INL/CON-22-69247-Revision-0

INL Digital Engineering: Model-Based Design, Digital Threads, Digital Twins, Artificial Intelligence,and Extended Reality for Complex Energy Systems

September 2022

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Changing the World's Energy Future

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INL Digital Engineering

Model-Based Design, Digital Threads, Digital Twins, Artificial Intelligence, and Extended Reality for Complex Energy Systems

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

Outline

Digital Transformation at INL

Digital Engineering

Model-Based Systems Engineering

Digital Thread

Digital Twin

Artificial Intelligence (AI)

Extended Reality (XR)

Digital Transformation at INL

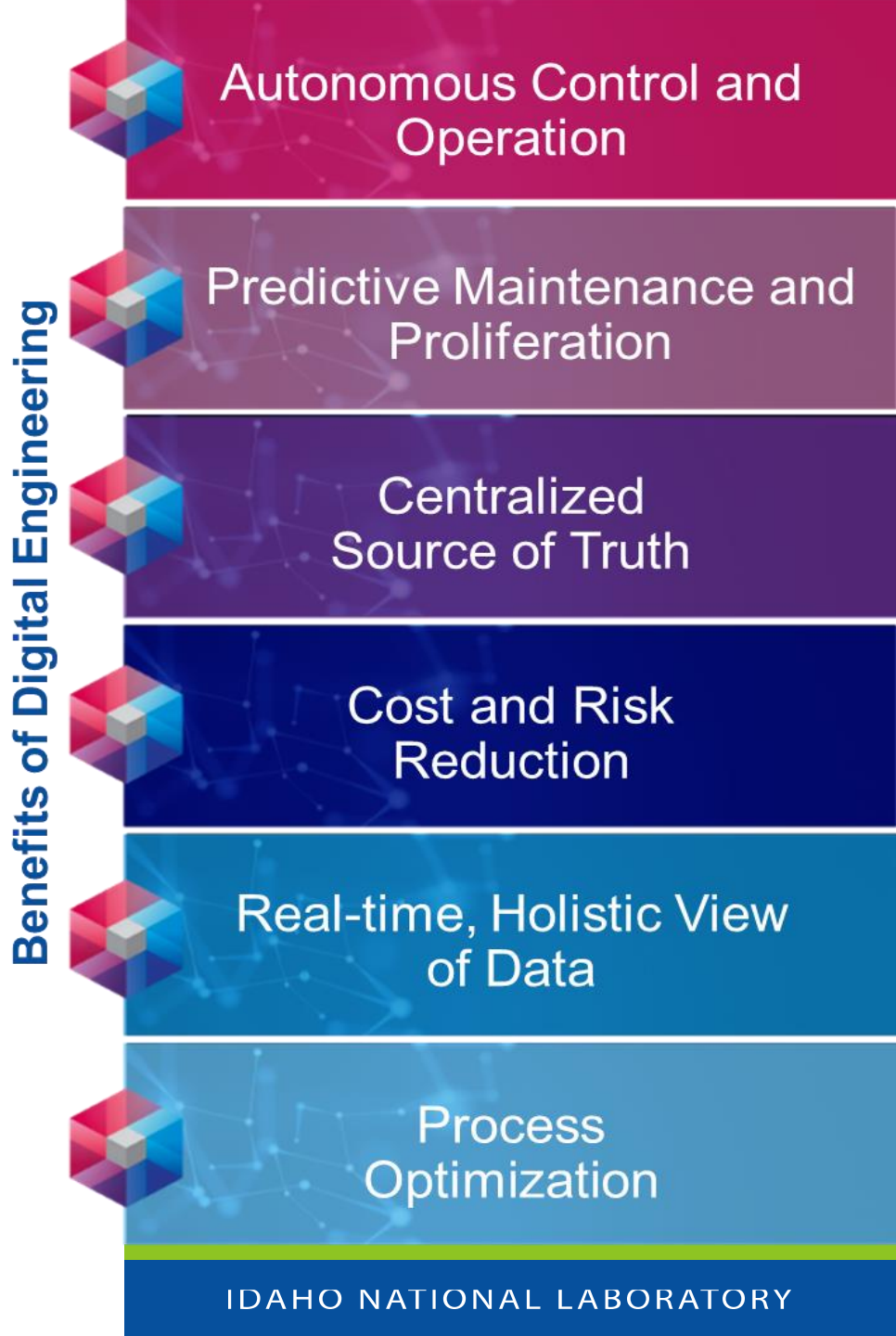
Digital **I**nnovation **C**enter of **E**xcellence serves as a virtual center to formalize and coordinate digital engineering, digital twinning, and digital transformation activities across next generation energy systems.

- **Advanced Manufacturing**: Advanced Material Property Prediction Twin, CyManII
- **Integrated Fuel Cycle Solutions**: BCTC Twin, Beartooth Twin, Plutonium Separation Twin
- **Integrated Energy Systems**: Nuclear-Renewable-Storage Twin
- **Nuclear Sustainment/Deployment**: ATR/Thermal Test Reactor Capability, LWRS, MAGNET Digital Twin, MARVEL, MCRE, NRIC, Project Pele, TerraPower Natrium
- **Secure and Resilient Cyber-Physical Systems**: Athena, Exotanium, Safeguards by Design Digital Twin, Signals Exploration Testbed (SET), Open Science Cloud, SONAR

Digital Engineering

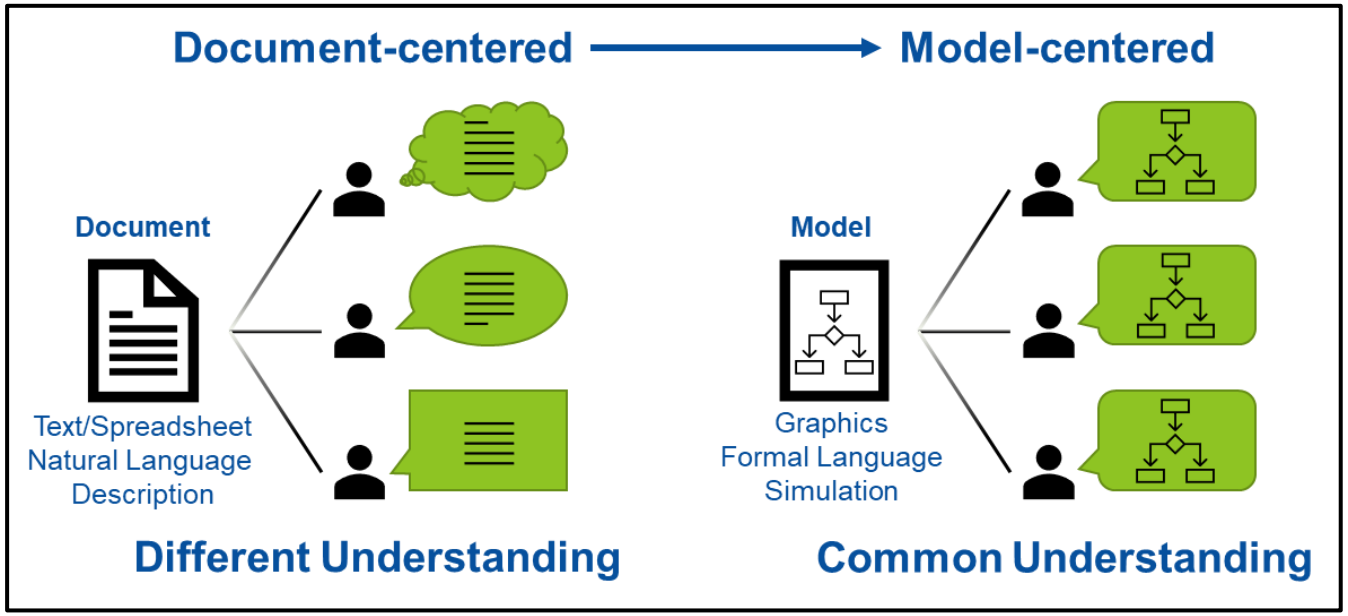
Digital engineering integrates information into the life cycle of a megaproject:

- **Model-based** approaches to apply engineering rigor across systems and facility design
- **Open-source digital thread** to connect data, assets, and analytics across energy systems
- **Explainable AI** with mathematical approaches to forecasting and anomaly detection
- **Immersive mixed reality** to visualize and interact with physical assets and virtual digital twins.



Model-Based Systems Engineering (MBSE)

- Transforms typical systems artifact documents to data objects
- Creates a live, digital, and single source of truth
- Ensures accurate building the first time
- System-of-system (SoS) interactions, interfaces, and dependencies
- Schedule and task breakdown.



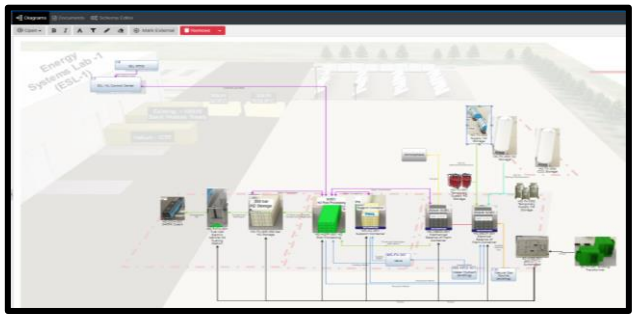
What is MBSE?

Model-based systems engineering is the formalized application of modeling and data-driven engineering that supports SoS design, analysis, verification, and validation development activities throughout the project lifecycle.

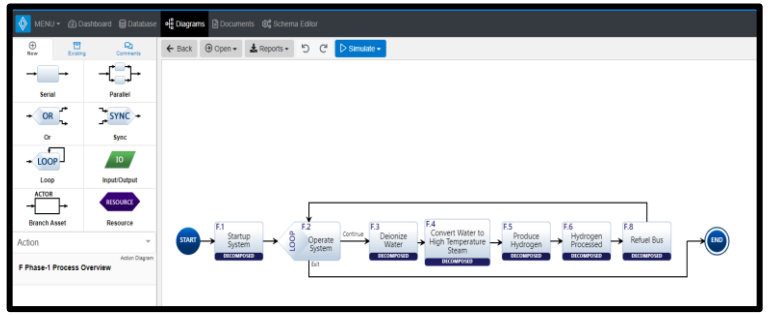
MBSE at INL

H2 scaling center: Hydrogen production and use demonstration

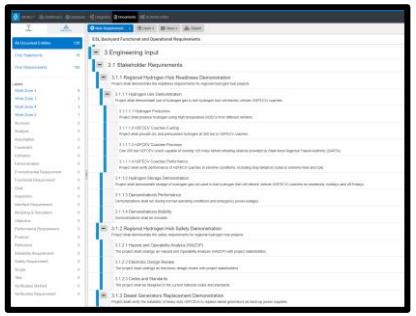
- H2 **produced** using high temperature electrolysis
- H2 **post-processed** and store
- H2 **used** to fuel H2 fuel cell electric vehicle (H2FECV) coaches



System Architecture
establishes centralized source of truth; enables testing of different configurations.



Functional Analysis
leverages simulation and drives requirement analysis.

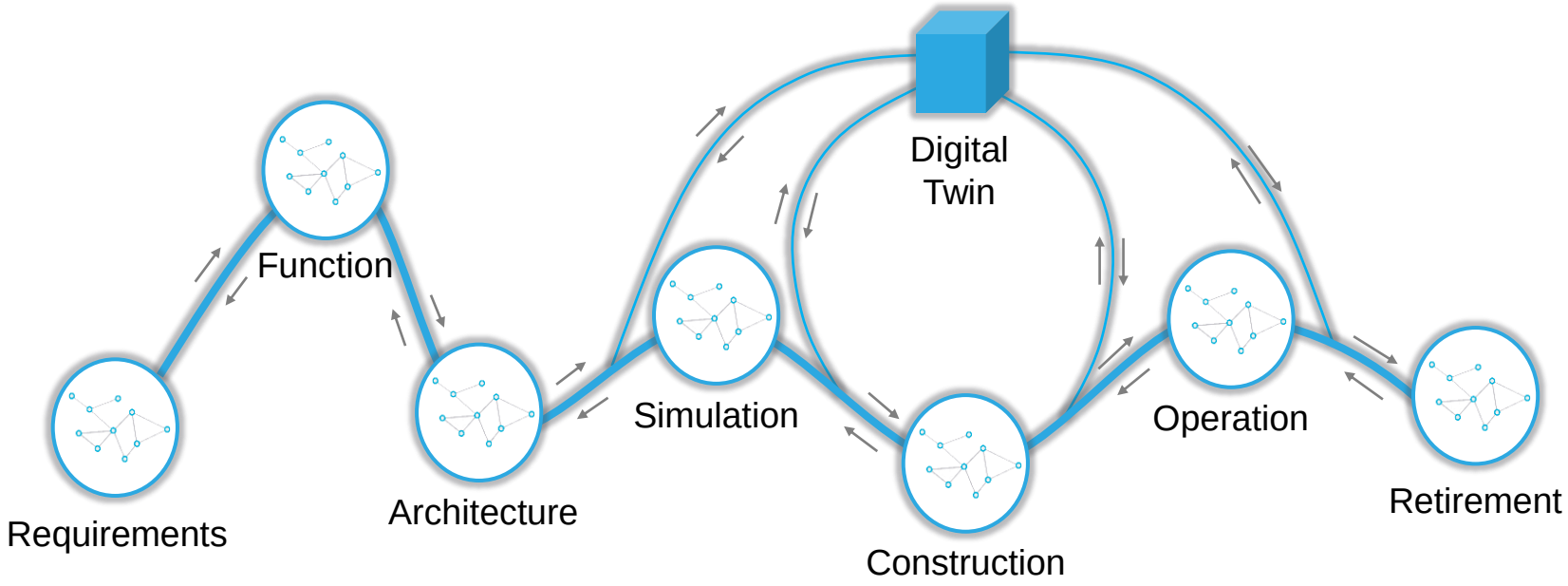


Requirements Engineering
provides connectivity to design.

MBSE in progress:

- H2 Scaling Center
- National Reactor Innovation Center (NRIC) Demonstration Testbeds
- NRIC Integrated Energy Systems
- Advanced Test Reactor Recapitalization
- Molten Chloride Reactor Experiment (MCRE)
- Microreactor Applications Research Validation and Evaluation (MARVEL)
- Biomass Feedstock National User Facility (BFNUF)
- Beartooth Nuclear Fuel Testbed

Digital Thread



- **Connects** MBSE model to digital definitions created later in the development process
- Maintains system **integrity** across lifecycle.

What is a Digital Thread?

A Digital Thread is an interconnected software data exchange used to enable digital engineering and digital twinning systems.

Digital Twin

- **Living virtual model** mirrors a physical asset to predict future behavior.
- **MBSE** defines architecture and ontology.
- **Real-time bi-directional communication** tracks and trends simulated and measured asset information.

Diverges from a traditional simulation

- Integration of real-time data
- Dynamic model update (AI/ML integration)
- Real-time operator feedback (visualization)
- Accurate predictions with fused (integrated) data
- Ability to enable autonomous control
- Distributed across computing platforms.

What is a Digital Twin?

Digital Twins represent the merging of integrated and connected data, sensors and instrumentation, artificial intelligence, and online monitoring into a single cohesive unit (INL definition).

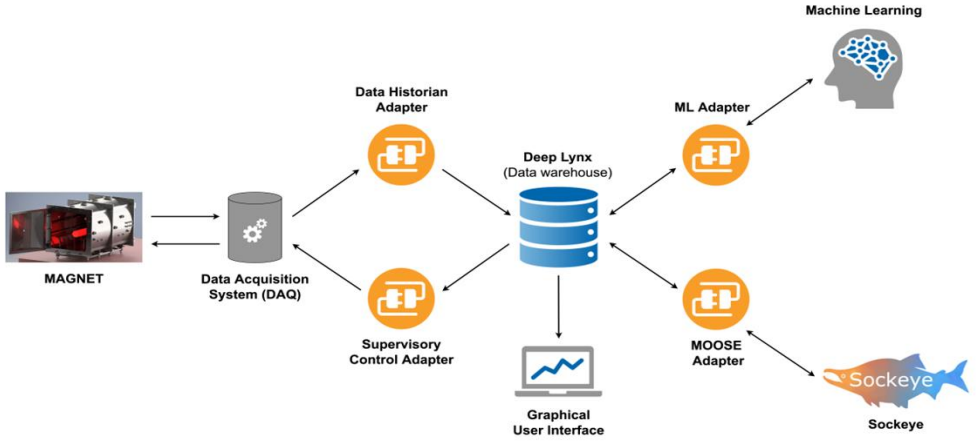
Digital Thread and Twin at INL

DeepLynx:

- Centralized digital twin data warehouse and live event system
- Ontological and time series storage of digital twin data streams
- Event system pushes and pulls data in real-time around a digital twin
- Offline historian capability across operating power plant fleet.

Digital Twins in progress:

- MAGNET non-fissile microreactor
- Beartooth nuclear fuel testbed
- PELE microreactor project
- Advanced manufacturing
- MARVEL microreactor informed operations
- Nuclear renewable storage.

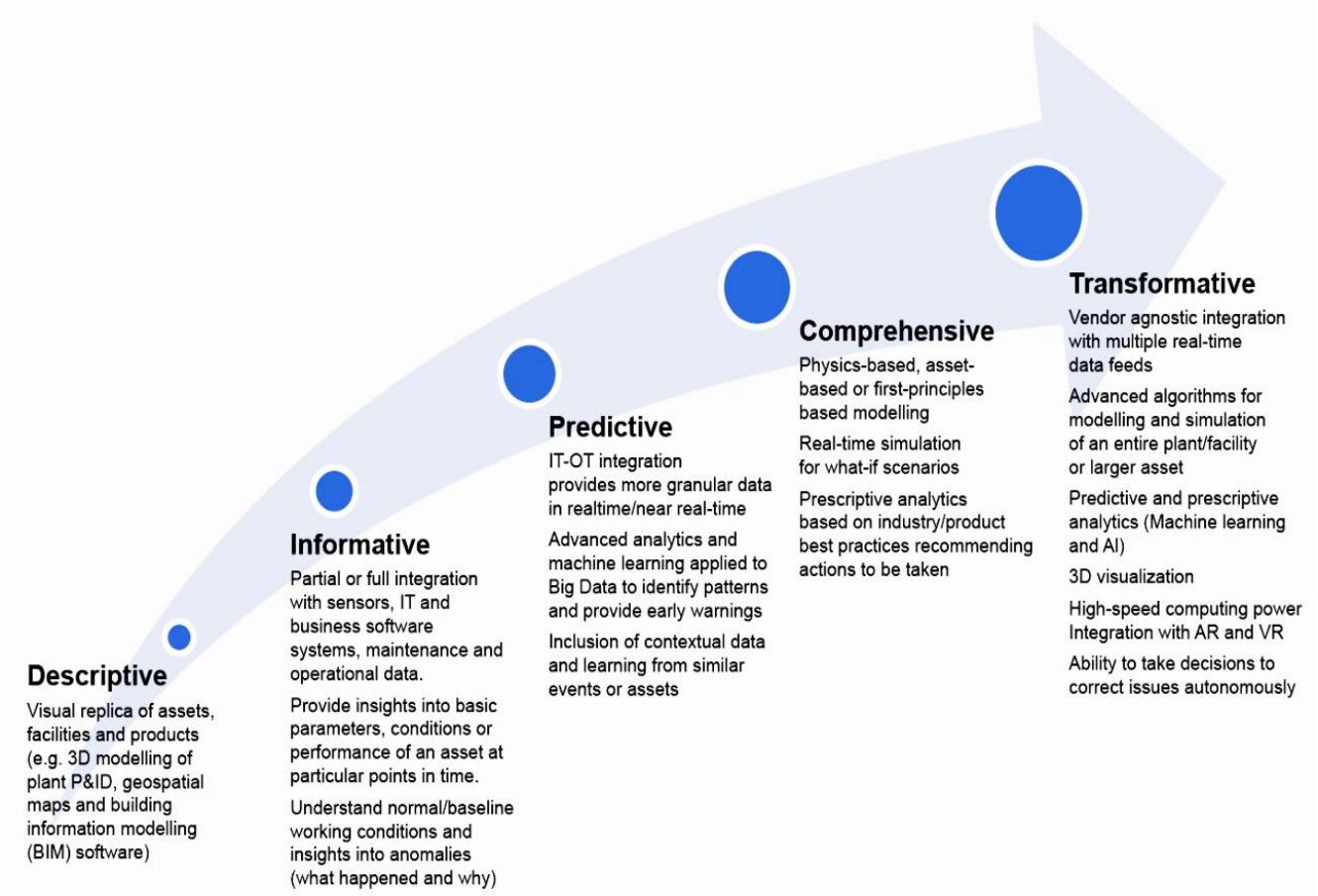


What is MAGNET?

- Microreactor Agile Non-Nuclear Experimental Test Bed
- Change temperature set point to upper or lower limit
- Digital twin predicts temperature will exceed threshold
- Temperature set point is updated to baseline temperature.

Artificial Intelligence

- Power plants (especially nuclear) heavily rely on staff
- **Automate** expensive and manual human activities
- Use available data to **predict** unobserved and difficult to measure instances
- Application requires:
  - Selecting compatible methods
  - Customizing methods
  - Combining methods
  - Integrating methods with other science processes (e.g., modeling tools).



Source: Verdantix Smart Innovators Digital Twins For Industrial Facilities

Artificial Intelligence at INL

AI in progress:

- Explainable AI
- Battery lifetime and failure mode estimation
- Insights of reaction mechanisms via transient kinetics
- Light Water Reactor Sustainability program
  - Anomalies detection
  - Automated fire watch
- MOOSE simulation environment
  - Predict fuels and materials.

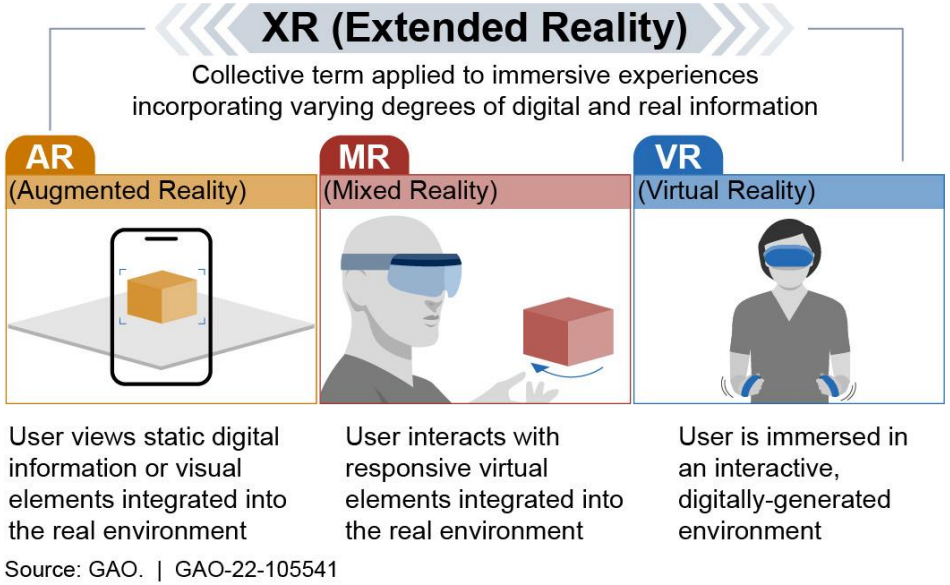
MAGNET

Two-Stage ML Process:

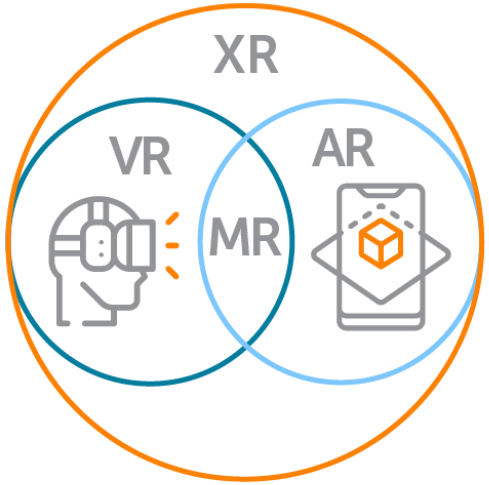
1. Variable selection between sensors
   - ML model: elastic-net regression using lasso penalties
   - Finds relationships between sensors to account for outliers
2. Multivariate forecasting
   - ML model: vector autoregressive (VAR)
   - Extrapolate sensor information in time

Result: Error of median forecast <0.3% for each thermocouple.

Extended Reality



Source: GAO. | GAO-22-105541



XR use for advanced digital twin visualization:

- Improved engineering design reviews:
  - Integrated building information management data and modeling
  - True dimensional design understanding
- Improved system operation
  - Integrated 2D dashboards and analytics
- Secure network support for Microsoft HoloLens 2 on export-controlled data

Extended Reality at INL

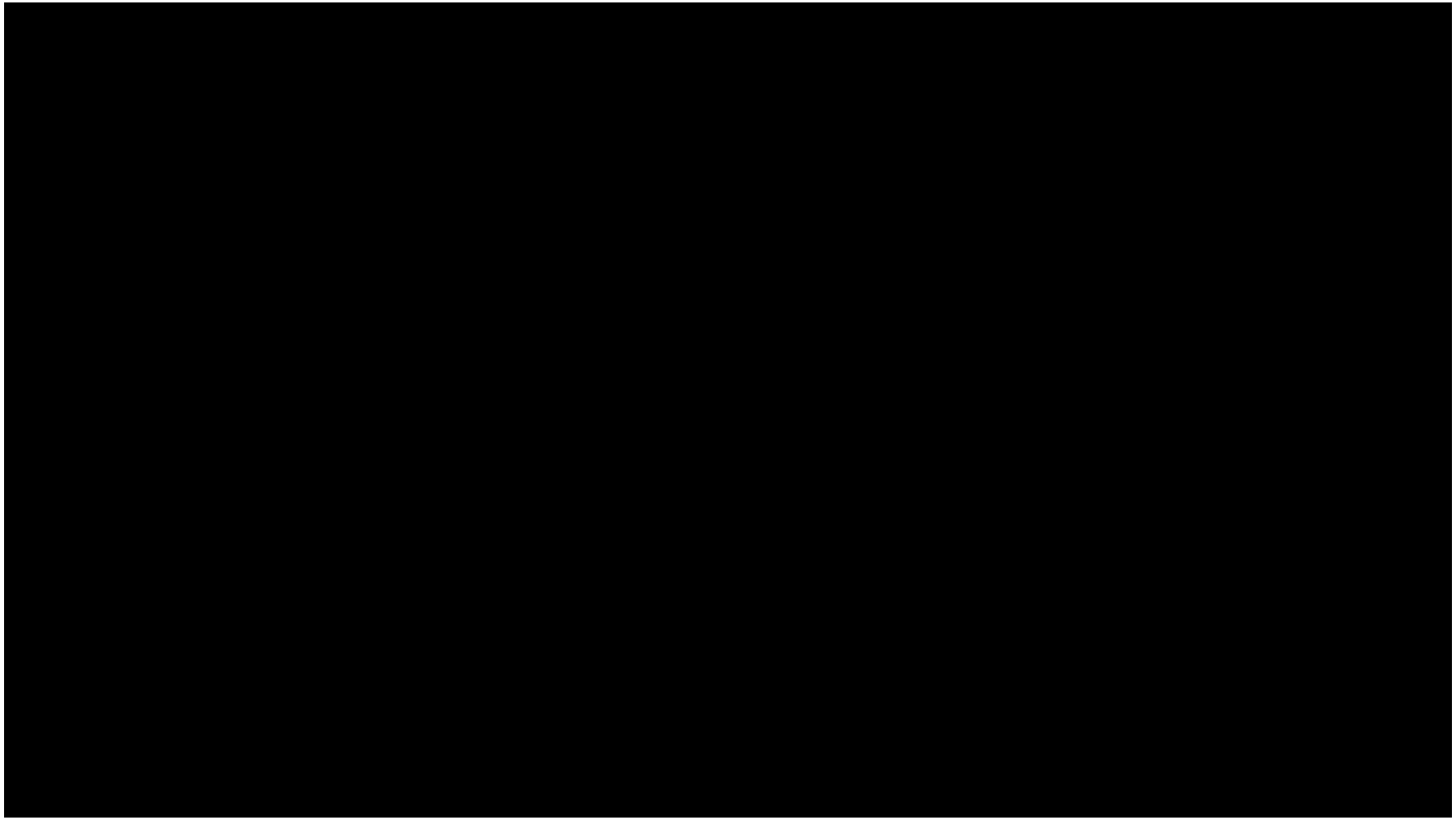
Beartooth Nuclear Material Testbed

- Fuel cycle is experiencing rapid transformation:
  - Smaller reactors
  - New fuel (HALEU, Pu, Th, etc.)
  - New materials and technology (Additive Manufacturing, malonamide, etc.)
- Supports fuel cycle R&D and modern non-proliferation mission
- XR used in design reviews and design verifications

XR in progress:

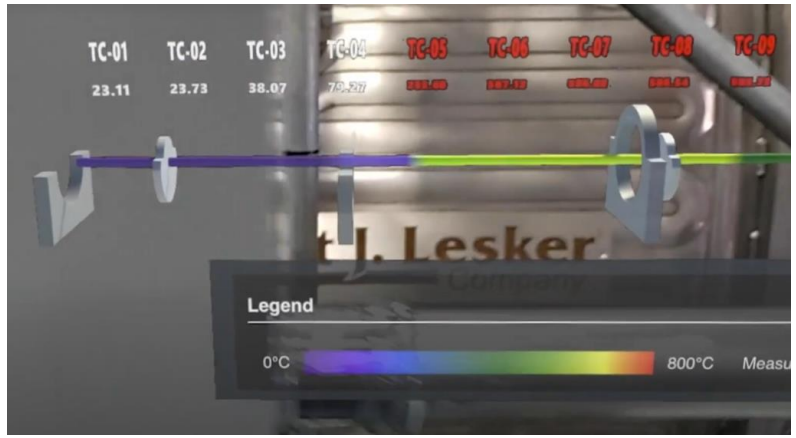
- Beartooth
- MAGNET
- Hydrogen Hub
- All Hazards Analysis
- C3 Facility Maintenance
- CISA Cyber Security Testbeds.

Digital Engineering Demonstration



Future Directions

- **Real-Time Digital Twin Human-Machine Interface (HMI)**
  - Traditional HMI's (e.g., laptops) are not useful during operations
  - Holographic MR platforms provide **data during operation** without hampering work
  - Game engines transform data into more **intuitive** representations for users than raw data.
- **Transforming Training**
  - Digital Twins provide real data to VR/MR trainings
  - Interactions are **richer and realistic** than traditional slides/videos
  - **Less expensive** than building mock-ups and enables dynamic interactions
  - Minimizes exposure to **risk.**



Partnerships

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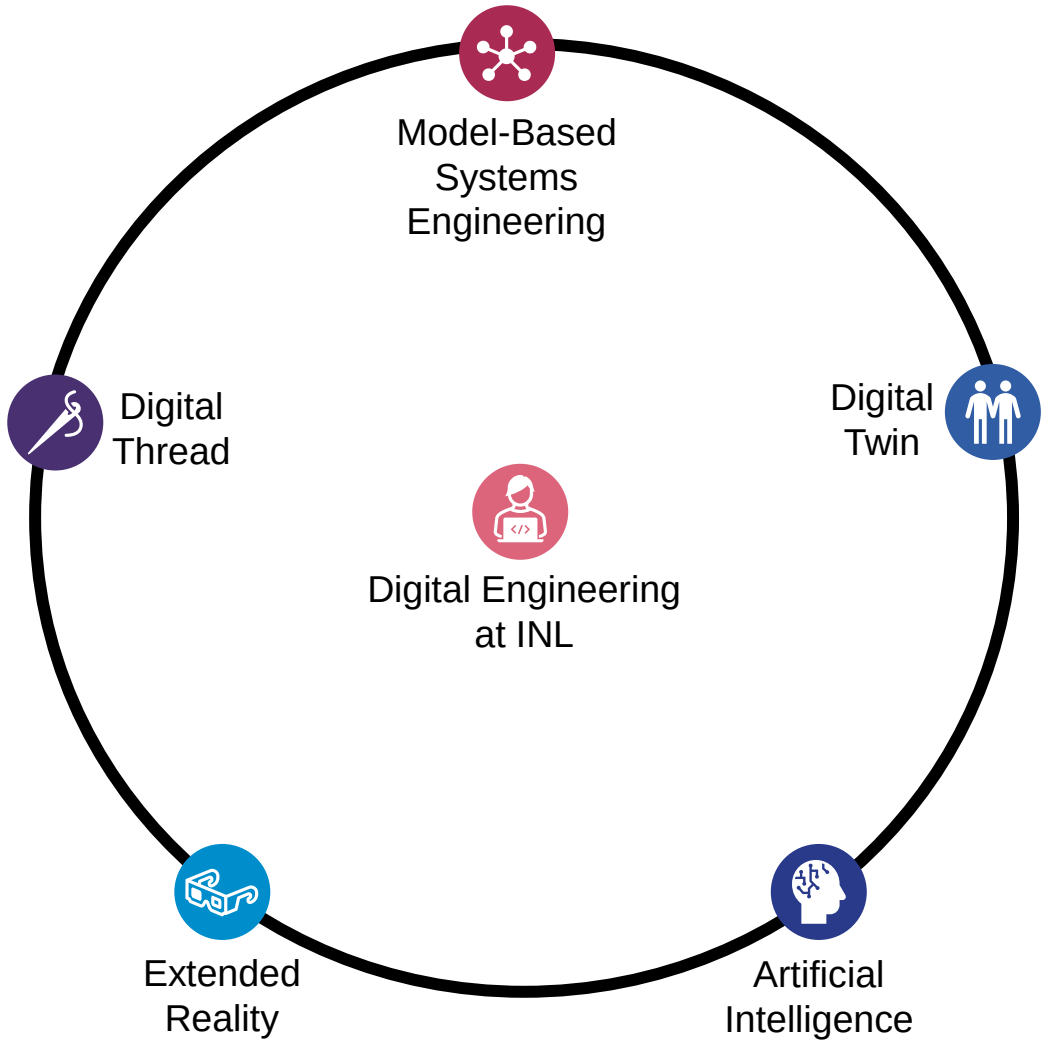
Summary

- Proven early success in autonomous digital twins
- Proven success in digital engineering design
- Expanding open-source technology
- Growing partnerships
- Advancing energy industry research through digital transformation.



Q & A

Idaho National Laboratory

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