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Summary of Factory Fueling and Testing Risks to Support the Transformation of Regulatory Requirements for Microreactors

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Nuclear Energy and Fuel Cycle Division

SUMMARY OF FACTORY FUELING AND TESTING RISKS TO SUPPORT THE TRANSFORMATION OF REGULATORY REQUIREMENTS FOR MICROREACTORS

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ABBREVIATIONS

CFR	Code of Federal Regulations
COL	combined license
HEPA	high efficiency particulate air
ITAAC	inspections, tests, analyses, and acceptance criteria
ITP	initial test program
LBE	licensing-basis event
LWR	light-water reactor
MARVEL	Microreactor Application Research Validation and Evaluation
ML	manufacturing license
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PITAP	Post manufacturing and construction Inspection, Testing and Analysis Program
QAP	quality assurance program
RG	Regulatory Guide
SR	safety-related
SSCs	structures, systems, and components
TREAT	Transient Reactor Test Facility
TRISO	tristructural-isotropic

ABSTRACT

Microreactors have the potential to open new markets and applications for nuclear energy. New manufacturing and operational regimes, such as factory fueling and testing prior to site installation, are being proposed to meet these new markets. The radiological hazards associated with commercial power reactors are not the same as the hazards of a reactor being constructed in a factory. Currently, a reactor operating license specified under 10 CFR Part 50, Part 52, or (in the near future) Part 53 is required prior to loading fuel in the reactor. This is logical for plants that are immediately to begin full-power operations soon after fuel loading. However, for microreactors, this may not be the case. Some deployment concepts may stage reactors as “ready to go” in a factory prior to site installation and startup. This approach is being considered in the case of diesel generator replacements, mobile or roaming mining operations, and emergency response situations, such as after a major disaster event. Therefore, it is necessary to evaluate hazards independently of the assumption of full-power operation. This report investigates the primary hazards unique to microreactors associated with low power reactor and physics tests necessary to confirm core safety assumptions, neutronic and core design performance parameters, and other assumptions.

1. INTRODUCTION

The US Department of Energy (DOE) Microreactor Program was established in FY 2019 to support R&D of technologies related to the development, demonstration, and deployment of low-power, transportable reactors to provide power and heat for decentralized generation in civilian, industrial, and defense energy sectors. Microreactors are a class of very small modular reactors (0.1–50 MWe) targeted for nonconventional nuclear markets. These include remote communities, mining sites, and remote defense bases, as well as applications such as humanitarian assistance and disaster relief missions. Such applications currently face economic and energy security challenges that can be uniquely addressed by this new class of innovative nuclear reactors.

To ensure economic viability and enable microreactor deployments, some novel construction, maintenance, fuel loading, testing, and operational regimes are being proposed to centralize functions and promote fleet-wide efficiency. In investigating the viability of such options, some regulatory changes or new guidance may need to be established. In this report, the option of fuel loading and factory testing of the microreactor is discussed. To promote discussion around the topic of regulatory change or new guidance, the hazards and technical attributes of this option are explored.

Three parts of the Code of Federal Regulations (CFR)—10 CFR Part 50 [1], 10 CFR Part 52 [2] and the newly proposed 10 CFR Part 53 [3], which detail the regulations for the Nuclear Regulatory Commission (NRC) to issue construction permits, operation licenses, combined licenses (COLs) and manufacturing licenses for nuclear power plants (NPPs)—mandate the inclusion of a quality assurance program (QAP) in license applications. An initial test program (ITP) includes the necessary series of tests, their procedures, and acceptance criteria to satisfy the QAP requirements. The ITP includes pre-operational tests, fuel loading and criticality tests, and startup tests, such as low-power physics tests and power ascension tests. The QAP applies to these aspects, and the option of factory testing is therefore interlinked with commercial NPP licensure.

With the prospect of assembly-line-like manufacturing and factory fueling, some microreactor developers may pursue low-power physics testing in the factory to minimize the time and potential risks associated with fuel loading and initiating operations at the deployment site. If fuel has been installed incorrectly or if some other issue is discovered during testing, then performing the necessary modifications in the factory rather than at the deployment site is highly preferrable. This approach would significantly improve the prospects of deploying microreactors to remote locations, where capabilities are limited to access and modify or repair the internals of a microreactor. Although commercial NPP regulations provide requirements on the licensing of microreactors and microreactor factories, discussion regarding on-site testing capabilities is still ongoing.

The primary objective of this effort is to initiate a discussion around fuel loading and startup testing with a nuclear license that is commensurate with the hazard and risk to the health and safety of the public. Specifically, this report is concerned with the risks related to low-power physics testing, a step in the ITP. It is important to recognize that the intent of a microreactor initial testing facility is to not generate appreciable power. Typically, low-power physics testing involves reaching power levels of less than 5% [4]. Microreactors have a full power output of less than 50MWe [5], so microreactor low-power physics testing involves power levels of approximately 2.5 MWe (i.e., definitely less than 10MWt). As a result, the power/heat and the amount (and rate) of fission products generated are "negligible."[1] Therefore, it should be recognized that the fundamental safety function [6] to be met during low-power physics testing of microreactors is reactivity control. Although the other two fundamental safety functions—heat removal and containment of fission products—are important for power reactor operation, if reactivity control is maintained, then there is no significant effect on the overall safety during low-power physics testing. Therefore, it should be considered that the nature of a microreactor test facility's license could be that of a research reactor or criticality experiment and not of a commercial power reactor. This option could include the issuance of a follow-on commercial construction and operations license after delivery of the microreactor to the site and all confirmation and inspection criteria are completed.

A review of past startup test accidents can lead to a meaningful discussion on potential worst-case accidents and support the discussion. The report is structured as follows:

- Section 2 provides a brief review of regulatory requirements for ITPs and the proposed regulations for completing ITPs at the manufacturing facilities.
- Section 3 contains a short review of the guidance on ITPs and the test phases and describes a hypothetical test facility.
- Section 4 describes an example low-power physics test and a hypothetical worst-case accident that can occur during low-power testing and its consequences.
- Section 5 summarizes the argument regarding the licensing requirements of a microreactor test facility.

This report assumes that the testing facility will be part of the overall manufacturing facility of the microreactors, and the terms "manufacturing facility," "factory," and "test facility" are used interchangeably in this document. Finally, it is recognized that some microreactor concepts may not or do not plan to employ factory testing; business needs and opportunities are unique to each case.

[1] Negligible relative to heat generated during full power operation and fission products generated during the lifetime of the reactor.

2. REGULATORY REQUIREMENTS AND PROPOSED REGULATIONS

2.1 REGULATORY REQUIREMENTS OF ITPS

1. Appendix B to 10 CFR Part 50, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," [7] requires that every application contains in its safety analysis report a description of the QAP to be applied during the design, fabrication, construction, and testing of the safety-related (SR) structures, systems, and components (SSCs) of the facility that play an important role in the prevention and/or mitigation of the consequences of hypothesized accidents that have the potential to cause "undue risks to the general health and safety of the public" and establishes the relevant quality assurance requirements.

2. 10 CFR Part 52.47 (b)(1) [8] mandates the establishment of a set of inspections, tests, and analyses and their acceptance criteria so that when those inspections, tests, and analyses are performed, if the acceptance criteria are met, they prove with a reasonable level of confidence that the NPP has been constructed and will operate in accordance with the design criteria, the provisions of the Atomic Energy Act, and the NRC's rules and regulations.

3. 10 CFR Part 53 subpart E [9] specifies that 53.610 (c) addresses the quality assurance activities equivalent to those specified in Appendix B to 10 CFR Part 50 and the inspections, tests, analyses, and acceptance criteria (ITAAC) in 10 CFR Part 52. 10 CFR 53.610 (c)(2) specifies that ITAAC presented in 53.1440 or comparable verifications must be addressed in the acceptance process following the construction or manufacturing of an NPP. 10 CFR 53.1440 mandates that to issue a COL, the NRC must find the following within the COL application: a set of inspections, tests and analyses (encompassing those applicable to emergency planning as well), which are performed by the licensee, as well as the respective acceptance criteria, which, if met during the QA process, can sufficiently prove that the facility has been constructed and will operate in accordance with the design criteria, provisions of the Atomic Energy Act, and the NRC's rules and regulations.

Specifically, tests should be performed to establish the following performance capabilities [10]:

1. The SSCs that are used to shut down or cool down the reactor under normal plant operating conditions and that are used to maintain the reactor in a safe condition for an extended shutdown period.
2. The SSCs that are used to shut down or cool down the reactor under transient conditions and hypothesized accident conditions and that are used to maintain the reactor in a safe condition for an extended shutdown period following such transients or accidents.
3. The SSCs that are used in adhering to the safety limits or limiting operating conditions presented in the plant's technical specifications.
4. The SSCs that are classified as engineered safety features or that are depended upon either to support the operation of engineered safety features or to make sure that their operation is within the specified design constraints.
5. The SSCs that are expected to function as specified in the design and final safety analysis report during a design-basis accident.

6. The SSCs that used to process, store, control, or restrict the release of radioactive materials.
7. The SSCs that are depended upon to preserve the integrity of and prevent damage to SR SSCs during both normal operation and accidents that include predicted transients and design-basis events.

In summary, the ITP aims to demonstrate that the nuclear facility will operate in accordance with the specified design criteria and that the SR SSCs will perform adequately and as designed so that the plant can be operated without any undue risk to the general health and safety of the public during normal operation as well as any anticipated operational occurrences or postulated accidents. Additional objectives of the ITPs include the following:

1. Validation of the analytical models and verification of the conservatism of the assumptions used in the prediction of plant behavior in response to hypothesized accident conditions and expected transients.
2. Familiarization of the plant operators and technical staff on the facility's operation. Although outside the scope of this report, the composition of the crew running ITPs in the context of factory testing is not completely addressed in existing regulations.
3. Verification and validation of the adequacy of the facility's operating and emergency procedures.

2.2 PROPOSED REGULATIONS FOR FACTORY TESTING

The policy issue document SECY-20-0093 [11] identified multiple items that need to be addressed for the licensing and regulation of microreactors. These items include the following:

i. Security
ii. Emergency preparedness
iii. Staffing, training, and personnel qualification
iv. Autonomous operations and remote operations
v. Regulatory oversight
vi. Aircraft impact assessment
vii. Annual fee structure
viii. **Manufacturing licenses** and transportation
ix. Population related and environmental siting considerations

Many of these topics were addressed in the development of 10 CFR Part 53 and proposed rules, which consist of technology-inclusive rules that allow for provisions that are scalable and proportionate to the risks posed by reactor technologies.

Specifically, SECY-24-008 [12], published in January 2024, presents two options for addressing the licensing of microreactor test facilities in the context of factory testing:

1. Power reactor license with a manufacturing license pursuant to 10 CFR Part 52 and either a COL in compliance with 10 CFR Part 52 or a power reactor construction permit and an operating license (OL) in compliance with 10 CFR Part 50. According to this option, each factory-fabricated microreactor module will be operated as a commercial reactor at the testing facility. This approach

would require conforming to the operational, security, emergency preparedness, radiation protection, and operator training and licensing requirements for power reactors. One disadvantage of this option is that it places a regulatory burden on both the microreactor manufacturer and the NRC staff because this process is similar to the licensing process of a large light-water reactor (LWR) and is out of proportion with the level of risk resulting from the low power levels and short durations of the tests.

2. Manufacturing license pursuant to 10 CFR Part 52 and power reactor construction permit and OL in accordance with 10 CFR Part 50 by adhering to the safety and environmental regulations applicable to **nonpower reactors**. This option conforms with Section 104 of the Atomic Energy Act [13], which requires that "*not more than 75% of the annual costs to the licensee of owning and operating the facility are devoted to the sale, other than for research and development, or education and training of* ***non-energy services,*** *energy or a combination of non-energy services and energy, and not more than 50% of the annual costs to the licensee of owning and operating the facility are devoted to the sale of energy*," conditioned on the definition of nonenergy services. However, Sections 103 and 104 concern the licensing of commercial and noncommercial reactors, and the target of this discussion is a reactor test facility. The primary objective of a microreactor test facility is to run ITPs and perform design validation, and any energy that is produced by such testing is minimal and is not sold. Further discussion is necessary to establish whether running an ITP is considered a nonenergy service. Such a consideration will enable the NRC to enforce only a minimum regulatory oversight to uphold common defense and security while safeguarding public health and safety. However, some of the regulations applicable to power reactors will still be relevant, such as the siting criteria in 10 CFR Part 100. One alternative to consider is making amendments to the Atomic Energy Act to include ITPs as a possible option for issuing class 104 licenses.

It should be noted that the objective of this effort is only to initiate a discussion on factory testing of microreactors. No new regulations or changes to regulations are proposed in this report

The proposed subpart E to 10 CFR Part 53, 53.620(d) established the requirement of including at least two independent physical mechanisms that can prevent criticality individually for fuel loading of a factory-fabricated microreactor at the manufacturing facility and subsequent transportation to the deployment site for operation under a COL. As a result, such a factory can operate with only a manufacturing license (ML) and may not require a COL. Although fuel loading has historically been considered the start of operations, the proposed rule suggests that disengaging these physical mechanisms that prevent criticality be interpreted as the start of operations. However, operational testing and the consequent generation of fission products would still require the facility to possess a COL, introducing the problem of operating the factory/facility with different licenses in different instances (i.e., ML during the manufacturing and fuel loading of a microreactor and COL during testing). Because such testing involves the generation of very little power for a short duration, the current COL requirements are too stringent, and some may not be necessary.

Taking this into account, the draft version of 10 CFR Part 53 subpart H, Licenses, Certifications and Approvals, Section 53.1480 combined license supporting testing of manufactured reactors [14] published in December 2024, proposed combining the ML with an abbreviated COL to issue a combined license for testing of manufactured reactors (COL-TMR), a new type of COL that would permit limited operational testing with low power levels for short durations. A brief summary of some of the relevant regulations proposed as part of 53.1480 is presented below:

1. 53.1480(a): A COL-TMR requires only fresh/unirradiated fuel be loaded into the manufactured microreactor with a license issued pursuant to 10 CFR Part 70 to authorize the testing of reactors at the test facility.
2. 53.1480(c)(i): It has been determined that fueled manufactured reactors are not in operation with two independent physical mechanisms that prevent criticality installed.
3. 53.1480(c)(ii): The COL-TMR issued pursuant to 10 CFR Part 53 will regulate manufactured commercial NPPs in which the criticality prevention configurations will be altered to allow testing, and the facilities that are used to perform such tests will limit the release of any radioactive materials caused by any licensing-basis events (LBEs).
4. 53.1480(c)(iv): The fueled manufactured reactor is considered to have commenced operation upon the initiation of the removal of any one of the independent physical mechanisms installed to prevent criticality.
5. 53.1480(c)(v): The fueled manufactured reactor is considered to not be in operation upon re-installment of the two physical mechanisms that prevent criticality. The facility will then be governed by the ML and associated licenses pursuant to 10 CFR 30 and 10 CFR 70, which regulate the possession and storage of fueled microreactors.
6. 53.1480(e)(1): The power levels during operation of a factory-fabricated reactor under a COL-TMR for testing should not exceed 5% of its rated thermal power, and the amounts and types of fission byproducts generated must be as specified in the associated 10 CFR Part 30 license and the relevant analyses.
7. 53.1480(e)(2)(i): It should be shown via analyses that the radiation dose at the exclusion area boundary as a result of any LBE does not exceed 0.1 rem over the span of a year.
8. 53.1480(e)(2)(ii): Any LBEs related to the testing of manufactured reactors under the issued COL-TMR must be mitigated by the design features in the reactor, adjusted according to the testing requirements and in the test facility, without any human intervention.
9. 53.1480(f)(5): It must be ensured that the SR SSCs and nonsafety related but safety significant SSCs of both the reactor and the facility, which aid in mitigating the potential radiological consequences of any LBEs, are available and ready for use during the testing.
10. 53.1480(f)(7): During testing, the staff must include at least one individual with expertise in nuclear core design or reactor physics pursuant to 53.730(f), one test engineer with the required qualifications under 53.730(f) in charge of the overall implementation of the test program, and one NRC-licensed operator pursuant to 53.810.
11. 53.1480(f)(11): The ITAAC for the factory specified in the COL-TMR and the ITAAC for the manufactured reactor that are to be satisfied prior to the beginning of the tests, including those specified in the ML, must be to be completed and confirmed by the NRC before the licensee initiates the removal of any one of the criticality-prevention mechanisms for testing the first manufactured reactor. The start of operation according to 53.1480(c)(iv) and the testing of subsequently manufactured reactors must commence only after satisfying the ITAAC in the COL-TMR for the manufactured reactor.

12. 53.1480(f)(12)(iii): For the reactors to be tested after the first manufactured reactor, the operation according to 53.1480(c)(iv) must not be commenced until the NRC verifies that the criteria in COL-TMR are satisfied for the manufactured reactor.

3. ITP GUIDANCE, TEST PHASES, AND HYPOTHETICAL TEST FACILITY

3.1 GUIDANCE DOCUMENTS AND RECOMMENDED PRACTICES FOR TEST PROCEDURE

The following documents provide guidance for ITPs, including the SSCs to be tested, and directions on the test procedures:

1. Regulatory Guide (R.G.) 1.68 Initial Test Programs (ITPs) for Water Cooled Nuclear Power Plants (Rev 2, 1978 [15] and Rev 4 2013 [10]). It is stated in [10] that the guide may not be applicable to ITPs required as part of new set of regulations issued after November 2012. However, Jackson et al. [16] consider the recommendations in R.G. 1.68 for the Microreactor Applications Research Validation and Evaluation (MARVEL) reactor startup because R.G. 1.68 offers extensive and general recommendations for startup testing and outlines good practices.
2. DANU-ISG-2022-06 [17] – Advanced Reactor Content of Application Project – Chapter 12: Post-manufacturing and construction Inspection, Testing and Analysis Program (PITAP) – Interim Staff Guidance (March 2024). This document is applicable to non-LWR permit applications.
3. ANSI/ANS-19.13-2024 [18] – Initial Fuel Loading and Startup Physics Tests for First-of-a-Kind Advanced Reactors. This proposed standard presents a description of initial startup testing, a required minimum test program, requirements of the test methods, and example technology-neutral and technology-dependent test methods.

Specifically, DANU-ISG-2022-06 [17] states that:

> "*For COLs referencing a Manufacturing License (ML), much of the PITAPs to resolve the Inspection, Testing, Acceptance and Analysis Criteria (ITAAC) may be performed at the manufacturer's facility and not at the COL final site provided that the subsequent fabrication, handling, installation and testing do not alter the properties. The COL holder has the responsibility for verifying ITAAC are complete*."

The tests conducted as part of the ITP should be performed using established procedures [10], [15]:

1. Which are developed and evaluated by personnel with the necessary level of experience and from relevant technical backgrounds.
2. Which include appropriate "checklists and signature blocks" to regulate test performance and the sequence in which the tests are conducted.
3. Which are approved by the people in the relevant management positions within the applicants' organizations.
4. Which include acceptance criteria that account for uncertainties considered in the analysis of transient events and accidents.
5. Which ensure that the testing instrumentation/infrastructure (e.g., probes, wiring) do not compromise existing electrical separation requirements.
6. Which include the participation of the principal design organizations and the test performance requirements that are established by them.

7. Which are developed and executed, taking into account in an appropriate manner, the operating experience, including any events/occurrences worth reporting from operating power plants.

Additionally, the designed test procedures must include steps to ensure that [10], [15]:

1. All prerequisites for a given test have been satisfied.
2. A sufficient level of instrumentation is available for the tests.
3. The tests are performed under suitable environmental conditions.

3.2 ITP PHASES AND TESTS CONDUCTED

Although low-power physics testing is the focus of this effort, a brief review of the tests performed before that as part of the ITP is presented below to understand the initial state of the reactor during low-power testing. SR SSCs are sufficiently inspected and tested, and their performance is validated before fuel is loaded into the reactor and power is generated.

The tests performed as part of the ITP/PITAP can be grouped into two phases [17]:

Phase 1: Pre-Operational Inspection,[2] Testing,[3] and Analysis:[4]
These are performed to demonstrate that the SSCs are constructed or manufactured in accordance with the design and will function as designed in the entire design range and all operating modes. Appendix A to R.G. 1.68 [10], [15] provides a list of SSCs that must be qualified in Phase 1 of the ITP/PITAP, including the following:

1. Reactor coolant systems: perform integrated systems test, vibration tests, pressure boundary integrity tests, etc.
2. Reactivity control systems: demonstrate scram capability, control rod withdrawal sequence control, withdrawal inhibit features, proper function of associated instrumentation systems, etc.
3. Reactor protection systems and engineered safety features: demonstrate function, including verification of response times of components such as sensors, flow control actuators, etc., as well as trip and alarm settings, trip logic, etc.
4. Residual or decay heat removal systems: demonstrate the operation of systems depended upon to dissipate thermal energy during transients.
5. Radiation protection systems: demonstrate function of systems used to measure or monitor radiation levels and limit or control the release of radioactivity, including area radiation monitors, personnel monitors, high efficiency particulate air (HEPA) filters, etc.

[2] Visual observations, physical examinations, or reviews of records via activities such as walkdowns, dimension measurements, nondestructive evaluations, and configuration checks performed to compare the state of the SSCs with their design features and corresponding design requirements [17].
[3] Evaluation of the performance of the SSCs via operation in manual, automatic, and any secondary modes of control, as well as in normal and degraded modes through which the SSCs are designed to operate [15], [17].
[4] Verification and validation of inputs in the safety analysis report via calculations or computations and other engineering or techniques or analyses [17].

These tests are performed without any fuel and any power or heat generated in the reactor. The testing can be performed in a graded manner so that the SSCs most important to the safety of the plant are given the highest attention during testing.

Phase 2: Initial Startup Testing:
Initial startup testing is performed after the successful completion of the pre-operational inspections, tests, and analyses. Table 1 presents an example list of reactor characteristics to be determined and the respective measurements used during initial startup. This table is adapted from a previous work [18].

Table 1. Reactor characteristics measured and confirmed during initial startup testing

Reactor characteristics	Purpose	Example measured parameters
Core reactivity, including fuel loading	To ensure that fuel is loaded safely and that inadvertent criticality is prevented.	• Critical fuel loading determined using inverse multiplication factor • Integral and differential control element worth measured at zero power and appropriate higher power levels • Critical control element positions measured at relevant reactor state points • Excess reactivity at zero power • Reactivity deficit at full power • Prompt and delayed neutron parameters • Neutron lifetime measured at zero power and relevant higher power levels • Control element worth interference
Reactor shutdown	To guarantee that the reactor can be shut down from any operating state, even when the most reactive control element is inoperative and remains in its most reactive position.	• Shutdown margin
Reactivity control	To verify the consistency between the transient operation of the reactor and the respective analytical calculations performed for safety analysis.	• Isothermal temperature coefficient • Power coefficient of reactivity • Prompt and delayed component temperature coefficients • Coolant void coefficient • Reactor stability during transient reactivity events • Reactivity response during pump startup and coast down • Load following
Power, temperature, and flow distribution	To guarantee that the parameters and assumptions used in the safety analysis are adequately accurate.	• Radial and axial power, temperature or flux distributions • Natural circulation • Flow distribution • Temperature distribution

Initial startup testing includes the following [15], [17]:

1. **Initial fuel loading and pre-critical tests:** Fuel must be loaded into the reactor in a safe, incremental manner that prevents unintentional criticality. All prerequisites must be satisfied prior to fuel loading. These include the preparation of analyses for evaluating responses during loading to ensure that sufficient instrumentation is available for continuous neutron flux monitoring throughout the core and

that the plant systems and components, such as reactivity control systems and safety systems, are functional. Additional safety measures to be followed include defining criteria for periodic data collection, independently verifying the proper installation of all fuel and control components, and defining the criteria for the functionality of plant systems and components, including reactivity control systems and other systems and components necessary to ensure the safety of the plant personnel and the public in the event of errors and malfunctions.

2. **Initial criticality**: Criticality should be approached in the same manner (i.e., using the same procedures that will be followed during the subsequent startups of the reactor during its operation, and neutron flux should be monitored continuously). Prerequisites to attain initial criticality include the following:

    i. Having all plant protection systems operable and ready, including the emergency shutdown system.
    ii. Implementing radiation monitoring and containment closure procedures.
    iii. Verifying shutdown margin for partially and fully loaded core.
    iv. Testing control element withdrawal[5] and insertion speeds, position indicators, and interlocks, including friction tests.
    v. Testing scram times with coolant flow and no flow in both hot and cold temperature conditions to guarantee that the reactor can be shut down in the required time.

3. **Low-power physics testing:** After fuel loading and achieving initial criticality, low-power tests (i.e., tests at power levels less than 5% of the rated thermal power of the reactor) are performed. The objectives of these tests are the following [15]:

    i. To complete the demonstration and verification of the functionality of the SSCs tested during pre-operational tests, with the inclusion of a heat source (i.e., an operating reactor).
    ii. To confirm the correctness and accuracy of the analytical models and their respective assumptions used in the safety analysis.

    A list of technology-neutral low-power tests to be conducted as specified in the guidance documents [10], [15], [17] is presented below:

    a. Measurement of moderator temperature coefficients over the range of temperature values during initial criticality.
    b. Measurements of control rod and control rod bank reactivity worths.
    c. Pseudo-rod-ejection tests.[6]
    d. Confirmation of adequate overlap of source and intermediate range neutron instrumentation.
    e. Flux distribution measurement for validating predictions and assumptions in safety analysis.
    f. Neutron and gamma radiation surveys.
    g. Confirming that process and effluent radiation monitors respond as intended.

[5] The term withdrawal is applicable to control rods. Herein, a similar meaning is assumed to be applicable for other types of control elements, such as control drums.
[6] Implemented as applicable to other types of reactivity control elements, such as control drums.

h. Demonstration of the functioning of control element withdrawal or insertion sequencers and control element withdrawal inhibition or block functions over the relevant power levels.
i. Confirmation of the primary containment ventilation system's ability to maintain the containment environment and the capabilities of important components in that system at the rated reactor coolant temperature.
j. Demonstration of the operability of power conversion systems (steam generation system in LWRs).
k. Demonstration of the control room control system's operability.
l. Measurement of scram time with reactor coolant at rated temperature.
m. Measurement of shutdown margin and shutdown time.
n. Demonstration of the residual or decay heat removal system's operability.
o. Vibration measurements of reactor vessel and coolant systems.
p. Demonstration of the operability of principal plant control systems.
q. Natural circulation tests of the reactor coolant systems.

These tests should be modified in a manner appropriate to microreactor features, such as passive safety systems, remote and autonomous operations, and functional containment.

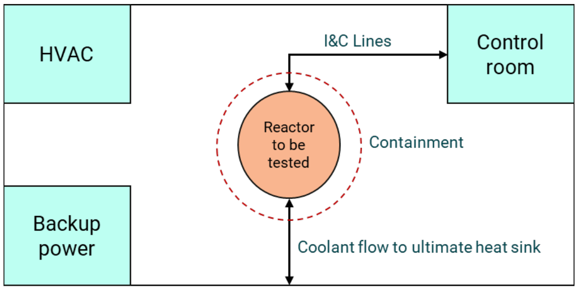
4. **Power ascension testing:** These tests are performed to demonstrate that the plant and all its systems perform as designed during normal operation and, to the extent possible and practical, during anticipated operational occurrences and postulated accidents. The tests are conducted at increasing power levels and should include power levels of 25%, 50%, 75% and 100%. Some of the reactor characteristics determined during these tests include reactivity coefficients, power vs. flow characteristics, neutron flux distributions, surface heat flux, and radial and axial power peaking factors.

3.3 A HYPOTHETICAL MICROREACTOR TEST FACILITY

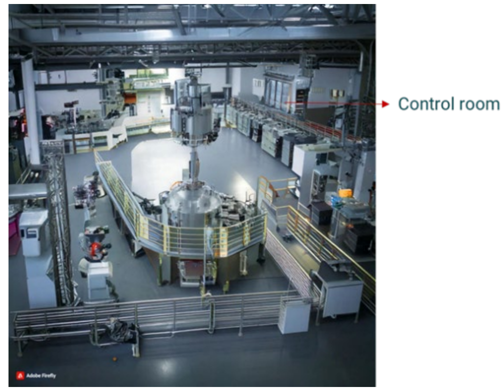
In summary, SSCs such as the reactivity control system, the reactor coolant system, the radiation protection system (including HEPA filters), reactor protection systems and engineered safety features, and residual and decay heat removal systems are tested without fueling. Fuel is loaded, pre-criticality tests are performed, and initial criticality is achieved while ensuring that all the required systems are ready and operable and that required safety prerequisites are met before the start of low-power physics testing. Hence a microreactor test facility must contain the following systems in addition to the reactor and its coolant:

1. Containment structure or a functional containment system.
2. Electrical systems, including backup power.
3. Instrumentation and control systems for collecting test data, monitoring the state of the reactor, and running the tests, including cables, connectors, and the required network infrastructure for communications.
4. Control room for the human operators and experts running the test program.
5. A secondary coolant system to act as heat sink for the reactor coolant (assuming that a power conversion unit is not built into the reactor).
6. A sufficiently capable heating, ventilation, and air-conditioning system or an air purification system with HEPA filters.
7. Cranes or other similar mechanisms to transport the microreactor.

A basic microreactor test facility similar to the Transient Reactor Test (TREAT) Facility at Idaho National Laboratory, which houses the MARVEL reactor, is shown in Figure 1.



a. Hypothetical test facility layout



b. AI-generated image of the internal layout hypothetical test facility. Tool used: Adobe Firefly.

c. The TREAT facility at Idaho National Laboratory. Source: Google Maps [19].

Figure 1. Hypothetical microreactor test facility similar to the MARVEL TREAT Facility.

The internal layout of the test facility is shown in Figure 1b in an image generated using Adobe Firefly. The microreactor to be tested is at the center with a control room at the top right corner of the image. The approximate dimensions of the TREAT facility are as follows using the scale at the lower right corner of Figure 1c:

1. Building dimensions: length = 120 ft, width = 75 ft, area = 900 sq ft.
2. Site dimensions (approximate value and a rectangular shape is considered): length = 450 ft, width = 325 ft, area = 146250 sq ft = 3.36 acres.

This facility also houses the TREAT reactor, and the MARVEL reactor is installed in a pit inside the building.

A more detailed layout of the internal structure of the test facility is presented using an example of a generic small modular reactor design [20], as depicted Figure 2 (reproduced from [20]). The site is assumed to be square in shape with a side length of 780 ft and an area of 14 acres. The reactor building was also considered to be square in shape with a side length of 100 ft and an area of 10,000 sq ft. The rated power of the small modular reactor considered is 1,000 MWt, and the containment walls are 4 ft thick. Although the microreactor test facility may not possess such shielding and containment structures, the design provides details of the relevant systems, a preliminary layout, and site dimensions.

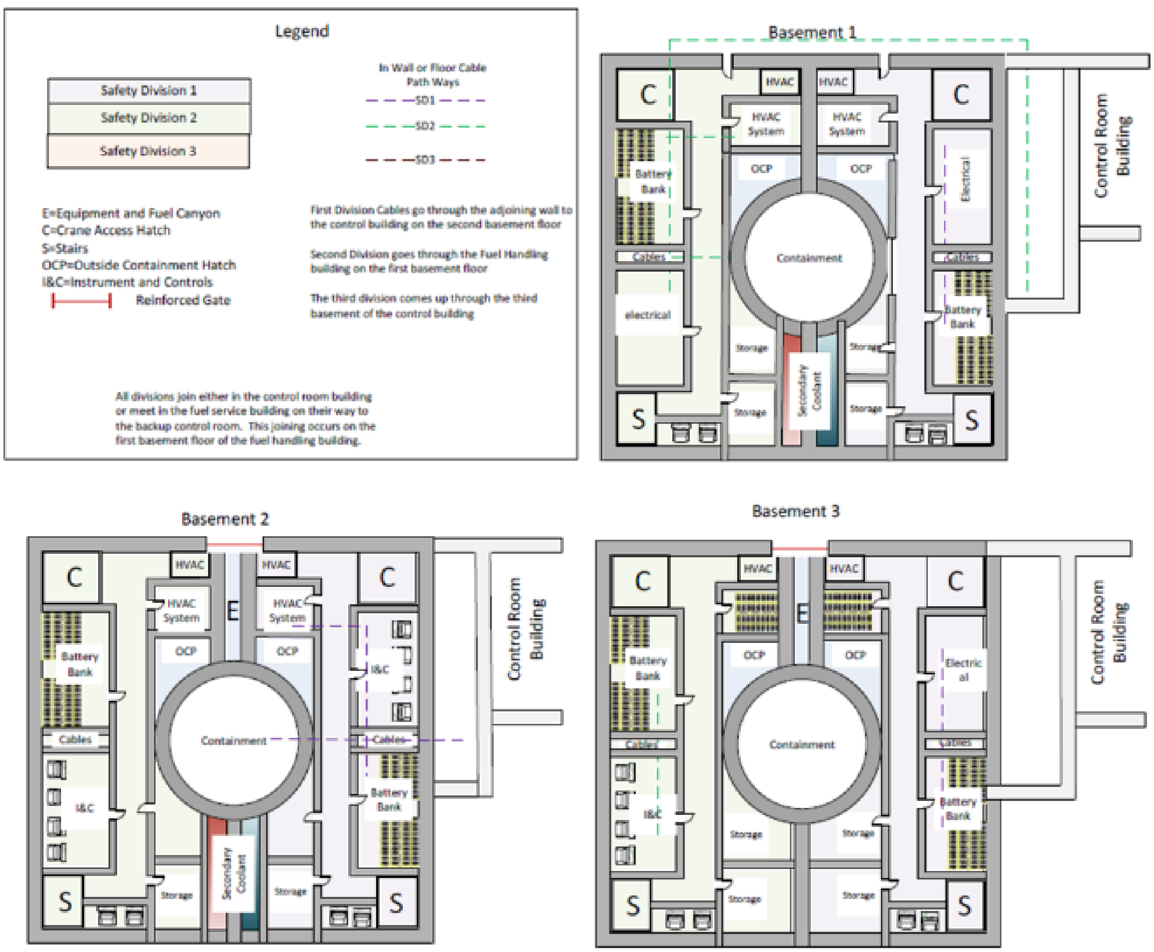


Figure 2. Detailed layout of a generic small modular reactor.

4. EXAMPLE LOW-POWER TEST AND HYPOTHETICAL WORST-CASE ACCIDENT

4.1 EXAMPLE LOW-POWER PHYSICS TEST

To estimate the worst-case consequences from the hazards presented by low-power testing of a microreactor in the factory, an example test and radionuclide dispersion calculation are performed. An example low-power physics test from [18], [21] is presented below. The aim of this description is to aid in understanding what happens and what can go wrong during such a test.

Test: Control element reactivity worth measurement.
Test objective: To validate the ability to control reactivity and to shut down the reactor. The measurements are used to verify the accuracy of the predictions/computations of the reactivity worth of the control elements.
Precautions: The reactivity should be at a value considerably lower than one that the control elements can constrain it to, and the experiment should be performed only over a small operating range.
Prerequisites: Necessary pre-operational, pre-critical, and criticality tests are successfully completed. The test criteria (i.e., conditions to determine success) and the test procedures, including the safety limits, limiting operating conditions, surveillance requirements, and administrative controls, are established. The availability of necessary equipment (e.g., instrumentation, safety systems) is established.
Initial condition: Fuel is loaded into the reactor along with a neutron source. The fuel is loaded to a "slightly over critical" state [21], and the control elements are fully inserted (i.e., into their least reactive position).
Experiment procedure: Only one control element is manipulated at a time, and each of the control elements is calibrated in the following manner:

1. A control element is carefully repositioned to bring the reactor to criticality until a low power level can be easily measured and a steady state is attained.
2. The control element under calibration is then slightly withdrawn by a measurable amount to increase the reactivity to a stable value, and the reactor period is measured.
3. The control element is then repositioned (to a slightly below critical level) to decrease reactivity and reduce the reactor power to the initial critical level. A steady state is reached.
4. Steps 1–3 are repeated with increasing movements, and the reactor periods are measured.
5. Steps 1–4 are repeated with all the control elements.

Care must be taken to ensure that the reactor power level is below 5% of its rated value. While control elements are moved to higher reactive positions for calibration, other control elements must be positioned further to decrease criticality. This approach ensures that the first control element can be withdrawn without making the reactor supercritical.
What can go wrong (example): Inadvertent increase of reactivity due to a failure of the control element control system or operator error [22].

4.2 HYPOTHETICAL WORST-CASE ACCIDENT

To facilitate a consequence estimation, gas-cooled reactor technology with tristructural-isotropic (TRISO) fuel is considered for this hypothetical worst-case accident. Figure 3 (reproduced from a previous work [23]) shows a pathway for radionuclide release in a gas-cooled reactor. A reactivity excursion event could rapidly increase fuel temperature, leading to stress and crack formation within the fuel particle that results in the release of fission products into the fuel matrix. This assumption may be incorrect or not applicable for all gas-cooled, TRISO-fueled reactor designs. This assumption is only permitted to estimate maximum hypothetical consequences like that typically employed in the safety and licensing basis for many research reactors in the US. If microreactor factory testing is to be permitted under nonpower and potentially under nonreactor licenses, then this type of overly conservative assumption may be expected.

For this example, the radionuclides can subsequently be released into the helium pressure boundary, the test facility building, and the outside environment. In the worst-case scenario, each barrier is assigned only the minimum estimate of expected performance, or retains the minimum quantity of dose-contributing radionuclides.

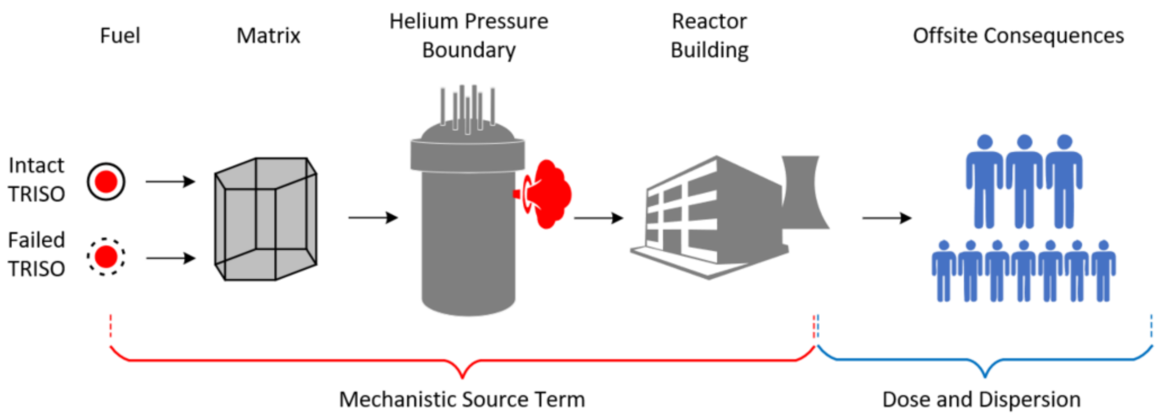


Figure 3. Gas-cooled reactor radionuclide release pathway.

The radionuclide inventory and release fractions presented in a previous work [23] are considered and scaled to a 10 MWt power level. This inventory [23] represents a core equilibrium condition over the fuel cycle, whereas fresh fuel is loaded into the reactor as part of the ITP, and the amount of fission products generated during low-power testing is negligible. This is both a significant assumption and significant challenge because detailed design information, such as core configuration, and additional neutronics simulations are needed to establish the fission product inventory during low-power testing. Therefore, it is recommended that for future hypothetical worst-case consequence estimates, designers justify some reduced quantity based on their testing program for their reactor design. Again, the unadjusted or maximum value is shown here to present an unbiased worst-case scenario.

An additional case in which the filtration system (an anticipated safety-significant system) in the test facility functions and results in the retention of 95% of all radionuclides except noble gases and iodine is considered as well [24]. Noble gases and iodine are completely released into the environment. The total effective dose as a function of distance from the release is calculated using HotSpot [25] and is depicted in Figure 4. The total dose remains below the prescribed value from 10 CFR 53.1480, even in the case of a worst-case accident with no filtration. Core equilibrium radionuclide inventories are used in this analysis, whereas fission products generated during low-power testing are almost negligible. The analysis is used only as a bounding case and to qualitatively show that the regulations proposed in 10 CFR 53.1480 are satisfied.

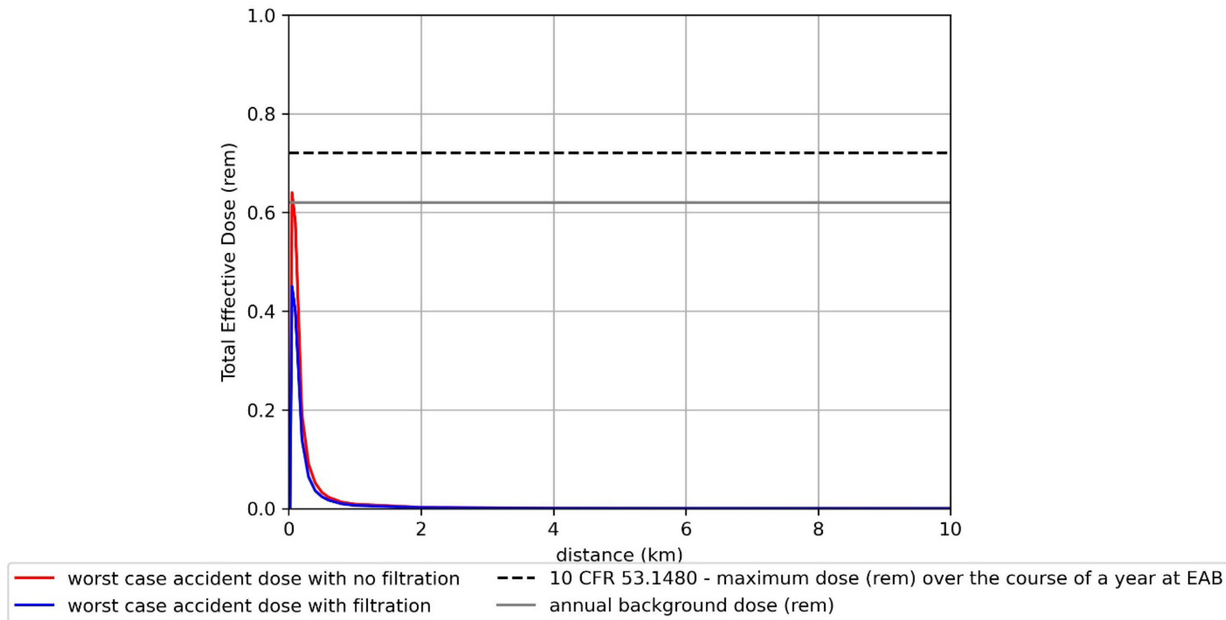


Figure 4. Total effective dose (rem) as a function of distance from the test facility building source.

By comparison, the maximum whole-body dose due to a maximum hypothetical accident at the MIT Nuclear Research Reactor is 0.3 rem at 16 m [26].

5. CONCLUSIONS

The risk presented by low-power physics testing of a microreactor with fresh fuel in a factory is primarily due to the criticality hazard and moving of control elements to measure key reactor properties prior to full-power operation. The importance of applying other safety functions for heat removal and containment of fission products as they would be applied for commercial power reactors is significantly reduced or not applicable. In the assessment of a highly conservative hypothetical worst-case accident, potential releases are well below annual background and regulatory limits for reactor operation.

This report also discusses potential microreactor factory layouts, background on what ITPs and low-power testing includes, and what the current and proposed Part 53 regulatory requirements will be. The intent of this background is to provide context and to frame the hazards presented by new microreactors with fresh fuel in the factory. Refueling and spent fuel handling risks are beyond the scope of this discussion. However, these issues can be included in future work and are especially relevant because if a confinement or containment exists for a larger radiological hazard, then the same facilities could potentially be used for testing a new microreactor with fresh fuel.

No new regulations or guidance are currently proposed. However, additional consideration is recommended for new or alternative existing regulatory paths for factory-fueled and -tested microreactors, recognizing that rapid, high-volume deployment regimes could be an evolutionary advantage for the US and global energy customers looking for reliable, secure, and safe energy sources. Obtaining existing 10 CFR 50/52/53 nonpower and power reactor licenses may be challenging for developers who want to test factory-fueled microreactors. However, a full discussion of these considerations is beyond the scope of this report.

Where future work would be beneficial in supporting the basis for further discussion of new or alternative regulatory paths for factory-fueled and -tested microreactors includes the following:

1. High-fidelity, time-dependent, reactor physics modeling of startup tests and control element movements to quantify both the criticality and fission product buildup hazards.
2. Assessment of microreactor deployment and operational opportunities afforded by expanded factory testing of fueled microreactors.
3. Identification and quantification of regulatory challenges associated with factory testing of fueled microreactors under existing nonpower and commercial power reactor licensing pathways.

Item 1 will further address the answer to the questions: *what can go wrong?* and *what are the consequences?* Item 2 will demonstrate the need and strategic importance of this capability for the microreactor industry. And finally, Item 3 will identify the regulatory barriers and better address the question: *what is most appropriate from the perspective of reasonable assurance of adequate protection?*

6. REFERENCES

[1] "PART 50—DOMESTIC LICENSING OF PRODUCTION AND UTILIZATION FACILITIES," NRC Web. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/full-text.html

[2] "PART 52—LICENSES, CERTIFICATIONS, AND APPROVALS FOR NUCLEAR POWER PLANTS," NRC Web. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/full-text.html

[3] "Part 53 – Risk Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," NRC Web. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/advanced/modernizing/rulemaking/part-53.html

[4] "Regulatory Guide 1.68: Initial Test Programs for Water-Cooled Nuclear Power Plants," United States Nuclear Regulatory Commission, R.G.1.68, Rev 4, 2013. [Online]. Available: https://www.nrc.gov/docs/ml1305/ml13051a027.pdf

[5] U. S. G. A. Office, "Science & Tech Spotlight: Nuclear Microreactors | U.S. GAO." [Online]. Available: https://www.gao.gov/products/gao-20-380sp

[6] "Proposal for a Technology-Neutral Safety Approach for New Reactor Designs," IAEA-TECDOC-1570, 2007. [Online]. Available: https://www-pub.iaea.org/MTCD/publications/PDF/TE_1570_web.pdf

[7] "Appendix B to Part 50—Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plan," NRC Web. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appb.html

[8] "§ 52.47 Contents of applications; technical information.," NRC Web. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part052/part052-0047.html

[9] "Regulations.gov." [Online]. Available: https://www.regulations.gov/document/NRC-2019-0062-0310

[10] "ml13051a027.pdf - R.G. 1.68 INITIAL TEST PROGRAMS FOR WATER-COOLED NUCLEAR POWER PLANTS Rev 4." Accessed: Mar. 17, 2025. [Online]. Available: https://www.nrc.gov/docs/ml1305/ml13051a027.pdf

[11] "NRC: Package ML20254A363 -SECY-20-0093: Policy and Licensing Considerations Related to Micro-Reactors." Accessed: Mar. 17, 2025. [Online]. Available: https://www.nrc.gov/docs/ML2025/ML20254A363.html

[12] "NRC: Package ML23207A252 -SECY-24-0008: Micro-Reactor Licensing and Deployment Considerations: Fuel Loading and Operational Testing at a Factory." [Online]. Available: https://www.nrc.gov/docs/ML2320/ML23207A252.html

[13] United States: Congress and United States: Congress, "Atomic Energy Act of 1946, as amended, and for other purposes." Accessed: Mar. 12, 2025. [Online]. Available: https://www.govinfo.gov/app/details/COMPS-1630

[14] "ML24344A037.pdf - Draft Section 53.1480." Accessed: Mar. 12, 2025. [Online]. Available: https://www.nrc.gov/docs/ML2434/ML24344A037.pdf

[15] "ML12216A007.pdf - R.G. 1.68 - INITIAL TEST PROGRAMS FOR WATER-COOLED NUCLEAR POWER PLANTS Rev 2." Accessed: Mar. 17, 2025. [Online]. Available: https://www.nrc.gov/docs/ML1221/ML12216A007.pdf

[16] J. H. Jackson, M. Patterson, and A. A. Jaoude, "MICROREACTOR APPLICATIONS, RESEARCH, VALIDATION, AND EVALUATION (MARVEL) REACTOR STATUS, CONSTRUCTION, AND TESTING." [Online]. Available: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_132605.pdf

[17] "DANU-ISG-2022-06 Interim Staff Guidance Associated with License Applications - Post-manufacturing and construction Inspection, Testing, and Analysis Program," NRC Web. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/isg/license-applications.html

[18] *ANSI/ANS-19.13-2024 - Initial Fuel Loading and Startup Physics Tests for First-of-a-Kind Advanced Reactors*. [Online]. Available: https://webstore.ansi.org/standards/ansi/ansians19132024?srsltid=AfmBOoq7_nNvU8515h5121QLNMaKcfc_zQnuPqoOfpKeWERBBvGluo8M
[19] "Google Maps," Google Maps. [Online]. Available: https://www.google.com/maps/@43.6019739,-112.6704766,199m/data=!3m1!1e3?entry=ttu&g_ep=EgoyMDI1MDMxNi4wIKXMDSoASAFQAw%3D%3D
[20] Lewis, Tom Goslee, B. Cipiti, S. Jordan, and G. Baum, "Generic small modular reactor plant design.," SAND2012-10406, 1096461, 463662, Dec. 2012. doi: 10.2172/1096461.
[21] J. B. Hoag, *Nuclear reactor experiments*. Van Nostrand, 1958.
[22] I. A. E. Agency, "Reactivity Accidents," International Atomic Energy Agency, Text, 1993. [Online]. Available: https://www.iaea.org/publications/1458/reactivity-accidents
[23] A. Huning, D. Shropshire, and E. Kurt, "Risk-Informed Opportunities and Challenges for Microreactors," in *18th International Probabilistic Safety Assessment and Analysis (PSA 2023)*, Knoxville, TN: American Nuclear Society, 2023, pp. 689–698. doi: 10.13182/PSA23-40924.
[24] D. E. Shropshire, E. G. Kurt, and A. Huning, "Cost Efficient-by-Design Microreactors: Trade-offs between cost, technical, and regulatory factors," Idaho National Laboratory (INL), Idaho Falls, ID (United States), INL/RPT-23-71387-Rev000, Dec. 2022. doi: 10.2172/1962047.
[25] "HotSpot - Health Physics Codes for the PC | NARAC." Accessed: Mar. 19, 2025. [Online]. Available: https://narac.llnl.gov/hotspot
[26] "ML053190384.pdf." Accessed: Mar. 19, 2025. [Online]. Available: https://www.nrc.gov/docs/ML0531/ML053190384.pdf