INL/MIS-24-76771-Revision-0

National Reactor Innovation Center Update

February 2024

Changing the World's Energy Future

Bradley John Tomer

Idaho National Laboratory

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

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National Reactor Innovation Center Update

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February 2024

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NRIC National Reactor Innovation Center

National Reactor Innovation Center Update

Brad Tomer

Acting Director, Chief Operating Officer

nric.inl.gov

01/25/2024

NRIC is a DOE program, launched in FY'2020

NRIC Enables Nuclear Reactor Tests & Demonstrations

- Authorized by the Nuclear Energy Innovation Capabilities Act (NEICA)
  - DOE-Office of Nuclear Energy; INL Nuclear Science & Tech
- Partner with industry to bridge the gap between research and commercial deployment
- Leverage national lab expertise and infrastructure

Vision: Enable commercial advanced nuclear by 2030

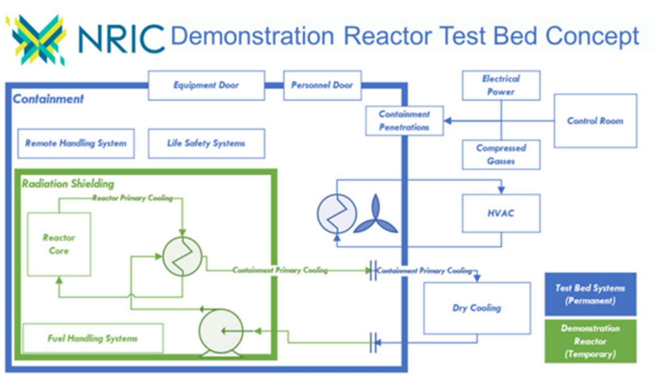
NRIC National Reactor Innovation Center

NRIC Testbed Strategy

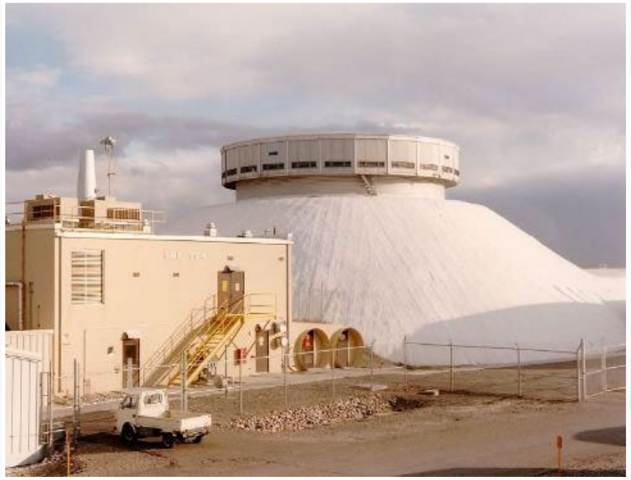
NRIC-DOME Testbed

- EBR-II Operated from 1964 to 1994
  - 62.5 MW thermal
- Repurposing EBR-II as NRIC-DOME
  - <$20MW_{th}$ <20% enriched fuels
  - Final design complete
  - Construction began 2023
  - First user expected 2026

Materials & Fuels Complex at INL



NRIC-LOTUS Testbed



- ZPPR Operated from 1969 to 1990
  - Used for transuranic and enriched-uranium material inspection/repackaging and experiments
- Repurposing ZPPR Cell as NRIC-LOTUS Testbed
  - Small KWth reactors
  - >20% enriched fuels
  - Conceptual design phase complete
  - Preliminary/Final Design Initiated
  - First user expected 2027/2028

NRIC National Reactor Innovation Center

Portfolio Designed to Empower Innovators

- Building foundation for testing
  - Advanced Reactor Test Beds
  - Experimental Facilities
  - Virtual Test Bed
- Addressing Costs & Markets
  - Advanced Construction Technologies
  - Digital Engineering for Nuclear
  - Maritime Applications

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NRIC-DOME Test Bed

(Demonstration of Microreactor Experiments)

Test Bed Ecosystem:

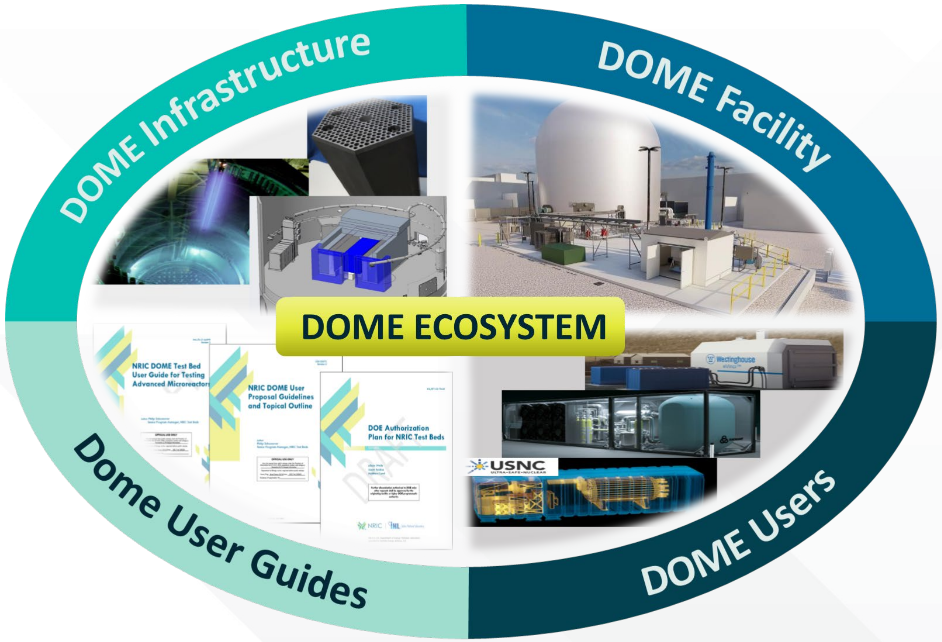
- DOME structure & Modular reactor shielding
- Complete end-to-end support equipment & user guide covering all stages of testing a reactor from design to decommissioning irradiated fuel & equipment

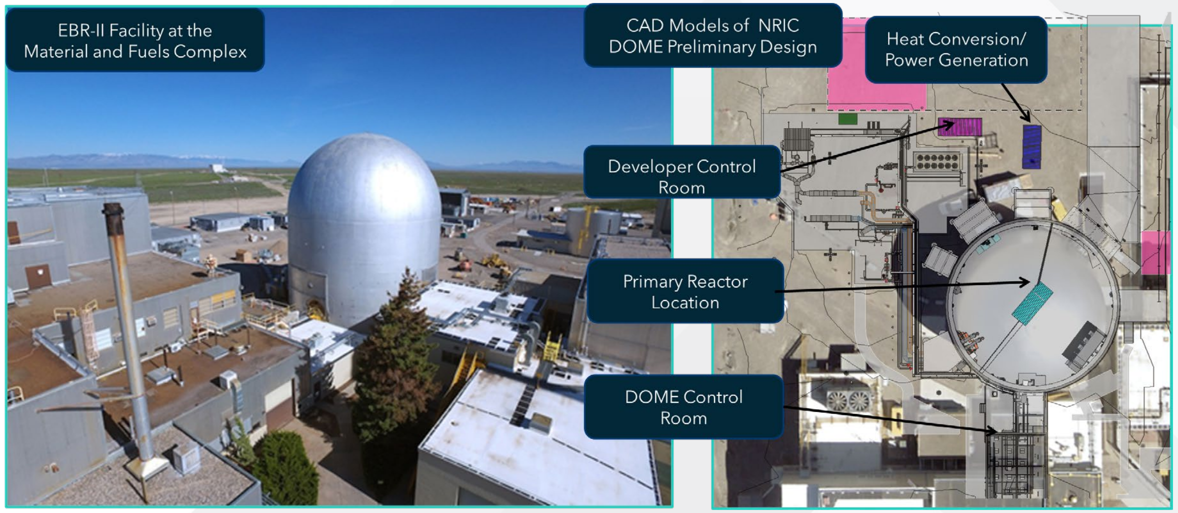
FY 23 Progress:

- Initiated construction and issued first user guide
- Streamlined reactor authorization process w/DOE-ID approval
- Secured pivotal agreements for fresh & irradiated fuel & reactor storage (CPP 651 and RSWF)
- Completed supplemental shielding conceptual design

Next Steps:

- Complete DOME construction – June 25
- Complete supplemental shielding fabrication – Jan 26
- Complete Operational readiness – June 26
- First reactor installed - 2026

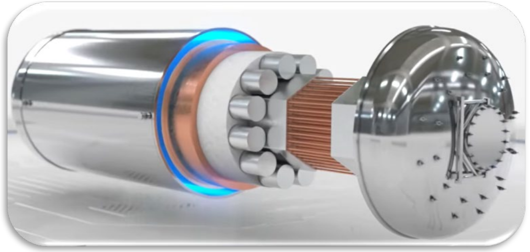


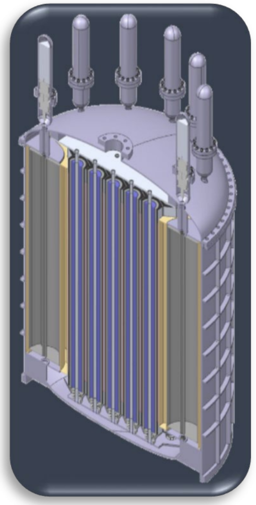


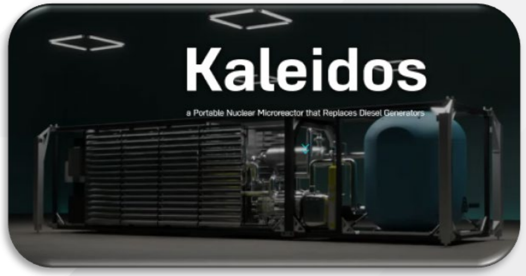
Front End Engineering & Experiment Design

- $4.5M in DOE-HQ funding w/NRIC issuing EOI/RFP
- 11 EOI responses and 5 RFP responses
- Conducted process in <5 months and awarded 3

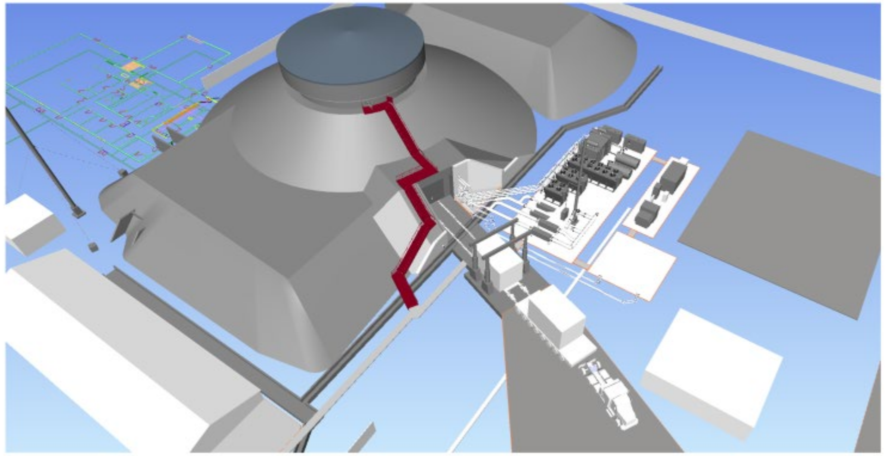
Developer	Reactor Name	Design	Power Mwe	Power MWth	Fuel Type	Fuel Enrichment	Primary Coolant	Moderator	Refueling Interval (Years)	Power Conversion System
Radiant	Kaleidos	HTGR	1.2	3.5	TRISO	19.75%	Helium	Graphite	6	Brayton Cycle
USNC	Pylon	HTGR		1	TRISO	9.90%	Helium	Graphite		Rankine
Westinghouse	eVinci NTR	Heat Pipe	1	3	TRISO	19.75	Sodium	Graphite	8	Brayton Cycle


Westinghouse - eVinci





NRIC-LOTUS Test Bed



Description

- Advanced Microreactors up to 500kW$_{th}$ using HEU
- 13ft X 13ft side entry
- 50kWth Ventilation: standalone/upgraded/neg pressure/stack
- Provides Safety-Class confinement
- 480V / 400Amp electrical Service
- ≈ 30ft diameter floor space with a 20ft ceiling, includes a recessed pit area.
- Designed up to 500kW$_{th}$ direct reactor cooling

Funding Profile

	Major Project Area	FY23	FY24	FY25	FY26	Notes
LOTUS Construction	LOTUS TEC Line Item	$22.25M	$32M	$18.75M		Total $73M
	Other Project Costs	$1M	$3M	$9M	$7.64M	Total $25M including FY21 and FY22 CO
	Totals	$23.25M	$35M	$27.75M	$7.64M	

- Cost Estimate: $66M low, $77M point; $98M high (budgeting number)
- LOTUS design & construction is a capital line-item project
- The project is managed as a 413.3B project with Gerardo Islas-Rivera as the Federal Project Director and Contracting Officer Representative; NE-3 is the Project Management Executive

Schedule
(Performance Baseline to be set at CD-2/3)

- Conceptual design completed - 12/21
- CD-0 (Mission Need) approved - 3/22
- CD-1 approved - 6/23
- Awarded prelim/final design - 6/23
- Final design complete - 4Q/FY24
- CD-2/3 approve baseline /start construction - 1Q/FY25
- Construction finish - 1Q/FY27
- Operational readiness - 4Q/FY27

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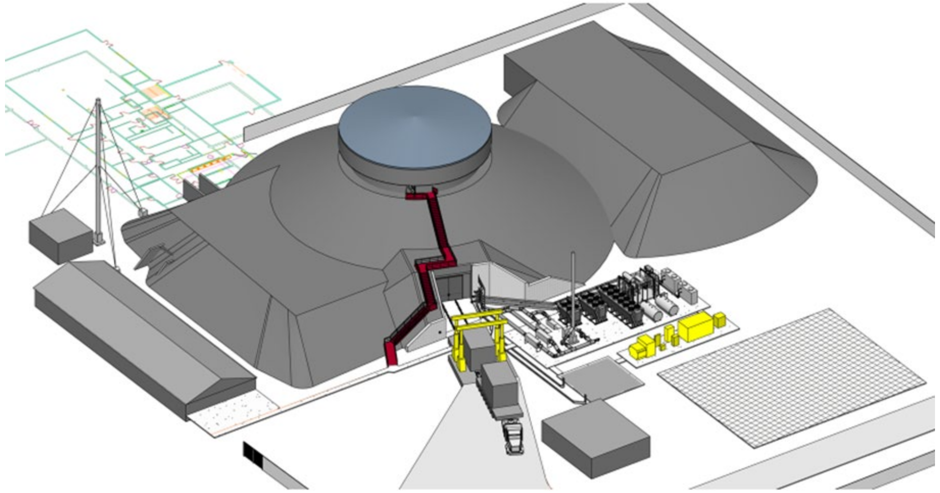
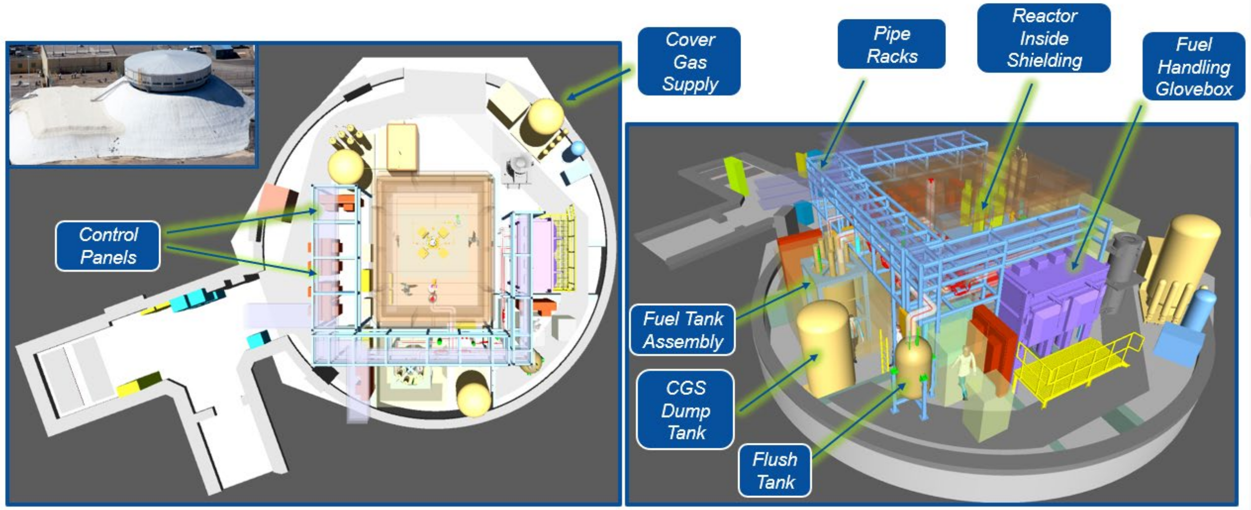
LOTUS Test Bed & MCRE Integration

Laboratory for Operation and Testing in the United States

- Maintaining collaboration on interfaces, design requirements, concept of operations
- Includes interfaces and requirements for the MCRE ARD aspects (reactor, shielding, fresh fuel canister, irradiated fuel canister, fueling glovebox)



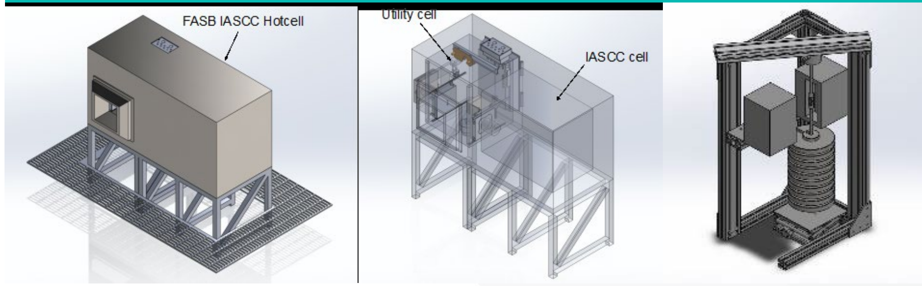


Continued MCRE ARD 3D digital integration and interface management work reduces the risk of any installation delays or infrastructure misalignment between LOTUS and MCRE.

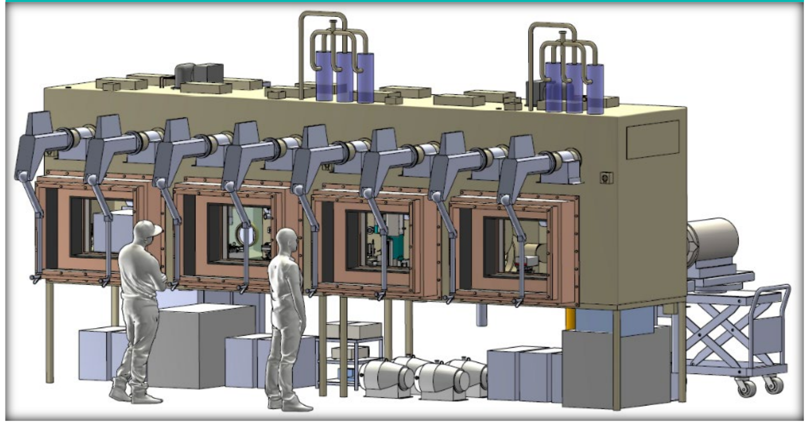
NRIC Experimental Infrastructure

Helium Component Test Facility [*2022*]

In-HotCell Thermal Creep Frame [*2025*]



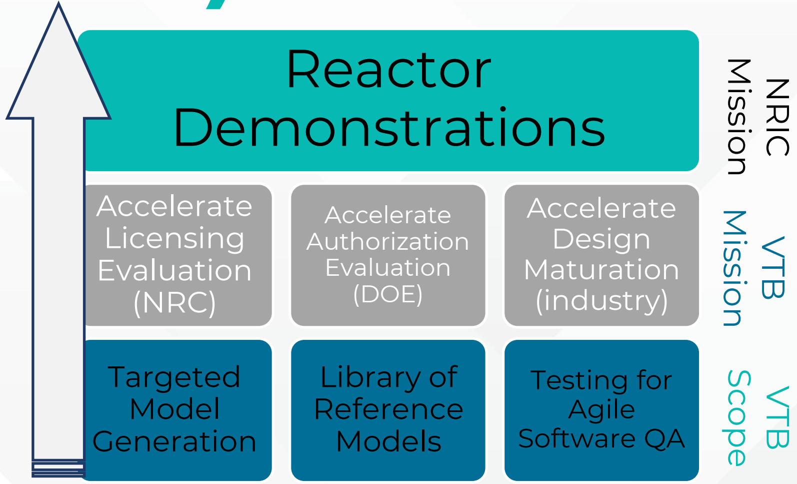
Molten Salt Thermophysical Examination Capabilities (MSTEC) [*2024*]

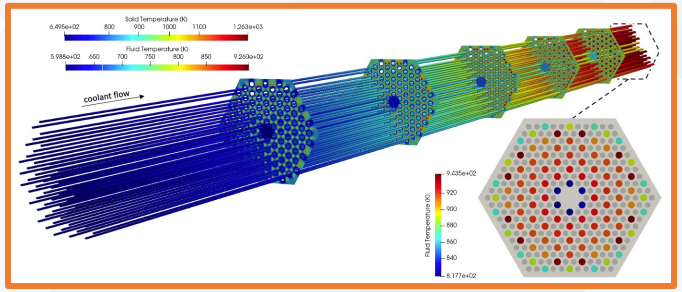


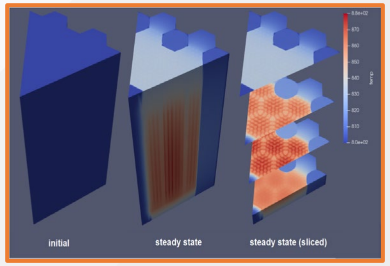
Mechanisms Engineering Test Lab (METL) [Operating]

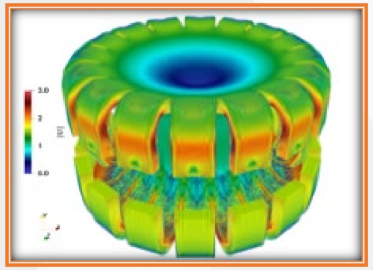
NRIC – Virtual Test Bed (VTB)

- Central location for reactor developers/stakeholders to access & leverage state-of-the-art ModSim models of advanced reactors to evaluate performance & safety
- Cross-laboratory and cross-program collaboration between NRIC and DOE Nuclear Energy Advanced Modeling and Simulation (NEAMS) program
- Repository/library of simulations for: sodium, gas, lead, micro, and molten salt reactors (continuously tested)
- Currently hosting 38 distinct models with 12 NEAMS codes showcases… **More coming soon!**
- Averaging ~250 visits/month (period between July-Sep 2023) – representation from Industry/Regulators/Academia
- FY23 –
  - Uploaded 19 new models to repository
  - Developed reference microreactor and MSR model for DOME and LOTUS testbeds respectively - MSR model already being leveraged for MCRE ARD confirmatory analysis
- FY24
  - Develop virtual model of the NRIC physical test bed (DOME) to accelerate the process for confirmatory safety analysis of future reactor tests
  - Continue uploading models from external programs to the VTB (NEAMS, ART, NRC, etc.)
  - Improve searchability of models and enable large scale testing on the INL HPC system



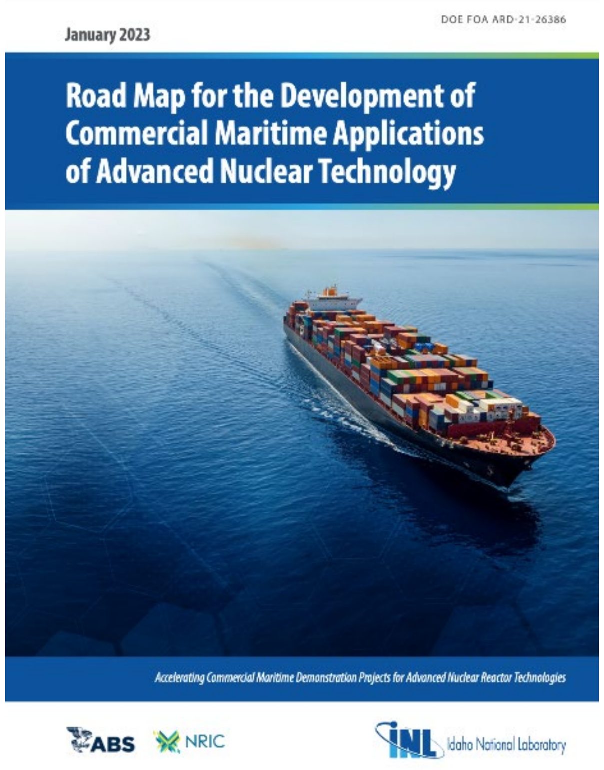






Addressing Cost and Markets

- Advanced Construction Technologies
- Digital Engineering & Knowledge Sharing/Lessons Learned
- Demonstration/Deployment Opportunities (Maritime)

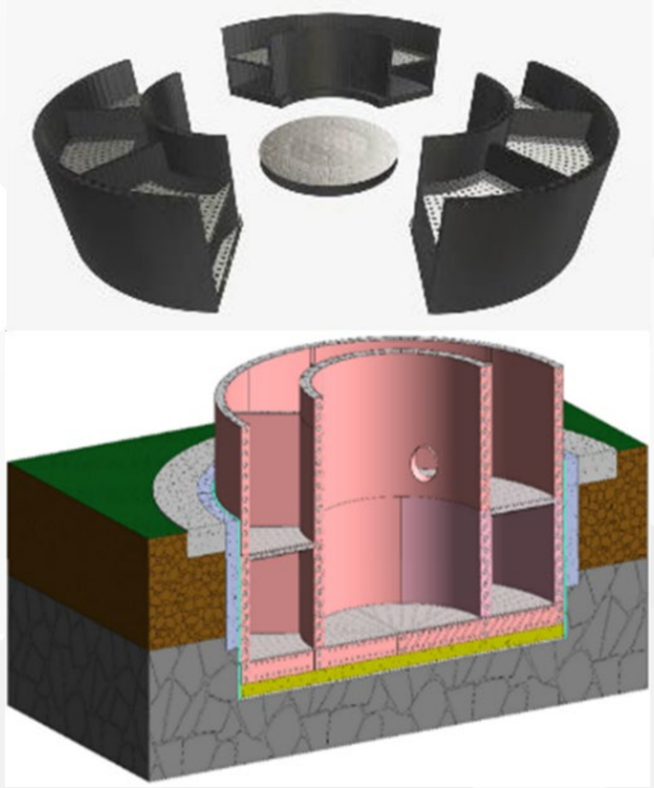

January 2023

DOE FOA ARD-21-26386

Road Map for the Development of Commercial Maritime Applications of Advanced Nuclear Technology

Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies

ABS NRIC INL Idaho National Laboratory



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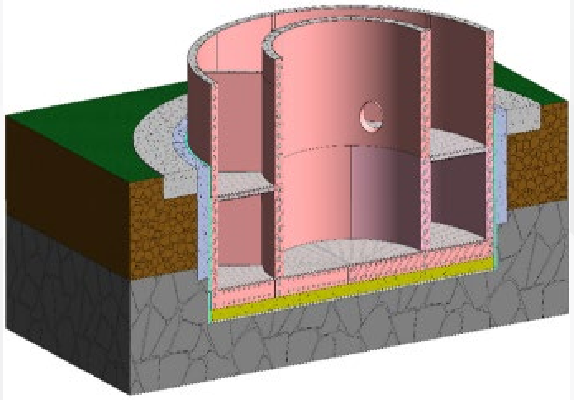
Advanced Construction Technology

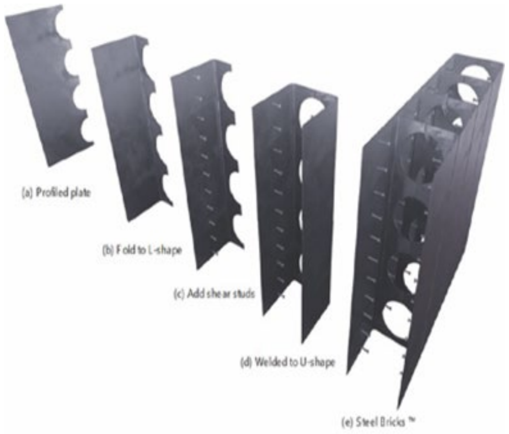
- **Cost Shared Project Awarded – January 2022**
- **Team - General Electric Hitachi**
  - EPRI, Black & Veatch, Purdue, UNCC, Nuclear Advanced Manufacturing Research Centre, Caunton Engineering w/Modular Walling Systems Ltd and Tennessee Valley Authority
- **Purpose - demonstrate technologies to:**
  - Reduce the cost of new nuclear builds by >10 percent
  - Speed the pace of advanced nuclear deployment
- **Two phase cost-shared project w/demo in FY2025**
  - Vertical shaft excavation techniques
  - Steel Bricks^{TM}
  - Advanced monitoring & digital twin technology



Steel Bricks is a trademark of Modular Walling Systems Holdings Limited

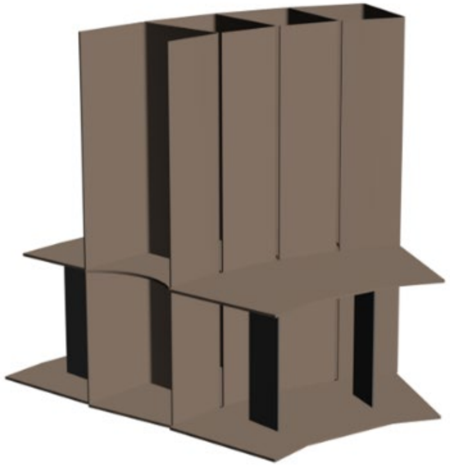
Steel Brick™ Concept

Next generation Steel Concrete Composite modules, for Seismic Category 1 structures installed in a radial configuration



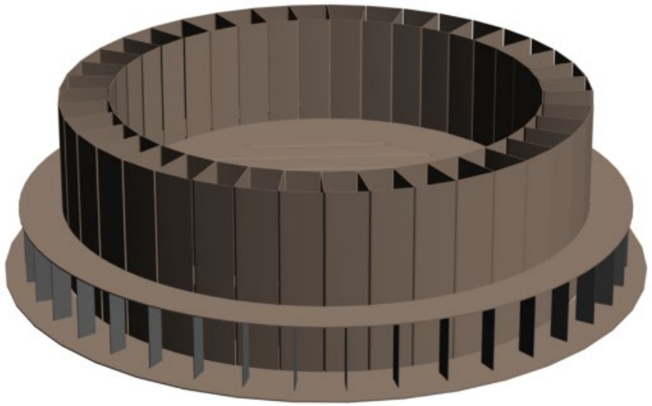
Steel Brick™ Fabricated at Shop

Concurrent wall fab and excavation
Reduced schedule duration



Steel Brick™ Modules
Shipped to site

Reduced onsite work
Improved quality
Less rework



Assembled in field, outside of pit, lowered into pit

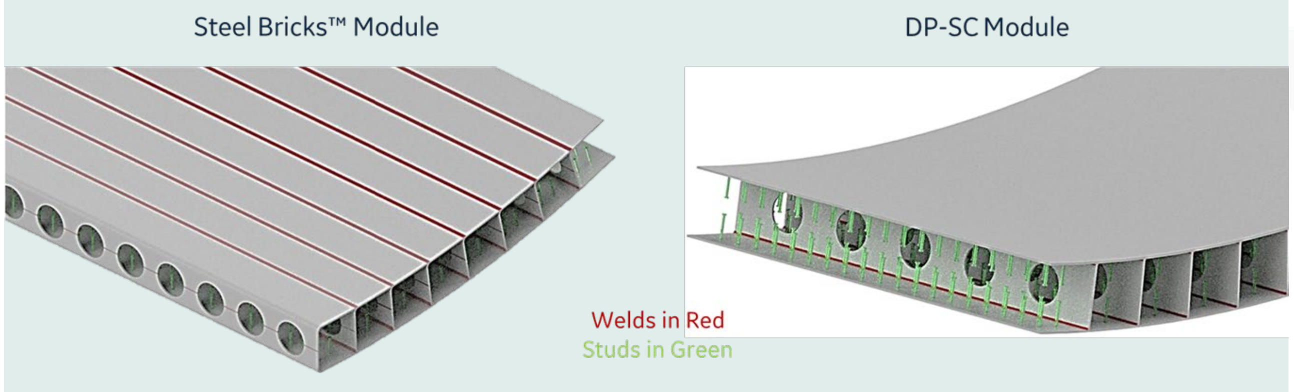
Phase I Accomplishments:

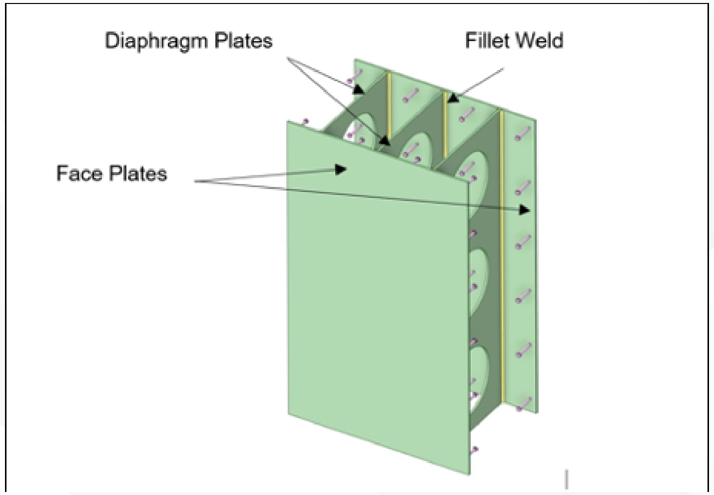
- Proved concept of fabricating Steel Bricks™ assemblies in factory setting demonstrating the ability to achieve tighter tolerances than conventional methods:
  - Demonstrated NDE methods to inspect the concrete for voids inside a steel encased brick
  - Developed welding methods using automatic devices to improve quality
  - Demonstrated the strength of Steel Bricks™ assemblies and diaphragm plate SC structures in general exceed values calculated using N690 equations
- Determined vertical shaft construction readiness using secant piles and diaphragm walls
- Established digital twin and monitoring techniques:
  - Demonstrated digital image capture of fabricated walls; confirmed digital twin technology use to evaluate the tolerances of assembly
  - Selected technology to record and evaluate ground motion pressure and movement against reactor building
- Pivoted design from Steel Bricks™ to Diaphram Plate Steel Composite (DPSC) saving $40M for Phase II
- Fully engaged NRC through the rotations of Fred Sock and Allen Fetter from NRC to NRIC

NRIC National Reactor Innovation Center

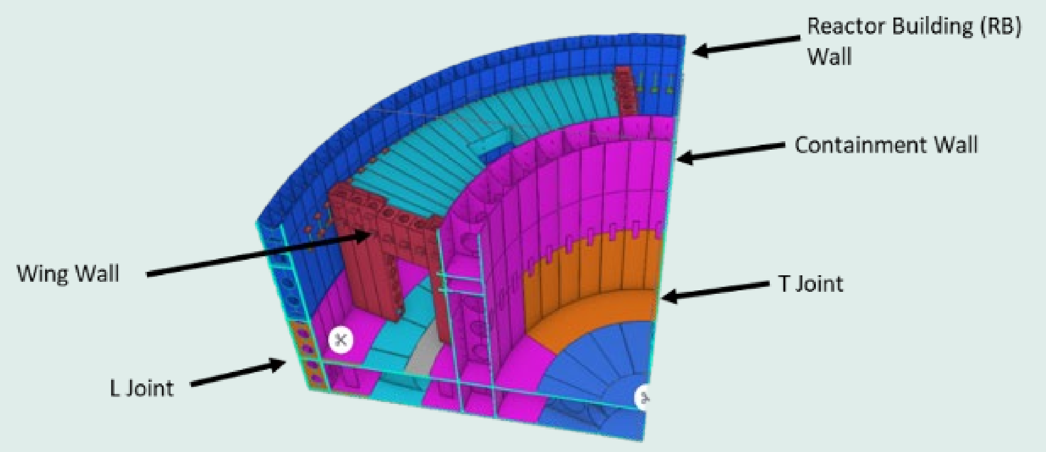
Next Steps

Design Pivot to Diaphragm Plate Steel Composite





- Extended phase I to July 2024
  - Fabricate and test DPSC
  - Establish design for phase II
- Award phase II for estimated 18 months
  - Build and test structure at Clinch River
  - Dissemble and decommission



Digital Twin – Advanced Construction

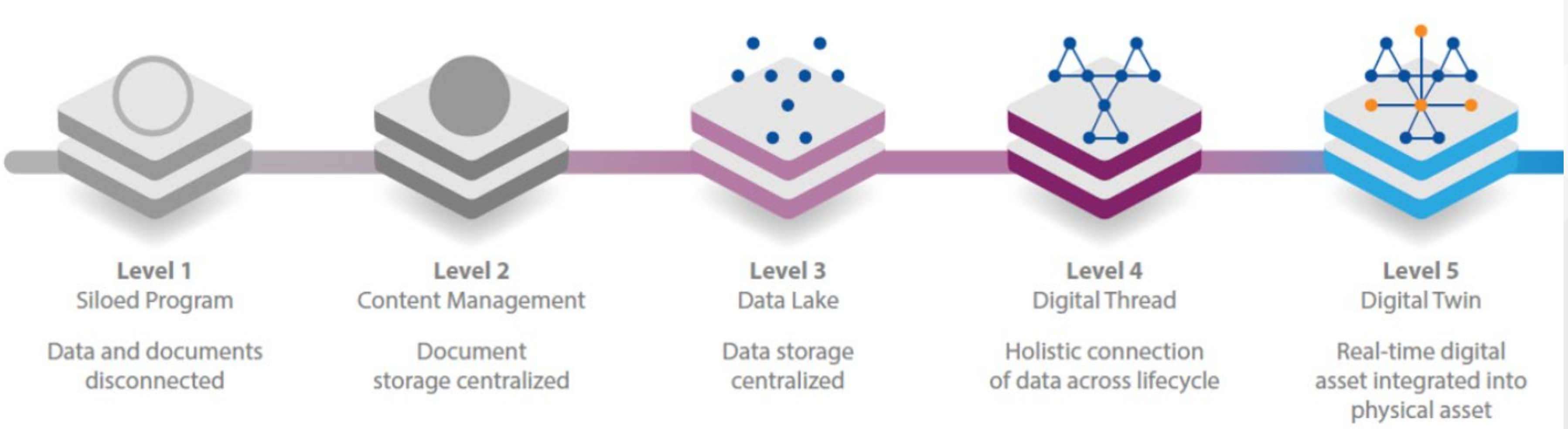
- State of the art replica of the structure to integrate sensor data, artificial intelligence, machine learning, and data analytics. Cradle to grave monitoring
- EPRI, University of North Carolina Charlotte, Nuclear AMRC
- Organizes all project data by component and by life-stage
  - Each module with its own rich information, models and sensors
    - Flow of information through the modules - Back and Forth
    - Ability to query, investigate, assess conditions of individual Steel Bricks™ in the structure.
  - Semi-automated procedures to update Building Information Modeling & Finite Element Analysis models from field measurements
  - Long-term monitoring combining structural models with:
    - Earth pressure sensors (lateral stress)
    - LiDAR scans of base, shaft walls and ground surface
    - Procedures to stream data from the field for real-time decision-making via wireless transmission of sensor data

Benefits of Testing & Demonstration

- Bridge the gap between development and commercialization
  - Mature technology readiness and reduce risks to participants for first of a kind build
  - Facilitate partnership between technology developers, end users, national labs, universities, regulators, industrial participants
- Learn by doing reduces risks associated with first commercial build
  - Identify materials standardly available
  - Optimize design
  - Establish procedures
  - Sequencing of operations
- Builds confidence with regulators
- Develops supply chain

NRIC Systems/Digital Engineering Overview

- Holistic approach to the design of a complex system:
  - Design using models/data instead of documents
  - Integration of data across models to realize significant risk reduction on project cost and schedule
  - Applying state-of-the art Model Based Systems Engineering Tools from requirements engineering through design, construction, and operations
  - NRIC-DEN (Digital Engineering for Nuclear) sharing this tool set architecture with industry partners and others to facilitate cost reductions and improve advanced reactor deployment



Will combine DOME model with reactor model to facilitate virtual fit up and testing

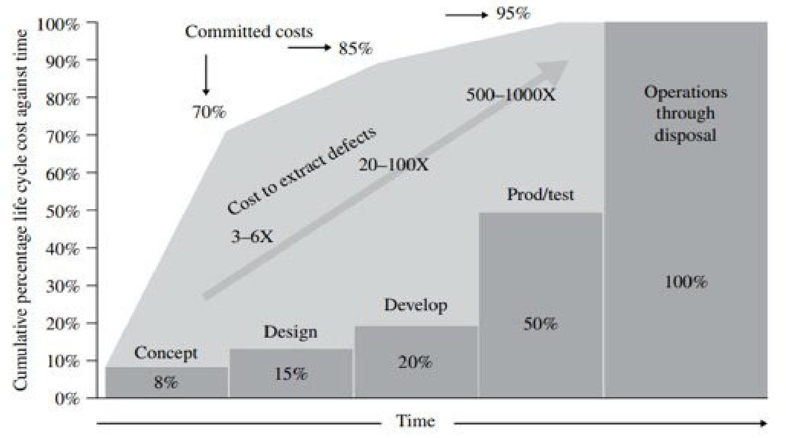
Why Systems/Digital Engineering?

- Provides for the most secure, highest quality, most accessible, fastest execution of large scale, complex projects
- Legacy & outdated systems dominate nuclear industry
  - Microsoft Word, PDFs, Spreadsheets, Paper Documents, Visio Diagrams, Legacy Systems
  - Engineering tools, if used, are disparate and siloed – lots of manually intensive rework
- NRIC sharing this tool set architecture
  - Partnering with EPRI (workshops)
  - ACTI digital twin
  - ARDP awardees

How Big Projects Performed

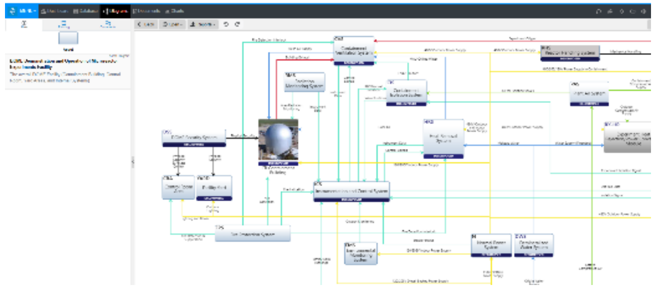
Source: Flyvbjerg Database

Project type	Mean cost overrun (%)	Projects (A) with ≥50% overruns (%)	Mean overruns of A projects (%)
Nuclear storage	238	48	427
Olympic Games	157	76	200
Nuclear power	120	55	204
Hydroelectric dams	75	37	186
IT	73	18	447
Nonhydroelectric dams	71	33	202
Buildings	62	39	206
Aerospace	60	42	119
Defence	53	21	253
Bus rapid transit	40	43	69
Rail	39	28	116
Airports	39	43	88



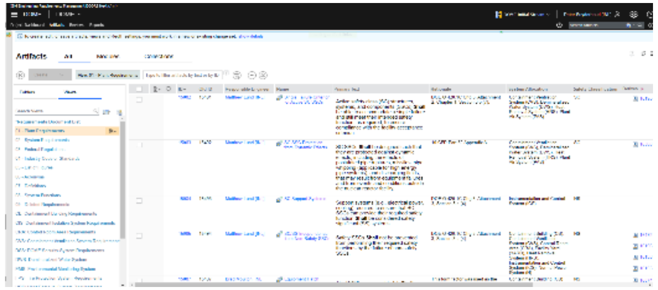
Systems Engineering

INNOSLATE®



Requirements Engineering

IBM Rational
DOORS Next Generation



Pull any data from one system and push to other systems – Single Source of Truth

windchill®

Product Lifecycle Management

PROCORE

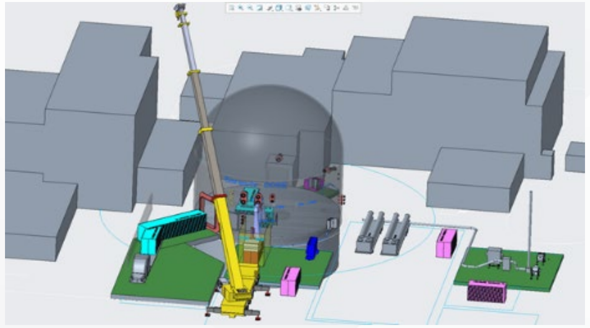
Construction Management

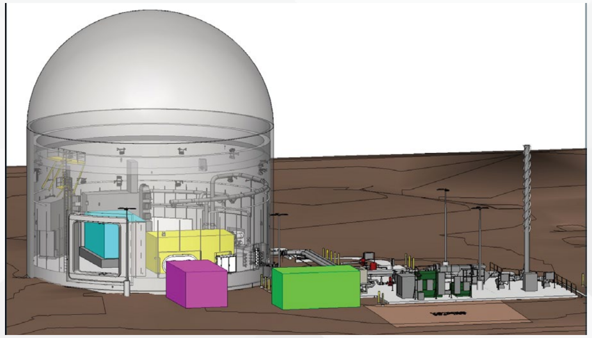
ABB

INL Asset Suite

creo®

3D CAD Digital Twin





AUTODESK® REVIT®

3D BIM Digital Twin

FY23: Deployed Windchill, integrated P6 schedule system, & deployed engineering V&V tool

FY24: Complete upgrade to DOME digital twin to include component information (informational digital twin)

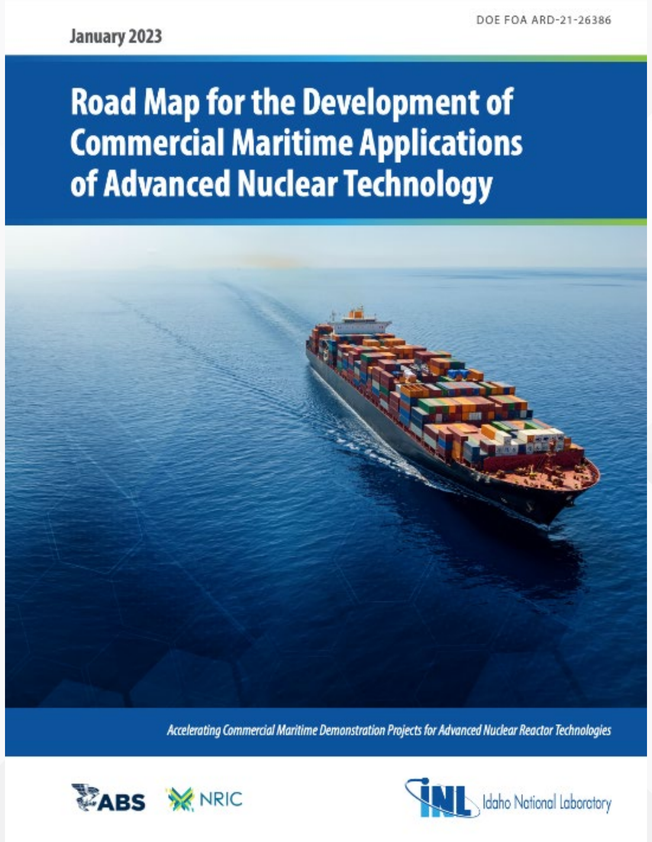
Evaluating Maritime Applications NRIC & American Bureau of Shipping (ABS)

Maritime Nuclear Application Group

- Collaboration with ABS and Morgan & Lewis Law Firm to establish a forum for the maritime and nuclear energy sectors to demonstrate advanced nuclear technologies
- Identifies domestic and international legal and regulatory hurdles, catalogs and share relevant information resources, and collaborates with global stakeholders
- 100+ members representing 40+ domestic/international companies from nuclear, shipping, and oil/gas industries including:
  - Westinghouse, NuScale, BWXT, NEI, Shell, NRC, US Coast Guard, etc.
- Conducting assessment of experimental and testing gaps to fill

Industry FOA Award 2022 - ABS Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies System

- Develop roadmap for maritime application test/demonstration projects.
- Reconcile maritime and nuclear licensing and conduct a regulatory gap analysis.
- Develop business cases & 2050 market potential for nuclear-marine applications.

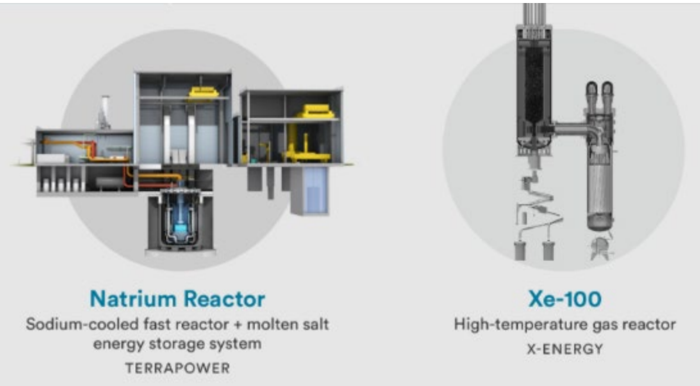


- IAEA Symposium – Deployment Of Floating Nuclear Power plants –Nov
- CORE POWER - DC – Oct

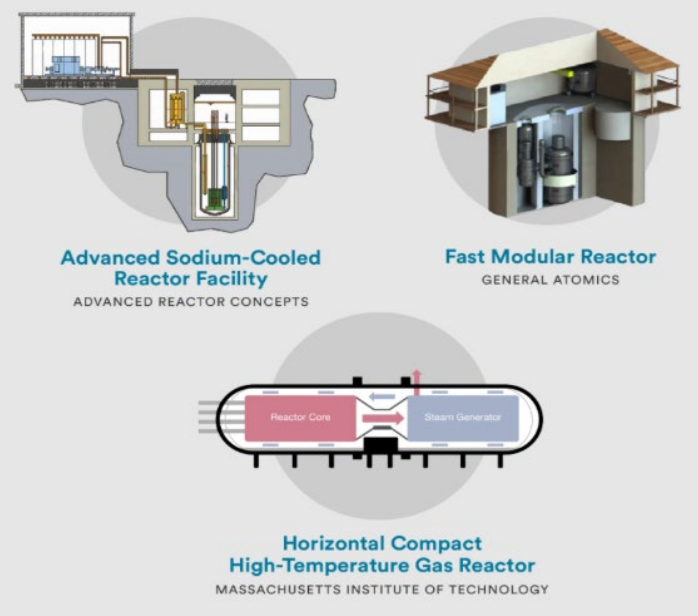
INL Participation in ARDP Projects

- 9 projects supported
- Scope range
  - Modeling & Simulation
  - Irradiation & PIE
  - Fuel design & fabrication
- ~$175M – 7 years
  - $1M - $75M per project
- NRIC/INL Coordinator
- NRIC Deployed Digital Engineering and project management tools

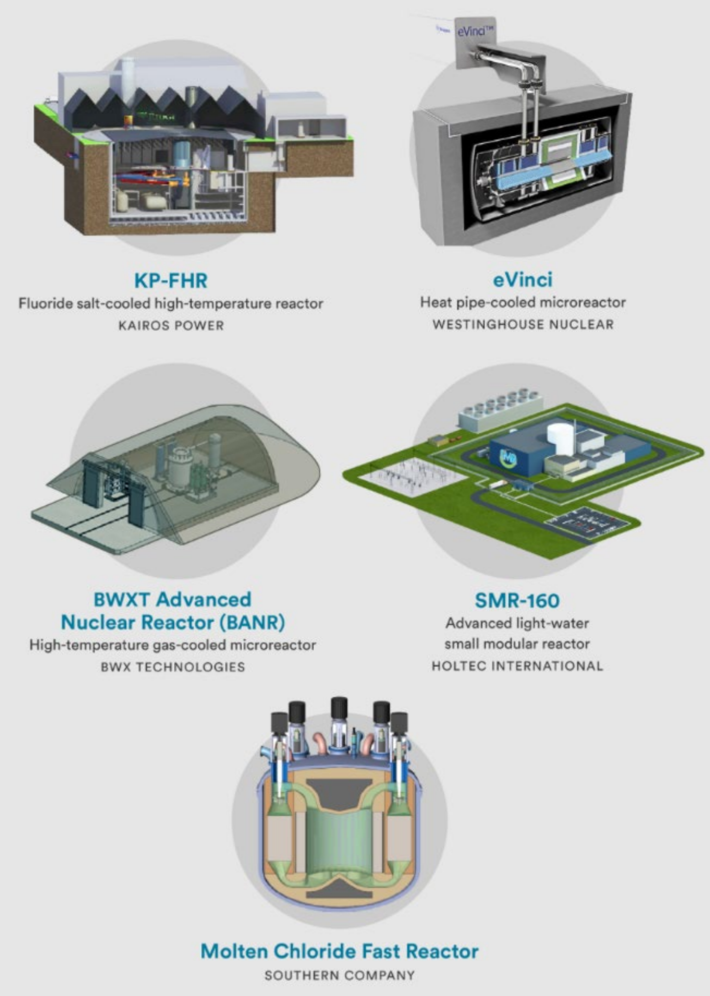
Demonstration



Concept Development



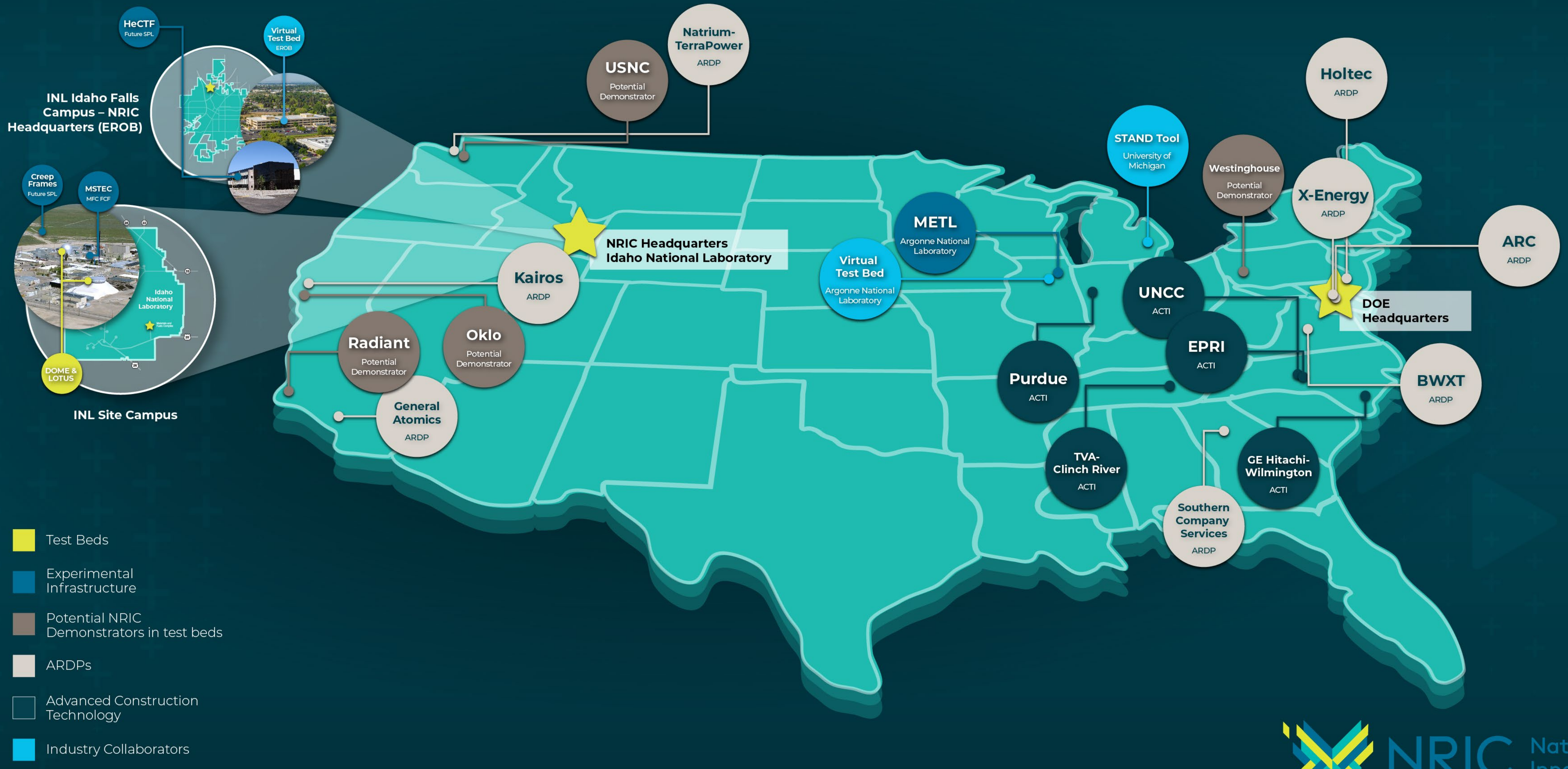
Risk Reduction



Companies NRIC Works To Support Include:

- Terrapower
- X-energy
- Kairos
- BWXT
- Oklo
- Holtec
- ARC Clean Energy
- General Atomics
- Micronuclear
- Radiant
- GE-Hitachi
- CorePower
- Westinghouse
- USNC
- AlphaTech
- Aalo

NRIC National Footprint



NRIC National Reactor Innovation Center

Program Goal and Objectives

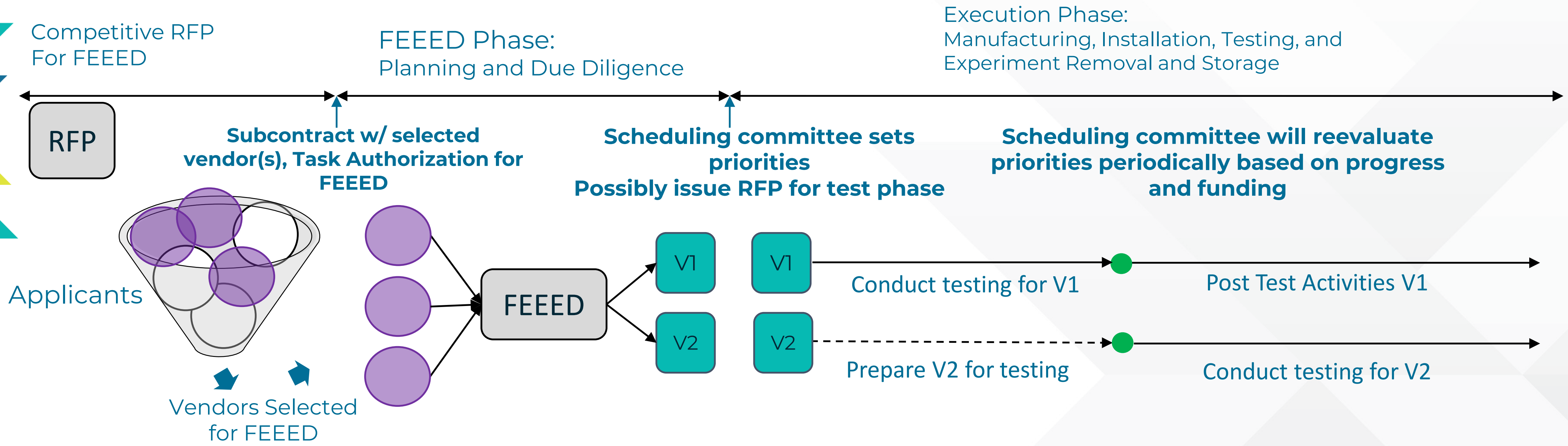
- Accelerate the testing and demonstration of advanced nuclear technology by providing access to national laboratory assets and expertise:
  - Establish & maintain four new experimental facility capabilities
  - MSTEC – 2025; METL – Operational; HeCTF – Operational; Creep Frames – 2026
- Construct and operationalize two large reactor test beds for integrated technology demonstrations and experimentation - 2028,
- Complete minimum of two advanced nuclear technology tests – 2030
  - Advanced Construction Technology – 2025
  - Advanced Microreactor test in DOME – 2027 & 2029

MSTEC Project Status

- Overview: A post-irradiation examination capability focused on fuel salts at high temperature
  - Shielded capability for high-actinide and irradiated salts
  - Thermophysical properties
  - Self-irradiation behaviors (including off-gas)
  - Versatile workspace for users (academia, industry, etc.) to test equipment on irradiated or actinide-bearing salts
- Timeline
  - FY20 – Design requirements for glovebox completed, purchased characterization equipment
  - FY21 – Issued PO for glovebox, installed characterization equipment (temporary)
  - FY22 – Facility D&D, glovebox build, scientist development on characterization equipment
  - FY23 – Completion of facility modifications, finalization of characterization equipment testing, fabrication of MSTEC
  - FY24 – Complete MSTEC fabrication, installation in FCF, and initiate acceptance testing
  - FY25 – Commissioning and readiness assessment

Agreement	Contract Value Related to Thermophysical Properties of MSR Fuel Salts
SPP with Seaborg Technologies of Denmark	$2,500,000
CRADA with Korean Atomic Energy Research Institute	$1,000,000
MCRE ARDP	~$1,500,000
MRTI Molten Salt Irradiation	$2,000,000
DOE MSR Campaign	$500,000
NNSA	Under development
Nonproliferation Stewardship Program (NSP)	Under development, $10-30,000,000

Proposed DOME Reactor Testing Program Process



Application Process	FEEED Phase Goals	Prioritization Options	Execution Phase Goals
• Solicit applications for Front End Engineering and Experiment Design for testing in DOME • Cost-shared RFP option: Evaluate and select multiple high-ranking projects based on availability of funds • Industry funded option: evaluate and recommend path forward	• Develop program plan for each advanced reactor selected under RFP including conceptual reactor design, reactor experiment test plan, safety documentation and DOE authorization plan, NEPA plan, detailed schedule and cost estimate for testing through decommissioning	• Scheduling committee consisting of NE5, INL (NS&T, NRIC & MFC), DOE-ID review results of FEEED phase and prioritize based on: Maturity of reactor design, availability of funding and funding source, access to fuel, and proposed schedule. (annual reassessment) • Based on availability of DOE funding may issue an RFP for testing phase • NE-5 final approver of priority	• Complete all outstanding design work • Manufacture, deliver, assemble, and install all hardware, software, and supporting equipment in the DOME • Execute experimental reactor test program • Remove experiment from the DOME • Deactivation and decommissioning

Thank you!

Questions?

NRIC National Reactor Innovation Center