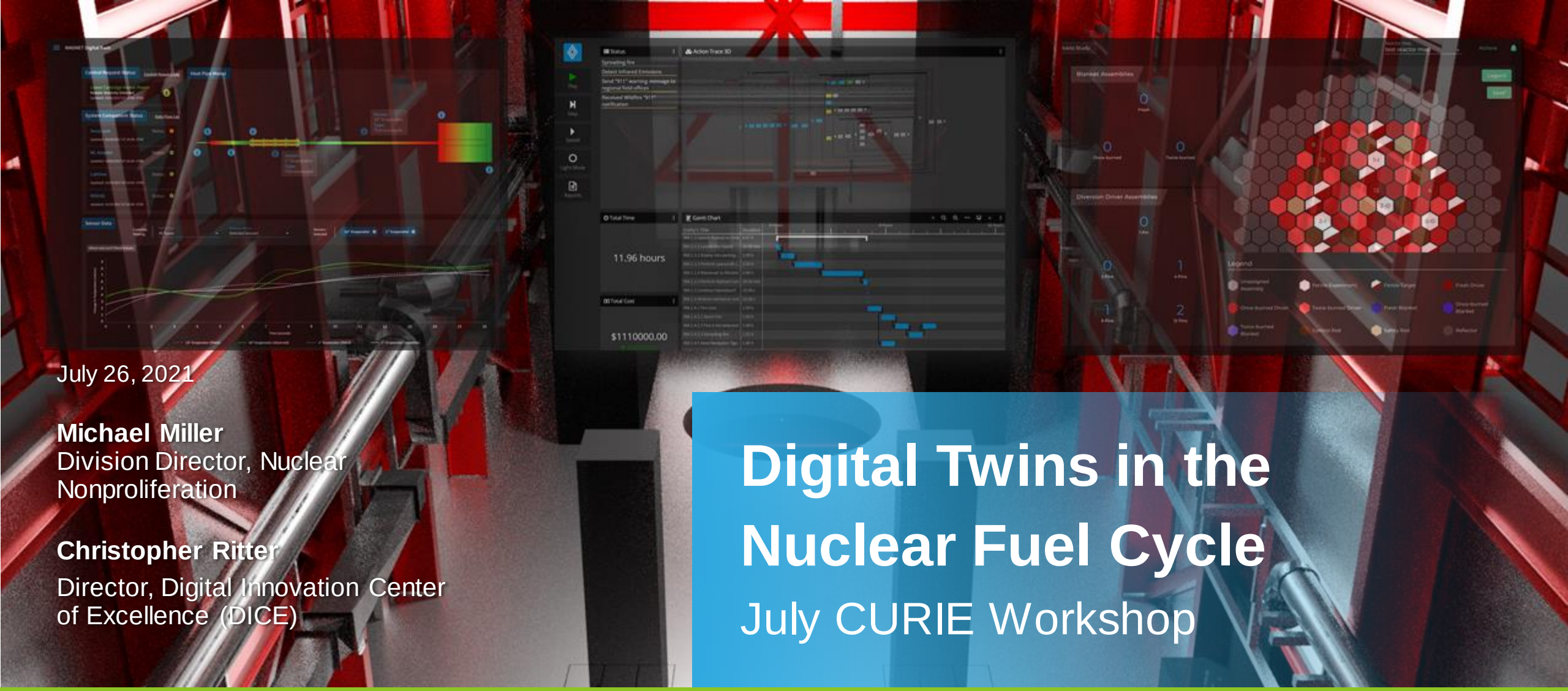


July 26, 2021

Michael Miller
Division Director, Nuclear Nonproliferation

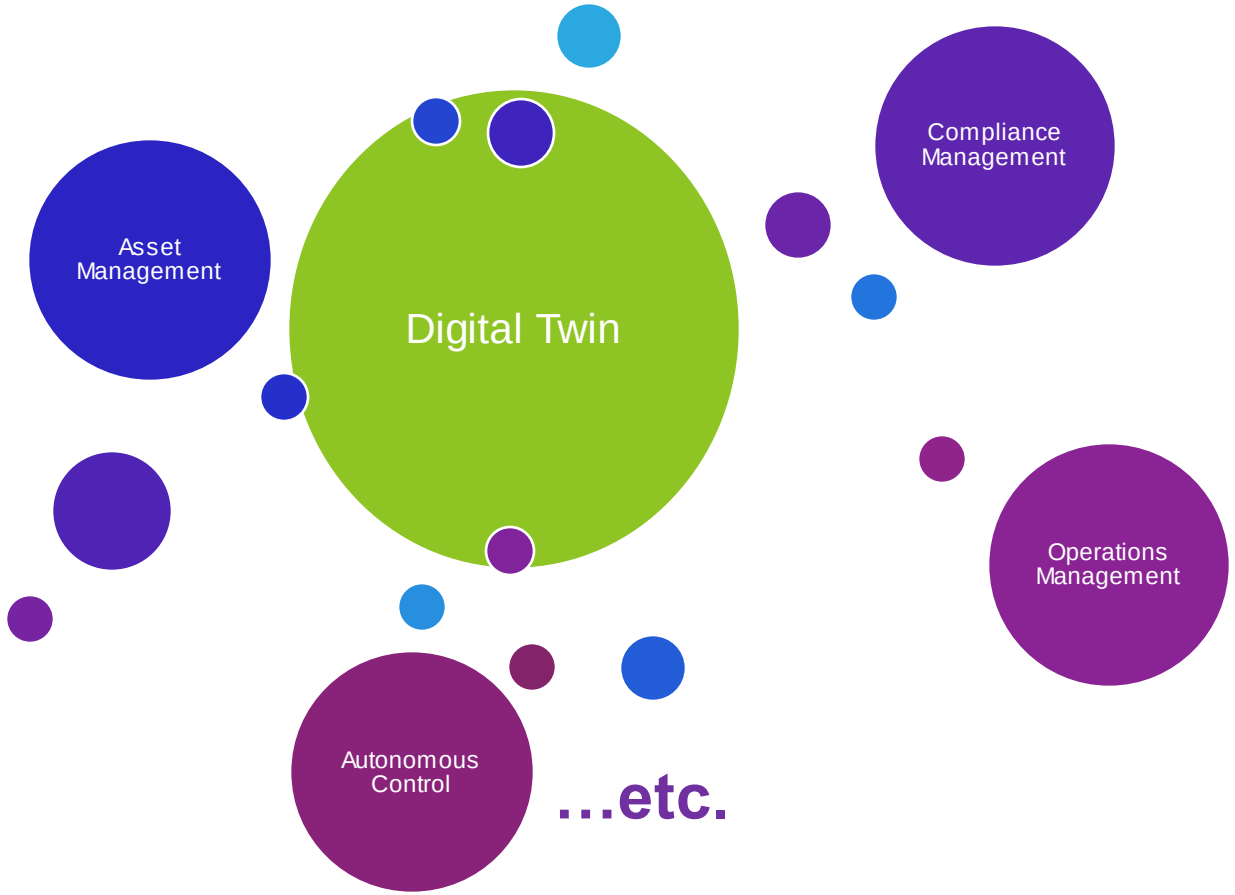
Christopher Ritter
Director, Digital Innovation Center of Excellence (DICE)

Digital Twins in the Nuclear Fuel Cycle

July CURIE Workshop

INL Idaho National Laboratory

What is a Digital Twin?



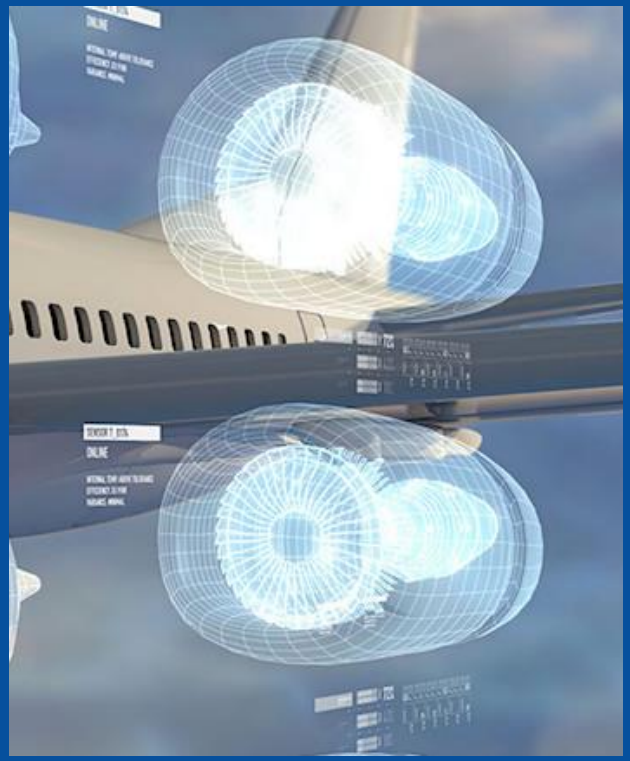
INL Definition: Digital Twins represent the merging of digital thread, controls theory, artificial intelligence, and online monitoring into a single cohesive unit, a virtual model that comprehensively captures all relevant aspects of the underlying system, utilizing bidirectional communication to track and trend both simulated and measured physical responses.

What is different than a traditional simulation?

- Integration of real-time data
- Dynamic model update (AI/ML integration)
- Real-time operator feedback (visualization)

Digital Twin Opportunity

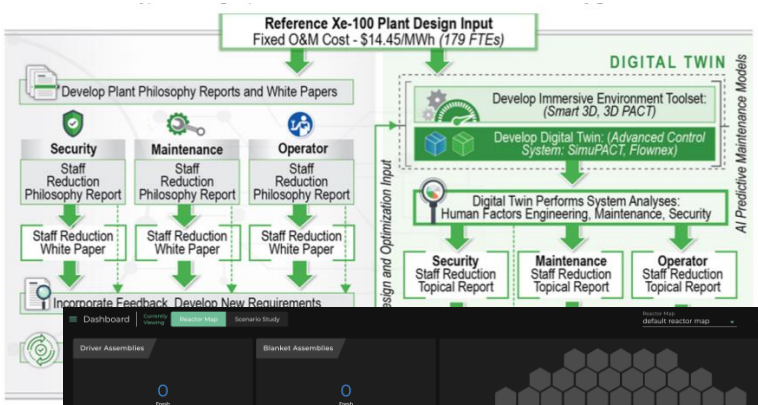
- **Operational Cost**
  - **14-23%** reduced operations cost (BCG [1])
  - **$1.05 billion** in cost avoidance (GE [2])
- **Asset Performance**
  - **40% improvement** in first-time quality (Boeing [6])
  - **10% improvement** in effectives (Gartner [2])
- **Growing Market and Technology**
  - Market is **~$3.1 billion** (2020) [5]
  - Market predicted to **$48.2 billion** by 2026 [5]



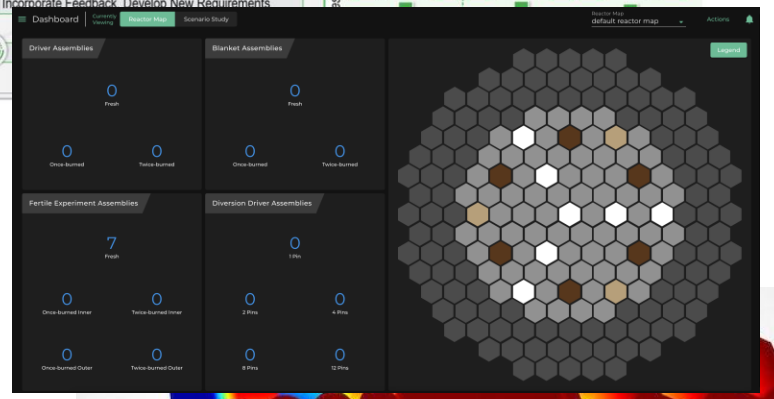
General Electric Aviation has digital replicas of every engine to monitor performance and predict maintenance issues. This approach reduces engine operational costs.

Nuclear Industry Examples

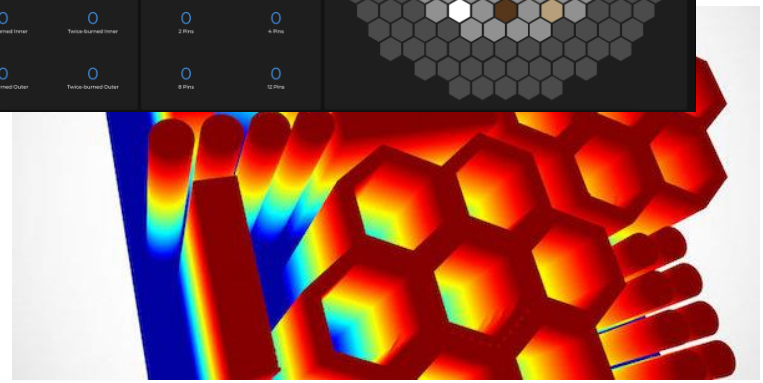
- **Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) [4]:** digital twin technology for advanced reactors to transform operations and maintenance (O&M) systems
  - ANL, EPRI, Framatome, GE Research, MIT, Moltex Energy, University of Michigan, X-Energy
- **DOE-NE**
  - **NRIC**: Model-based systems engineering (MBSE) and integrated 3D approach for test bed design
  - **TCR**: Digital platform for advanced manufacturing with integrated AI/ML
  - **VTR**: Advanced integrated digital ecosystem for reactor design with digital twin end-goal
- **NNSA:** Safeguards by Design Digital Twin



X-Energy



NNSA



TCR

Safeguards Digital Twins Video

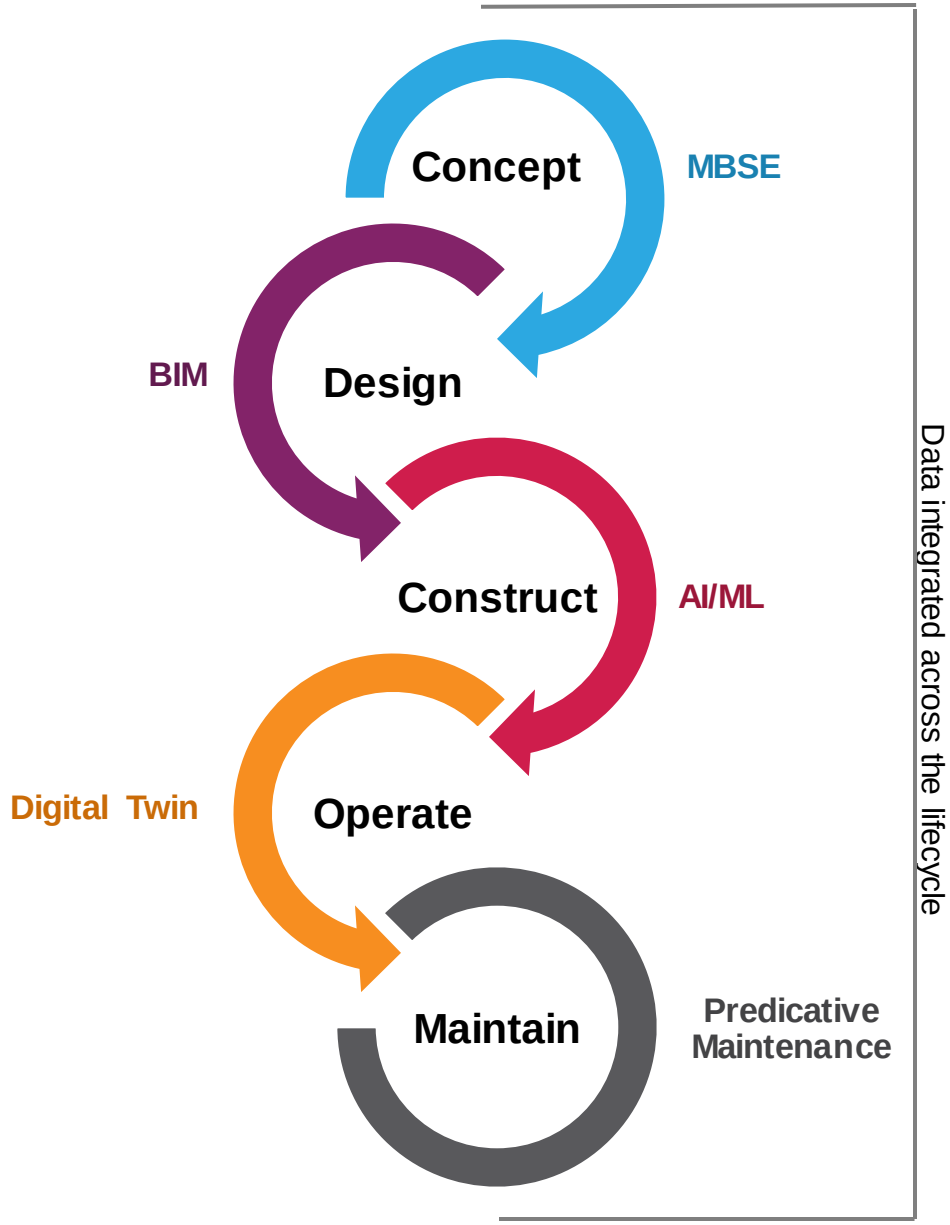
Digital Engineering

INL Definition: Digital Engineering embodies a deliberate transformational approach to the way systems are conceptualized, designed, constructed, operated, maintained, and retired.

Digital Engineering Design

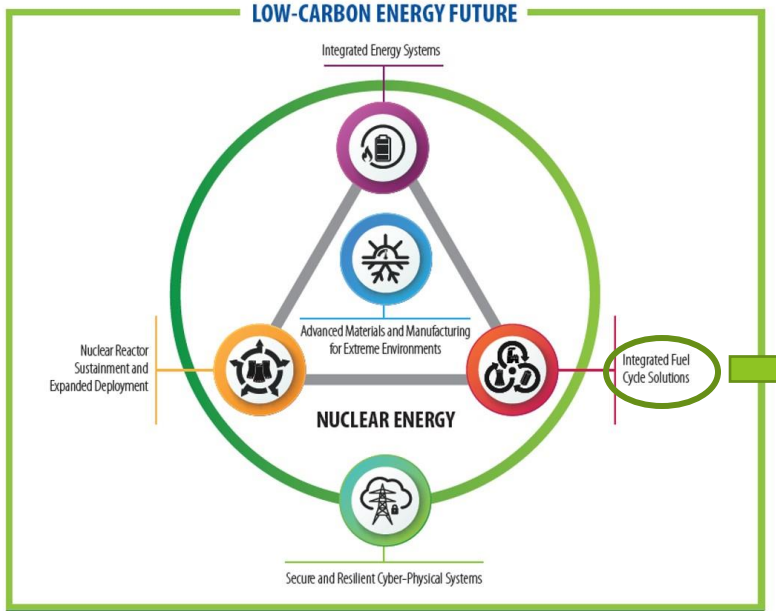
- **Capital and Operational Cost**: 15-25% cost savings in design, engineering, construction phase (BCG [1])
- **Schedule**: New sixth-generation stealth fighter already built with ~10-year schedule reduction [3]
- **Performance:** 25% productivity increase at Mortenson Construction using Virtual Design and Construction (VDC)
- **Risk**: Significant reduction of cascading risk (silent error) introduction in design of complex systems

AI/ML: Artificial Intelligence / Machine Learning
BIM: Building Information Management
MBSE: Model-Based Systems Engineering



Beartooth Test Bed Vision

INL supports the safe, secure, and economic management of nuclear fuel from conception to final disposition



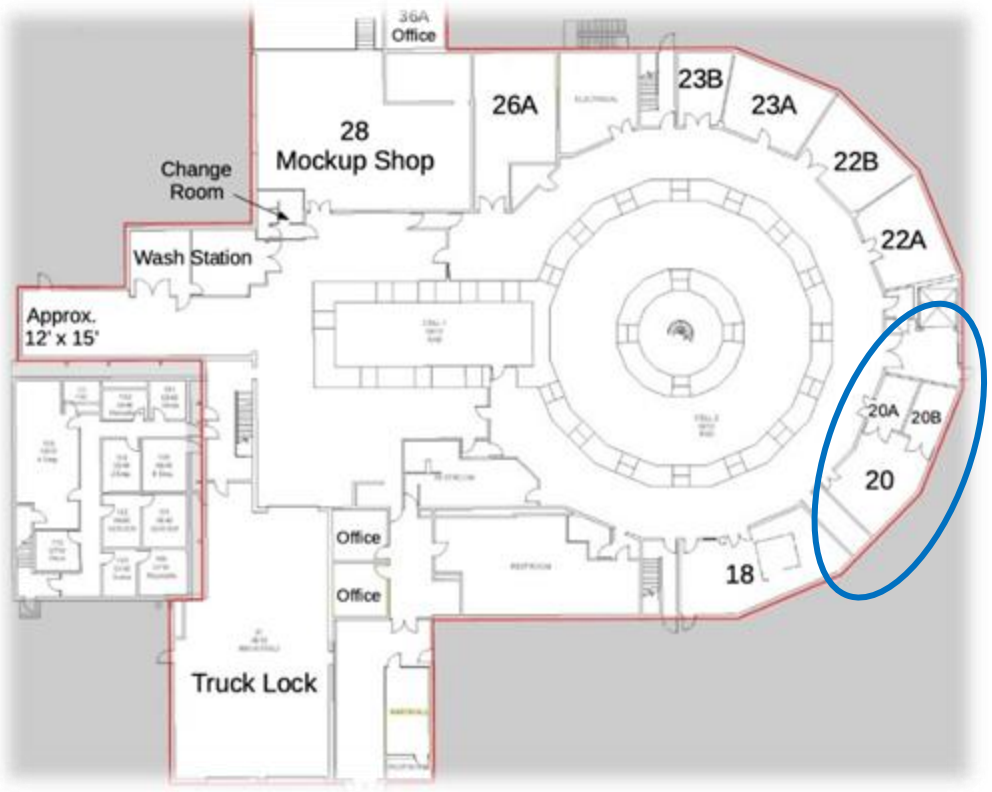
- *Supports **sponsor diversification** by capitalizing in growing NNSA, NHS, DTRA and AI-Data Science initiatives and budgets*
- *Provides an integrated **civilian nuclear fuel cycle test bed capability** not available at any other national laboratory*
- *Develops **key infrastructure** that supports RD&D of **national security solutions** for the evolving civilian nuclear fuel cycle*
- ***Develops new scientists and safeguards inspectors** to support fuel cycle and nonproliferation objectives*

Beartooth Test Bed

Beartooth - SNM Test Bed

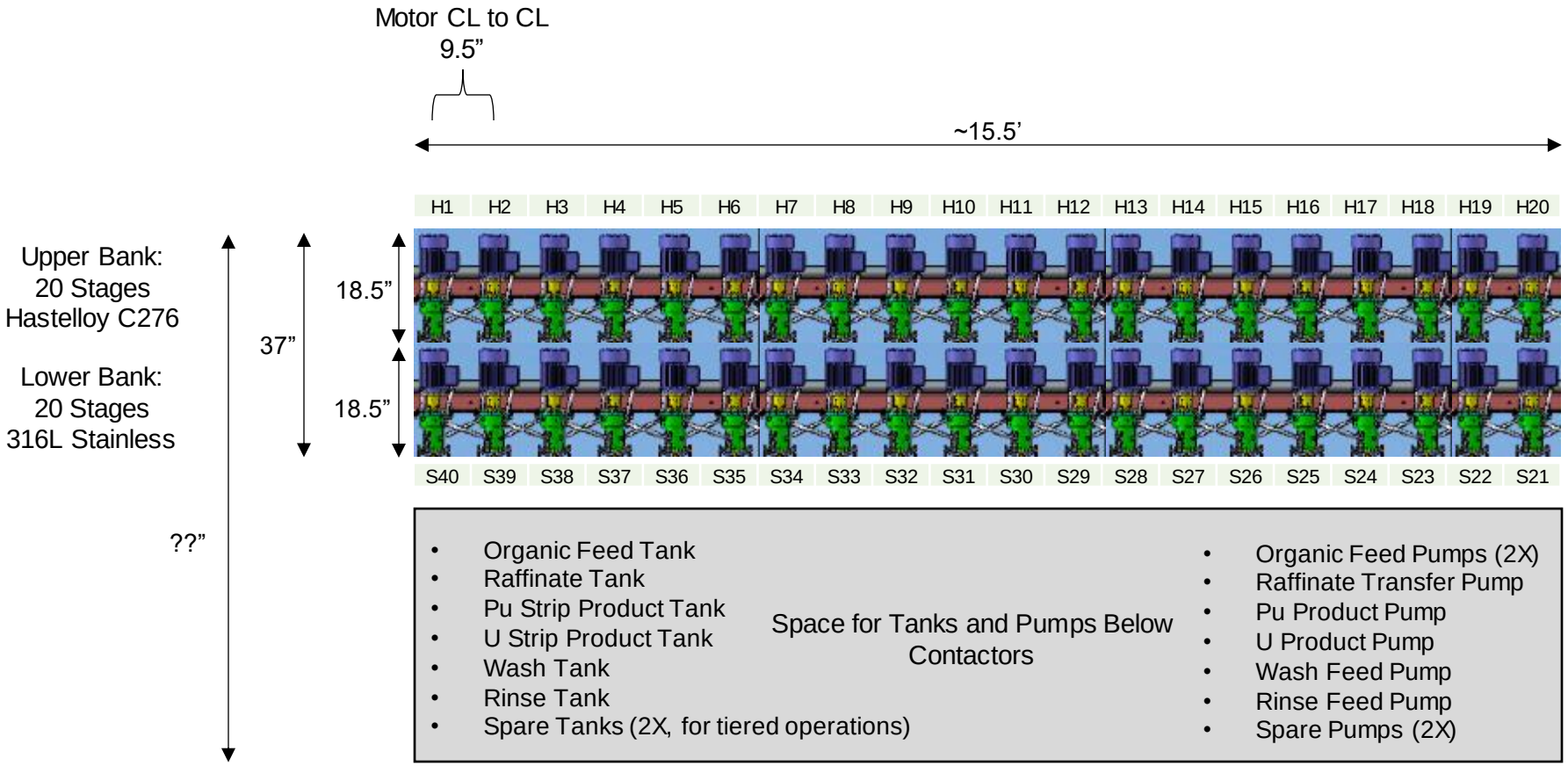
Objective – Provides an integrated civilian nuclear fuel cycle test bed capability for **testing new nonproliferation technologies**

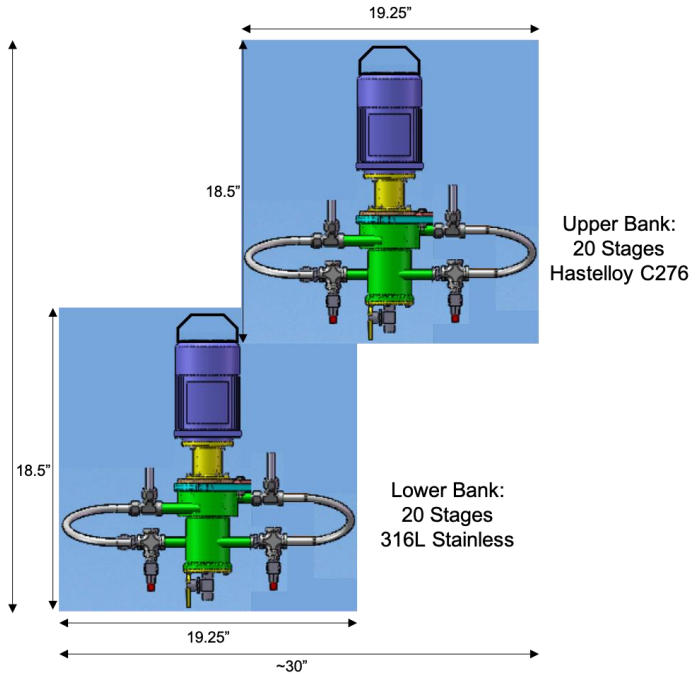
- *Platform for instrumentation development supporting tracking and accounting of special nuclear material and proliferation detection of the evolving nuclear fuel cycle*
- *Develops new AI and ML methods to inform nonproliferation decision making*



Location – MFC FCF
Hazard Category II Facility

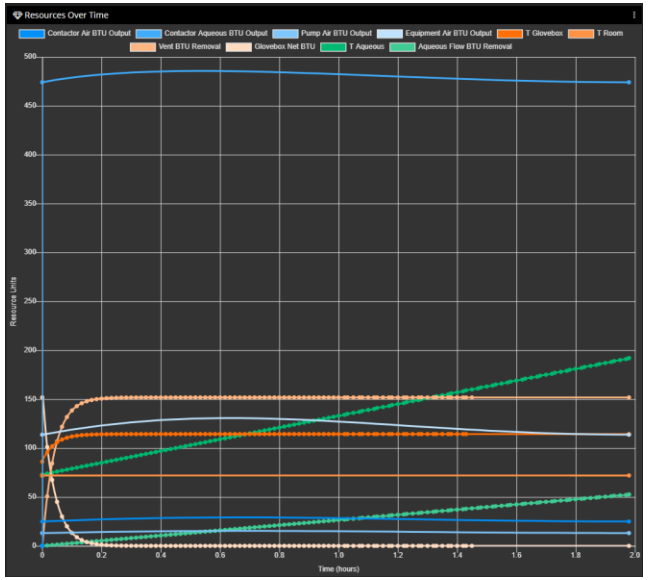
Conceptual Layout: Front & Side Profile

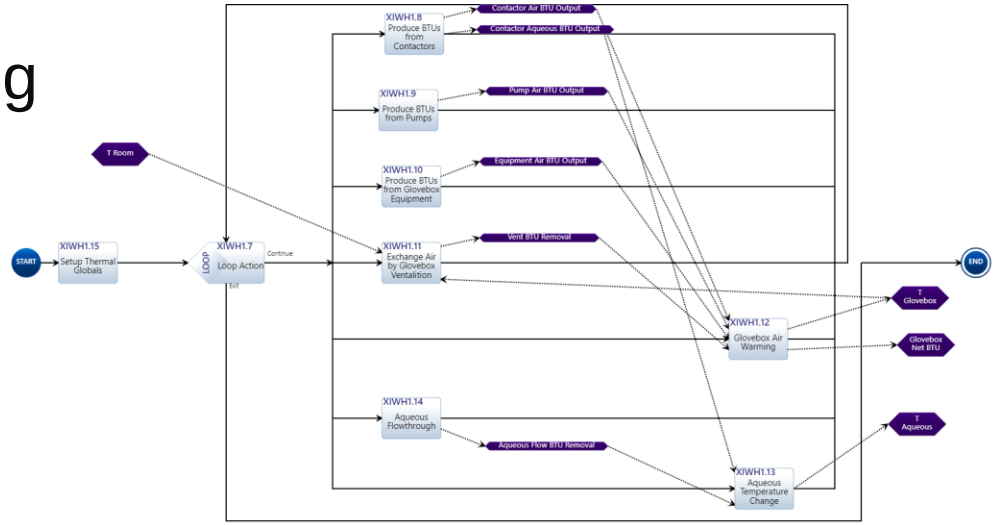




Digital Engineering Design with MBSE

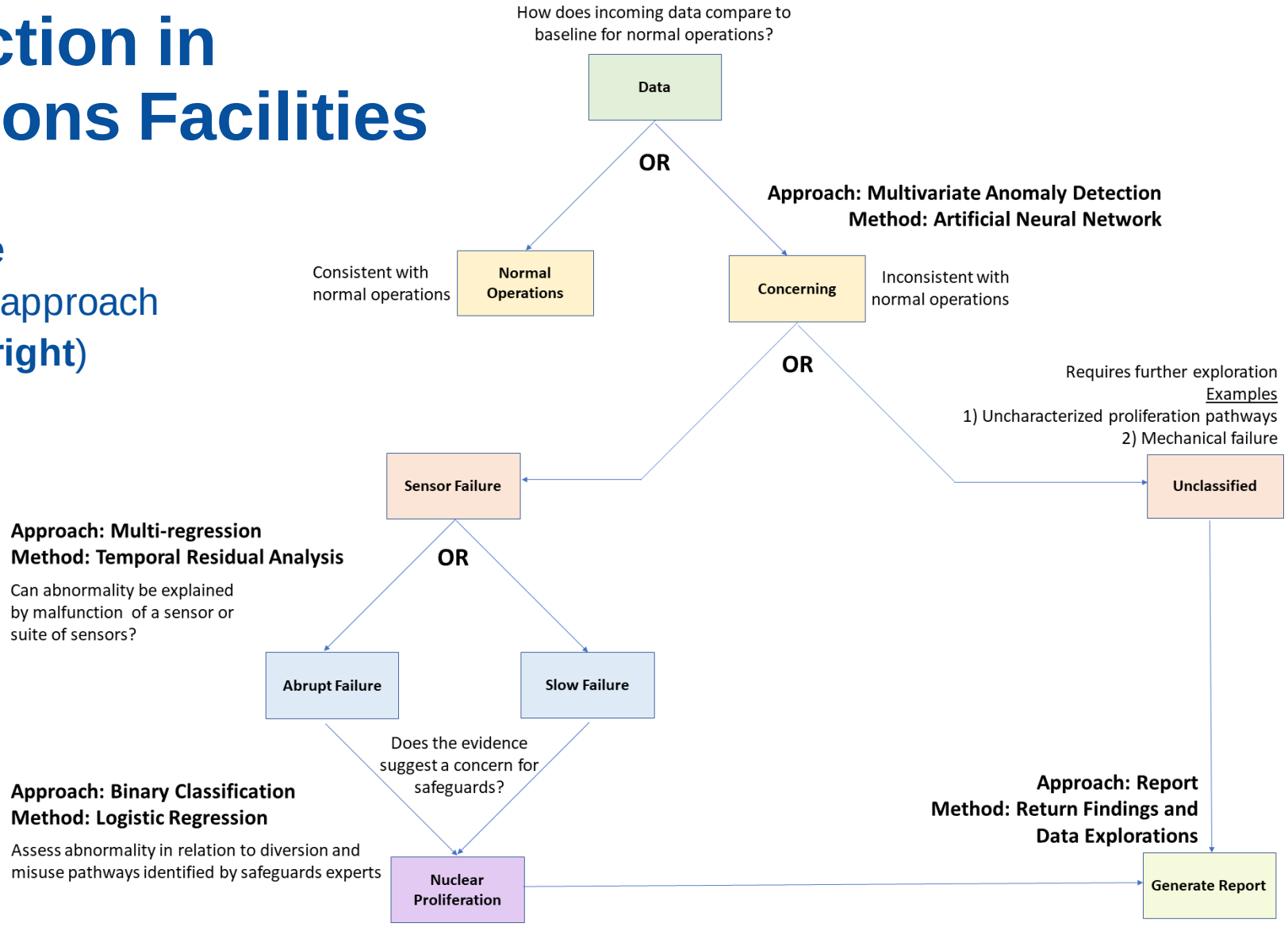
- MBSE: Integrated data approach to modeling to requirements, design, analysis, and test (V&V)
  - Enables validation of assumptions and parameters early in the process
  - Provides traceability to documentation such as requirements for traceability
  - Reduces silent error introduction: Modelling out assumptions such as heating/cooling early in the conceptual design proved that there were additional parameters or requirements that needed defined in the design.





Developing a Digital Twin for Proliferation Detection in Chemical Separations Facilities

- **Transferable Solutions**
  - Framework digital twin architecture
  - Break AI/ML goals into simple Q/A approach
  - Prescribe a data driven workflow (**right**)
- **Bonneville County Technology Center (BCTC) to Beartooth Testbed**
  - Transparent system monitoring
  - Automated status reporting
  - Proliferation detection
- **Flexible Approach**
  - Algorithms can be specialized for individual applications
  - Infrastructure remains constant



Fuel Cycle Digital Twin Summary

- Digital twin and digital engineering techniques are under application in reactor safeguards and fuel cycle facility development (**Beartooth**)
- Proven to significantly **reduce costs (14-23%)** and **increase performance** in automotive and aerospace industries
- **Transformational approach** to operation and maintenance across nuclear fuel cycle with innovation growing at a rapid pace
- Advanced nuclear digital twins **currently funded** through ARPA-E GEMINA, DOE-NE, and NNSA
- Digital engineering proven success in nuclear design: VTR has **sustained milestone performance** across a geographically dispersed team due to our digital engineering strategy
- Digital twin+ AI enables sophisticated proliferation analysis to allow mitigation of diversion and misuse scenarios through safeguards by design and real time monitoring for detection and automated conclusions
- Deployed and **advanced nuclear twins in development** in industry, academia, and the national laboratories

	BOC Power Difference (%)	EOC Power Difference (%)	BOC CR Insertion Depth (cm)	EOC CR Insertion Depth (cm)	Plutonium Generated (kg)
BOC Power Difference (%)	1.0	0.12	-0.64	-0.74	-0.62
EOC Power Difference (%)	0.12	1.0	0.61	-0.06	-0.08
BOC CR Insertion Depth (cm)	-0.64	0.61	1.0	0.52	0.39
EOC CR Insertion Depth (cm)	-0.74	-0.06	0.52	1.0	0.96
Plutonium Generated (kg)	-0.62	-0.08	0.39	0.96	1.0

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Acronyms

ECI: Export Controlled Information

HPC: High Performance Computing

MAGNET: Microreactor AGile Non-nuclear Experimental Testbed

NNSA: National Nuclear Security Administration

NRIC: National Reactor Innovation Center

OUO: Official Use Only

STIC: Strategic Thermal Irradiation Capability