Digital Twins in the Nuclear Fuel Cycle
July CURIE Workshop

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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]
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
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
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

Upper Bank:
20 Stages
Hastelloy C276

Lower Bank:
20 Stages
316L Stainless

- Organic Feed Tank
- Raffinate Tank
- Pu Strip Product Tank
- U Strip Product Tank
- Wash Tank
- Rinse Tank
- Spare Tanks (2X, for tiered operations)

Space for Tanks and Pumps Below Contactors

- Organic Feed Pumps (2X)
- Raffinate Transfer Pump
- Pu Product Pump
- U Product Pump
- Wash Feed Pump
- Rinse Feed Pump
- Spare Pumps (2X)

Motor CL to CL
9.5"

~15.5"

H1  H2  H3  H4  H5  H6  H7  H8  H9  H10  H11  H12  H13  H14  H15  H16  H17  H18  H19  H20

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
References

5. https://www.computer.org/csdl/magazine/co/2021/04/09399932/1sF3E3EoCas

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