INL/MIS-24-81052-Revision-0

Perspectives on Potential Advanced Construction Technologies for Nuclear Energy

October 2024

Changing the World's Energy Future

Brad Tomer, Svetlana Lawrence, Allison E Ray, Sam Reiss, Philip Schoonover, Peter Anton Suyderhoud

Idaho National Laboratory

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NRIC National Reactor Innovation Center

Perspectives on Potential Advanced Construction Technologies for Nuclear Energy

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October 8, 2024

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nric.inl.gov

MIS-24-81052

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

NRIC National Reactor Innovation Center

Portfolio Built to Empower Innovators

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

Advanced Construction Technologies

Demonstrate technologies that:

- Reduce cost of new nuclear builds by 10%+
- Compress construction schedule by as much as 25%
- Reduce required site work & improve overall quality of structure
- Support long-term structure monitoring

Phase One (Expected completion Dec 2024)

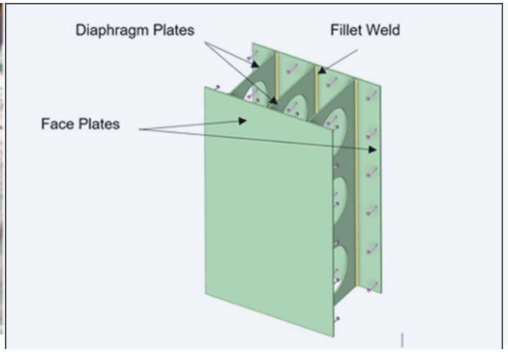
- Prototype modular steel/concrete composite walling system
- Developed non-destructive examination and welding techniques
- Demonstrated strength of wall systems

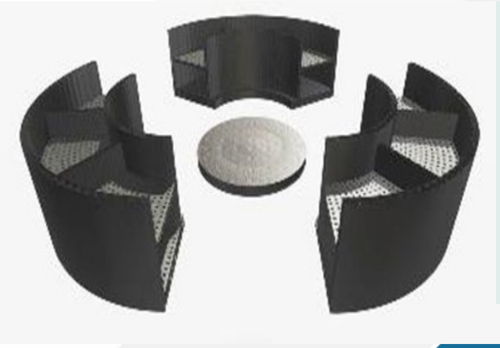
Phase Two (Expected start Jan 2025)

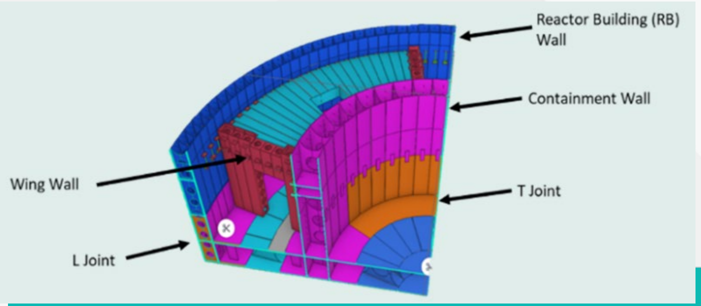
- Demonstrate 60-degree pie shape containment walling system
- Inner and outer walls, base mat integration, multi-story
- Deploy digital twin plus sensor technology for monitoring

Team – General Electric Vernova

EPRI, Black & Veatch, Purdue, UNCC, Nuclear Advanced Manufacturing Research Centre, Caunton Engineering w/Modular Walling Systems Ltd, Aecon Wachs, and Tennessee Valley Authority





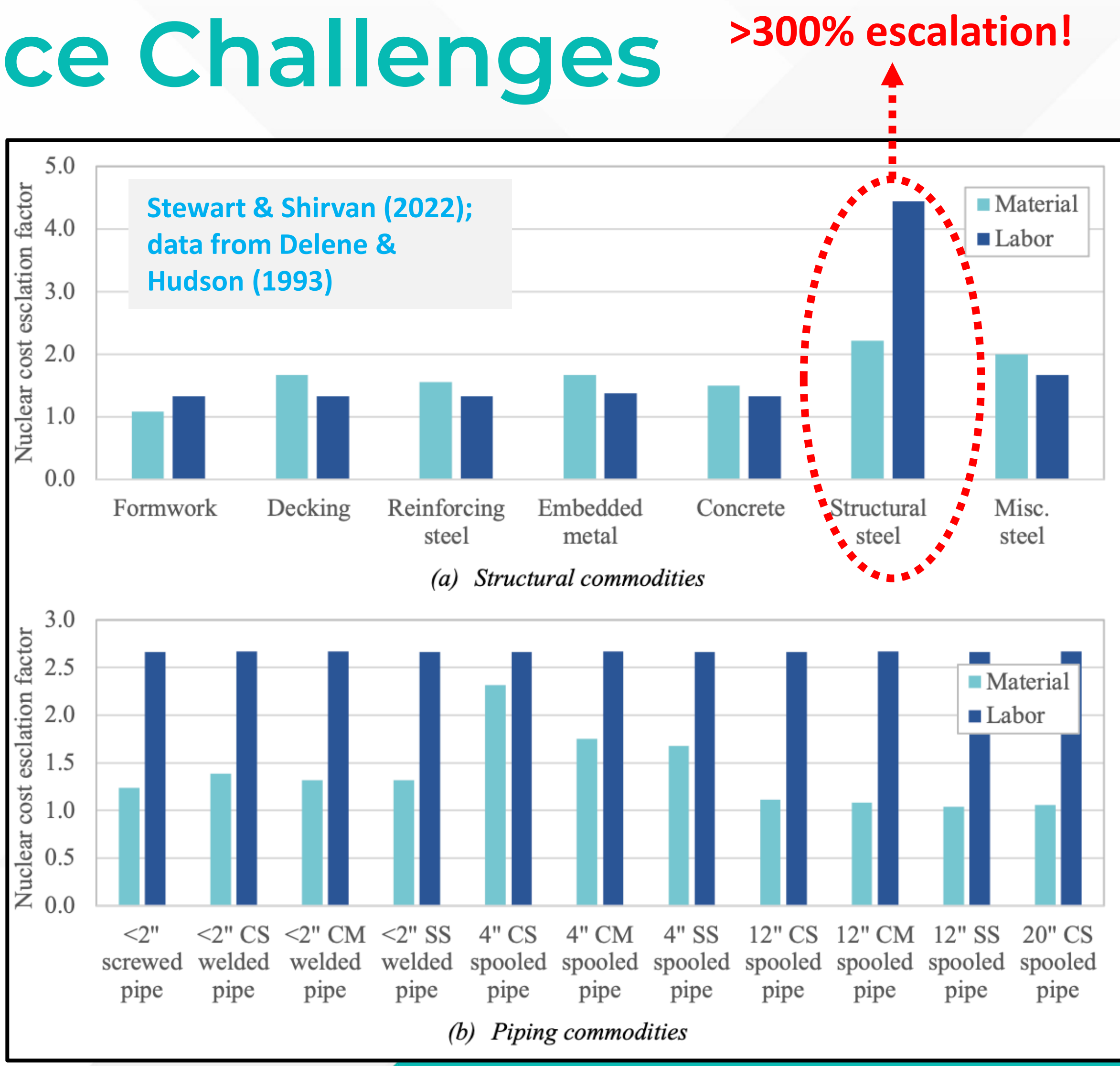


Additional Technologies and Efforts that could improve nuclear energy deployment

- Risk-informed regulations for constructing advanced nuclear facilities.
- Digital Twins for Developing and Deploying Advanced Nuclear Facilities.
- Construction and testing of structural elements using high temperature concrete.
- Diaphragm wall construction testing and demonstration.
- Testing of Robotic and 3-D printing of reinforced concrete techniques
- Full-size demonstration of steel/concrete composite modular walling systems.
- Seismic Isolators in Advanced Nuclear Reactor Construction.

Nuclear Quality Assurance Challenges

- **Economics**: Studies have shown significant cost escalation associated with meeting nuclear quality assurance standards (10 CFR Part 50 Appx B and ASME NQA-1)
- **Supply chain**: Due to lack of recent activity, nuclear-certified suppliers are sparse, causing supply-chain bottlenecks (and further cost escalation)
- **Need for modernization:** Nuclear quality requirements were developed independently from the non-nuclear industry, which has evolved significantly in their QA/QC processes (e.g., manufacturing, software)
- **Recognition of Advanced Reactor Intrinsic Safety:** the designs of advanced reactors mitigate many of the risks associated with LWRs through innovative or intrinsic features.



Potential Solutions

- Use Risk-Informed Performance-Based (RIPB) approaches to minimize the number of safety-related systems and components in the plant
- Develop organized trainings, workshops, and guidance for an efficient implementation of NQA-1 and code quality requirements
- Use of non-nuclear supply chain: Improve commercial grade dedication (CGD) processes or develop a pathway to meet Part 50 Appx B requirements using ISO 9001 / ISO 19443
- Review and make improvements in NQA-1 and individual design codes (e.g., ASME B&PV, ACI 349 for reinforced concrete, etc.) to be consistent with modern manufacturing/construction/software development methods
- Use of digital engineering and digital twins to manage and ensure quality as well as other requirements

NRIC NQA-1 Feasibility Study

- DOE-funded study to develop a roadmap for reducing quality assurance related cost escalations and evaluate the feasibility of different approaches. (Sep 2024 – Feb 2025)

Scope

- Review the differences between nuclear and non-nuclear quality assurance standards and best practices, and how they impact safety, and quality of the final product.
- Through an in-person workshop, gather input from a variety of stakeholders (industry groups, advanced reactor and light-water reactor developers, nuclear and non-nuclear EPCs and vendors/suppliers, and NRC) on pain points in the application of NQA-1, best practices, and potential solutions (focus on civil construction (major cost driver), other safety-related systems, structures, and components, as well as software)
- **“Nuclear Quality Assurance Challenges Workshop”** to be organized in the Nov-Dec 2024 timeframe, likely in Washington, DC (details TBD)
- Use workshop input to develop a roadmap incorporating various solutions and cost mitigation strategies (Feb 2025)

What is Digital Engineering?

Digital Engineering & Digital Transformation

Transform the way we **design** and **operate** energy assets:

1. Deliver *semi-autonomous design*, *autonomous operation*, and *real-time anomaly detection*
2. Drive research across compute platforms with integrated **human centered visualization**
3. Integrate threads of **data**, **visualizations**, AI/ML, and physics **models** into a cohesive **digital twin**

1. Transform the way Organizations / Projects Generate Data	→	2. Transform the way Organizations / Projects Store and Connect Data	→	3. Transform the way Organizations / Projects Use and Automate Data
Model-Based Engineering		Digital Threads		Data Pipelines
Systems Engineering		Data Warehouses		Data Analysis
Model-Based Systems Eng.		Product Lifecycle Management		Artificial Intelligence
Simulation		Configuration Management		

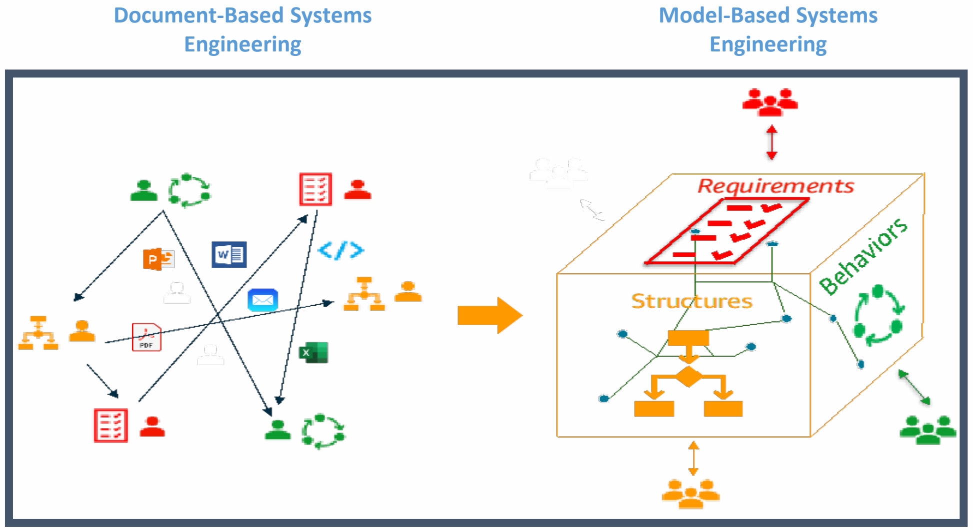
Computing Infrastructure, Cloud Hosting, Authentication, etc.

Culture and Workforce Adoption

Transforming How INL Performs Engineering

What

- Shift from document-based, static approaches to the use of models and an underlying database as the means of information exchange
- Transforms typical document artifacts to **data objects**
- Models and data form an integral part of the technical baseline, not just visual depictions

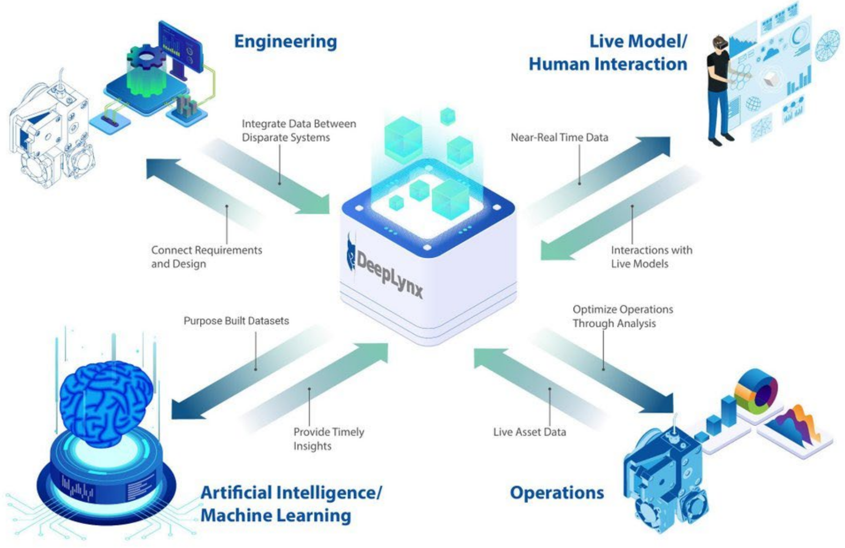


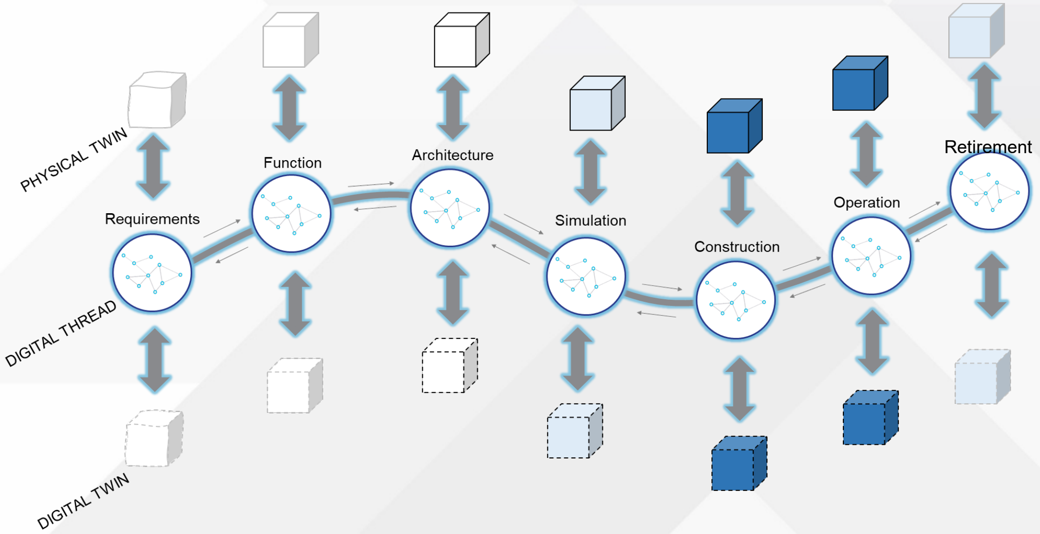
How

- Web-based, cloud-hosted software applications with broad access for collaboration
- **Innoslate** for functional analysis and concept of operations
- **IBM DOORS Next** for powerful RM functions above what MBSE tools offer
- Building Information Modeling (BIM) and Model Based Definition (MBD) tools: **Autodesk Revit, Creo,** etc.
- **Matlab/Simulink** for functional first order physics modeling in lieu of P&IDs and paper-based outputs
- **PTC Windchill** for product lifecycle management (PLM) i.e. storing, versioning, and maintaining engineering data and associated reviews
- **Coming Soon:** Design engagement/review solution that will solve challenges associated with commenting and incorporating feedback

Digital Threads

- **Interconnected** software data exchange used to enable digital engineering and digital twinning systems
- **Connects** data to other digital definitions created later in the development process
- Maintains system **integrity** across lifecycle
- Developed open-source Digital Thread / Data Warehouse platform: Deep Lynx
- Standardized ontologies to store and relate information: DIAMOND, AMMONOID, GEM
- Suite of software adapters using open-source directed acyclic graph (DAGs) technology





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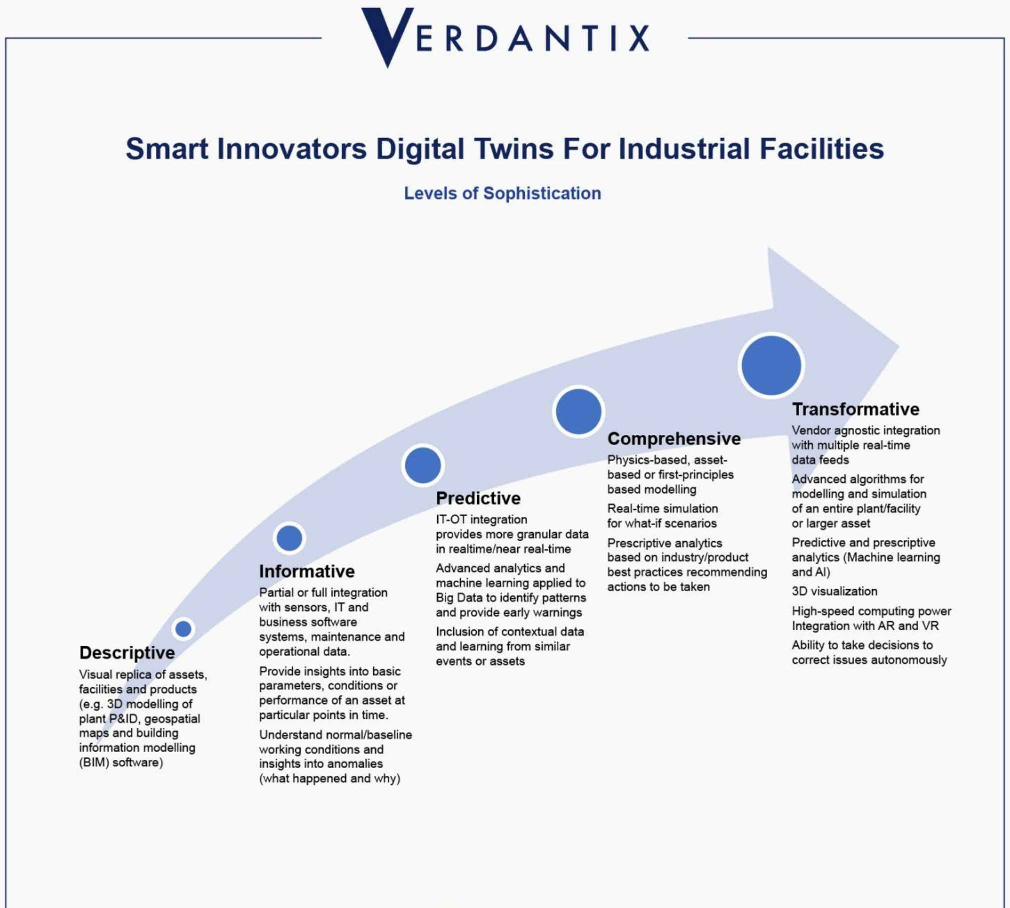
Digital Twins

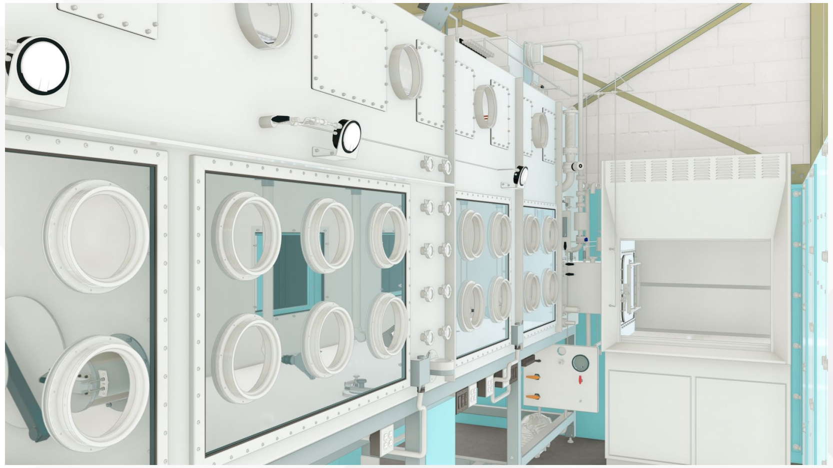
- INL definition: Digital Twins represent the merging of integrated and connected data, sensors and instrumentation, artificial intelligence, and online monitoring into a single cohesive unit.
- Focused on the implementation of “Predictive” and “Comprehensive” digital twins
- What is different than a traditional simulation?
    - Integration of real-time data
    - Dynamic model update (AI/ML integration)
    - Real-time operator visualization
    - Accurate predictions with fused (integrated) data
    - Ability to enable autonomous control
    - Distributed across computing platforms



Source: Verdantix Smart Innovators Digital Twins For Industrial Facilities

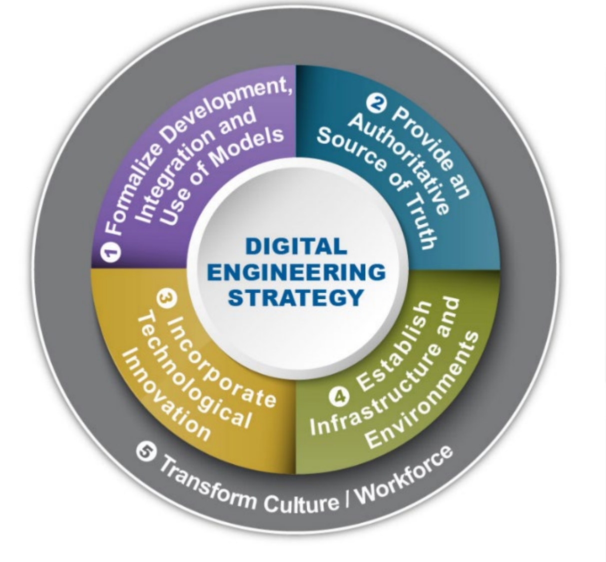
Visualization and Extended Reality

- A graph and source of information is nice, but humans are visual – we need a better way to consume data
- Extended reality (XR)
  - Virtual reality (VR)
  - Augmented reality (AR)
  - Mixed reality (MR)
- Centering information on models facilitates understanding
- Engineers can interact with visualization – inspect, change, delete, etc.



Digital Engineering (DE)

- **What?** An integrated digital approach that uses authoritative sources of truth for data and models across disciplines to support project lifecycle activities from concept through disposal
- **Why?** With typical industry project **cost overruns** of 241% and 180% in **schedule delay**, digitization of the overall processes can have a significant impact on nuclear deployment and cost viability
- **Implementation Process & Progress to Date**
    1. Transform the way organizations generate design data by deploying **model-based tools**: IBM DOORS Next, Innoslate MBSE, PTC Creo, Autodesk Revit, etc. [Complete, TRL 9]
    2. Transform the way organizations manage, store, and connect data using **digital threads** to form a comprehensive **digital ecosystem**: PTC Windchill, INL Deep Lynx Warehouse, software adapters & APIs, etc. [In Process, TRL 6]
    3. Transform the way organizations leverage data using **digital twin** technology: extended reality (XR), Unity game engine, real-time data acquisition (DAQ), machine learning (ML), artificial intelligence (AI) [In Process, TRL 3]
- **Next Steps:**
    - Progress digital ecosystem development and release "playbook" and open-source code repository
    - Develop first nuclear facility digital twin at DOME incorporating physics-based modeling, predictive machine learning, real-time data feedback, etc.



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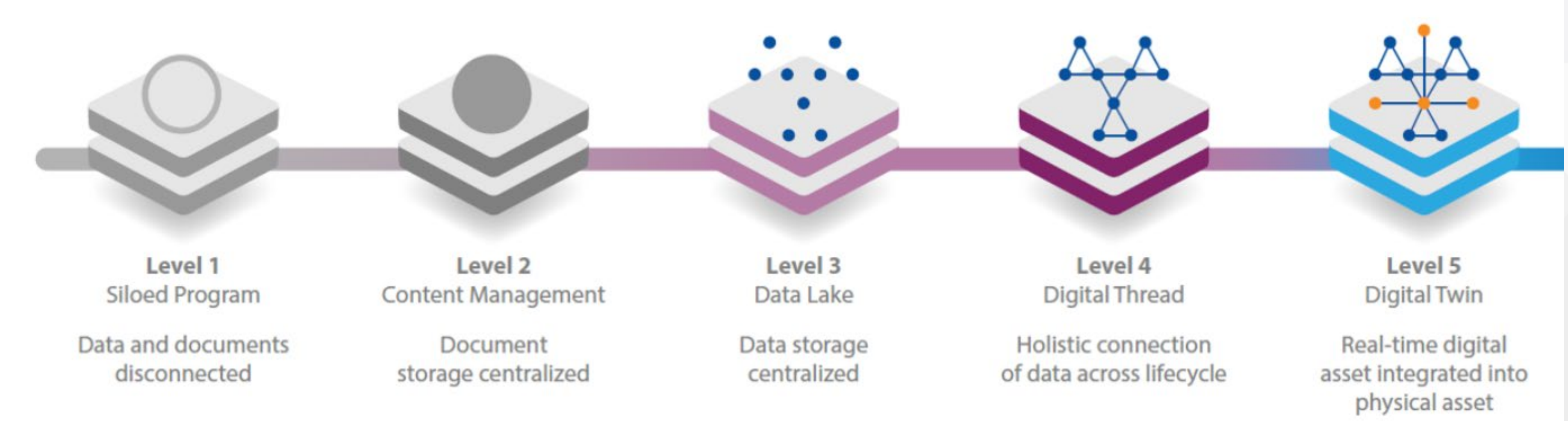
NRIC Systems/Digital Engineering Overview

- 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

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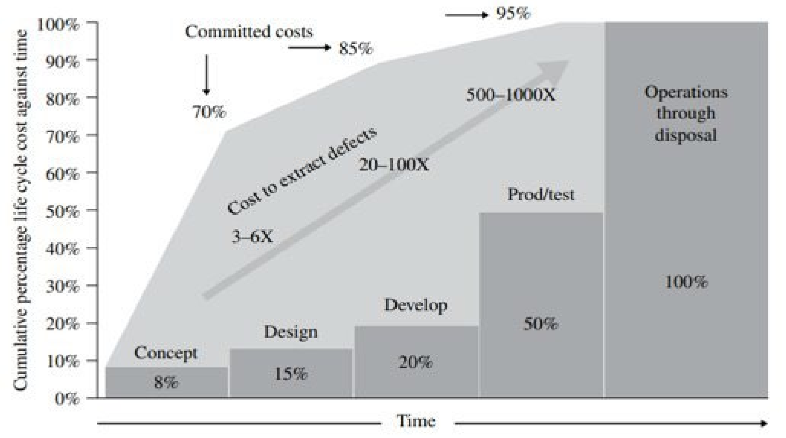
Why Systems/Digital Engineering?

- 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



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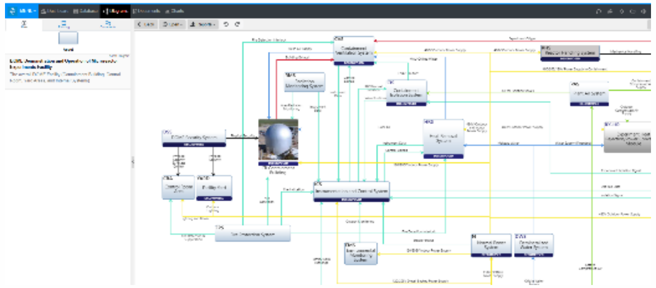
INNOSLATE

Systems Engineering

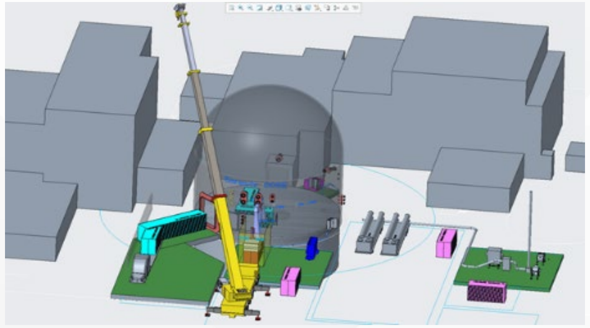


windchill

Product Lifecycle Management

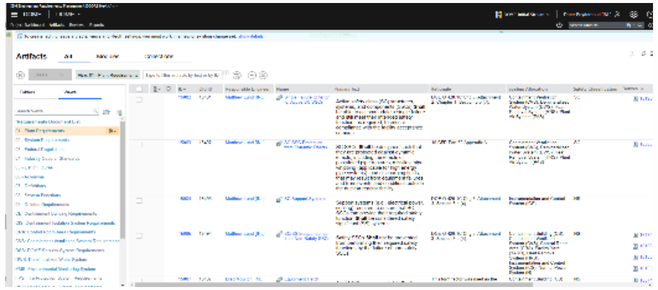
creo

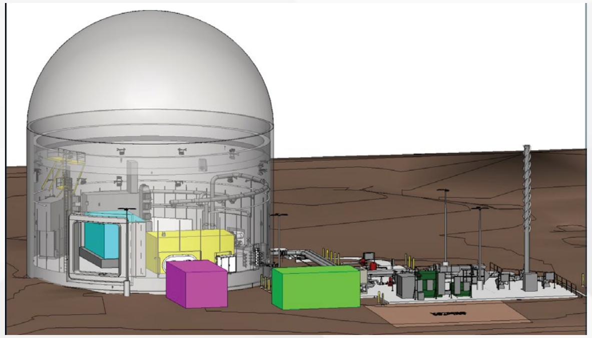
3D CAD Digital Twin



IBM Rational
DOORS Next Generation

Requirements Engineering





AUTODESK REVIT

3D BIM Digital Twin

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

PROCORE

Construction Management

ABB

INL Asset Suite

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)

Digital Twin – Advanced Construction

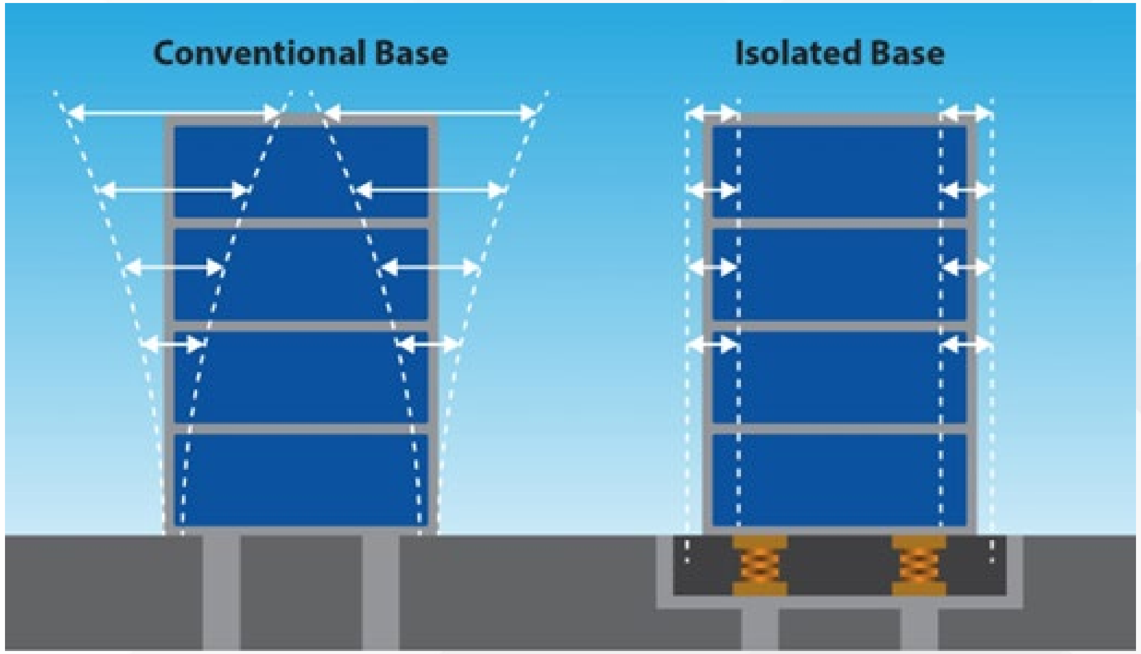
- State of the art replica of the structure to integrate sensor data, artificial intelligence, machine learning, and data analytics. Cradle to grave monitoring
- EPRI, University of North Carolina Charlotte, Nuclear AMRC
- Organizes all project data by component and by life-stage
  - Each module with 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

3D Printing Concrete for Nuclear Applications

- **Significant Time Reduction:** 3D printing greatly accelerates construction, enabling around-the-clock building and eliminating many traditional, time-consuming steps.
- **Cost Efficiency:** Reduced labor needs and material waste from 3D printing leads to substantial cost savings.
- **Enhanced Structural Integrity:** Tailored designs and improved material properties enhance safety and durability.
- **Faster Operational Readiness:** Quicker construction allows for earlier project completion and operation, leading to a faster return on investment.
- **Increased Worker Safety:** Through standardized procedures and modularized construction enabled by 3D printing the risk to on-site workers can be reduced.

Seismic Isolators in Advanced Nuclear Reactor Construction

- Seismic isolators enhance safety and resilience, reducing risk of damage during earthquakes.
- Innovative technology contributes to isolator reliability and effectiveness and holds promise for modular construction approaches.
- Integrating seismic isolators with advanced reactors may exceed requirements for nuclear safety, streamlining the regulatory process.
- Isolation can reduce costs by preventing structural damage and limiting downtime for repairs.



Arrows indicate the impact of shaking on structures with conventional (left) and isolated (right) bases. On the right, "seismic isolators" fixed at the base of the structure help to absorb the shock of an earthquake.

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1/21/2025

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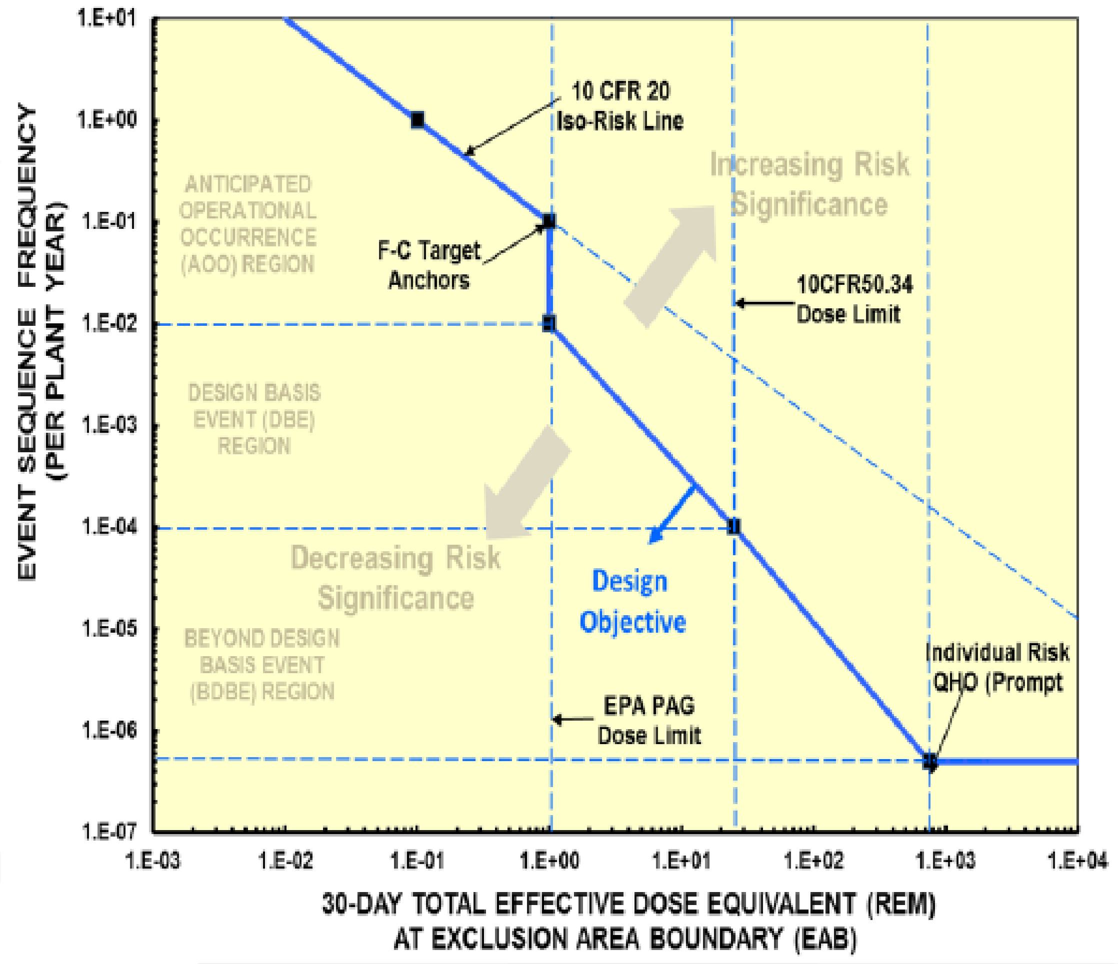
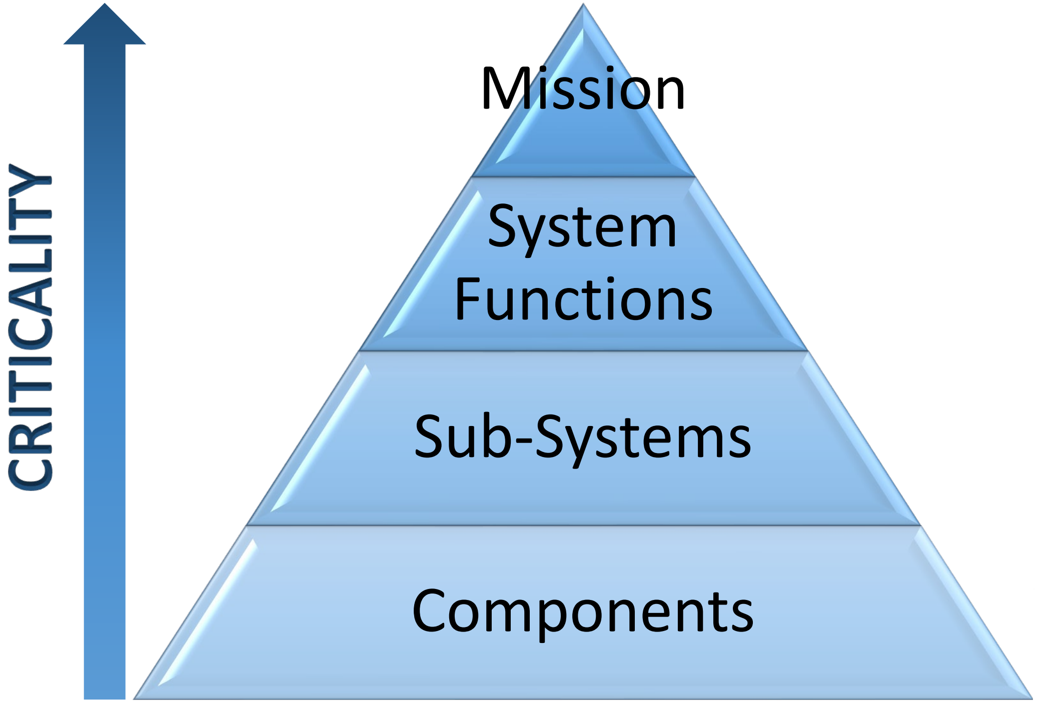
Risk-Informed Performance-Based Licensing Approach for Advanced Reactors

- **Risk-Informed Performance-Based** approach to inform
  - LBE selection
  - Choice of performance monitoring strategies
- Use of phenomenological modeling and simulations
  - Significantly reduces reliance on assumptions
- Every event sequence is explicitly modeled
  - Removes the necessity of bounding (i.e., conservative) scenarios
- Risk measured in actual consequences, NOT surrogate metrics
- Allows use of safety margins expressed in metrics other than “risk”
  - Time
  - Defect size
  - Radiation dose

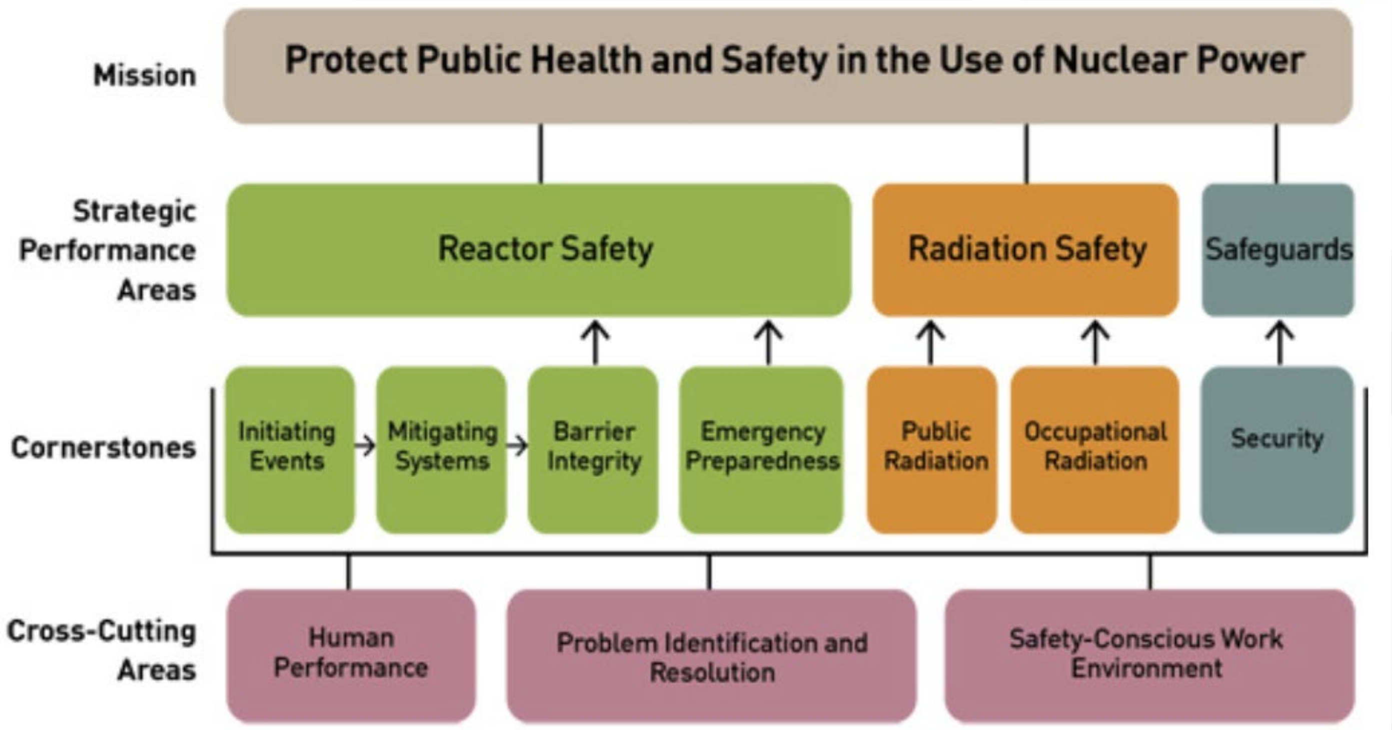


NEI 18-04: Figure 3-1. Frequency-Consequence Target

Reimagining Requirements Management

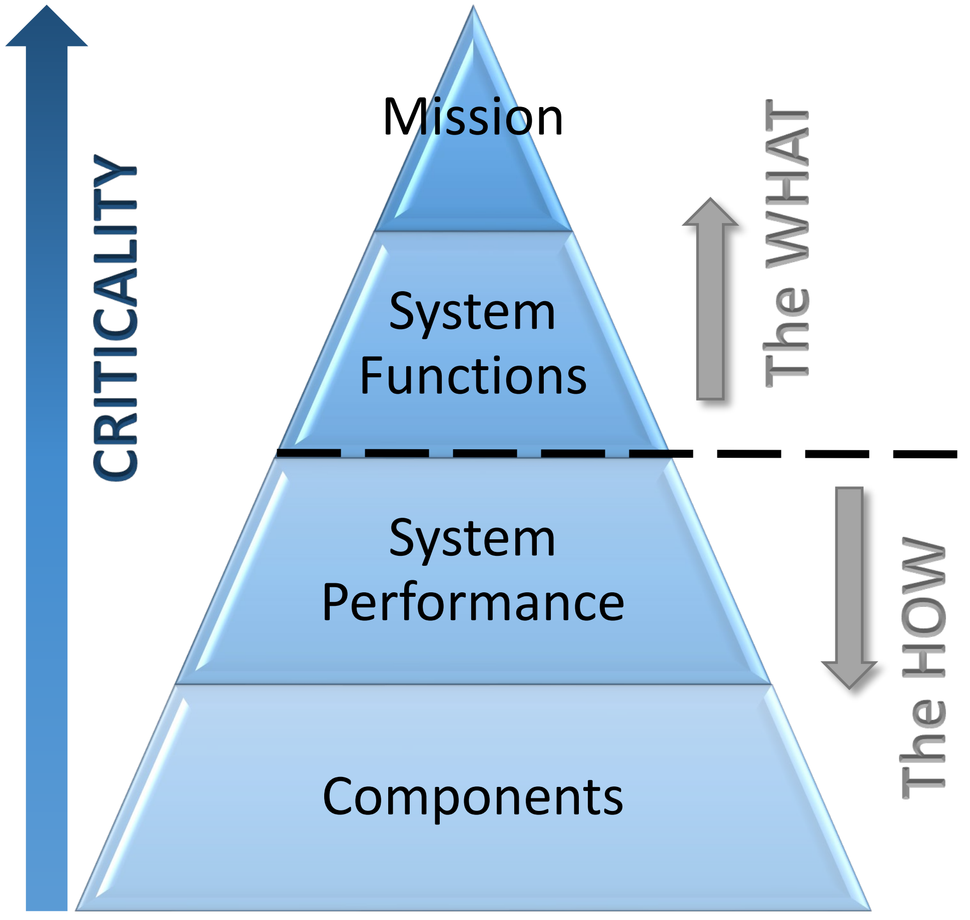


Typical System Hierarchy

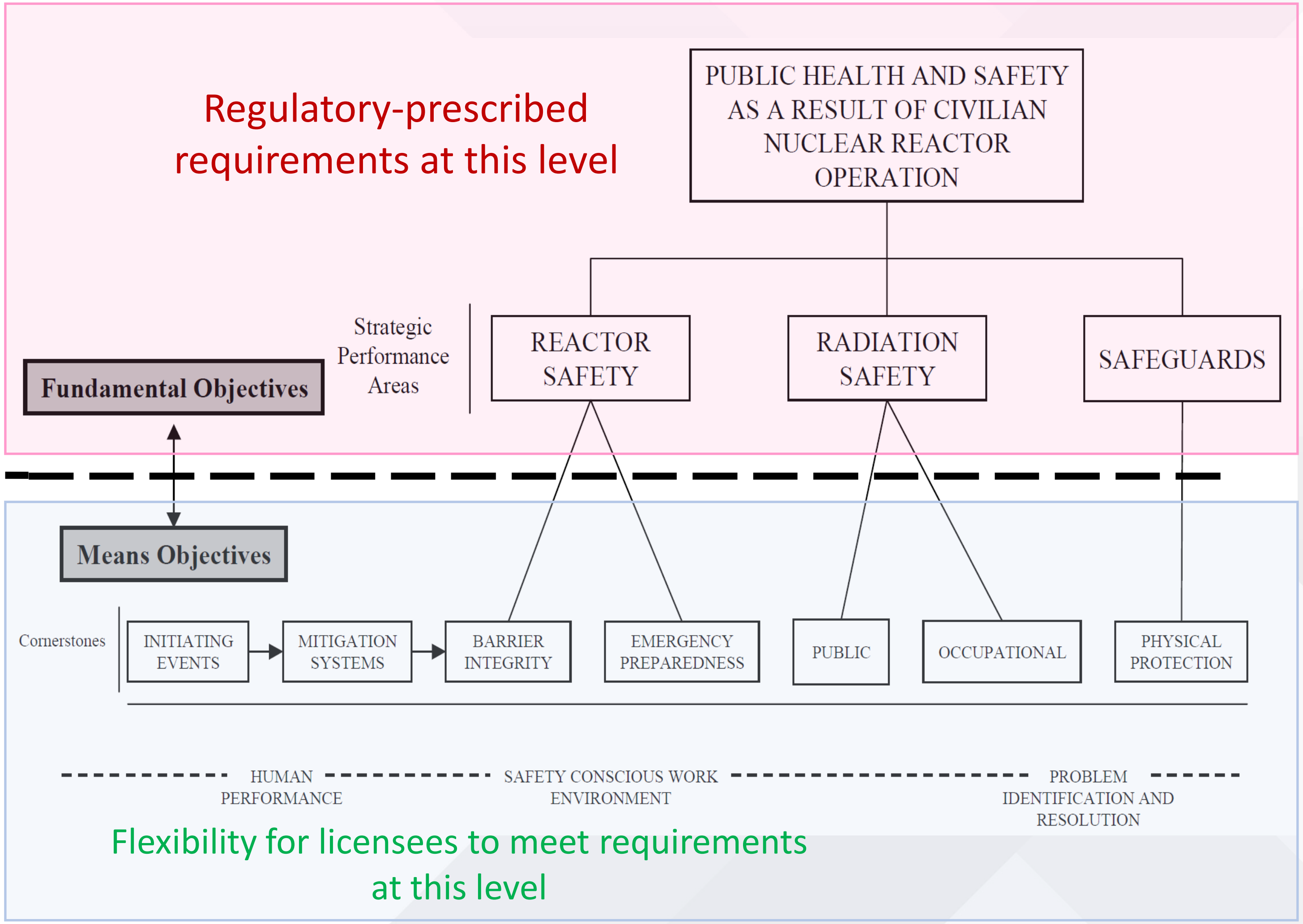


NRC Reactor Oversight Framework
https://www.nrc.gov/reactors/operating/oversight/rop-description.html

Reimagining Requirements Management (cont'd)

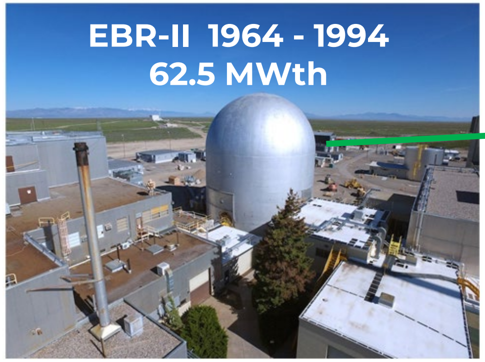


Typical System Hierarchy



Reactor Oversight Process Objectives Hierarchy

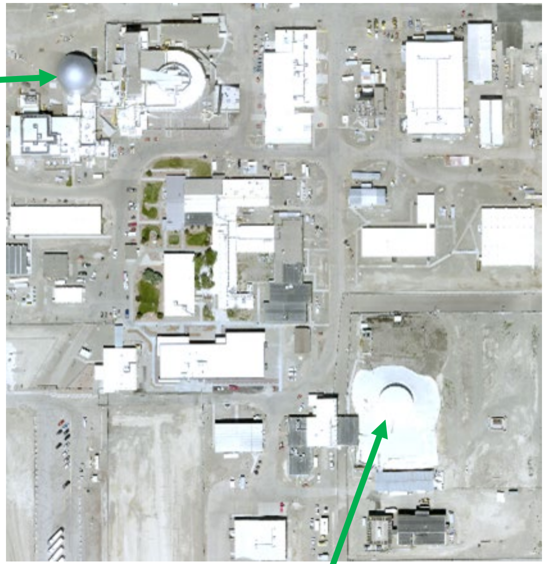
NRIC Advanced Reactor Testbed Capabilities



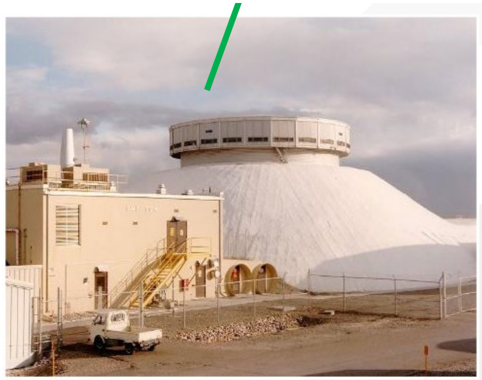
Demonstration of Microreactor Experiments (DOME)

- DOME is the repurposed EBR-II structure
- Designed for Advanced Microreactors up to $20MW_{th}$
- Designed for High-Assay Low-Enriched Uranium (HALEU) fuels < 20% enrichment
- Accommodates ISO 668 High-Cube Shipping Containers up to 40ft long.
- 480V / 400Amp electrical Service
- ≈ 78 ft diameter floor space with an 80ft ceiling
- 300kWth of environmental cooling expandable to $500KW_{th}$

Materials & Fuels Complex at INL



ZPPR 1969 to 1990
Transuranic and HEU inspection repackaging and experiments

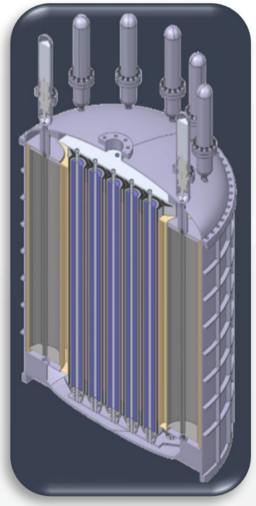


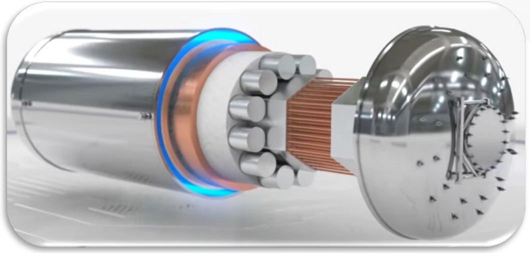
Laboratory for Operations and Testing in the US (LOTUS)

- LOTUS is the repurposed ZPPR structure
- Designed for HEU fuels
- Cell Heat Removal – (2) redundant HVAC packages – 50kWth
- Reactor Heat Removal – Design only – Min: $25KW_{th}$; Max: 500 kW_{th}
- In Cell Equipment Power
  - Normal – 480VAC, 450A, 3 phase
  - Auxiliary – 208VAC, 160A, 3 phase
- Cell Provides Radiological Confinement
- Cell Geometry – 30ft usable inner diameter; 16ft 11in (bottom of crane hook); Recessed pit area
- Entry Tunnel – 13ft x 13ft
- Polar Crane Capacity – 5 tons

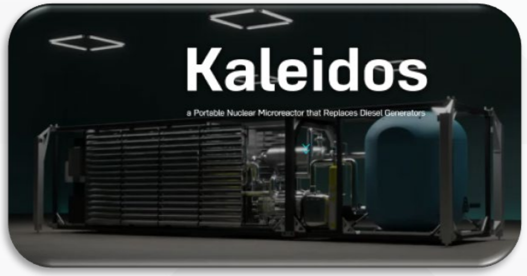
NRIC-DOME Testbed

- Construction Start Q4 2023
- Operational Readiness – June 2026
- First user expected – 2026
- 3 users going through front-end engineering and experiment design



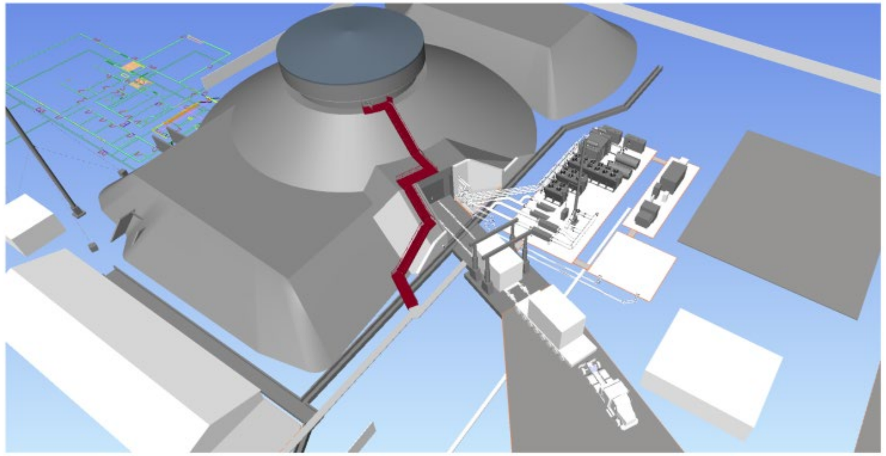


Westinghouse - eVinci

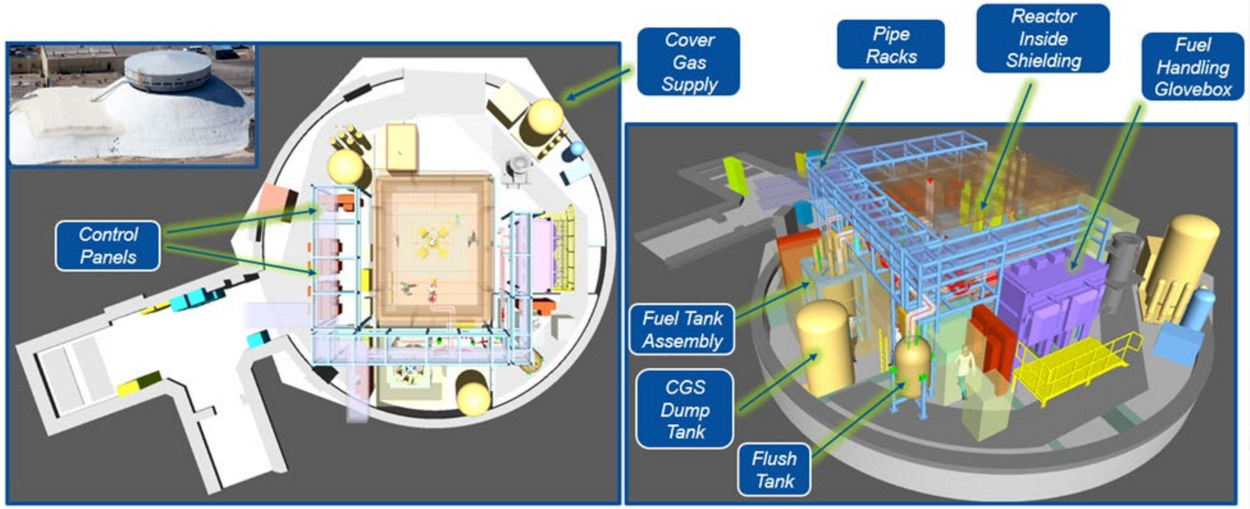


Developer	Reactor Name	Design	Power Mwe	Power MWth	Fuel Type	Fuel Enrichment	Primary Coolant	Moderator	Refueling Interval (Years)	Power Conversion System
Radiant	Kaleidos	HTGR	1.2	3.5	TRISO	19.75%	Helium	Graphite	6	Brayton Cycle
USNC	Pylon	HTGR		1	TRISO	9.90%	Helium	Graphite		Rankine
Westinghouse	eVinci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

NRIC-LOTUS Testbed



LOTUS Conceptual Design Model



Molten Chloride Reactor Experiment integrated into LOTUS

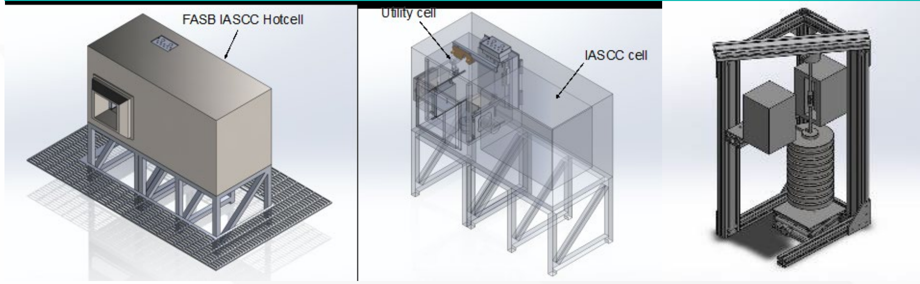
- Line-item project: CD-1 Approved 6/23
- Preliminary design review: Feb 2024
- Complete Construction: FY27
- First User: Molten Chloride Reactor Experiment

- Southern Company & Terra Power
- Funded through DOE Advanced Reactor Demonstration Program Risk Reduction
- Reactor Install: FY27/28

NRIC Experimental Infrastructure

Helium Component Test Facility [*2022*]

In-HotCell Thermal Creep Frame [*2025*]

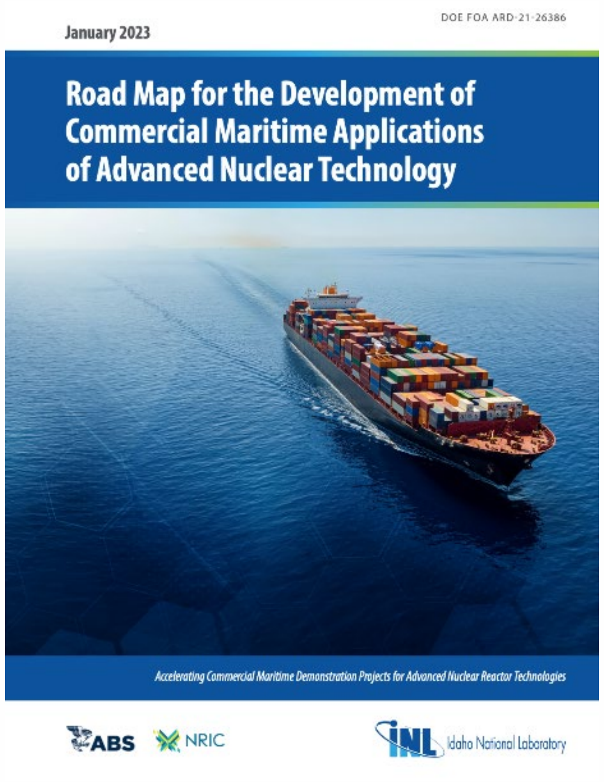


Molten Salt Thermophysical Examination Capabilities (MSTEC) [*2025*]

Mechanisms Engineering Test Lab (METL) [Operating since 2018]

Addressing Cost and Markets

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

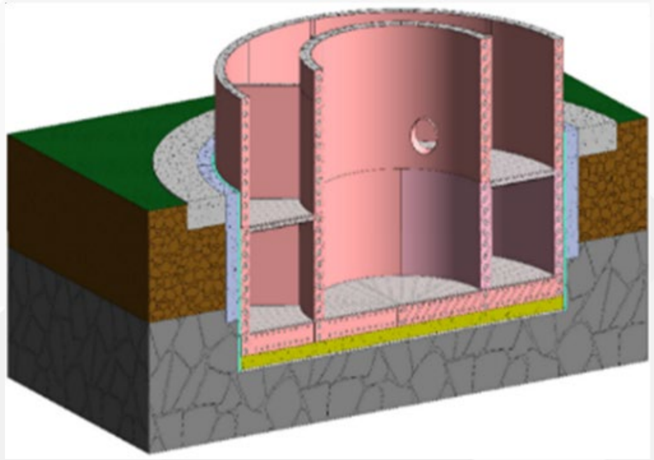

January 2023

DOE FOA ARD-21-26386

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

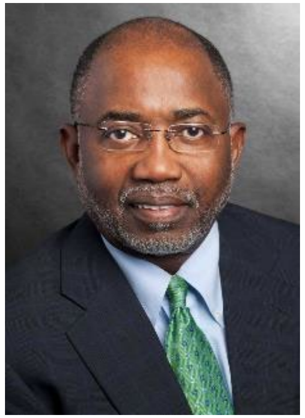
Accelerating Commercial Maritime Demonstration Projects for Advanced Nuclear Reactor Technologies

ABS NRIC INL Idaho National Laboratory



NRC Collaboration

- Congress recognized the importance of agency coordination in the Nuclear Energy Innovation Capabilities Act
- DOE/NRC MOU to “coordinate DOE and NRC technical readiness and sharing of technical expertise and knowledge on advanced nuclear reactor technologies and nuclear energy innovation, including reactor concepts demonstrations, through the [NRIC].”
    - NRIC Rotations



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- Monthly Coordination Calls – DOE/NRC/NRIC