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Readiness Report for DOE Support of Maritime-Related Demonstration Projects of Advanced Nuclear Technology

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Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies

ABS

NRIC | INL Idaho National Laboratory

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Executive Summary

This report is the fourth deliverable of a series of reports set forth by the Department of Energy (DOE), led by the American Bureau of Shipping (ABS), for the research award, “Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies.” The report highlights the key findings and recommendations on the nuclear-maritime testing opportunities available at U.S. national laboratories.

This report is based on the results of two Information Needs Requests (INRs)—one to assess the marine industry’s needs and the other to evaluate potential testing and other supported opportunities for nuclear-maritime applications at U.S. national laboratories and university nuclear laboratories. The scope of this research to define opportunities for testing and potential constraints is described by Figure ES1. The evaluated laboratories were U.S.-based public facilities that possess established nuclear research capabilities. The analysis revealed a clear demand for robust and reliable testing solutions in the nuclear-maritime domain. U.S. national laboratories and university nuclear laboratories have a host of testing opportunities that address many of the indicated industry testing needs. Table 1 in the main report body refers to the list of laboratories that responded to the second INR, and Table 3 in the main report body summarizes the testing opportunities provided by the laboratories and the identified constraints. However, there are also notable constraints bounding the existing opportunities at U.S. national laboratories and university laboratories—most notably the lack of testing sites that can simulate sea conditions for nuclear reactors and a disparity between the quantity of modeling and simulation and physical testing capabilities. The lack of clear regulatory requirements for nuclear-maritime reactors presents a challenge when determining how to best address these testing constraints. As nuclear-maritime regulation develops, it is possible that new physical testing and demonstration capabilities will need to be created to sufficiently support industry needs.

Future research at the National Reactor Innovation Center (NRIC) will focus on broadening the understanding of the constraints and the testing capacity of U.S. national laboratories and university nuclear laboratories to meet the current demand. Detailed evaluations will be conducted to identify specific testing opportunities within the United States that may require enhancement. A thorough capacity and critical capability analysis of U.S. national laboratories and university nuclear laboratories will also be undertaken to assess existing testing opportunities to meet increased demand and to identify the investments necessary to scale up testing opportunities efficiently and effectively.

Through these strategic efforts, the aim is to address the current constraints and position U.S. national laboratories and university nuclear laboratories to meet the evolving and expanding testing needs of the nuclear, maritime, oil, and gas industries. This forward-thinking approach will position the United States to the forefront of nuclear-maritime applications testing and demonstration, supported by national technology advancement and energy security. In addition, this work supports the recently issued nuclear Executive Orders (EOs). Specifically, EO 14299, “Deploying Advanced Nuclear Reactor Technologies for National Security”, and EO 14300, “Ordering the Reform of the Nuclear Regulatory Commission,” by ensuring the rapid development, deployment, and use of advanced nuclear technologies; and increasing the deployment of new nuclear reactor technologies, such as Generation III+ and IV reactors, modular reactors, and microreactors to support America leading the commercialization of affordable and abundant nuclear energy.

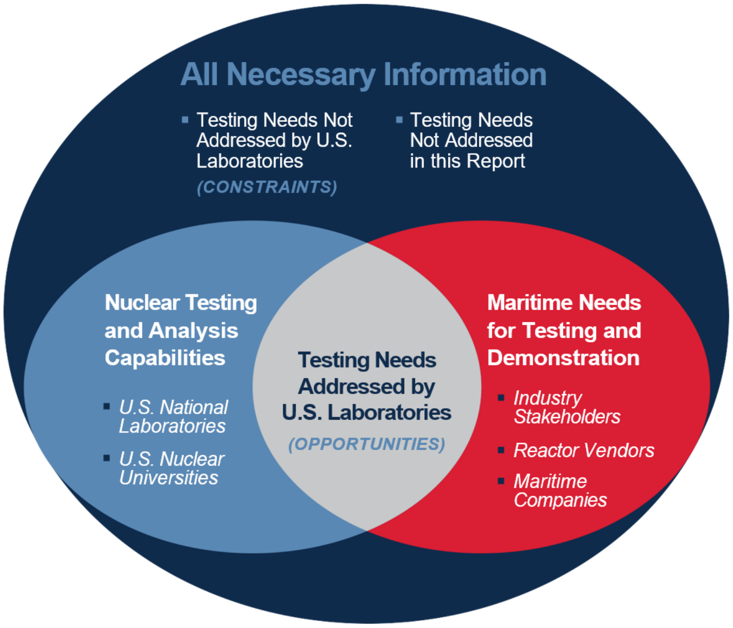

Figure ES1. Testing opportunities and constraints for nuclear-maritime demonstration.

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ACRONYMS

ABS .... American Bureau of Shipping

AM .... Additive Manufacturing

ANL .... Argonne National Laboratory

APS .... Advanced Photon Source (ANL)

ATLAS .... Argonne Tandem Linac Accelerator System (ANL)

ATR .... Advance Test Reactor (INL)

BNL .... Brookhaven National Laboratory

BPVC .... Boiler and Pressure Vessel Code

CFCT .... Chemical and Fuel Cycle Technology

DOE .... Department of Energy

DOME .... Demonstration of Microreactor Experiments (INL)

GEANT4 .... Geometry and Tracking 4 Software

GTech .... Georgia Institute of Technology

GWU .... George Washington University

HALEU .... High-Assay Low-Enrichment Uranium

HPC .... High-Performance Computing

IML .... Irradiated Materials Laboratory (ANL)

INL .... Idaho National Laboratory

INR .... Information Needs Request

ISU .... Idaho State University

IVEM .... Intermediate Voltage Electron Microscopy

KSU .... Kansas State University

LOCA .... Loss Of Coolant Accident

MAGNET .... Microreactor Agile Non-Nuclear Experimental Testbed (INL)

MASK .... Maneuvering and Sea Keeping Basin

MCNP .... Monte Carlo N-Particle Transport Code

MERF .... Materials Engineering Research Facility (INL)

METL .... Mechanisms Engineering Test Loop Facility (ANL)

METLab .... Mechanical and Environmental Testing Laboratory (ANL)

MIT .... Massachusetts Institute of Technology

MITR .... MIT Reactor

MOOSE .... Multiphysics Object-Oriented Simulation Environment

MSTEC .... Molten Salt Thermophysical Examination Capability (INL)

NCSU .... North Carolina State University

NE .... DOE Office of Nuclear Energy

NDE .... Nondestructive Examination

NRC .... Nuclear Regulatory Commission

NRIC .... National Reactor Innovation Center

NSTF .... Natural convection Shutdown heat removal Test Facility (ANL)

OSU ..... Oregon State University
PIV ..... Particle Image Velocimetry
PMEC ..... Pacific Marine Energy Center (OSU with others)
PNNL ..... Pacific Northwest National Laboratory
PPE ..... Personal Protective Equipment
PUR-1 ..... Purdue University Reactor Number One
PWR ..... Pressurized-Water Reactor
RPL ..... Radiological Processing Laboratory (PNNL)
R&D ..... Research and Development
SMR ..... Small Modular Reactor
SNL ..... Sandia National Laboratories
SRIM ..... Stopping and Range of Ions in Matter
TCAD ..... Technology Computer-Aided Design
TREAT ..... Transient Reactor Test Facility (INL)
TRIGA ..... Training Research Isotope General Atomics
TRISO ..... Tristructural Isotropic Particle Fuel
UBuff ..... University at Buffalo
UMich ..... University of Michigan
UTenn ..... University of Tennessee
UTD ..... University of Texas at Dallas
USU ..... Utah State University
UWM ..... University of Wisconsin–Madison
WEC ..... Wave Energy Converters

SECTION 1

1 Introduction and Purpose

This report is the fourth deliverable of a series of reports set forth by the Department of Energy (DOE), led by the American Bureau of Shipping (ABS), for the research award, "Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies." This follows the first report, "Road Map for the Development of Commercial Maritime Applications of Advanced Nuclear Technology," which laid out a preliminary road map for commercial nuclear-maritime demonstration projects. The second ("Configurations of Commercial Advanced Nuclear-Maritime Applications") and third reports ("Report on Potential Challenges and Impacts of Advanced Nuclear Maritime Applications in the U.S.") addressed the configuration models and technical, regulatory, and economic challenges to the adoption of nuclear technology in the commercial marine industry.

This work supports the recently issued nuclear Executive Orders (EOs). Specifically, EO 14299, "Deploying Advanced Nuclear Reactor Technologies for National Security", and EO 14300, "Ordering the Reform of the Nuclear Regulatory Commission," by ensuring the rapid development, deployment, and use of advanced nuclear technologies; and increasing the deployment of new nuclear reactor technologies, such as Generation III+ and IV reactors, modular reactors, and microreactors to support America leading the commercialization of affordable and abundant nuclear energy.

This document identifies testing opportunities and associated constraints at U.S. national laboratories and U.S. university nuclear laboratories that seek to address industry needs for testing maritime nuclear applications. While the focus of this report is on maritime nuclear applications, many of the opportunities discussed in this report are useful beyond maritime- specific applications. By determining these constraints, the National Reactor Innovation Center (NRIC) can aim to develop engineering requirements and specifications needed for maritime testing platforms. The information for this report was collected through Information Need Requests provided in Appendix A and B.

1.1 Regulatory Considerations

Many of the constraints identified in this report are related to the needs of physical versus modeling- and simulation-based testing. The action required to address these needs will depend on the regulatory requirements for nuclear-maritime technologies, which currently do not exist in the United States. While determining the regulatory requirements for nuclear-maritime applications is outside the scope of this report, they will be critical to completely identify the constraints and limitations between industry needs and U.S. testing capabilities. These considerations are discussed further in Section 5.6. The subject should be revisited and analyzed for a complete gap determination.

1.2 NRIC Program Description

NRIC is a DOE Office of Nuclear Energy (NE) program, headquartered at Idaho National Laboratory (INL). The NRIC program is designed to enable fueled reactor experiments for projects funded by the private sector by creating infrastructure useful to a range of innovators.

Common needs in any reactor experiment include a site for testing, nuclear fuel, and a regulatory pathway for licensing. In addition, NRIC works with the nuclear industry to understand where there are common barriers or opportunities for testing. NRIC does not provide support directly to any one concept; rather, the program methodically reduces the expense and timeline associated with innovation in nuclear by investing in capabilities that benefit multiple technologies.

One such application NRIC is interested in is advanced nuclear technologies for maritime applications. To support this endeavor, NRIC, along with ABS and Morgan, Lewis, and Bockius LLP, formed the Maritime Nuclear Applications Group. This is a working group that supports the near-term field testing of advanced reactor technologies in marine settings by aligning with the goals and mission of NRIC.[a]

1.3 U.S. National Laboratories' Roles in the Life Cycles of Fueled Reactor Experiments

The U.S. industrial base regularly makes use of the distinctive qualities and capabilities of designated user and shared research and development (R&D) facilities to support its basic research, applied research, and experiment development. Some of the national laboratory capabilities introduced in this report benefit from operational status as a designated user facility or shared research and development facilities. This status is important to consider when planning future research and testing activity.

1.3.1 Designated User Facilities

To accelerate the development of science and technology and to support DOE mission requirements, designated user facilities are typically purpose-built and have open access operating modes. DOE fully funds the design, construction, and operational costs of these facilities, and by waiving fees for designated user facilities on the condition that researchers publish their findings in scientific and technical literature, designated user facilities lower financial challenges that may otherwise limit innovation and the pursuit of new scientific knowledge. Some relevant designated user facilities include the Advanced Photon Source (APS) and Argonne Tandem Linac Accelerator System (ATLAS) at Argonne National Laboratory (ANL) and the Advanced Test Reactor (ATR) at INL.

1.3.2 Shared Research and Development Facilities

Along with designated user facilities, DOE also runs shared R&D facilities, which are usually built to fulfill particular program mission needs but may also become accessible to users as the NRIC Program Office mission requirements change.

Other formal agreements, such as Cooperative Research and Development Agreements and Strategic Partnership Projects with the hosting DOE national laboratory, are required to gain access to these facilities.

When it comes to these facilities, DOE covers operational costs for mission-related activities, but non-mission-related activities require separate cost recovery mechanisms for external users.

1.4 Nuclear Energy University Program

The Nuclear Energy University Program is a DOE-based organization that provides research grants to university laboratories for R&D and infrastructure [1]. It seeks to align the nuclear energy research being conducted at U.S. colleges and universities with NE's mission and goals. The program supports projects that focus on the needs and priorities of NE, including fuel cycle, reactor concepts, and other research supporting the NE mission.

[a] More information about NRIC can be found on their website: https://nric.inl.gov.

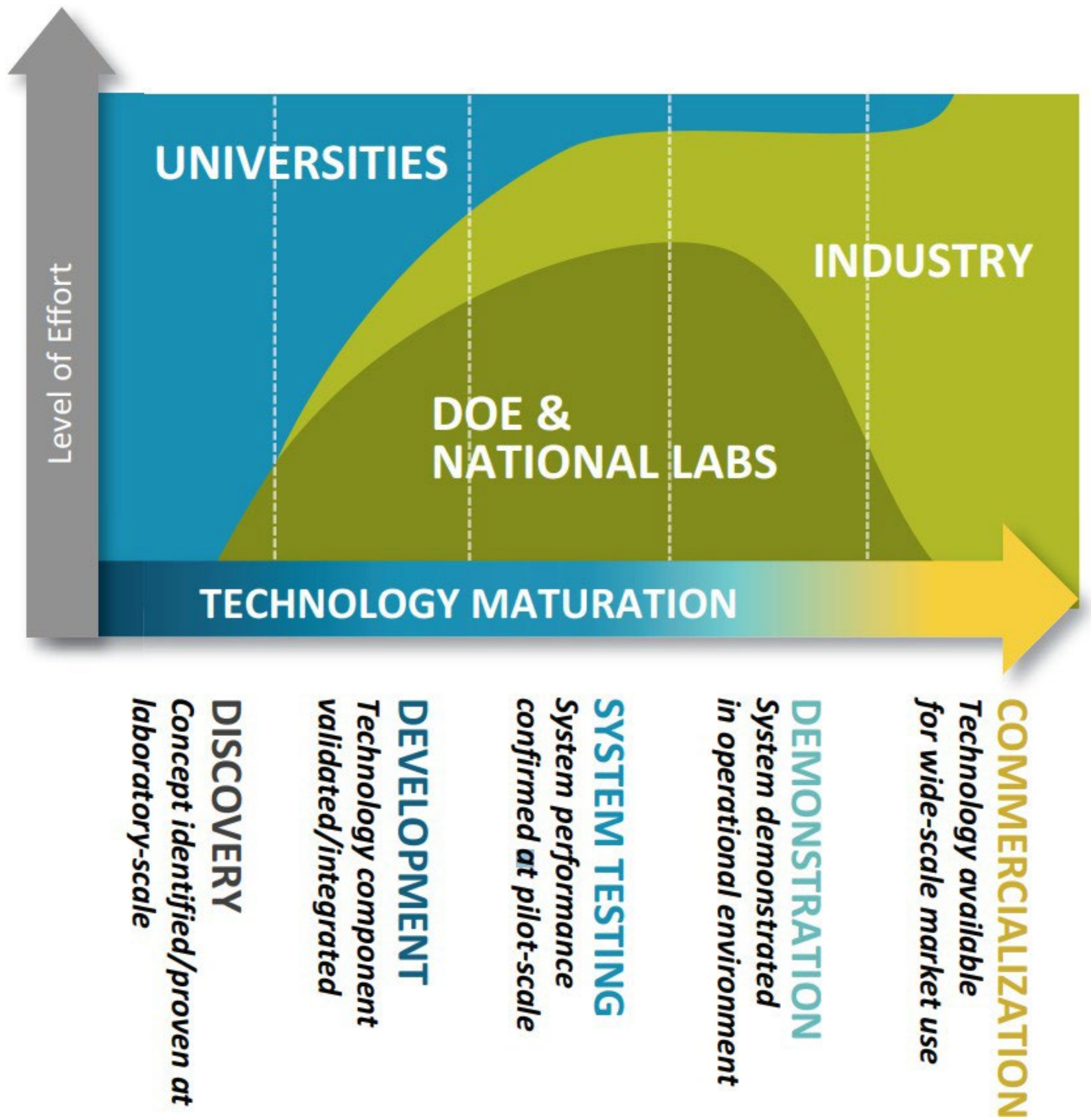

Figure 1. DOE national laboratories' relationship to universities and industry [2].

SECTION 2

2 Maritime Readiness Assessment Process

The maritime readiness assessment process for nuclear-maritime applications follows a three-step process:

1. *Identify Industry Testing Needs*—Gather information about the current state of nuclear-maritime applications, including the technologies being developed and the needs of the industry.
2. *Identify Laboratory Capabilities to Address Testing Needs*—Gather information about the testing capabilities that exist from national laboratories and university nuclear laboratories.
3. *Identify the Constraints*—Evaluate which testing requirements cannot be met by comparing Step 1 and Step 2.

2.1 Information Needs Requests

2.1.1 Industry Stakeholders INR (INR No.1)

The industry stakeholders' Information Needs Request (INR) No. 1, was assembled to assess nuclear, maritime, and oil and gas companies on their plans and testing needs regarding nuclear-maritime applications. INR No. 1 is provided in Appendix A for information. The responses were used to identify what testing opportunities U.S. national laboratories and universities will need to facilitate for testing nuclear-maritime applications. INR No. 1 included questions regarding:

- The types of nuclear-maritime applications in which the companies are interested.
- The timeline for developing and deploying nuclear-maritime applications.
- The testing capabilities that companies would need to test nuclear-maritime applications.

2.1.2 U.S. National Laboratories and University Laboratories INR (INR No. 2)

INR No. 2 was created using the results from INR No. 1 and was directed at the U.S. national laboratories and university nuclear laboratories to assess testing opportunities relevant to the needs of nuclear-maritime applications identified by industry stakeholders. INR No. 2 is provided in Appendix B for context. The INR focused on five general areas of testing capabilities:

- *Safety*—Questions related to safety systems, alarms, and physical scenario analysis.
- *Materials and Chemicals*—Questions regarding materials and chemicals testing.
- *Maritime Testing*—Questions regarding testing methods for maritime applications.
- *Security*—Questions regarding security concerns with a maritime nuclear reactor.
- *General Research*—Questions regarding a laboratory's ability to execute various research topics or activities (e.g., research on small modular reactors or heat-pipe reactors).

2.2 Laboratory Respondents for Information Needs Requests

INR No. 1 was sent to 41 companies across the nuclear, maritime, and oil and gas industries. Due to the disclaimers from the companies, the list of companies that responded to INR No. 1 remains anonymous. In total, 12 out of 41 potential responses were received for INR No. 1. INR No. 2 was sent to six U.S. national laboratories and 43 university laboratories. Nineteen out of 49 potential responses were received for INR No. 2 (Table 1). The responses from both INRs are detailed in Sections 3 and 4.

The laboratories were chosen based on the following criteria:

- U.S.-based public facilities: Facilities that DOE has direct influence over and that have received DOE funding for research activities. Limiting the research facilities to public facilities with strong connections to DOE better suits the objectives of this report.
- Nuclear laboratories: Laboratories that have proper licensing to conduct nuclear research bounded the scope of applicable laboratories. Therefore, only organizations with established nuclear laboratories were contacted for INR No. 2. However, laboratories with maritime-exclusive testing capabilities should not be excluded from future research activities.

Likely, there are additional maritime nuclear testing capabilities that are not covered in this report due to:

- The limited number of laboratories that were contacted.
- The limited number of responses received compared to the number of laboratories contacted.
- The limited detail in the responses.

Thus, the information presented in this report should not be viewed as comprehensive but rather as an initial overview of the maritime nuclear testing landscape in the United States. Future outreach to additional laboratories should be conducted to comprehensively capture testing opportunities. See all recommendations for future work in Section 6.1.

Table 1. U.S. national laboratory and university laboratory INR No. 2 respondents.

INR No. 2 Respondents
ANL
Brookhaven National Laboratory (BNL)
INL
Pacific Northwest National Laboratory (PNNL)
Sandia National Laboratories (SNL)
George Washington University (GWU)
Georgia Institute of Technology (GTech)
Idaho State University (ISU)
Kansas State University (KSU)
Massachusetts Institute of Technology (MIT)
North Carolina State University (NCSU)
Oregon State University (OSU)
Purdue University
University at Buffalo (UBuff)
University of Michigan (UMich)
University of Tennessee (UTenn)
University of Texas at Dallas (UTD)
University of Wisconsin–Madison (UWM)
Utah State University (USU)

SECTION 3

3 Evaluation of Maritime Application Needs

The maritime application needs were determined based on the comprehensive data gathered from INR No. 1, which focused on multiple facets, including safety protocols, material and chemical testing, maritime-specific testing, security concerns, and general research topics. Each section was crafted to gather information on specific testing needs for their licensing cases. General research topics were a category of responses that did not fit into a particular topic and referred to activities that companies indicated they were interested in studying.

The responses were organized into categories and similar responses were amalgamated. Sections 3.1–3.5 list the key research and testing needs indicated by the industry stakeholders from INR No. 1. It should be noted that the items listed below are not comprehensive of the entire landscape of nuclear-maritime research and testing needs. Rather, they are simply summarized responses from the companies who responded to INR No. 1.

3.1 Safety

3.1.1 Reactor Operations Under Severe Conditions

This section identifies testing and research needs that address operations in adverse environmental conditions impacting reactor performance for maritime applications:

- Seismic shock testing: Evaluating the reactor's robustness and structural integrity when subjected to seismic activity.
- Acceleration testing: Assessing how the reactor responds to any changes in velocity and accelerations of a vessel carrying a reactor.
- Vibration testing: Testing the reactor's resilience to continuous oscillations or harmonics that may result from motions or other machinery.
- Simulated sea trials: Replicating conditions a reactor might face at sea to gauge its overall performance and safety.
- Computational fluid dynamics analysis: Using computational models to analyze the flow of liquids and gases within the reactor, ensuring optimal operations under various conditions.
- Finite-element analysis: A numerical method for predicting how a reactor might respond to external forces, temperature changes, and other physical effects.
- Dynamic stability simulations: Using simulations to understand the reactor's stability under dynamic, changing conditions.
- Control system testing: Ensuring the reactor's control systems function correctly and safely under all normal and off-normal events or conditions.
- Redundancy and resiliency testing: Verifying that redundant systems are in place and operational in case primary systems fail.
- Equipment securing and restraint system: Assessing how well reactor components are secured to prevent movement or damage under all normal and off-normal events or conditions.
- Human factors testing: Evaluating the ease and safety of human interaction with the reactor systems, ensuring that operators can manage reactor systems under maritime conditions.
- Mechanical system rigidity testing: Checking the sturdiness of the reactor's mechanical systems, ensuring they resist deformation under load.

3.1.2 Alarm Systems

This section identifies testing and research needs that address various alarm systems that could be needed on a nuclear-maritime application:

- Radiation alarms: Systems that alert personnel to abnormal radiation levels, critical for ensuring the safety of personnel.
- Gas detection alarms: Systems that detect potentially hazardous and radioactive gases, ensuring a safe environment.
- Reactor parameter alarms: Systems that notify operators of any parameters within the reactor that might be outside safe or optimal ranges.
- Emergency cooling system alarms: Systems that alert operators of issues within the cooling mechanism, crucial for preventing overheating.
- Containment integrity alarms: Systems indicating breaches or potential breaches in the reactor's containment structures.

3.1.3 Fire Safety

This section identifies testing and research needs that address the unique fire safety and firefighting concerns on a maritime application with a reactor and other radioactive materials:

- Sea water interaction with reactor systems: Understanding potential hazards when sea water contacts reactor systems, especially in emergencies.
- Onboard low-level waste and contaminated personal protective equipment (PPE): Ensuring safe storage and handling of waste materials and PPE that might be contaminated.
- Electrical systems: Evaluating fire risks associated with electrical components and ensuring they are adequately protected.
- Containment integrity: Checking the reactor's structures for their ability to contain potential hazards, especially in the case of fire.
- Insulation materials: Evaluating materials used for insulation against fire risks, ensuring they do not contribute to fire hazards.

3.1.4 Physical Scenario Analysis

This section identifies testing and research needs that address the effect of certain accident scenarios that may occur on a maritime application fit with a reactor:

- Loss of coolant accident (LOCA): Assessing the reactor's safety protocols and mechanisms in case of coolant loss, an accident that could lead to fuel overheating.
- Ship sinking: Verify that, even in the event of a ship sinking, the reactor remains in a subcritical state, preventing a self-sustaining chain reaction.
- Extreme weather conditions: Testing the reactor's durability and stability under extreme weather conditions, such as hurricanes.
- Steam generator tube rupture: Assessing safety measures and responses if the tubes in a steam generator were to fail, which could lead to potential hazards.
- Blast analysis: Evaluating the reactor's robustness against explosions or other sudden overpressure events, both internal and external.

3.2 Materials and Chemicals

3.2.1 Materials Testing

This section identifies testing and research needs regarding materials in reactor systems of various designs in a marine environment, including chemical, mechanical, and radiological testing:

- Ceramic or metallic-based high-assay, low-enriched uranium (HALEU) for fuel: Testing and evaluating the performance of HALEU, which is a potential fuel for modern reactors, in maritime conditions.
- Graphite moderator: Assessing the efficiency and safety of graphite, used to slow down neutrons in reactors, in marine environments.
- B4C control drums: Testing boron carbide control drums, which absorb neutrons and help control the reactor.
- Chloride-based or fluoride-based molten salts: Evaluating these as potential coolants or fuel carriers in certain reactor designs for their safety and efficiency in maritime settings.

3.2.2 Chemical Incompatibilities Testing

This section identifies testing and research needs regarding the incompatibility of materials and chemicals in a marine environment (e.g., sea water) that are found in a reactor system (such as coolants):

- Compatibility of hydraulic fluids: Ensuring that hydraulic fluids used in reactor systems do not react adversely with other materials or under specific conditions.
- Fluid and gas interaction: Studying potential interactions between fluids and gases that could compromise the reactor's safety or performance.

3.3 Maritime Application Testing

3.3.1 Reactor Testing

This section identifies testing and research needs that address the demonstration of reactor performance. Much of this is also applicable to onshore applications, but it is important to distinguish that there may be specific criteria that would be applied solely to a maritime situation. From small scale to full scale, for a maritime application, the following would need to be addressed:

- Radiation monitoring: Continuously checking for and measuring radiation for safety purposes.
- Core integrity testing: Evaluating the robustness of the reactor core, ensuring it remains intact and functional under maritime conditions.
- Fuel integrity, handling, and disposal through its lifecycle: Assessing the safety and efficiency of fuel from reactor assembly to disposal, considering maritime conditions.
- Environmental impact assessment: Studying the potential environmental impacts of the reactor at any location including the marine environment.

3.3.2 Nondestructive Examinations

This section identifies testing and research needs regarding nondestructive evaluation (NDE) capabilities used for monitoring quality on a marine vessel containing a reactor:

- Ultrasonic testing: Using high-frequency sound waves to detect flaws or issues in materials without causing damage.
- Radiographic testing: Using x-rays to view inside components and detect flaws or anomalies.
- Magnetic particle testing: Using magnetic fields to detect surface and near-surface flaws in ferromagnetic materials.

3.4 Security

This section identifies testing and research needs regarding security concerns that impact both the design of the reactor as well as how personnel interact with the reactor systems on a maritime application. Like the previous section, the following may also apply to onshore systems but can see specificities for the maritime industry:

- Physical security: Ensuring that the reactor and safety-significant components are safeguarded against unauthorized access or tampering.
- Communication security: Protecting communication lines associated with the reactor, ensuring data integrity and confidentiality.
- Cybersecurity: Protecting the reactor's digital systems against cyber threats, hacks, or unauthorized access.
- Security breach simulations: Running simulated breaches to test the reactor's security measures and response protocols.

3.5 General Research

This section identifies nonspecific testing and research needs that do not fit into a particular category:

- Performance requirements: Studying the required performance metrics and ensuring the reactor meets or exceeds them under maritime conditions.
- Reliability and redundancy requirements: Ensuring the reactor operates reliably and has adequate backup systems in place.
- Research on thermal and fast reactors in a marine environment: Studying different reactor types to determine their suitability for maritime applications.
- Radiation shielding requirements of a small modular reactor (SMR) or microreactor on a maritime platform with crew considerations: Evaluating the protection measures in place to shield crew, personnel, passengers, and potentially the public from radiation on maritime platforms.

SECTION 4

4 Existing Testing Opportunities

Utilizing the insights collected from INR No. 1, INR No. 2 was developed to extend the research and inquiry to U.S. national laboratories and universities. INR No. 2 was tailored to focus on the maritime application demonstration and testing needs that had been identified, providing a brief explanation for each topic to guide the recipients in their responses. For example, the question "Can your laboratory perform radiological monitoring related nuclear-maritime demonstration tests?" was given the following description: "Implementing a comprehensive radiological monitoring system to continuously monitor radiation levels both within the reactor system and in the surrounding environment."

By leveraging the preliminary findings, INR No. 2 aimed to gauge the testing capabilities of research institutions to meet these specific needs. These capabilities were identified as opportunities and were evaluated based on two primary criteria:

1. *Physical testing capabilities*—This describes equipment and facilities that allow users to test objects and systems under naturally occurring conditions.
2. *Modeling and simulation capabilities*—This describes software and computer codes that allow users to test objects in systems using physics-based equations and numerical estimations.

Respondents were asked if they possess various capabilities in these categories. Generally, where both physical and simulation testing are possible, physical testing capabilities are regarded as more valuable compared to simulated testing capabilities, as simulations are limited by numerical approximations. Physical unit testing of subsystems also has built-in assumptions, so neither testing type yields a perfect demonstration of the final system performance in operation.

Some capabilities will only exist in one of these spheres, such as a finite-element analysis being a simulated capability, which is important to consider when determining constraints.

Table 2 shows the general responses from each of the laboratories that responded to INR No. 2. Every question offered the following response options:

- "Yes—Physical Test" if the lab had physical test equipment.
- "Yes—Mod/Sim" if the lab had modeling and simulation capabilities.
- "Yes—Both" if the lab had both physical test equipment and modeling and simulation capabilities.
- "Yes" if the lab generally had testing capabilities in that area in some other nature that did not designate another response.
- "No" if the lab had no such testing capabilities.
- "N/A" if the lab did not answer.

INR No. 2 respondents were prompted and encouraged to provide additional comments on their answers if they wished. These additional details are discussed in Sections 4.1 and 4.2, presented in alphabetical order of facility.

While INR No. 2 was targeted at laboratories with known nuclear testing facilities, some of the capabilities highlighted by the respondents are non-nuclear, such as the PNNL-Sequim campus, which specializes in marine-based testing. These non-nuclear facilities are not licensed for nuclear testing and experimentation; however, they remain useful in supporting the broader testing landscape for nuclear-maritime applications, which does not entirely involve nuclear-based experimentation. Additionally, these non-nuclear facilities could potentially be modified to handle nuclear testing. Such scenarios would likely require DOE or the Nuclear Regulatory Commission (NRC) approval on a case-by-case basis prior to any nuclear-related testing.

Table 2. Testing opportunities for maritime nuclear applications at U.S. national laboratories and university nuclear laboratories.

Can your laboratory test to ensure proper reactor operations under severe conditions for nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
SA1	...seismic shock testing?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	Yes-Both	Yes	No	Yes	N/A	No	N/A	No	No	Yes	Yes-Both	No	No	No	N/A
SA2	...acceleration testing?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	Yes-Both	Yes	No	No	N/A	No	N/A	No	No	Yes	Yes-Mod/Sim	No	Yes-Both	No	N/A
SA3	...vibration testing?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	Yes-Both	Yes	No	Yes	N/A	No	N/A	No	No	Yes	Yes-Both	No	No	Yes-Mod/Sim	N/A
SA4	...simulated sea trials?	N/A	No	N/A	Yes-Mod/Sim	Yes-Mod/Sim	Yes	No	No	N/A	No	N/A	No	No	Yes	Yes-Mod/Sim	No	Yes-Both	No	N/A
SA5	...computational fluid dynamics analysis?	Yes-Mod/Sim	No	Yes-Mod/Sim	Yes-Mod/Sim	Yes-Mod/Sim	Yes	Yes	Yes	Yes	Yes-Mod/Sim	N/A	Yes-Mod/Sim	Yes-Mod/Sim	Yes	Yes-Mod/Sim	Yes	No	Yes-Mod/Sim	Yes
SA6	...finite element analysis?	Yes-Mod/Sim	N/A	Yes-Mod/Sim	Yes-Mod/Sim	Yes-Mod/Sim	N/A	N/A	N/A	N/A	Yes-Mod/Sim	N/A	Yes-Mod/Sim	Yes-Mod/Sim	Yes	Yes-Mod/Sim	N/A	No	Yes-Mod/Sim	N/A
SA7	...dynamic stability simulations?	Yes-Mod/Sim	No	Yes-Mod/Sim	Yes-Mod/Sim	Yes-Mod/Sim	Yes	No	No	Yes	Yes-Mod/Sim	N/A	No	Yes-Mod/Sim	Yes	Yes-Both	No	No	Yes-Mod/Sim	Yes
SA8	...control system testing?	N/A	No	Yes-Both	Yes-Both	Yes-Both	Yes	No	Yes	N/A	No	N/A	No	Yes-Mod/Sim	No	Yes-Both	No	No	No	N/A
SA9	...redundancy & resiliency testing?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	—	Yes	No	Yes	N/A	No	N/A	No	Yes-Both	Yes	Yes-Mod/Sim	No	Yes-Both	No	N/A
SA10	...equipment securing and restraint system?	N/A	No	Yes-Both	Yes-Both	Yes-Both	Yes	No	No	Yes	No	N/A	No	N/A	Yes	Yes-Both	No	No	No	N/A
SA11	...human factors testing?	N/A	Yes	Yes-Both	Yes-Mod/Sim	Yes-Mod/Sim	No	No	No	N/A	No	N/A	No	N/A	Yes	Yes-Mod/Sim	Yes	No	Yes-Mod/Sim	N/A
SA12	...mechanical system rigidity testing?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	Yes-Physical Test	Yes	No	No	N/A	No	N/A	No	N/A	Yes	Yes-Both	No	No	No	N/A

Can your laboratory test the following unique fire safety requirements for nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
SA13	…radiation alarms?	N/A	No	Yes-Both	Yes-Both	NA	No	Yes	Yes	Yes	No	N/A	No	Yes-Physical Test	No	Yes-Physical Test	No	Yes-Physical Test	N/A	N/A
SA14	…gas detection alarms?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	Yes	Yes	N/A	N/A	No	N/A	No	Yes-Both	No	No	No	No	N/A	N/A
SA15	…reactor parameter alarms?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	NA	No	Yes	N/A	No	N/A	No	Yes-Physical Test	No	No	No	No	N/A	N/A
SA16	…emergency cooling system alarms?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	No	No	N/A	No	N/A	No	Yes-Both	No	No	No	No	N/A	N/A
SA17	…containment integrity alarms?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	No	No	N/A	No	N/A	No	Yes-Physical Test	No	No	No	Yes-Physical Test	N/A	N/A
SA18	…reactor trip alarms?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	Yes	Yes	N/A	No	N/A	No	Yes-Physical Test	No	No	No	No	N/A	N/A
SA19	…emergency shutdown alarms?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	Yes	Yes	N/A	No	N/A	No	Yes-Physical Test	No	No	No	No	N/A	N/A
SA20	…containment venting alarms?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	Yes	No	N/A	No	N/A	No	No	No	No	No	No	N/A	N/A
SA21	…emergency communication alarms?	N/A	No	Yes-Both	Yes-Both	N/A	N/A	Yes	No	N/A	No	N/A	No	No	No	No	No	No	N/A	N/A
SA22	…emergency evacuation alarms?	N/A	No	Yes-Both	Yes-Both	N/A	N/A	No	No	N/A	No	N/A	No	Yes-Physical Test	No	No	No	No	N/A	N/A
SA23	…spill overboard alarms?	N/A	N/A	Yes-Both	N/A	N/A	N/A	N/A	N/A	N/A	No	N/A	No	No	N/A	No	N/A	No	N/A	N/A

Can your laboratory test for the following alarms for nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
SA24	…sea water interaction with reactor systems?	N/A	No	Yes-Both	Yes-Both	NA	No	Yes	Yes	Yes	No	N/A	No	Yes-Physical Test	No	Yes-Physical Test	No	Yes-Physical Test	N/A	N/A
SA25	…onboard low-level waste and contaminated PPE?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	Yes	Yes	N/A	N/A	No	N/A	No	Yes-Both	No	No	No	No	N/A	N/A
SA26	…electrical systems?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	NA	No	Yes	N/A	No	N/A	No	Yes-Physical Test	No	No	No	No	N/A	N/A
SA27	…containment integrity?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	No	No	N/A	No	N/A	No	Yes-Both	No	No	No	No	N/A	N/A
SA28	…insulation materials?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	No	No	N/A	No	N/A	No	Yes-Physical Test	No	No	No	Yes-Physical Test	N/A	N/A
SA29	…smoke control systems?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	Yes	Yes	N/A	No	N/A	No	Yes-Physical Test	No	No	No	No	N/A	N/A
SA30	…compatibility of equipment?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	Yes	Yes	N/A	No	N/A	No	Yes-Physical Test	No	No	No	No	N/A	N/A
SA31	…redundant systems?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	N/A	N/A	Yes	No	N/A	No	N/A	No	No	No	No	No	No	N/A	N/A
SA32	…passive fire protection?	N/A	No	Yes-Both	Yes-Both	N/A	N/A	Yes	No	N/A	No	N/A	No	No	No	No	No	No	N/A	N/A

Can your laboratory test for the following physical scenarios for nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
SA33	…loss of coolant accident (LOCA)?	Yes-Both	Yes	Yes-Both	Yes-Mod/Sim	Yes-Both	Yes	Yes	No	N/A	Yes-Mod/Sim	N/A	Yes-Mod/Sim	Yes-Both	No	Yes-Mod/Sim	No	No	Yes-Mod/Sim	No
SA34	…remaining subcritical following ship sinking?	Yes-Mod/Sim	Yes	Yes-Both	Yes-Mod/Sim	Yes-Both	No	Yes	Yes	N/A	Yes-Mod/Sim	N/A	Yes-Mod/Sim	No	No	Yes-Mod/Sim	No	No	Yes-Mod/Sim	No
SA35	…hurricane conditions?	N/A	Yes	Yes-Mod/Sim	Yes-Mod/Sim	Yes-Mod/Sim	Yes	No	No	N/A	Yes-Mod/Sim	N/A	No	No	No	Yes-Mod/Sim	No	No	No	No
SA36	…steam generator tube rupture?	Yes-Both	Yes	Yes-Both	Yes-Both	Yes-Both	Yes	Yes	No	N/A	Yes-Mod/Sim	N/A	No	Yes-Both	No	Yes-Both	No	No	Yes-Mod/Sim	No
SA37	…blast analysis?	N/A	No	Yes-Both	Yes-Both	Yes-Both	No	No	No	N/A	Yes-Mod/Sim	N/A	No	Yes-Mod/Sim	Yes	No	No	No	No	No
SA38	…station blackout and emergency backup power?	Yes-Mod/Sim	N/A	Yes-Both	Yes-Both	Yes-Mod/Sim	N/A	N/A	N/A	N/A	Yes-Mod/Sim	N/A	No	Yes-Mod/Sim	N/A	No	N/A	No	No	No
SA39	…collision or grounding (with another vessel or aircraft)?	N/A	No	Yes-Both	Yes-Mod/Sim	Yes-Both	Yes	No	No	N/A	Yes-Mod/Sim	N/A	No	N/A	Yes	Yes-Mod/Sim	No	No	No	No

Can your laboratory test for the following materials in marine environment?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
MC1	…loss of coolant accident (LOCA)?	Yes-Both	No	Yes-Both	Yes-Both	Yes-Both	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	No	No	No	No	Yes-Mod/Sim	No
MC2	…remaining subcritical following ship sinking?	Yes-Both	Yes	Yes-Both	Yes-Both	Yes-Physical Test	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	Yes	Yes-Physical Test	No	No	Yes-Mod/Sim	No
MC3	…hurricane conditions?	Yes-Both	Yes	Yes-Both	Yes-Both	Yes-Physical Test	N/A	Yes	Yes	N/A	Yes-Both	N/A	No	Yes-Both	Yes	Yes-Physical Test	No	No	No	No
MC4	…steam generator tube rupture?	Yes-Both	Yes	Yes-Both	Yes-Both	Yes-Physical Test	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	No	Yes-Physical Test	No	No	Yes-Both	No
MC5	…blast analysis?	Yes-Both	Yes	Yes-Both	Yes-Both	Yes-Physical Test	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	No	Yes-Physical Test	No	No	Yes-Both	No
MC6	…station blackout and emergency backup power?	Yes-Physical Test	Yes	Yes-Both	Yes-Both	Yes-Both	N/A	Yes	Yes	N/A	Yes-Both	N/A	No	Yes-Both	No	Yes-Physical Test	No	No	Yes-Both	No
MC7	…collision or grounding (with another vessel or aircraft)?	Yes-Physical Test	N/A	Yes-Both	Yes-Both	Yes-Both	N/A	N/A	N/A	N/A	Yes-Both	N/A	Yes-Physical Test	No	N/A	Yes-Physical Test	N/A	No	Yes-Both	N/A
MC8	…inert gases such as helium or CO_2?	Yes-Both	N/A	Yes-Both	Yes-Both	Yes-Both	N/A	N/A	N/A	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	N/A	Yes-Physical Test	N/A	No	Yes-Both	N/A
MC9	…chloride-based or fluoride-based molten salts?	Yes-Both	N/A	Yes-Both	Yes-Both	Yes-Both	N/A	N/A	N/A	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	N/A	Yes-Physical Test	N/A	No	Yes-Both	N/A

Can your laboratory perform the following chemical incompatibilities tests for nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
MC10	...loss of coolant accident (LOCA)?	Yes-Both	No	Yes-Both	Yes-Both	Yes-Both	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	No	No	No	No	Yes-Mod/Sim	No
MC11	...remaining subcritical following ship sinking?	Yes-Both	Yes	Yes-Both	Yes-Both	Yes-Physical Test	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	Yes	Yes-Physical Test	No	No	Yes-Mod/Sim	No

Can your laboratory perform the following chemical incompatibilities tests for nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
MT1	...radiological monitoring?	Yes-Both	No	Yes-Both	Yes-Both	Yes-Both	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	No	No	No	No	Yes-Mod/Sim	No
MT2	...core integrity testing?	Yes-Both	Yes	Yes-Both	Yes-Both	Yes-Physical Test	N/A	Yes	Yes	N/A	Yes-Both	N/A	Yes-Physical Test	Yes-Both	Yes	Yes-Physical Test	No	No	Yes-Mod/Sim	No
MT3	...reactor shutdown testing?	Yes-Physical Test	No	Yes-Physical Test	Yes-Both	Yes-Both	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
MT4	...fuel integrity, handling and disposal through its lifecycle?	Yes-Both	No	Yes-Physical Test	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
MT5	...environmental impact assessment?	Yes-Both	No	N/A	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	Yes-Both	No	Yes-Physical Test	No	No	No	N/A
MT6	...control systems functional testing?	Yes-Both	No	N/A	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
MT7	...replica testing?	Yes-Physical Test	No	Yes-Both	Yes-Both	N/A	No	Yes	No	N/A	N/A	N/A	No	No	No	Yes-Both	No	No	Yes-Both	N/A
MT8	...any unique testing capabilities not indicated above?	Yes-Both	No	N/A	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	No	No	Yes-Both	No	No	No	N/A

Can your laboratory perform the following nondestructive testing for nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
MT9	…ultrasonic testing?	Yes-Both	No	Yes-Both	Yes-Both	Yes-Both	No	No	No	N/A	N/A	Yes-Both	Yes-Physical Test	Yes-Both	No	No	No	No	No	N/A
MT10	…radiographic testing?	Yes-Both	No	Yes-Both	Yes-Both	Yes-Both	No	Yes	Yes	N/A	Yes-Physical Test	N/A	No	Yes-Both	No	Yes-Both	No	No	Yes-Both	N/A
MT11	…magnetic particle testing?	Yes-Physical Test	No	N/A	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
MT12	…liquid penetrant testing?	Yes-Physical Test	No	Yes-Physical Test	Yes-Both	Yes-Both	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
MT13	…eddy current testing?	Yes-Both	No	Yes-Physical Test	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
MT14	…acoustic emission testing?	Yes-Both	No	N/A	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	Yes-Both	No	Yes-Physical Test	No	No	No	N/A
MT15	…shearography?	Yes-Both	No	N/A	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
MT16	…digital radiography?	Yes-Physical Test	No	Yes-Both	Yes-Both	N/A	No	Yes	No	N/A	N/A	N/A	No	No	No	Yes-Both	No	No	Yes-Both	N/A
MT17	…phased array ultrasonics?	Yes-Both	No	N/A	Yes-Both	N/A	No	No	No	N/A	N/A	N/A	No	No	No	Yes-Both	No	No	No	N/A

Can your laboratory test for the following nuclear-maritime demonstrations security concerns requirements?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
S1	…physical security?	Yes-Mod/Sim	No	Yes-Both	Yes-Mod/Sim	Yes-Both	No	No	No	N/A	Yes-Mod/Sim	N/A	No	No	Yes	No	No	No	No	N/A
S2	….access control and authorization?	N/A	No	Yes-Both	Yes-Mod/Sim	Yes-Both	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
S3	...communication security?	N/A	No	Yes-Both	Yes-Both	Yes-Both	No	No	No	N/A	N/A	N/A	No	Yes-Physical Test	No	No	No	Yes-Mod/Sim	No	N/A
S4	…personnel screening?	N/A	No	Yes-Both	Yes-Mod/Sim	Yes-Both	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
S5	…accountability of nuclear material?	Yes-Mod/Sim	No	Yes-Both	Yes-Mod/Sim	Yes-Both	No	Yes	Yes	Yes	N/A	N/A	Yes-Mod/Sim	Yes-Both	No	Yes-Both	Yes	No	No	N/A
S6	…security infrastructure resilience?	Yes-Mod/Sim	No	Yes-Both	Yes-Mod/Sim	Yes-Both	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A
S7	…cyber security?	Yes-Both	N/A	Yes-Both	Yes-Both	Yes-Both	N/A	N/A	N/A	N/A	N/A	N/A	No	Yes-Physical Test	N/A	Yes-Both	N/A	Yes-Mod/Sim	No	N/A
S8	...security breach simulations?	Yes-Mod/Sim	No	Yes-Both	Yes-Mod/Sim	Yes-Both	No	No	No	N/A	N/A	N/A	No	No	No	No	No	No	No	N/A

EXISTING TESTING OPPORTUNITIES

Can your laboratory perform research on the following topics regarding nuclear-maritime demonstrations?		ANL	BNL	INL	PNNL	SNL	GWU	GTech	ISU	KSU	MIT	NCSU	OSU	Purdue	UBuff	UMich	UTenn	UTD	UVM	USU
GR1	...performance requirements?	Yes-Mod/Sim	Yes	Yes-Both	Yes-Mod/Sim	Yes-Both	N/A	N/A	Yes	N/A	Yes-Both	N/A	No	Yes-Physical Test	Yes	Yes-Both	Yes	Yes-Mod/Sim	N/A	No
GR2	...sea state requirements?	Yes-Mod/Sim	No	Yes-Mod/Sim	Yes-Mod/Sim	Yes-Mod/Sim	Yes	Yes	No	N/A	Yes-Mod/Sim	N/A	No	Yes-Physical Test	No	Yes-Both	No	No	No	No
GR3	...reliability and redundancy requirements?	Yes-Mod/Sim	Yes	Yes-Both	Yes-Both	Yes-Both	Yes	Yes	Yes	N/A	Yes-Mod/Sim	N/A	No	No	Yes	Yes-Mod/Sim	Yes	Yes-Mod/Sim	Yes-Mod/Sim	No
GR4	...research thermal and fast reactors in a marine environment?	Yes-Mod/Sim	Yes	Yes-Both	Yes-Both	Yes-Both	Yes	Yes	No	N/A	Yes-Both	N/A	Yes-Mod/Sim	Yes -Both	Yes	Yes-Mod/Sim	Yes	Yes-Mod/Sim	Yes-Mod/Sim	No
GR5	...research heat-pipe reactors and other naturally circulated coolant systems?	Yes-Both	No	Yes-Both	Yes-Both	Yes-Both	No	No	Yes	N/A	Yes-Both	N/A	Yes-Mod/Sim	Yes-Both	No	Yes-Both	Yes	No	Yes-Both	No
GR6	...computer simulation of maritime environments for an SMR or microreactor?	Yes-Mod/Sim	Yes	Yes-Both	Yes-Mod/Sim	Yes-Mod/Sim	No	No	No	Yes	Yes-Mod/Sim	N/A	Yes-Mod/Sim	Yes-Both	No	Yes-Mod/Sim	Yes	Yes-Mod/Sim	Yes-Mod/Sim	No
GR7	...radiation shielding requirements of an SMR or microreactor on a maritime platform with crew considerations?	Yes-Mod/Sim	No	Yes-Both	Yes-Both	Yes-Both	N/A	N/A	Yes	N/A	Yes-Both	N/A	Yes-Mod/Sim	Yes-Both	Yes	Yes-Both	Yes	Yes-Mod/Sim	Yes-Mod/Sim	No
GR8	...best-fit reactor technology for offshore oil and gas platforms?	Yes-Mod/Sim	Yes	Yes-Both	Yes-Mod/Sim	Yes-Mod/Sim	No	No	No	Yes	Yes-Mod/Sim	N/A	No	Yes-Mod/Sim	No	No	Yes	No	Yes-Mod/Sim	No
GR9	...ship motion testing?	Yes-Mod/Sim	No	Yes-Mod/Sim	Yes-Both	N/A	Yes	Yes	No	N/A	Yes-Mod/Sim	N/A	No	Yes-Both	Yes	Yes-Both	No	No	No	No

GR10	…reactor performance study during normal operations at sea?	Yes-Mod/Sim	Yes	Yes-Both	Yes-Mod/Sim	N/A	Yes	Yes	Yes	N/A	Yes-Mod/Sim	Yes-Mod/Sim	Yes-Physical Test	Yes-Both	No	Yes-Mod/Sim	Yes	No	Yes-Mod/Sim	No
GR11	…remote maintenance/ inspection systems?	Yes-Both	No	Yes-Both	Yes-Both	Yes-Physical Test	No	No	No	N/A	Yes-Both	N/A	No	Yes-Both	No	Yes-Mod/Sim	Yes	Yes-Mod/Sim	No	No

4.1 U.S. National Laboratories

This section outlines testing opportunities at the U.S. national laboratories that responded to INR No. 2 and provided additional information about research and testing capabilities suited to support maritime reactor testing, including ANL, INL, Pacific Northwest National Laboratory (PNNL), Brookhaven National Laboratory (BNL), and Sandia National Laboratories (SNL).

Additional testing opportunities likely exist at other national laboratories and additional outreach is recommended for a comprehensive review of potential testing opportunities for maritime.

4.1.1 Argonne National Laboratory

ANL, in Lemont, Illinois, specializes in a variety of research areas and has a range of opportunities for testing radioactive material and exposing objects to ionizing radiation. It hosts several facilities that could have relevant capabilities for demonstrating maritime reactors:

- The ATLAS is a superconducting linear accelerator for heavy ions at energies in the vicinity of the Coulomb barrier [1]. ATLAS provides experimental equipment such as the Canadian Penning Trap mass spectrometer, the Fragment Mass Analyzer, the Argonne Gas-Filled Analyzer, the Helical Orbit Spectrometer, the Enge Magnetic Spectrograph, Gammasphere, and/or GRETINA, multisampling ionization chamber, and the X-Array.
- The APS provides ultra-bright, high-energy storage ring generated x-ray beams for research [4].
- The Mechanisms Engineering Test Loop Facility (METL) is an intermediate-scale liquid metal experimental facility that provides purified, reactor-grade sodium to various experimental test vessels to test small-to-intermediate-scale components and systems that are required to operate in an advanced reactor environment [5].
- The Natural Convection Shutdown Heat Removal Test Facility (NSTF) is a large-scale facility for evaluating the performance capabilities of decay heat removal systems [6]. NSTF's purpose is to examine passive safety for future nuclear reactors, provide a framework to explore alternative reactor design concepts, and generate benchmarking data to validate advanced computer models.
- Building 206 at the Engineering Development Labs is a building at ANL that can perform the engineering development of reactor systems and components, with the Pressure Drop Experimental Loop for Investigations of Core Assemblies in Advanced Nuclear Reactors test facility (discussed below), sodium materials testing loops, and the CAFÉ experimental area.
- The Pressure Drop Experimental Loop for Investigations of Core Assemblies in Advanced Nuclear Reactors is a novel experimental facility designed and constructed at ANL to recreate the hydraulic flow conditions for advanced reactors.
- The Argonne Liquid Metal Experiment Facility is designed for research using liquid metal systems, which reaches areas as varied as nuclear physics, material science, and nuclear engineering.
- The Intermediate Voltage Electron Microscopy (IVEM) facility is a dual ion beam facility for in situ Transmission Electron Microscope studies of defect structures in materials under controlled ion irradiation and implantation and sample conditions. The IVEM facility is unique in its ability to image the changes in atomic structure and defect formation during irradiation at high magnification. IVEM's important advantages include:
  - Real-time observation of defect formation and evolution during irradiation.
  - Well-controlled experimental conditions (constant specimen orientation and area, specimen temperature, ion type, ion energy, dose rate, dose, and applied strain).
  - Refine and validate computer model simulations of irradiation defect states.
  - High-dose ion damage is produced in hours, rather than the years such damage would require in a nuclear reactor, supporting studies of material response to high doses of particle (ion and neutron) irradiation.
  - In situ ion irradiation does not produce any radioactivity in samples.
- The Irradiated Materials Laboratory (IML) contains four beta-gamma hot cells and glove boxes. This facility is used to conduct research on the behavior of commercial and advanced nuclear reactor materials, including fuel cladding, pressure vessel steels, and other in-reactor components, during long-term operations in corrosive and irradiation environments.
- The Mechanical and Environmental Testing Laboratory (METLab) hosts a suite of testing capabilities used for evaluating the mechanical performance of structural materials under various loading, temperature, and environmental conditions.
- The Metal Additive Manufacturing (AM) Laboratory possesses a suite of manufacturing and post build treatment capabilities, focusing on advancing the fundamental science related to metal AM technologies, innovations in component design, rapid prototyping, and performance testing.
- Nondestructive evaluation and testing facilities contain state-of-the-art NDE laboratories including microwave and millimeter wave, acoustic and ultrasonic, x-ray, thermal imaging, optics, and eddy current for health monitoring of materials and components used in aerospace, defense, and power generation (fossil and nuclear) industries as well as for medical and scientific research.
- The Thermal Hydraulic Experimental Test Article is a 450 liter pool-type sodium facility that offers high-fidelity experimental data for nuclear reactor systems code development.
- The Sodium Materials Testing Loops at ANL are forced-convection sodium loops used to test advanced structural materials in controlled sodium environments at temperatures up to ~700°C.
- The Activated Materials Laboratory is a new radiological facility located at ANL's APS. It assists the nuclear community in examining radioactive samples at the High-Energy X-ray Microscope and other beamlines at the APS.
- The Chemical and Fuel Cycle Technology (CFCT) Molten Salt Properties Laboratories include equipment and instruments used to perform thermophysical and thermochemical property measurements of radiological molten salts to support the development, design, and deployment of molten-salt reactor technology. Analytical equipment includes differential scanning calorimeters, viscometers; solid and liquid salt density measurements; benchtop laser flash analysis equipment, furnaces, and devices for solubility measurements; and instruments for thermogravimetric and vapor analyses.

- The CFCT Materials Characterization Laboratories include equipment and instruments used to produce advanced materials and characterize material microstructures and degradation behaviors, including radiological vitreous, ceramic, metallic, and mixed-phase materials.
- These include resistance and induction furnaces, metallography and standard laboratory equipment, potentiostats and electro-corrosion equipment, and a dedicated radiological scanning electron microscope and x-ray diffractometer.
- The Argonne Robotics and Augmented Reality Laboratory develops and tests customized robotics system solutions in support of programs using cross-cutting target applications in unstructured environments, including manufacturing, energy and nuclear industries, and field and service robotics. Its nuclear applications encompass inspection, material handling, decommissioning, and operation and maintenance tasks in nuclear reactors and waste facilities. Based on decades of R&D, it has developed a robotic digital twin framework that allows the rapid development of an analysis of robotic solutions optimized over its lifecycle—design, prototyping, operation, and maintenance.
- The technology basis of the robotic digital twin includes:
    - Telerobotic control and human-robot interaction.
    - Real-time sensing and reconstruction.
    - Virtual-reality simulation.
    - Multimodal augmented-reality operator interface.
    - Cyber-physical system based on a robot operating system.
    - Artificial intelligence and machine learning integration of process and system optimization.
- ANL's Materials Engineering Research Facility (MERF) applies advanced synthesis and processing protocols, advanced in situ and operando characterization and modeling and simulation for the science-based scale up of newly invented experimental materials and chemicals. The facility produces kilogram quantities of materials and makes samples available for industrial evaluation, prototyping, and to support further research. The MERF develops economically viable processes for materials manufacturing at scale and produces detailed process descriptions for accurate cost (technoeconomic) modeling. The MERF is an integral part of the laboratory's Materials Manufacturing Innovation Center. The MERF's capabilities include:
    - Development of analytical methods and quality control procedures for new material specifications.
    - Scale up of the manufacturing processes for newly discovered materials and chemicals.
    - Analysis and refinement of processes for material and chemical synthesis.
    - Providing kilogram quantities of novel materials to industry for testing.
    - Evaluation of emerging manufacturing technologies.
    - Workforce development on process R&D, scale up, advanced characterization, modeling and simulation, and advanced materials manufacturing.

4.1.2 Idaho National Laboratory

INL, in Idaho Falls, Idaho, specializes in research related to nuclear energy, integrated energy, and national security and has several unique capabilities, including:

- The Neutron Radiography facility for radiography and rapid turnaround irradiation.
- Microgrid in box capability that may be useful for floating barges.
- Various capabilities for heat and hydrogen generation.
- Cybersecurity expertise.

INL also has several facilities that could be used to support maritime environment testing:

- The DOE Microreactor Program is developing a thermal-hydraulic test capability called the Microreactor Agile Non-Nuclear Experimental Testbed (MAGNET). MAGNET will use electrical heating elements to simulate core thermal behavior, primary heat exchanger performance, and passive decay heat removal for heat-pipe and gas-cooled microreactors [7]. Additionally, MAGNET will provide a facility for researchers and technology developers to test new microreactor concepts in a relevant environment to advance technical maturity. MAGNET also has a helium test loop referred to as Helium Component Testing Out-of-pile Research. INL indicated that MAGNET could be used for physical and simulated research into heat-pipe reactors and other naturally circulated coolant systems, and physical and simulated materials testing of helium as a coolant in a maritime environment.
- The NRIC Demonstration of Microreactor Experiments (DOME) is a test bed site capable of hosting operational nuclear reactor concepts that produce less than 20 MW of thermal power, regulated under DOE authorization [8]. INL indicated that NRIC DOME could be used for physical and simulated research into radiational shielding requirements for an SMR or a microreactor in a maritime environment.
- The ATR is a 250 MW pressurized-water test reactor with 77 testing positions [9]. It is the largest test reactor in the United States. ATR allows reactor developers to study the effects of intense neutron and gamma radiation on reactor materials and fuels.
- The Molten Salt Thermophysical Examination Capability (MSTEC) is a shielded argon glovebox for irradiated and nonirradiated actinide materials [10]. MSTEC offers a suite of thermophysical property characterization equipment, multifunctional furnaces, and versatile workspaces for lab-scale experiments. Equipment within the MSTEC shielded glovebox has been designed for use with high-temperature fluids, such as molten salts, and modified to be operated remotely when necessary for handling samples. INL indicated that MSTEC could be used for both simulated and physical testing of chloride- and fluoride-based molten salts in a maritime environment.

The Materials and Fuels Complex itself hosts several facilities, including:

- The Hot Fuel Examination Facility for conducting post-irradiation examinations of fuels and materials [11], which provides the ability to remotely handle and perform detailed nondestructive and destructive examinations of highly irradiated fuel and material samples. Its argon-atmosphere hot cell, labs, and special equipment handle a variety of fuel forms, including tiny particles, 4 foot research reactor plates, and full-sized commercial rods.
- The Experimental Fuels Facility is a 5,000-square-foot nuclear fuel fabrication facility that houses a wide range of fuel fabrication and material handling capabilities [11]. Basic capabilities include uranium and uranium alloy casting and extrusion, processing uranium metal and ceramics at all enrichments, fabrication and handling of alloys and powders, and a machine shop with radiological and non-radiological areas.
- The Irradiated Materials Characterization Laboratory focuses on microstructural, microchemical, and micromechanical analysis and thermophysical characterization of irradiated nuclear fuels and materials [11]. Its unique design incorporates advanced characterization instruments that are sensitive to vibration, temperature, and electromagnetic interference into modular radiological shielding and confinement systems. The shielded instruments allow characterization of highly radioactive fuels and materials at the micro, nano, and atomic levels, the scale at which irradiation damage processes occur.
- The Analytical Laboratory provides the chemical, radiochemical, physical, and analytical data needed for various research and engineering development programs, and for applied research and engineering development activities supporting advanced nuclear fuel design, waste management, environmental, and other INL programs [11].
- The Fuel Manufacturing Facility focuses on R&D of transuranic metallic and ceramic fuels [11]. Additionally, the material storage vault contains and supplies various INL and off-site facilities with feedstock materials.
- The Transient Reactor Test (TREAT) Facility is an air-cooled, graphite-moderated, thermal-spectrum nuclear test reactor designed to test reactor fuels and structural materials [8]. TREAT also includes the micro–Reactor Experiment Cell (T-REXC). INL indicated that TREAT could be used for physical and simulated research into radiation shielding requirements for an SMR or a microreactor in a maritime environment.

4.1.3 Pacific Northwest National Laboratory

PNNL, in Richland, Washington, specializes in research related to marine and earth sciences, sustainable energy, and national security and offers several facilities that could be used to support maritime environment testing:

- The PNNL-Sequim campus, in Sequim, Washington, houses the only marine research facilities in the DOE complex, including:
  - The Aquatic Research Laboratories, which enable research on chemical, biological, or physical components and processes under controlled conditions and can provide any mix of freshwater and saltwater for research in static, flow-through, filtered, or raw conditions [12].
  - The Hyperbaric Laboratory, where research is conducted on the physical and chemical processes occurring in ocean waters as deep as 2 km below the surface [12].
  - Eight large, outdoor research tanks ranging from 31,000 to 62,000 L, where parameters such as temperature, salinity, turbidity, and tidal fluctuations can be precisely controlled [12].
  - Two marine test sites at Sequim Bay and Clallam Bay, at which PNNL has authorization for activities such as floating platforms and seabed tests [12].
  - A mesoscale, littoral wave tank capable of delivering waves at a range of frequencies (0–60 Hz) that includes a heat exchanger that allows for rapid cooling or heating of seawater [12].
- The Radiochemical Processing Laboratory (RPL) has a range of testing opportunities in radiochemistry, including process development, chemical and physical separations, tritium processing, spectroscopic online process monitoring, radiological nuclear resonance spectroscopy, and nuclear forensics [13]. RPL also specializes in nuclear materials characterization, which includes post-irradiation characterization, microanalysis, spent nuclear fuel, reactor dosimetry, and nuclear nonproliferation monitoring.
- The 318 Building, a subsection of PNNL’s RPL, houses several ionizing radiation laboratories for irradiating artifacts with beta, neutron, and gamma radiation of various energies, including:
  - The Low Scatter Neutron Facility, which is used for neutron and gamma irradiation on a raised platform [14].
  - The High Exposure Facility, which is used for characterizing radiologically active or contaminated samples with instruments such as scanning electron microscopes and a thermal gravimetric analysis at up to 200,000 rad/hr for small items and 50,000 rad/hr for larger items [14].
  - The BETA Irradiation Facility, which contains calibration and irradiation apparatus and supplied sources to comply with international secondary standards for beta irradiations [14].
  - The Industrial X-Ray Facility, which contains more than 60 beams (20 keV to 320 KeV, 0.2 mR/hr to 6,000 R/hr) [14].
  - The Irradiation Well Room for calibrations and testing of radiation detectors and other items (100 rad/hr to 10,000 mrad/hr) [14].
  - The GAMMA Bunker for high-dose gamma irradiations of samples [14].
- The PNNL Physical Sciences Division has a broad range of research opportunities encompassing basic and applied chemistry, catalysis, materials science, geosciences, and chemical physics [15].
- The Materials Science and Technology Laboratory is focused on identifying and predicting how materials degrade in extreme environments, particularly before macroscopic damage propagates and leads to the failure of safety-related systems, structures, and components [16]. The lab has opportunities to:
  - Characterize stress corrosion cracking to provide insight into failure mechanisms and enable safe and reliable nuclear power.

  - Develop robust materials that can withstand the extremes of radiation, high temperatures, stress, and corrosion.
  - Use multiscale modeling, simulation, and physics-informed machine learning to augment experiments providing the technical basis for nuclear fuels, advanced structural materials, and fusion plasma facing materials.
  - Employ electron microscopy and microanalysis, including optical metallography, electron backscatter diffraction, atom probe tomography, and chemical imaging at the atomic level.
  - Detect and analyze damage from neutrons, high temperatures, corrosion, transmutation, and high concentrations of gases such as helium and hydrogen.
  - Develop new metal fuel fabrication techniques, such as the rolling and extrusion of fuel, mechanical testing at elevated temperatures, and high-resolution characterization, to support the development of new fuel materials and geometries and serve the next generation of nuclear reactors.

4.1.4 Sandia National Laboratories

SNL, in Albuquerque, New Mexico, performs research under the U.S. National Nuclear Security Administration and generally offers several capabilities, including:

- Lab-scale, 6-degree-of-freedom shaker tables.
- Small- and large-scale testing capabilities for:
  - Mechanical shock.
  - Vibration testing.
  - Impact and drop testing.
  - Thermal and fire testing.
  - Other external environments.
- Mechanistic modeling and experimental investigations for the corrosion of nuclear systems, structures, and components exposed to saltwater brines.
- Monitoring the electrical conductivity of specimens exposed to fire conditions.
- High-heat flux tests on insulation materials to characterize the material response.

Coupled fluid-mechanical simulations to develop validated models of ship and shipborne systems subjected to shock loading from underwater insults, including the preliminary shock wave and the secondary reflections and cavitation collapse and consequent interactions.

- High-performance computing (HPC) capabilities to model maritime environments (such as currents and waves) and technologies, devices, and control systems to harness power via wave energy converters (WEC) and current energy converters, which may have cross-purpose applications to model ocean environments for other technologies.
- MELCOR and MACCS simulation tools for determining radiological consequences of accident scenarios.
- CTH for blast effect simulations as well as an onsite explosive range for experimental validation and testing.
- A significant suite of security-related physical and simulation capabilities, including:
  - Force-on-force exercises.
  - Limited-scope performance testing (detection, assessment, delay, response).
  - Adversary path planning.
  - Neutralization analysis.
  - Vulnerability analysis.
  - Material control & accounting, physical protection, and severe accident analysis.
  - Examining sabotage targets for various reactor types.
  - Examining economic impacts of adversary attacks.
  - Cost and benefit analysis of adding security components.
- A staff of health physicists and dosimetrists.
- A significant background in robotics, unmanned aircraft systems, unmanned underwater vehicles research, and radiation effects on electronics.

SNL also has several facilities that could be used to support maritime environment testing:

- The Gamma Irradiation Facility provides the high-fidelity simulation of nuclear radiation environments for materials and component testing [17]. It can produce a wide range of gamma radiation environments (from 10-3 to over 6.5 × 10^2 rad/second) using cobalt-60 sources and can irradiate objects as small as electronic components and as large as an Abrams M1 tank.

4.2 University Laboratories

This section outlines testing opportunities at U.S. university nuclear laboratories that responded to INR No. 2 and provided additional details about testing opportunities. Additional opportunities likely exist at other university laboratories and additional outreach is recommended for a comprehensive review of potential opportunities.

4.2.1 George Washington University

George Washington University (GWU) is a private research university located in Washington, D.C. GWU has proposed one facility that could be used to support maritime environment testing:

- The Thermo-Fluids Laboratory specializes in research on fluid-structure interaction, multiphase flows, and buoyancy-driven flows [18]. Applications range from industrial to environmental flows, naval applications, and nuclear thermal-hydraulics and security. Research equipment includes a 20 × 8 × 4 ft sloshing tank that is excited linearly with a 20 kips (100 kN) hydraulic actuator.

4.2.2 Georgia Institute of Technology

The Georgia Institute of Technology (GTech) is a public research university in Atlanta, Georgia. GTech has opportunities to support the following:

- Materials testing of HALEU in a maritime environment. GTech holds licenses to handle HALEU and other similar materials.
- Materials testing of graphite in a maritime environment. GTech has a graphite pile that could be used to support such testing.

- Physical and simulated research on the following miscellaneous topics in a maritime environment:
  - Sea state requirements. This includes a custom wave tank and access to Naval Surface Warfare Center Maneuvering and Sea Keeping Basin (MASK) for complex sea states.
  - Reliability and redundancy requirements. This includes a sloshing tank that can be used to test components and system reliability.

4.2.3 Kansas State University

Kansas State University (KSU) is a public research university in Manhattan, Kansas, with the following opportunities to support:

- Research into computer simulations for an SMR or microreactor in a maritime environment. This includes the Beocat HPC system with Monte Carlo N-Particle Transport Code (MCNP), Particle and Heavy Ion Transport Code System, and GEANT4 radiation transport simulation code packages.

KSU also has facilities that could be used to support maritime environment testing:

- The KSU TRIGA Mark II Nuclear Reactor Facility is a test reactor that supports academic and education programs, research, industrial service, and outreach [19]. The reactor is licensed to operate at up to 1.25 MW. Its research capabilities include a variety of neutron beams for detector testing, internal imaging using neutron radiography and tomography, tracer isotope production, and trace element analysis via neutron activation analysis. Available experiments include:
  - Neutron activation analysis using HPGe spectrometers.
  - Neutron irradiation: ~108–1,018 neutrons/cm2.
  - Gamma irradiation up to ~500 krad/hr for samples smaller than 50 mL and up to ~1 krad/hr for samples up to 20 L.
  - Neutron radiography.
  - Neutron detector testing for four beam ports with distinct neutron spectra and a Cf-252 neutron and gamma source.

4.2.4 Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT) is a private research university in Cambridge, Massachusetts. MIT facilities could be used to support maritime environment testing:

- The MIT Reactor (MITR) is a test reactor facility. It is a light-water cooled and moderated, heavy-water reflected nuclear reactor that utilizes flat, finned, aluminum-clad plate-type fuel elements [20]. The average core power density is about 70 kW per liter. The maximum fast and thermal neutron flux available to experimenters are 1.2×10^{14} and 6×10^{13} neutrons/cm^2-s, respectively. Experimental facilities available at the MIT research reactor include two medical irradiation rooms, beam ports, automatic transfer facilities (pneumatic tubes), and graphite reflector irradiation facilities. In addition, several types of in-core experimental facilities are available. MIT indicated anything that can fit within a 1 × 20 inch volume can be irradiated in MITR at neutron fluxes similar to commercial pressurized-water reactors (PWR).
- The joint MIT and INL Center for Reactor Instrumentation and Sensor Physics functions as a technology innovation, development, and maturation hub by connecting experts from diverse organizations to devise solutions for sensing and instrumentation and to test these systems under irradiation. Its goal is to advance the current state of automation in nuclear systems.
- The Ultrasonic Material Characterization Laboratory researches wave propagation in heterogeneous media to retrieve information on the microarchitecture of heterogeneous solids [22]. This laboratory can perform physical and simulated ultrasound analysis of tristructural isotropic (TRISO) fuel pebbles.

4.2.5 Oregon State University

Oregon State University (OSU) is a public research university in Corvallis, Oregon, with opportunities to support:

- Physical materials testing of coolants in a maritime environment, including helium, CO_2, lead, and chloride- or fluoride-based molten salts. For chloride- or fluoride-based molten salts, OSU has a thermographic analysis and differential scanning calorimetry mass spectrometry system that can characterize the salt's thermal properties between room temperature and 1600°C, under different gas atmospheres, and oxidative or reductive environments.
- Physical materials testing of moderators in a maritime environment, including graphite and tungsten. OSU specified capabilities to test on a scale from 1 micrometer to 100 mm.

OSU also has several facilities that could be used to support maritime environment testing:

- The Materials for Extreme Environments and Nuclear Applications Laboratory at OSU focuses on understanding the mechanical performance of materials as affected by fabrication, processing, and service exposure (thermomechanical and irradiation). The outcomes benefit both fundamental knowledge advancement and the DOE nuclear and fusion sectors in accelerated alloy design, development, and deployment. The lab has several unique capabilities, including:
  - The Nuclear Metallurgy Lab is licensed to receive, handle, and process radioactive materials, performing sample preparation (cutting, polishing), optical and scanning electron microscopy based characterization, and focused ion beam based micro milling. The lab is equipped with a precision saw, mounting press, grinder polisher, vibratory polisher, inverted metallurgical microscope, and scanning electron microscope and focused ion beam dual beam system.
  - The Multiscale Mechanical Lab facilitates two in situ scanning electron microscope mechanical testing systems, operating at micro- and mesoscales, respectively. With capabilities to customize testing fixtures, samples of different geometries range from m to a few mm. Sizes can be tested under different loading conditions at up to 800°C.
  - The Thermophysical Lab for Environmental Sensitive Materials facilitates a nuclear-grade glovebox to handle environmentally sensitive materials and performs a thermal analysis on such materials as nuclear fuel and molten salts, using a simultaneous thermal analysis system and mass spectrometry. The system operates at up to 1600°C with transient heating and cooling capabilities up to 20°C/s, under oxidizing, reducing, and inert environments.

- The Laser Ultrasonic Multifunctional Apparatus utilizes laser ultrasonics for sample surface processing (such as laser shock peening) and non-contact materials characterization (such as through surface acoustic wave and laser shock adhesion). It facilitates a nanosecond pulsed laser with a pulse energy up to 850 mJ, a picosecond microchip laser with a pulse width of 500 picoseconds and energy of 45 J, and a 150 W continuous laser.

- The Nuclear Materials Degradation Laboratory at OSU studies materials degradation and performance in extreme environments relevant to advanced and next-generation nuclear reactor systems, including liquid metal and molten-salt-cooled thermal and fast reactors. The lab has several testing opportunities, including:
  - The Glovebox for Experimental Liquid Sodium is a combined thermal hydraulic and materials test facility comprised of three separate independent sodium loops: the Diagnostics Loop, the High-Temperature Instrumentation Loop, and the Corrosion Experimental Loop. It enables testing in both static and flowing chemistry-controlled liquid sodium environments at up to 550°C [23].
  - The Molten Salt Load Frame is a dual-chamber autoclave and an Interactive Instruments Model 5K Servo that enables mechanical testing of materials with simultaneous exposure to molten-salt environments. It can achieve temperatures up to 700°C [23].
  - The Salt Prototyping and Development Environment, which is a simple static molten-salt crucible test facility contained within an inert atmosphere glovebox. It is primarily used for static corrosion coupon testing material samples in addition to studies of salt chemistry and chemical monitoring [23].
- The Radiation Center at OSU is a large facility that hosts a collection of highly specialized experimental and laboratory facilities as well as the School of Nuclear Science and Engineering. The experimental facilities include the 1.1 MW Oregon State TRIGA Reactor, state-of-the-art thermal-hydraulic test facilities, and a wide array of equipment that permits researchers to use radiation in their research [24].
- The Pacific Marine Energy Center (PMEC) is a consortium of universities, including OSU, focused on the responsible advancement of marine energy, including wave, tidal, riverine, and offshore wind resources [25]. PMEC has a number of capabilities, including:
  - Hydrodynamic simulation of ocean sea states and dynamic response of floating bodies using numerical simulation software like WEC-Sim, ProteusDS, OrcaFlex, etc.
  - Moorings, anchors, and other ocean equipment simulation.
  - Scaled tank testing in the O.H. Hinsdale Wave Laboratory.
- OSU indicated PMEC can support simulated research on sea state requirements and ship motion testing and physical research on reactor performance during normal operations at sea and remote maintenance and inspection systems.

4.2.6 Purdue University

Purdue University is a public research university in West Lafayette, Indiana. Its facilities could be used to support maritime environment testing:

- The Purdue University Reactor Number One (PUR-1) is an experimental reactor that is licensed to operate at a thermal power up to 12 kW and a maximum thermal neutron flux of 2.1×10^{10} n/cm^2·s [26]. There are several dry irradiation tubes with a maximum size of 3.5 inches and irradiation ports within the graphite reflector surrounding the core that can be used for fueled experiments. The PUR-1 facility also has an array of spectrometers for radiation detection experiments. Purdue indicated that PUR-1 has:
  - Experience with reactor technologies, safety analysis, and licensing.
  - Experience with radiation shielding, radiation detection, and measurement.
  - Expertise in nuclear particle transport with MCNP and other tools.
  - Ability to utilize TMFD sensor technologies for gamma-beta blind spectroscopic detection of neutrons and heavy ion transport.
  - License that permits testing of highly enriched uranium to low-enriched uranium materials alongside actinides and beta-gamma emitters.
  - Fully digital instrumentation and control and an established test bed for testing control systems (e.g., PLCs, FPGAs).
  - Established remote two-way communications and a digital twin for cybersecurity research.
  - Radiation detectors that offer directional position sensing tracking of special nuclear materials even under extreme 10,000 R/h gamma-beta backgrounds.

4.2.7 University of Buffalo

The University at Buffalo (UBuff) is a public research university in Buffalo, New York. UBuff has facilities that could be used to support maritime environment testing:

- The Structural Engineering and Earthquake Simulation Laboratory has the capacity to execute static and dynamic tests, using high-performance actuators, high-force capacity actuators, high-performance 6-degree of freedom earthquake (or motion) simulators, and reinforced structures for testing lateral and vertical loads [27]. The laboratory also includes a wind tunnel and a furnace to support work in fire engineering.
- Faculty affiliated with the laboratory have expertise in structural mechanics and dynamics, blast, impact, earthquake, fire, and wind engineering, computational fluid mechanics and dynamics, model-in-the-loop testing (which will become important for equipment qualification), vibration protection and mitigation, and HPC. The laboratory holds an NQA 1 accreditation.

4.2.8 University of Michigan

The University of Michigan (UMich) is a public research university in Ann Arbor, Michigan. UMich has various capabilities to support:

- Physical materials testing of coolants in a maritime environment, including potassium sodium nitrate ($KNaNO_3$), helium, carbon dioxide (CO_2), lead, and chloride- or fluoride-based molten salts. UMich specified:
  - Inability to test supercritical CO_2.
  - Availability of static and flowing tests for lead and molten salts.

  - The UMich Structural Engineering Lab has physical and simulated seismic shock and vibration testing capabilities to investigate aspects of safe reactor operation under severe maritime conditions. The structural engineering lab has several uniaxial test frames that can apply loads between 25 and 1,000 kips (11.3 to 45.3 metric tonnes) up to approximately 1 Hz [28]. Several large hydraulic actuators are available with varying stroke lengths and capacities (up to 300 kips/136.0 metric tonnes tension, 450 kips/204.1 metric tonnes compression) for full-scale testing in conjunction with reinforced structures for testing lateral and vertical load.

4.2.9 University of Texas at Dallas

The University of Texas at Dallas (UTD) is a public research university in Richardson, Texas, with some capabilities to support:

- Physical and simulated testing to investigate aspects of safe reactor operation under severe maritime conditions, including accelerations, and redundancy and resiliency. This includes electronics test hardware, software, and simulation tools like Geometry and Tracking 4 Software (GEANT4), Stopping and Range of Ionizing Matter Software (SRIM), Technology Computer-Aided Design (TCAD), and accelerated testing with heavy ions, alpha particles, and neutrons as part of programs to determine electronics reliability against single-event effects, displacement damage dose, and total ionizing dose effects.
- Physical testing of alarms in a maritime environment, including radiation detection and containment integrity. This includes alpha and gamma sources capable of triggering alarms.
- Simulated research on the following miscellaneous topics in a maritime environment:
  - Reliability and redundancy requirements. This includes a custom parallel high-voltage test system that was used at Los Alamos National Laboratory and is capable of stressing power transistors at up to 1,200 V with 200 devices in parallel. This enables precise understanding of reliability in terrestrial neutron fields. The same equipment could be used in the beam of a nuclear reactor to allow extrapolation of electrical device performance in a naval reactor environment.
  - Radiation shielding requirements of an SMR or microreactor. This includes software and simulation tools like GEANT4, SRIM, and TCAD.
  - Remote maintenance and inspection systems. This includes nonintrusive fault detection methods for shipboard power systems, using voltage and current signals and machine learning methods.
- UTD facilities could be used to support maritime environment testing:
  - The Fluids, Turbulence Control & Renewable Energy Lab focuses on experimental fluid dynamics in both air and water flows. Facilities include:
    - A time-resolved 3D particle image velocimetry (PIV) system to measure “instantaneous flow features, particle motions, and structure dynamics” of fluids in motion [29]. This system may be utilized for the physical testing of fluid and gas interactions in a marine environment.
    - A temperature-adjustable flow visualization water channel, with test section of 0.2 × 0.2 × 2 meters and freestream velocity up to 1.3 m/s [29]. The incoming flow temperature can be set lower than ambient. UTD indicated that this system can be utilized for the physical and simulated testing of sea trials under severe conditions.
- The Design and Optimization of Energy Systems Lab performs research on sustainable energy systems to support the modernization of the electricity infrastructure and the transition of the electricity industry to a paradigm based on high penetrations of renewable energy and energy efficiency technologies [30].
- The Center for Harsh Environment Semiconductors and Systems conducts research to advance the fundamental understanding of processes, materials, and devices for harsh environments (e.g., extreme temperatures, radiation exposure) [31] and is comprised of several facilities, including:
  - Physical Characterization Lab
  - Radiation Sensor Lab
  - Theory/Modeling/Machine Learning.

4.2.10 University of Wisconsin–Madison

The University of Wisconsin–Madison (UWM) is a public research institution in Madison, Wisconsin, with a wide array of experimental facilities and capabilities and modeling and simulation expertise:

- A 1 MW Training Research Isotope General Atomics (TRIGA) reactor is available for experiments involving the irradiation of samples and equipment.
- Active flow loops of a wide variety of reactor-relevant coolants (e.g., Cl and F molten salts, liquid metals, supercritical fluids) studying both fundamental coolant performance and material compatibility.
- Ion Beam Laboratory for accelerated irradiation testing of various materials, including materials exposed to coolants for compatibility.
- AM facilities to explore novel alloys for specific extreme environments.
- Surface modification technologies to improve material compatibility while preserving bulk properties.
- 3D CAD-based radiation transport for radiation shielding analysis of complex geometries and criticality analysis in off-normal conditions (OpenMC, MCNP6).
- Computational modeling of severe accidents (MELCOR, RELAP, TRACE) across a range of reactor technologies, including lab-scale experiments for validating individual effects.
- Design and analysis of novel reactor concepts and components.
- Technoeconomic analysis of reactor integration into varied energy systems.
- Multiphysics simulation of reactor systems with tools including BISON, Griffin, Cardinal, from the Multiphysics Object-Oriented Simulation Environment (MOOSE) family, as well as the ARC suite for metal-cooled fast reactors.

SECTION 5

5 Assessment of Maritime Application Testing Opportunities and Constraints

There was an analysis that examined industry testing needs for maritime applications against testing opportunities available at U.S. national laboratories and university nuclear laboratories. The analysis was performed by comparing the results of the industry stakeholders INR No. 1 and the U.S. national laboratories and university nuclear laboratories INR No. 2. High-level recommendations for NRIC are provided to develop a pathway for addressing these constraints. The results of this analysis are summarized in Table 3.

5.1 Safety

Testing opportunities for assessing reactor safety include testing under severe operating conditions, testing of alarms, fire safety, and physical scenarios. Both simulated and physical testing capabilities were identified in the responses, primarily from U.S. national laboratories.

Several specific capabilities identified for testing under severe operating conditions include:

- LS Dyna software at ANL.
- The MOOSE framework at INL.
- The PNNL 318 Facility.
- SNL's host of safety-related testing capabilities, which includes a blast range for physical blast analysis testing.
- The KSU TRIGA Mark II Reactor Facility.
- The UBuff Structural Engineering and Earthquake Simulation Laboratory.
- The UMich CEE structures lab.
- GEANT4, SRIM, TCAD, and software at UTD.
- ANL Zero Power Reactor containment facilities for severe accident testing.

However, in the remaining categories, there were few details provided by the respondents. Alarms testing appeared to lack opportunities, with only 50% of the respondents responding “yes” to questions regarding alarms testing. Additionally, there were no testing opportunities indicated for the following areas of interest to industry stakeholders:

- Impact and sudden deceleration alarms.
- High-amplitude ship motion alarms.
- Flooding and water detection alarms.

5.2 Materials and Chemicals

Overall, the respondents offer opportunities to support a wide range of both physical and simulated material and chemical tests in a maritime environment:

- INL’s MSTEC site for testing molten salts under irradiated conditions in a marine environment.
- INL’s MAGNET facility for testing helium as a coolant for a microreactor.
- Sequim’s saltwater testing facility, which can be used for testing reactor materials when exposed to seawater.
- The time-resolved 3D PIV system at UTD for testing fluid and gas interactions within a reactor.
- ANL’s host of materials testing facilities, which include:
  - IVEM Facility.
  - IML.
  - METLab.
  - Metal Additive Manufacturing Laboratory.
  - NDE and Testing Facilities.
  - The CFCT Pyroprocess Engineering Facilities.
  - The CFCT Molten Salt Properties.
  - The CFCT Materials Characterization Laboratories.
  - ATLAS (see above).
- APS.
- Argonne’s MERF.

Beyond these cases, specific details on equipment and software at these laboratories were not provided. In general, the university nuclear laboratories can support benchtop-scale experimentation, while national laboratories can support larger scale testing.

- There were no testing opportunities indicated from the responses for the following areas of interest to industry stakeholders:
  - Encapsulated metal hydrides.
  - Ship hull cladding.
  - ASME Boiler and Pressure Vessel Code (BPVC) approved materials.

5.3 Maritime Application Testing

5.3.1 Reactor Testing

Physical and simulated testing capabilities for reactor testing are available across the universities and national laboratories based on responses to INR No. 2. INL has the potential to serve as a fuel and materials testing site with ATR and TREAT. DOME and the Laboratory for Operating and Testing in the U.S. (LOTUS) both act as facilities for testing microreactors; however, they are not equipped to test reactors in a marine environment. ANL has a host of specialized facilities, such as APS, ATLAS, NSTF, and METL, which could support the testing of niche cases, such as molten-salt reactors. For reactor testing in a marine environment, the Sequim marine test site at PNNL is of particular interest. Sequim is permitted to install floating platforms at their Sequim Bay and Clallam Bay sites, which could be used for testing a reactor in a marine environment. However, these sites would need DOE or NRC approval on a case-by-case basis before reactors can be tested at these locations.

There were no testing opportunities indicated from the responses for the following areas that are of interest to industry stakeholders:

- Speed ramp up and ramp down for mobile vessels.
- Power scale up to 600 MW.
- Power supplementation systems, with a focus on onboard hydrogen generation.

5.3.2 Nondestructive Examination

The national laboratory respondents, primarily ANL and PNNL, indicated simulated and physical nondestructive examination capabilities that are applicable to maritime environments regarding all of the NDE scenarios included in the INR. However, specific equipment and software were not specified.

5.4 Security

Testing opportunities for security were more available at national laboratories compared to university laboratories. The national laboratory respondents generally indicated both simulated and physical testing capabilities across all the security areas of interest. The System's Engineering Facility at PNNL, ANL's Packaging, Certification, and Life Cycle Management system, and SNL's host of security-based testing opportunities are of particular interest. However, outside of these cases, the national laboratories did not provide additional details on security testing opportunities.

5.5 General Research

Several facilities were indicated as having opportunities to support industry-desired areas of research:

- The Sequim Marine Science Laboratory and 318 Facility at PNNL.
- Materials and Fuels Complex, MAGNET, NRIC DOME, LOTUS, TREAT, and T-REX C facilities at INL.
- B206, B308, B212, B205, and B315 facilities at ANL.
- A custom wave tank and access NSWCCD MASK for complex sea states at GWU.
- Experimental reactors at KSU (TRIGA Mark II), MIT (MITR), and Purdue (PUR 1).
- The numerous capabilities of PMEC at OSU, which includes:
    - Hydrodynamic simulation of ocean sea states and dynamic response of floating bodies with numerical simulation software like WEC-Sim, ProteusDS, OrcaFlex, etc.
    - Moorings, anchors, and other ocean equipment simulation.
    - Scaled tank testing in the O.H. Hinsdale Wave Laboratory.
- A custom parallel high-voltage test system used at Los Alamos National Laboratory that was developed by UTD.

However, outside of these cases, the national laboratories did not provide additional details on testing opportunities. Additionally, the number of simulated testing capabilities exceeds physical testing capabilities across all the general research areas indicated.

5.6 Summary of Opportunities and Constraints for Maritime Nuclear Application Testing

Testing opportunities at U.S. national laboratories and U.S. university nuclear laboratories include both physical and simulated testing capabilities and are available at multiple locations. Capabilities range from materials testing in a marine environment to the simulation of ocean conditions. Opportunities at university nuclear laboratories were not as comprehensive as national laboratories. However, they offer niche capabilities that could prove useful to industry stakeholders in some scenarios. NRIC encourages early engagement with these laboratories so testing opportunities can be adapted to address unique constraints of maritime nuclear technologies.

From the results of the industry INR as to the demonstration needs, and the assessment of current capabilities of U.S. national laboratories and university nuclear laboratories, some key constraints are identified, regardless of the potential future requirements established by regulations for nuclear licensing.

One potential major constraint identified by the laboratories is the lack of a nuclear test reactor site that could test the reactor performance under simulated or actual sea conditions. This constraint may be significant as it directly impacts the safe and effective operation of nuclear-maritime applications. Without clear regulatory guidance on the demonstration requirements for nuclear-maritime reactors, it is difficult to know whether a physical test site will be needed or if a simulated test bed is sufficient. However, if regulation deems a physical test bed necessary for demonstration and safety-basis purposes, this constraint will need to be addressed. Future work will be focused on determining the technical requirements for a physical test bed and where modeling and simulation can be used in its place.

Another constraint identified is the disparity between the laboratories' modeling and simulation versus their physical testing capabilities. Physical testing capabilities are important checks and opportunities to validate simulated data. In addition, physical experimentation and physical test beds are especially necessary for testing new technologies, evaluating chemical or physical aspects that do not have much experimentation data, those tests for which there is no software or modeling capability developed yet to investigate.

Currently, physical testing capabilities are lacking in quantity relative to modeling and simulation capabilities, indicating a potential need for national laboratories to enhance their physical testing capabilities and bring them in line with modeling and simulation capabilities.

This would not only lead to more reliable and accurate testing of nuclear-maritime applications but also drive further advancements in the industry. However, significantly increasing the number of physical testing opportunities could be prohibitively expensive.

Further information on laboratory testing capabilities is to be determined. Details regarding specific capabilities (including equipment, facilities, and software), scale (e.g., benchtop scale versus full scale), and throughput capacity (e.g., one test per year versus ten), were generally not indicated by INR No. 2 respondents. This information is important for NRIC to understand the cost of addressing constraints of current maritime reactor testing capabilities.

Table 3 presents a comprehensive representation of the identified constraints between the industry's testing needs, and the testing opportunities offered by the information provided by U.S. national and university nuclear laboratories, as derived from the results of both INRs.

Table 3. Summary of industry testing needs, testing opportunities at U.S.–based laboratories, and testing constraints for maritime nuclear applications.

Category	Subcategory	Industry Testing Opportunities of Nore at U.S. National Laboratories and University Nuclear Laboratories[b]	Industry Testing Needs	Testing Constraints to Address[c]
Safety	Performance Under Severe Conditions	**ANL**—LS Dyna software for seismic simulation. **PNNL**—318 Facility can generally support testing. **INL**—Software packages, including Pronghorn tool, MOOSE framework, and MATSON tool. **SNL**—Lab-scale, 6-degree-of-freedom shaker tables as well as small- and large-scale testing capabilities for: • Mechanical shock. • Vibration testing. • Impact and drop testing. • Thermal and fire testing. **UBuff**—Structural Engineering and Earthquake Simulation Laboratory earthquake simulators. **UTD**—Dynamic water channel at the Fluids, Turbulence Control & Renewable Energy Laboratory. Accelerated ion testing for electronics reliability, including simulation tools such as GEANT4, SRIM, and TCAD. **UMich**—CEE Structures Laboratory uniaxial test frames.	• Seismic testing • Acceleration testing • Vibration testing • Computational fluid dynamics analysis • Finite element analysis • Dynamic stability simulations • Control system testing • Emergency response drills • Redundancy and resilience testing • Equipment securing and restraint systems • Human factors testing • Mechanical systems rigidity testing	Expand physical testing capabilities for simulated sea trials and human factors testing
	Alarms	**ANL**— **Calibrated** radiacs for testing radiation alarms. **PNNL**—Radiochemical Processing Laboratory, 318 facility, and Physical Science Facilities can generally support testing. **KSU**—Testing radiation detection via rad sources at the KSU TRIGA II Reactor. **Purdue**—Ultra-trace levels of alpha-fission-neutron emitting radionuclides. **UTD**—X-ray, gamma, and alpha sources to trigger radiation alarms.	• Radiation detection • Gas detection • Reactor parameters • Emergency cooling system • Containment integrity • Reactor trip • Emergency shutdown • Containment venting • Emergency communications • Emergency evacuation • Spill overboard • Impact and sudden deceleration • High-amplitude ship motion • Flooding and water detection	Focused on operational integration without specific recommendations for nuclear technology offshore

Category	Subcategory	Industry Testing Opportunities of Nore at U.S. National Laboratories and University Nuclear Laboratories[b]	Industry Testing Needs	Testing Constraints to Address[c]
Safety *cont.*	Fire Safety	**PNNL**—The Sequim Marine Science Laboratory, Radiochemical Processing Laboratory, and Physical Science Facilities can generally support testing. **SNL**—Testing of system exposure to seawater, electrical conductivity monitoring of specimens exposed to fire conditions, and high-heat flux testing on insulation materials are available.	• Sea water interaction with reactor systems • Onboard low-level waste handling • Electrical systems • Containment integrity • Insulation materials • Smoke control systems • Fire compatibility of equipment • Fire detection and suppression • Passive fire protection systems	No specific constraints to address
	Physical Scenario Analysis	**PNNL**—Physical Science Facilities can generally support steam generator tube rupture analysis. **SNL**—MELCOR and MACCS (simulation tools for determining radiological consequences of accident scenarios). CTH for blast effect simulations as well as an onsite explosive range for experimental validation and testing. **Purdue**—Expertise in shock physics and structural responses. **UBuff**—Structural Engineering and Earthquake Simulation Laboratory can generally support testing. **UWM**—MELCOR for severe accident analysis and OpenMC and MCNP for criticality analysis.	• Hurricane conditions • Steam generator tube rupture • Remaining subcritical following ship sinking • LOCA • Collision or grounding • Station blackout • Blast analysis	Expand physical testing capabilities for LOCA, ship sinking, hurricane conditions, station blackout, and collision and grounding

Category	Subcategory	Industry Testing Opportunities of Nore at U.S. National Laboratories and University Nuclear Laboratories[b]	Industry Testing Needs	Testing Constraints to Address[c]
Materials & Chemicals	Fuel	**PNNL**—The Sequim Marine Science Laboratory, Radiochemical Processing Laboratory, and Physical Science Facilities can generally support testing. **ANL**—Performance of defueled cladding at the IML. **GTech**—Licenses to handle LEU and HALEU. **Purdue**—Broad scope license that permits testing of highly enriched uranium to low-enriched uranium materials alongside actinides and beta-gamma emitters. **UMich**—Can test depleted and natural uranium. **OSU**—Limited to benchtop-scale testing.	• Zirconium hydride • HALEU • TRISO • UO2-LEU • PWR fuel bundles	Develop facilities for novel fuel fabrication Testing capabilities to address: • Zirconium hydride and other metal-hydride-based fuels
	Coolant	**PNNL**—The Sequim Marine Science Laboratory, Radiochemical Processing Laboratory, and Physical Science Facilities can generally support testing. **ANL**—Testing at B205 Chemical and Fuel Cycle Technology Labs and B206 Engineering Development Labs. **INL**—Helium component of MAGNET test facility. Additionally, INL MSTEC facility for testing molten salts. **UMich**—Static and flowing tests for molten salts and lead. Can test subcritical CO_2. **OSU**—Limited to benchtop-scale testing. Thermographic analysis and differential scanning calorimetry system to characterize thermal properties of molten salts between room temperature and 1600°C. **UWM**—Experimental experience with all the coolants identified.	• Potassium sodium nitrate ($KNaNO_3$) • Helium • Carbon dioxide (CO_2) • Lead • Chloride/fluoride molten salts	No specific constraints to address
	Moderator	**PNNL**—The Sequim Marine Science Laboratory, Radiochemical Processing Laboratory, and Physical Science Facilities can generally support testing. **ANL**—Testing at B212—METLab suit of various materials testing capabilities. **GTech**—Graphite pile. **OSU**—Limited to benchtop-scale testing. Mechanical characterization methods for graphite and tungsten from micrometer to 100 mm scale.	• Graphite • Boron carbide (B4C) • Tungsten • Encapsulated metal hydride	Develop and determine testing capabilities to address encapsulated metal hydrides

Category	Subcategory	Industry Testing Opportunities of Nore at U.S. National Laboratories and University Nuclear Laboratories[b]	Industry Testing Needs	Testing Constraints to Address[c]
Materials & Chemicals *cont.*	Miscellaneous	Testing capabilities not indicated.	• Hull cladding • Core internal materials • Fuel cladding • ASME BPVC approved materials	Testing capabilities to address: • Hull cladding • ASME BPVC approved materials
	Chemical Incompatibilities	**PNNL**—The Sequim Marine Science Laboratory, Radiochemical Processing Laboratory, and Physical Science Facilities can generally support testing. **ANL**—B205 Chemical and fuel Cycle Technology Lab. **UTD**—Time-resolved 3D PIV system at Fluids, Turbulence Control & Renewable Energy Laboratory. **UWM**—Experimental experience with all the coolants identified for coolant-material compatibility testing.	• Mixing of molten salts and salt water • Coolant chemistry • Fuel-cladding interaction • Saltwater corrosion inhibition • Tritium interactions • General fluid-gas interactions	No specific constraints to address
Maritime Application Testing	Reactor Testing	**ANL**—APS, ATLAS, NSTF, METL, and others can generally support testing. **PNNL**—The Sequim Marine Science Laboratory, Radiochemical Processing Laboratory, and 318 Facility can generally support testing. • Sequim has several facilities, including the Aquatic Research Laboratories, Hyperbaric Laboratory, large outdoor research tanks, wave tanks, and two marine test sites (Sequim Bay and Challam Bay) that could be used to support marine reactor testing. **INL**—ATR and TREAT can generally support testing. **MIT**—MITR can generally support testing with small-scale irradiation experiments. **NCSU**—Control system modeling and testing using Simulink. **Purdue**—PUR-1 can generally support testing. **UBuff**—Structural Engineering and Earthquake Simulation Laboratory can generally support testing.	• Simulated sea trials • Radiological monitoring • Core integrity • Reactor shutdown • Fuel integrity, handling, and disposal • Replica testing • Control systems functionality • Environmental impact assessment • Testing site, such as a floating platform • Speed ramp up and ramp down for mobile vessels • Applications for cargo ships, passenger vessels, and offshore barges • Power scale from 5 to 600 MW scale • Power supplementation systems, including hydrogen generators	Develop a site for mid-scale and full-scale reactor testing in a marine environment. In particular, investigate the use of Sequim Bay and Challam Bay sites at PNNL as a potential location for testing Testing capabilities to address: • Speed ramp up/ ramp down for mobile vessels • Power scale up to 600 MW • Power supplementation systems, with a focus on aboard hydrogen generations

Category	Subcategory	Industry Testing Opportunities of Nore at U.S. National Laboratories and University Nuclear Laboratories[b]	Industry Testing Needs	Testing Constraints to Address[c]
Maritime Application Testing *cont.*	Nondestructive Examination	**PNNL**—Radiochemical Processing Laboratory and Physical Science Facilities can generally support testing. **ANL**—Non-Destructive Examination Lab, this lab supports most of industry's identified testing needs. **NCSU**—Ultrasonic Material Characterization Laboratory.	• Ultrasonic testing • Radiographic testing • Magnetic particle testing • Liquid penetrant testing • Eddy current testing • Acoustic emission testing • Infrared thermography • Shearography • Digital radiography • Phased array ultrasonics	No specific constraints to address
Security	Nuclear Security	**ANL**—Packaging, Certification, and Life Cycle Management (PCLCM) program. The Strategic Security Sciences Division can support various aspects of safeguards and security. **PNNL**—Systems Engineering Facility can generally support testing of communications security. **SNL**—A significant suite of security-related physical and simulation capabilities, including: • Force-on-force exercises. • Limited-scope performance testing (Detection, Assessment, Delay, Response). • Material Control & Accounting, physical protection and severe accident analysis. • Examining sabotage targets for various reactor types. • Examining economic impacts of adversary attacks. • Cost and benefit analysis of adding security components. **Purdue**—PUR-1 can generally support testing.	• Storage of fuel in packaged reactor containment • Refueling both on and off board • Sonar and radar • Submerged actors • Communication security • Physical security	Expand physical testing capabilities for physical security, accountability of nuclear material, and security infrastructure resilience Testing capabilities to address: • Sonar and radar • Refueling management, both on and off board • Storage of fuel
	Personnel	Physical and simulated capabilities are available across the national laboratories. The number of simulated testing capabilities exceeds physical testing capabilities.	• Nuclear safety training • Reactor operation • Security awareness • Access control and authorization	Testing capabilities to address: • Reactor operation • Nuclear safety training
	Cyber Security	**PNNL**—Systems Engineering Facility can generally support testing. **Purdue**—PUR-1 can generally support testing.	Compliance with the National Institute Standards and Technology Cybersecurity Framework	No specific constraints to address

Category	Subcategory	Industry Testing Opportunities of Nore at U.S. National Laboratories and University Nuclear Laboratories[b]	Industry Testing Needs	Testing Constraints to Address[c]
General Research	General Research	**PNNL**—Sequim Marine Science Laboratory, 318 Facility can generally support testing. **INL**—Materials and Fuels Complex, MAGNET, NRIC DOME, LOTUS, TREAT, and T-REX C facilities can generally support testing. **SNL**—Wide array of research capabilities in areas such as robotics, nuclear economics, dosimetry, HPC, and more. **GWU**—Access to a custom wave tank and to NSWCCD MASK for complex sea states **KSU**—TRIGA Mark II Reactor can generally support testing, as well as the KSU HPC system for simulation. **MIT**—MITR can generally support testing with small-scale irradiation experiments. **Purdue**—PUR-1 can generally support testing. **UBuff**—Structural Engineering and Earthquake Simulation Laboratory can generally support testing. **OSU**—PMEC has a number of capabilities, including hydrodynamic simulation of ocean sea states and dynamic response of floating bodies with numerical simulation software like WEC-Sim, ProteusDS, OrcaFlex, etc. Moorings, anchors, and other ocean equipment simulation. Scaled tank testing in the O.H. Hinsdale Wave Laboratory. **UTD**—Thermal-electric models of nuclear-powered ships, including SMRs. Fault detections methods for shipboard power systems, using voltage and current signals and machine learning methods. Custom parallel high-voltage test system used at Los Alamos National Laboratory. **ANL**—Wide array of research capabilities in areas such as robotics, reactor performance studies, reactor simulation with HPC, and more. **UWM**—UWM TRIGA Reactor. 3D CAD-based tools for radiation shielding analysis.	• Reactor performance requirements • Sea state requirements • Thermal and fast reactors • Heat-pipe reactors and other naturally circulated coolant systems • Radiation shielding requirements of an SMR or microreactor • Best-fit reactor technology class for offshore oil and gas platforms • Ship motion testing • Reactor performance studies during normal operations at sea • Remote maintenance and inspection systems	Expand physical testing capabilities across all of the indicated general research areas

[b] The opportunities indicated in this column are not comprehensive of the full scope of capabilities indicated by the INR respondents. Rather, this column summarizes the most notable opportunities indicated by the respondents (i.e., where the most additional details were provided).

[c] Some rows are indicated as "No specific gaps to address" under NRIC Gaps to Address. This does not indicate that there are no gaps at all; rather, this indicates that the only gaps to address are general ones, such as investigating scale and throughput capacity of the laboratory capabilities.

CONCLUSION

6 Conclusion

After conducting two INRs—one to determine the nuclear-maritime needs of companies across various industries and another to assess the testing opportunities of U.S. national laboratories and university nuclear laboratories—valuable insights were gained into existing testing infrastructure. The results indicate that there are constraints in terms of the testing opportunities offered by U.S. national laboratories and university nuclear laboratories when it comes to testing nuclear-maritime applications.

Without clear regulatory guidance on the demonstration requirements for nuclear-maritime reactors, it is difficult to presume whether a physical test site that can replicate sea conditions for nuclear reactors will be needed or, alternatively, if a simulated test bed is sufficient. The current landscape suggests a strong reliance on modeling and simulation, which, while valuable for initial design and analysis, may not fully address the comprehensive validation needs for novel maritime nuclear technologies. Full-scale physical testing could provide irrefutable evidence of system performance and safety under the dynamic and often unpredictable conditions of a marine environment.

However, if regulation deems a physical test bed necessary for demonstration and safety-basis purposes, this constraint will need to be addressed by the U.S. national laboratories. This would necessitate significant investment in infrastructure capable of simulating complex sea states, including wave, current, and motion effects, while also being equipped for radioactive material handling and reactor operation. The development of such a facility would also require engagement between nuclear experts, maritime engineers, and regulatory bodies to ensure its efficacy and compliance with future standards. Recent efforts by DOE through initiatives such as the "Pathway to Test Advanced Reactors" are actively addressing these needs by streamlining access to federal facilities and expertise. Additionally, the Executive Order on reforming nuclear reactor testing at DOE facilities underscores a commitment to remove bureaucratic hurdles and accelerate the deployment of new nuclear technologies, including those for maritime applications.

Responses to INR No. 1 revealed an estimate of demand for testing solutions of nuclear-maritime applications. This potential demand underscores the need for U.S. national laboratories to address the identified constraints and bolster the testing opportunities that they can provide for industry stakeholders. The growth of the advanced nuclear technology sector, particularly in its application to maritime transport and offshore energy, suggests that existing testing capabilities may soon be outpaced by industry needs, creating a bottleneck for innovation and deployment.

INR No. 2 was directed toward U.S. national laboratories and university nuclear laboratories to evaluate their existing testing capabilities for nuclear-maritime applications based on the results of INR No. 1. The results showed that, while there are certain established capabilities, there is an opportunity for improvement and development to meet the evolving requirements of these industries, as shown in Table 3. This underscores the necessity for national laboratories to invest in and enhance their testing capabilities, thereby addressing the constraints of current laboratory testing capabilities. This enhancement should also consider the development of new, specialized testbeds tailored to the unique challenges of nuclear-maritime integration, such as those involving propulsion systems, specialized shielding for crew and cargo, and enhanced accident tolerance in marine environments. The integration of advanced computational fluid dynamics and structural analysis with physical mock-ups and component testing could also bridge some of the current gaps.

6.1 Recommendations for Future Work

Moving forward, continued independent efforts at NRIC may focus on broadening the understanding of the scope of the constraints in available testing opportunities and the potential significant surge in capacity needed of the U.S. national laboratories. It is recommended that NRIC initiate a series of detailed evaluations to identify specific areas within the DOE testing capabilities regime that require enhancement.

These targeted assessments would provide a granular understanding of the current constraints and should inform the strategy to address them. The scope of these targeted assessments may include but not be limited to:

- Initiating conceptual design of dynamic floating test bed facility that would address the lack of a physical, sea condition test bed for nuclear-maritime reactors. This facility would ideally replicate the dynamic forces and environmental conditions encountered at sea, allowing for realistic testing of reactor performance, stability, and safety systems under operational and off-normal marine conditions. Such a facility could also serve as a proving ground for novel reactor designs and propulsion systems specifically engineered for maritime applications.
- Conducting a thorough capacity analysis of U.S. national laboratories testing capabilities identified in this report. This will entail an extensive study of physical, human, and technological resources. The objective of this analysis will be twofold: to gauge the laboratories' current capabilities to meet increased demand and to identify the investments necessary to scale up operations efficiently and effectively. By understanding the scale at which the laboratories can operate, the industry can plan for growth and ensure that capabilities align with industry demands. This analysis should extend beyond current capacity to project future needs based on the anticipated growth of maritime nuclear technology.
- Investigating the use of private partnerships in which industry stakeholders can build facilities with federal grants as incentives for closing funding gaps and alleviating the financial burden on laboratories. These partnerships could leverage private sector innovation and investment while providing access to specialized federal expertise and infrastructure, accelerating the development and deployment of critical testing capabilities. Mechanisms for intellectual property sharing and cost recovery would need to be carefully structured to benefit all parties.
- Establishing a DOE topical report to be submitted to the NRC for their consideration that encapsulates the current capabilities of the national laboratory enterprise to determine if those experimental and modeling capabilities are sufficient to support companies for their licensing cases. This topical report could set the foundation for enabling current experiments or determining if future testing platforms to indeed need to be developed to meet the needs of the licensing authority. This foundational document would serve as a crucial reference point for both developers and regulators, providing a clear understanding of the established testing and validation pathways. Furthermore, it could identify areas where regulatory frameworks may need to evolve to accommodate the unique characteristics of maritime nuclear applications, fostering a more predictable and efficient licensing process.
- Exploring the potential for international collaborations to share expertise and resources in developing specialized maritime nuclear testing facilities, potentially reducing the individual burden on national laboratories and accelerating global advancements in the field.

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APPENDIX A

Appendix A: Industry Stakeholders Information Needs Request

This section lists the questions used in the Industry Stakeholders Information Needs Request (INR No. 1). INR No. 1 was constructed to assess nuclear, maritime, and oil and gas companies' plans regarding nuclear-maritime applications. Questions were split into multiple choice and short answer categories.

Multiple Choice Questions

Multiple choice questions covered a variety of topics. Response options were "Yes," "No," or "N/A" if the company did not wish to answer.

Respondents were prompted and encouraged to provide additional comments on their answers if they wished. The questions were:

1. Is your company interested in demonstrating a reactor for maritime application?
2. Is your company interested in demonstrating a maritime application before 2030?
3. Is your company interested in demonstrating a maritime application after 2030?
4. Does your company have a design of a demonstration reactor for maritime application?
5. Are you interested in using a DOE containment structure or building and/or site services to support maritime-nuclear demonstration?
6. Does your company need access to DOE-based modeling and simulation software, such as high powered computing (HPC) for maritime demonstrations?
7. Does your company intend to utilize some kind of floating platform to replicate marine environment during testing?
8. Does your company intend to use on-board energy storage or power supplementation?

Short Answer Questions

Like the multiple choice questions, the short answer questions covered a variety of topics.

These questions required more detailed answers and did not fit well as multiple choice questions. The questions were:

1. What types of information does the company require from a maritime demonstration or test?
2. What type of reactor is your company planning to implement? (examples include light water (LWR), heavy water (HWR), boiling water (BWR), pressurized water (PWR), molten salt (MSR), high-temperature gas (HGTR), heat pipe, small modular (SMR), microreactor, etc.)
3. What is the power scale of the reactor for the maritime application?
4. What is the intended refueling/ decommissioning mechanism? (i.e., would the entire reactor containment be removed from the vessel or just the reactor?)
5. What types of materials do you want to test in marine environment?
6. What types of water chemistry tests do you intend to perform maritime demonstrations?
7. What type of fuel is planned to be used in a maritime demonstration?
8. What type of vessel does your company intend to use a reactor on (cargo ship, offshore rig, passenger vessel, etc.)?
9. What types of testing would your company perform for maritime demonstrations to account for:
   a. dampening of vibrations.
   b. list/trim/pitch of the vessel.
   c. transient power for variable speed/ramping capabilities.
   d. noise from the reactor.
   e. leakage (water and gas tightness).
   f. stopping ability.
   g. heat sink for reactor decay heat when there is no propulsion.
   h. radiation shielding.
10. What types of non-destructive examinations for maritime demonstrations does your company intend to perform?
11. How will your company store and handle radioactive fission by-products on board? Does your company require testing for radioactive fission by-product containment in a marine environment?
12. What are the unique fire safety considerations for your company's maritime vessel?
13. What alarm requirements need to be tested for nuclear incidents onboard a vessel?
14. What types of testing are needed to ensure proper reactor operations under severe conditions that cause sudden accelerations (ensuring constant circulation and preventing trips of mechanical equipment)?
15. What types of chemical incompatibilities testing does your company want to investigate for maritime demonstrations?
16. What is your company design basis worst case scenario for maritime demonstrations?
17. What testing requirements does your company have to address security concerns onboard a vessel due to the added nuclear technology?
18. What special training and certification of vessel staff and engineers will be required for nuclear-maritime sea-trial?

APPENDIX B

Appendix B: U.S. National Laboratories and University Laboratories Information Needs Request

This section lists the questions used in the U.S. national laboratories and university laboratories Information Needs Request (INR No. 2). INR No. 2 was created using the results from INR No. 1 and was directed towards national laboratories and universities to assess their testing capabilities relevant to the needs of nuclear-maritime applications identified following INR No. 1.

Questions were split into five general categories: general research, materials and chemicals, maritime testing, safety, and security. Furthermore, questions were asked generally with several subtopics that acted as extensions of the main question.

The questions were all multiple choice with the following response options:

- "Yes—Physical Test" if the lab had physical test equipment.
- "Yes—Mod/Sim" if the lab had modeling and simulation capabilities.
- "Yes—Both" if the lab had both physical test equipment or modeling and simulation capabilities.
- "Yes" if the lab generally had testing capabilities in that area.
- "No" if the lab had no such testing capabilities.
- "N/A" if the lab did not wish to answer.

Respondents were prompted and encouraged to provide additional comments on their answers if they wished.

General Research

1. Can your laboratory perform research on the following topics regarding nuclear maritime demonstrations:
    a. ... performance requirements?
    b. ...sea state requirements?
    c. ...reliability and redundancy requirements?
    d. ...research thermal and fast reactors in a marine environment?
    e. ...research heat-pipe reactors and other naturally circulated coolant systems?
    f. ...computer simulation of maritime environments for an SMR or microreactor?
    g. ...radiation shielding requirements of an SMR or microreactor on a maritime platform with crew considerations?
    h. ...best-fit reactor technology class for offshore oil and gas platforms?
    i. ...ship motion testing?
    j. ...reactor performance study during normal operations at sea?
    k. ...remote maintenance/inspection systems?

General Research

2. Can your laboratory test for the following materials in marine environment:
    a. ...ceramic or metallic based high assay, low enriched uranium (HALEU) for fuel?
    b. ...graphite moderator?
    c. ...B4C control drums?
    d. ...lead?
    e. ...tungsten?
    f. ...potassium sodium nitrate ($KNaNO_3$)?
    g. ...tristructural isotropic (TRISO) fuel?
    h. ...inert gases such as helium or CO_2?
    i. ...chloride-based or fluoride-based molten salts?
3. Can your laboratory perform the following chemical incompatibilities tests for nuclear maritime demonstrations:
    a. ...compatibility of hydraulic fluids?
    b. ...fluid and gas interaction?

Maritime Testing

4. Can your laboratory perform the following nuclear-maritime demonstration tests:
    a. ...radiological monitoring?
    b. ...core integrity testing?
    c. ...reactor shutdown testing?
    d. ...fuel integrity, handling and disposal through its lifecycle (including in the case of stationary applications, like an offshore platform)?
    e. ...environmental impact assessment?
    f. ...control systems functional testing?
    g. ...replica testing?
    h. ...any unique testing capabilities not indicated above?
5. Can your laboratory perform the following non destructive testing for nuclear maritime demonstrations:
    a. ...ultrasonic testing?
    b. ...radiographic testing?
    c. ...magnetic particle testing?
    d. ...liquid penetrant testing?
    e. ...eddy current testing?
    f. ...acoustic emission testing?
    g. ...shearography?
    h. ...digital radiography?
    i. ...phased array ultrasonics?

Safety

6. Can your laboratory test to ensure proper reactor operations under severe conditions that cause sudden accelerations (ensuring constant circulation and preventing trips of mechanical equipment) for nuclear-maritime demonstrations:
   a. ...seismic shock testing?
   b. ...acceleration testing?
   c. ...vibration testing?
   d. ...simulated sea trials?
   e. ...computational fluid dynamics analysis?
   f. ...finite element analysis?
   g. ...dynamic stability simulations?
   h. ...control system testing?
   i. ...redundancy & resiliency testing?
   j. ...equipment securing and restraint system?
   k. ...human factors testing?
   l. ...mechanical system rigidity testing?
7. Can your laboratory test for the following alarms for nuclear maritime demonstrations:
   a. ...radiation alarms?
   b. ...gas detection alarms?
   c. ...reactor parameter alarms?
   d. ...emergency cooling system alarms?
   e. ...containment integrity alarms?
   f. ...reactor trip alarms?
   g. ...emergency shutdown alarms?
   h. ...containment venting alarms?
   i. ...emergency communication alarms?
   j. ...emergency evacuation alarms?
   k. ...spill overboard alarms
8. Can your laboratory test the following unique fire safety requirements for nuclear maritime demonstrations:
   a. ...sea water interaction with reactor systems?
   b. ...onboard low-level waste and contaminated PPE?
   c. ...electrical systems?
   d. ...containment integrity?
   e. ...insulation materials?
   f. ...smoke control systems?
   g. ..compatibility of equipment?
   h. ...redundant systems?
   i. ...passive fire protection?
9. Can your laboratory test for the following worst case scenario for nuclear maritime demonstrations:
   a. ...loss of coolant accident (LOCA)?
   b. ...remaining subcritical following ship sinking?
   c. ...hurricane conditions?
   d. ...steam generator tube rupture?
   e. ...blast analysis?
   f. ...station black-out and emergency backup power?
   g. ...collision or grounding (with another vessel or aircraft)?

Security

10. Can your laboratory test for the following nuclear-maritime demonstrations security concerns requirements:
   a. ...physical security?
   b. ...access control and authorization?
   c. ...communication security?
   d. ...personnel screening?
   e. ... accountability of nuclear material?
   f. ...security infrastructure resilience?
   g. ...cyber security?
   h. ...security breach simulations?

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