NRIC National Reactor Innovation Center

MARITIME NUCLEAR APPLICATION GROUP

NRIC Maritime Overview

Update

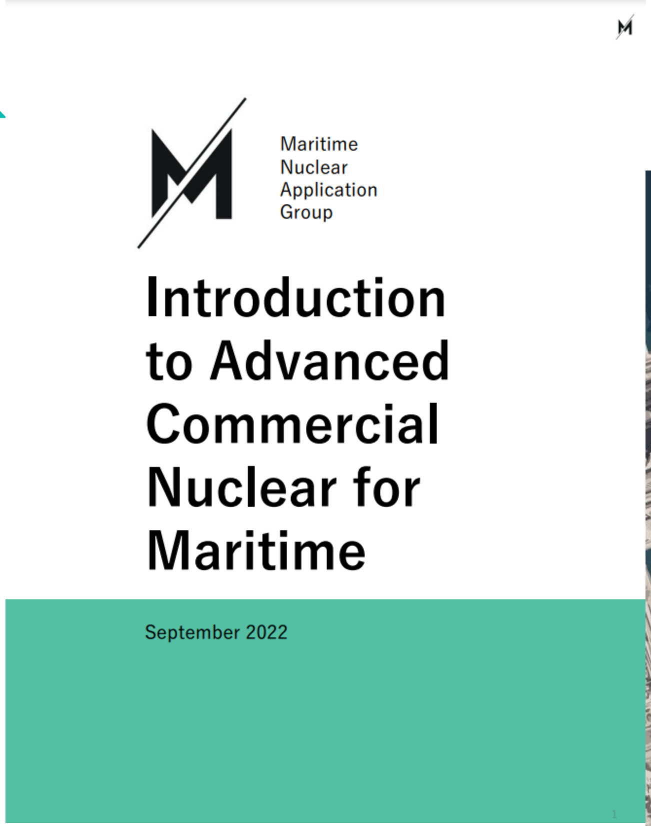
Sanjay Mukhi – NRIC Collaboration Manager

4/24/2024

Key Maritime Initiatives

- **ABS iFOA**
  - Built demonstration project pathways and business cases
  - Developed value proposition models for advanced reactor integrated with maritime applications
  - Currently assessing DOE Lab readiness for maritime demonstration projects
  - Will publish guidance on key technical, regulatory, and policy issues for maritime demonstration projects
- **Maritime Nuclear Applications Group (MNAG)**
  - Serves as a resource hub for 130+ members (develops research that highlights areas for additional consideration, and hosts quarterly meetings and for 4 working groups) from the following industries:
    - **Advanced nuclear:** Vendors, National Labs, Policy non-profits, Academia
    - **Maritime:** Vessel Owner/Operators, Classification, Maritime Law, Insurance, Flag States
    - **Government:** Department of Energy – Nuclear Energy Office, U.S. Coast Guard, Nuclear Regulatory Commission, Department of Transport / U.S. Maritime Administration
- **Nuclear Energy University Program**
  - Supporting UT-Dallas with a project on Thermal-Electric Energy Management of an All-Electric Ship with Advanced Nuclear Reactors
  - INL collaboration with MIT – Examine Integrated Marine Platform for Hydrogen and Ammonia Production

MNAG Reports


Maritime Nuclear Application Group

Introduction to Advanced Commercial Nuclear for Maritime

September 2022


INL/EXT-22-69884

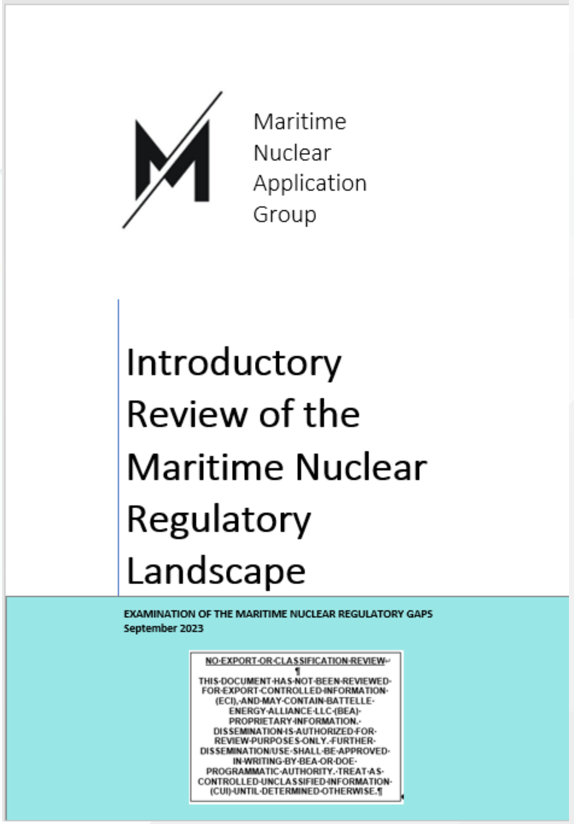
NRIC INL Idaho National Laboratory

Challenges and Opportunities for the Development of Commercial Maritime Surface Vessel Nuclear Propulsion (CMNP)

October 2022

River Bennett, Graduate Researcher

INL is a U.S. Department of Energy National Laboratory operated by Batelle Energy Alliance, LLC


Maritime Nuclear Application Group

Introductory Review of the Maritime Nuclear Regulatory Landscape

EXAMINATION OF THE MARITIME NUCLEAR REGULATORY GAPS

September 2023

NO EXPORT OR CLASSIFICATION REVIEW

THIS DOCUMENT HAS NOT BEEN REVIEWED FOR EXPORT CONTROLLED INFORMATION (ECI), AND MAY CONTAIN BATTELLE ENERGY ALLIANCE LLC (BEA) PROPRIETARY INFORMATION. DISSEMINATION IS AUTHORIZED FOR REVIEW PURPOSES ONLY. FURTHER DISSEMINATION/USE SHALL BE APPROVED IN WRITING BY BEA OR DOE PROGRAMMATIC AUTHORITY. TREAT AS CONTROLLED UNCLASSIFIED INFORMATION (CUI) UNTIL DETERMINED OTHERWISE.

Upcoming Report:

Economic, Environmental, Social Report

Working Groups

MNAG's Mission:

Maritime Nuclear Application Group (MNAG) is a **research hub** and **resource center** that brings together experts from the maritime and nuclear energy sectors to facilitate the demonstration of advanced nuclear technologies for a range of marine applications.

NRIC National Reactor Innovation Center

R&D / Technology Development WG

Chair: MPR (interim)
Members:
lgilber@sandia.gov
Claudia.gasparrini@rina.org
skeenan@bahamasmaritime.com
veigel@bertlingship.de
Mikal.boe@corepower.energy
szielonka@rccl.com
maguirht@westinghouse.com
hnorton@starbulk.com

Notable Achievements:

- Supported industry needs requests for ABS deliverable
- Supporting engineering requirements evaluation for maritime demonstration

Next Steps: Develop scoping document to support and MNAG report focused on evaluation and criteria for appropriate reactor technologies for maritime applications

Regulatory Working Group

Chair: agrodecki@ace-maritime.com
Members:
mdevos@prodigy.energy
Claudia.gasparrini@rina.org
Mdowling@eagle.org
Andrea.cogliolo@rina.org
jestephes@bwxt.com
lgilber@sandia.gov
alex.polonsky@morganlewis.com
skeenan@bahamasmaritime.com
Mikal.boe@corepower.energy
szielonka@rccl.com
Wscottedwards1967@gmail.com
patrick.pennella@morganlewis.com
m.steer@usnc-tech.com

Notable Achievements:
- Development of the Introductory Landscape Paper – heavy input and coordination from across the working group to develop this document, which took a 8 months of effort.

Next Steps: Develop scoping document to support addressing the regulatory gaps identified in the landscape report

NRIC National Reactor Innovation Center

Social, Environmental, and other Public Interests Working Group

Chair: c.walker@shippinginsight.com
Members:
agrodecki@ace-maritime.com
Claudia.gasparrini@rina.org
mdowling@eagle.org
Giorgio.desciora@rina.org
jestephens@bwxt.com
c.walker@shippinginsight.com
maguirht@westinghouse.com

Notable Achievements:
- Developed wireframes for MNAG website
- Developed Terms of Reference document for maritime nuclear

Next Steps: Supporting the development of the Social, Environmental, and Economics Impacts paper

Financial Considerations, Investments, and Insurance Working Group

Chair:
thomas.davies@corepower.energy
Members:
Claudia.gasparrini@rina.org
Mikal.boe@corepower.energy
veigel@bertlingship.de
grant.eskelsen@morganlewis.com
mdevos@prodigy.energy

Notable Achievements:
- Working group stood up in February 2024

Next Steps: Supporting the development of the Social, Environmental, and Economics Impacts paper

NRIC National Reactor Innovation Center

Newsletter and Membership

NRIC National Reactor Innovation Center | MARITIME NUCLEAR APPLICATION GROUP

Welcome to the February edition of the Maritime Nuclear Application Group Monthly Newsletter. This curated selection of articles aims to facilitate knowledge sharing of advanced nuclear technologies for maritime applications.

Featured Articles

South Korea's Largest Shipbuilder Makes Nuclear Move

SOURCE: Splash 24/7
DATE PUBLISHED: February 6, 2024
SUMMARY: "HD Korea Shipbuilding & Offshore Engineering (KSOE), a sub-holdings company of HD Hyundai, has held a joint research and technology exchange meeting with TerraPower and CORE POWER with plans unveiled to develop small modular nuclear reactors for use on newbuilds.'"

Prodigy and Westinghouse Targeting Launch of eVinci Floating Nuclear Plant in Canada by 2030

SOURCE: Power Magazine
DATE PUBLISHED: January 24, 2024
SUMMARY: "The project will potentially integrate a single or multiple 5-MWe eVinci microreactors within a Prodigy Microreactor Power Station—a purpose-designed floating facility that will likely be deployed at a shoreline."

Shipping's Nuclear Option in the Move Towards Net Zero: Is it Viable?

SOURCE: Hellenic Shipping News
DATE PUBLISHED: February 14, 2024
SUMMARY: This article provides an in-depth panorama of issues related to nuclear power in shipping, including regulatory, safety concerns, financial issues, and insurance.

Top locations by opens

USA	44	66.7%
Hong Kong	5	7.6%
Netherlands	5	7.6%
Ukraine	2	3.0%
Denmark	2	3.0%

~40% Membership increase since May 2023

Currently 130 members across industries interested in advancing maritime nuclear

NRIC National Reactor Innovation Center

Special Thank You to the MPR Team for Programmatic Support for our Maritime Initiative!

Questions?

NRIC National Reactor Innovation Center

MARITIME NUCLEAR APPLICATION GROUP

NRIC Testing Capability Analysis

Constraints and Limitations between Industry Needs and US Testing Capabilities

Sanjay Mukhi – NRIC Collaboration Manager

Agenda

- Purpose
- Testing Opportunities and Constraints
- Deliverable
- Deliverable Status
- Regulatory Considerations
- Evaluation of Maritime Application Needs
- Testing Constraints to Address
- Questions

Purpose

- Give an effort overview
- Provide a deliverable status
- Identify next steps

Testing Opportunities and Constraints

Gathering Information:

- Information Needs Request No. 1

  Target: Maritime/Offshore Industries

  Request: Information on what testing will be needed for maritime-nuclear applications

  Responses: 12 / 41 Vendors (30%)

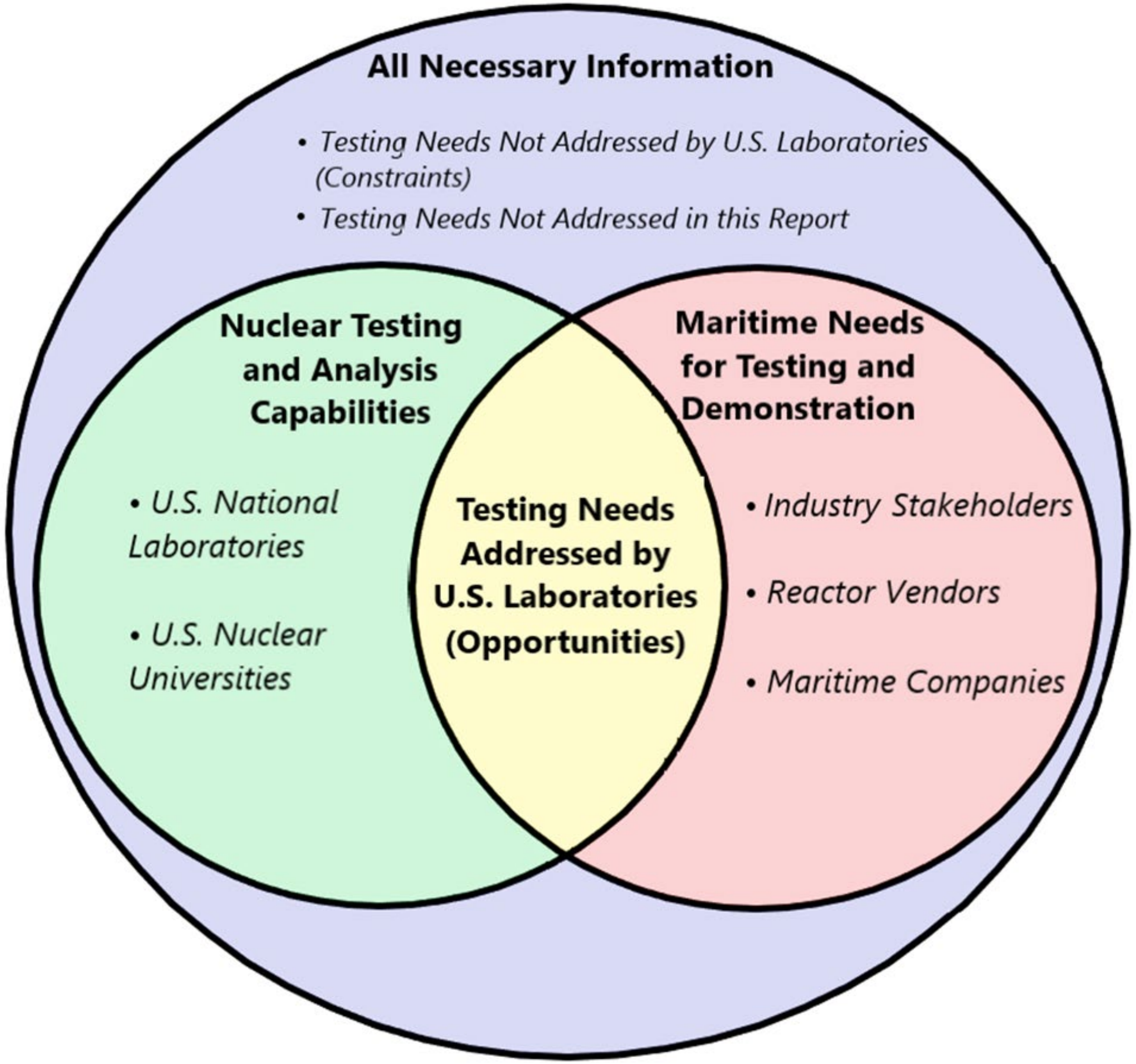
- Information Needs Request No. 2

  Target: Maritime/Offshore Industries

  Request: Information on what testing will be needed for maritime-nuclear applications

  Responses:

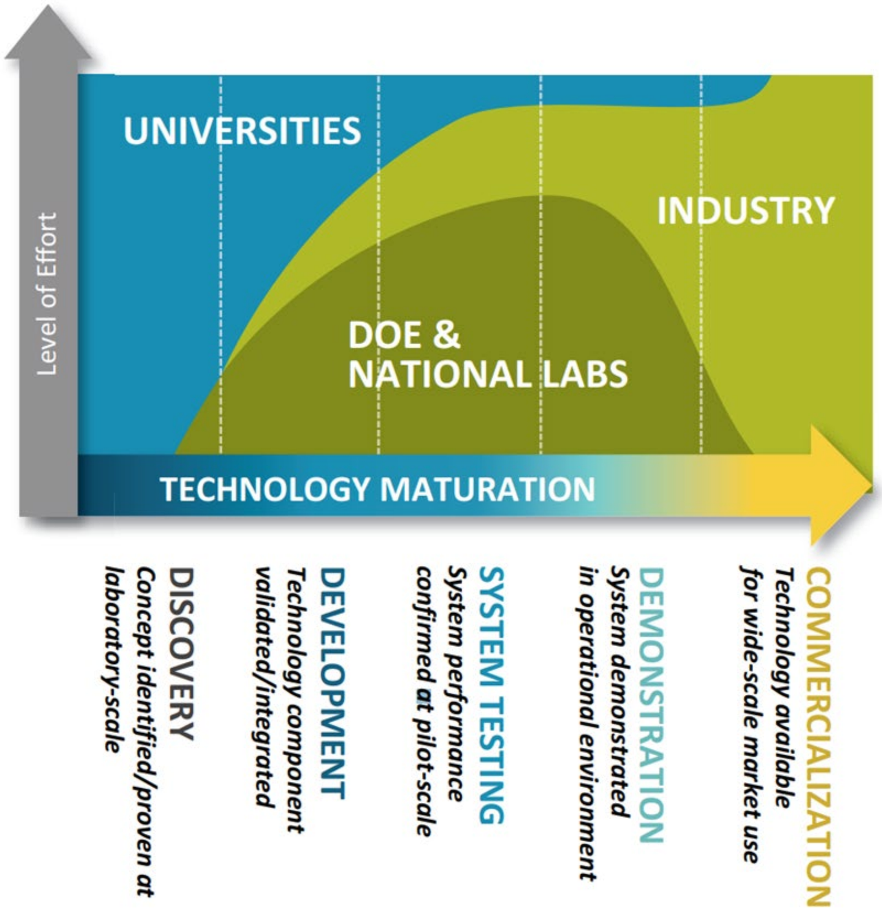
  - 19 / 43 - US Universities (44%)
  - 5 / 6 - US National Labs (83%)



Deliverable

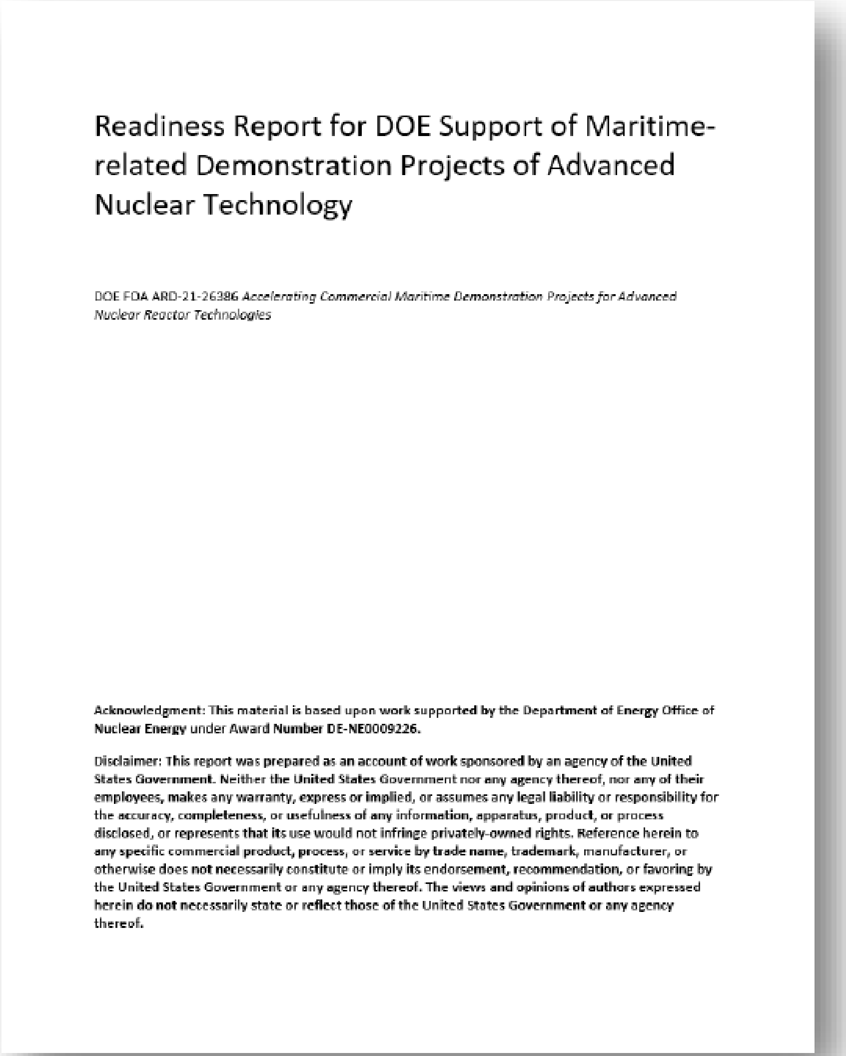
Testing Needs that need to be Addressed by U.S. Laboratories and Nuclear Universities

- Review of Capabilities for:
  - Reactor Operations under Severe Conditions
  - Alarm Systems
  - Fire Safety
  - Physical Scenario Analysis
  - Materials and Chemical Tests
  - Reactor Operations in Marine Environment
  - Non-Destructive Examination (NDE)
  - Security
  - General Research (DOE)



Deliverable Status

- External and Peer Review – Complete
- Ongoing NRIC Technical and Lab Review, including Formatting
- Submittal to DOE in December 2023



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

DOE FOA ARD-21-26386 *Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies*

Acknowledgment: This material is based upon work supported by the Department of Energy Office of Nuclear Energy under Award Number DE-NE0009226.

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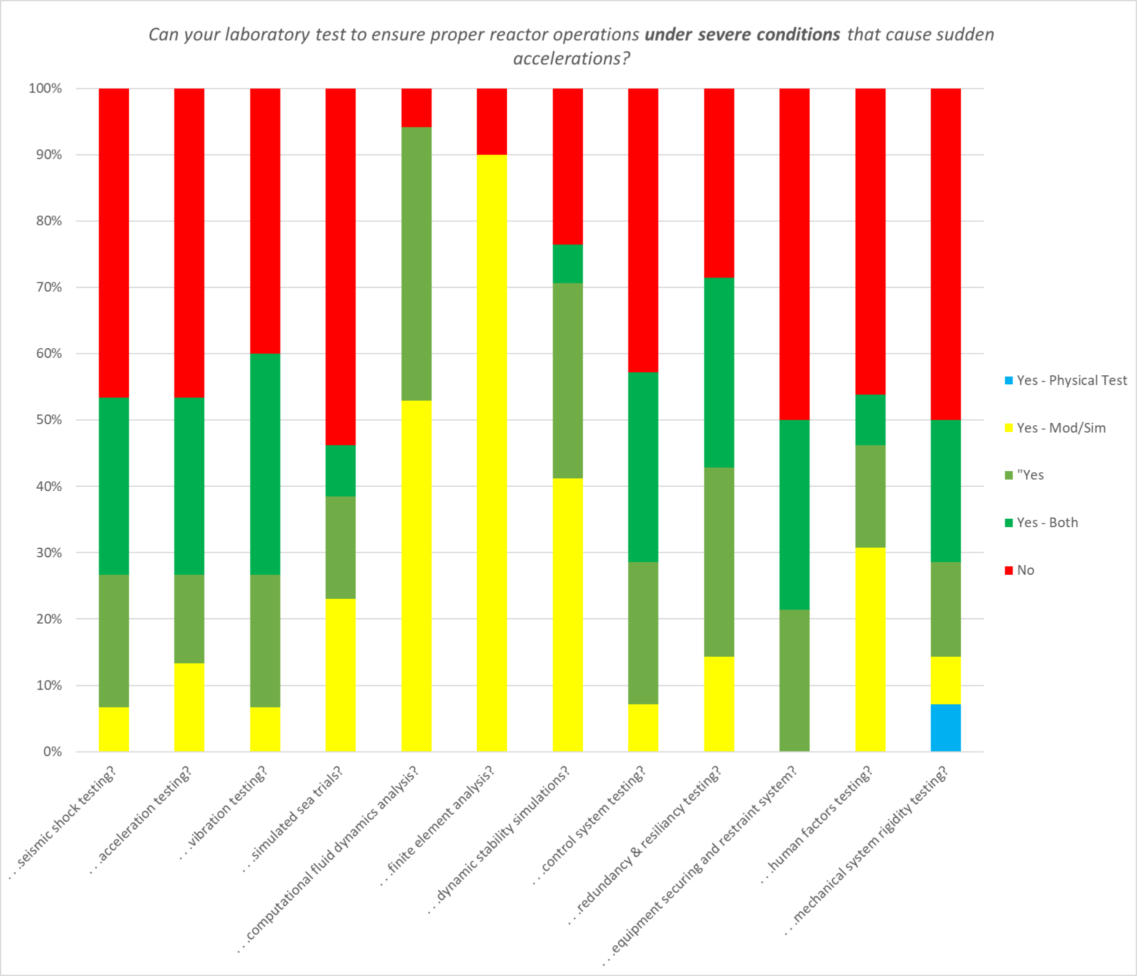
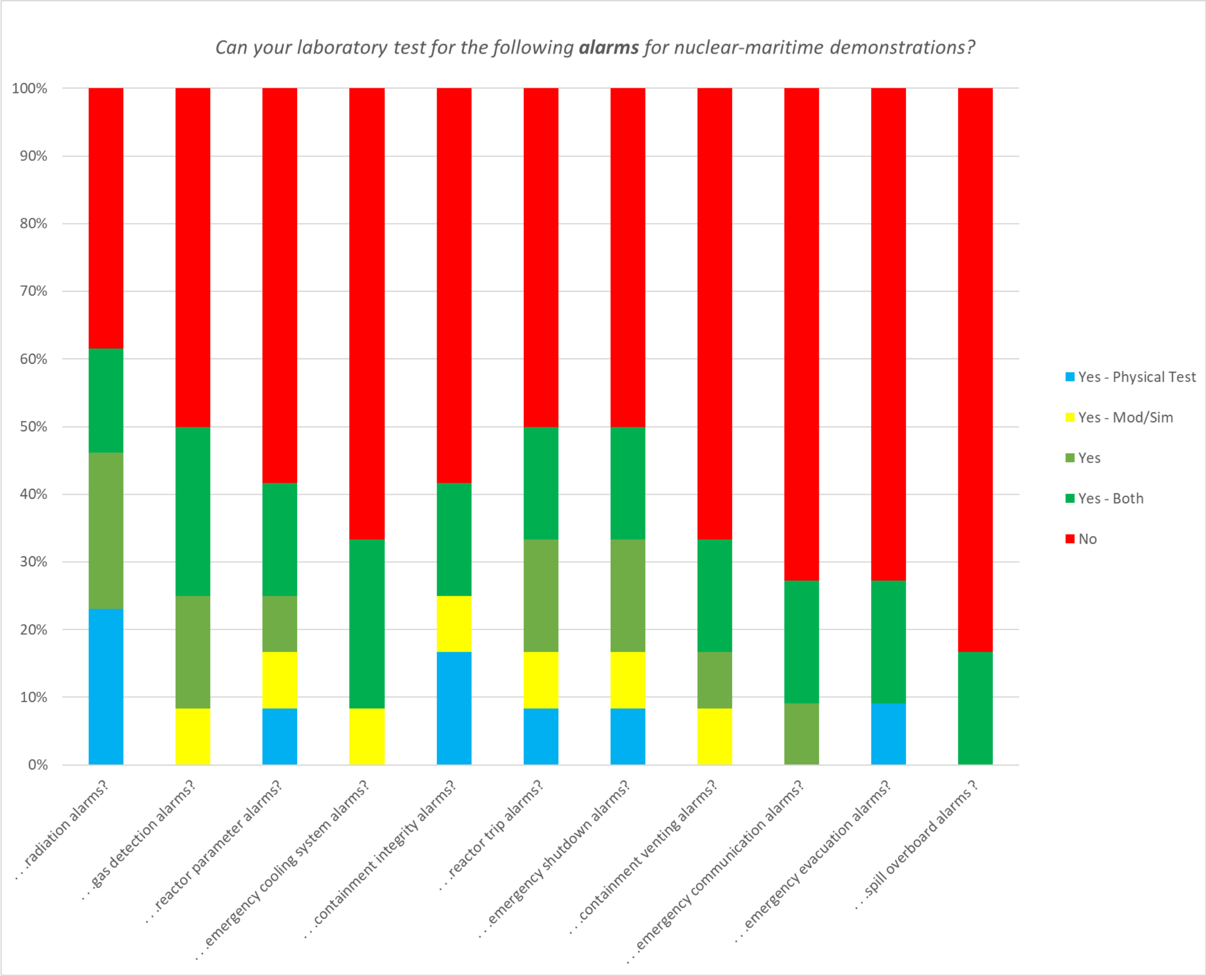
Regulatory Considerations

- The action required to address these needs will **depend on the regulatory requirements** for nuclear-maritime technologies, which currently do not exist in the US.
- 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/limitations between the industry needs and U.S. testing capabilities.
- The subject should be **revisited** and analyzed for a complete gap determination.

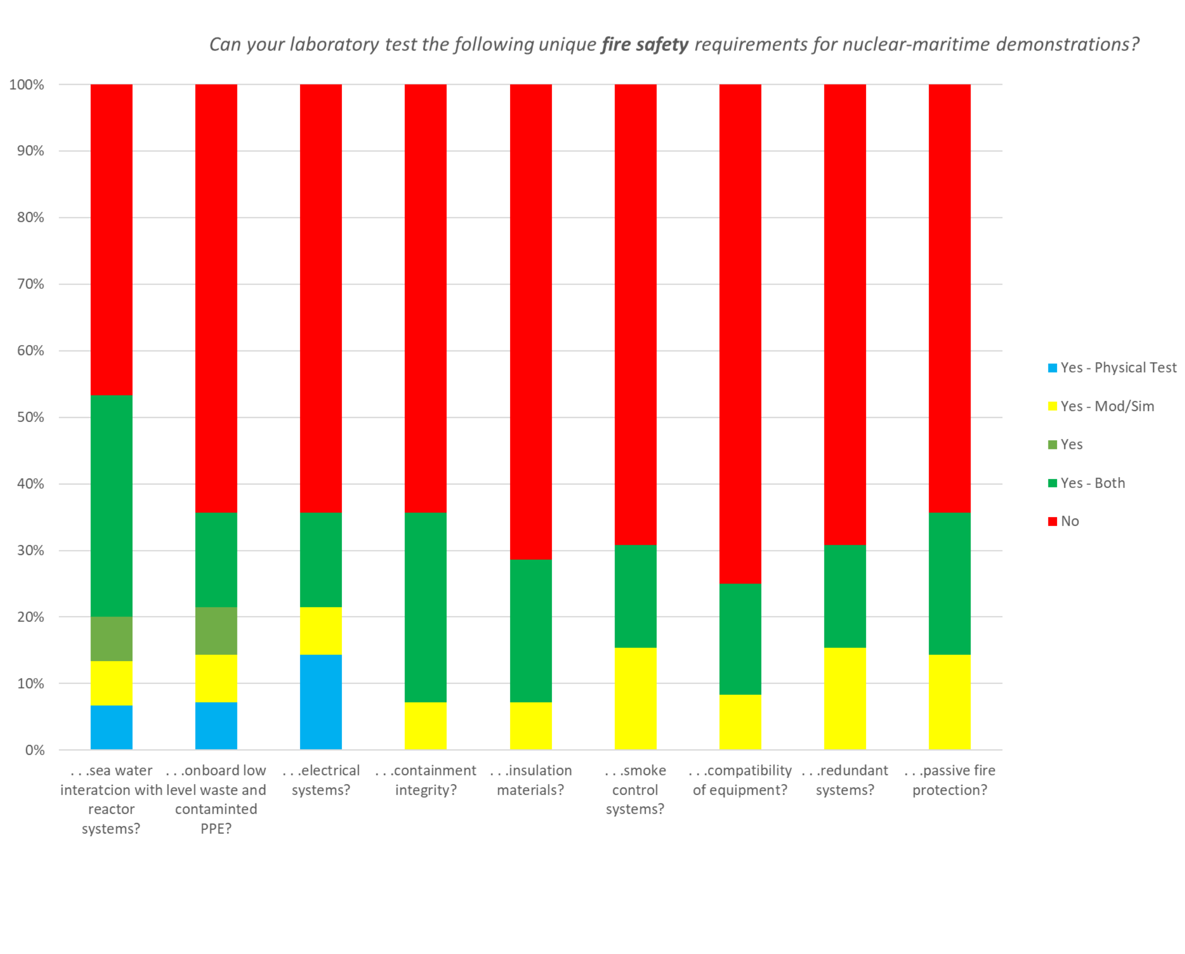
Evaluation of Maritime Application Needs

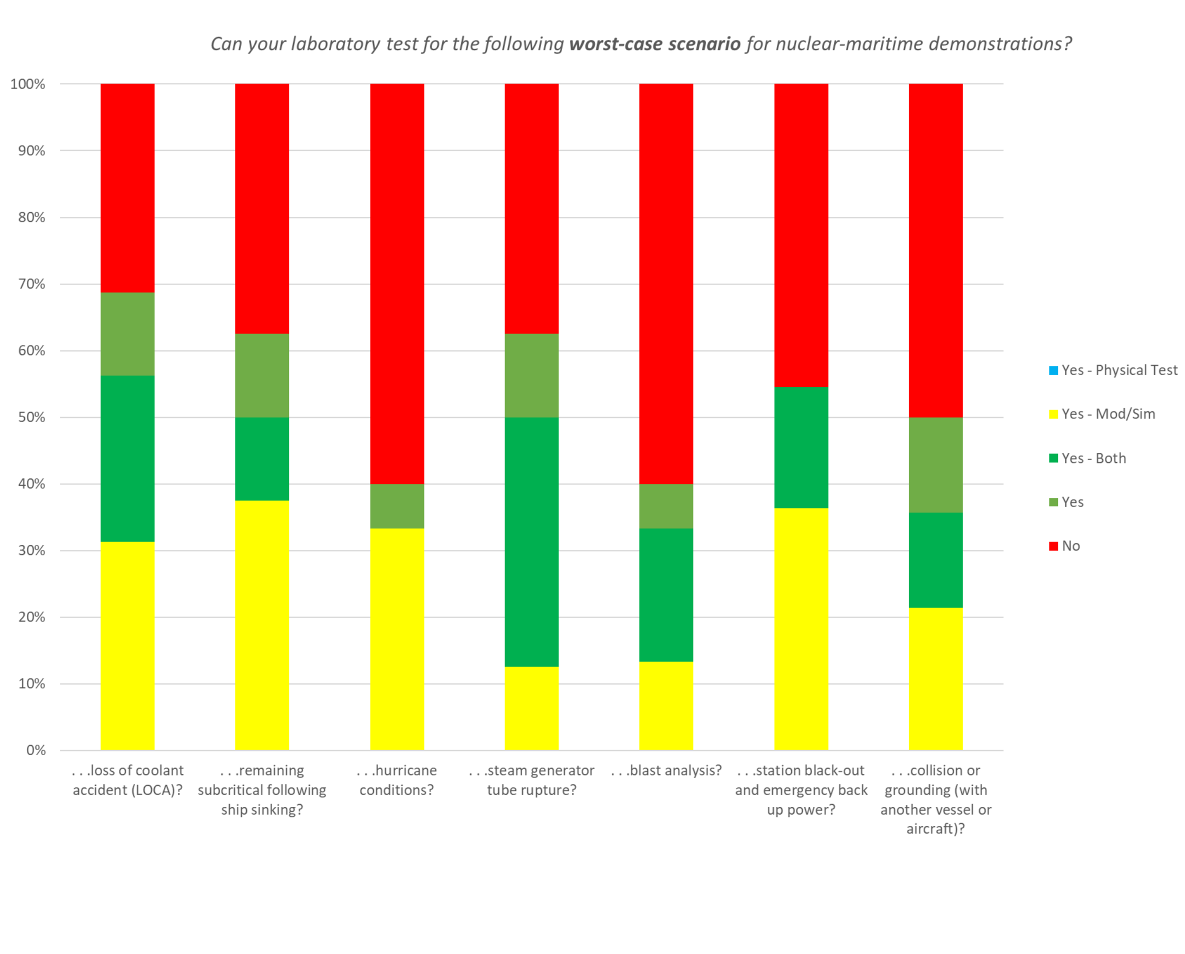
Safety (Part 1 of 2)





Safety (Part 2 of 2)





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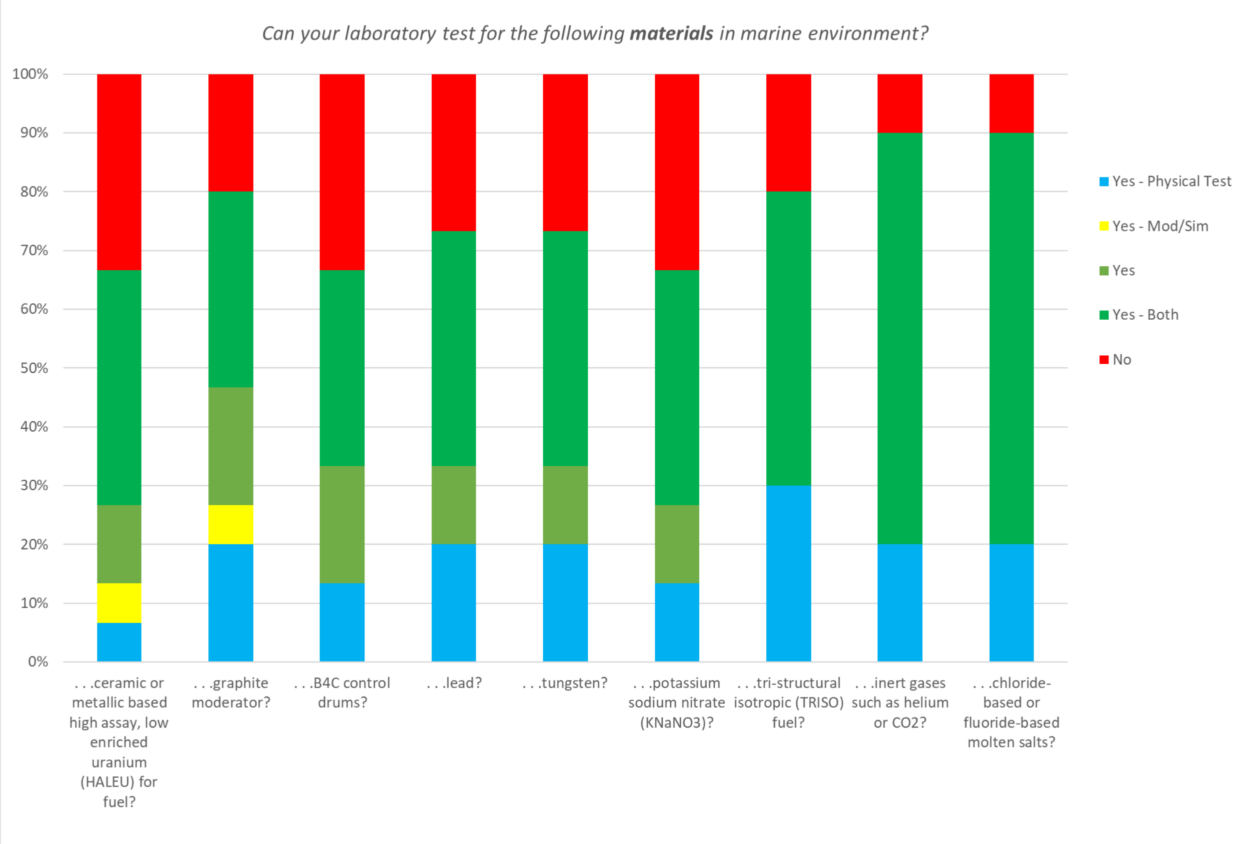
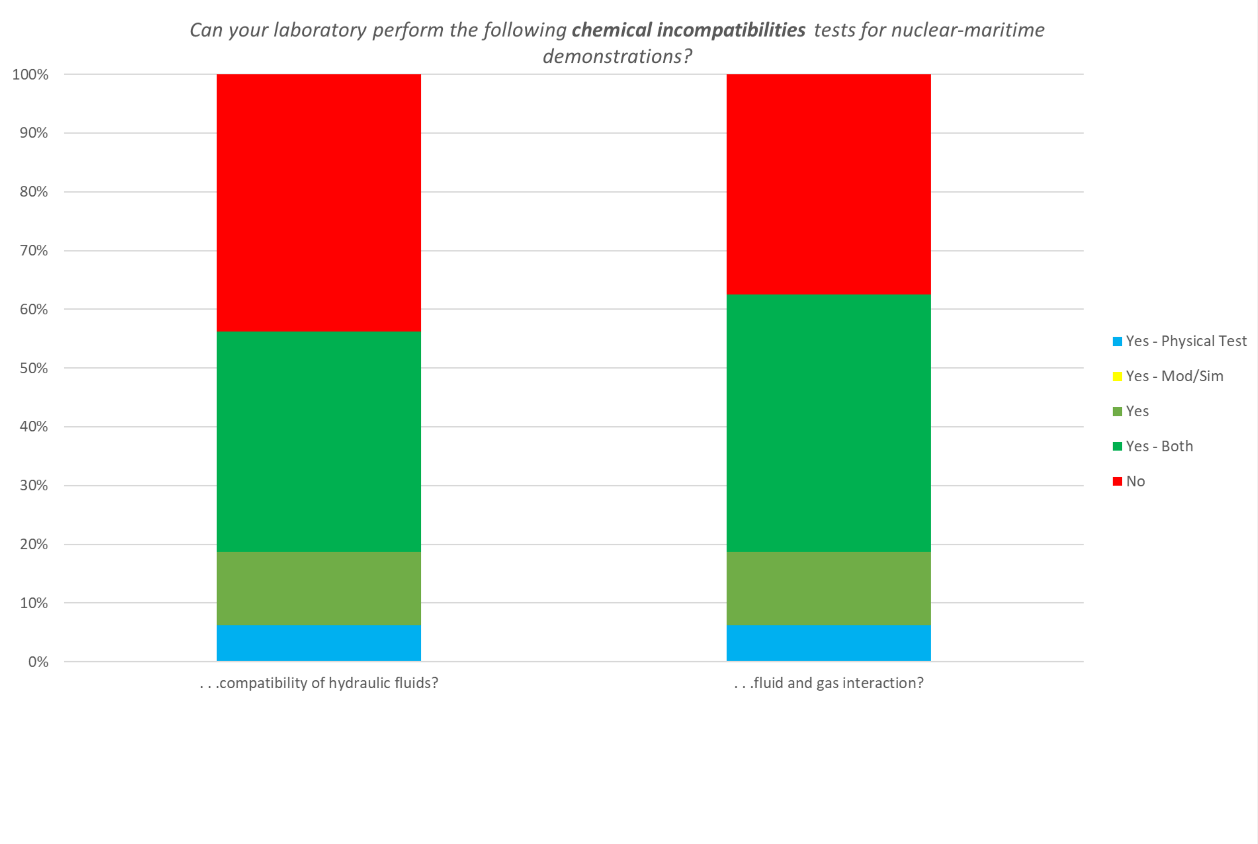
Materials and Chemicals





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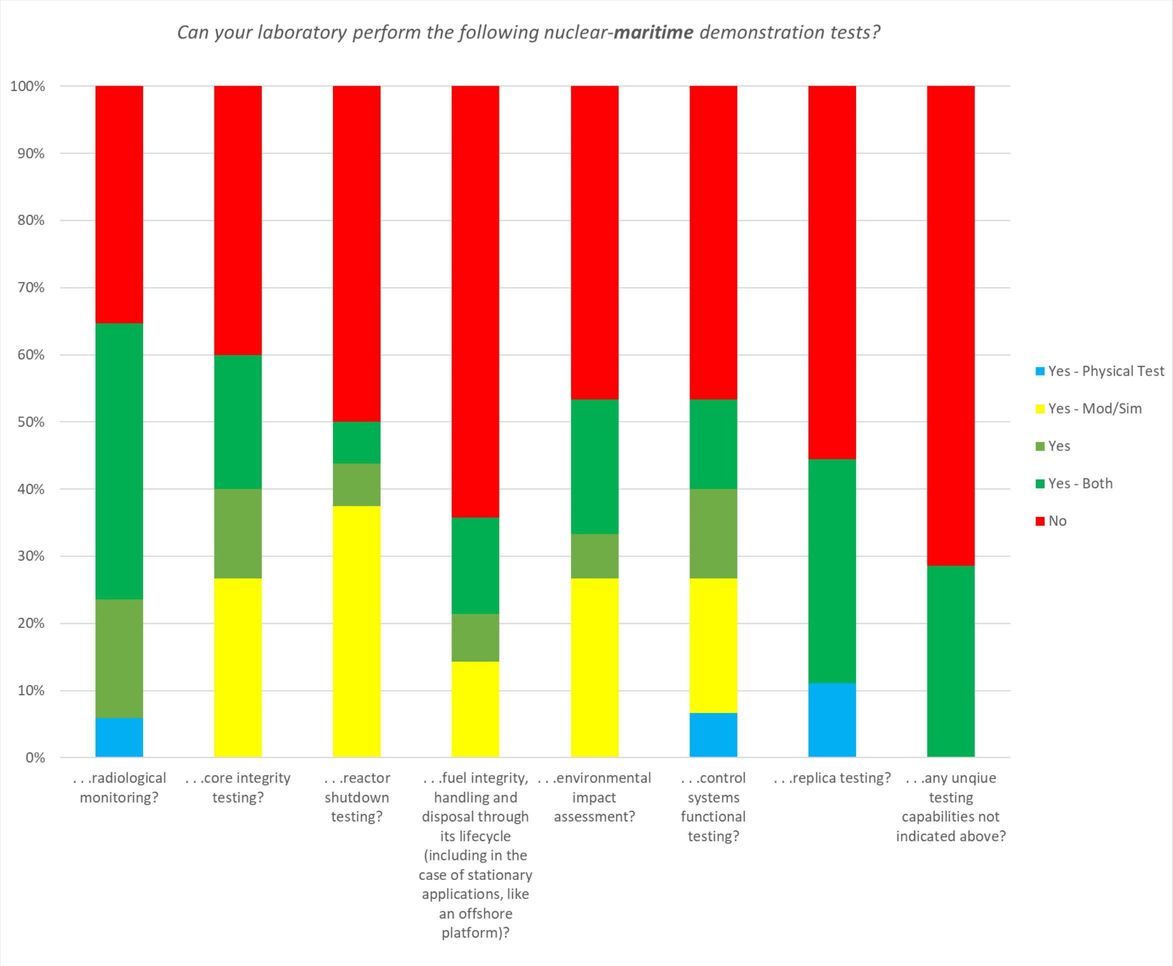
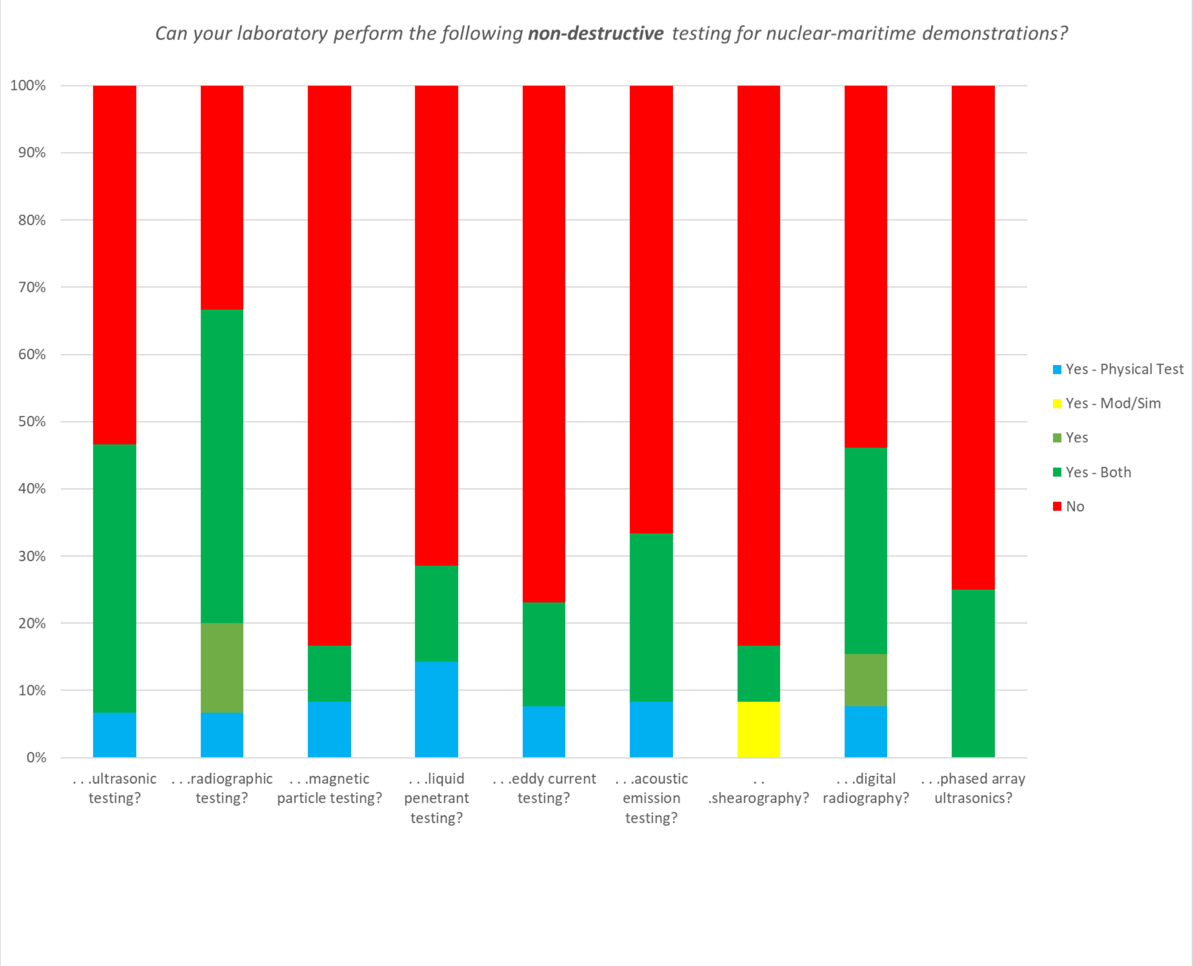
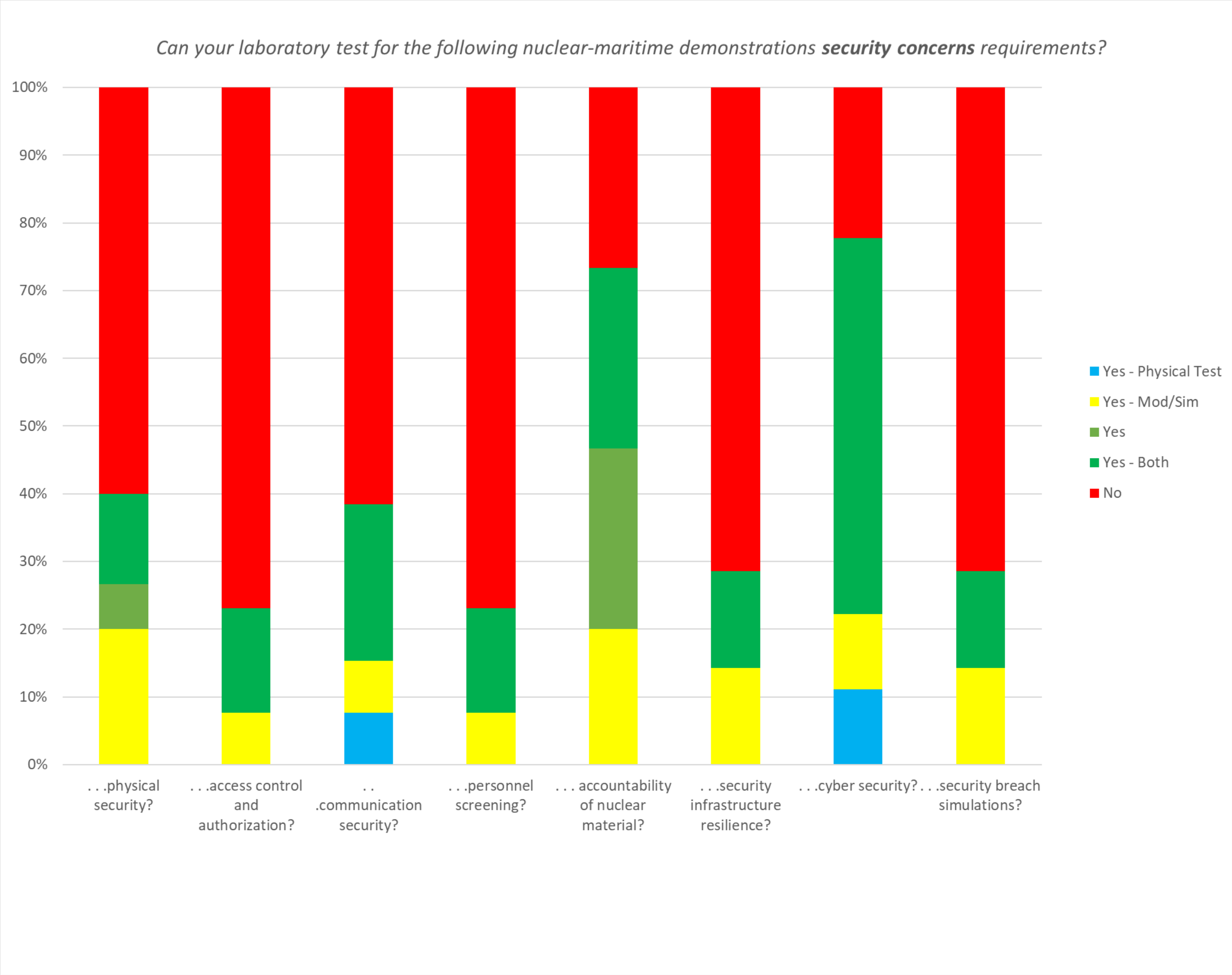
Maritime Testing





Security



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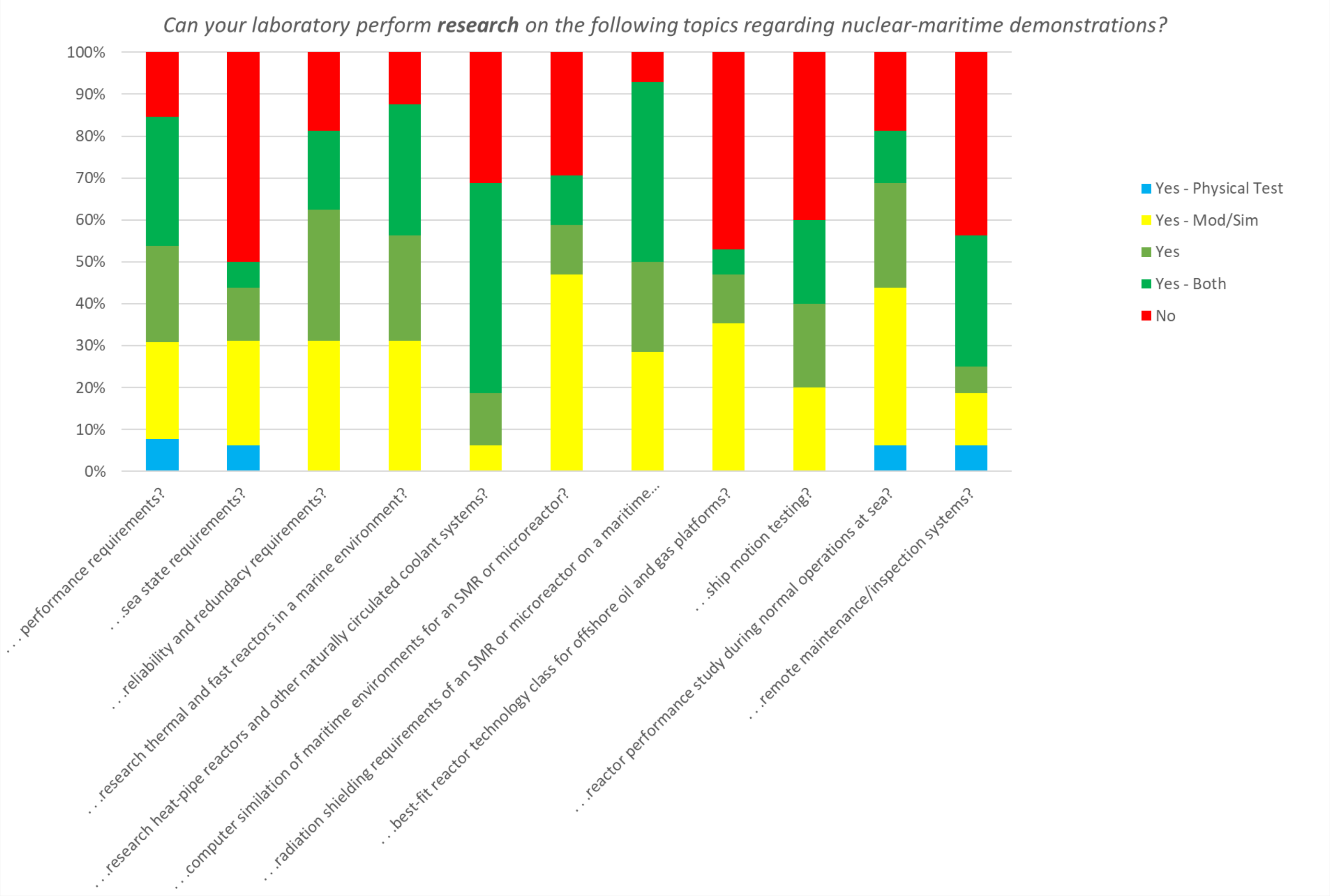
General Research



Testing Constraints to Address

Category	Testing Constraints to Address

Safety	• Expand physical testing capabilities for simulated sea trials and human factors testing.
	• Testing capabilities to address:
	  o Impact/sudden deceleration
	  o High amplitude ship motion
	  o Flooding water detection
	  o Spill overboard
	• Expand physical testing capabilities for LOCA, ship sinking, hurricane conditions, station blackout, and collision/grounding.

Materials and Chemicals	• Develop facilities for novel fuel fabrication.
	• Testing capabilities to address:
	  o Zirconium hydride and other metal hydride-based fuels.
	  o Hull cladding.
	  o ASME BPVC approved materials

Maritime Application Testing	• Develop a site for mid-scale/full scale reactor testing in a marine environment.
	• Testing capabilities to address:
	  o Speed ramp up/ramp down for mobile vessels.
	  o Power scale up to 600 MW.
	  o Power supplementation systems, with a focus on onboard hydrogen generation.

Security	• Expand physical testing capabilities for physical security, accountability of nuclear material, and security infrastructure resilience.
	• Testing capabilities to address:
	  o Sonar/Radar.
	  o Refueling management, both on and off board.
	  o Storage of fuel.
	  o Reactor operation.
	  o Nuclear safety training

Next Steps

- NRIC Review System
  - Submittal to DOE end of March 2024

- Engineering Requirements and Cost Estimate – Ship Motion Testing Facility

- Capacity analysis of the resources of the U.S. national laboratories

Questions?

National Reactor Innovation Center

MARITIME NUCLEAR APPLICATION GROUP

Introductory Review of the Maritime Nuclear Regulatory Landscape

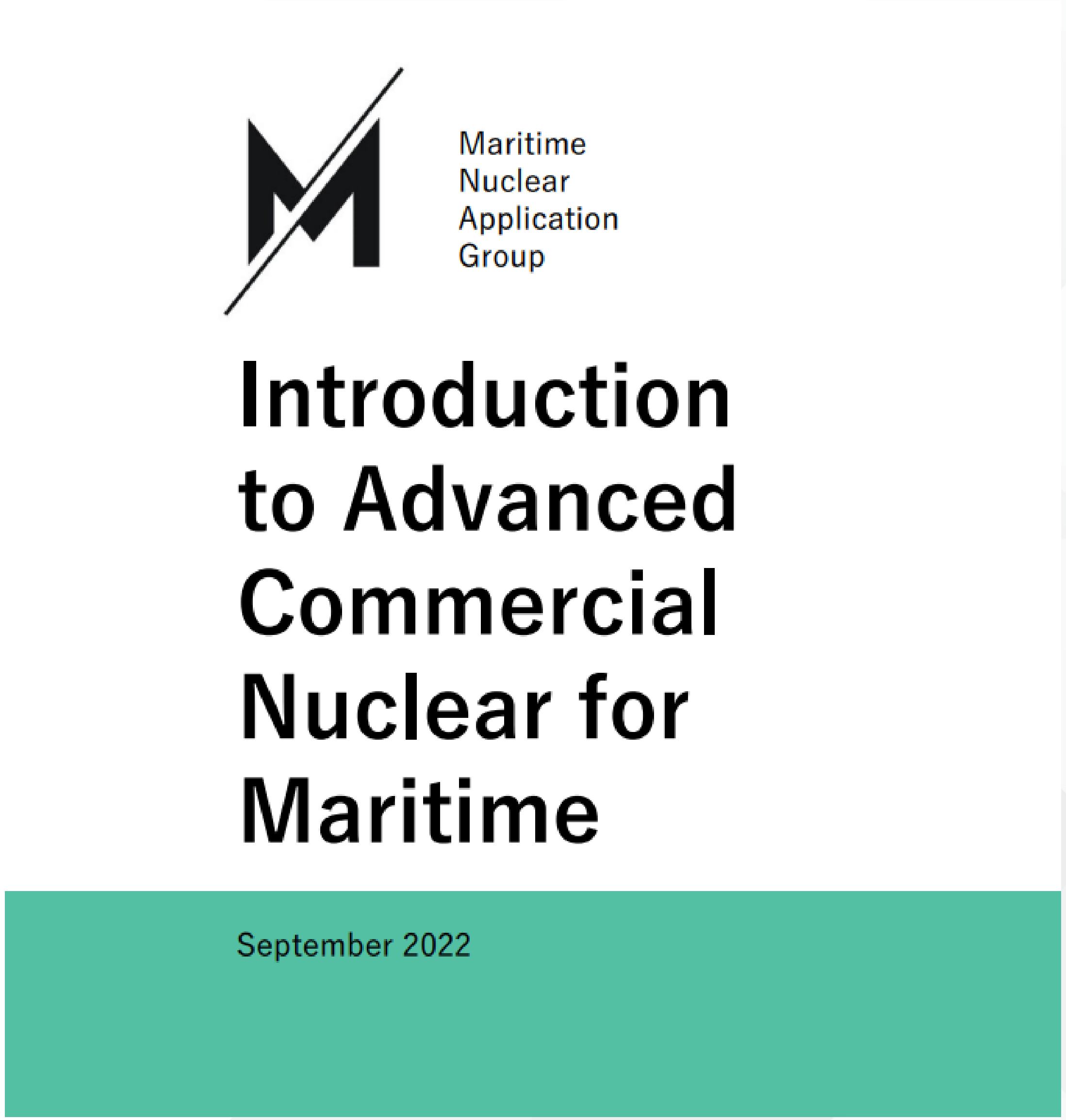
Sanjay Mukhi – NRIC Collaboration Manager

4/24/2024

History - MNAG Report No.1

Introduction to Advanced Commercial Nuclear for Maritime

"The second report will address the regulatory landscape and the gap between nuclear and maritime regulations that must be bridged. Current applicable rules will be introduced, and the regulatory requirements required on both nuclear and marine industries will be examined."


Maritime Nuclear Application Group

Introduction to Advanced Commercial Nuclear for Maritime

September 2022

NRIC

Scope

- **Introductory review of the regulatory landscape** pertaining to advanced nuclear developments within the maritime industries, both historical and current, identifying the key parties that will be involved in future regulation.

- Aims to begin establishing a regulatory connection (parity) between the two sectors by **identifying high-level regulatory gaps that must be bridged in any future regulatory framework**.

Approach and Timeline

1st Phase		2nd Phase		

CORE POWER Initial Draft	**Regulatory WG** 1st Review	Incorporate Comments	**Regulatory WG** 2nd Review	Incorporate Comments	**NRIC Review System**
Summer 2022	June 2023	October 2023	January 2024	February 2024	Feb. 29, 2024

Regulatory WG

Regulatory WG	
Chairperson:	
Alan Grodecki	ACE Maritime
Members:	
Marcel Devos	Prodigy
Meg Dowling	ABS
Scott Edwards	CORE POWER
Claudia Gasparrini	RINA
Andrea Cogliolo	RINA
Stephanie Weir	INL
Alex Polonsky	Morgan & Lewis
Stephen Keenan	Bahamas Maritime Authority
Mikal Boe	CORE POWER
Simon Zielonka	Royal Caribbean Cruises Ltd.
Patrick Pennella	Morgan & Lewis

Table of Contents

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Maritime Nuclear Applications that will need to be Regulated

- Floating Nuclear Power Plants (FNPPs) could be deployed to serve one or more specific functions, including:
  - heavy payload, energy transportation and resilient mobile power for the U.S. Dept. of Defense,
  - mobile water desalination,
  - offshore processing and production,
  - clean energy provision for offshore drilling and production,
  - flexible power for coastal industry and communities,
  - decarbonizing ports and shoreline installations,
  - hydrogen production and low carbon fuels,
  - clean energy provision in support of maritime green corridors, or
  - offshore industries and for load balancing intermittent offshore energy.

Understanding Maritime Laws and Regulations for Nuclear Applications

Multiple touchpoints exist between the nuclear and maritime regulations governing FNPPs. For example, in the United States these include:

- Flag State oversight
- Port State Control
- Local Environment Regulation
- National Nuclear Regulations
- The ISPS Code
- Pilot Requirements
- Tug Requirements
- Stevedore Requirements
- Shipping Traffic Acts
- Inland Navigation Police Regulations (BPR)
- Shipping Regulations for Territorial Waters (STZ)
- Compulsory Pilotage Decree 1995
- Decree on Pilot Exemption Certificate Holders Shipping Traffic Act
- Regulation for Licensed (Maritime) Pilots
- Regulation for the Prevention of Pollution from Ships
- Regulation on the Transportation of Dangerous Substances, 2007
- Port Management Bylaws
- Regulation for Communication and Pilot requests sea shipping
- Regulations for seagoing vessels required to notify port authorities
- Regulations Notifications and Communication Shipping
- United States Coat Guard (USCG) guidelines and statutes
- Submerged Lands Act of 1953
- Rivers and Harbors Act
- Outer Continental Shelf Lands Act
- Clean Water Act
- Maritime Mammal Protection Act
- Coastal Zone Management Act
- Magnuson-Stevens Fishery Conservation and Management Act
- National Historic Preservation Act
- National Maritime Sanctuaries Act

FNPP Licensing Concerns

- The absence of a recognized process for a country to adopt or accept the results of the country-of-origin regulators' decision or mechanisms to approve, license, supervise, and enforce requirements upon the FNPPs, which hampers the ship's acceptance in foreign ports. This points to a likely preference for bilateral arrangements between countries for deployment of FNPPs.
- Absence of a specific licensing mechanism for civilian reactors installed on commercial ships. Some licensing efforts have occurred, with a notable example in the United States from the NS Savannah which was launched in 1959 and operated till 1972 visiting 45 foreign and 32 domestic ports over its operating timeframe.
- Licensing for advanced reactor designs (ARDs) has limited experience using new licensing approaches such as the proposed 10 CFR Part 53 in the U.S.

Part 53 – Maritime Applications

The following recommendations were identified to support maritime applications use of Part 53:

- Include special applications of nuclear power explicitly in Part 53, such as floating nuclear power and maritime propulsion, to expand the technological scope of the licensure procedure.
- Collaborate with the IMO to align the maritime propulsion requirements in Part 53 with the commercial maritime industry, thereby enhancing the likelihood of international recognition and adoption.
- Utilize historical licensure documents, such as those for the NS Savannah licensed by the AEC, to establish a baseline and incorporate FNPP requirements into Part 53.

International Organizations - IAEA

In addition to the work already being done at the IAEA, the following considerations and conditions of maritime applications will need to be addressed:

- Conduct of Operations of Transportable Nuclear Module(TNM)/FNPP/Mobil Nuclear Power Plant (MNPP)
- Use of onsite refueling versus use of site replaceable factory fueled and sealed reactors
- Use of systems and components that are necessary for proper functioning of safety and security features at the site of operation
- The concept of a site has not been defined for nuclear propulsion in IAEA safety standards and remains a subject to be resolved

International Organizations - IMO

IMO Resolution A.491(XII) Safety Code for Nuclear Ships (the Code) provides design considerations useful for FNPP's:

- The evaluation of local meteorological conditions, population density, and land use factors on a nuclear ship.
- Consequences of natural phenomena, such as unusual sea currents, tornadoes, tsunamis, hurricanes, gusts, snow, and ice.
- Inertial forces acting on the vessel in a rough sea.
- The effects of collision, grounding, or explosion-induced shock loading on reactor plant components.
- Ship motion effects on reactor controls and dynamic behavior.
- Capacity of a ship's reactor safety systems to function without malfunction under specific conditions.
- Radiological requirements, with an emphasis on minimizing exposure and staying within applicable dose-equivalent limits.
- Requirements concerning damage stability, floodability, fire safety, expected reactor casualties, radiation safety, waste management, operating and survey requirements, and quality assurance.

Emergency Considerations

- **DBT/BDBT**: The ship's design and care in navigation should address the Design Basis and Beyond Design Basis Threat (DBT/BDBT), which traditionally include design against aircraft crash for land-based commercial nuclear plants. The maritime environment could expand the DBT/BDBT to design against maritime collisions and grounding.
- **Control and Operation of the vessel:** This would be an integral part of the facility's safety and security case. The specific assigned roles within the licensee's organization (e.g. Vessel Captain) must demonstrate s competence in dealing with vessel-related accident conditions involving the release of radioactive material, including the safety of the reactor installation.
- **Port Authority's Responsibility:** To define executive responsibility for action concerned with the safety of the port. including if/how the port would support the emergency response provisions of the nuclear facility.
- **Public Safety and Health**: Prior to designating a port as safe for use by nuclear ships, there should be full consultation with appropriate bodies for a clear definition of responsibilities., interfaces and accompanying procedures to execute a timely and coordinated response. These may include police, health officials and those concerned with agriculture and food. Arrangements should be made for control, evacuation, and medical treatment in the case of contamination.

Emergency Considerations

- **Environmental Hazard**: Arrangements should be made to communicate civil authorities and government bodies in a timely manner commensurate with accident progression, severity and offsite consequences predicted in consideration of changing conditions.
- **Expert Assistance:** Timely involvement of qualified persons to support information gathering for environmental monitoring, meteorology, health physics, and engineering for assessing hazards.
- **Captain's Licensee's Accident Management Reporting Structure**: Responsible for immediate and accurate reporting of abnormal reactor conditions, timely updates on progress of accident management activities and evolutions in potential consequences. In a traditional maritime based facility, this primary responsibility would fall to the Captain.

Results

Next Steps:
Developing scoping document for an MNAG report focused on recommendations for addressing the identified gaps

Summary of Regulatory and Licensing Gaps	
1.	Need to reduce licensing cost and timeline **(influenced by the readiness of the applicant, the state of design completion and the ability/authority of the regulator and its framework)**
2.	Need for clarity on how to complete consistent licensing at an international scale and in a cost-effective manner
3.	Internationally recognized classification authority and procedure for nuclear-powered ships
4.	Integrating maritime security with nuclear security
5.	International Nuclear Transportation Framework integrated with Nuclear Maritime Applications
6.	Clarity on how emergency planning basis requirements can be met with appropriate methodologies to enable risk informed emergency planning zones commensurate with on specific design characteristics and site-specific considerations
7.	Clarity on an appropriate End-of-Life Framework for FNPP projects
8.	Clarity on and potential of restrictions on Port Access for FNPP

Questions?

POCs:

- Sanjay Mukhi (Sanjay.Mukhi@inl.gov)
- Alan Grodecki (agrodecki@ace-maritime.com)
- Marcel Devos (marcel.devos@live.com)
- Meg Dowling (MDowling@eagle.org)

DOE IFOA to ABS & NRIC: Advanced Nuclear Maritime Demonstration Projects

Award Number: DE-NE0009226

Update to NRIC Program Review

Meg Dowling | April 24, 2024

Team Members & Project Contacts

ABS Project Team

Name	Company	Role Title
Meg Dowling	ABS	Project Coordinator
Gareth Burton	ABS	Principal Investigator
Domenic Carlucci	ABS	Co-Principal Investigator
David Johnson	ABS Contractor	Consulting SME
Crystal Duplechin	ABS	Project Management Office
Kathryn Dodd	ABS	Project Accounting

Gratis Support

Name	Company	Role Title
Keith Letourneau	Blank Rome LLP	Nuclear Legal SME
Alex Polonsky	Morgan, Lewis & Bockius LLP	Nuclear Legal SME

Award Partners

Name	Company	Role Title
Jacopo Buongiorno	MIT Contractor	Consulting SME
River Bennett	ABS Contractor	Consulting SME
Sanjay Mukhi	NRIC (INL)	NRIC Project Manager
Marvin Fielding	NRIC (INL)	NRIC/INL Program Manager
Jorge Arvelo	MPR Associates Inc	NRIC Consultant
Wesley Price	MPR Associates Inc	NRIC Consultant
Sean Robinson	MPR Associates Inc	NRIC Consultant
Abdalla Abou-Jaoude	INL	NRIC & INL SME

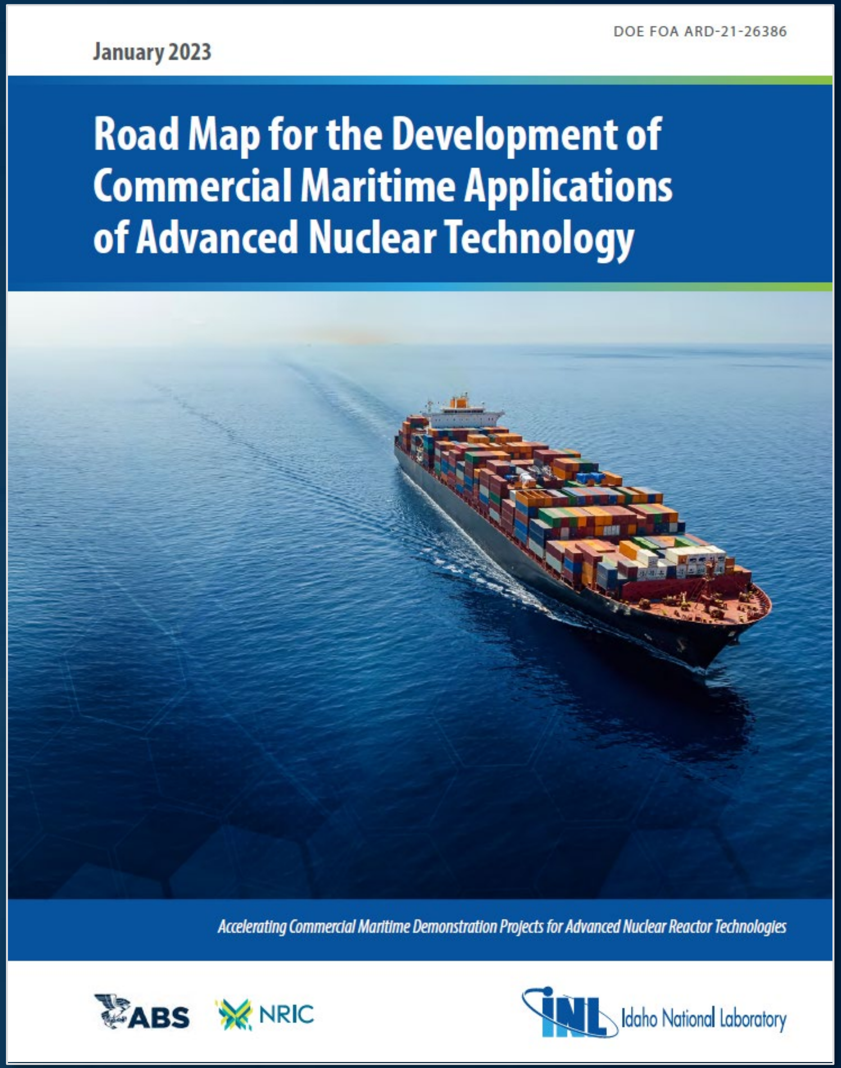
ABS

Overall Project Schedule

Task/Milestone/Deliverable	Year 1												Year 2											
	Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
	Jul-22	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23	May-23	Jun-23	Jul-23	Aug-23	Sep-23	Oct-23	Nov-23	Dec-23	Jan-24	Feb-24	Mar-24	Apr-24	May-24	Jun-24
Task 1: Develop Demonstration Project Pathways and Business Case																								
Deliverable 1-1: Road Map for the Development of Commercial Maritime Applications of Advanced Nuclear Technology						**D**																		
Task 2: Develop Models of Various Advanced Reactor Technologies Integrated with Maritime Applications																								
Deliverable 2-1: Configurations of Commercial Advanced Nuclear-Maritime Applications										D														
Deliverable 2-2: Report on Potential Barriers and Impacts of Advanced Nuclear-Maritime Applications in the U.S.																**D**								
Task 3: Assess and Enhance DOE Readiness for Demos																								
Deliverable 3-1: Readiness Report for DOE Support of Maritime-Related Demonstration Projects of Advanced Nuclear Technology																					**D**			
Task 4: Develop Guidance for Addressing Key Technical, Regulatory, and Policy Issue for Maritime Demonstration Projects																								
Deliverable 4-1: Overcoming Barriers to Nuclear-Maritime Demonstrations																								**D**

ABS

Task 1 Summary



Task 1 – Key Takeaways

High-level Demonstration/Regulatory Factors

Land Based Site

Reactor Onshore

Applications:

- Microreactor or SMR sited at port producing electricity, heat, or synthetic fuels

Fixed Station Demonstrations

Reactor Offshore: Offshore Power Consumption

Applications:

- Small floating power station for offshore industry
- Floating datacenter

Reactor Offshore: Onshore Power Consumption

Applications:

- Small floating power station for coastal industry
- Small floating power station for offshore eFuels production
- Floating water desalination plant

Mobile Demonstrations

Reactor Offshore: Nuclear Powered Vessels *(Domestic Transport)*

Applications:

- Nuclear electric river towboat
- Nuclear electric offshore support vessel
- Nuclear electric tanker
- Nuclear drill ship
- Nuclear electric dredging vessel
- Nuclear powered container ship
- Nuclear electric dry cargo ship
- Nuclear electric gas carrier
- Nuclear electric car carrier with electric vehicle charging and power to shore
- Nuclear electric passenger ship

Reactor Offshore: Nuclear Powered Vessels *(International Transport)*

Applications:

- Nuclear powered container ship
- Nuclear electric dry cargo ship
- Nuclear electric gas carrier
- Nuclear electric car carrier with electric vehicle charging and power to shore
- Nuclear electric passenger ship
- Nuclear powered container ship
- Nuclear electric deep sea tug
- Nuclear electric ice breaker with reverse cold ironing facility
- Nuclear electric tanker

Task 1 – Key Takeaways: Regulatory Gap Analysis

	Activity or Milestone	Description (jurisdiction, authority, etc.)	Gaps – what may need to be addressed?
Nuclear Technology	Experimental Reactor License	DOE	Does not allow commercial applications
	Commercial Reactor License	NRC	Reactor Design Certification, Operating License, Manufacturing License, Fueled Reactor transportation, physical protection systems
Marine Technology	Equipment Certification	Recognized Organization	Does not typically cover nuclear reactors
	Classification Approval	Classification Society	Missing or lacking Rules for Nuclear Vessels/Offshore Structures
	Statutory Approval	Flag State	Missing or lacking Rules for Nuclear Vessels/Offshore Structures
Location-Based Regulatory Milestones:	Territorial Waters & Internal Waters	National Authority, Local Authority	Issues involving or allowances of nuclear material and reactors
	EEZ Waters	National Authority	Issues involving or allowances of nuclear material and reactors
	International Waters	Enforced by member states	Missing or lacking updated rules for Nuclear Vessels/Offshore Structures (Beyond SOLAS Chapter VIII) [58]
	Transport of Nuclear Fuel	Applicable transportation authority	Covered under the Irradiated Nuclear Fuel (INF) Code of the IMO
	Transport of fueled reactor	Applicable transportation authority	Missing or lacking updated rules for transporting reactors carrying unused or partially used nuclear materials
Application-Based Regulatory Milestones:	Power to Nearby Offshore Installations	Specific requirements for integration	Missing or lacking Rules for Nuclear Vessels/Offshore Structures
	Power Self-Consumption Onboard (integrated with marine systems)		Missing or lacking Rules for Nuclear Vessels/Offshore Structures

Complete Gap Analysis provided in Deliverable 1-1

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Task 1 – Key Takeaways: 2050 Demand

Application	Potential 2050 Demand
Port Producing Electricity	+3 to 5 ports powered by advanced nuclear power
Land-Based Heat and Synthetic Fuels	+ 35 to 70 million metric tonnes of hydrogen production powered by advanced nuclear power
Floating Data Center	+ 9 to 35 advanced nuclear powered floating data centers
Floating Power for Coastal Energy	+ 1 to 2GW advanced nuclear powered floating black-start capacity
Offshore Synthetic Fuel	2.5 to 5 million metric tonnes of floating hydrogen production powered by advanced nuclear power
Floating Desalination	+2 to 6 floating advanced nuclear powered desalination plants by 2050 in U.S.
U.S. Commercial Ship Propulsion	+5 to 11 U.S. ships using advanced nuclear propulsion
Global Commercial Ship Propulsion	+328 to 820 global ships using advanced nuclear propulsion (including U.S. vessels)

Other Information Summarized:

- History of Maritime-Nuclear Applications, Commercial and Navy
- Summary of Decarbonization Drivers
- Potential Benefits of Nuclear Power for Maritime Applications
- Introduction to Potential Barriers or Issues
- Introduction to INL Facilities and Demonstration Capabilities
- Proposed Milestones for Demonstration in Nuclear and Maritime Industries
- Key aspects of Regulatory Landscape: Social License, Location, Nuclear Use

Complete 2050 Demand Estimate provided in Deliverable 1-1, including assumptions used

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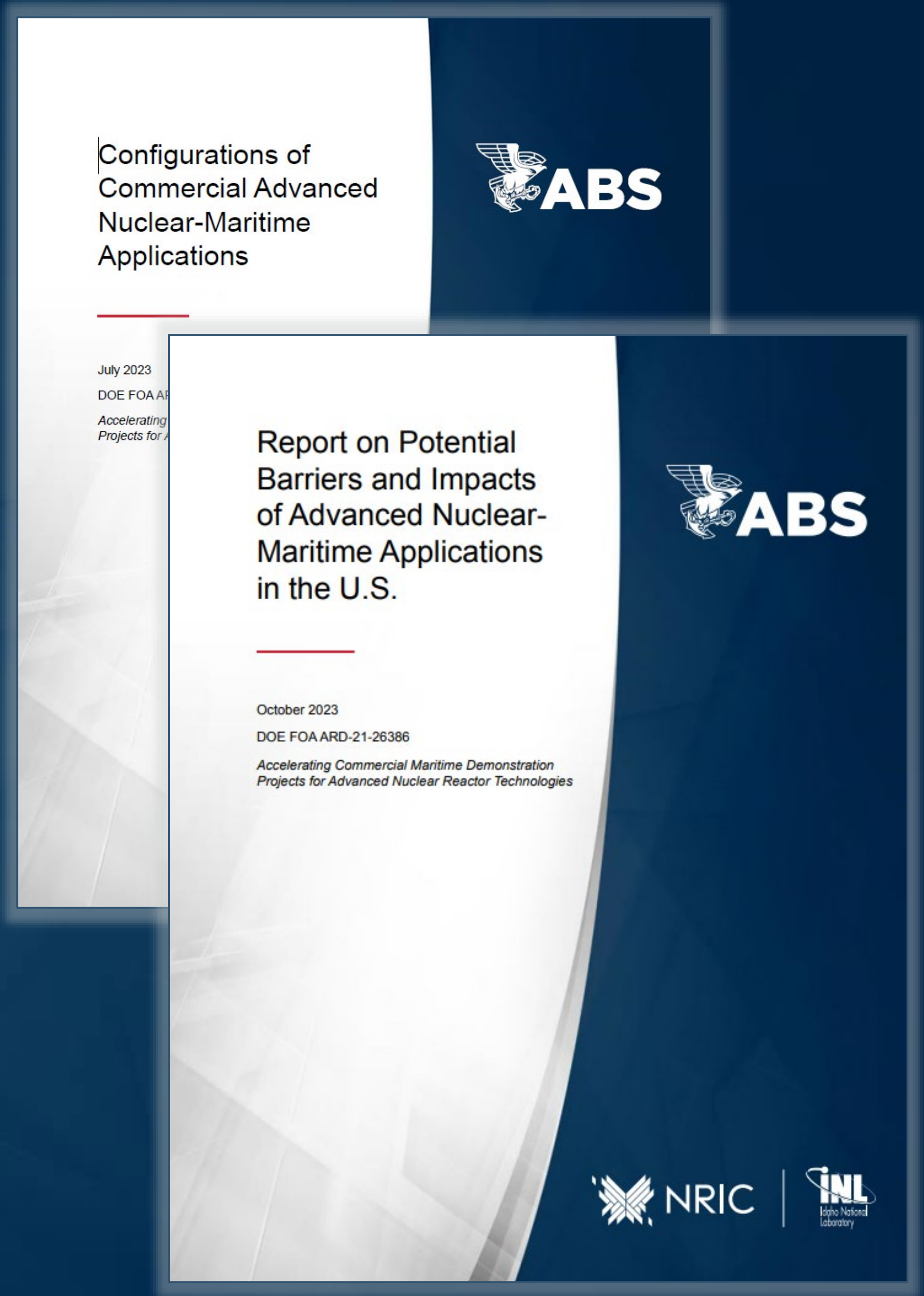
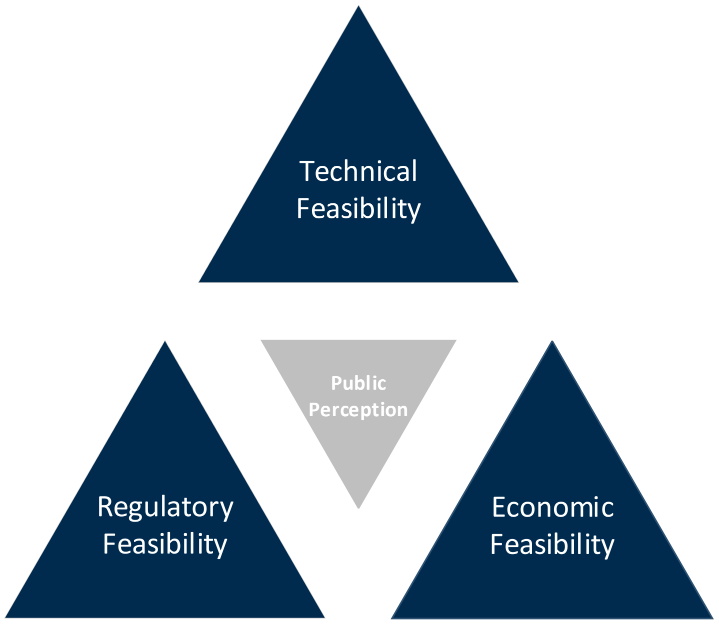
Task 2 Summary

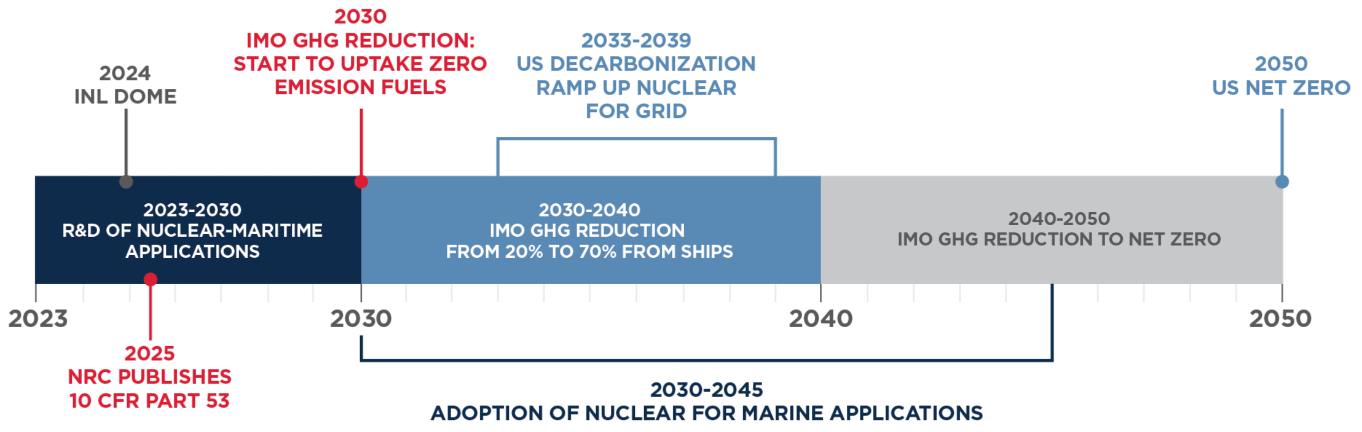


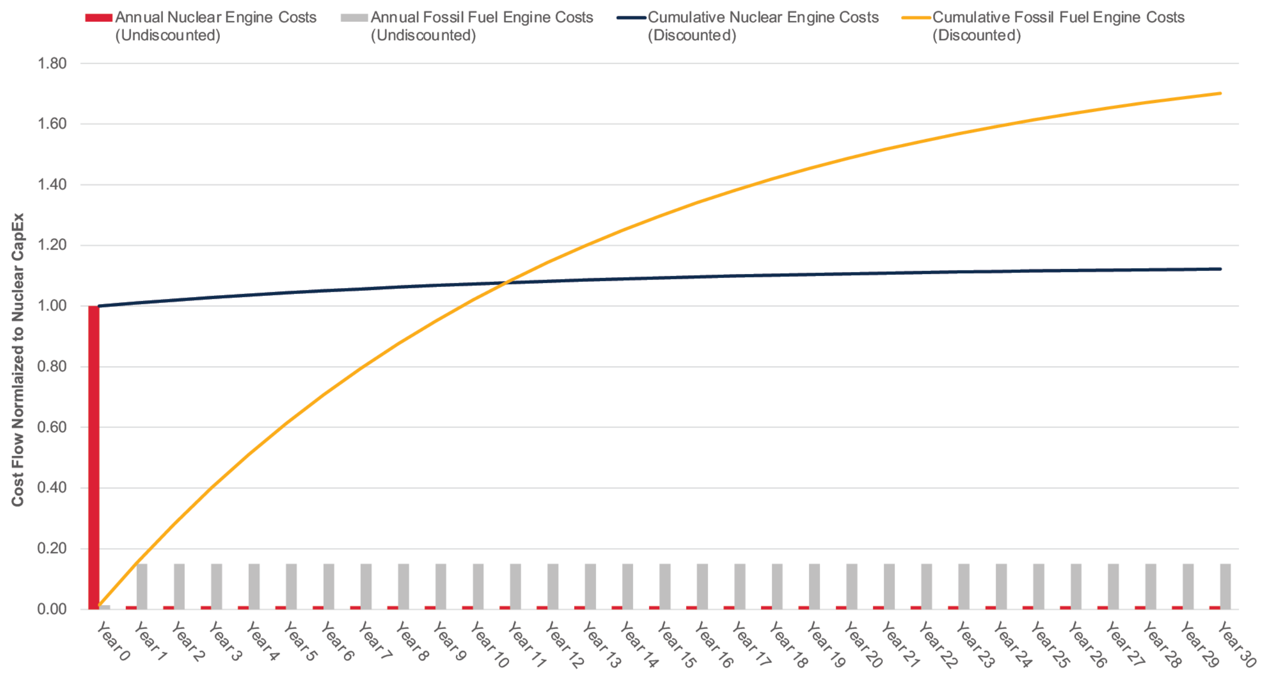
Task 2 – Key Takeaways: Deliverable 2-1

- Introduction to Technical, Regulatory, and Economic Feasibility Requirements
- Proposed / Expected Timelines
- Introduction to Advanced Reactor Technology and Types of Reactors
- Techno-economic Evaluation and Example Configurations
  - Nuclear Power for Synthetic Fuel Production
  - Nuclear Propulsion for Ships
- Appendices for Additional Information
  - Details of Technical Criteria for Marine Applications
  - Introduction to Nuclear Energy
  - Additional Regulatory Information for Targeted U.S. States
  - Additional Information of U.S. Agencies
  - Details of Nuclear-Maritime Economic Evaluations

Task 2 – Key Takeaways: Deliverable 2-1







Task 2 – Key Takeaways: Technology Suitability

Reactor Size	Fixed Land/coast	Fixed offshore only	Fixed offshore w/ onshore grid coupling	Mobile local	Mobile international
Large (> 300 MWe)	✓			✗	✗
SMR (< 300 MWe)	✓	✓	✓	✓	✓
Micro (< 20 MWe)				✓	✓
Reactor Type					
Light Water Reactor (LWR)	✓				
Sodium Fast Reactor (SFR)	✓			✗	✗
Lead Fast Reactor (LFR)					
High-Temperature Gas Reactor (HTGR)	✓	✓	✓		
Fluoride High-Temperature Reactor (FHR)	✓	✓	✓	✓	✓
Molten Salt Reactor (MSR)	✓	✓	✓	✓	✓
Heat Pipe Reactor (HPR)	✓			✓	✓

Complete Suitability Tables provided in D2-1 and D2-2

Example Potential Barriers – D2-2 Table 1 (shortened for viewing)

Key Barrier	Technical Issues	Regulatory Issues	Economic Issues
Security, Non-Proliferation & Export Control	• Design for security and non-proliferation risks • Direct attack or sabotage may involve potentially severe technical consequences to the unit and to future designs or applications.	• ITAR, trade controls, or other restrictions may block nuclear ships, marine units, or marine nuclear materials from entering foreign ports. • Potentially restrictive to operational areas.	• Direct attack or sabotage may have severe economic repercussions on the industry beyond just the vessel or marine unit. • Security arrangements/personnel may increase costs.
Nuclear Licensing	• May require re-design or additional testing or demonstration efforts.	• Licensing effort may be challenging and delayed for new or unique technologies or applications.	• May be costly for new technology or applications
Demonstration and Testing	• Specific maritime nuclear testing equipment and platforms may need to be developed.	• New material may require code case for standardization.	• May involve developing new codes or standards, increasing the overall costs of the application.
Business Case	• High upfront (CAPEX) costs • Development potentially restricted if engineering solutions do not show as economically feasible.	• Policy or regulations may affect regional & global market landscapes. • Sustainable carbon pricing schemes/policy may not incorporate nuclear power for maritime applications.	• Failure to understand or estimate economic factors appropriately may potentially involve severe consequences to owners/investors.
Nuclear Waste, Decommissioning & Vessel Recycling	• Maintenance and servicing may require specialized and complex remote handling equipment due to shutdown radiation fields.	• Unclear on regional and international waste management. Potentially restrictive to implement or approve if no arrangement for transport or long-term waste disposal is available.	• Arrangements for transport or disposal may be prohibitively costly to implement.
Supply Chain and Fuel Availability	• Supply chain for other advanced materials and plant components may not be developed or available.	• HALEU availability. • Regulations related to trade may restrict supply chains and material or parts availability.	• The supply chain for advanced materials may be expensive.
Support Infrastructure	• Shipyards and ports may not be suitable to handle nuclear material.	• Gaps in nuclear or maritime regulations may cause issues when technology interfaces with infrastructure and land-based support efforts.	• Crew and personnel may not be trained; potential rising costs of personnel.
Public Policy/Public Acceptance Barriers	• Negative public perception may reduce number of dedicated engineers and technicians interested in supporting the development of the technology.	• Negative public perception may result in restrictive transport or trade policy or regulations regionally or globally.	• Negative public perception may limit investment opportunities.

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Task 3 Summary

Submitted to DOE end of March 2024

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

DOE FOA ARD-21-26386 *Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies*

Acknowledgment: This material is based upon work supported by the Department of Energy Office of Nuclear Energy under Award Number DE-NE0009226.

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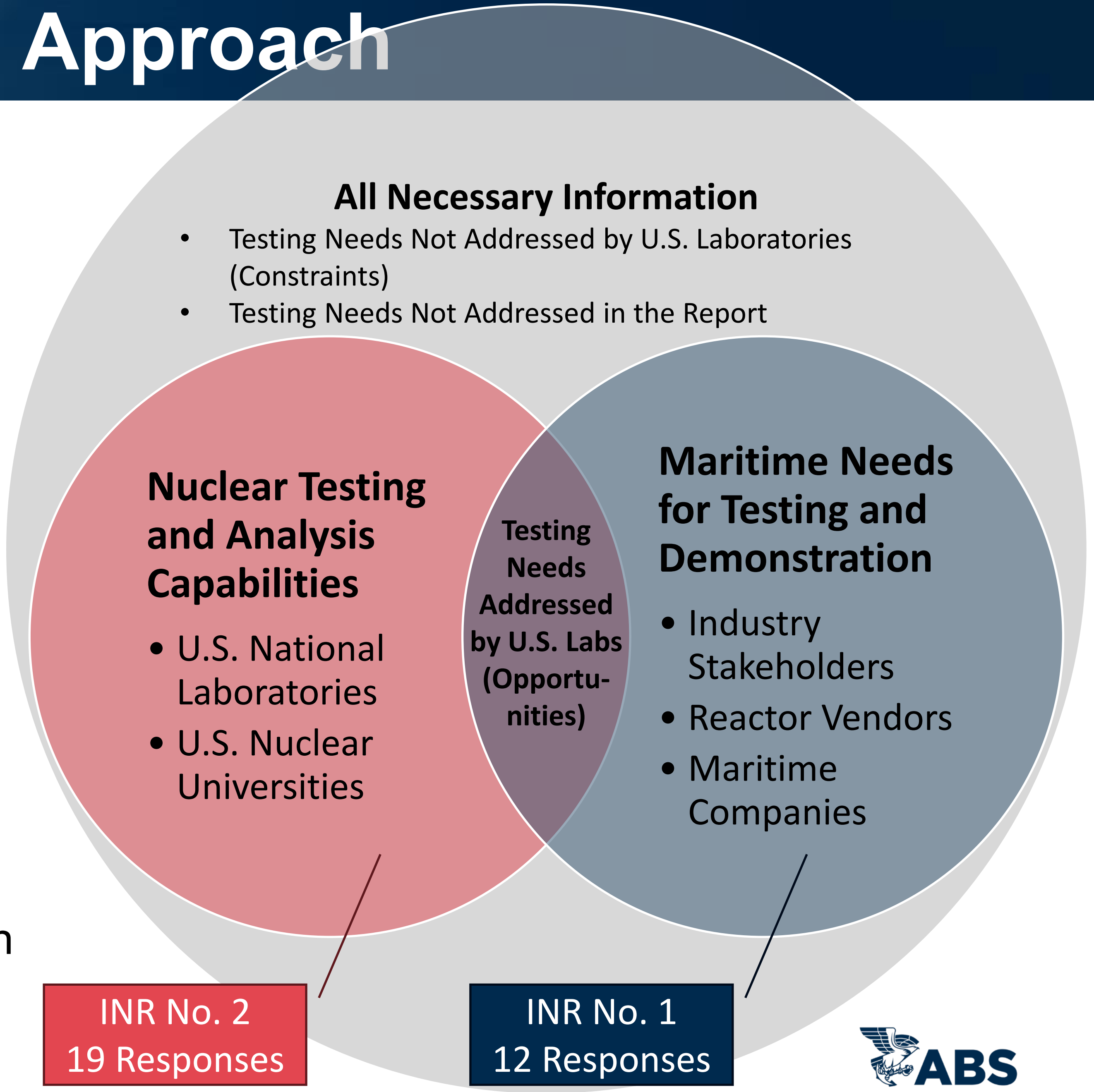
Task 3 – Key Takeaways: Approach

Gathering Information:

1. **Information Needs Request Form No. 1**
   - **Target:** Maritime/Offshore Industries
   - **Request:** Information on what testing will be needed for maritime-nuclear applications
2. **Information Needs Request Form No. 2**
   - **Target:** U.S. National Laboratories and U.S. University Nuclear Laboratory Facilities
   - **Request:** Information on capabilities that could support maritime-nuclear application demonstration testing

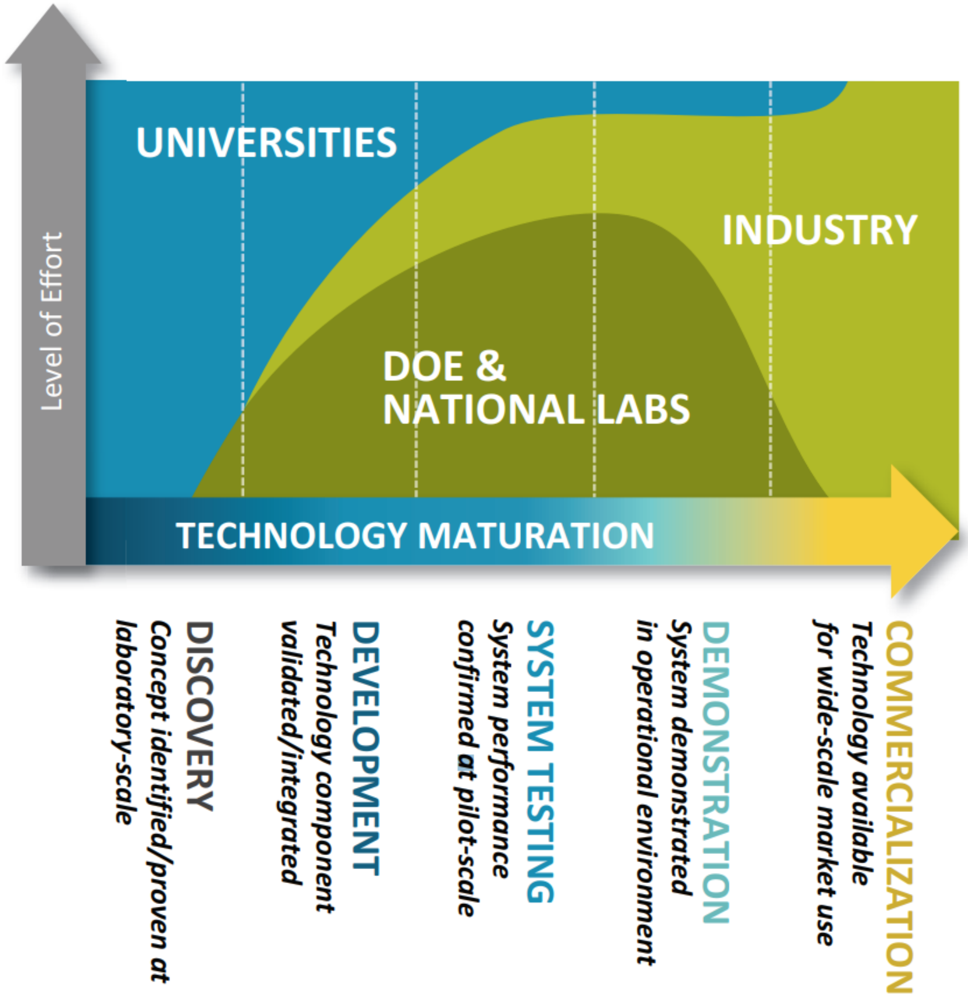


Task 3 – Key Takeaways

Testing Needs Addressed by U.S. Laboratories and Nuclear Universities

Review of Capabilities for:

- Reactor Operations under Severe Conditions
- Alarm Systems
- Fire Safety
- Physical Scenario Analysis
- Materials and Chemical Tests
- Reactor Operations in Marine Environment
- Non-Destructive Examination (NDE)
- Security
- General Research (Other)



DOE National Laboratories' Relationships to Universities and Industry in the Energy Innovation System Source: Energy.Gov

Task 4 Summary

To be Submitted 30 June 2024

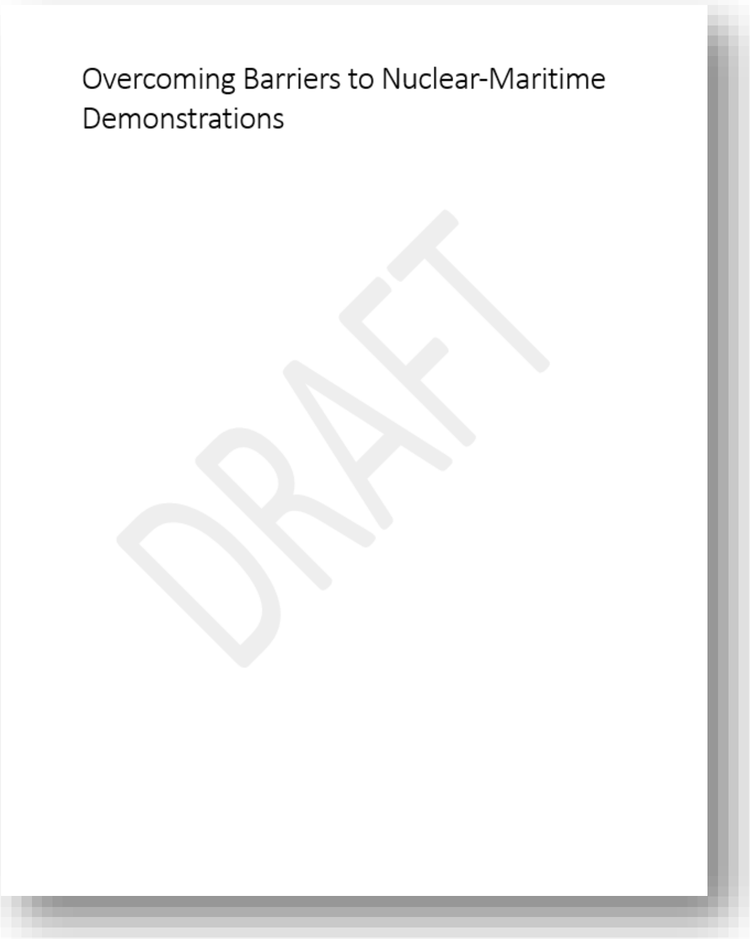
Task 4 Approach – Addressing Barriers

Responses typically fall under one or more categories to overcome potential barriers or issues to adoption:

Code Standardization / Regulatory Harmonization	Crew Certification & Personnel Training	Cybersecurity	Establish Fuel Supply	
Funding Policy	Investment	Leasing Scheme	Leverage Government/ Navy Experience	Successful Land-Based Reactor Demonstration/ Deployment
Operational Procedures	Public Education/PR	Robust Design	Robust Testing or Demonstration	

Task 4 Deliverable

- Summarize and describe potential barriers to advancing nuclear-maritime technology and novel applications
  - Consider both U.S. and International barriers
- Provide Recommendations to Address Key Barriers
  - Summary of Solicited Input from Industry Experts
  - Literature review of other identified approaches to address barriers
  - Prioritization of recommendations and actions to address barriers
- Conclusion and Recommendations for Future Work


Overcoming Barriers to Nuclear-Maritime Demonstrations

DRAFT

Project Next Steps

- Complete and Submit Task 4 Deliverable
- Collaborate with DOE to receive comments and recommended edits to modify final draft documents
- Support the Publication of Deliverables through 2024/2025

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Thank You

www.eagle.org

National Reactor Innovation Center Program Review
April 23-24

Integrated Thermal-Electric Energy Management of All-Electric Ship with Advanced Nuclear Reactors

Principal Investigator: Jie Zhang (UTD)
Other Contributors: Bikash Poudel, Binghui Li (INL), Meg Dowling (ABS), Soroush Senemmar, Sobhan Badakhshan, Ali Mahboub Rad, Roshni Anna Jacob (UTD)

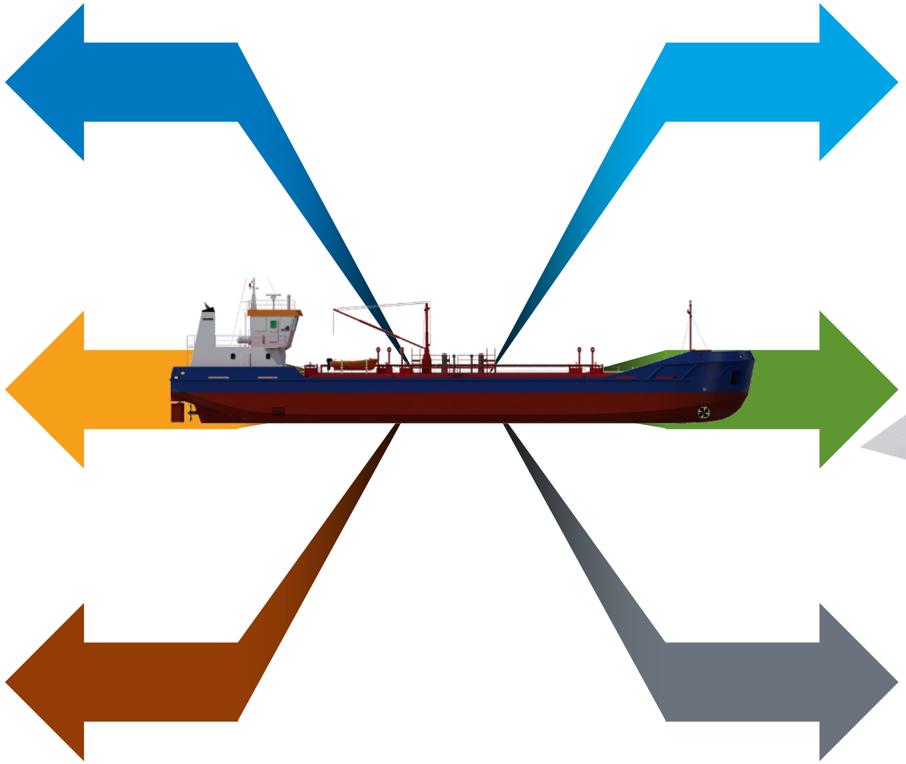
Background and Research Objective

- **Maritime shipping** is transporting more than 80% of the world's commodities and global trading operating and they account for over **3% of global greenhouse gas emissions**.
- **Nuclear powered ships** have promising advantages in terms of energy efficiency, greenhouse gas emission, and fuel costs.
- Recently, many ships have been using **electric propulsion systems**, called integrated power system (IPS).
- The integration of electric propulsion system in IPS creates significant new challenges in the area of **ship energy management**.
  - In particular, the integration of electric propulsion and its power electronic converters into the shipboard power system increase the requirement for cooling demand.
- The **overarching objective of this project** is to comprehensively model, design, and evaluate the use of **advanced nuclear reactors** in future nuclear-powered ships with IPS, to enhance the efficiency, reliability, and resilience of shipboard energy systems.

Project Management

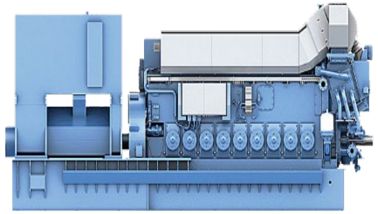
Key Research Objectives	Year 1				Year 2				Year 3			
	1	2	3	4	1	2	3	4	1	2	3	4
Task I: Modeling of Nuclear-Powered Ships	●	●	●	●	●	●						
1.1 Heat generation model	●	●	●									
1.2 Thermal-electric co-simulation	●	●	●	●	●	●						
Task II: Total-ship Energy Management			●	●	●	●	●	●				
2.1 Economic dispatch			●	●	●	●						
2.2 Dynamic control					●	●	●	●				
Task III: Ship-to-Grid Simulations					●	●	●	●	●	●		
Task IV: HIL Test							●	●	●	●	●	●

Task I: Modeling of Nuclear-Powered Ships



Generation

Future SPS needs **more generation capacity** due to the constantly increasing demand.



Energy Storage System

Future SPS will leverage energy storage systems to **improve the energy efficiency** and response to pulsed loads.

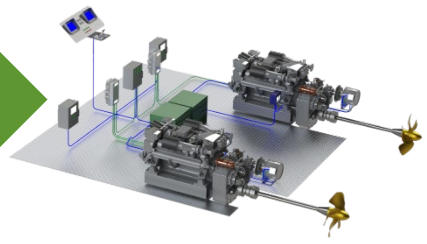
Power Conversions

Future SPS uses more power electronic-based converters to **meet the vast variety range of electric demands.**

Pulsed Loads

Some unique loads will be added to SPS (e.g., **laser weapons**), and these loads can make future SPS more complex.

Integrated Power and Energy System

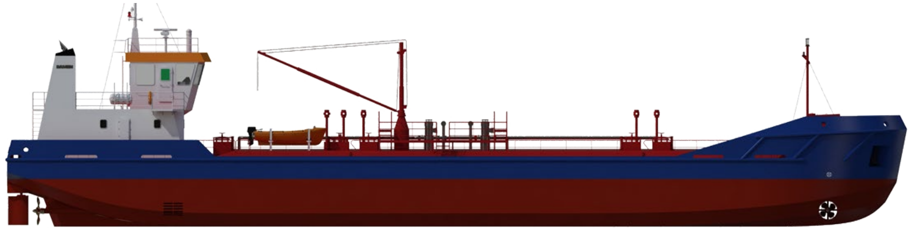


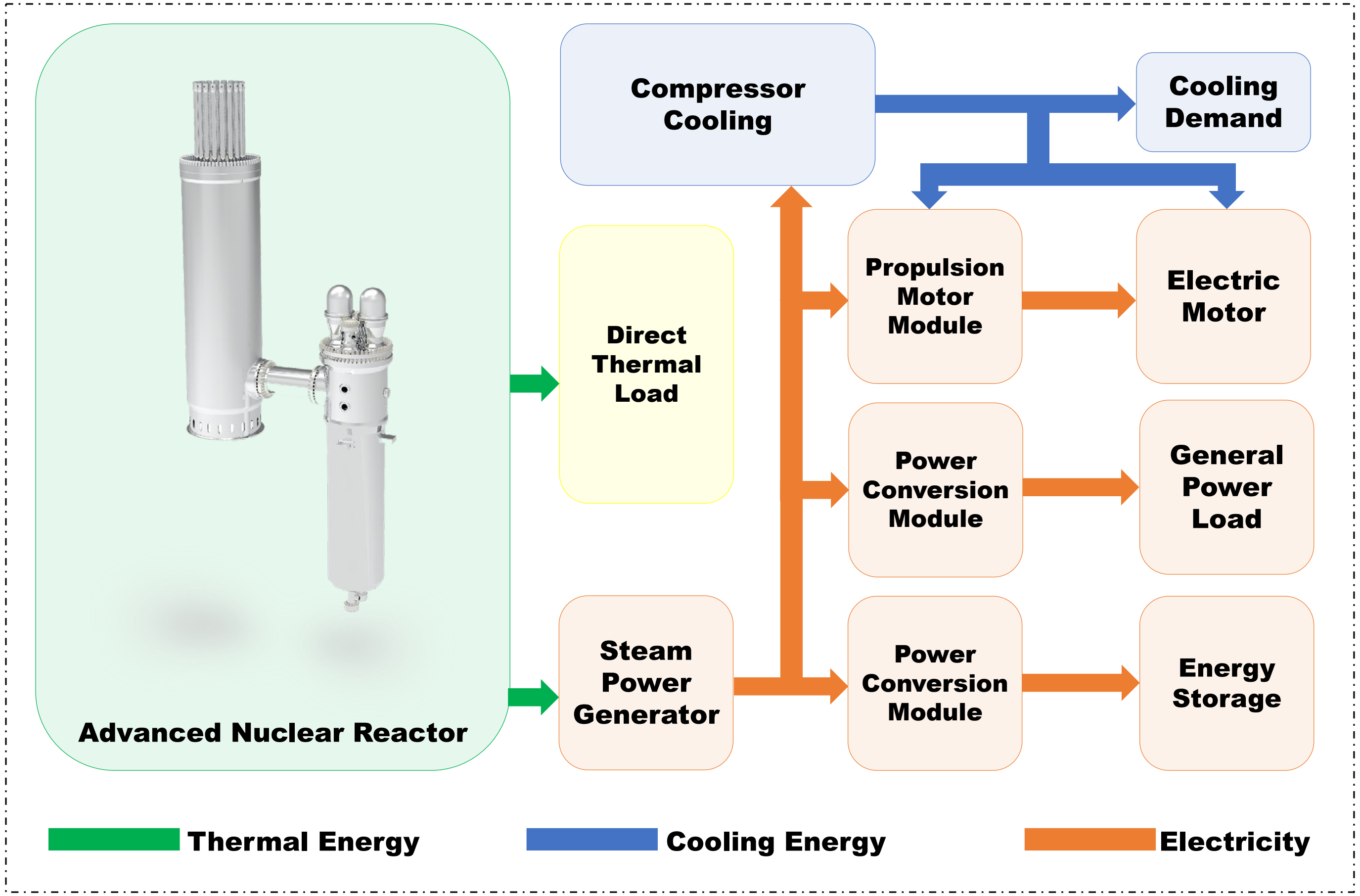
Integrated power system provides electric power to the total ship (**propulsion and ship service**) with an integrated plant.

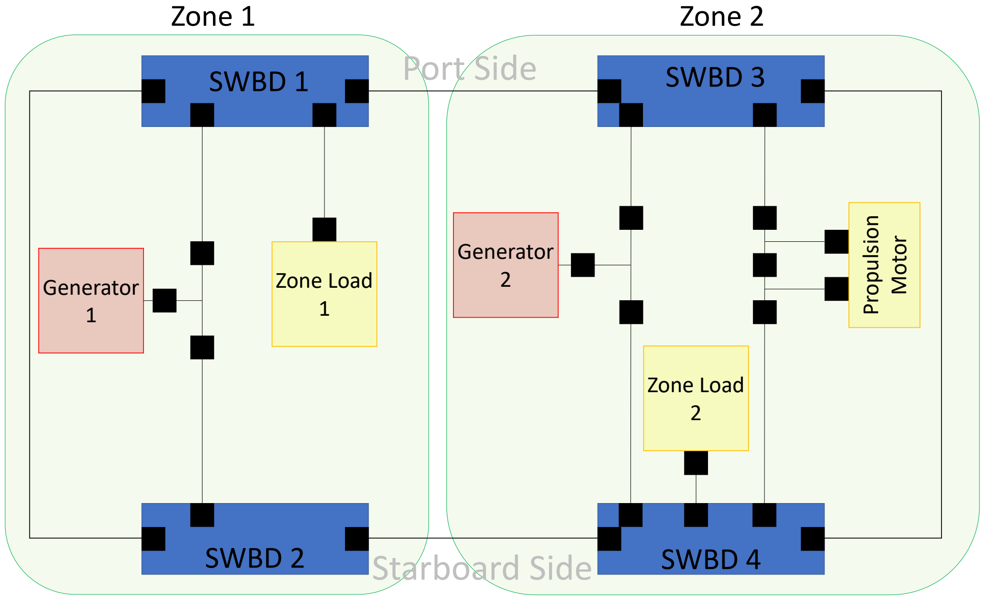
Ship to Grid Connection

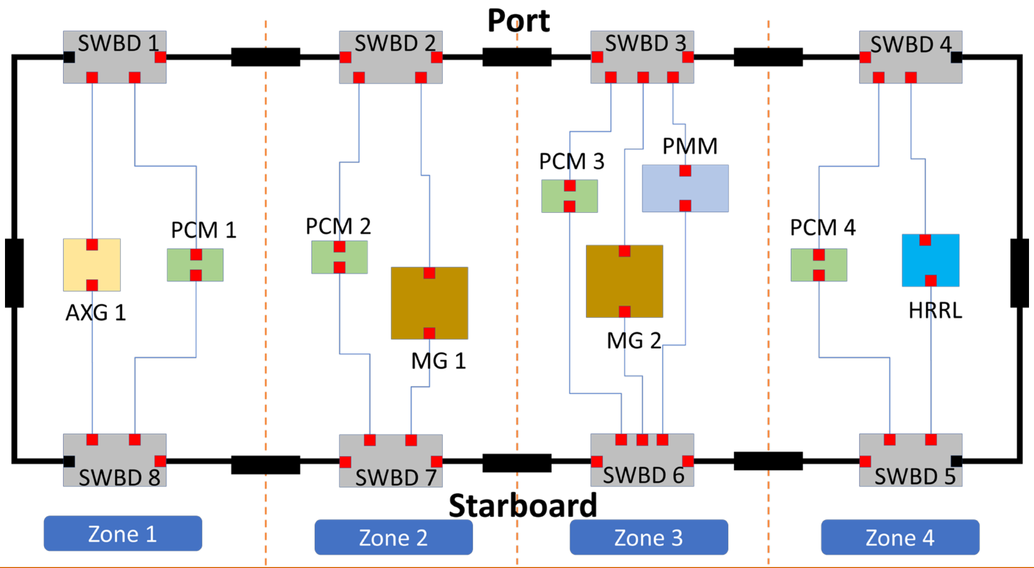
Future SPS will have more **interaction with terrestrial power network** to charge/discharge the energy storage system and help improve the grid operation and resilience.

Task I: Modeling of Nuclear-Powered Ships



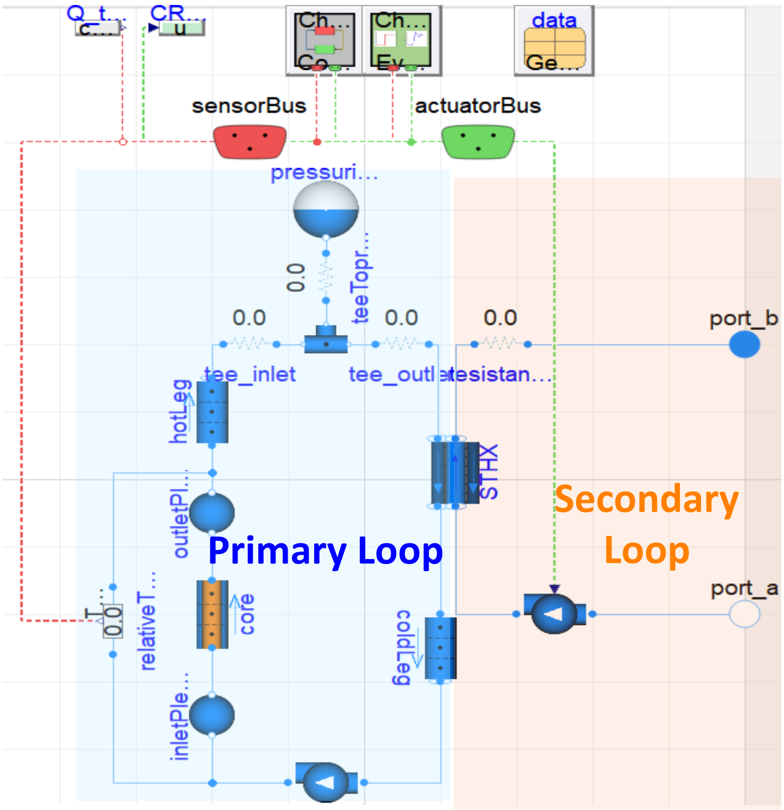






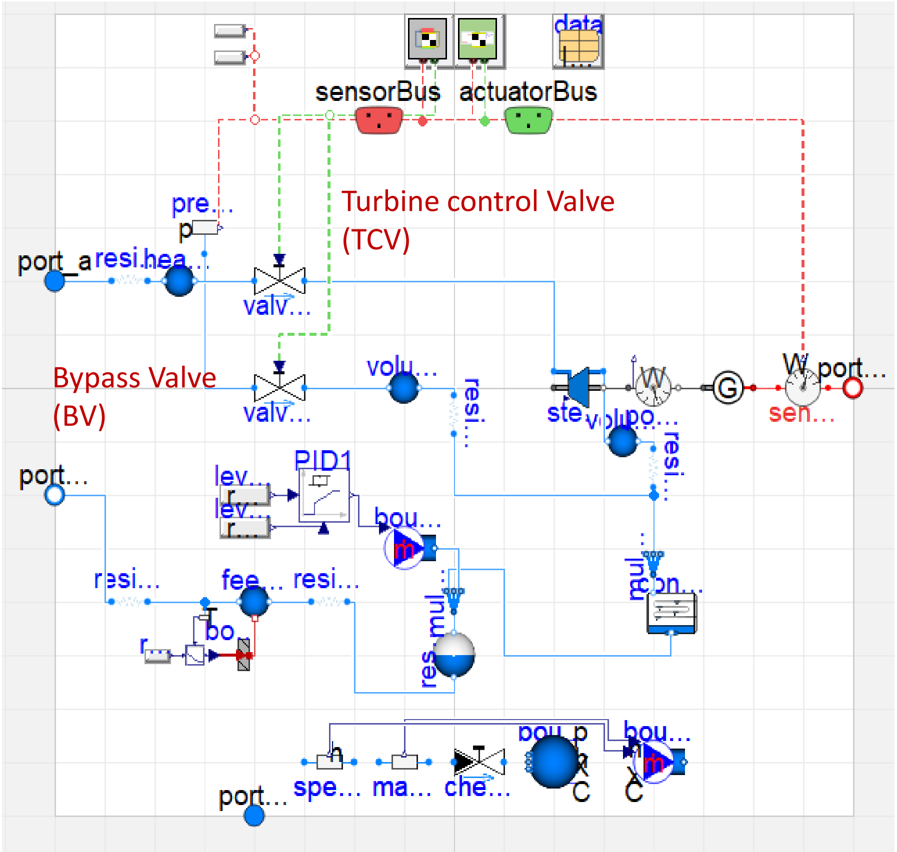
Physical System Modeling in Modelica

Nuclear Reactor as the Primary Energy Supply System



- The dynamics of the pressurizer, steam generator, and reactor core dynamics are modeled in **TRANSFORM**.
- The thermo-fluid behavior of the reactor core is modeled by fuel pin and coolant channel, and core neutronics represented by one group point kinetics.
- Control module includes core rod reactivity, pressurizer pressure, and pump mass flow rate.

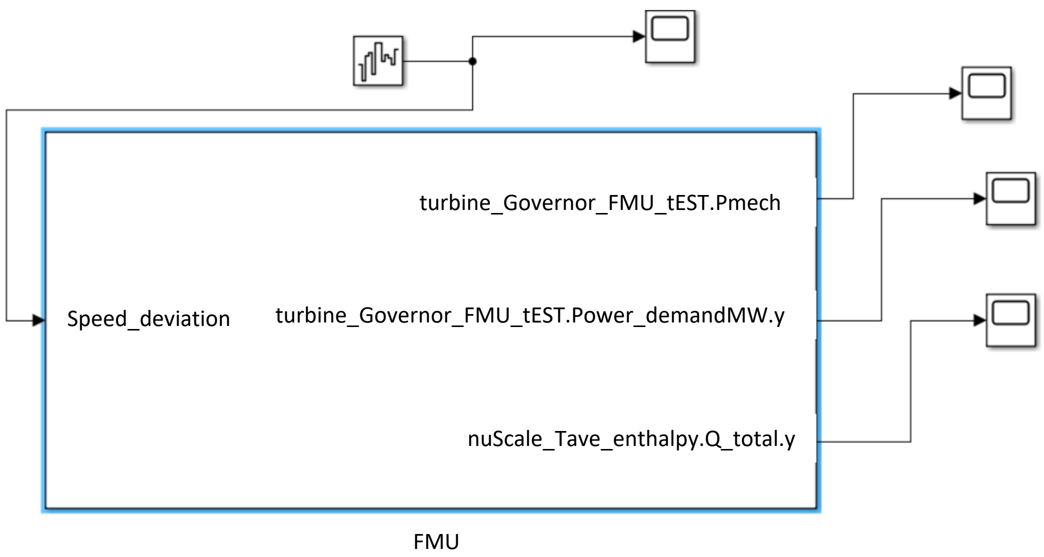
Balance of Plant (BOP) for power conversion

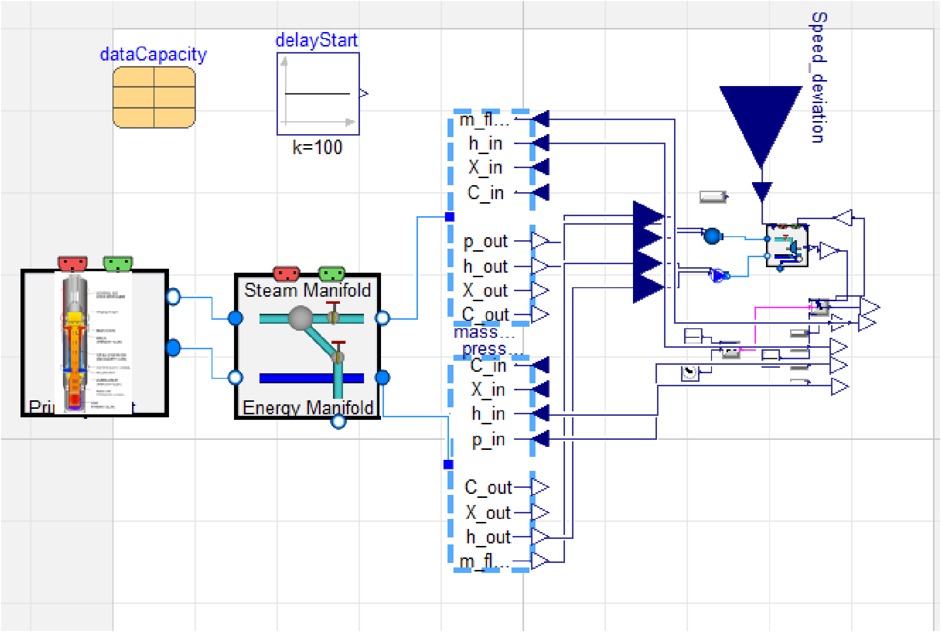


- A **pressurized water reactor** is modeled, which has a nominal thermal power of 160 MWt and an electrical equivalent of 50 MWe.

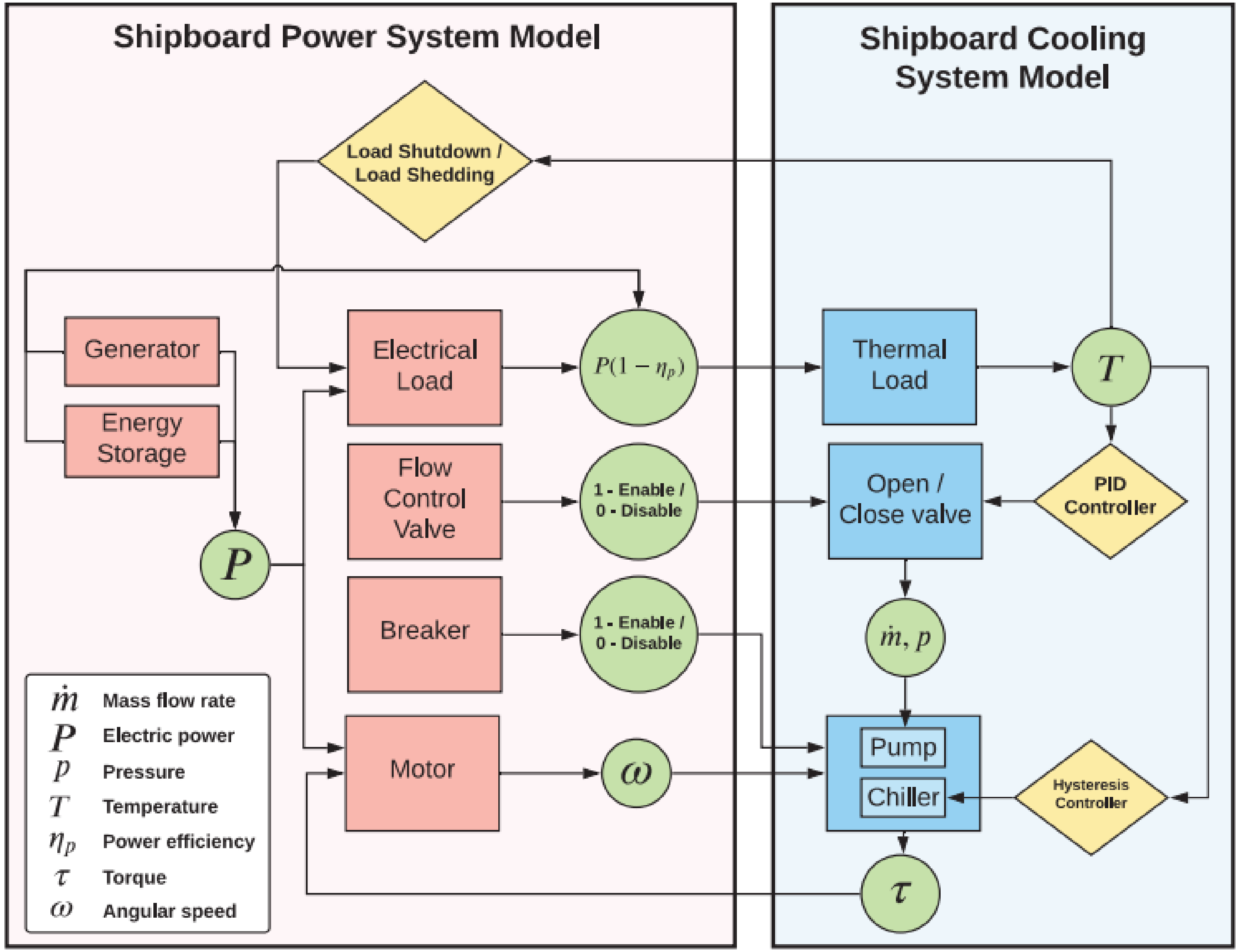
Functional Mock-up Unit for SMR Integration

- The FMU consists of the SMR model with the BOP which includes the turbine model, a governor model is added to this version.
- The FMU obtains a speed deviation per unit input from Simulink model and provides the mechanical power output, SMR thermal power from the Dymola model.





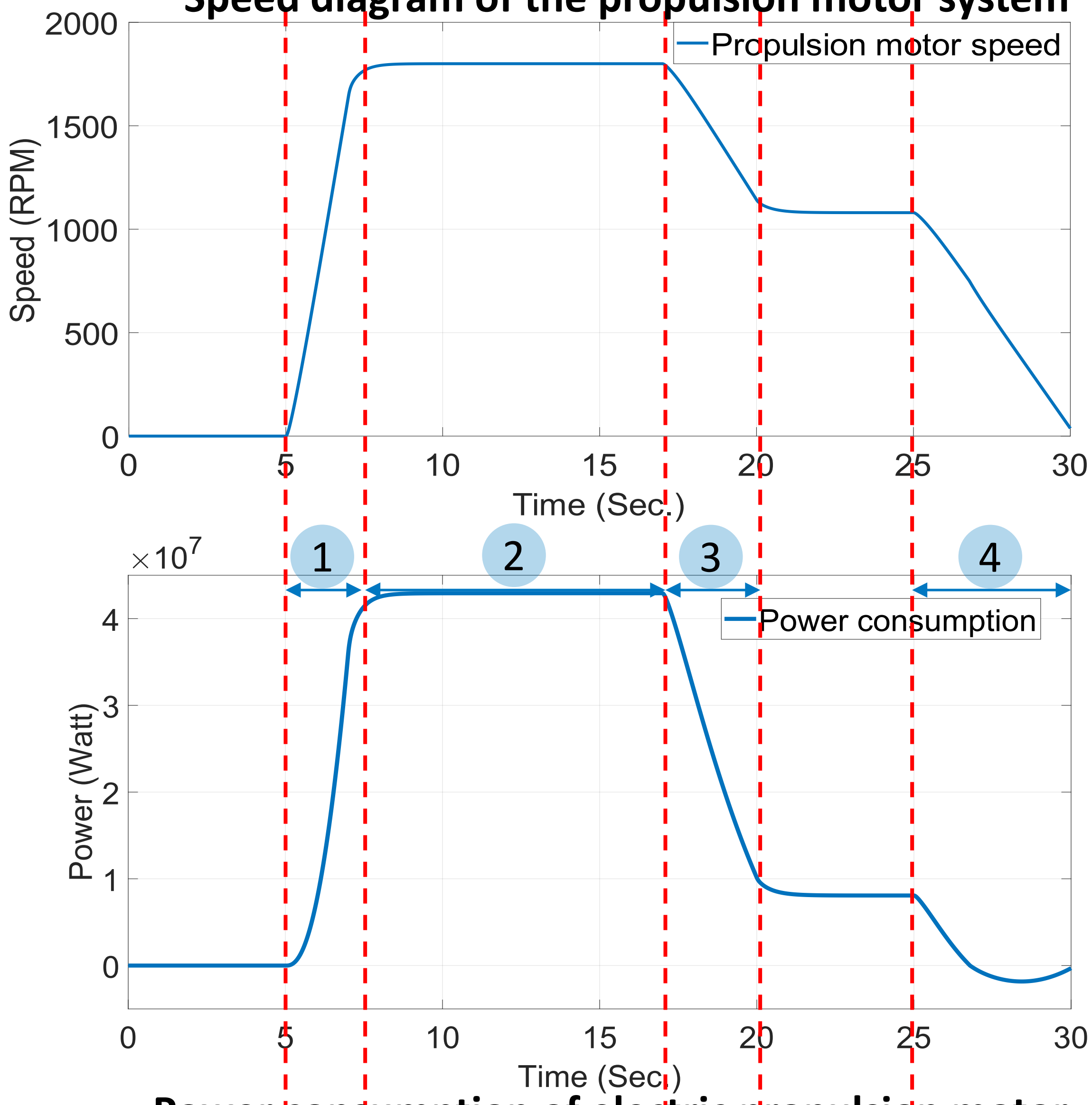
Interdependent Shipboard Energy System



Interdependent Shipboard Energy System

- The study includes **sharp acceleration** (seconds 5 to 7, zone 1), **steady state** (seconds 7 to 17,zone 2), **sharp deceleration** (seconds 17 to 20,zone 3), and **soft deceleration** (seconds 25 to 30, zone 4).
- The rated speed of the propulsion motor is 1800 rpm, while the full rated speed and 60% of rated speed are simulated as steady state situations.
- The power consumption of a motor shows a **nonlinear** relationship with the speed.
  - Reducing the speed of the motor from 100% to 60% can cause a sharp decrease in power consumption, i.e., from 42 MW to less than 10 MW.
- This non-linear behaviour is the main reason for the significant power reduction observed during sharp deceleration of the motor.

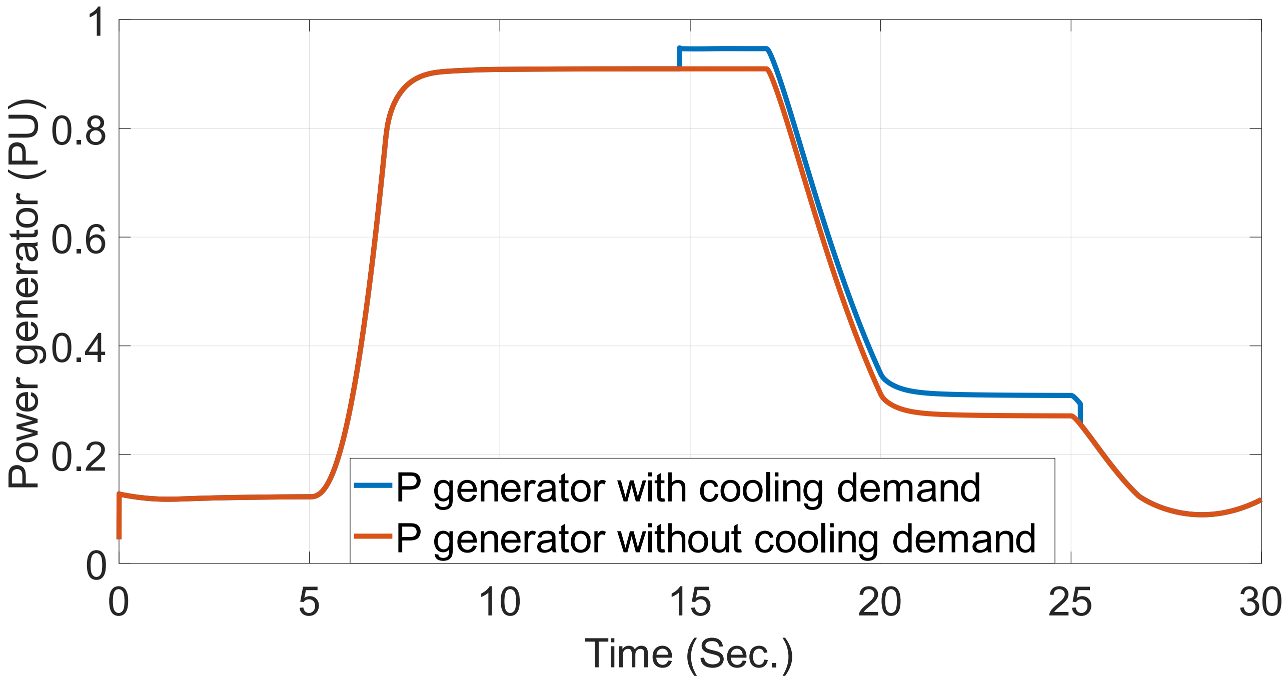
Speed diagram of the propulsion motor system



Power consumption of electric propulsion motor

Interdependent Shipboard Energy System

- There is a notable increase in the generator's output power following the initiation of the cooling system.
- The output power may rise from 90% to 95% of the rated power, primarily due to the activation of pumps in the cooling system.
- It is crucial to ensure that these power fluctuations do not push the generator into an overload situation.



The output power of one generator with and without considering the cooling system

Task II: Total Ship Energy Management

- Dynamic Modeling and Simulations of SMR-BESS-AES
  - The **reliable operation** of the ship system is essential for the **safety** of the ship and its crew.
  - Dynamic Modelling and Simulation of **SMR**
  - Dynamic Modelling and Simulation of **BESS**
  - Overall Dynamic Modelling and Simulation of **SMR-BESS-AES**
- Case Study
  - Scenario I – Rapid changes in electric motor loads
  - Scenario II – Rapid changes in electric motor loads with pulse loads

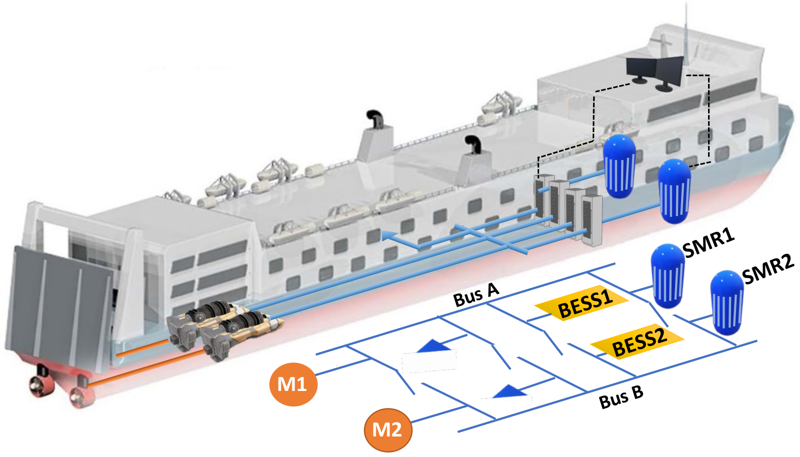
Dynamic Modeling and Simulations of SMR-BESS-AES

- Due to the limitations of the SMR as the primary source of energy, it is not flexible enough to quickly respond to large instantaneous changes in the ship's loads, such as pulse loads and maneuvering in electric motor drive systems.

- The control systems should be designed to be able to handle various scenarios such as ship acceleration, deceleration, and weather conditions.

- The frequency of an electric system is an important indicator of the balance between the electricity supply and demand.

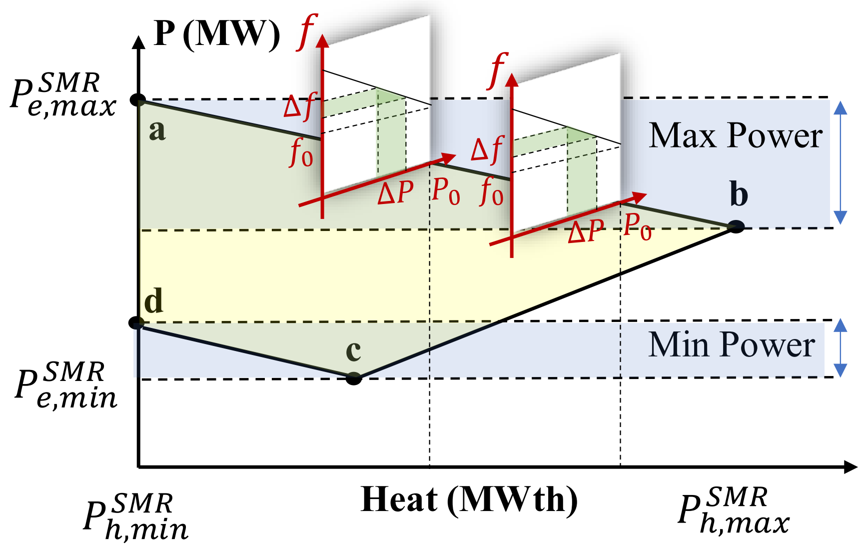
- Batteries can respond quickly to frequency deviations as the primary frequency units by injecting or absorbing power into the grid.



Configuration of an all-electric ship with SMR-BESS

Dynamic Modeling and Simulation of SMR

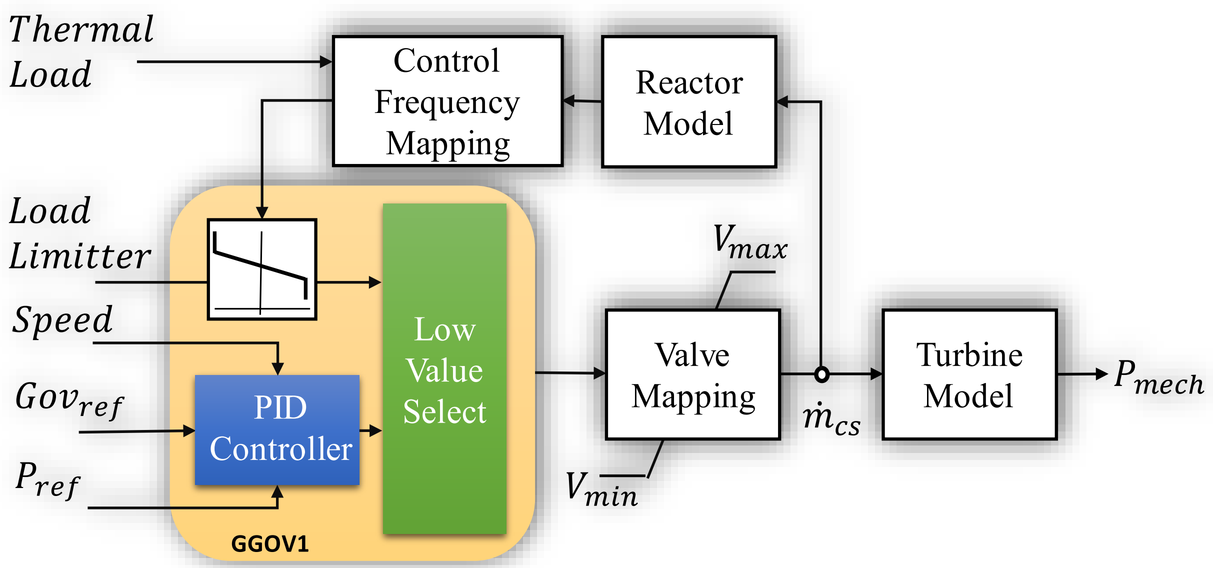
- Control frequency mapping is based on the SMR's feasible operation region, and the frequency control system uses a feedback loop to adjust power output and maintain stable frequency. Reference values for governor characteristics are adjusted according to the SMR's thermal load.



Feasible region of the SMR's operation and control frequency mapping

- The dynamic modeling of an SMR and its incorporation into the standard GE-General Governor (GGOV1) is employed for SMR's turbine-governor model.

- The GGOV1 model has a limit on the variable valve's closing and opening rates.

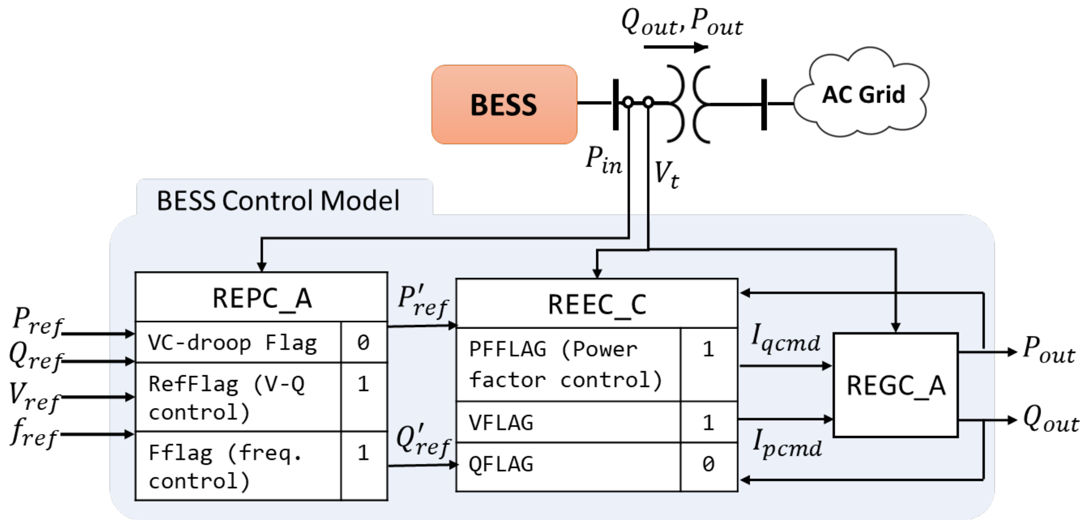


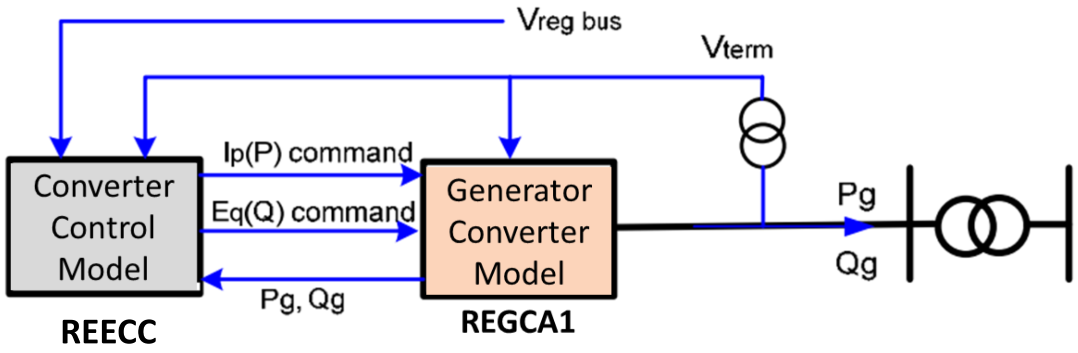
Block diagram of the SMR model with GGOV1 modification

Dynamic Modeling and Simulation of BESS

- BESS is considered as the primary source of frequency control. The **REPCA** (Renewable Plant Control A) plant controller can also be used with the **REECC** (Renewable Energy Electrical Control) and **REGCA** (Generator Control) models to allow for emulating various functionalities, such as frequency regulation, reactive power control, voltage control, and active power curtailment.

- By leveraging the three modules: REECC, REGCA, and REPCA according to the Western Electricity Coordinating Council (**WECC**) we could simulate dynamic model of BESS.

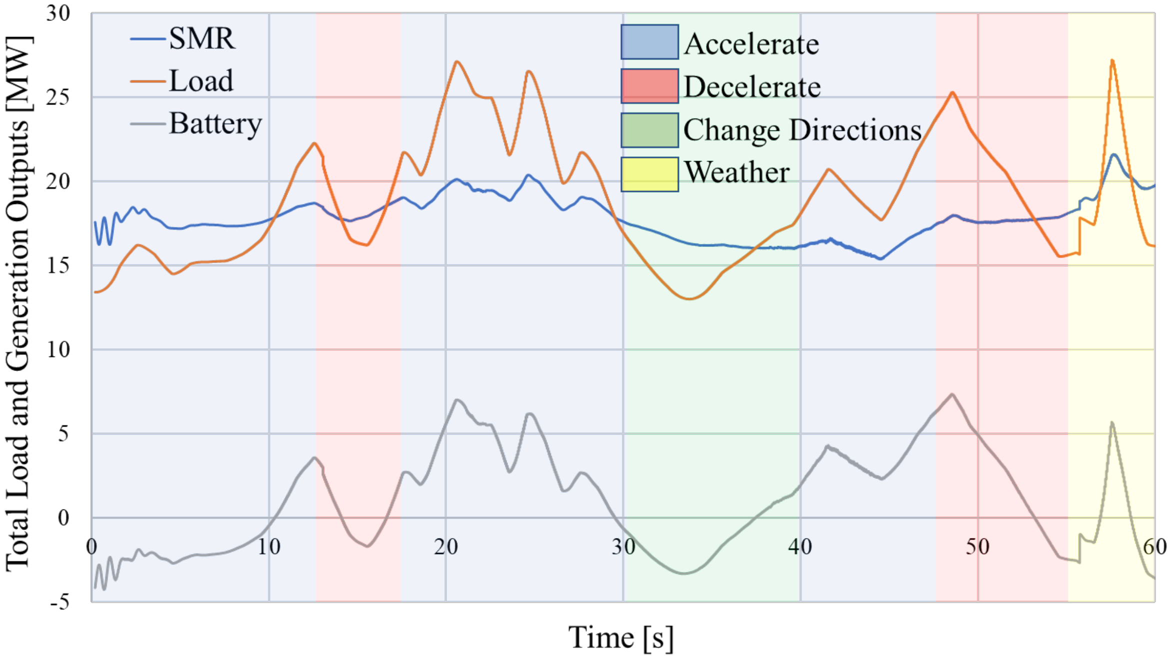




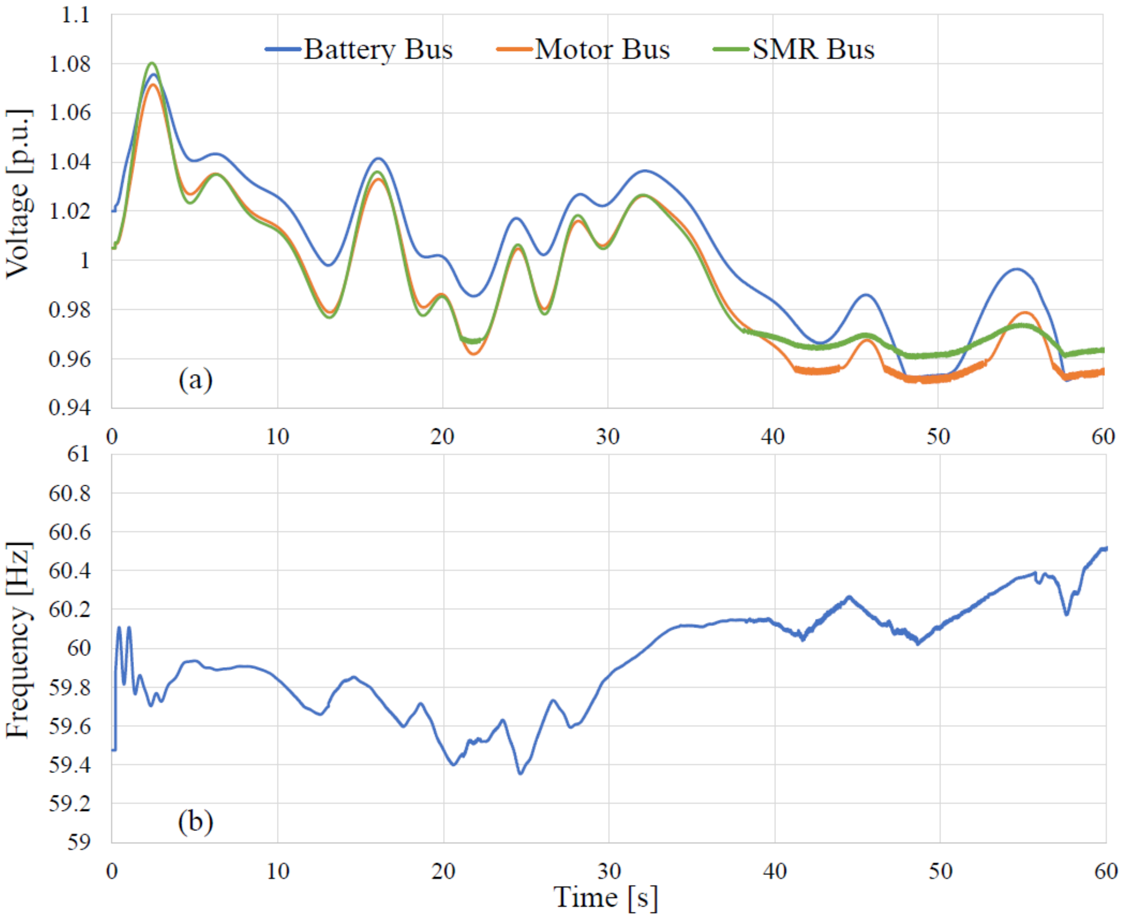
The frequency control model of BESS by the generic stability mode

Scenario I – Rapid Changes in Electric Motor Loads

- The following figure depicts a load profile under different operating conditions. In response to the frequency deviation, the SMR's electrical output is modified by the battery energy system to compensate for the remaining mismatches between the demand and supply.



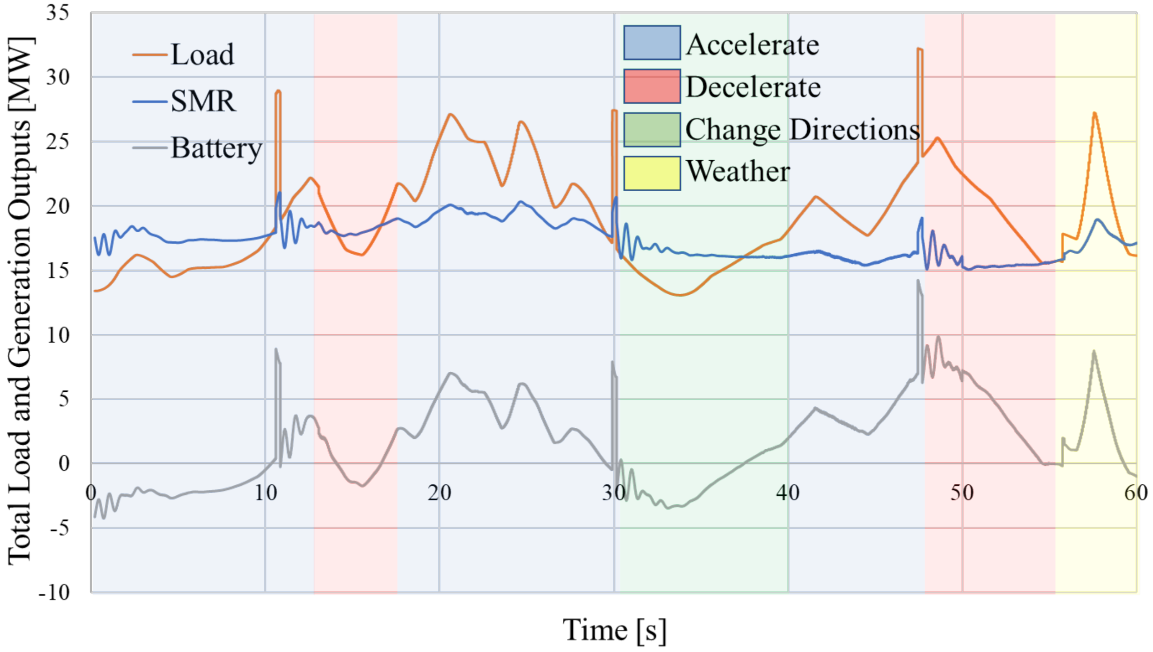
The electric load profile of the AES microgrid and the total generation units output during the operation



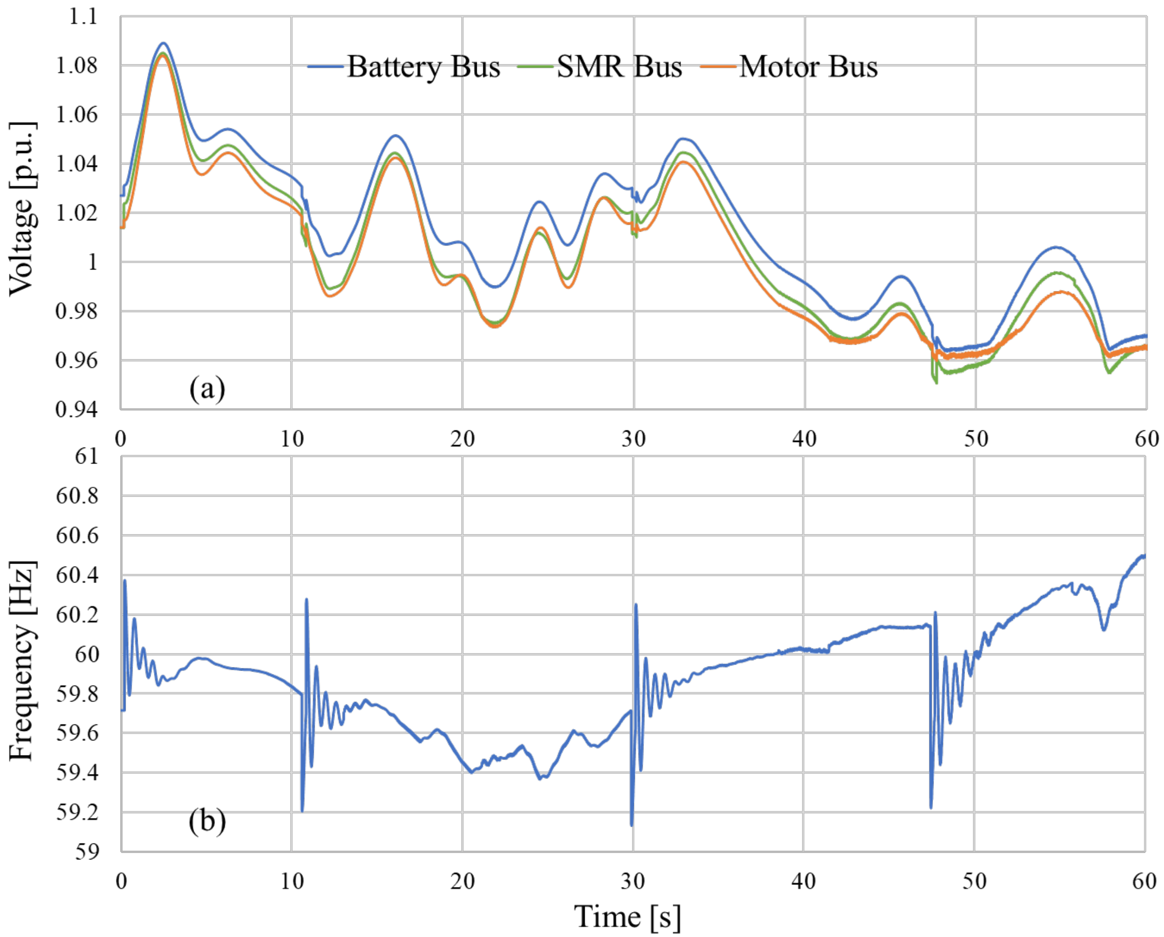
Dynamic response of the SMR-BESS-AES to the different modes of operation in Scenario I: (a) voltage amplitude of the buses, and (b) grid frequency profile

Scenario II – Rapid Changes in Electric Motor Loads with Pulse Loads

- In response to the frequency deviation, the SMR's electrical output is modified by the battery energy system to compensate for the remaining mismatches between the demand and supply and improve the flexibility of the SMR-AES.



The electric load profile of the AES microgrid and the total generation units output during the operation



Dynamic response of the SMR-BESS-AES to the different modes of operation with pulse loads: (a) voltage amplitude of the buses, and (b) grid frequency profile

A Comparative System Configuration Analysis

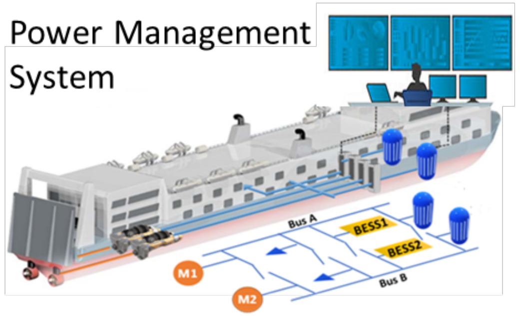
❑ **Energy management** on all-electric ships is coordinated through **voyage scheduling** and **generator scheduling** to ensure efficiency and reliable operation.

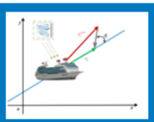
Energy Management

Voyage Scheduling

Generation Scheduling

Power Management System

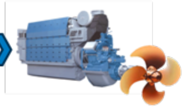


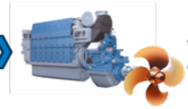


Uncertainty wind and wave speed on voyaging speed

Voyage path, including distance, speed profile, and any relevant environmental factors like weather patterns or wave conditions.

Determine power required Based on voyaging (Speed-Power Load Pattern)





Estimated Energy Capacity For Different Energy Supply Systems

Battery Ship	Hydrogen	Ammonia	SMR Ship

Apply power load pattern to all systems for optimal sizing and security-constrained dispatch of load

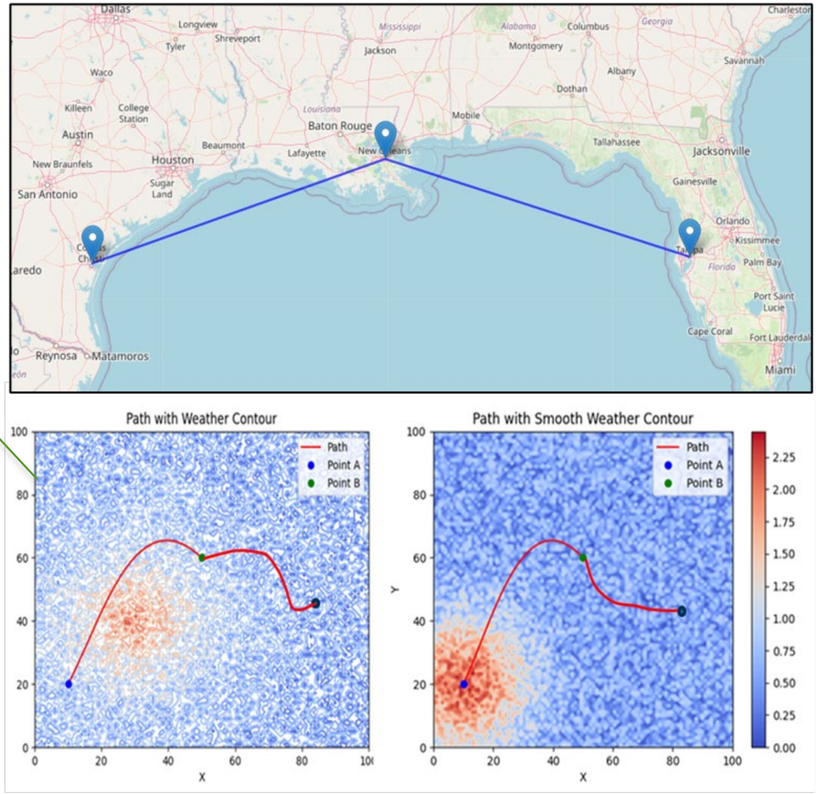
Comparative Energy Efficiency Analysis

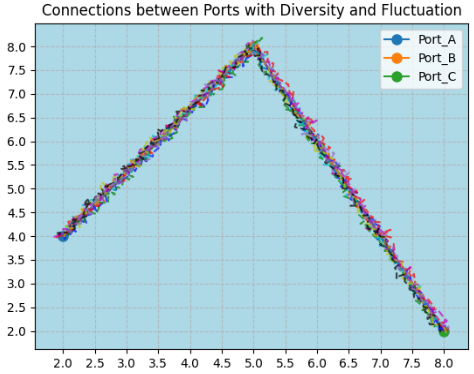
Economic Dispatch and Sizing

- ❑ **The weather conditions** influences **navigation decisions** and **operational efficiency.**

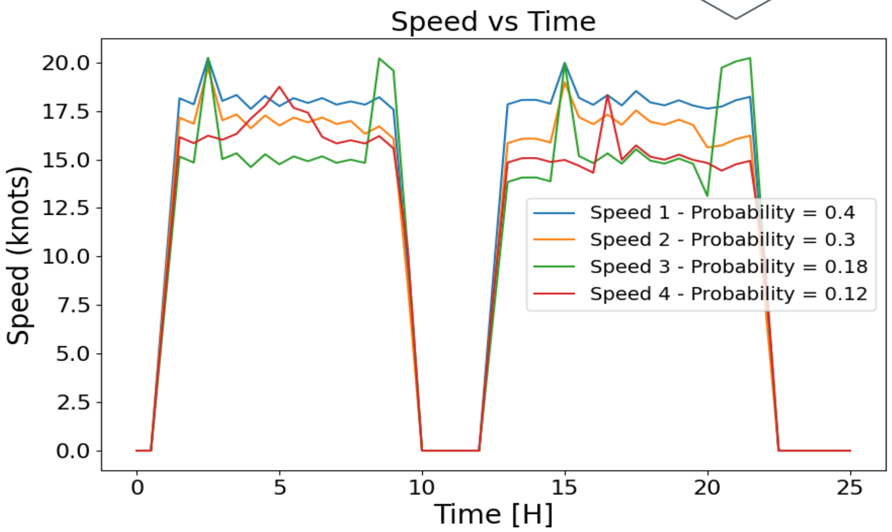
The wave height at various forecast times along the voyage route.

The ship's voyage path would vary depending on weather conditions.



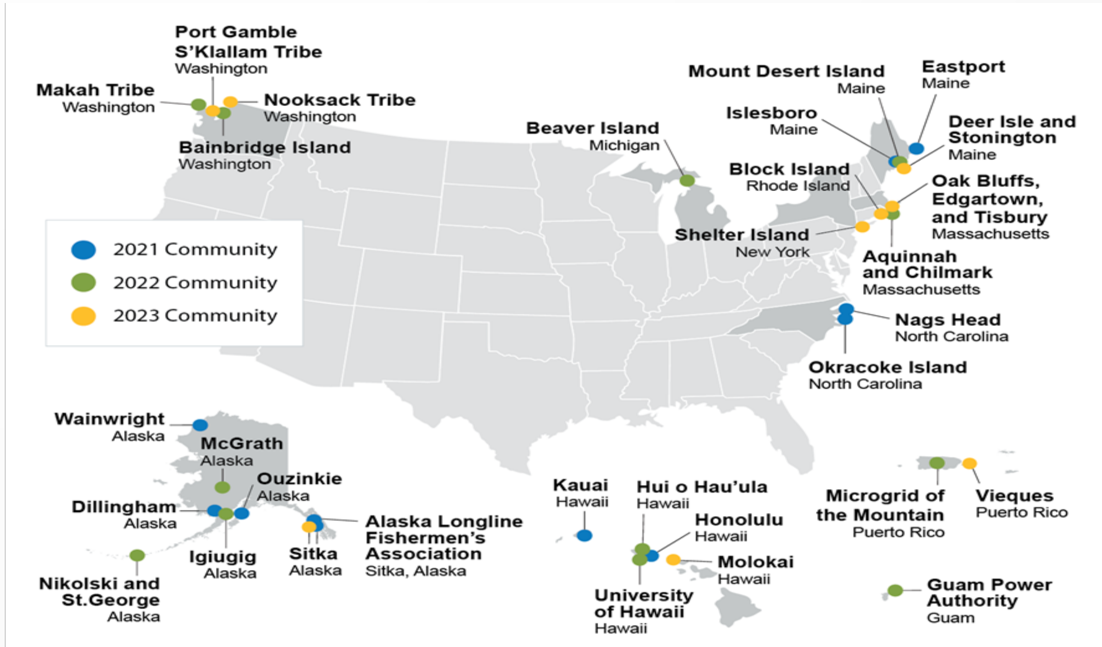


Various routes correspond to diverse speed profiles with different probabilities

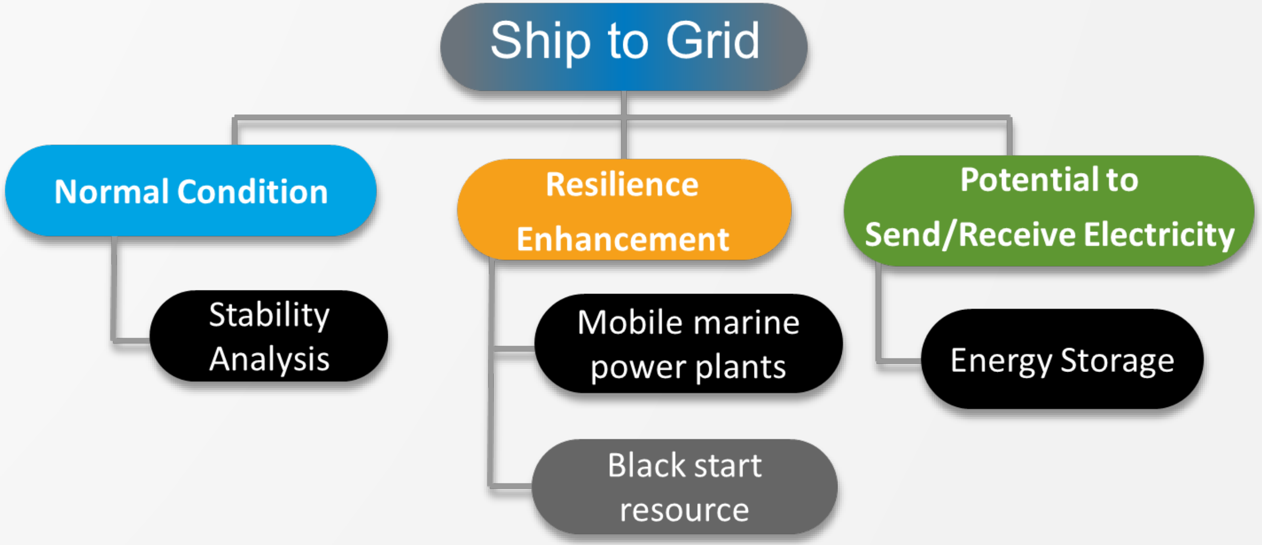


Task III: Terrestrial Power Grid Resilience Enhancement via Ship-to-Grid

- "**Ship to Grid**" involves the use of the ship's onboard power generation systems to supply electricity to the local grid infrastructure. The ship essentially acts as a **mobile** power generation unit, offering flexibility and support to the onshore electrical grid.



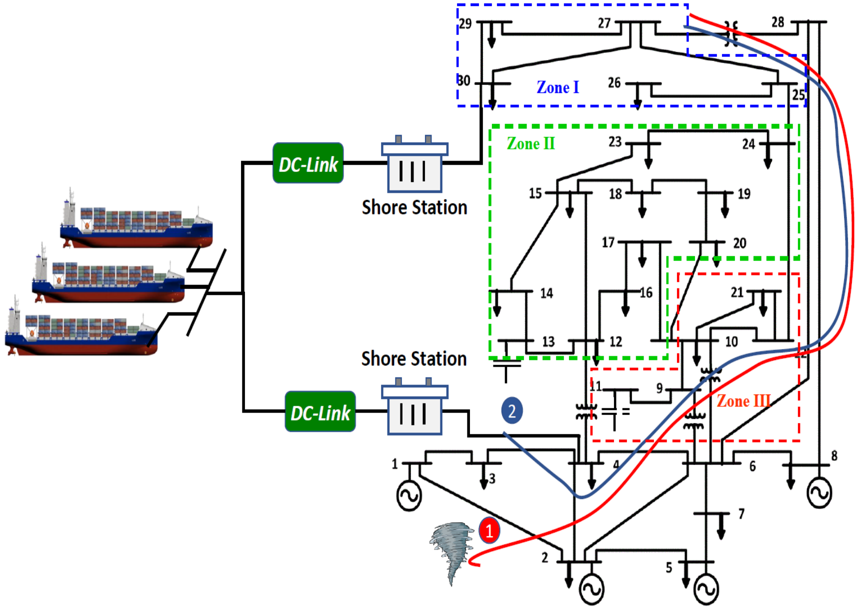
The U.S. Department of Energy's (DOE) Energy Transitions Initiative Partnership Project (ETIPP) comprises multiple projects focused on developing sustainable, resilient, and reliable energy systems for these communities.



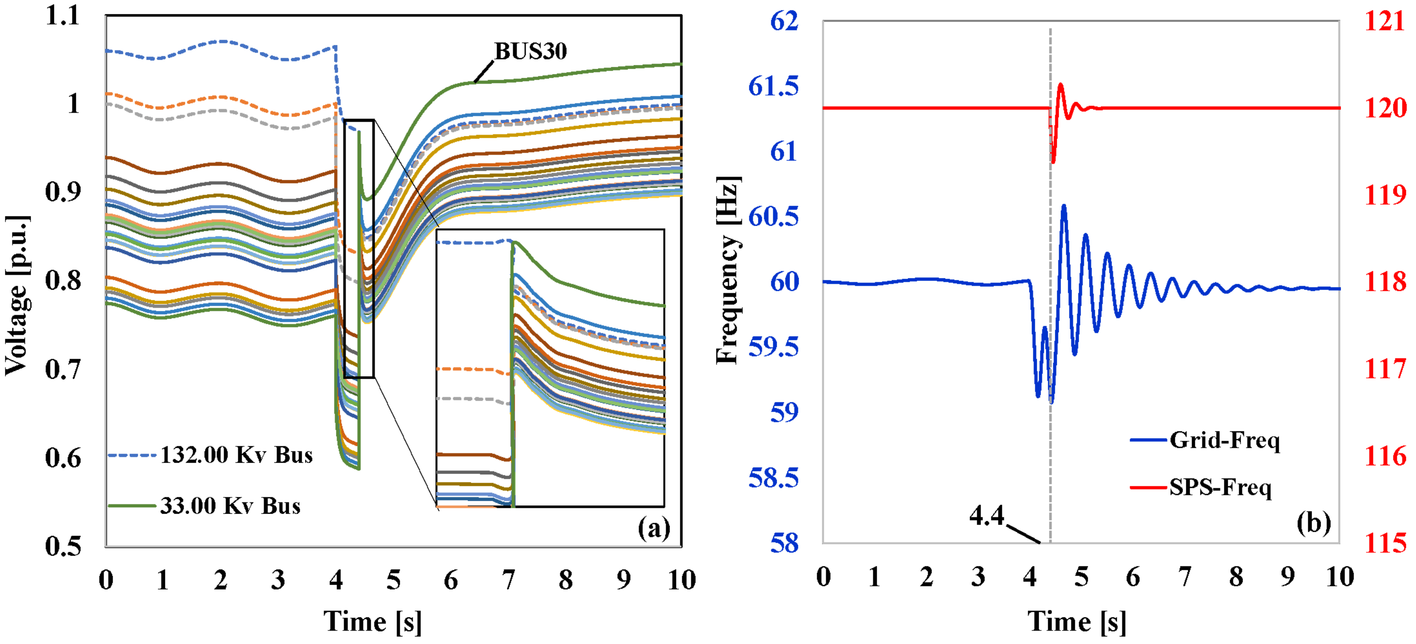
https://www.energy.gov/eere/articles/doe-partners-9-island-and-remote-communities-boost-resilience-and-plan-low-cost

Task III: Terrestrial Power Grid Resilience Enhancement via Ship-to-Grid

- This task will develop a coordinated framework of connecting advanced nuclear-powered ships with the terrestrial power network to enhance the power network resilience during disruptive events.
- Power system dynamic equivalent models for both shipboard power systems and shoreline grids will be developed, by considering of the impacts on conventional coherency-based dynamic modeling for nuclear-powered ship-to-grid integration.



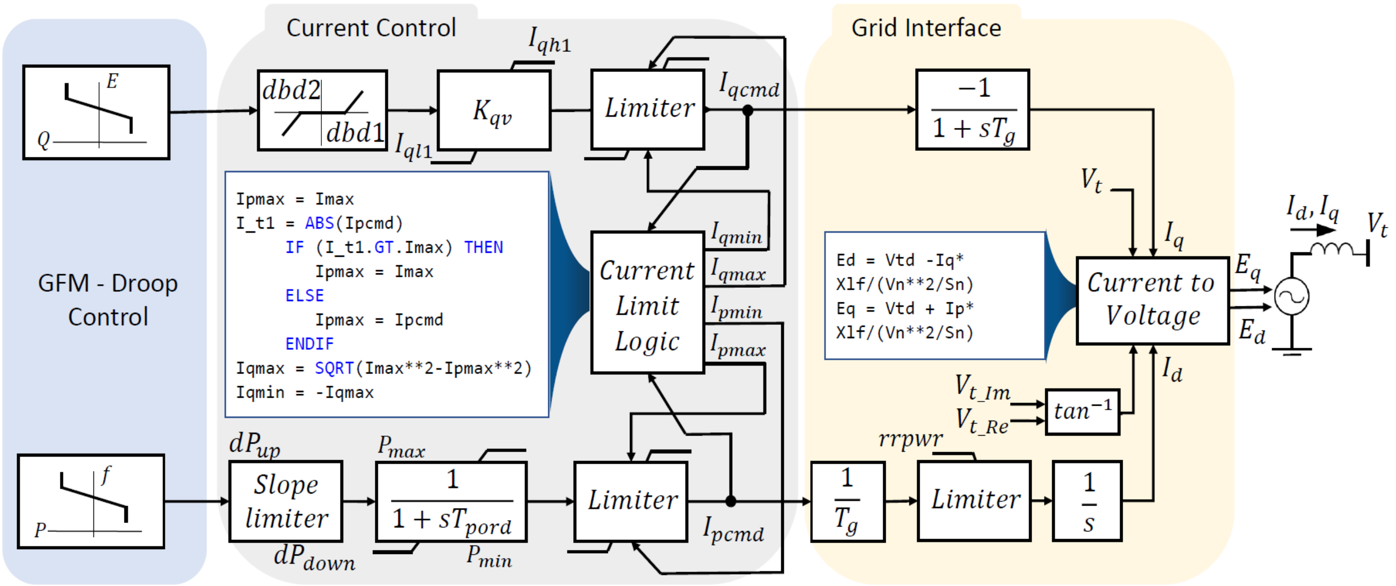
Modified IEEE 30-bus test system affected by a hurricane disruptive event with two different trajectories



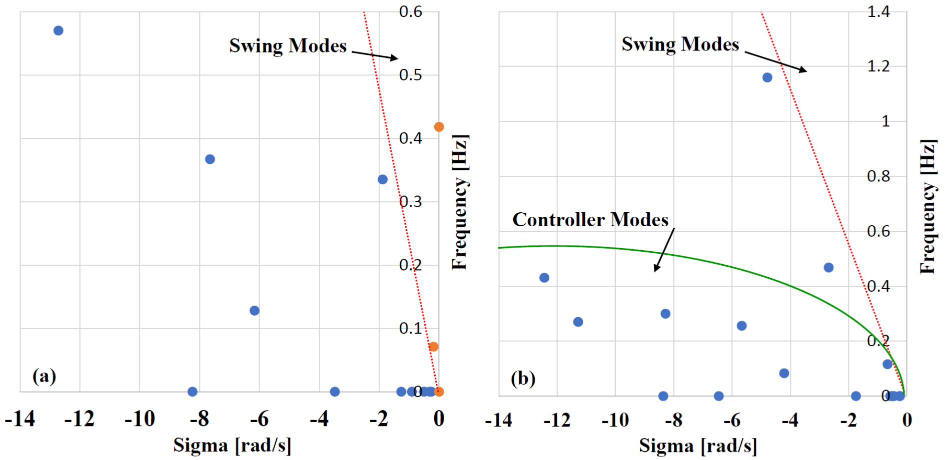
(a) System voltage and (b) frequency profiles for the interconnected SPS to grid

*Badakhshan, S., Rahman, J. and Zhang, J., Black Start of Coastline Power Networks From Grid-forming Ship-to-Grid Services. (under review)

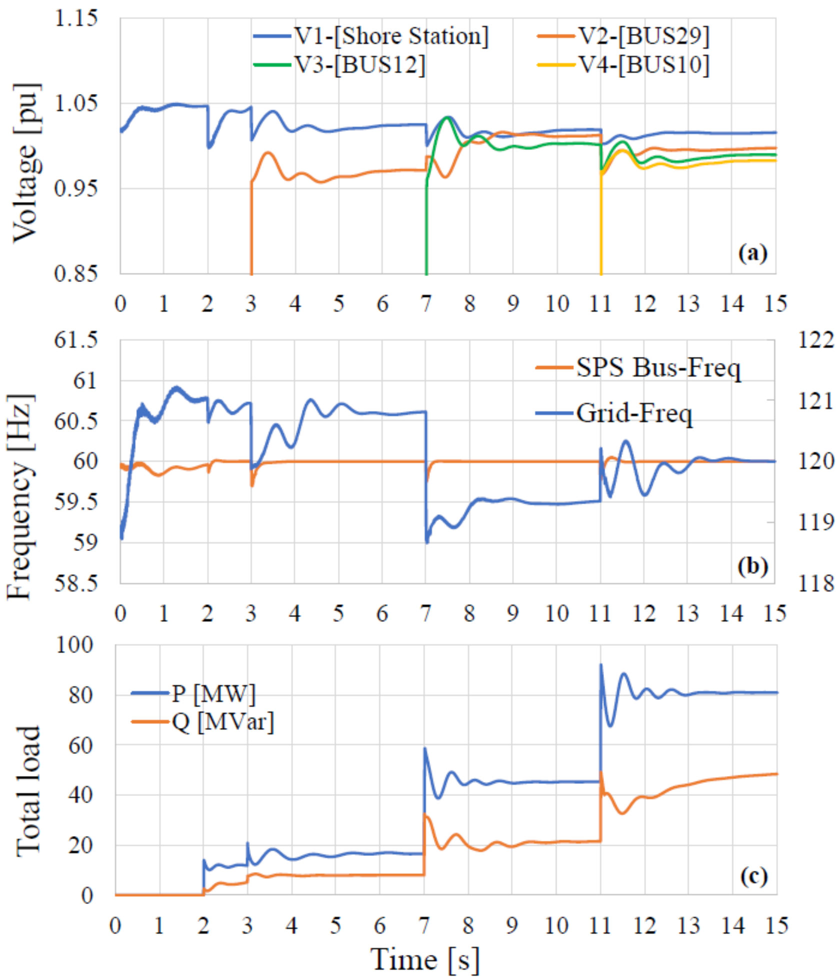
Task III: Terrestrial Power Grid Resilience Enhancement via Ship-to-Grid



Dynamic grid interface of the grid-forming control



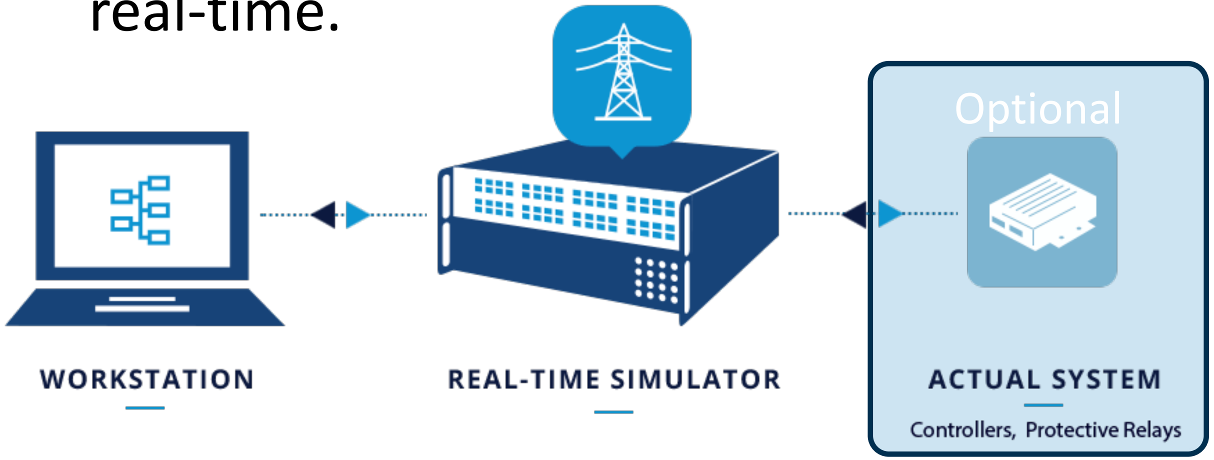
System eigenvalues: (a) Coastline power grid without SPS; (b) SPS interconnected

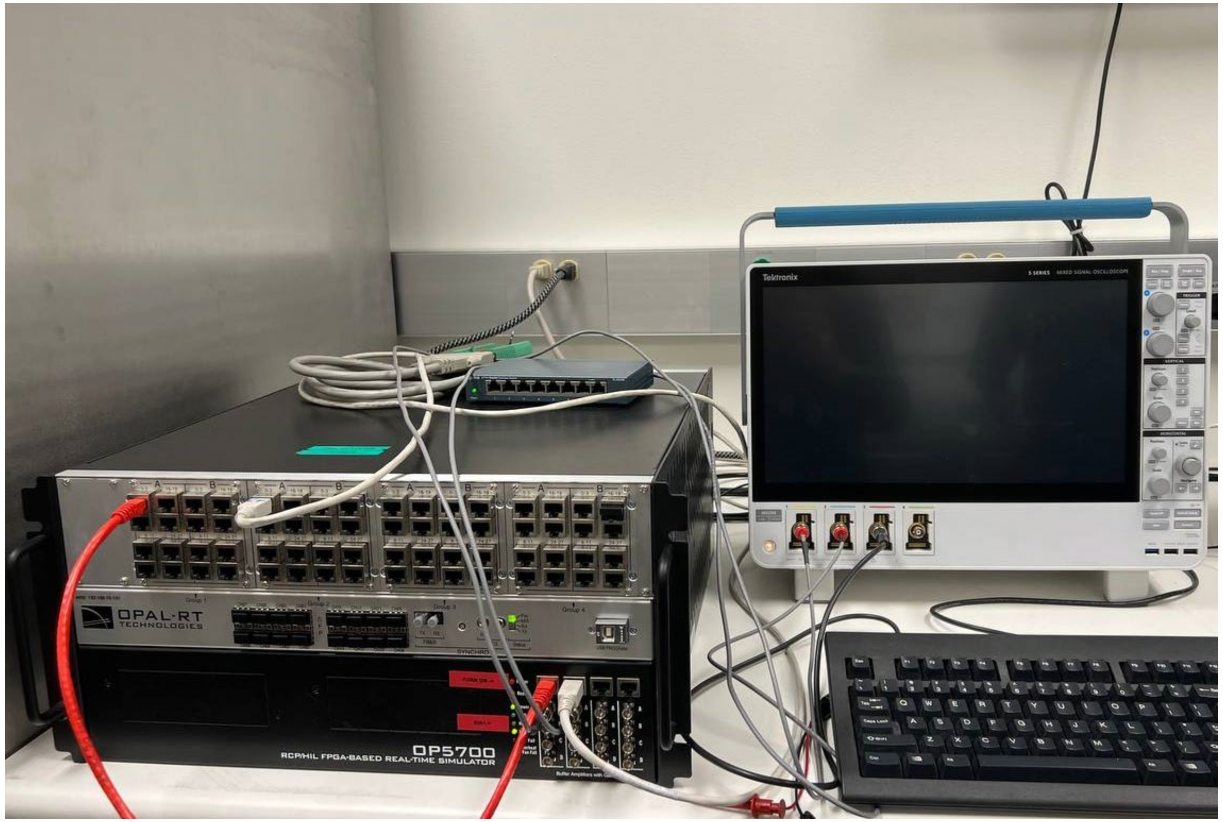


Dynamic simulation results of the black start of the grid with SPS: (a) voltage amplitude of the buses, (b) grid and SPS frequency profiles, and (c) total active and reactive load pick up

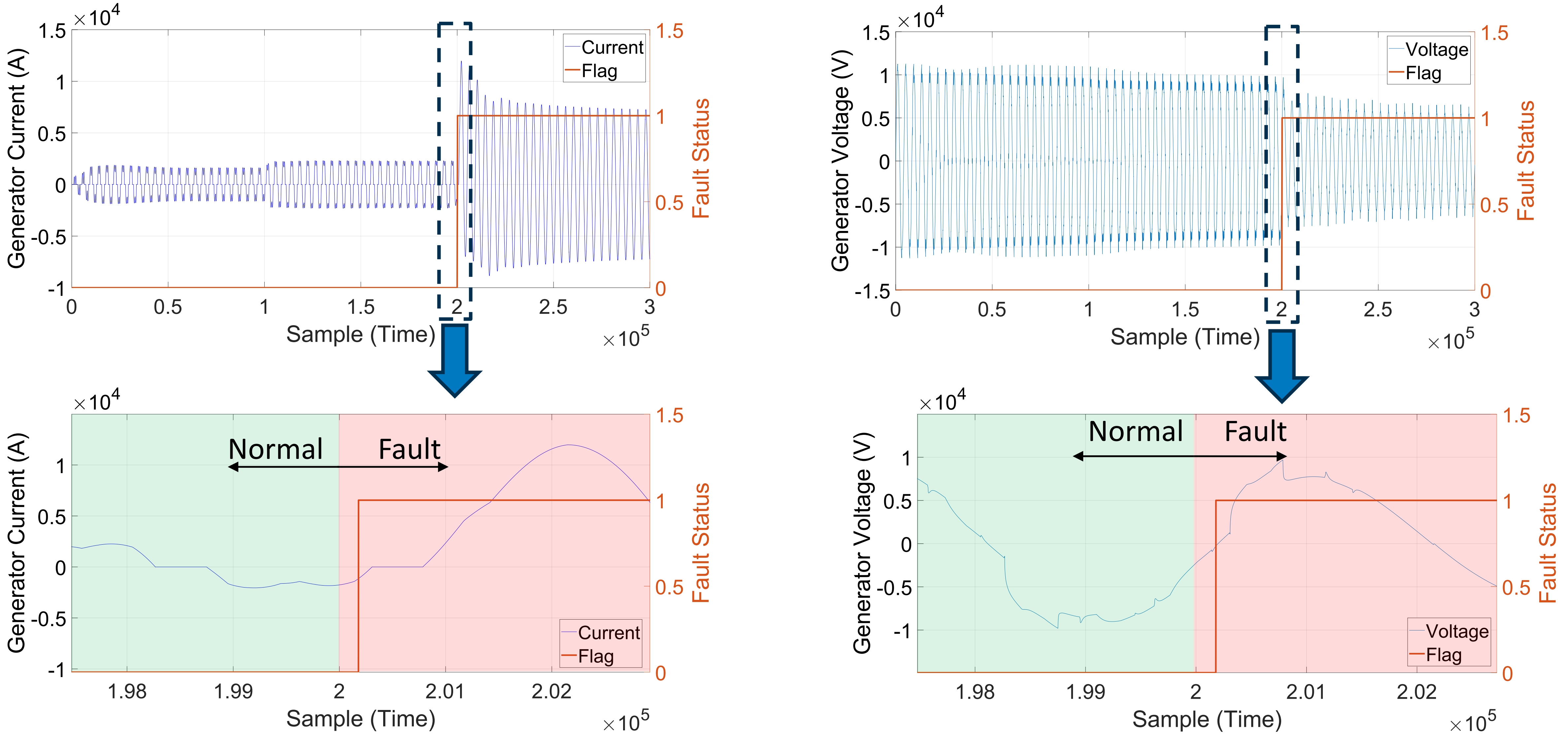
Task IV: Hardware-in-the-Loop (HIL) Test

- HIL simulation involves dedicated hardware, such as FPGA-based simulators, to achieve **high-speed** and **low-latency** real-time simulation.
- OPAL-RT systems are commonly used for **testing and validating** control systems in power systems.
- OPAL-RT real-time simulation has **high fidelity** and **low-latency** performance; thus, it can provide extremely **accurate** and **deterministic** simulation results in real-time.





Task IV: Hardware-in-the-Loop (HIL) Test



Conclusion and Future Works

Conclusion

- A dynamic model of **Small Modular Reactor** was developed and simulated to ensure the reliable operation of future **SMR-based all-electric ships**.
- A thermal electrical model of SMR-based shipboard energy system was developed and the interdependency between thermal and electrical networks was evaluated.
- Case studies showed the proposed SMR-based shipboard energy system can provide **flexible operations** in the presence of **highly variable loads** due to rapid load changes under scenarios such as ship acceleration, deceleration, and under pulse loads or severe weather conditions.
- The SMR-based shipboard energy system could effectively **mitigate the impact of pulse loads** on the shipboard power system and prevent any out-of-range voltage drops or spikes, frequency variations.

Future Works

- Explore advanced control and monitoring systems to study the integration of SMR-based shipboard energy system to the terrestrial power network (Task III).
- Modeling the thermal dynamics of SMR and considering the thermal-electrical dynamics of all electric ships (Task II and IV).

Publications

Journal Papers:

- S. Badakhshan, J. Rahman and J. Zhang, Black Start of Coastline Power Networks From Grid-forming Ship-to-Grid Services, *IEEE Transactions on Smart Grid*, Vol. 15, Issue 2, 2024, pp. 1670-1679.
- Senemmar, S., Jacob, R. A. and Zhang, J., Non-Intrusive Fault Detection in Shipboard Power Systems using Wavelet Graph Neural Networks, *Measurement: Sensors,* 2024. (under review)
- Senemmar, S. and Zhang, J., Wavelet-based Convolutional Neural Network for Non-Intrusive Load Monitoring of Next Generation Shipboard Power Systems, *Measurement: Sensors*, 2024. (under review)

Conference Papers:

- Badakhshan, S., Senemmar, S. and Zhang, J., Dynamic Modeling and Reliable Operation of All-Electric Ships with Small Modular Reactors and Battery Energy Systems, IEEE Electric Ship Technologies Symposium (ESTS), Old Town Alexandria, VA, August 1 - 4, 2023.
- Senemmar, S., Badakhshan, S. and Zhang, J., Dynamic Modeling and Simulation of Thermal-Electrical Energy Systems in MVDC All-Electric Ships with Small Modular Reactors, IEEE Electric Ship Technologies Symposium (ESTS), Old Town Alexandria, VA, August 1 - 4, 2023.

Questions


multidisciplinary
design
optimization
linear
system
failure
solar
data
cost
engineering
deformation
statistical
battery
fidelity
energy
experiments
optimum
surrogate
learning
reliability
evaluation
methodology
decomposition
renewable
mathematical
stochastic
algorithm
exploration
minimization
approximation
objective
criteria
bounds
illustration
complex
equivalence
uncertainty
computing
displacement
probabilistic
metamodeling
wind
inequality
nonlinear
integer
mining
bayesian
gradient
heuristic
storage
discrete
machine
power
recursive
structural
loads
value

IES-NEUP, Integrated Marine Platform for Hydrogen and Ammonia Production

National Reactor Innovation Center

Program Review

April 24, 2024

MIT Energy Initiative

CORE-POWER

Idaho National Laboratory

Diagram of floating nuclear platform: baseload ammonia production, no storage*

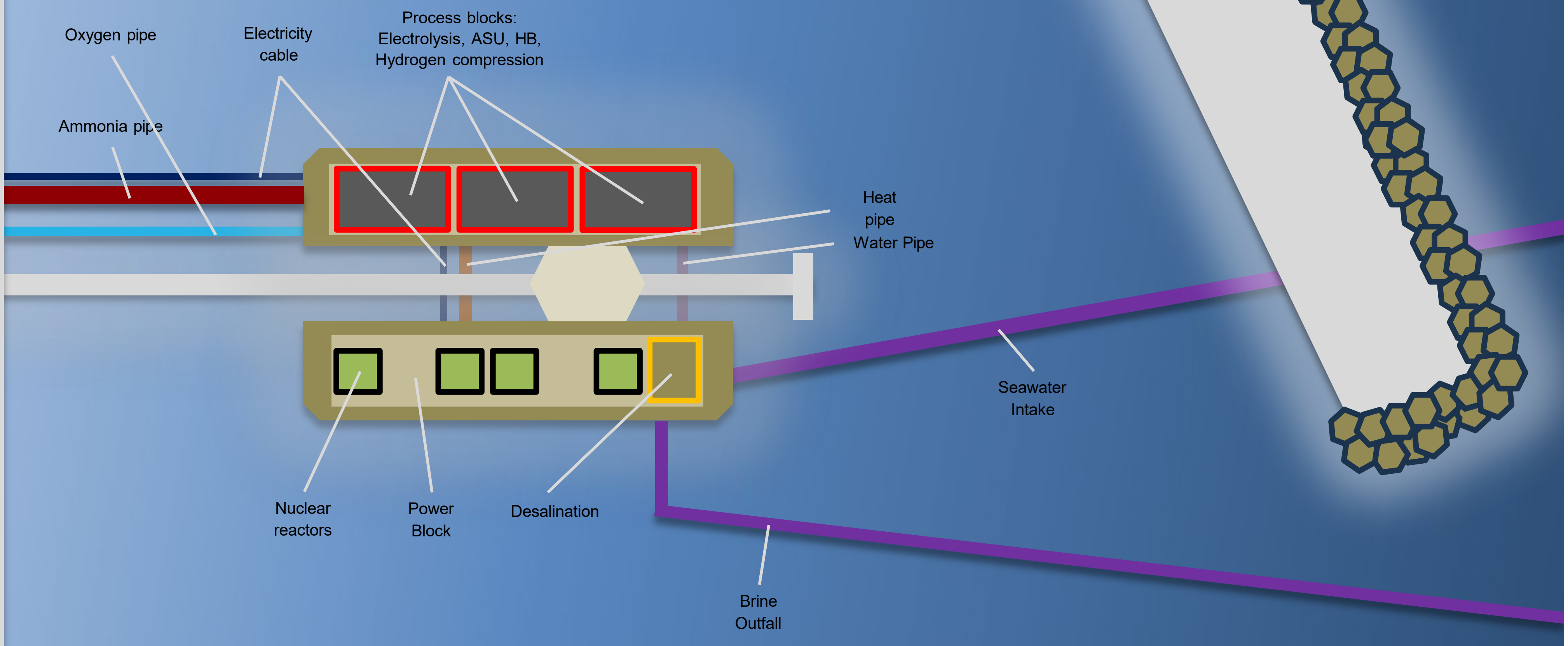


Figure not to scale. Diagram only for artistic purposes, does not reflect the exact final appearance of the platform

Tasks

Task 1. Alternative Configurations.

1. **Siting Options and Regulatory Requirements.**
2. **Storage Options and System Flexibility.**
3. **Evaluating Platform Cost.**

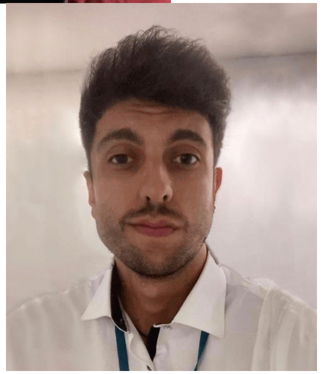
Task 2. Integration to Regional Economy, Grid and Hydrogen Cluster.

1. **Flexibility and Storage Optimization.**
2. **Electricity market model.**
3. **Overall economics.**

Students & Postdocs

Hanna Won
MS, Systems Design and Engineering, '24

Ahmet Kavur
MS, Environmental Systems and Policy & Energy, (ETH Zürich) '24



Heddy Barale
MIT Postdoc
PhD, Nuclear Engineering, CEA Cadarache, France '23

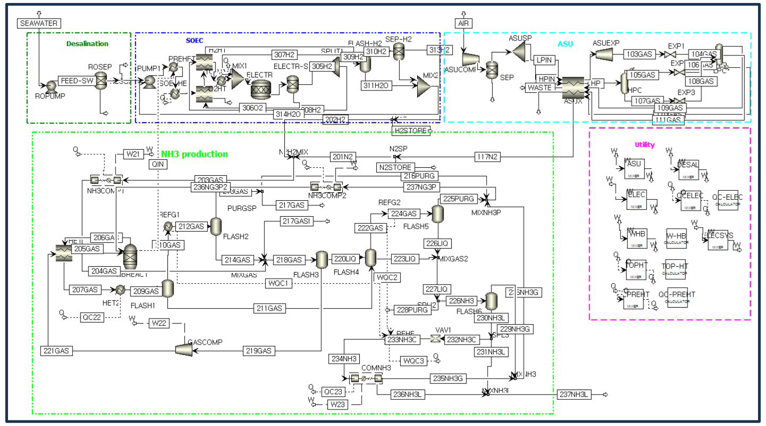
Shealey Callahan
UROP '27

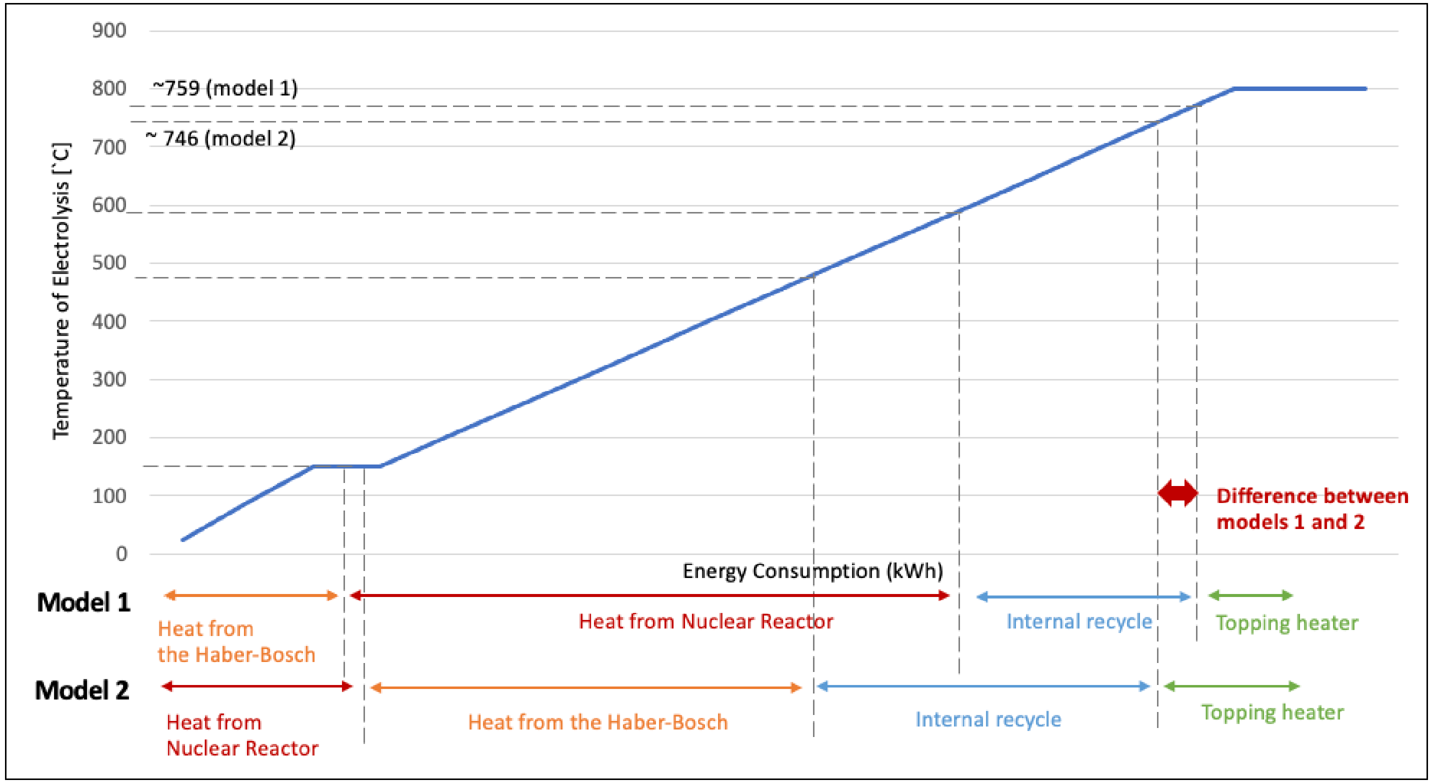
Jakob Byrd
MechE '25

Senior Researchers:
MIT: Dr. John Parsons and Dr. Charles Forsberg
INL: Dr. Abdalla Abou-Jaoude
Core Power: Giulio Gennaro, Thomas Davies, Dr. Rory Megginson, Ioannis Kourasis.

Aspen Process Modeling

	Nuclear reactor	Electrolyzer
Model 1	MSR	HTSE
Model 2	LWR	HTSE
Model 3	MSR	PEM
Model 4	LWR	PEM





Source: MS Thesis (2024), Hanna Won.

Building off of, and benchmarking against:

- Wendt, D., Knighton, L., & Boardman, R. (2022). High temperature steam electrolysis process performance and cost estimates. INL/RPT-22-66117-Rev000, 1867883.
- Wood, R. A., Boardman, R. D., & Patterson, M. W. (2010). Nuclear-integrated ammonia production analysis. Idaho National Laboratory Technical Evaluation TEV-666.

Flexibility

Electrolysis Flex and H2 Storage

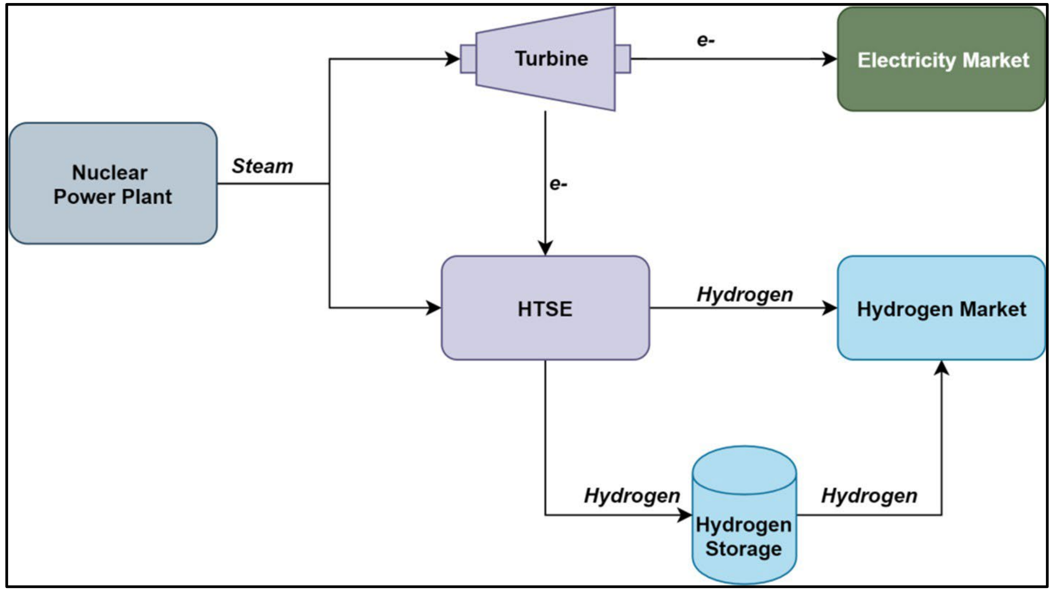


Image credit: (Frick et al., 2022).

Thermal Storage

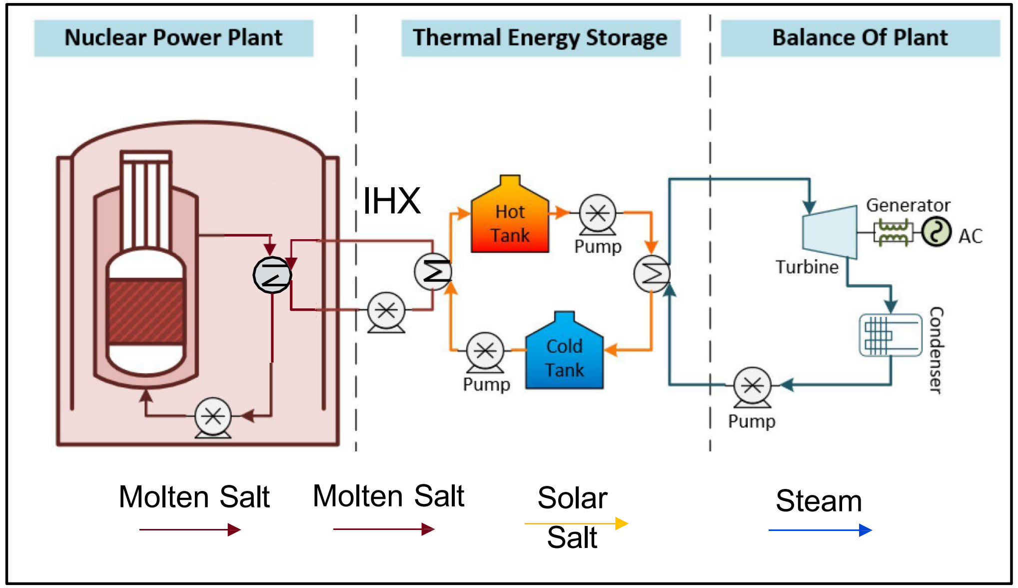


Image credit: (Saeed et al., 2022).

Following and adapting:

- Frick, K., Wendt, D., Talbot, P., Rabiti, C., & Boardman, R. (2022). Technoeconomic assessment of hydrogen cogeneration via high temperature steam electrolysis with a light-water reactor. Applied Energy, 306, 118044.
- Shigrekar, A., Toman, J., & Saeed, R. M. (2023). Synthetic Electricity Market Data Generation and HERON Use Case Setup of Advanced Nuclear Reactors Coupled with Thermal Energy Storage Systems.
- Saeed, R. M., et al. (2022). “Multilevel Analysis, Design, and Modeling of Coupling Advanced Nuclear Reactors and Thermal Energy Storage in an Integrated Energy System.” INL/RPT-22-69214 Rev. 000, Idaho National Laboratory, Idaho Falls, ID..

Techno-Economic Model

Excel-based
DCF model.

Calculates:
- LCO Heat
- LCO Electricity
- LCO Water
- LCO Hydrogen
- LCO Ammonia

Sankey Diagram of the Cost Flows for Ammonia Production

Normalized to the Levelized Cost of Ammonia (2023 PEM - Base Case) [$/ ton NH3]

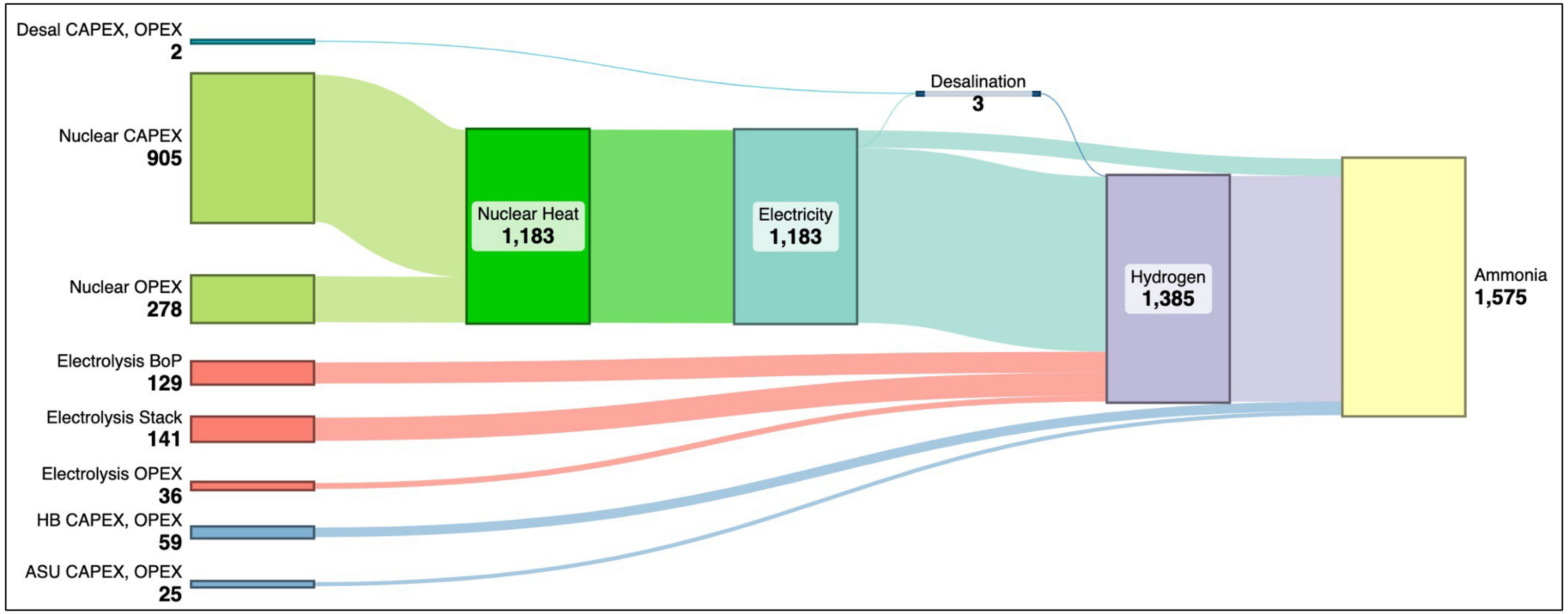


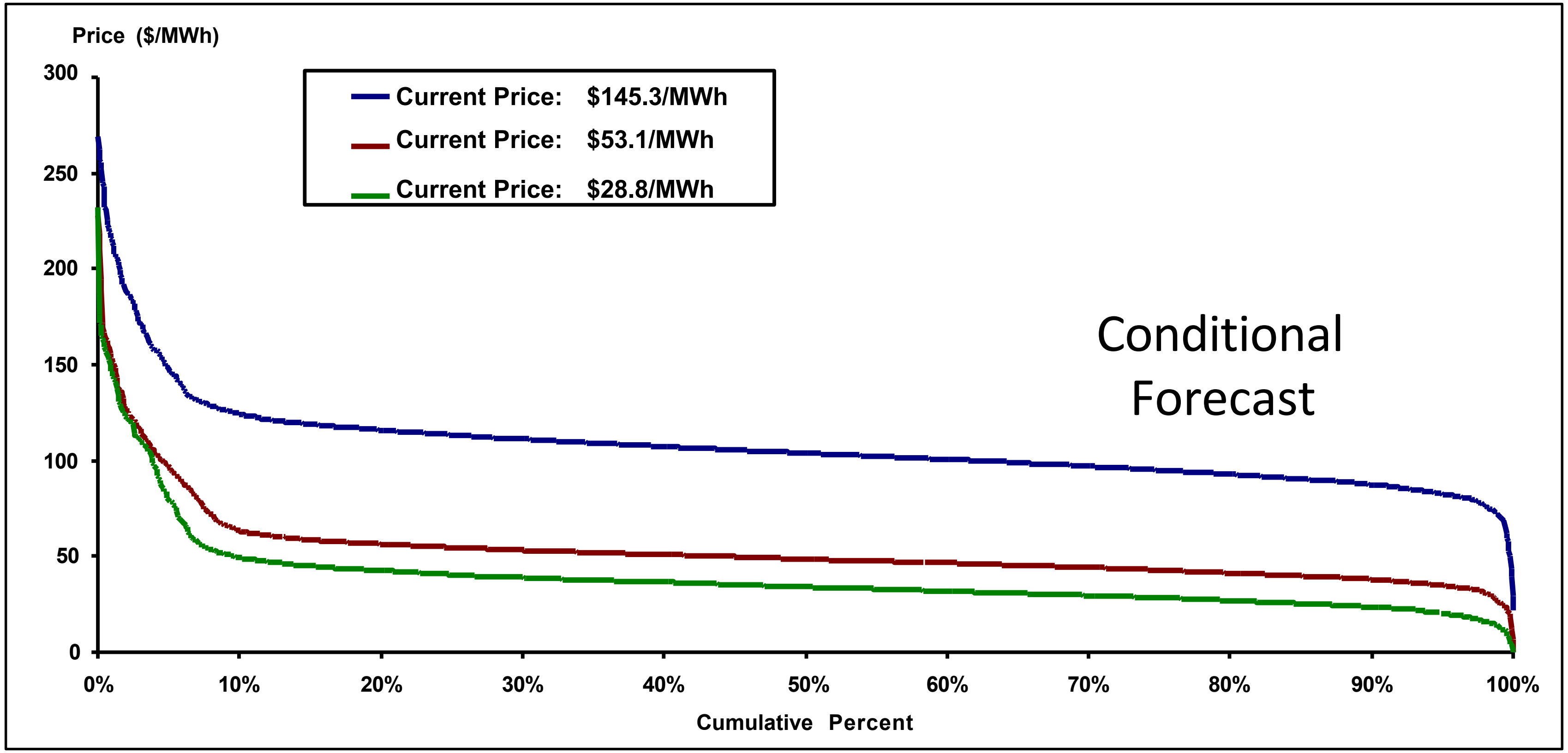
Figure: *Sankey diagram of the cost drivers of Ammonia production by the integrated maritime nuclear system, normalised to the Levelized Cost of Ammonia, given in 2022$ per ton of NH_3 produced*

Source: MS Thesis (2024), Ahmet Kavur, forthcoming.

Electricity Price Modeling

1. Statistical models of historical time series.
    - INL's RAVEN
    - Stochastic process models

2. Structural models of future decarbonized systems.
    - NREL's Cambium
    - MIT's GenX



The End

National Reactor Innovation Center

A Risk Assessment Approach to Transportation Package Approval of a Transportable Nuclear Power Plant For Maritime Shipment

Presented by Harold Adkins (Pacific Northwest National Laboratory)

04/24/2024

Challenge and Context

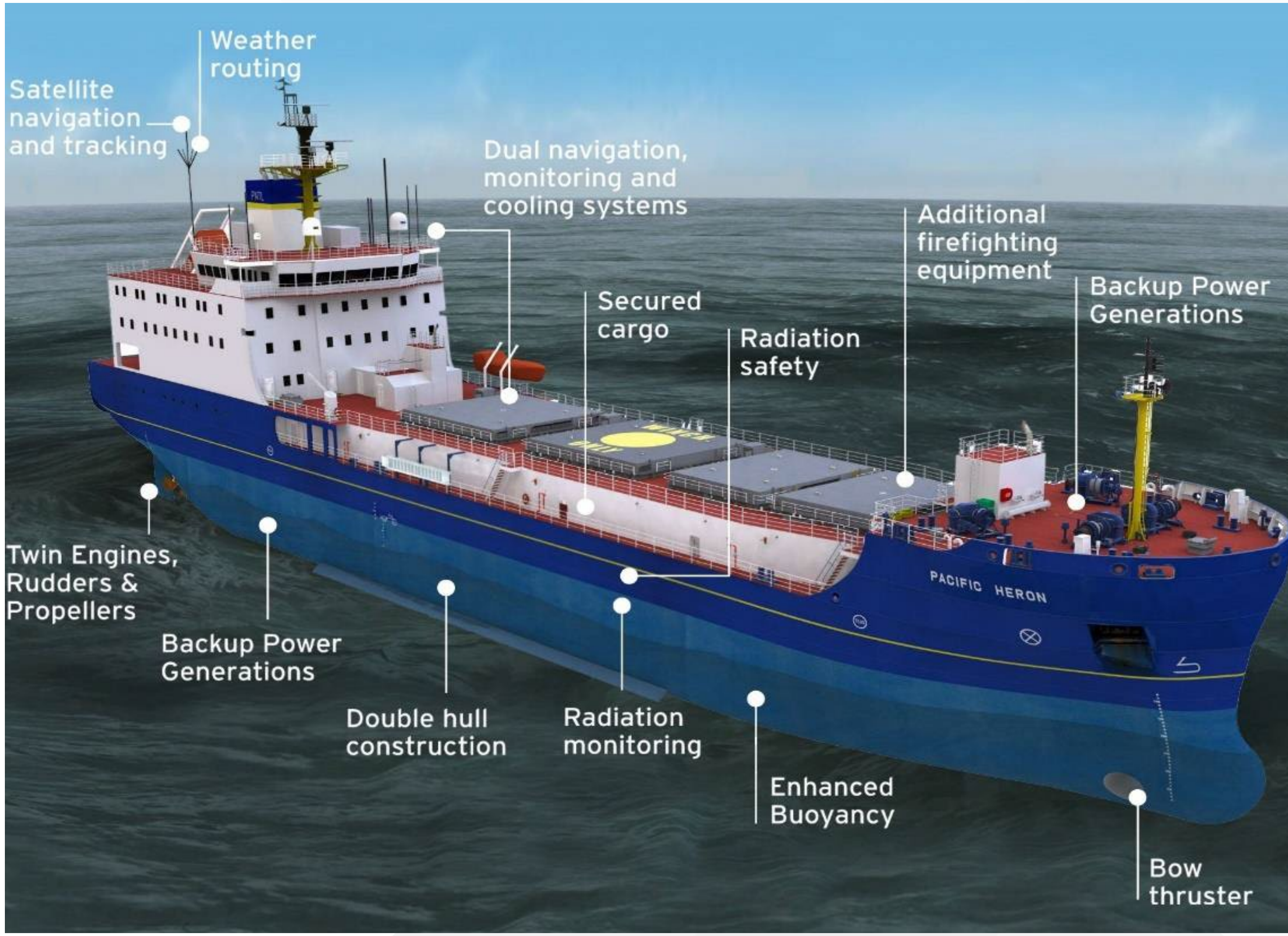
- With respect to licensing, it is anticipated that a transportable nuclear power plant (TNPP) will not meet all Part 71 of Title 10, Code of Federal Regulations (10 CFR Part 71) regulations for maritime shipment due to TNPP functional requirements
- Thus, use of a licensing strategy rooted in a partial exemption request with additional compensatory measures under 10 CFR Part 71.12 is preferred:
  - Use U.S. Navy/Coastguard escorts
  - Use pair of ships for mutual support
  - Avoid congested areas/traffic/ports
  - Training for emergency responders at ports
- Employ a probabilistic risk assessment (PRA) approach in the strategy to show shipping a TNPP would be safe
- Approach would be provided to vendors like BWX Technologies, X-energy etc. who will defend safety basis in their application to the Nuclear Regulatory Commission
- A TNPP is different than a traditional spent fuel package:
  - Would be fueled using Tri-structural ISOtropic particle fuel (TRISO), less than 20 MW thermal, factory preloaded w/fresh fuel
  - Type AF package initially→ Type BF when used, no refueling in the field
  - Would be akin to a radioactive material (RAM) package/CONEX box

Background and What's Been Done

- PRAs have been used for nuclear reactors & storage systems since the 1970's (e. g. WASH-1400, NUREG-1935, NUREG-2125 etc.) and environmental impact study (EIS) repository work. SAND98-1178 (1998) developed a maritime PRA
- Maritime strategy builds on similar highway efforts by Maheras et al. (2021)/Cole (2022). Current presentation details can be found in the report by A. Rigato et al. (2024)
- Previous maritime PRA focused on accident scenarios that could seriously challenge a transportation package (fire & ship-to-ship collisions). These are adopted in this work
- TNPP expected to ship on a Class INF 3 ship. Nuclear Transport Services (NTS) is main source of data for current maritime strategy. NTS:
  - 50+ years of shipping (and rail), over 5,000,000 nautical miles (NM) sailed
  - Only global shipper of Cat. 1 material (highly enriched uranium, spent nuclear fuel, mixed-oxide fuel, etc.)
  - NTS has four Class INF 3 ships, Department of Energy (DOE) only ships Category 1 material with NTS
  - Has shipped thousands of metric tons of spent fuel, 2000+ casks
  - No reported incidents such involving fire/collision
  - 180+ shipments using Class INF 3 ships

Ship Features

- NTS Class INF 3 ships (4 total):
  - Purpose built
  - Improved stability/fire protection
  - Double hulled
  - Temperature control for cargo
  - Crew/emergency training
  - Radiological equipment protection
  - DOE only ships Category 1 material with NTS
  - Twin engines/rudders/propellers
  - Satellite navigation/tracking/backup communication
  - Spare electrical supplies
  - Enhanced buoyancy
- Liquid natural gas/liquid petroleum gas (LNG/LPG) tankers share similar features (double hulled construction, well trained crew). LNG/LPG used as surrogates for nuclear fuel carriers in prior work



NTS' Pacific Heron

NRIC National Reactor Innovation Center

Approach and The Need for More Data

- Key is to show casualty rates per nautical mile of travel for ship-to-ship collisions and fire related events are exceedingly small, and thus potential radioactive material release rates are small, allowing a strong safety basis to be demonstrated in an application
- PRA scenario/considerations (event tree) include:
  - Whether TNPP carrying ship is struck/TNPP hold is struck
  - Whether a TNPP could be damaged
  - Fire starts on TNPP carrying ship/spreads to TNPP hold
  - Any casualty rate sensitivity to route/port
  - TNPP carrying ship sinks
  - Approach also employs fire spread model, radioactive release model, consequence of release model
- Previous maritime effort is 25+ years old (SAND98-1178 [1998]). Used LNG and LPG casualty data as a surrogate for radioactive material carriers. Need updated data and ideally, nuclear fuel carrier data

New Data and Analysis

- Use S&P Global data via Maritime Portal (online). It has:
  - Casualty data for nuclear fuel carriers (13 active) in addition to 200+ other types of ships (LNG, LPG tankers, yachts, fishing vessels etc.) going back to 1950 or so. Available casualty data includes pirating, foundering, fire, etc.
  - Ship characteristics (weights, shipbuilder, engine specs, dimensions, flag, year built etc.) for nearly 160,000 ships
  - Movement data (goes back 15 years for many ships). Automatic Identification System (AIS) Live tracking info for many ships (1 year's worth on average) and shows active location on global map.
- Calculate total distance travelled by all nuclear fuel carriers for past 15 years based on ports visited, using Veson Nautical tool (Maritime Portal). Casualties divided by total distance is the casualty rate per nautical mile.

Results

- NTS Global
  - No incidents of fire or collisions over 50+ years of operation with 5,000,000+ NM of travel
- S&P Global (nuclear fuel carriers):
  - No incidents of fire
  - No collisions in past 25 years. Three collisions were reported prior to 1999 (2 while ships were moored). Minor ship damage reported. Not clear if carrying any cargo
  - 1,200,000+ NM of estimated travel in past 15 years
- LNG/LPG rates calculated using S&P Global data, compares well to SAND98-1178 / Gucma and Mou (2022). LNG/LPG rates are assumed to be conservative

S&P Global Casualty Data from 2008-2022

Quantity	Accident/Nautical Mile
Liquefied Natural Gas (LNG) Fire Rate	3.0×10^{-9}
Liquefied Propane Gas (LPG) Fire Rate	6.5×10^{-8}
LNG Collision Rate	2.8×10^{-8}
LPG Collision Rate	1.4×10^{-7}
Nuclear Fuel Carrier Collision Rate	0.0
Nuclear Fuel Carrier Fire Rate	0.0

Conclusions and Next Steps

- Radioactive material shipments using Class INF 3 ships have been, and continue to be, very safe. This is supported by S&P global casualty data for nuclear fuel carriers. NTS data should be used as the cornerstone for a licensing strategy for maritime shipment of a TNPP supported by S&P Global data
- Important to note that potential release/consequence rates are smaller than tabulated accident rates above. A specific fragility model of the TNPP itself has not been defined but can be adopted easily, as can a specific vessel model
- PRA approach is intended to be living and breathing in nature. Events can be added/eliminated, TNPP fragility model can be added when information becomes available. Newer fire spread models, release models, etc. can all be incorporated easily in this approach
- Approach can be extended to air transport

Questions?

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