental safety functions and the proposed definitions of those functions for review by and discussion with the NRC.

While the NRC has not yet issued final regulatory guidance or made a policy decision that specifically defines a set of fundamental safety functions to be used for regulatory purposes, for purposes of the TICAP effort, it is necessary to establish and define a set of fundamental safety functions to continue the development of the additional regulatory guidance that is the intent of this integrated industry effort. Based on the assessment contained herein, the recommended set of fundamental safety functions is:

1. Controlling Reactivity
2. Removing Heat from the Reactor and Waste Stores
3. Limiting the Release of Radioactive Materials

A more detailed definition of what is included within each of these fundamental safety functions can be found in Section 3 of this report. These fundamental safety functions provide comprehensive coverage of important plant functions for a spectrum of reactor technologies postulated licensing basis events and design basis accidents that, if satisfied, will provide reasonable assurance of adequate protection of the health and safety of the public and the environment.

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## List of Abbreviations

| | |
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| AOO | Anticipated Operational Occurrence |
| CNSC | Canada Nuclear Safety Commission |
| DG | Draft Regulatory Guide |
| DID | Defense-in-Depth |
| DOE | Department of Energy |
| FSF | Fundamental Safety Function |
| IAEA | International Atomic Energy Agency |
| LBE | Licensing Basis Event |
| LMP | Licensing Modernization Project |
| LWR | light water reactor |
| NEI | Nuclear Energy Institute |
| NGNP | Next Generation Nuclear Plant |
| non-LWR | non-light water reactor |
| NRC | Nuclear Regulatory Commission |
| NUREG | Nuclear Regulatory Commission technical report designation |
| PDC | Principal Design Criteria |
| PRA | Probabilistic Risk Assessment |
| PSF | PRA Safety Function |
| QHO | Quantitative Health Objective |
| RIPB | risk-informed and performance-based |
| SAR | Safety Analysis Report |
| SECY | NRC Office of the Secretary designation for documents containing policy, rulemaking, and adjudicatory matters as well as general information for action or consideration by NRC |
| SSCs | Structures, Systems, and Components |
| TICAP | Technology Inclusive Content of Application Project |

# 1.0 INTRODUCTION AND BACKGROUND

## 1.1 TICAP Description

Non-light water reactor (non-LWR) technologies will play a key role in meeting the world's future energy needs and will build on the foundation established by the current light water reactor (LWR) nuclear energy fleet. Given the long timeframe and significant financial investment required to mature, deploy, and optimize these technologies, an efficient and cost-effective non-LWR-licensing framework that facilitates safe and cost-effective construction and operation is a critical element for incentivizing private sector investment. The Technology Inclusive Content of Application Project (TICAP) is an important step in establishing that licensing framework. This Department of Energy (DOE) cost-shared, owner/operator-led initiative will produce guidance for developing content for specific portions of the Nuclear Regulatory Commission (NRC) license application Safety Analysis Report (SAR) for non-LWR designs.

Existing LWRs are the country's largest source of emissions-free, dispatchable electricity, and they are expected to remain the backbone of nuclear energy generation for years to come. However, as the energy and environmental landscape has evolved, interest has grown in advanced nuclear energy systems that promise superior economics, improved efficiency, greater fissile-fuel utilization, reduced high-level waste generation, and increased margins of safety. In addition to electricity generation, these technologies can expand the traditional use of nuclear energy by providing a viable alternative to fossil fuels for industrial process heat production and other applications.

The current regulatory framework for nuclear reactors was developed over decades for LWRs using zirconium-clad uranium oxide fuel and coupled with the Rankine power cycle. Many advanced, non-LWRs are in development, with each reactor design differing greatly from the current generation of LWRs. For example, advanced reactors might employ liquid metal, gas, or molten salt as a coolant, enabling them to operate at lower pressures but higher temperatures than LWRs. Some employ a fast rather than a thermal neutron spectrum. A range of fuel types are under consideration, including fuel dissolved in molten salt and circulated throughout the primary coolant system. In general, advanced reactors emphasize passive safety features that do not require rapid action from powered systems to prevent radionuclide releases. Given these major technical differences, changes to the current regulatory framework are needed for the deployment of advanced reactor designs.

Therefore, the DOE authorized TIPAC, a utility-led initiative to improve the effectiveness and efficiency of the NRC's current regulatory framework. The initiative recognizes that significant levels of industry input and advocacy are needed in collaboration with the NRC to enable the regulatory changes needed for advanced reactors.

The portions of the SAR on which this work will focus are those directly informed by the processes defined in the Nuclear Energy Institute (NEI) publication NEI 18-04, "Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Bass Development." The TICAP guidance will help ensure sufficiency and completeness of information submitted to the

NRC while avoiding unnecessary burden on the applicant commensurate with the complexity of the design being reviewed.

The goal of TICAP is to develop license application content guidance with the following attributes:

- Technology inclusive to be generically applicable to all non-LWR designs
- Risk-informed and performance-based (RIPB) to:
  - Focus the content of the application on the information that NRC needs to make a safety determination.
  - Create coherency and consistency in the scope and level of detail of information to be provided in the license application for various advanced technologies and designs.
  - Provide for flexibility during construction.
  - Encourage innovation by focusing on the final results as opposed to the pathway taken to achieve the results.

This modernized, technology inclusive RIPB license application content will advance:

- The NRC's longstanding focus on and commitment to continuous improvement
- The industry (developers and owners/operators) goal of having a safety-focused review that minimizes the burden of generating and supplying information that is not important to a safety determination
- The NRC and industry objective of reaching agreement on how to implement reasonable assurance of adequate protection for non-LWRs
- NRC's stated objective and policy statement regarding the use of risk-informed decision-making to remove unnecessary regulatory burden

TICAP will build on the success of the Licensing Modernization Project (LMP) that produced NEI 18-04. That document presented a modern, technology-inclusive, RIPB process for selection of Licensing Basis Events (LBEs); safety classification of structures, systems, and components (SSCs) and associated risk-informed special treatments; and determination of Defense-in-Depth (DID) adequacy for non-LWRs. The TICAP application guidance will focus on the portion of the application generated by using the LMP methodology and the information that supports the applicant's safety case. Ultimately, the information presented in the application must demonstrate reasonable assurance of adequate protection of public health and safety.

## 1.2 Purpose of Definition of Fundamental Safety Functions for Advanced Non-LWRs

TICAP will generate a number of products culminating in an NEI document that will be submitted to the NRC for endorsement. The NEI document will provide guidance for key elements of the content of an advanced reactor license application. While each of these products will be discussed with the NRC, only the NEI content of application guidance will be submitted for NRC endorsement. Figure 1 provides a list of the products with the subject of this report highlighted. Each of these products is described below.


**Figure 1. TICAP Products**

- Fundamental Safety Functions (FSFs) Definition (this report)—A set of high-level functions, labeled as Fundamental Safety Functions (also known as performance objectives), will be defined that, when demonstrated, satisfy the public safety objective of the Atomic Energy Act. The FSFs are applicable, as relevant, throughout the lifetime of the facility for which the license is being submitted.
- Regulation Mapping to Fundamental Safety Functions—The underlying safety basis of the current regulatory requirements will be identified and will be mapped to one or more of the FSFs.
- SAR Options Assessment—Topics in a traditional NUREG-0800 light water reactor SAR will be screened to identify candidate areas in which application of the LMP methodology could bring greater clarity to the level of detail and the necessary and sufficient design and risk information needed to support a technology-specific safety case. It is important to note that only those sections/elements that are part of both the LMP's processes and their expected outputs will be targets of this project.
- LMP-Related Safety Case—The input (e.g., data, design information, analytical programs, and tools such as a probabilistic risk assessment) used to generate and select the LBEs, classify SSCs, and determine DID adequacy, as well as the outputs (e.g., the SSC classification results), will be delineated.
- Differences Between Licensing Paths—It is recognized that different applicants may select different licensing paths (e.g., combined construction and operating license, construction permit/operating license, or design certification) to deploy their reactor designs. To facilitate the execution of these options, the scope, levels of detail, and the maturity of the information that needs to be provided for several typical licensing paths will be defined.
- Tabletop Exercises—To improve the efficacy of the proposed process, some elements of the recommendations will be subjected to trial use tests. This effort will be supplemented by discussions with user communities (e.g., developers and/or prospective site applicants) in order to obtain the maximum independent insights on the proposed processes. Guidelines for conducting these tabletop exercises will be generated prior to the initiation of the exercises.
- Formulation of Technology Inclusive Content of Application—The task will address the formulation of application content from the safety case established using the LMP methodology. In addition, potential advanced reactor application structures (formats) will

be reviewed and evaluated to identify and recommend an acceptable approach for organizing the information in the overall SAR. The SAR structure should convey the level of detail and the necessary and sufficient design and risk information that supports the safety case clearly and should facilitate an efficient and effective NRC review.

- NEI Content of Application Guidance Document—The results of the above deliverables/activities will be finalized in an NEI document that will be submitted to NRC for endorsement. This deliverable will be an integrated product of various predecessor products that have been modified and incorporated into the NEI guidance document.

This report is the first in the series of documents that will serve to provide guidance for the appropriate scope and level of detail for the RIPB portions of a Safety Analysis Report section of an application for a license under 10 CFR Parts 50, 52, and potentially Part 53 (to be proposed). This report will define a set of FSFs for review by and discussion with the NRC. The recommended set of FSFs will be evaluated as part of the ongoing TICAP activities with the idea of evolving the definitions, if necessary, to assure maximum inclusivity of technology options.

The objective of this report is to recommend a set of FSFs that embody the underlying safety objectives of the technical requirements within the scope of the current SAR portion of the application for operating a commercial nuclear power plant. The set of FSFs will serve as a common set of functions that the safety case for all designs (independent of the technology) would address. It will also serve as a reference for the next phases of the TICAP efforts to identify the necessary information that demonstrates that these FSFs are met. The NRC has not yet issued final regulatory guidance or made a policy decision that specifically defines a set of FSFs to be used for regulatory purposes. Therefore, alignment on the FSFs is a necessary first step in developing the guidance envisioned by the subsequent TICAP activities that, when demonstrated, will satisfy the underlying public safety objective of the Atomic Energy Act.

The scope of this report is constrained to the elements of the SAR that are governed by the scope presented in the NEI 18-04 guidance document. The guidance document describes acceptable processes for selection of LBEs, safety classification of SSCs and associated risk-informed special treatments, and determination of the DID adequacy for a technology-inclusive array of advanced non-LWR designs. The document focused on establishing guidance for advanced non-LWR designs so license applicants can develop inputs that can be used to establish design bases and the relation of the design bases to the applicable technical regulatory requirements for protection of the public from radiological exposure. The generated information will demonstrate compliance with applicable requirements, including but not limited to the contents of applications required in 10 CFR 50.34 (a), (b), and 10 CFR 52.47, 52.79, 52.137, and 52.157. In its draft regulatory guide DG-1353, NRC stated that NEI 18-04 defined a methodology for applicants to identify and provide the appropriate level of information needed to satisfy parts of the regulatory requirements contained in the regulations listed above.

An application for a license requires more than just a discussion of the design basis and potential LBEs of a technology-specific reactor. It requires the incorporation of topics such as emergency and security plans, radiation protection plans, quality assurance plans, maintenance and startup programs, and technical specifications. The specific contents of a license application are outside the scope of this report and will be the subject of future TICAP activities. However, there may be opportunities to use the results of some of the evaluations performed using the LMP methodology to establish the level of detail that is necessary and sufficient to demonstrate that the programs will meet the regulations in those portions of the license application. This report is not intended to revisit the structure, process, regulatory basis, or content of the LMP methodology.

## 2.0 REGULATORY FOUNDATION AND PRECEDENTS

The overarching safety objectives of NRC nuclear reactor regulation originates with the Atomic Energy Act of 1954 and the statutes that amended it. The objectives of the Act are to promote the common defense and security and provide a reasonable assurance of adequate protection of public health and safety and the environment. The current regulations, regulatory guidance, policies, and practices developed by the NRC have evolved over more than 40 years of licensing and operating experience almost exclusively with LWR technology. Based on independent reviews of the current regulations, including the work performed in support of Next Generation Nuclear Plant (NGNP), Regulatory Guide 1.232 (advanced reactor design criteria), and the LMP, the following can be concluded:

- At the highest level, the safety objectives of the body of regulation are generally applicable to non-LWRs. The main challenge with the body of regulations is the level of large LWR-specific prescription that is provided in the regulations and supporting guidance documents.
- At the highest level, the regulations provide reasonable assurance that a set of properly defined FSFs, if demonstrated by a reactor design, can provide adequate protection of public health and safety.

To modernize the nuclear regulatory infrastructure, in 1995 the NRC published "Final Policy Statement on the Use of Probabilistic Risk Assessment (PRA) Methods in Nuclear Regulatory Activities," (60 FR 42622) which states in part:

> *"The use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy."*

The NRC communicated its expectations for advanced reactors in the 2008 Policy Statement on the Regulation of Advanced Reactors, (73 FR 60612):

> *"… the Commission expects that advanced reactors will provide enhanced margins of safety and/or use simplified, inherent, passive, or other innovative means to accomplish their safety and security functions."*

The number of NRC publications that include discussion of the Commission's intent to enhance the use of risk-informed and performance-based information in the regulatory decision-making process is extensive, and they will not be repeated in their entirety here. However, there are important publications, discussed below, that showcase the evolution of regulatory thinking from a prescriptive set of regulations to a philosophy that is receptive to a more performance-based and risk-informed set of FSFs that is more technology inclusive while demonstrating that the underlying safety basis for specific regulations would be met. Therefore, as a first step in defining a set of FSFs, it is important to review the history of some relevant regulatory documents that illustrate the movement of the NRC toward potential acceptance of the use of a formal set of FSFs as a sufficient set of functional requirements, that, when demonstrated by the plant design, provide reasonable assurance of adequate protection and therefore would permit the NRC to reach a safety finding.

### 2.1 Future Plant Licensing Framework

Efforts to improve the licensing process and incorporate the use of more risk-informed processes date back to the late 1990s and early 2000s. The culmination of multiple regulatory efforts that considered incorporating risk-informed decision-making into the licensing process was the publication in 2007 of NUREG-1860, "Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing." The stated purpose of the NUREG was to establish the feasibility of developing a risk-informed and performance-based regulatory structure for the licensing of future nuclear power plants. The NUREG presented what it referred to as a "framework" that comprised an approach, scope, and criteria that could be used to develop a stand-alone set of requirements to serve as an alternative to 10 CFR 50 for licensing future nuclear power plants. The framework was a top-down approach with the goal of achieving a level of safety commensurate with that defined by the Quantitative Health Objectives (QHOs) in the NRC Safety Goal Policy Statement of 1986.

The framework addressed risks during full power, low power, and shutdown operations. It also addressed risks from both internal and external events. Thus, it included seismic, fire, and flooding (internal and external) risks as well as risks from high winds and tornados. While it did not use the FSF concept, it did include what was referred to as safety fundamental protective strategies. The framework postulated that these strategies set the design, construction, and operating conditions that, if met, would ensure protection of public health and safety with a high degree of confidence. The framework identified five protective strategies—physical protection, stable operation, protective systems, barrier integrity, and protective actions.

The framework also included the application of PRAs into the design and review process. The framework asserted that the primary role of the PRA was to generate a complete set of transient and accident sequences to provide a rigorous accounting of performance challenges and associated uncertainties. The accident sequences would be used to evaluate the level of safety for a specific nuclear technology by comparing the PRA results with the QHOs and introduced for the first time a frequency-consequence curve. The framework used the frequency-consequence curve and the accident sequences to generate a set of LBEs that would subsequently be used to assess the safety and protective features of a specific nuclear technology. The framework structure marked a stark departure from the process of prescriptive regulation and set the stage for the introduction of more risk information into the development of design and future regulation of nuclear power plants. Some of the concepts contained in NUREG-1860 can be found in the licensing modernization activities that are being implemented by NRC today.

### 2.2 SECY 18-0096 "Functional Containment Performance Criteria for Non-Light-Water Reactors"

The NRC's existing regulations and guidance for nuclear reactors are primarily developed for LWRs and include protections against design basis accidents that reflect the traditional approach of multiple barriers providing DID to limit releases of radioactive material to the public. The containment structures for LWRs have been designed to control the leakage of radioactive materials following design basis accidents that can damage the fuel cladding and pressure boundary. However, the operating conditions, coolants, and fuel forms used with non-LWR technologies differ significantly from LWRs. These technological differences create opportunities for alternate approaches to fulfil the underlying safety objective of limiting the release of radioactive materials.

In SECY 18-0096, NRC introduced the concept of FSFs into regulatory decision-making for advanced reactors and listed the FSFs as controlling reactivity and reactor power, removing heat, and limiting the release of radioactive materials from a reactor facility. Attachment 2 to SECY 18-0096 notes that the need to fulfill FSFs is currently incorporated into the NRC's General Design Criteria as well as other international standards. The attachment states:

> *"The phrase "fundamental safety functions" is taken from International Atomic Energy Agency(IAEA) Specific Safety Requirements SSR-2/1 (Revision 1), "Safety of Nuclear Power Plants: Design" dated February 2016 and align with NRC requirements, such as the general design criteria for LWRs, which are organized in terms of "protection and reactivity control," "fluid systems," and " reactor containment."*

While SECY 18-0096 does not specifically conclude that a one-to-one relationship exists, it does suggest that the NRC is receptive to the idea that the satisfaction of a set of FSFs could translate to the satisfaction of existing design requirements and other governing regulations and that a risk-informed demonstration that FSFs are satisfied could be an alternative means of demonstrating compliance with existing regulations. On the basis of supporting the policy position of a functional containment, the staff spoke of three FSFs that are necessary to provide assurances of adequate protection of public health and safety. The staff used the concept of FSFs in concert with risk assessment methodologies to justify its position in support of the use of functional containment for non-LWRs.

The staff also stated that similar approaches would be addressed within such activities as the LMP for other FSFs. Such a statement suggests that the three FSFs presented in the subject SECY may not be a comprehensive set of functions necessary to reach a licensing decision. However, the NRC's use and acceptance of the policy of making regulatory decisions predicated on risk information and a demonstration that FSFs will be available to mitigate releases advances the philosophy that a demonstration of how FSFs are met could provide reasonable assurance of adequate protection.

## 2.3 Licensing Modernization Project

While the NUREG-1860 efforts did not lead to an alternative set of requirements and associated regulatory processes or guidance, the publication did introduce some concepts that are useful in developing a framework for the licensing of advanced non-LWRs. Notable activities include the recent publication for use of Regulatory Guide 1.232, "Guidance for Developing Principal Design Criteria for Non-Light Water Reactors," in 2018 and the publication for comment of Draft Regulatory Guide DG-1353, "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors" in 2019. DG-1353 endorses the methodology and principles contained in NEI 18-04, "Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development." DG-1353 describes NEI 18-04 as providing one acceptable method for determining the appropriate scope and level of detail for parts of an application for licenses, certifications, and approvals for non-LWRs and further supports the use of FSFs, which it describes as controlling reactivity and reactor power, removing heat, and limiting the release of radioactive materials.

DG-1353 states that the design process and related development of licensing basis information will need to provide an assessment of how the FSFs of reactivity control, heat removal, and retention of radioactive materials will be accomplished. DG-1353 and its endorsement of NEI 18-04 establish an initial framework for a satisfactory demonstration of FSFs as a means to assure adequate protection of public health and safety. More recently, the NRC provided its categorizations of a set of FSFs in its report to Congress dated July 12, 2019. In that report, the NRC describes a set of FSFs as controlling reactivity, removing heat from the reactor and waste stores, and limiting the release of radioactive materials.

### 2.4 Alternative Set of Fundamental Safety Functions

A task within the scope of the TICAP activities was to reexamine the sets of FSFs that have been previously described and to consider other options of FSFs to assure maximum inclusiveness of technologies. With this task in mind, a new option for defining FSFs that uses similar but slightly different language was evaluated. In this report, this option will be known as the alternative option, and its proposed set of FSFs are termination of fission, removal of heat that threatens fission product control, and retention of fission products. This set of potential FSFs are similar to those that were previously mentioned in the documents referenced above. For example, reactivity control would be replaced by termination of fission. The assessment of the various alternatives found in Section 3 provide additional insight.

### 2.5 International Use of Fundamental Safety Functions

#### 2.5.1 International Atomic Energy Agency

The concept of making licensing decisions based on assuring the satisfaction of a set of FSFs has been used internationally and incorporated into safety standards issued by other regulatory authorities. For example, the International Atomic Energy Agency (IAEA) Specific Safety Requirements SSR 2/1, "Safety of Nuclear Power Reactors: Design" published in February 2016 incorporated the regulatory philosophy of demonstrating a set of three FSFs in establishing the necessary levels of safety for operating LWRs. In the IAEA document, these FSFs are control of reactivity, removal of heat from the reactor and fuel store, confinement of radioactive material, shielding against radiation, and control of planned radioactive releases as well as limitation of accidental radioactive releases. The set of FSFs draws heavily from LWR operating experience, but the guidance was developed in broad terms so that applicability to other technologies could be achieved.

The IAEA standard also recognized that other essential elements are needed to provide the necessary levels of safety; however, IAEA did not establish language for FSFs in these areas. Specific examples of important regulatory topics not included in the IAEA definitions of FSFs include emergency preparedness, security and safeguards, and radiation protection of workers.

### 2.5.2 Canadian Nuclear Safety Commission

Application of the FSF concept into the licensing and review process for small modular and advanced reactors can also be found in the guidance published by the Canadian Nuclear Safety Commission (CNSC). CNSC RD-367, "Design of Small Reactor Facilities," published in February 2014 is referenced as the guidance governing small reactor licensing and defines FSFs as functions that must be available during normal operation, during any anticipated operational occurrences, and during any design basis accidents. These functions include:

1. Control of reactivity
2. Removal of heat from the core
3. Confinement of radioactive material
4. Control of operational discharges and hazardous substances
5. Limitation of accidental releases
6. Monitoring of safety-critical parameters to guide operator actions

The document also draws substantially from the Canadian reactor experience and the IAEA safety guides. However, with the advent of vendor design reviews for non-LWRs, the guidance supporting these FSFs has been adapted to non-LWR technologies. CNSC RD-367 goes on to note that the above functions also facilitate response to beyond design basis accidents to the extent practicable. The regulatory document also does not present FSFs for topics such as security or emergency preparedness, although it does recognize their importance, and information on those topics is required as part of a license application.

The CNSC has been implementing the use of a graded risk approach and an FSF concept in its current reviews of non-LWR applications for small and micro-reactors.

## 3.0 ASSESSMENT OF ALTERNATIVE SETS OF FUNDAMENTAL SAFETY FUNCTIONS

In any nuclear technology, the overall risk of a specific nuclear facility is obtained by considering the entire set of potential events and their respective probabilities (or frequencies) and consequences. There are two principal elements that must receive consideration when assessing a facility's overall risk: accident prevention and accident mitigation.

### 3.1 Assessment of Options

An assessment of sets of FSFs must emphasize a broad envelope of functions that may or may not be applicable for a specific technology. The sets of FSFs presented below are very similar in structure and scope, yet there are different points of emphasis within each.

#### 3.1.1 Controlling Reactivity Safety Function

The FSF of controlling reactivity is intended to control normal plant operation and to prevent abnormal plant conditions from escalating into a more significant licensing basis event. Reactivity control also helps facilitate any response to an accident, should one occur, by shutting down the nuclear reaction and reducing the heat generation within the plant that other installed systems would be required to mitigate.

The IAEA equivalent FSF is control of reactivity; CNSC presents it as control of reactivity; NRC states it as controlling reactivity in its Congressional report (Reference 8) but also states it as reactivity and power control in DG-1353 (Reference 4). From a simple comparison, it is apparent that regulatory bodies believe that control of the reactivity present in reactors is an essential safety function. The alternative option has, from its title, more emphasis on the importance of terminating the chain reaction and achieving a safe shutdown state. While termination of the nuclear chain reaction is very important, the seeming emphasis on just termination of fission would potentially eliminate examination of potential initiating events that would examine potential nuclear excursions involving fissile material handling and storage or operation in different plant modes.

During the assessment of this safety function, a proposal to rename the first FSF as control of heat generation was evaluated. In discussing the merits of this proposal, the principal views expressed in support of the use of control of heat generation was that the revision was intended to cover the need for molten salt reactors to prevent freezing of the fuel/salt mixture and concerns that the resulting flow blockage could create reactivity control issues. The supporters of this view also presented the view that while recognizing the importance of controlling reactivity as an important safety function, it was not as fundamental as controlling heat generation and heat removal because if there is a failure to control reactivity without concurrent or resulting failure to control heat generations and removal, there are no safety consequences. The proponents of this alternative FSF also support a view that control of reactivity may not assure control of heat generation given the unique design of molten salt reactors.

In contrast, views expressed in support of the use of the FSF as controlling of reactivity centered around two topics. First, without introduction of the fission process through increased reactivity, there would be no energy delivered to the primary system coolant or moderator, and, by extension, no heat generated to create a heat imbalance. Second, while the supporters of the revised FSF acknowledge that criticality and reactivity concerns would exist in places not typically associated with nuclear fission, the control of heat generation description would not be as technology inclusive and would not seem to establish functional requirements to avert inadvertent criticality concerns in areas of the plant not inside the primary system. Potential concerns would be for reactivity excursions in off-gas systems, fuel handling, fuel storage, or waste storage areas. After some interactive discussion on the various pros and cons, there was no unanimity of views on how to proceed, although a larger consensus supported retaining "control of reactivity" as the title of the FSF.

The NRC language of controlling reactivity from the July 12, 2019, Congressional report (Reference 8) is the most recent NRC description of fundamental safety functions and is the preferred language for this FSF. A broad interpretation of this FSF is also encouraged to be more technology inclusive. Acknowledging that there is no unanimity of view on this FSF, for future use within TICAP, the FSF will be described as controlling reactivity. The FSF of controlling reactivity is defined as the active, passive, or inherent means provided (1) to control the nuclear chain reaction consistent with the intended plant operating conditions, (2) to terminate the nuclear chain reaction when transient or accident conditions dictate that the facility must be shut down, and (3) to prevent inadvertent criticality in the reactor core, primary system, fuel handling system, or other areas of the plant where inadvertent criticality is an adverse condition that could result in unacceptable radiological consequences.

### 3.1.2 Removing Heat from the Reactor and Waste Stores Safety Function

The FSF of removing heat serves two critical objectives. First, removal of the generated heat, whether during normal operation, following an Anticipated Operational Occurrence (AOO), an LBE, or a design basis accident would serve to assure that equipment would operate within the environmental envelope for which it is designed and qualified. Second, heat removal would serve to prevent an AOO or LBE from progressing into a more severe event category and, as such, would serve to mitigate the potential for releases of radioactivity from the facility. The options will be examined in that light.

The IAEA equivalent FSF lists it as removal of heat from the reactor and fuel store; CNSC presents it as removal of heat from the core; NRC provides it as removal of heat from the reactor and waste stores. All proposals emphasize the removal of heat; however, the location and breadth of examination are different.

The options provided by IAEA and NRC appear to be most similar, with the only variant being the inclusion of fuel store versus waste store. Therefore, these two options could be synonymous upon closer examination of the implementing guidance. Both options recognize that heat may be generated away from the reactor, and therefore, adoption of either of these options would require the examination of potential licensing basis events broader than just heat removal from the reactor and primary system. In some advanced reactor technologies, there may not be a core as is present in contemporary LWR plants, and therefore, the application of the CNSC option would not be immediately apparent. The CNSC option would appear on the surface to be limited in its application in that heat sources that could result in potential challenges to release of radioactive materials might be present in other areas of the plant.

The alternative option presents a narrower scope in that it emphasizes only control of residual heat (interpreted as decay heat because of this option's earlier emphasis on termination of fission) and then further narrows the heat management to only that portion of the residual heat that would challenge release pathways for radioactive materials. While it can be argued that the particular focus on challenges to the release pathways is consistent with the LMP focus on meeting the frequency-consequence curve, the limitations of this option appear to be its focus only on residual heat and not heat generated during operations or following other potential licensing basis events or accidents where, because of postulated component or system malfunctions, the reactivity control safety function is not successfully performed.

Based on the discussion above, the broader treatment of heat removal is preferred, and the IAEA/NRC language is recommended. For future use in TICAP activities, the FSF of Removing Heat from the Reactor and Waste Stores is defined as the active, passive, or inherent means provided (1) to remove the heat generated from the nuclear chain reaction in the nuclear fuel, primary system, or fuel handling system during normal plant operating modes or following postulated transients or accidents, (2) to remove the decay or residual heat from the reactor, primary system, or fuel handling system when the nuclear chain reaction is terminated and when the facility is shut down, and (3) to remove the residual heat from material that is being stored in fuel handling or waste handling areas so that unplanned releases of radioactive materials from the plant do not occur.

### 3.1.3 Limiting the Release of Radioactive Materials

While all the FSFs are important, the FSF of limiting the release of radioactive materials is of larger significance because it represents the ultimate objective of protecting the public from exposure to radiation. For many licensing basis events, the previous two FSFs address the avoidance of precursor conditions that would challenge or exacerbate the release of radioactive materials. The plant design features included to limit potential releases to the environment, whether they be physical barriers or systems, present the final in-plant opportunity to assure that public health and safety are protected.

The IAEA lists the equivalent FSF as the confinement of radioactive material; CNSC also presents it as confinement of radioactive material; NRC states it as limiting the release of radioactive materials. Again, all proposals emphasize the goal of limiting releases of radioactive materials to the environment and minimizing radiological exposures to the public. From an assessment standpoint, there is little difference, if any, between the options. Each option would assess potential licensing basis events in the same manner and would examine the success or failure of SSCs that would serve to delay or interdict the release of radioactive materials following an AOO, licensing basis event, or design basis accident.

Given that there are no distinguishable differences between the scope and breadth of the options, the use of the NRC language is preferred and is recommended. Therefore, for use in future TICAP activities, the FSF of Limiting the Release of Radioactive Materials is defined as the active, passive, or inherent means provided to prevent or mitigate the release of radioactive materials from the facility to the public and the environment.

### 3.1.4 Recommended Set of Fundamental Safety Functions

The recommended set of FSFs includes the following:

1. Controlling Reactivity

   The FSF of controlling reactivity is defined as the active, passive, or inherent means provided (1) to control the nuclear chain reaction consistent with the intended plant operating conditions, (2) to terminate the nuclear chain reaction when transient or accident conditions dictate that the facility must be shut down, and (3) to prevent inadvertent criticality in the reactor core, primary system, or other areas of the plant where inadvertent criticality is an adverse condition that could result in unacceptable radiological consequences.

2. Removing Heat from the Reactor and Waste Stores

   The FSF of Removing Heat from the Reactor and Waste Stores is defined as the active, passive, or inherent means provided (1) to remove the heat generated from the nuclear chain reaction during normal plant operating modes so that the nuclear fuel and primary system retain their integrity, (2) to remove the decay or residual heat from the reactor and primary system when the nuclear chain reaction is terminated and when the facility is shut down, and (3) to remove the residual heat from material that is being stored in waste handling and fuel handling areas so that unplanned releases of radioactive materials from the plant do not occur.

3. Limiting the Release of Radioactive Materials

   The FSF of Limiting the Release of Radioactive Materials is defined as the active, passive, or inherent means provided to prevent or mitigate the release of radioactive materials from the plant to the public and the environment.

These FSFs provide comprehensive coverage of important plant functions for a spectrum of reactor technologies' postulated licensing basis events, and design basis accidents. Currently, there would seem to be no need to expand the set of FSFs beyond those given here. However, should the subsequent guidance development activities identify a need to revise the definitions or add to the list of FSFs, the topic of FSFs will be revisited.

The role that each FSF plays within a specific technology may not be equivalent. The role of limiting releases of radioactive material may be the ultimate functional objective; however, that does not mean that the remaining FSFs are not needed. There may be instances within specific designs or technologies when it appears that an FSF is not needed. In actuality, the FSF is being provided by some inherent means incorporated by the reactor designer. It will be the responsibility of the applicant to provide the discussion that demonstrates how the FSF is being satisfied by the inherent means included in the design.

## 4.0 APPLICABILITY OF THE RECOMMENDED FUNDAMENTAL SAFETY FUNCTIONS

As with all regulatory documents, it is important to define the scope of the activities to be covered by the recommended FSFs. As mentioned earlier, this report is not expanding the scope of evaluation documented within NEI 18-04. The FSFs would be applicable to both internal and external events, including events initiated by seismic, fire, and flooding (internal and external) events from high winds and tornados. Unique site characteristics would also be included as initiating events such as hazardous materials being transported near the site, pipelines, and small aircraft from regional airports. Initiating events associated with fuel handling systems, fuel storage, or waste stores will be dependent on the specific technology and on the extent to which initiating events are possible and would need to be evaluated.

## 5.0 IMPORTANCE OF REGULATORY MAPPING

Within the current regulatory framework, the technical requirements of the content of an application are focused on providing adequate information related to how the proposed design demonstrates compliance with applicable regulations. For LWRs, the current regulatory requirements provide the necessary reasonable assurance of adequate protection required by the Atomic Energy Act. Therefore, the application of a set of FSFs should be able to be mapped to the underlying objectives of the existing regulations. The mapping provides the basis that satisfaction of the FSFs provides the necessary burden of proof that the design complies with the underlying objectives of the existing regulatory requirements with appropriate margins and will still provide adequate DID across the full range of LBEs associated with the specific design.

In order to provide adequate assurance, it will be necessary to identify all current regulatory requirements for applications at a high level and to establish the regulatory relationship of the high-level regulations within the TICAP scope to the FSFs. The product of this mapping will demonstrate that the set of FSFs is comprehensive for non-LWR technologies and will be provided later as part of the overall process of developing the regulatory guidance on the appropriate level of detail for the content of an application for a license.

## 6.0 CONCLUSIONS

In summary, the use of an FSF framework, when implemented in concert with the LMP methodology described in detail in NEI 18-04, can be a reasonable surrogate for the current licensing process of strict compliance with a prescriptive set of regulations designed for LWR technologies. Based on the assessment above, the recommended set of FSFs includes the following:

1. Controlling Reactivity

   The FSF of controlling reactivity is defined as the active, passive, or inherent means provided (1) to control the nuclear chain reaction consistent with the intended plant operating conditions, (2) to terminate the nuclear chain reaction when transient or accident conditions dictate that the facility must be shut down, and (3) to prevent inadvertent criticality in the reactor core, primary system, or other areas of the plant where inadvertent criticality is an adverse condition that could result in unacceptable radiological consequences.

2. Removing Heat from the Reactor and Waste Stores

   The FSF of Removing Heat from the Reactor and Waste Stores is defined as the active, passive, or inherent means provided (1) to remove the heat generated from the nuclear chain reaction during normal plant operating modes so that the nuclear fuel and primary system retain their integrity, (2) to remove the decay or residual heat from the reactor and primary system when the nuclear chain reaction is terminated and when the facility is shut down, and (3) to remove the residual heat from material that is being stored in waste handling and fuel handling areas so that unplanned releases of radioactive materials from the plant do not occur.

3. Limiting the Release of Radioactive Materials

   The FSF of Limiting the Release of Radioactive Materials is defined as the active, passive, or inherent means provided to prevent or mitigate the release of radioactive materials from the plant to the public and the environment.

These FSFs, as defined within this document, provide comprehensive coverage of important plant functions for a spectrum of reactor technologies, postulated license basis events, and design basis accidents.

The development of additional guidance on the content of applications will use the FSFs as defined in this report to develop the more detailed safety content of potential license applications. The LMP methodology will systematically demonstrate that the selected LBEs adequately cover the range of hazards to which a specific design would be exposed and properly reflect the potential impacts on structure, system, and component design criteria and failure modes that are appropriate for the design under review. The methodology provides a well-structured, safety-focused, and risk-informed process to comply with the existing body of deterministic and prescriptive regulations. Further, an applicant following the NEI 18-04 methodology will be able to confirm that the SSCs are designed to perform the functions required to prevent or mitigate potential radionuclide material release from the facility. An applicant following the methodology can demonstrate that the SSCs that perform the functions are adequately capable, reliable, diverse, and/or redundant across the layers of defense provided by the design as evident from the evaluation of DID.

However, it is acknowledged that an application that uses the methodology in the NEI 18-04 guidance document to demonstrate that the set of FSFs is satisfied is not a sufficient legal basis for the NRC to issue a license. An applicant will need to address as part of the application such programmatic topics as quality assurance, radiation protection of workers, security, financial assurance, and emergency preparedness, to name just a few, before the NRC would have sufficient information to reach an overall conclusion that all the regulations would be met and that the proposed facility could be constructed and operated in accordance with the Commission requirements. To the extent that additional guidance is needed for satisfaction of these ancillary requirements, that guidance for non-LWR advanced reactors is beyond the scope of TICAP and may be addressed by other initiatives.

## 7.0 REFERENCES


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