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Regulatory Review of Micro-Reactors – Initial Considerations

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) is working to have an effective and efficient mission readiness for reactors that differ considerably from those currently licensed. Micro-reactors, that is, reactors that have a thermal power of no more than tens of megawatts, are one class of these advanced reactors. This report is to articulate the technical and regulatory issues that will need to be addressed for NRC to have the ability to review licensing applications for micro-reactors. Many of the issues center around the fact that a) these reactors may be operated remotely and/or semi-autonomously and b) it will be difficult to analyze risk from new, unique, technologies. Initial thoughts are given on how probabilistic methods could be used to determine risk and how the current approach for reviewing non-power reactors could be useful for micro-reactors.

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ACRONYMS

AEA	Atomic Energy Act
AOO	Anticipated Operational Occurrence
ASME	American Society of Mechanical Engineers
BDBE	Beyond Design Basis Event
CFR	Code of Federal Regulations
ConOps	Concept of Operations
DBA	Design Basis Accident
DBEHL	Design Basis External Hazard Level
DG	Draft Regulatory Guide
DOD	Department of Defense
DOE	Department of Energy
FMEA	Failure Modes and Effects Analyses
FPP	Fire Protection Plan
HAZOP	Hazard and Operability
IAP	Implementation Action Plan
INL	Idaho National Laboratory
ISG	Interim Staff Guidance
LBE	Licensing Basis Event
LMP	Licensing Modernization Project
LWR	Light Water Reactor
MHA	Maximum Hypothetical Accident
MLD	Master Logic Diagram
NFPA	National Fire Protection Association
NPH	Natural Phenomena Hazards
NEI	Nuclear Energy Institute
NPUF	Non-Power Production and Utilization Facility
NRC	U.S. Nuclear Regulatory Commission
PRA	Probabilistic Risk Assessment
RADS	Reliability and Availability Data System
Rx	Reactors
SECY	NRC Commission Paper
SMR	Small Modular Reactor
SRM	Staff Requirements Memorandum
SSCs	Structures, Systems, and Components
TI-RIPB	Technology-Inclusive Risk-Informed Performance-Based
TRISO	Tristructural Isotropic

1 INTRODUCTION

1.1 Background

Over the past several years there has been significant interest in the development and regulatory needs of advanced reactors that will be very different from the light water power reactors and the research and test reactors that are currently licensed in the U.S. Advanced reactors may be different because they use gas, liquid metal, or molten salt as a coolant; have a fast neutron spectrum; have a unique fuel form; or because of many other design and operational features. One type of advanced reactor is the micro-reactor, which is generally small (less than roughly tens of megawatts-thermal (MWt)), with low potential accident consequences and generally of simpler design.

To prepare for all potential non-light water reactor (LWR) application submittals, the NRC has developed a vision and strategy document [1-1] that outlines the tasks that must be undertaken to advance technical and regulatory readiness and related communications for these reactors. That document is supported by implementation action plans (IAPs) [1-2] that cover the actions to be taken in the next five years based on six basic strategies. IAP Strategy 3 is relevant to micro-reactors as it discusses developing guidance for a flexible review process within the bounds of existing regulations. For micro-reactors a flexible review process would include sufficient information to provide reasonable assurance of public health and safety. IAP Strategy 5 involves the identification and resolution of technology-inclusive policy issues.

A micro-reactor might be used for generating electricity or process heat for commercial, military, or space applications. There are currently more than ten companies with different micro-reactor designs [1-3]. Proposed designs have unique heat removal systems, for example, using heat pipes; or new fuel forms that have not previously been licensed such as TRISO fuel particles[a]. Some proposed designs are considering factory manufacturing and transporting the reactor to a site fully fueled where they may be operated remotely or semi-autonomously. The exposure to the public from any postulated accident in some designs may be essentially zero or much lower than current acceptance criteria. These features may impact the regulatory approach and hence, it is necessary to consider the policy and technical hurdles that would need to be addressed by NRC.

Furthermore, there are questions as to what the starting point for regulatory consideration of micro-reactors would be. For example, if they are power reactors, should they be reviewed like large power reactors but taking into account their unique features–similar to the approach taken for so-called small modular reactors? If they have low source terms like non-power reactors should they be reviewed in a similar fashion to what is done for a research or test reactor? If they are to be factory built, how does applying for a Manufacturing License change the review? And if they are small

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[a] In general, the details of the designs are proprietary and are not publicly available. Some specific design information is given in [1-4, 1-5].

enough to have a risk no larger than existing radioactive (non-reactor) sources, should they be reviewed in that way?

1.2 Objective

In light of the unique aspects of micro-reactors, the NRC is considering a specific regulatory approach for reviewing them. The objective of this report is to discuss relevant issues—a starting point for more specific recommendations as to how these issues will be resolved. This includes both technical and regulatory issues and the relevance of what permit or license, or other safety evaluation might be the objective of such a review. Two issues have been selected for more detailed discussion; namely, the use of a non-power reactor approach for reviewing licensing submissions and the application of risk analysis.

The report is based on relevant NRC regulations or guidance (e.g., *Code of Federal Regulations* (CFR), Commission (SECY) papers and corresponding Staff Requirements Memoranda (SRMs)) including both those that are specific to non-LWRs as well as those that are from more general NRC policy but still applicable. Relevant guidance from other U.S. agencies, international organizations, or industry stakeholders is also considered. The report is an initial study to identify regulatory gaps that might exist and could influence recommendations in the future as to how they might be handled with changes to regulations, policies, and/or guidance. It is clear that much more work is needed to delineate the alternatives that may apply and to determine the review process.

Items of interest for micro-reactors that are not included in the report are annual fees, the front and back end of the corresponding fuel cycle, environmental reviews, and the need for specialized computer tools to assist in the review process.

1.3 Outline of Report

Chapter 2 summarizes 20 technical and regulatory issues that arise because of the unique features of micro-reactors relative to reactors that have been licensed in the past. Some of these issues are directly related to obtaining risk insights and some are directly related to the potential for remote or semi-autonomous operation. Chapter 3 discusses how an application review might take place using the current approach for non-power reactors (e.g., research and test reactors) as a starting point. This approach has credence because the accident source term may be similar for micro-reactors and existing non-power reactors. Chapter 4 discusses risk analysis as it might be applied to micro-reactors. This includes consideration of probabilistic risk assessment as it is currently applied to power reactors as well as alternatives that only utilize some probabilistic methods or are completely deterministic. Because there are references to Parts of Title 10 of *the Code of Federal Regulations* (10 CFR) throughout this report, a list of the titles of the relevant sections/parts is given in the Appendix.

1.4 References

1-1. NRC, “NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness,” U.S. Nuclear Regulatory Commission, 2016.

1-2. NRC, “NRC Non-Light Water Reactor (Non-LWR) Vision and Strategy – Staff Report: Near Term Implementation Action Plans,” Volume 1, Executive Information and Volume 2, Detailed Information,” U.S. Nuclear Regulatory Commission, 2016.

1-3. GAIN-EPRI-NEI-US NIC Micro-Reactor Workshop, https://gain.inl.gov/SitePages/Workshops.aspx June18-19, 2019.

1-4. Patrick Ray Mcclure, David Irvin Poston, Venkateswara Rao Dasari, and Robert Stowers Reid, “Design of Megawatt Power Level Heat Pipe Reactors,” LA-UR-15-28840, Los Alamos National Laboratory, November 12, 2015.

1-5. A. Maioli et al., “Westinghouse eVinci™ Micro-Reactor - Licensing Modernization Project Demonstration,” EMR_LTR_190010, Southern Company, August 2019.

2 TECHNICAL AND REGULATORY POLICY ISSUES

2.1 Introduction

In this chapter technical and policy issues related to micro-reactors are summarized. Some of the issues will require specific action by the NRC, for example, rulemaking for policy issues or regulatory guidance for technical issues; and some issues may be covered as a result of the needs of other types of advanced reactors or covered by existing regulatory pathways. Some issues may require knowing more about potential micro-reactor designs before they can be addressed. Accordingly, some issues may present themselves as micro-reactor designs evolve.

The issues discussed in Section 2.2 are listed in Table 2-1 and are a subset of issues of interest to NRC. As noted in the table, many of these issues are also being discussed by stakeholders in industry [2-1, 2-2]. Several issues are connected to one another, for example, items 2, 3, and 4 are connected to risk modeling, and items 10-14 relate to operations.

Table 2-1 Issues Addressed in this Report

	Issue
1	Risk Modeling/Probabilistic Risk Assessment
2	Testing Programs and Prototypes
3	Operating Experience
4	Industry Codes and Standards
5	End of Life Determination
6	Seismic and Other Natural Phenomena Hazards
7	Fire Protection Regulations
8	Siting (Remote vs Population Centers)
9	Inspection and Oversight[†]
10	Remote Operations[†]
11	Autonomous Operations[†]
12	Control Room Design[†]
13	Staffing Requirements for Licensed Operators[†]
14	Maintenance and Surveillance[†]
15	Emergency Preparedness[†]
16	Security[†]
17	Radiation Protection Requirements
18	Aircraft Impact Assessment[†]
19	Containment Structure
20	Manufacturing License
[†]Identified by industry as a priority issue.	

2.2 Technical and Regulatory Policy Issues

Risk Modeling – Probabilistic Risk Assessments (PRAs)

Risk modeling has become an essential part of any licensing process because of its usefulness in the design process and because a description of the PRA and its results are a required part of licensing applications. For micro-reactors this would involve modeling unique features associated with these reactor designs, for example, passive components with associated active components and/or sensors for monitoring, parameters that indicate failure in safety features, and power systems not used in current nuclear applications. These new features bring in additional issues relating to lack of operating experience, limited use of written procedures, and non-applicability of traditional failure detection by surveillance of safety systems. In that regard, PRA modeling of micro-reactors may have to address many different issues compared to that for PRAs of large LWRs or non-LWRs. Risk analysis is discussed further in Chapter 4.

Testing Programs and Prototypes

The NRC Roadmap for Non-LWRs [2-3] discusses testing of advanced reactor design features to ensure that designs are sufficiently mature for NRC review and approval. Micro-reactors are expected to have features that are unique for nuclear applications and without any direct operating experience. Vendors of reactors may have to decide where they need separate tests to address these new features or prototype testing to demonstrate safety.

10 CFR Part 52.47(b)(2) provides criteria to determine if the designer has sufficiently justified the advanced reactor design that a design certification can be awarded. Consistent with the criteria, the staff prepared SECY-91-074, “Prototype Decisions for Advanced Reactor Designs,” [2-4] to delineate how to determine the testing needs and the need for prototype facilities for a certification-by-test approach. Based on the SECY, Enclosure 1 to the Roadmap discusses testing needs for advanced reactor designs. The process presented involves a series of questions that enable the applicant to consider the testing objectives, evaluate those objectives in ascending order of testing complexity and value, combine tests where possible, analyze the results against the regulatory requirements, and determine the applicability or deficiency of the testing or the new reactor design.

To move forward with this issue, it is necessary to review the process and the list of questions used considering the unique micro-reactor design features that may be associated, and then assess the need for changes, if any, to the existing process for micro-reactor regulation and certification.

Operating Experience

Micro-reactors are new and are expected to have unique components and operational philosophies. Accordingly, there may be limited or no data on direct operating experience. The Advanced Reactor Policy Statement [2-5] addressed the role of supporting technology in advanced reactor designs and NRC staff's position on development and utilization of the policy statement (NUREG-1226) [2-6] discusses and encourages use of operating experience. NUREG-1226 states that "The available sources of operating experience should be used whenever possible. It is emphasized that sources of useful operating experience are not limited to reactors." NUREG-1226 also discusses the use of foreign information and data: "the use of foreign data to support a U.S. advanced reactor design is acceptable provided the staff has sufficient access to the design, analysis and experimental data being used."

This approach to the use of operating experience in new LWR designs is already incorporated in the staff's review of human factors engineering described in NUREG-0711 [2-7], which is used by the staff along with Chapter 18 (Human Factors Engineering) of NUREG-0800 [2-8]). Review criterion 3.4.1 (1), *Predecessor/Related Plants and Systems,* of NUREG-0711 indicates that "For applicants proposing to use new technology or systems that were not used in the predecessor plants, the OER [operating experience review] should review and describe the operating experience of any other facilities that already use that technology."

For micro-reactors, data relating to heat pipes, supercritical CO_2, and other potential components are expected to be gathered from non-nuclear experience. The operating environment of the available data may be different than that for micro-reactors. This issue is discussed further in Chapter 4, in relation to risk analysis.

Industry Codes and Standards

NRC usually depends on industry codes and standards to address equipment performance, qualifications, and testing requirements. Micro-reactors may be associated with new types of equipment that have never been manufactured before or equipment that may not have been used in the nuclear industry. Hence, it will be necessary to understand how new codes and standards might assist in the review process for micro-reactors.

End of Life Determination

The operating life cycle of micro-reactors are expected to be different from the reactors currently licensed by the NRC. Some micro-reactors are expected to operate for a fixed period without refueling and maintenance. In particular, many designs currently being considered (e.g., from Westinghouse, Oklo, NuScale (single-unit NuScale Power Module), General Atomics, and X-Energy) (Appendix A of [2-2]) are expected to operate for at least 10 years without refueling and some for as long as 20 years. Determination of the long refueling/life cycles is unique to micro-reactors and will need to be addressed in the regulatory review process.

Seismic and Other Natural Phenomena Hazards (NPH)

For micro-reactors, the risk of significant radiation release initiated by NPH is expected to be significantly reduced compared to current commercial power reactors. The design operating life (e.g., 10 years), the ease/cost of replacement, and the radiological consequences of failure will be factors in defining the NPH performance targets. It is conceivable that performance targets for NPH may be eliminated completely, based on risk-informed, performance-based methodologies. The overriding consideration in a micro-reactor design may be to maintain operability following an NPH event, thereby requiring hardening against NPH.

The potential for factory fabrication of a standard design, followed by transportation to and installation at locations unknown at the design stage does pose unique technical issues for addressing natural phenomena hazards in general, and especially the seismic hazard. The 10 CFR Part 52 “Design Certification” experience for LWRs has demonstrated the difficulty in specifying generic seismic design loads, applicable to a wide range of possible sites within the Eastern United States. For micro-reactors, the potential sites are more broadly based. Two possible approaches to deal with this are:

1. The standard structural design is sufficiently robust to survive a very conservatively defined generic dynamic loading resulting from transportation and earthquake, without compromising dimensional stability and operability. This would be demonstrated by generic testing of a prototype.

2. The standard design includes vibration isolation components to mitigate both transportation and seismic dynamic loading. The vibration isolation components could be designed for generic dynamic loading or, in some cases, may need to be designed for a specific application (transportation-earthquake combination). This would be demonstrated by testing.

Micro-reactors that are not factory assembled and transported to the site may require one of the above approaches to be applied to factory-assembled discrete modules, and a more traditional site-specific seismic analysis of the on-site assembled micro-reactor.

The effects of NPH such as wind, tornado, and hurricane, can be minimized by below-grade installation and a protective cover. The micro-reactor could be protected for virtually any magnitude of these NPH. This would also minimize exposure to an external terrorist threat or vandalism. The poterntial for weather-induced flooding should be minimized by proper site selection, to the extent practical.

Regulatory review approaches or alternatives can be defined considering different designs, whether factory assembled or site assembled, if there is inclusion of vibration isolation components to mitigate NPH impacts, and for other related issues.

Fire Protection

Regulatory Guide 1.189, Rev. 3, “Fire Protection for Nuclear Power Plants,” [2-9] includes a section “Other New Reactor Designs.” Section 9.5.1.2 of NUREG-0800, which is for LWRs, [2-8] discusses the Risk-Informed, Performance-Based Fire Protection Program.

For micro-reactors, a risk-informed, performance-based approach may be used to simplify the fire protection requirements and their review. The Standard Review Plan (NUREG-0800) discusses the elements that are reviewed for a fire protection program and hence, should be reviewed to delineate the applicable elements for review of a micro-reactor fire protection program.

Siting (Remote vs Population Centers)

Some micro-reactors are being designed for siting in remote locations without access to the electrical grid and no/low population in the vicinity. They may also be sited at locations where mining or other industrial activities are being conducted. The siting analyses that may be applicable may be different than what are currently required. NRC may need to define a new rule for such siting or additional guidance for existing rule may apply to facilitate licensing applications and their review.

Inspection and Oversight

Due to their smaller size, a large portion or the complete micro-reactor can be fabricated in the factory. This is different from the reactors that have been licensed previously by the NRC. At the same time, operation of the reactors may be largely autonomous requiring minimal oversight.

As a result of the above, resident inspectors during operation may no longer be required, but additional inspection during the construction phase may apply. Micro-reactors may include unique components that have never been manufactured before, requiring specific testing. Much or all of the startup testing may be conducted at the factory. Construction inspection may need to be broadened and may be conducted by NRC inspectors during periodic visits, as opposed to a resident inspector at the factory.

Some site preparation and on-site construction activities are expected. Micro-reactors are designed to use fewer components and structures and accordingly, perhaps fewer issues are expected. NRC inspection at some intervals along with inspection during the installation and startup may be considered adequate.

NRC has flexibility in defining the inspection and oversight process for micro-reactors considering their unique characteristics and associated needs within the current rules and regulations. These considerations may lead to defining new inspection manuals and procedures for micro-reactors addressing the needs of the oversight process with different implementation plans. Taking into consideration that micro-reactors may be fabricated at a factory, risk-informed inspections at the factory by NRC inspectors are discussed in Chapter 4.

Remote Operations

The concept of operations (ConOps) for some micro-reactors may include the use of remote operations. The reactor will be located at the desired site while monitoring, and if necessary control, may be handled from a remote location. Such a ConOps is not addressed in current review guidance.

Autonomous Operations

While the detailed ConOps of specific micro-reactor designs is not yet known, it is likely that increased autonomy of operations will be a defining design characteristic. Autonomy can be conceptualized as a scale extending from completely manual operations (all operations performed by human crews) to full autonomy (monitoring and control of reactor operations performed by automation systems with no human intervention). There are many waypoints between these extremes where the level of human involvement decreases and the degree of autonomy increases. In a semi-autonomous plant, some aspects of operations are performed automatically, while others are performed by human crews. Exactly where specific micro-reactor designs fall on this scale will depend on their ConOps. High degrees of autonomy will raise regulatory challenges since they will represent a departure from many regulatory requirements and may require exemptions that need to be reviewed.

An example is control room (and plant) staffing. Currently, staffing requirements for licensed operators are defined in 10 CFR Part 50.54(m) and all operating power plants meet these requirements. An exemption from this regulatory requirement will be needed for applicants of designs proposing a ConOps with few to no on-site staff. The NRC staff can use NUREG-1791 ("Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR Part 50.54(m)") [2-10] to support these reviews. However, this guidance specifically focuses on the review of minimum staffing in the main control room. It is focused on changes to in-plant staffing in a dedicated control room and may not be applicable to a design not containing a traditional control room (see the discussion of Control Room Design below).

Thus new guidance is needed.

Control Room Design

10 CFR Part 50.34(f)(2)(iii) requires applicants to provide a control room design that reflects state-of-the-art human factor principles prior to committing to the fabrication or revision of fabricated control room panels and layouts. Acceptance criteria for human factor engineering design methodology are provided in NRC guidance documents for LWRs [2-7, 2-11, 2-12]. A highly-autonomous micro-reactor, may not have a control

room that can be reviewed using the staff's existing criteria. New review guidance may be needed for reviewing alternative control room designs and for exemption requests pertaining to control room location and design.

Furthermore, the guidance and review criteria for non-power reactors in NUREG-1537 [2-13] Section 7.6, Control Console and Display Instruments, states that "The non-power reactor control room, containing the control console and other status display instruments is the hub for reactor facility operation. It is the location to which all information necessary and sufficient for safe and effective operation of the facility is transmitted, and the primary location from which control and safety devices are actuated either manually or automatically." Acceptance criteria for control console review are provided. Similarly, NUREG-1537 Chapter 12 addresses facility staffing requirements and related considerations such as qualifications, selection, and training.

An autonomous micro-reactor or one that is a remotely operated micro-reactor may not have a control room that can be reviewed using the staff's existing criteria. New review guidance may be needed. At a minimum, the staff will need guidance for reviewing exemption requests pertaining to control room location and design.

Staffing Requirements for Licensed Operators

As noted in the discussion of Autonomous Operations above, the current staffing requirements for licensed operators are defined in 10 CFR Part 50.54(m). As discussed above, however, some micro-reactor designs may propose a ConOps with few on-site staff. Furthermore, staffing positions may differ from those in current regulations and review guidance. Applicants may apply for exemption requests from these regulatory requirements. Currently, detailed guidance for performing staffing reviews (including how to make exemptions) is provided in several documents [2-7, 2-10, 2-11, 2-14]. However, that guidance is focused on staffing in a dedicated control room and may not be applicable to reactor designs based on novel ConOps. Thus, additional guidance will be needed.

Maintenance and Surveillance

Micro-reactor designs are very different than current LWRs and maintenance and surveillance requirements are expected to be significantly different. Some micro-reactors being considered are expected to operate continuously for 10 to 20 years without the need for shutdown for refueling. These reactors are expected to include very few moving parts requiring minimal maintenance. Surveillance requirements are also expected to be different.

Micro-reactor designs that operate purely using natural physical forces with very few moving parts are being designed to require minimal or no maintenance. Application of the maintenance rule (10 CFR 50.65) is expected to be different and significantly simpler. These reactors may, however, be associated with some types of surveillance to ensure continued operation. An alternative approach to determining the maintenance and surveillance needs for these facilities will need to be defined.

Emergency Preparedness

For remotely sited micro-reactors, emergency preparedness will be different from other types of reactors. In such situations, micro-reactors may not have a Technical Support Center near the facility and may not need an on-site plan. Outside resources can arrive at a later time after an emergency and the role of the emergency assistance can be different.

The current rulemaking on emergency preparedness [2-15] for small modular reactors and other new technologies is considering a performance-based approach for emergency preparedness and may be applicable to micro-reactors.

Security

Security requirements for micro-reactors will depend on design features along with site characteristics. Three types of locations can be considered: (a) Department of Defense (DOD) or Department of Energy (DOE) facilities, (b) remote locations, and (c) private property along with other industrial facilities. Appropriate design basis threat and response may need to be defined for each of these types of locations.

DOD and DOE facilities will require reduced security requirements as they will have existing physical security and emergency response capabilities. NRC guidance can be provided for these facilities to ensure additional security and emergency response measures that may be needed.

Security requirements for remote locations may be defined at the site selection stage to allow for appropriate measures considering the time needed for any kind of response. This may involve setting up a larger perimeter with monitoring devices. Private property with other industrial facilities in populated areas will require defining appropriate threats and physical security measures commensurate with the proposed physical security rule modifications.

Radiation Protection Requirements

The Standard Review Plan [2-8] addresses the radiation protection review for LWRs. It addresses four different areas: (a) assuring that occupational radiation exposures are as low as reasonably achievable, (b) radiation sources, (c) radiation protection design features, and (d) operational radiation protection program. For micro-reactors, the radiation protection requirements will depend on the radiation sources and the radiation protection design features for the design. Elements of the existing guidance may be used for the review of micro-reactor applications.

jAircraft Impact Assessment

Micro-reactors because of their size and design may not be as vulnerable to aircraft impacts as existing reactors. The likelihood of impacts is small in remote locations, and the consequences are expected to be minimal. However, in some conditions and for some designs, aircraft impact can have unacceptable consequences. An approach or criteria may be defined to identify the cases where aircraft impact assessment may be needed. Risk assessment for the facility can provide useful input in defining the approach/criteria.

Containment Structure

In SRM-SECY-18-0096 [2-16], the Commission approved NRC staff proposed functional containment performance criteria in SECY-18-0096 [2-17] for non-LWRs. The proposed methodology is expected to be used by the designers in a manner that is technology inclusive, risk-informed, and performance-based. In this approach, the performance criteria for the design features associated with retaining radioactive materials within a facility will be established based on the range of event categories and the related success criteria for each category. In addition, assessments are performed to ensure that sufficient defense-in-depth has been incorporated into the designs and programmatic controls. It is anticipated that the design features will limit potential offsite doses to values below those that would justify alternative offsite emergency planning. Evaluation of the proposed performance-based containment criteria for applicability to micro-reactor designs can define the specific needs or alternatives that apply.

Manufacturing License

In general, there are several ways in which applicants engage with the NRC, for example: as a power reactor through either 10 CFR Part 50 or 10 CFR Part 52; as a non-power reactor (under 10 CFR Part 50); and through a manufacturing license (under 10 CFR Part 52).[b] One of the deployment strategies for micro-reactors is as a pre-fabricated mobile nuclear power plant. 10 CFR Part 52 Subpart F provides for manufacturing licenses, which essentially allows for pre-fabrication of nuclear power plants and then installation and operation at separately approved sites (via other licensing processes in 10 CFR Part 50 or 10 CFR Part 52). There is also provision in both 10 CFR Part 50 and 10 CFR Part 52 (Appendix N in both Parts) for the construction and operation of nuclear power reactors of identical design at multiple sites.

[b] Historically there was another class of power reactor licensed pursuant to subsection 104b of the Atomic Energy Act (AEA) as amended prior to December 19, 1970. These power reactors were part of the Atomic Energy Commission Cooperative Power Reactor Demonstration Program. The AEA currently restricts the use of subsection 104b such that it can only be used when specifically allowed by Congress. It might be possible to reinstate 104b regulations to allow for commercial demonstration of micro-reactors. However, this is an approach that is not recommended herein.

A manufacturing license can provide a method for licensing a micro-reactor when the site or location where the micro-reactor will be used has not been defined. This would facilitate the development of micro-reactors by separating the micro-reactor development and manufacturing process from the siting and environmental issues. Micro-reactor developers can have formal NRC involvement, interact with NRC, and obtain a license. NRC oversight would focus on design reviews along with inspections, tests, analyses and acceptance criteria verification. NRC approval for siting and construction would be the responsibility of the ultimate customer. Applications for early site permit, construction permit, or combined construction and operating license will be separate from the manufacturing process.

The manufacturing licensing process can be modified for micro-reactors to provide incremental progress toward licensing of a manufactured micro-reactor. Like the standard design approval process, the scope of a manufacturing licensing process for micro-reactors can include the complete design or the major portions thereof. Manufacturers would have the opportunity to limit the scope of early submittals to major portions of a design focusing on the aspects related to controlling the risks to public health and safety. Current regulation for a manufacturing license does not allow an applicant to apply for a major portion, but a revision to providing such an option can be advantageous and can facilitate the process. Defining such major portions may be difficult but can have many benefits to both the manufacturer and the regulatory oversight/review process.

2.3 References

2-1. M. Nichol, Presentation at "Public Meeting on Possible Regulatory Process Improvements for Advanced Reactors," https://www.nrc.gov/docs/ML1922/ML19228A263.pdf, August 15, 2019.

2-2. NEI, "Roadmap for the Deployment of Micro-reactors for U.S. Department of Defense Domestic Installations," Technical Report, Nuclear Energy Institute, October 4, 2018

2-3. NRC, "A Regulatory Roadmap for Non-Light Water Reactors," U.S. Nuclear Regulatory Commission, December 2017.

2-4. NRC, "Prototype Decisions for Advanced Reactor Designs," SECY-91-074, U.S. Nuclear Regulatory Commission, March 19, 1991.

2-5. NRC, "Policy Statement on the Regulation of Advanced Reactors," 73 FR 60612, U.S. Nuclear Regulatory Commission, October 14, 2008.

2-6. P.M. Williams and T.L. King, "Development and Utilization of the NRC Policy Statement on the Regulation of Advanced Nuclear Power Plants," NUREG-1226, U.S. Nuclear Regulatory Commission, June 1988.

2-7. J.M. O'Hara, J.C. Higgins, S.A. Fleger, and P.A. Pieringer, "Human Factors Engineering Program Review Model," NUREG-0711, Rev. 3, U.S. Nuclear Regulatory Commission, 2012.

2-8. NRC, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," NUREG-0800, U.S. Nuclear Regulatory Commission, March 2007.

2-9. NRC, "Fire Protection for Nuclear Power Plants," Regulatory Guide 1.189, Rev. 3, U.S. Nuclear Regulatory Commission, February 2018.

2-10. J. Persensky, A. Szabo, C. Plott, T. Engh, and A. Barnes, "Guidance for Assessing Exemption Requests from the Nuclear Power Plant Licensed Operator Staffing Requirements Specified in 10 CFR Part 50.5m," NUREG-1791, U.S. Nuclear Regulatory Commission, 2005.

2-11. NRC, Standard Review Plan [2-9] Chapter 18, "Human Factors Engineering," U.S. Nuclear Regulatory Commission, 2016.

2-12. J. O'Hara, W. Brown, P. Lewis, and J. Persensky, "Human-System Interface Design Review Guidelines," NUREG-0700, Revision 2, U.S. Nuclear Regulatory Commission, 2002.

2-13. NRC, "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors: Part 1, Format and Content; Part 2, Standard Review Plan and Acceptance Criteria," NUREG-1537, U.S. Nuclear Regulatory Commission, 1996.

2-14. NRC, Standard Review Plan [2-8], Chapter 13, "Conduct of Operations," U.S. Nuclear Regulatory Commission, 2016.

2-15. NRC, "Rulemaking Plan on Emergency Preparedness for Small Modular Reactors and Other New Technologies, SECY-16-0069, U.S. Nuclear Commission, May 31, 2016.

2-16. NRC, "Staff Requirements Memorandum - SECY-18-0096 - Functional Containment Performance Criteria for Non-Light-Water-Reactor," U.S. Nuclear Regulatory Commission, December 4, 2018.

2-17. NRC, "Functional Containment Performance Criteria for Non-Light-Water-Reactors," SECY-18-0096, U.S. Nuclear Regulatory Commission, September 18, 2018.

3 REVIEW OF MICRO-REACTOR APPLICATIONS

3.1 Non-Power Reactor Approach

Non-power reactors (NPRs) licensed by the NRC encompass research and test reactors (RTRs), medical isotope production reactors, and reactors to be used for medical therapy. The licensing authority is based on Sections 103 and 104 of the Atomic Energy Act as amended [3-1] and class 103 and class 104 licenses are explained under 10 CFR Part 50.21 and 10 CFR Part 50.22. These reactors are also referred to as non-power production and utilization facilities (NPUFs).

The distinction between a research and a test reactor (or test facility) is currently the licensed operating power. Test reactors have powers above 10 MWt and have to abide by more stringent regulatory requirements than research reactors. The differentiation of the two types of reactors may change in the future as a petition for rulemaking [3-2] asks for a risk-informed approach to differentiate reactors. The criterion for being a test reactor would be having an accident dose to a member of the public above 1 rem (0.01 Sv). This criterion is also what is currently in an NRC proposed rule [3-3] on NPUF license renewal to reduce requirements for low risk research reactors.

Since the maximum off-site dose for micro-reactors is expected in most designs to fall under this (1 rem) limit, it is useful to consider the way in which research reactors are licensed. One aspect of that review involves NUREG-1537, "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors" [3-4]. This document consists of Part 1 with format and content guidance for applicants and licensees and Part 2 with a standard review plan with acceptance criteria for NRC reviewers.

The format and content guide has provided a uniform format for presenting information in non-power reactor applications, helped ensure completeness of information provided, assisted the Commission staff and others in locating information, and aided in increasing the efficiency of the review process. The format and content guide represents a format for non-power reactor applications that is acceptable to the NRC staff. The standard review plan ensures the quality and uniformity of staff reviews. Overall, this document provides uniformity, streamlines the process, and facilitates licensing of NPRs.

The NUREG-1537 guidance addresses many aspects of NPR licensing including issues that are uniquely associated with NPRs. This includes construction permit and initial operating license, license amendment, decommissioning and license termination, and highly enriched to low-enriched uranium core conversions. Selected regulations that are applicable to NPRs are also identified. Although micro-reactors may not be non-power reactors (i.e., they may be used to generate electricity), regulations could be changed in the future to allow them to be licensed in a manner similar to NPRs.

A review could be undertaken to assess if a NUREG-1537 style document can apply for micro-reactors that can facilitate guidance for both the applicants and the reviewers. Issues for micro-reactors discussed earlier, e.g., applicability of regulations, control room design, staffing requirements, seismic analysis, along with emergency planning and physical security can be discussed in this framework blending in regulatory requirements for power reactors as may be needed. The technical issues identified in Chapter 2 above would provide the focus of that review.

This approach could result in safety analysis reports that are more in line with micro-reactors than if the current regulatory guidance for format and content [3-5] and the Standard Review Plan [3-6] for power plants were applied. Two topics relevant to power reactors that are not considered in NUREG-1537 might need to be decided. One is information on power conversion or the application of process heat in the balance of plant and the second is the application of probabilistic risk assessment to understand the limiting source term for radiological release.

One way in which this approach would be different from that used for power reactors is the use of a maximum hypothetical accident rather than a probabilistic approach to consequence analysis. This is discussed further in Section 4.3.

Table 3-1 summarizes how that review and modification/rewrite of NUREG-1537 might proceed for Part 1 guidance to applicants. Part 2 also has to be considered and might require more effort than Part 1 as not only does new technology need to be considered, but also new acceptance criteria that are risk-informed and performance-based.

The idea of adapting NUREG-1537 to a new type of non-power reactor has precedent. When a liquid fuel reactor and liquid fuel accelerator target were planned for commercial isotope production it was realized that the original version of NUREG-1537 was only partially applicable. Hence, an Interim Staff Guidance (ISG) was developed to augment NUREG-1537 [3-7] and currently, a revision of NUREG-1537 is being written taking into account the ISG. Another example of how NUREG-1537 might be modified is recent work sponsored by DOE to understand how a molten salt (liquid fuel) non-power reactor might be licensed [3-8].

Table 3-1 Suggested Modifications to NUREG-1537 Part 1

NUREG-1537 Part 1 Section		Modification
INTRODUCTION		
Background		Major. NRC history with advanced reactors (Rx), liquid fuel systems for isotope production, and the recent regulatory defining of non-power production and utilization facilities has to be added—all in the context of micro-Rx. Defining reactors according to public dose needs to be updated and consistent with any policy changes being recommended for micro-Rx.
Document Structure		To be modified after all chapters are modified. This section should be after General Requirements.
General Requirements		Minor changes related to micro-Rx context.
Contributors		
References		References in all chapters need to be updated.
1 THE FACILITY		
1.1 Introduction		Minor
1.2 Summary and Conclusions on Principal Safety Considerations		Minor
1.3 General Description of the Facility		Need to introduce concept of site being a factory with transportation to another site to be determined later.
1.4 Shared Facilities and Equipment		Minor unless certain designs call for multiple reactors at a location.
1.5 Comparison with Similar Facilities		Although there may not be any similar facilities for certain designs, there may be non-reactor facilities and systems that are used in new micro-Rx designs. Also relevant may be the use of ConOps info from remote operations or high autonomy in other facilities as a basis for ConOps for the new design.
1.6 Summary of Operations		Minor in this chapter but with notation that unique features (e.g., remote operation) are dealt with elsewhere.
1.7 Compliance with the Nuclear Waste Policy Act of 1982		Not clear why this compliance is singled out here.
1.8 Facility Modifications and History		Could eliminate consideration of license renewals.

NUREG-1537 Part 1 Section		Modification
2 SITE CHARACTERISTICS		Essential information is still needed but review has to consider that a site may not yet be known.
3 DESIGN OF STRUCTURES, SYSTEMS AND COMPONENTS		Design will take into account unique features such as testing done at manufacturing site and remote location.
3.1 Design Criteria		Minor
3.2 Meteorological Damage 3.3 Water Damage 3.4 Seismic Damage		Minor
3.5 Systems and Components		As currently written, this duplicates Section 3.1. Instead, a section on inspections, testing and maintenance to assure operability for the lifetime of the facility might be added.
4 REACTOR DESCRIPTION		
4.1 Summary Description		Minor; but additional features of a micro-Rx should be enumerated.
4.2 Reactor Core		Minor
4.2.1 Reactor Fuel		Minor
4.2.2 Control Rods		Minor; should change subject to “Control Elements.”
4.2.3 Neutron Moderator and Reflector		Should be “Other In-Vessel Systems/Components” to be inclusive of cooling system (summary only) and region outside of core (reflector).
4.2.4 Neutron Startup Source		Minor; consideration should be given to having this information with instrumentation and control (I&C) as the startup source can be considered part of startup I&C methodology.
4.2.5 Core Support Structure		Minor
4.3 Reactor Tank or Pool		Change subject to “Reactor Surroundings” which may or may not be a tank or pool and which could include biological shield.
4.4 Biological Shield		Major. Could be incorporated into Section 4.3. Consider shielding by burial. Consider analysis results to be given in nuclear design section. Note changes in Appendix 4.1 (below).

NUREG-1537 Part 1 Section		Modification
4.X Neutronic and Thermal-Hydraulic Analytical Methods (possible new section)		Need to consider coupled analysis as well as separate sections on neutronics and thermal-hydraulics. Requirements for each are found in current Sections 4.5 and 4.6.
4.5 Nuclear Design		No change in introductory remarks.
4.5.1 Normal Operating Conditions		Most of required discussion applicable. Limiting core configuration should be for situation where the safety margin during an event is reduced the largest amount. Need to consider potential for load-following and instability.
4.5.2 Reactor Core Physics Parameters		Analysis methods should be covered under Section 4.X (above). Otherwise only minor changes.
4.5.3 Operating Limits		Minor
4.6 Thermal-Hydraulic Design		Major. Should be organized like nuclear design sections with methodology, then characteristics. Methods should include statistical analysis, not just engineering factors. Consider heat pipes in discussing what parameters are important. Consider load following and stability.
Appendix 4.1 Regulatory Guide 2.1 Shield Test Program…Biological Shielding		Eliminate and include modern references in Section 4.4
5 REACTOR COOLANT SYSTEMS		Information before Section 5.1 should be part of 5.1 (duplicative now).
5.1 Summary Description		Major. Must now include discussion of coolant systems other than the usual water systems (e.g., liquid metal, gas). Need to add tertiary systems if present.
5.2 Primary Coolant System		Major. Has to consider heat pipe systems and in general, coolants other than water (e.g., liquid metal, gas). Not clear why control/safety instrumentation is in this section.
5.3 Secondary Coolant System		Could be “Secondary and Tertiary …”
5.4 Primary Coolant Cleanup System		Could be a subsection of 5.2. Must take into account coolants other than water.
5.5 Primary Coolant Makeup Water System		Could be a subsection of 5.2. Must take into account coolants other than water.
5.6 Nitrogen-16 Control System		Major. Could be a subsection of 5.2 (e.g., 5.2.3 “Coolant Radioactivity Control.” Must

NUREG-1537 Part 1 Section		Modification
		take into account problems with coolants other than water.
5.7 Auxiliary Systems Using Primary Coolant		Could be just "Auxiliary Coolant Systems" to cover the various systems discussed herein.
6 ENGINEERED SAFETY FEATURES		Introductory material covered in other sections.
6.1 Summary Description		Major
6.2 Detailed Description		Separate sections needed for confinement/containment and emergency cooling system. Major update needed to accommodate micro-Rx designs
7 INSTRUMENTATION AND CONTROL SYSTEMS		
7.1 Summary Description		Major
7.2 Design of Instrumentation and control Systems 7.3 Reactor Control System 7.4 Reactor Protection System 7.5 Engineered Safety Features Actuation systems 7.6 Control Console and Display Instruments 7.7 Radiation Monitoring Systems		Major. In general, much of the existing discussion applicable to micro-Rx. However, these sections need to account for unique features such as remote and semi-autonomous operation. The implications of these unique features for staffing and control room design will be significant.
8 ELECTRICAL POWER SYSTEMS		
8.1 Normal Electrical Power Systems 8.2 Emergency Electrical Power Systems		Major as some micro-Rx designs may only need minimal electrical power.
9 AUXILIARY SYSTEMS		Major. Needs to be considered when more details of micro-Rx design are known.
10 EXPERIMENTAL FACILITIES AND UTILIZATION		Not applicable for current micro-Rx designs. Could be description of connected industrial facility supported by micro-Rx.
11 RADIATION PROTECTION PROGRAM AND WASTE MANAGEMENT		Major. Needs to be considered in the context of very low amounts of radioactivity.

NUREG-1537 Part 1 Section		Modification
12 CONDUCT OF OPERATIONS		
12.1 Organization 12.2 Review and Audit Activities 12.3 Procedures 12.4 Required Actions 12.5 Reports 12.6 Records 12.7 Emergency Planning 12.8 Security Planning 12.9 Quality Assurance 12.10 Operator Training and Requalification		Major. All of these sections are unique for micro-Rx designs. Issues of remote/semi-autonomous operation, monitoring, emergency intervention, etc. need to be addressed.
12.11 Startup Plan 12.12 Environmental Reports		Minor
13 ACCIDENT ANALYSIS		
Introduction		Minor but needs to be brought up-to-date.
13.1 Accident Initiating Events and Scenarios		Of particular importance is the potential use of the maximum hypothetical accident (MHA) to show acceptability of the design. This might be an acceptable alternative to carrying out a PRA. Other accident descriptions in this section require minor modification (and "Experiment Malfunction" is not relevant).
13.2 Accident Analysis and Determination of Consequences		This is mostly standard for safety analysis. However, minor modifications would be useful, e.g., asking for limiting assumptions and relevant Technical Specifications. PRA could be of help in defining scenarios (here and for Section 13.1).
13.3 Summary and Conclusions		
14 TECHNICAL SPECIFICATIONS		
Appendix 14.1 Format and Content of Technical Specifications for Non-Power Reactors		Major update; indeed, almost equivalent to updating the entire NUREG-1537. Need review of ANSI/ANS 15.1 to understand its applicability. If applicable, need to use current version; not version used in 14.1.
15 FINANCIAL QUALIFICATIONS		Not considered at this time.
16 OTHER LICENSE CONSIDERATIONS		Major update. This chapter could incorporate some of the unique issues for

NUREG-1537 Part 1 Section		Modification
		micro-Rx. For example, it could be where power conversion or balance-of-plant for process heat application is discussed.
16.1 Prior Use of Reactor Components		Can be treated elsewhere.
16.2 Medical Use of Non-Power Reactors		Not relevant.
17 DECOMMISSIONING AND POSSESSION-ONLY LICENSE AMENDMENTS		Not considered at this time.
18 HIGHLY ENRICHED TO LOW-ENRICHED URANIUM (LEU) CONVERSIONS		Not relevant–all micro-Rx will use LEU; most likely high-assay LEU.
APPENDIX A - APPLICABILITY OF SELECTED REGULATIONS … TO NON-POWER REACTORS		This would be a valuable (but not necessary) addition.

3.2 Applicability of Other Approaches

The Licensing Modernization Project (LMP) approach for licensing basis development [3-9] can also be considered in developing a NUREG-1537 style document. The LMP developed risk-informed performance-based guidance for non-LWR licensing basis development. The LMP described acceptable processes for selecting Licensing Basis Events (LBEs); safety classification of systems, structures, and components (SSCs) and associated risk-informed special treatment; and determination of defense-in-depth adequacy applicable to a technology-inclusive array of non-LWR designs. This approach factors into the risk analysis discussed in Chapter 4.

The experience when small modular reactors (SMRs) were introduced also needs to be factored into how a review should proceed. For example, the American Nuclear Society report on SMR generic licensing issues [3-10] considers issues related to staffing, physical security, manufacturing, inspections, tests, analyses, acceptance criteria, etc. Guidance for reviewing SMRs was developed in several “Design Specific Review Standards” to modify the power reactor “Standard Review Plan.”

3.3 References

3-1. Atomic Energy Act of 1954, Public Law 703, 1954.

3-2. NIST, Petition for Rulemaking and Comment in NRC-2011-0087-0023, National Institute of Standards and Technology, June 7, 2017.

3-3. NRC, “Non-Power Production or Utilization Facility License Renewal,” proposed rule, Federal Register Vol. 82, No. 60, March 30, 2017.

3-4. NRC, “Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors: Part 1, Format and Content; Part 2, Standard Review Plan and Acceptance Criteria,” NUREG-1537, U.S. Nuclear Regulatory Commission, 1996.

3-5. NRC, “Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants (LWR Edition),” Regulatory Guide 1.70, U.S. Nuclear Regulatory Commission, 1978.

3-6. NRC, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition,” NUREG-0800, U.S. Nuclear Regulatory Commission, March 2007.

3-7. NRC, “Final Interim Staff Guidance Augmenting NUREG-1537, Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors: Part 1, Format and Content; Part 2, Standard Review Plan and Acceptance Criteria, for Licensing Radioisotope Production Facilities and Aqueous Homogeneous Reactors,” U.S. Nuclear Regulatory Commission, October 17, 2012.

3-8. R.J. Belles, G.F. Flanagan, and M. Voth, “Proposed Guidance for Preparing and Reviewing Molten salt Nonpower Reactor License Applications,” ORNL/TM-2018/834, Oak Ridge National Laboratory, May 2018.

3-9. NEI, “Risk-Informed Performance-Based Guidance for Non-Light water Reactor Licensing basis Development,” Draft Report Revision N, NEI 18-04, Nuclear Energy Institute, September 28, 2018.

3-10. ANS, “Interim Report of the American Nuclear Society President’s Special Committee on Small and Medium Sized Reactor (SMR) Generic Licensing Issues,” American Nuclear Society, July 2010.

4 RISK ANALYSIS

4.1 Introduction

In this chapter, risk from micro-reactor operation is considered in a risk-informed, performance-based context. The probabilistic processes that are embedded in a probabilistic risk assessment (PRA) are considered along with the issues that may need to be addressed in defining a regulatory approach for reviewing micro-reactor risk analysis. The focus is on the aspects that are unique to micro-reactors and may require different treatment compared to larger size reactors. Most of the current activities relating to advanced non-LWRs implicitly consider larger size reactors without addressing the specific needs of micro-reactors. Here, the focus is on micro-reactors and the issues that may require attention in the regulatory approach considering the risk assessment approaches that apply in general.

Micro-reactors are expected to be associated with many of the following features that have implications in their risk assessment and risk modeling:

- small reactor power level
- remote siting of the reactor
- inherent safety features
- use of passive systems and passive system reliability
- operation for a long period, for example 10 years, without maintenance or refueling
- construction and fabrication of the reactor at a factory
- new technologies such as unique components that have never been manufactured before, which lack operating experience and performance data

Risk assessment is discussed below considering these features and the associated regulatory considerations.

4.2 Applying Risk Analysis

Current regulation requires development of a Level 1 and a Level 2 PRA for new power reactor designs. The Nuclear Energy Institute (NEI) report on “Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development,” (NEI 18-04) [4-1] uses PRA to develop a risk-informed, performance-based guidance for non-LWR licensing basis development. It notes that “given the simple systems, inherent characteristics, and minimal possible public health hazards expected for many non-LWR designs, especially those with low power levels, the PRA complexity necessary to support decision-making and an application should be less complex than for operating LWR plants.” It presents a technology-inclusive, risk-informed, performance-based process for licensing non-LWRs where a PRA of the facility is integral to the process. The PRA is developed at an early stage and as the design matures, the scope and level of the PRA expands and is used to support design decisions along the way. The PRA development is a continuum as well, maturing with the designs of systems. The scope of the PRA is expected to address all plant conditions and hazards, including both internal and external events, and all radiological sources at the site. NRC Draft Regulatory Guide 1353, “Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors,” [4-2] endorses the NEI approach with clarifications and points of emphasis.

Maioli et al. [4-3] conducted an eVinci Micro-Reactor Licensing Modernization Project Demonstration to exercise key processes in the LMP Guidance Document, NEI 18-04, to gain insights on adaptability to micro-reactor technology. They developed a limited scope PRA model including a preliminary Failure Modes and Effects Analysis (FMEA), preliminary selection of Licensing Basis Events (LBEs), preliminary identification of required safety functions, preliminary safety classification of SSCs, preliminary list of design basis accidents, and documentation of a partial evaluation of defense-in-depth adequacy. At this early stage, the evaluation was constrained by available supporting information and the scope and level of detail of the PRA model is expected to be refined as more information becomes available.

The features of micro-reactors–inherent safety, simple systems, minimal number of components, and minimal or negligible possible public health hazards because of low power levels and remote siting–imply that the PRA models are expected to be relatively simple compared to the PRAs for currently operating plants or other designs (e.g., small modular reactors (SMRs)).

Even though a traditional full scope, Level 3 PRA for micro-reactors may not be desired, many elements of the PRA can be useful tools for supporting regulatory decisions and are expected to be applied. These tools are usually probabilistic, are used in the overall PRA methodology, and can be effectively used in the analyses.

Regulatory review approaches can be defined both when PRA modeling as defined in NEI 18-04 is used and when probabilistic approaches addressing specific aspects of micro-reactor licensing are used satisfying regulatory requirements as they apply to micro-reactors. Discussions below relating to risk modeling on specific issues are examples of the way issues relating to micro-reactors can be addressed and regulatory review approaches may be developed.

Licensing Basis Events

The definition of Licensing Basis Events, as discussed in NEI 18-04, includes various event types: anticipated operational occurrences (AOOs), design basis events (DBEs), beyond design basis events (BDBEs), and design basis accidents (DBAs). These definitions have been effectively used to address safety for nuclear reactors in general, and are meaningful in the context of emergency operating procedures, severe accident management guidelines, extreme damage mitigation guidelines, etc.

Since micro-reactors may be remotely sited and operated with minimal role for an operator, many of the procedures and guidelines that have been applied for large LWRs may not apply and defining event types based on previous designs may not be meaningful. For micro-reactors, a simpler definition of event types may be appropriate and help in defining the safety analyses needs for these reactors from regulatory perspectives.

NUREG-1860, "Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing," [4-4] presented a probabilistic binning of LBEs that may be used to define the event types for micro-reactors as shown in Table 4-1. The types of events that may apply to micro-reactors are expected to be small and can be defined searching these three event types. These event types are similar to and can be associated with AOOs, DBEs, and BDBEs, but do not need to relate to operating procedures, as they may not apply for micro-reactors.

Table 4-1 Event Types

Event Type	**Category**	**Expected Frequency (per reactor year)**
Expected to occur during the lifetime	Frequent	$\geq 10^{-2}$
Expected to occur during the lifetime of the population of plants	Infrequent	$< 10^{-2}$ to $\geq 10^{-5}$
May challenge Commission's Safety Goals	Rare	$<10^{-5}$

Selection of Licensing Basis Events

The selection of LBEs using a risk-informed approach supports two purposes, as summarized in NUREG-1860:

- assures that the design meets the design criteria for various accident challenges with adequate defense-in-depth (including safety margin) to account for uncertainties, and

- evaluates the design from the standpoint of the dose guidelines in the siting criteria of 10 CFR Part 100.

The process outlined in NEI 18-04 starts with an initial list of LBEs that is then supplemented with risk-informed and performance-based evaluations including evaluation of defense-in-depth adequacy. The LBE selection process consists of ten tasks which include PRA development and update. The task to perform LBE evaluation consists of five subtasks. These approaches are applicable and effective because of the potential complexity of the systems and the large number of events and accident sequences that require consideration and evaluations in general. For micro-reactors, because of the relative simplicity of the design, the level of effort required will be less than that for large LWRs or SMRs.

The expected number of events and accident sequences to be analyzed are small in a micro-reactor design and the process can be made simple. LBEs can be defined deterministically based on engineering analyses of the design and its safety features along with the use of tools of risk analysis to identify and supplement additional events, as applicable. This approach does not require conduct of a PRA but uses specific features or tools that are used in a PRA to support the needs for a micro-reactor design and, therefore, without the burden of conducting a full-scope PRA.

The process can consist of the following three activities:

1. Deterministic evaluation to identify events of the three types defined above in Table 4-1

The list of events applicable to a micro-reactor design can be developed based on traditional deterministic analyses similar to the way it has been done previously for different designs as an input to a PRA. It will take into consideration the prior experience from similar designs, experience of the nuclear industry, and the licensing of reactors.

Inherent safety features will automatically be considered in defining the design basis events and beyond design basis events. Explicit analysis of these features to demonstrate events or types of events that are eliminated for the design are considered part of the evaluations.

The initial set is expected to start with internal events and then expand to include design basis seismic events and other external events that the facility is expected to be subjected to. A set of design basis external hazard levels (DBEHLs) is expected to be defined as part of the design and licensing basis. Using the DBHELs, external events applicable to the design can be defined based on traditional deterministic analyses. Available methods, data, design, site information, and supporting guides and standards will allow the development of the list of LBEs.

2. Risk analysis tools to identify additional events, as applicable

Risk analysis tools such as a Master Logic Diagram (MLD) and Failure Modes and Effects Analyses (FMEA) provide systematic analysis methods to identify the initiating events applicable to a design. These methods are part of the PRA methodology and are traditionally used to identify the initiating events in a PRA for new designs. They are included in an ANS/IEEE PRA procedures guide [4-5] and an ASME/ANS "Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications" [4-6] and are among the recommended approaches in an Idaho National Laboratory white paper [4-7] on next generation nuclear plant PRA.

MLD can be used to search for initiating events for a micro-reactor design, particularly focusing on those events that may have been missed in traditional deterministic analyses. FMEA can then be used to ensure the completeness of the event selection process. As stated in NEI 18-04 [4-1], FMEA provides a technically sound understanding of the potential failure modes of the reactor concept, how the plant responds to such failure modes, and how protective strategies can be incorporated into the safety design. It will also allow for direct incorporation and consideration of the inherent safety features applicable to the design.

Whenever multiple reactors are considered together, the impact of external events such as external floods or seismic events that can impact multiple reactors concurrently is considered in the evaluation.

3. Finalize the list addressing regulatory considerations

The list of LBEs is finalized combining the LBEs identified from deterministic analyses with those obtained using the risk analyses tools. For micro-reactors, other events (e.g., sabotage and cyber attacks) may be relevant and may also be included.

In summary the review of the selection of Licensing Basis Events for micro-reactors needs to consider the following two aspects:

- defining a review process for the selection of Licensing Basis Events with alternatives that are acceptable for licensing, and

- developing guidance for the use of Master Logic Diagram and Failure Modes and Effects Analyses in micro-reactor designs.

Defense-in-Depth Considerations and Criteria for the LBEs

NEI 18-04 presents a risk-informed, performance-based method for evauation of defense-in-depth adequacy. For micro-reactors, a simplified approach, based more on deterministic analyses can be adequate. Deterministic criteria, coupled with demonstrating that the Commission's Safety Goals are satisfied for the rare, catastrophic event applicable to micro-reactors, can be demonstrated to be the appropriate basis for regulatory review and licensing of micro-reactors.

Examples of criteria that may apply for micro-reactors are presented in Table 4-2. This is developed considering the current requirements and the criteria discussed in NUREG-1860.

Passive System Reliability

Micro-reactors are expected to operate for their lifetime without any repair, replacement, or rejuvenation of their structural passive components. Minimal use of active components or components with moving parts is intended. Depending on the lifetime, the effects of aging for the passive components may be relevant. Reliability of passive systems and components may dominate risk from micro-reactors and regulatory review approaches may need to be defined for these designs.

Table 4-2 Acceptance Criteria for LBEs

Frequency Category	Acceptance Criteria for LBEs
Frequent	• No barrier failure (beyond the initiating event) • No impact on fuel integrity or lifetime and safety analysis assumptions • Redundant means of reactor shutdown, unless inherent safety features achieve shutdown • Redundant means of decay heat removal, unless inherent safety features of the design achieve the function.
Infrequent	• A coolable geometry is maintained • At least one barrier remains • At least one means of reactor shutdown remains functional • At least one means of decay heat removal remains functional.
Rare	• Satisfies dose limits and Commission's Safety Goals

In the PRAs for currently operating LWR plants, passive SSC reliability plays a role in initiating event frequencies such as for loss-of-coolant accidents and internal floods, and in the fragility evaluation for seismic events. Pipe break frequencies for the initiating events are estimated based on pipe failure data and exposure time. The failure modes in the estimation of failure rates include all failures requiring repair or replacement such as wall thinning, cracks, leaks, and ruptures of various sizes up to and including complete severance of the pipe.

The reliability characteristics of the piping systems are modeled considering piping and reliability integrity management programs (e.g., leak detection systems, surveillance programs, system leak and pressure tests, and in-service inspections). In the case of micro-reactors, these types of programs may not be used or required influencing the assessment of passive system reliability.

In recent years, advancements have been made in assessing passive component reliability using Markov modeling approaches [4-8]. In a Markov model for a pipe, Markov states of a pipe additional to success and failure are considered. For example, the state for any one component can include operating (without any detectable damage), maintenance for flaws detectable by non-destructive testing, repairs for detectable leaks, and failure or rupture. The Markov model considers transition between the states and the rate of transitions between the states to estimate the pipe rupture or failure frequency.

Markov models for piping systems are further being pursued considering the physics of failure, that is, feasibility of constructing Markov models of components that contain physics-based transition rates are being studied. In such a model, the rates are based on the physical processes of material degradation as opposed to a statistical parameter characterization based on service data. An example study considered stress corrosion cracking of a reactor coolant system alloy and used crack growth rate models to estimate the failure rate [4-8]. These types of models can quickly become complex when a large number of states are involved.

For micro-reactors, Markov modeling using physics of failure can be attractive since service data may not be available as new technology and new components are introduced. In some cases, data from operating experience in other industries may have to be considered with adjustments. An issue unique to micro-reactors is that the components may not be repaired or refurbished thus requiring the computer models to be developed to have the option to analyze components with such operational features.

The regulatory review approaches for micro-reactors may have a significant focus on passive component reliability and can involve addressing the following aspects:

- assessment of different types of approaches for evaluating passive component reliability and identification of approaches that are applicable for micro-reactor regulation
- evaluation and guidelines for the passive component reliability models that are applicable
- assessment of the applicable computer models and their use in the regulatory process
- regulatory review guidance and approaches considering the different ways passive component reliability can be addressed in regulatory applications.

It is conceivable that because of the emphasis in advanced reactors on passive components, significant advances will take place in modeling passive component reliability and the regulatory process may benefit from defining requirements that may apply for the new methodologies to be developed.

<u>Three-Dimensional (3D) Physics Simulation Toolkits to Supplement Risk Analyses</u>

Extended use of simulation may provide beneficial information in addressing the safety of micro-reactors. With advances in computer technology, these types of analyses can be feasible and practical. If and when developed, when simulating accident sequences as part of a safety analysis, physics-based simulations can be defined and run for one or more scenarios enhancing the understanding of the accident progression. Smith et al. [4-9] discussed these possibilities in relation to SMRs in an advanced PRA framework. The discussion presented here is based on that conceptual presentation and approach. The intent in this discussion is to suggest that such approaches can be of benefit in a micro-reactor PRA and the regulatory review may need to consider and prepare for such analyses.

Smith et al. [4-9] describes a possible PRA scenario to explain how physics-based simulation can be used and help in safety analyses. Consider a seismic event (which occurs stochastically and with different magnitudes) and look at implications at a micro-reactor site. For a given earthquake that is produced for the PRA, the results of a structural analysis (which could be a load-capacity calculation or detailed 3D energy transfer modeling) are used to interpret the calculations into a state such as "no damage," "cracked," or "disabled." The simulation can then continue by transferring the physics-based mechanistic calculation into an impact in the accident scenario. For example, if the component is cracked, the cracked component may experience a dislocation (crack grows) or further damage. If the component was a pipe containing water, then flow out of the pipe can be modeled resulting in additional impact.

Physics based 3D-environment models, available from other industries, can mimic realistic physics such as flowing water and objects impacting other objects. The environment model, for example, can know what the pipe material is, how fast it is going to impact items around it (if it cracks and breaks loose), its impact orientation, etc. This example scenario is one possible outcome of the seismic event and multiple scenarios can be defined and analyzed. These types of 3D physics simulations coupling probabilistic and mechanistic calculations together can help search for vulnerabilities, are realistic, can be efficient, and are insightful for licensing. In spite of the significant assumptions and modeling uncertainties that will remain, useful knowledge can be obtained for highly unlikely scenarios helping regulatory decisions. Smith et al. provides more detailed representation and analysis of the conceptual approach.

Hence, the regulatory review of micro-reactors can take into consideration such analyses by

- developing the applicability of such analyses and encouraging the applicants to develop the necessary tools and carry out specific evaluations, and
- preparing regulatory review considerations for and defining the role of such analyses in micro-reactor licensing.

<u>Data to Support Risk Analyses</u>

Micro-reactors may have unique components that have never been manufactured before, and lack operating experience and performance data. It may also include components (e.g., heat pipes) that have been used in non-nuclear industries and operating experience data under those, possibly different, conditions are expected to be available. Available data for some components may need to be modified considering the different operating conditions, e.g., minimal or non-existent maintenance, that may apply in a micro-reactor.

Similar issues, although slightly different, were faced with LWR PRA studies and significant methodologies were developed by NRC to address them. NRC's operating experience database includes the Reliability and Availability Data System (RADS) and RADS analysis software [4-10] which are designed to estimate industry and plant-specific reliability and availability parameters for selected components in risk-important systems for use in risk-informed applications [4-11].

Similar efforts will be needed along with possibly some methodological improvements to address the specific needs of micro-reactors and their associated components. The scope of RADS and RADS analysis can be expanded to include micro-reactors. In this way, regulatory review data needs will be defined, along with the methodological improvements and data collection, providing the needed data for regulatory review.

Risk-Informed Inspection at the Factory During Construction

Micro-reactors may be largely fabricated at a factory, as opposed to field fabrication, and minimal activity may be carried out at a site for installation and start of operation. It is expected that NRC will conduct inspection at the factory and will need to define a process and procedure for inspection focusing on risk-significant aspects.

The risk-informed inspection process currently used for large LWRs may need some modification and more emphasis on construction errors that could be significant during operation may be desirable. Again, in the absence of detailed PRA models which may not prove to be effective, use of risk analysis tools to develop approaches for identifying the components to conduct inspections and maintain focus on significant construction errors can be the basis for defining these modifications.

Accident sequence analyses for micro-reactors discussed below as part of an alternative to a full-scope PRA can be used, along with deterministic considerations, and can be used to create a list of components for conducting NRC inspections at the construction stage. Construction errors which can invalidate design assumptions can be studied using methods like hazard and operability (HAZOP) studies.

HAZOP is a structured and systematic technique for system examination and risk management. It is based on the theory that assumes a system risk is caused by deviations from design and operating conditions. It is used to identify potential hazards and operability problems in a system that can lead to nonconforming products. Identification of the deviations is aided by “guide words” that provide focus on possible deviations.

4.3 Alternatives to PRA Modeling and Assessment

NEI 18-04 [4-1] presented a technology-inclusive, risk-informed, and performance-based process for selection of Licensing Basis Events; safety classification of structures, systems, and components and associated risk-informed special treatments; and determination of defense-in-depth for non-light water reactors. The process is based on a sound, full-scope PRA that includes appropriate probabilistic models using available standards to develop and evaluate safety design outcomes for a design. A PRA would be developed early in the design stage and updated as appropriate for each stage of the design.

For micro-reactor designs, developing a full-scope PRA and applying it to different aspects of the licensing process can be burdensome and at the same time, may be unnecessary. The benefits of a PRA in complex systems such as large or small modular nuclear power plants are considered significant whereas for a micro-reactor, because of its relatively smaller size and associated simplicity, they may be marginal. An alternative to PRAs for micro-reactors can be considered that will retain the necessary insights for licensing the micro-reactors while avoiding the unnecessary burden and complications that may result from pursuing a PRA-centered evaluation.

An alternative to PRA models for micro-reactors can be considered where deterministic analyses, as traditionally have been used in the licensing process, is complemented with some probabilistic-based analyses that are now typically considered part of a PRA model. In such an alternative the useful insights that can be obtained for micro-reactor licensing and regulatory review can be retained while the significant burden and complications for a full-scope PRA is avoided. Probabilistic or PRA-type evaluation that could provide additional insights for micro-reactor review and licensing that could be performed without significant burden can be considered in the following three ways:

1. Use of risk tools for identification of Licensing Basis Events

This involves conducting a systematic analysis for identification of initiating events in micro-reactor designs and is applicable because of the new and unique design and operational features that may be associated with such designs. This has been discussed earlier where Master Logic Diagram and Failure Modes and Effects Analyses are considered in searching for initiating events that may apply for a plant. These analyses are qualitative and can be effective in ensuring that inherent safety features are considered appropriately.

2. Accident sequence analysis for selected initiating events

Accident sequence analysis for selected accidents can be performed to obtain insights for the licensing process and other applications. This is similar to that done in an LWR PRA model where core damage frequency is calculated--but can be significantly simpler. In this case, event tree analysis is expected without the need for detailed fault-tree analysis that is typically the case. If the system design contains redundancy involving many components, then fault tree analysis can apply. Systematic analyses of all accident sequences are not needed since the intent is not to calculate any risk metric. Possibly one or more accident sequences from each of the three types of accidents to be considered can be analyzed. The primary intent would be to obtain an understanding of the accident progression and associated insights for regulatory review and licensing. Data needs can be limited by requiring order of magnitude evaluation of the accident sequences.

3. Consequence analysis of catastrophic events for demonstration of compliance with the Commission's Safety Goals

Consequence analysis can be conducted only for a catastrophic event for demonstration of compliance with the Commission's Safety Goals [4-12]. A bounding analysis demonstrating that the Safety Goals are not violated can suffice. This can be akin to the maximum hypothetical accident (MHA) analysis carried out for research and test reactors as the source term and/or radiological consequences are similar to those for micro-reactors. However, the MHA can also be used to prove that consequences are less than regulatory limits, for example, less than the 1 rem (0.01 Sv) limit separating research and test reactors.

The MHA is defined for research and test reactors under the assumption that it bounds any credible accident that would release fission products. NUREG-1537 [4-13] defines the accident for specific reactor types and power levels without a probabilistic analysis. The assumptions that are acceptable for analyzing the MHA in a reactor of less than 2 MWt differ from those to be used for higher power reactors. How this might be applied to the entirely new technologies being used in micro-reactors is not clear. If the first step would be to assure that the release of fission products is not credible, then the application of probabilistic methods might still be needed.

In summary, the regulatory approach could define the types of evaluations including the use of risk analysis tools that will be adequate for acceptability of micro-reactor applications without the need for a full scope PRA.

4.4 References

4-1. NEI, "Risk-Informed Performance-Based Guidance for Non-Light water Reactor Licensing basis Development," Draft Report Revision N, NEI 18-04, Nuclear Energy Institute, September 28, 2018.

4-2. NRC, "Guidance for a Technology-Inclusive, Risk-informed and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors," Draft Regulatory Guide 1353, U.S. Nuclear Regulatory Commission, April 2019.

4-3. A. Maioli et al., "Westinghouse eVinci™ Micro-Reactor - Licensing Modernization Project Demonstration," EMR_LTR_190010, Southern Company, August 2019.

4-4. NRC, "Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing," NUREG-1860, U.S. Nuclear Regulatory Commission, December 2007.

4-5. ANS/IEEE, "PRA Procedures Guide," NUREG/CR-2300, American Nuclear Society and Institute of Electrical and Electronics Engineers, January 1983.

4-6. ASME/ANS, “Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications,” ASME/ANS RA-Sa-2009, American Society of Mechanical Engineers, American Nuclear Society, 2009.

4-7. INL, “Next Generation Nuclear Plant Probabilistic Risk Assessment White Paper,” INL/EXT- 11-21270, Idaho National Laboratory, 2011.

4-8. K. Fleming et al., “Treatment of Passive Component Reliability in Risk-Informed Safety Margin Characterization,” INL/EXT-10-20013, Idaho National Laboratory, September 2010.

4-9. C. Smith et al., “Small Modular Reactor (SMR) Probabilistic Risk Assessment (PRA) Detailed Technical Framework Specification, INL/EXT-13-28974, Idaho National Laboratory, April 2013.

4-10. NRC, “Reliability and Availability Data System,” https://nrcoe.inl.gov/resultsdb/RADS/, U.S. Nuclear Regulatory Commission, 2019.

4-11. C.L. Atwood et al., “Handbook of Parameter Estimation for Probabilistic Risk Assessment,” NUREG/CR-6823, SAND2003-3348P, Sandia National Laboratory, November 2002.

4-12. NRC, “Safety Goals for the Operation of Nuclear Power Plants; Policy Statement,” U.S. Nuclear Regulatory Commission, Federal register, Vol. 51, p. 30028, August 21, 1986.

4-13. NRC, “Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors: Part 1, Format and Content; Part 2, Standard Review Plan and Acceptance Criteria,” NUREG-1537, U.S. Nuclear Regulatory Commission, 1996.

APPENDIX

Code of Federal Regulations (10 CFR) Referenced In This Report

Part	Title
50	DOMESTIC LICENSING OF PRODUCTION AND UTILIZATION FACILITIES
50.21	Class 104 licenses; for medical therapy and research and development facilities
50.22	Class 103 licenses; for commercial and industrial facilities
50.23	Construction permits
50.34	Contents of applications; technical information
50.48	Fire protection
50.54	Conditions of licenses
50.65	Requirements for monitoring the effectiveness of maintenance at nuclear power plants
Appendix A	General Design Criteria for Nuclear Power Plants
Appendix N	Standardization of Nuclear Power Plant Designs: Permits to Construct and Licenses to Operate Nuclear Power Reactors of Identical Design at Multiple Sites
50.71	Maintenance of records, making of reports
52	LICENSES, CERTIFICATIONS, AND APPROVALS FOR NUCLEAR POWER PLANTS
52.47	Contents of applications; technical information
Subpart F	Manufacturing Licenses
Appendix N	Standardization of Nuclear Power Plant Designs: Combined Licenses to Construct and Operate Nuclear Power Reactors of Identical Design at Multiple Sites
100	REACTOR SITE CRITERIA