INL/MIS-22-65669-Revision-0

EPRI DE Presentation

January 2022

Christopher S Ritter

Changing the World's Energy Future

Idaho National Laboratory

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Digital Engineering Presentation to EPRI

January 24, 2022

INL/MIS-22-65669-Rev000

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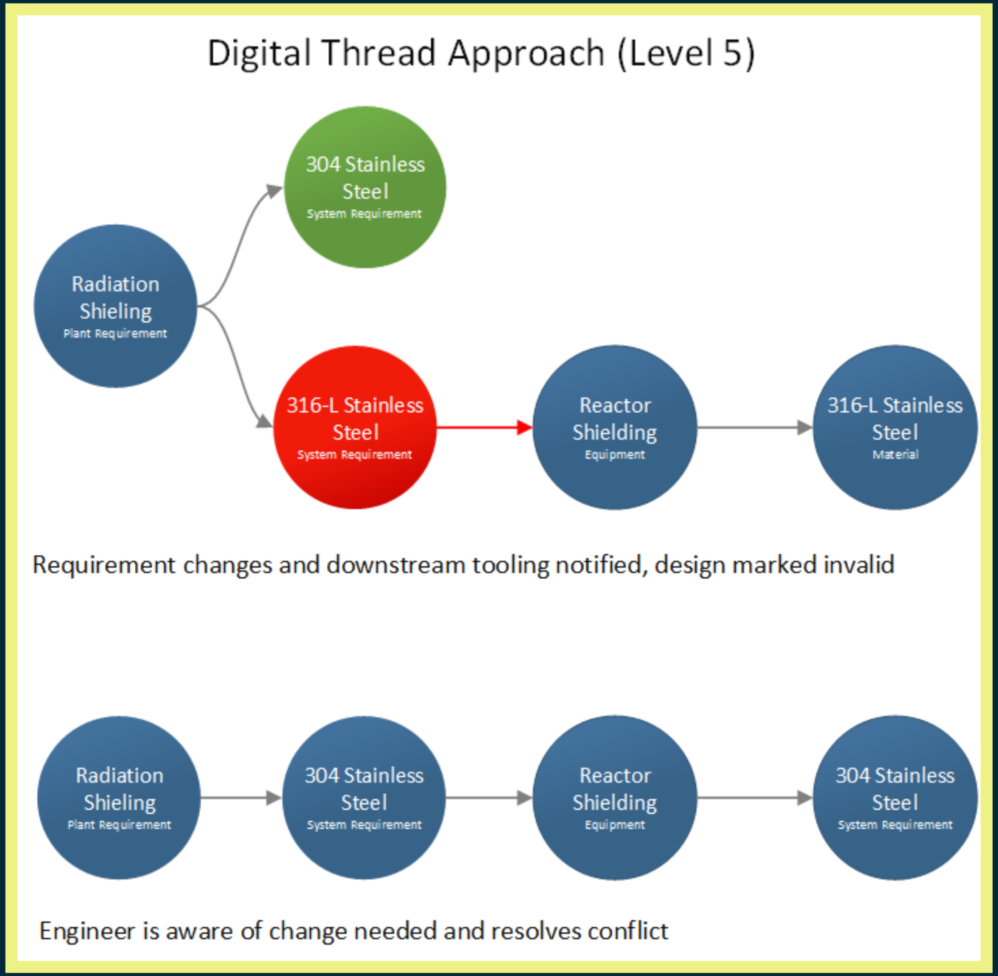
Digital Engineering Overview

Chris Ritter

Digital Engineering Department Manager

Complex Engineering Challenges

- Nuclear Needs Innovation in America
  - Plant Vogtle
  - V.C. Summer Nuclear Station
  - Westinghouse
- Kilopower Project KRUSTY Test (LANL)
  - Design change from 316-L Stainless Steel to 304 Stainless Steel
  - Miscommunication between reactor and mechanical designers occurred for change in materials of shielding
  - Caused schedule delays
  - Overall project was successful but at larger scale problem would be magnified
- Outside Nuclear Challenges: Joint Strike Fighter, Boeing 787, Airbus A380



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Digital Engineering Advantage

What is Digital Engineering?

Digital Engineering (DE) embodies a deliberate transformational approach to the way systems are designed, engineered, constructed, operated, maintained, and retired.

Why?

“Air Force flies 6th-gen stealth fighter – 'super fast' **with digital engineering**” – Air Force has already built and flown a new sixth-generation stealth fighter jet originally scheduled for ~2030 (almost a decade early).

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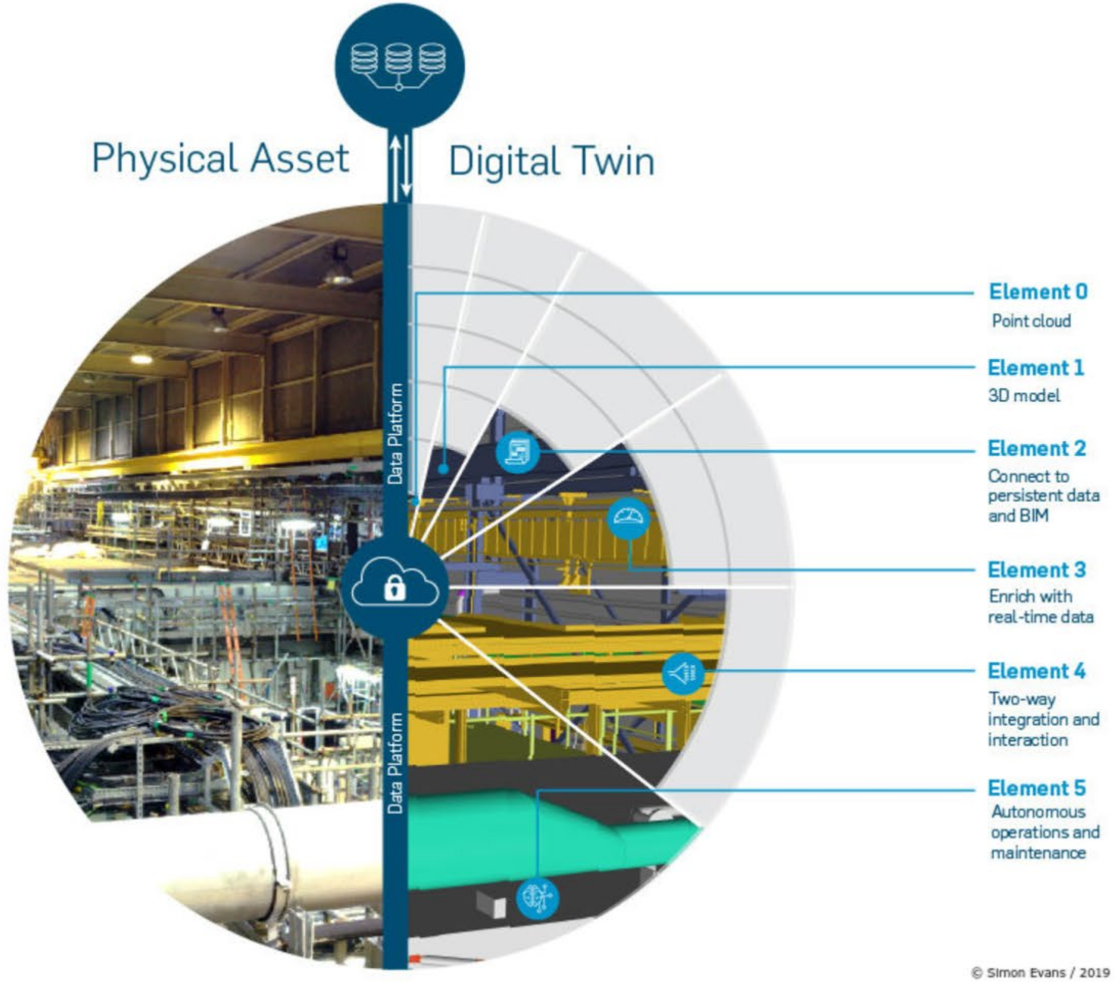
Autonomous Reactor Digital Twin



Maturity Element *(logarithmic scale)*	Defining principle	Outline usage
0	Reality capture *(e.g. point cloud, drones, photogrammetry)*	• Brownfield (existing) as-built survey
1	3D model *(e.g. object-based, with no metadata or BIM)*	• Design/asset optimisation and coordination
2	Connect model to persistent data and BIM *(e.g. documents, drawings, asset management systems)*	• 4D / 5D simulation • Design / asset management • BIM Stage 2
3	Enrich with real-time data *(e.g. from IoT, sensors)*	• Operational efficiency
4	Two-way data integration & interaction	• Remote & immersive operations • Control physical from digital
5	Autonomous operations & maintenance	• Complete autonomous operations & maintenance

Via CDBB National Digital Twin Programme

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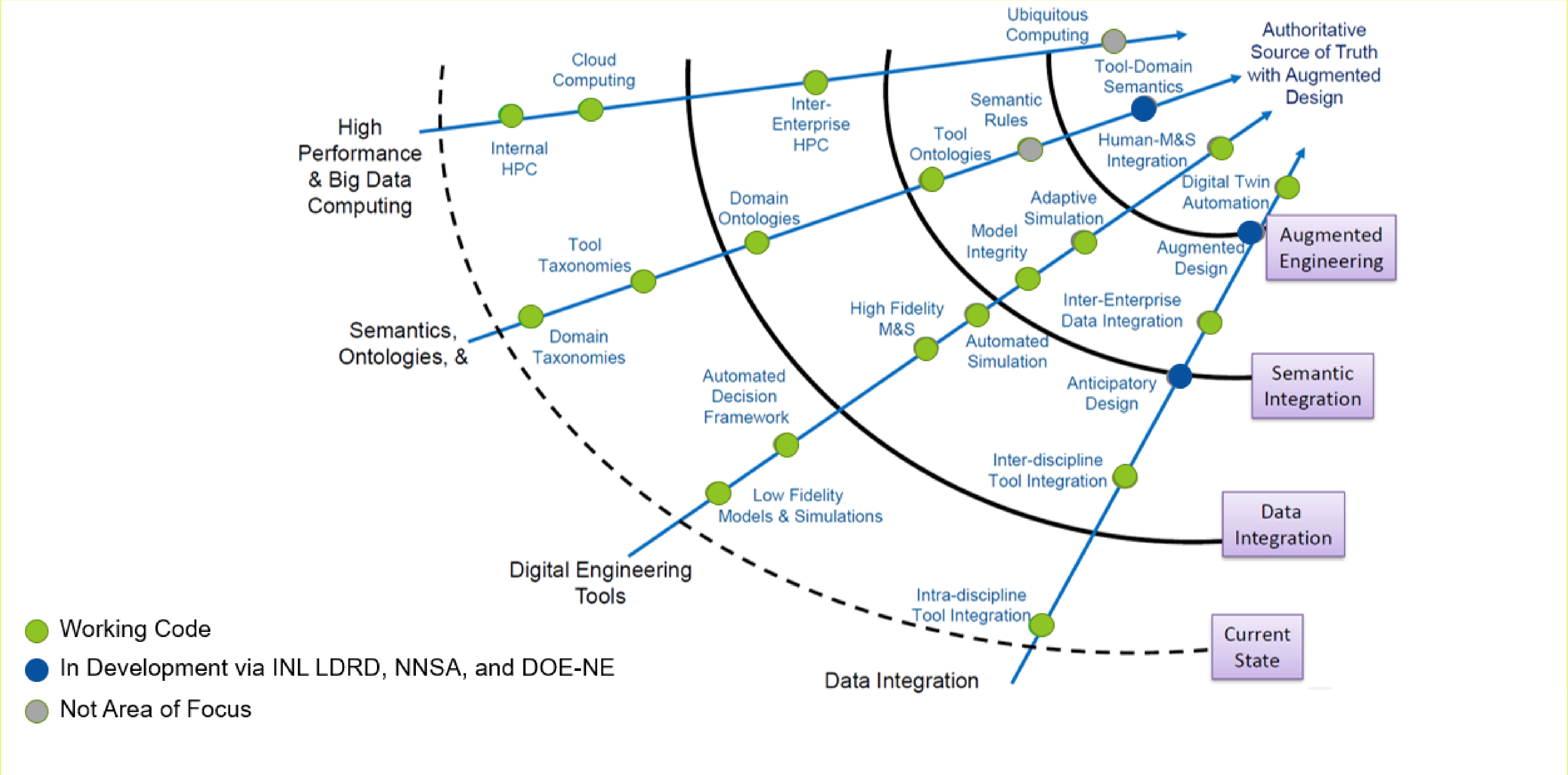
INL Digital Engineering Status (based on SERC DoD UARC plan)



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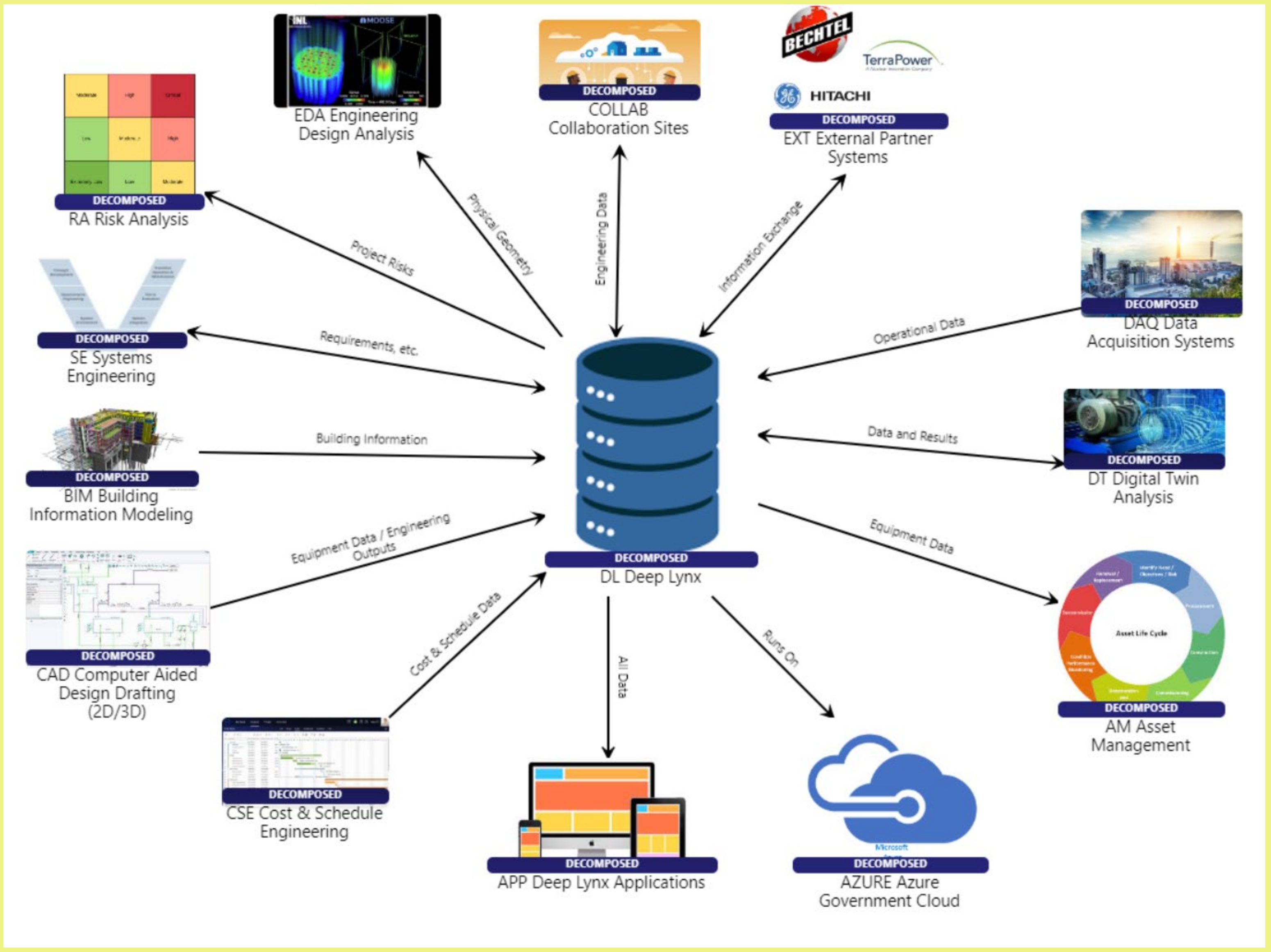
Digital Engineering Projects in Nuclear



- **Already central to the following projects nuclear digital engineering and digital twinning strategies:**
  - DOE NE LWRS Datawarehouse
  - INL MAGNET Digital Twin
  - Commercial Natrium
  - DOE NNSA DE
  - DOE NNSA Safeguards Digital Twin
  - DOE NE NRIC Test Beds
  - INL TTRC
  - DOE NE VTR
  - DoD Pele Project

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NRIC Test Beds

Phil Schoonover
NRIC Senior Program Manager

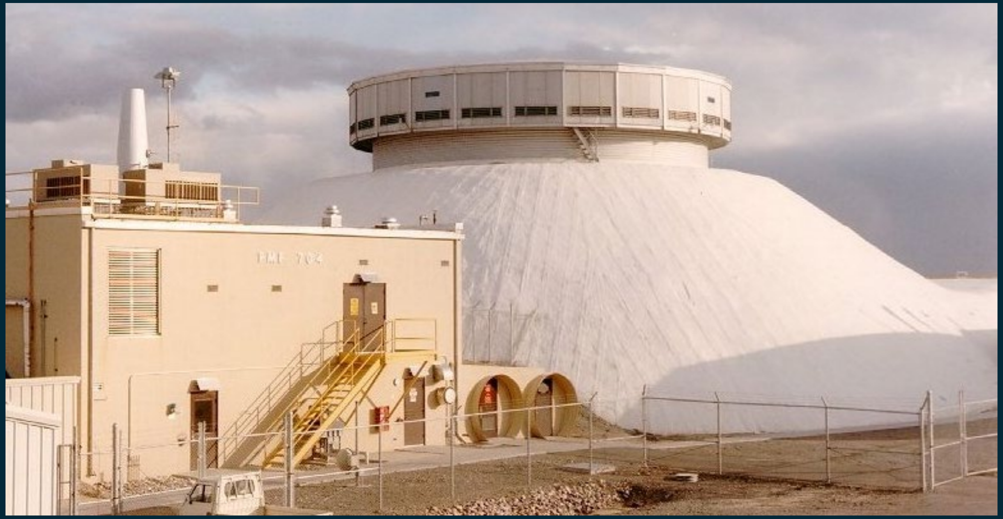
Peter Suyderhoud
Model-Based Design Group Lead

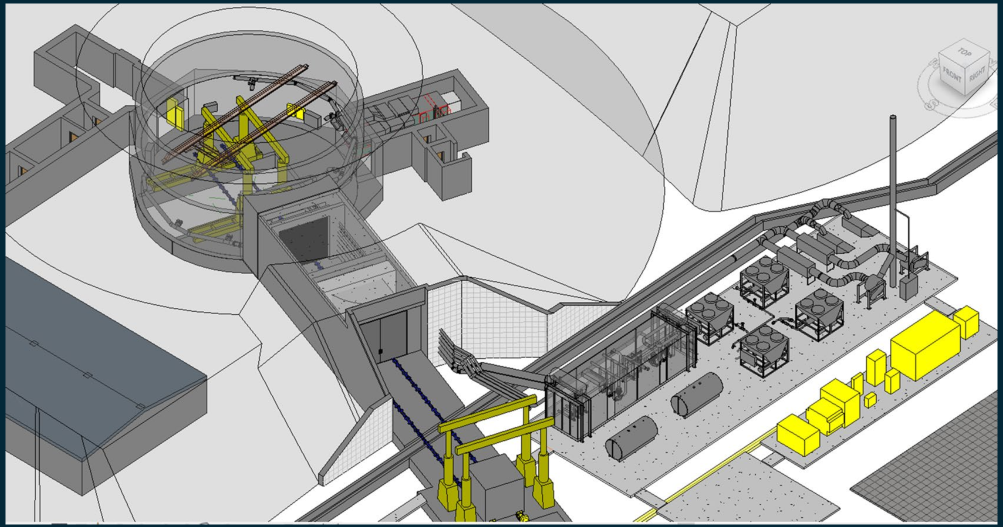
Why NRIC Needs Digital Engineering

- Digital engineering provides for the most secure, highest quality, most accessible, fastest execution of large scale and complex projects
- NRIC is charged with making nuclear development and commercialization better, faster, and cheaper to support the industry and enhance public acceptance
- NRIC expects to “Do it right.” every time and provide the most advanced look at reactor and testbed integration and designs

Laboratory for Operation and Testing in the United States (LOTUS) Test Bed

- Refurbished Zero Power Physics Reactor (ZPPR) Facility at INL
- < 500 kWth reactor experiments
- Safeguards Category I material
- 15+ new or modified systems
  - Direct reactor cooling, confinement space cooling, normal and backup power, etc.
- Compatible with molten salt concepts





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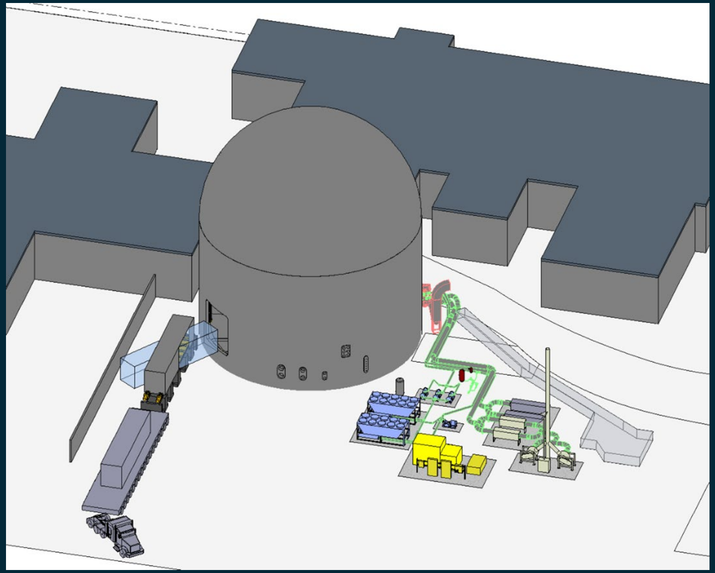
Demonstration and Operation of Microreactor Experiments (DOME) Test Bed

- Refurbished Experimental Breeder Reactor (EBR)-II Facility at INL
- < 20 MWth reactor demonstrations
- Safeguards Category 4 material
- 10+ new permanently installed systems
  - Over/under pressure protection, ventilation, containment isolation, pressure vessel penetrations, etc.
- Compatible with HTGRs, GFRs, mobile reactors, etc.



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NRIC Digital Engineering Requirements

- Full documentation of all project requirements in a living single source of truth
- Tools for plant-level architecture, interface management, and functional analysis
- 3D modeling for design, simulation, and analysis.
- Democratized access to all data in real time with cloud-based infrastructure
- Concurrent, collaborative engineering processes with access for all project stakeholders and design agencies

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NRIC Digital Engineering Solution

- IBM Engineering Lifecycle Management DOORS Next: An enterprise level, database driven, requirements, verification, and traceability tool
- Innoslate: Database-driven, architecture and Model Based Systems Engineering (MBSE) tool
- PTC Creo: CAD software suite
- PTC Windchill: Enterprise level PLM/PDM, model and document configuration management and change control tools

Define → **Design** → **Manage**

INNOSLATE® IBM DOORS creo® windchill®

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Starting the NRIC Digital Thread

- Deep Lynx Data Warehouse
- Ion Digital Engineering Application Suite (IDEAS) interface.
  - A unified web application that holds all adapters and utilities created for NRIC
  - Available at https://denric.azureacc.inl.gov
- File Tracer: an application to create and view the connections between MBSE data and a 2D CAD file.
- PLM API: a REST API for PLM tool interactions.
- Requirements Adapter: automatically transfers project requirements defined in IBM DOORS to Innoslate

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Microreactor Applications Research Validation and Evaluation (MARVEL)

Yasir Arafat

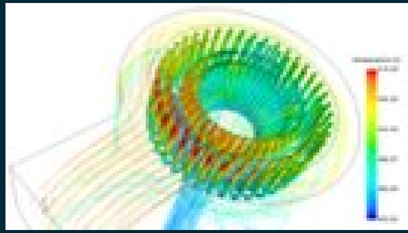
MARVEL Project & Technical Lead

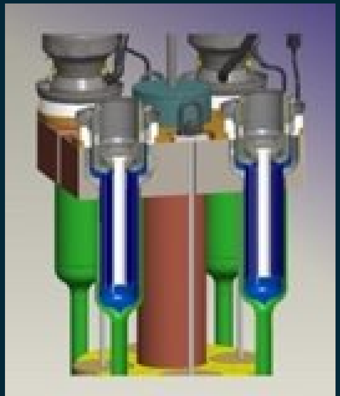
Paul Plachinda, P.h.D.

Digital Design Scientist

Project Parameters

- ***Inspired by*** SNAP 10A
  - Fuel pins: TRIGA Fuel, UZrH1.6 , 19.75 % enriched, OD, 30wt% uranium
  - Thermal Power – 100 kWth,
  - Four BeO ex-core reactivity control drums, with B4C poisons
- ***Primary Circulation*** (natural convection) – NaK eutectic
- ***Secondary Circulation*** (natural convection) – PbBi eutectic
- ***Power Generation:*** *Four helium Stirling engines @ 400–* 500 C inlet T
- Electrical Output ~20 kWe
- Max High Grade heat ~ 45 kWth @ 450°C
- Max Low Grade heat ~ 75 kWth @ 50°C





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Project Goals and Objectives

- Goal:
  - Rapid development of a small-scale microreactor that provides a test platform for microreactor applications

- Primary Objectives:
  - Produce an operational microreactor in the most <u>accelerated timeline possible</u>
  - Project shall result in an operational reactor that produces <u>combined heat and power (CHP)</u> to a functional microgrid
  - Transfer <u>lessons learned</u> to commercial developers

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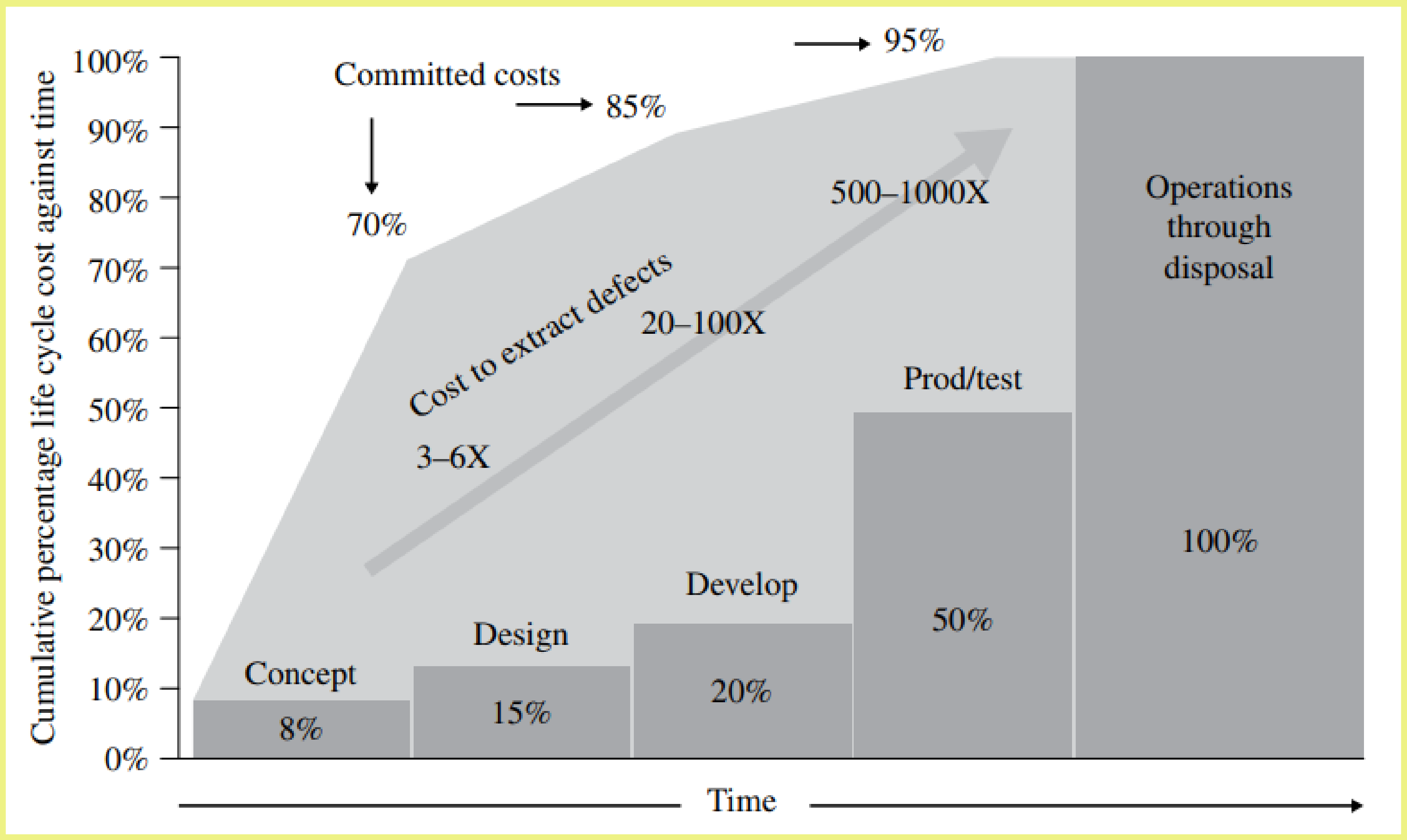
Why Systems Engineering?



[Source: INCOSE Systems Engineering Handbook]

- Other industries have successfully adopted SE:
  - Aerospace
  - Aviation
  - Automotive
  - Defense
- The Return on Investment for SE effort can be as high as 7:1 for programs expending little to no SE effort. For programs expending a median level of SE effort, the ROI is 3.5:1.
- Data shows that a spend of 8% of project budget on effective Systems Engineering - much less than you typically spend on fixing errors - reduces the average cost of projects by >20% and increases your likelihood of delivering on time by 50%.

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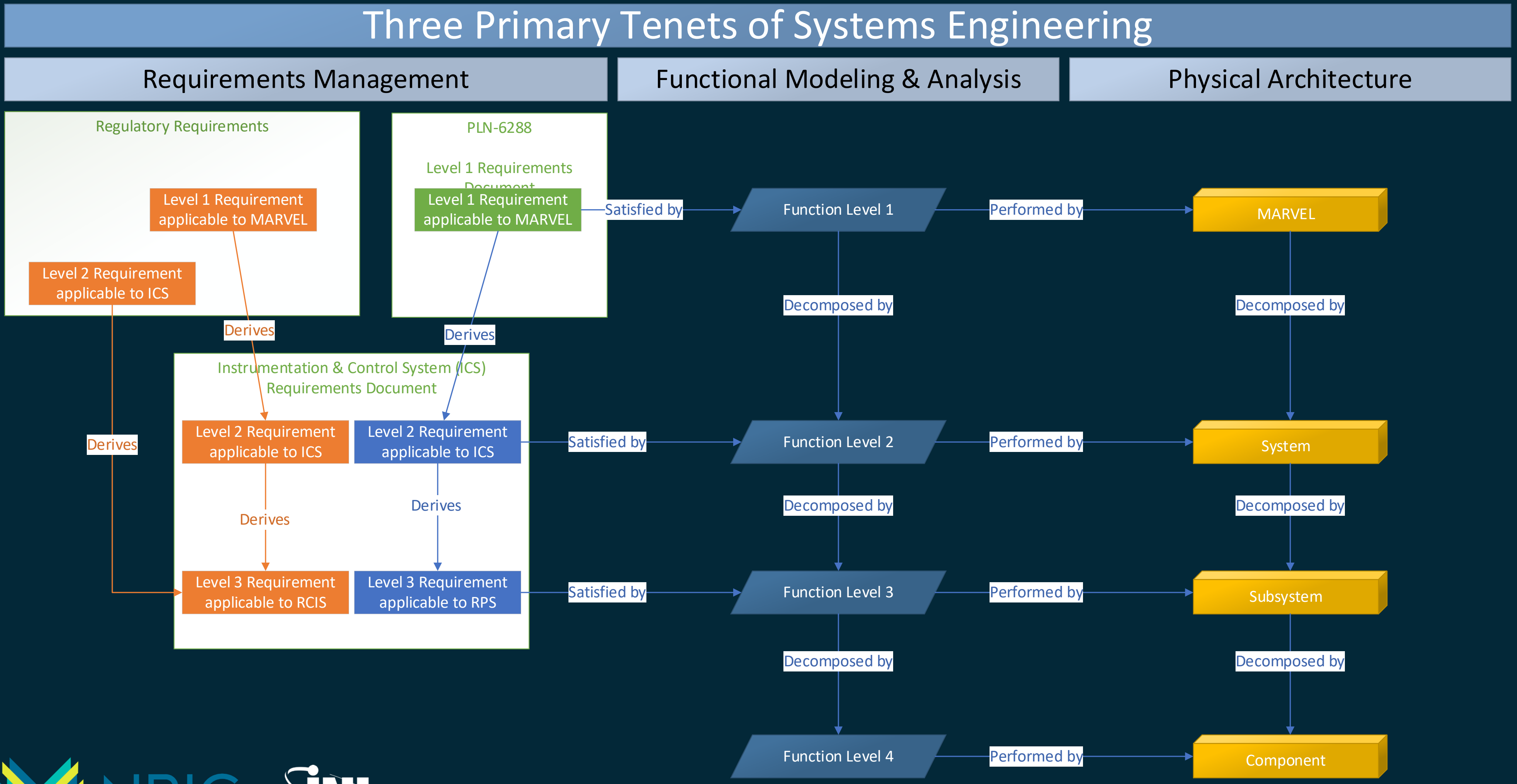
Model-Based Systems Engineering (MBSE)

- Legacy SE processes have flaws
  - Document-based (i.e. Word, PDF) processes are time intensive and costly
  - Impact analysis is completely manual
  - Databases are used after the fact to stash already-completed information
  - Software & design tools are disparate and siloed

- Is this "wrong"? No, but it's not efficient.

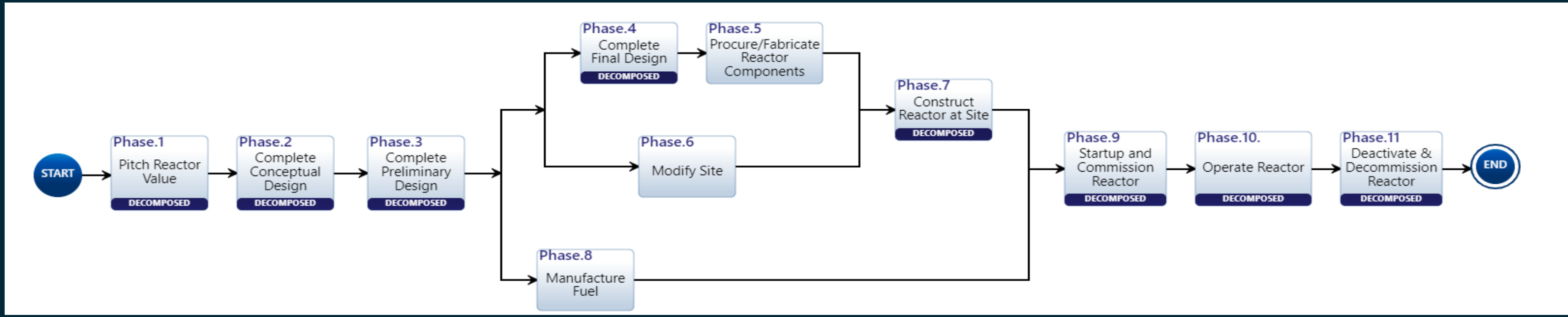
- Model-Based Systems Engineering (MBSE)
  - Shift from a document-based approach to the use of models/databases for information exchange using a MBSE platform (Innoslate)
  - Models form an integral part of the technical baseline
  - Departure from static PDFs

Developing an MBSE Framework/Schema



Functional Modeling & Concept of Operations

- Need to establish the functional requirements of the end system
  - Traditionally: Use the “shotgun” approach or whatever comes to our heads in the moment – typically leads to gaps in coverage
  - MBSE: Sequentially and systematically lay out and order the envisioned functions to understand relationships, dependencies, and the flow of operations
- This forms the Concept of Operations (ConOps) or how the system will work in its intended environment
- The ConOps leads to a physical architecture and a baseline of project requirements



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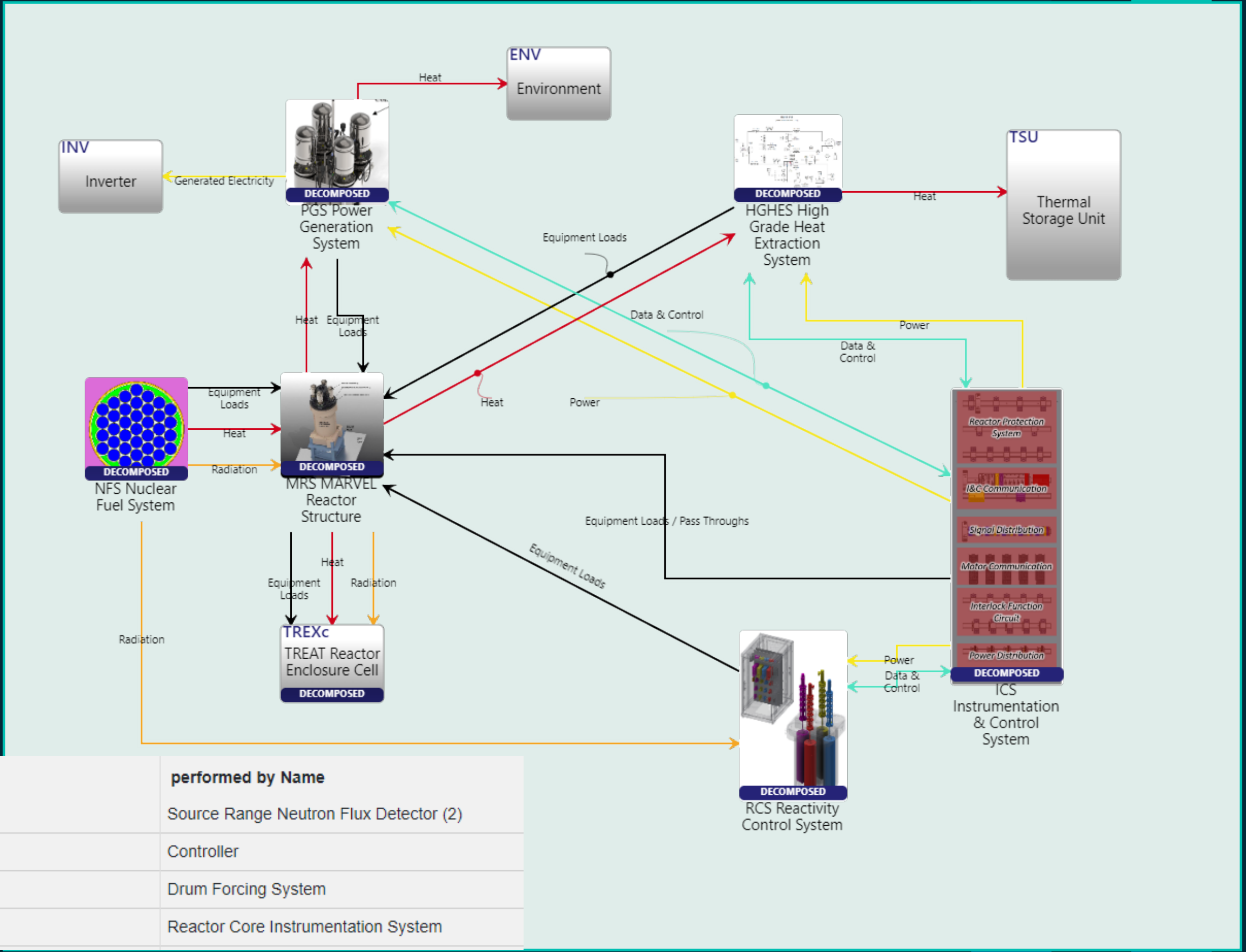
Synthesizing a Physical Architecture

- Once the functional baseline is established, a physical architecture or design can be developed to match or perform the functions envisioned for the system
  - Develop Process Flow Diagrams (PFDs)
  - Define system, subsystem, and component interfaces
  - Build relationships between functions and systems to validate the ConOps is fulfilled by the physical design



Number	Name	performed by Number	performed by Name
Phase.9.3.3	Measure Nutron flux	RCIS-NFI-0002	Source Range Neutron Flux Detector (2)
Phase.9.3.4	Compare flux to the expected values	MCS-CTRL-9046	Controller
Phase.9.3.5	Increase reactivity by rotating CDs	DFS	Drum Forcing System
Phase.9.3.6	Measure reactor physics parameters	RCIS	Reactor Core Instrumentation System

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Molten Chloride Reactor Experiment (MCRE) ARD

Nick Smith

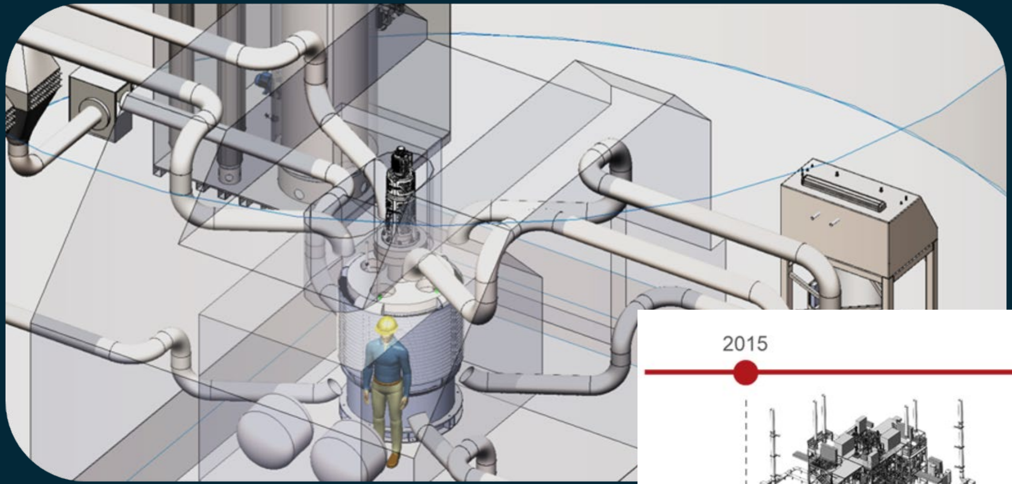
INL MCRE Project Director

Peter Suyderhoud

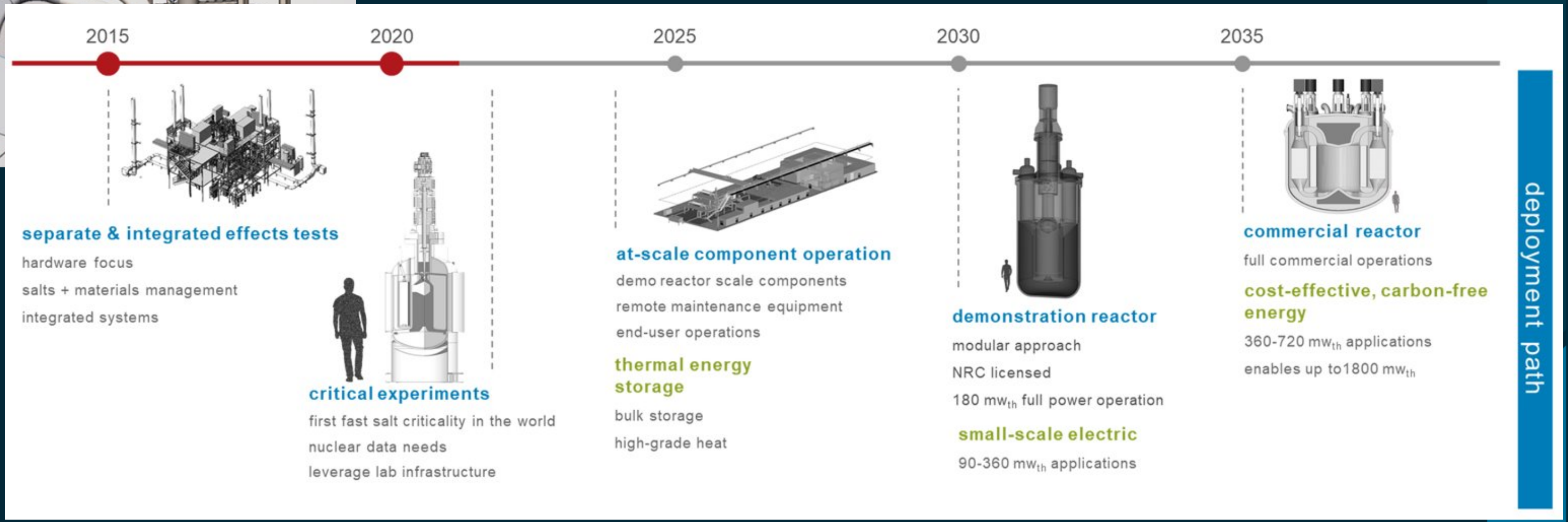
Systems/Digital Engineering Lead

MCRE Overview

- The Molten Chloride Reactor Experiment (MCRE) is a liquid fueled, fast spectrum, HEU, experimental reactor that will operate in the LOTUS test bed at INL



- It will be the second large demonstration undertaken by Southern Company and TerraPower along the Molten Chloride Fast Reactor (MCFR) development path



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INL Scope of Work

During this 5-year project INL will develop salt containers, synthesize fuel salt, install MCRE in LOTUS, operate the reactor, and D&D MCRE at the end of the project.

MCRE Fuel Salt

- Fuel Salt Containers (FSC)
- Irradiated Salt Containers (ISC)
- Fuel Salt Synthesis Line (FSSL)
- Production of MCRE Fuel Salt

MCRE-LOTUS

- Design Integration
- Quality Assurance
- Environmental
- Nuclear Safety
- Safeguards & Security
- Construction Integration
- Operations
- D&D

Technology Development Fuel Salt

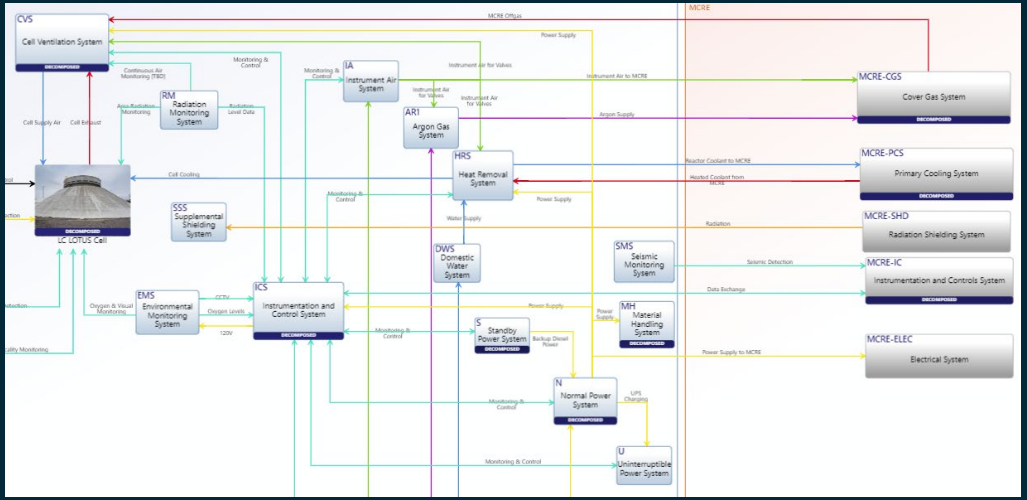
- Clean Fuel Salt TH-Properties
- Fuel Salt Capsule Irradiation
- Irradiated Fuel Salt TH-Properties
- Chemical Speciation and Transport Phenomena

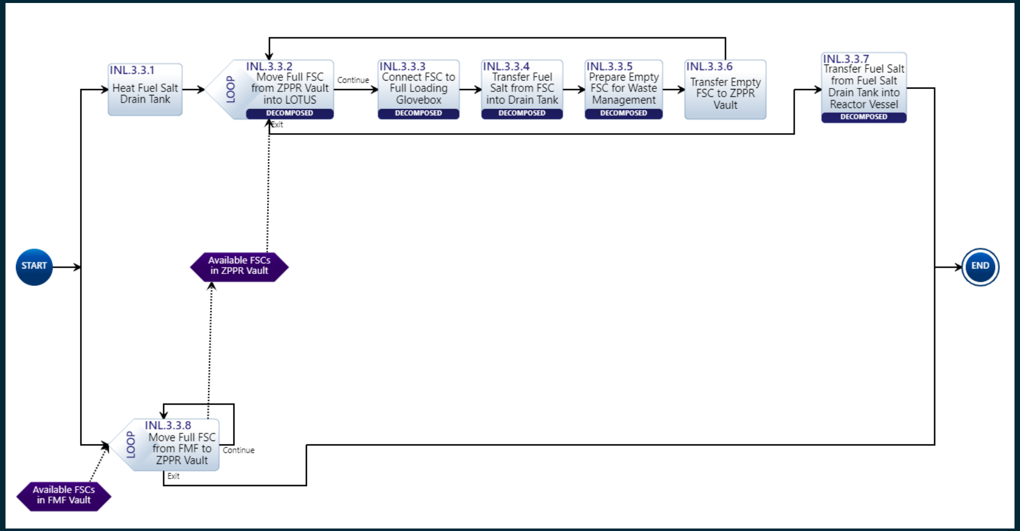
Project Challenges

- Complex interfaces
  - Integrating a nuclear island, balance of plant, and fuel management capabilities – each developed by separate organizations working in siloed networks
  - Interface Requirements
- Fuel salt synthesis technology development
- Maintaining QA

MBSE Will Help Mitigate These Challenges

- Functional modeling within a cloud-based, real-time platform will ensure all team members have access to a single source of truth and are working to the latest Concept of Operations
- Physical modeling ensures the interface between two entities is shared and agreed upon vs. maintained in two separate systems





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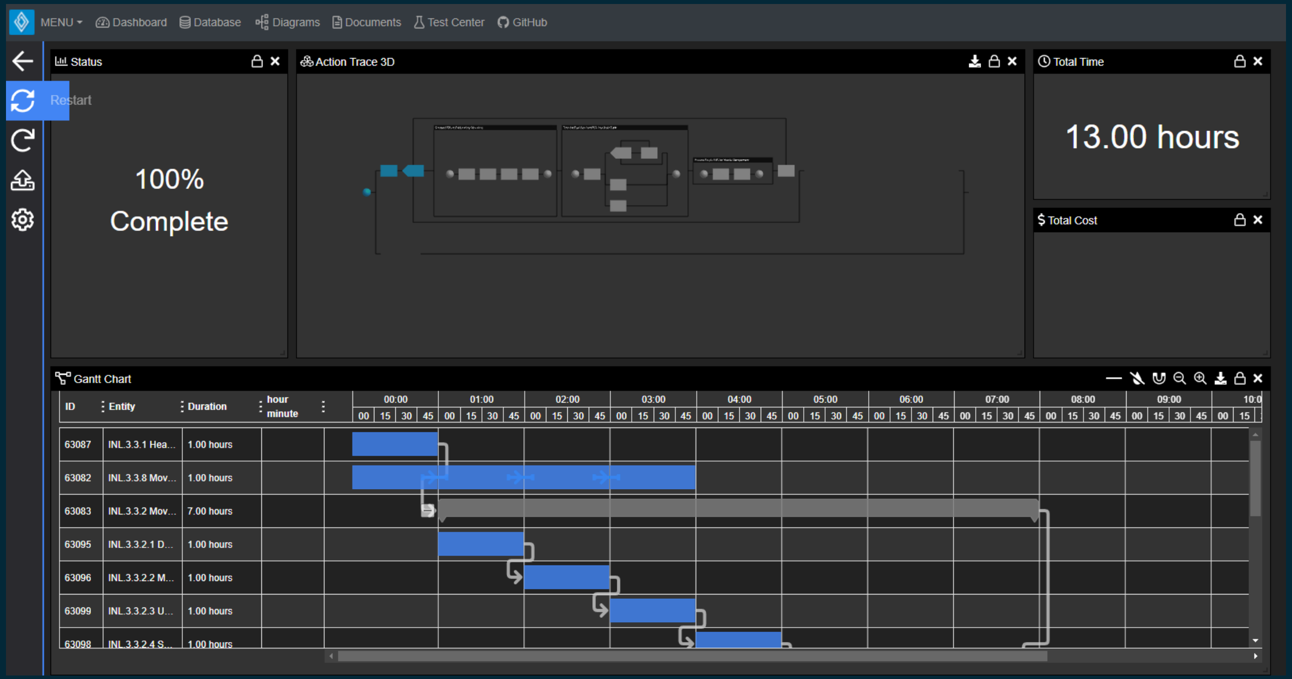
Model Execution/Simulation

- Executing functional models can provide estimates of:
  - Process duration
  - Resource consumption
  - Project cost
  - Critical path activities
- All in support of performing analysis of alternatives (AoA), Trade Studies, etc.



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MAGNET

Jeren Browning
Group Lead, Digital Engineering

John Jackson, Ph.D.
National Technical Director –
DOE Microreactor Program

Microreactor AGile Non-Nuclear Experimental Test Bed (MAGNET)

- General-purpose, non-nuclear microreactor test bed
- Thermal-hydraulic and materials performance data for design performance verification and analytical model validation (V&V)
- Expandable design with capability to demonstrate an integrated power conversion unit (PCU)
- Advanced sensors identification, development, and testing for potential autonomous operation
- Enhance readiness of public stakeholders, particularly DOE laboratories and the U.S. NRC, to design, operate, test, and license microreactor components

- Construction complete
- I&C installation evolves as necessary
- System commissioned August 2021
- Updating for He component testing

Parameter	Value
Chamber Size	5 ft x 5 ft x 10 ft
Heat Removal	Liquid-cooled chamber walls, gas flow
Connections	Flanged for gas flow and instrumentation feed through and viewing windows
Coolants	Air, inert gas (He, N_2)
Gas flow rates	Up to 43.7 ACFM at 290 psig
Design pressure	22 barg
Maximum power	250 kW
Max Temperature	750 C
Heat Removal	Passive radiation or water-cooled gas gap calorimeter

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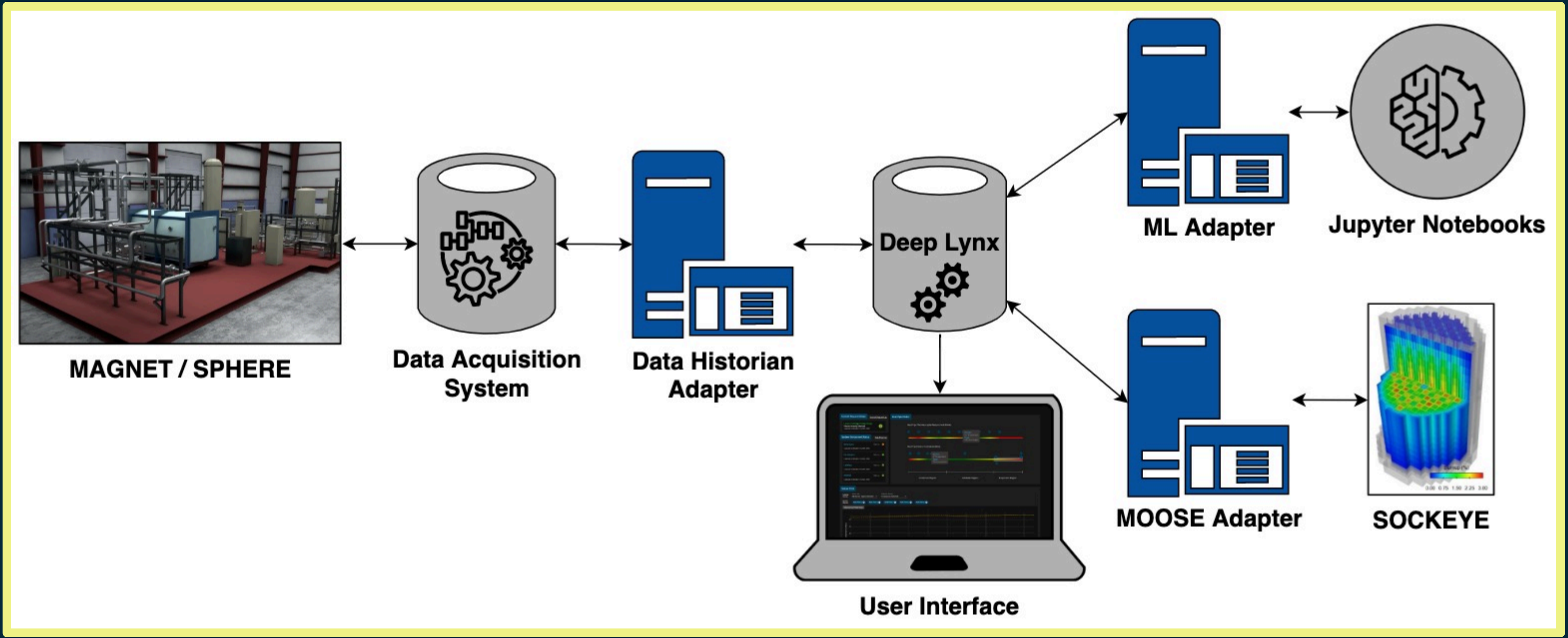
Digital Twin Goals

- Provide unattended operation and remote monitoring of a live asset
- Create reusable components to establish a digital twin framework
- Three core functionalities:
  - Multiphysics modeling
  - Machine learning/artificial intelligence
  - Data acquisition system integration

Architecture



- More information: https://www.youtube.com/watch?v=40RFNtcrE1Q

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Beartooth

Kaleb Houck
Architect, Digital Engineering

Troy Burnett
Project Engineer, Beartooth

Beartooth Nuclear Material Testbed - Background

- Evolving Civilian Nuclear Fuel Cycle
  - Global civilian fuel cycle is going through a rapid transformation
    - Movement to smaller reactors
    - New reactors are using new fuels (HALEU, Pu, Th, etc.)
    - New materials and technology (Additive Manufacturing, malonomide, etc.)
- Support for Modern Non-proliferation Mission
  - Current capabilities aging and insufficient
  - US leadership being lost to other countries (France, Russia, China, India, South Korea)
  - New R&D Capability needed to close gap!

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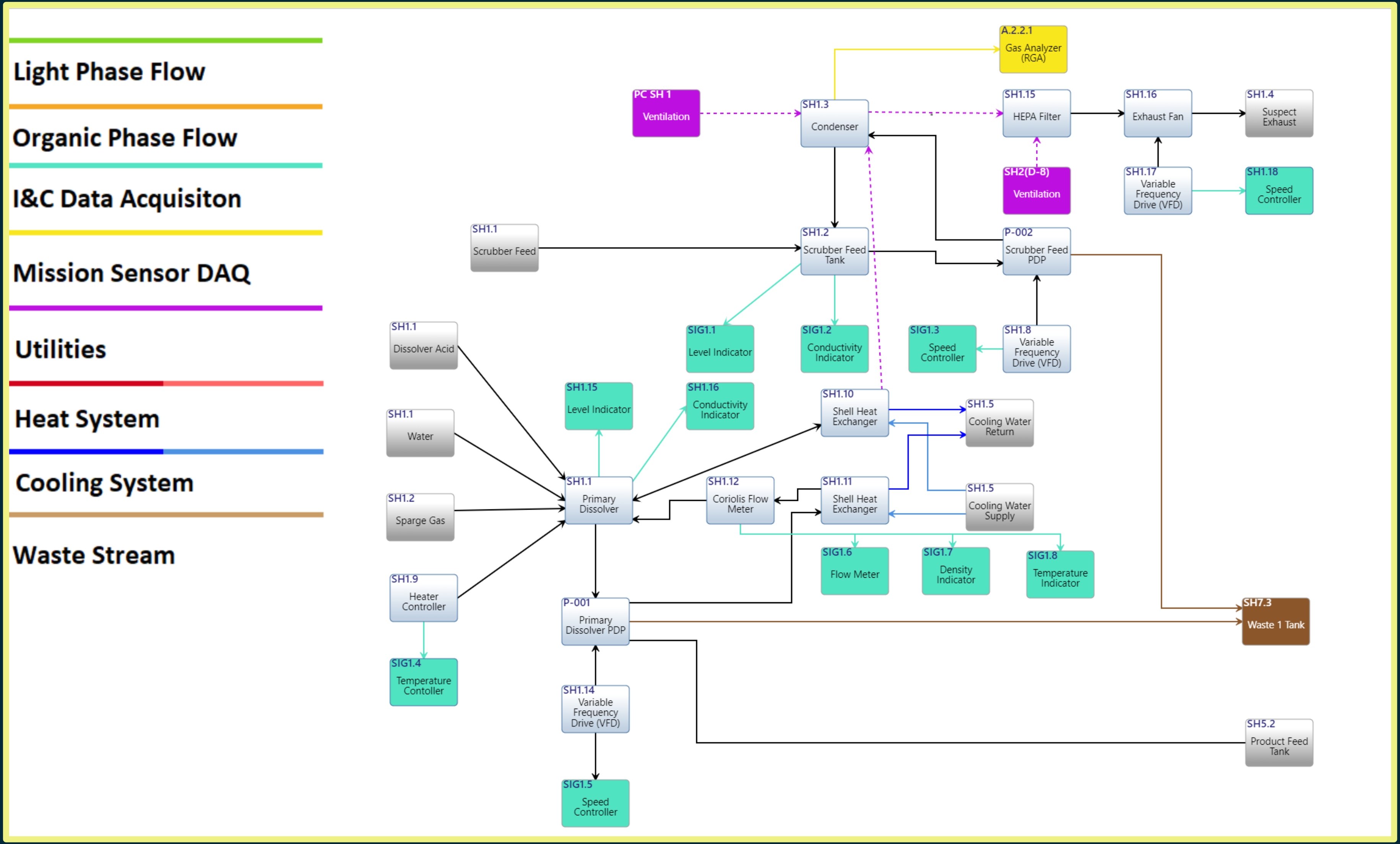
MBSE Efforts around Beartooth



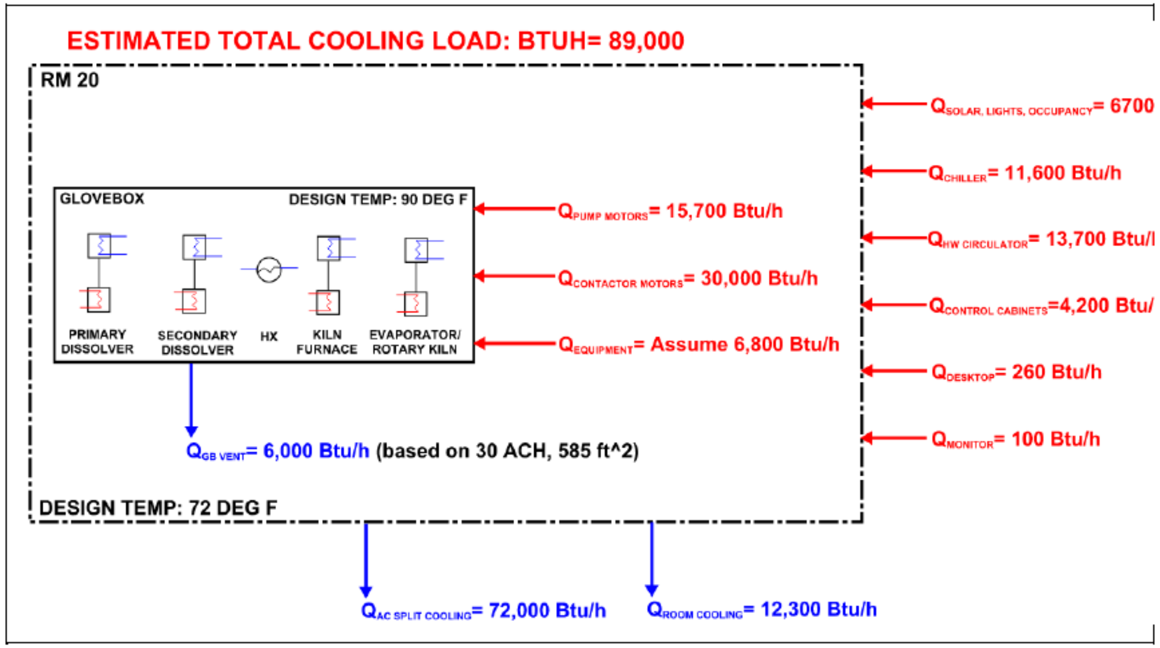


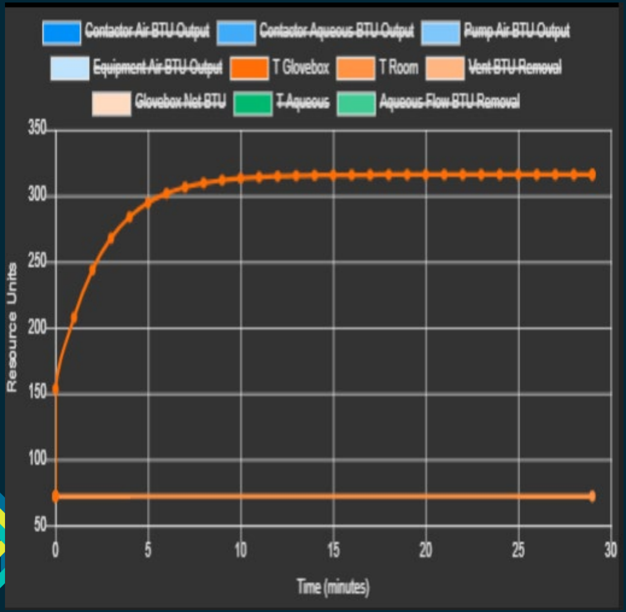
Figure 23. HVAC Cooling Loads

First observation: Pumps/Contactors are cooled by solution flow (modeled)

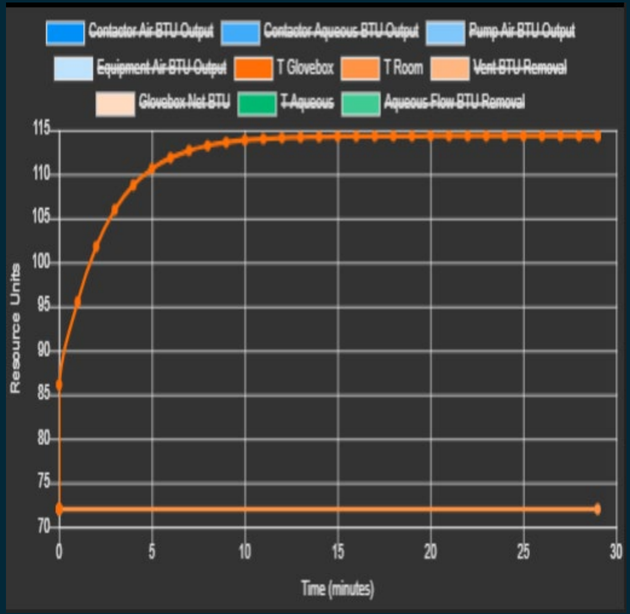
Still too hot: Evaporators/Dissolver/Kiln also transmit energy to solution. Not modeled yet, need solution heating.

Once solution thermal modeling complete: helps satisfy heating requirements of dissolver.

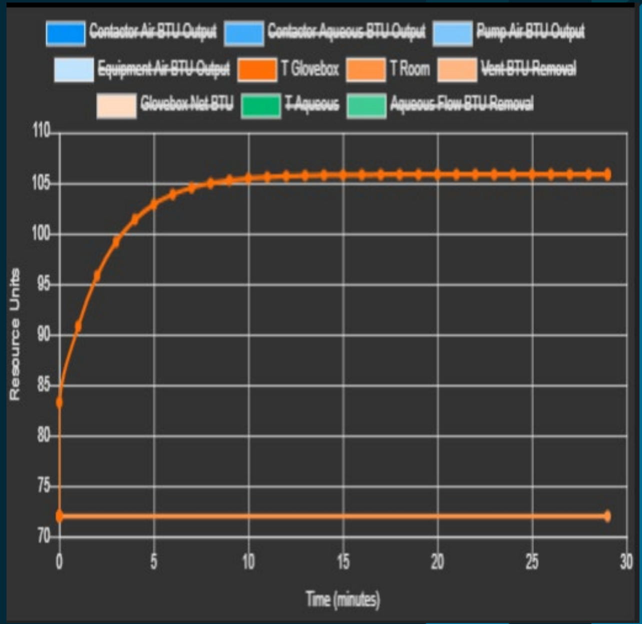
CDR Assumptions



95% BTU to Solution Flow



99% BTU to Solution Flow



Augmented Reality for Design Review

- Used in Preliminary Design to collaborate on the model
- Light weight way to collaborate and review. Send as a 'Box-like' link to be viewed on phones and tables
- Can be made to scaled to table size to 1-1 size

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Mixed Reality for Design Review

- Used in Preliminary Design to verify the model by INL, DOE-ID, and Walsh Engineering
- Provides a true dimensional understanding of the design by allow people to interact with full size model
- Created questions by end users on various aspects of the design that 2D models did not elicit

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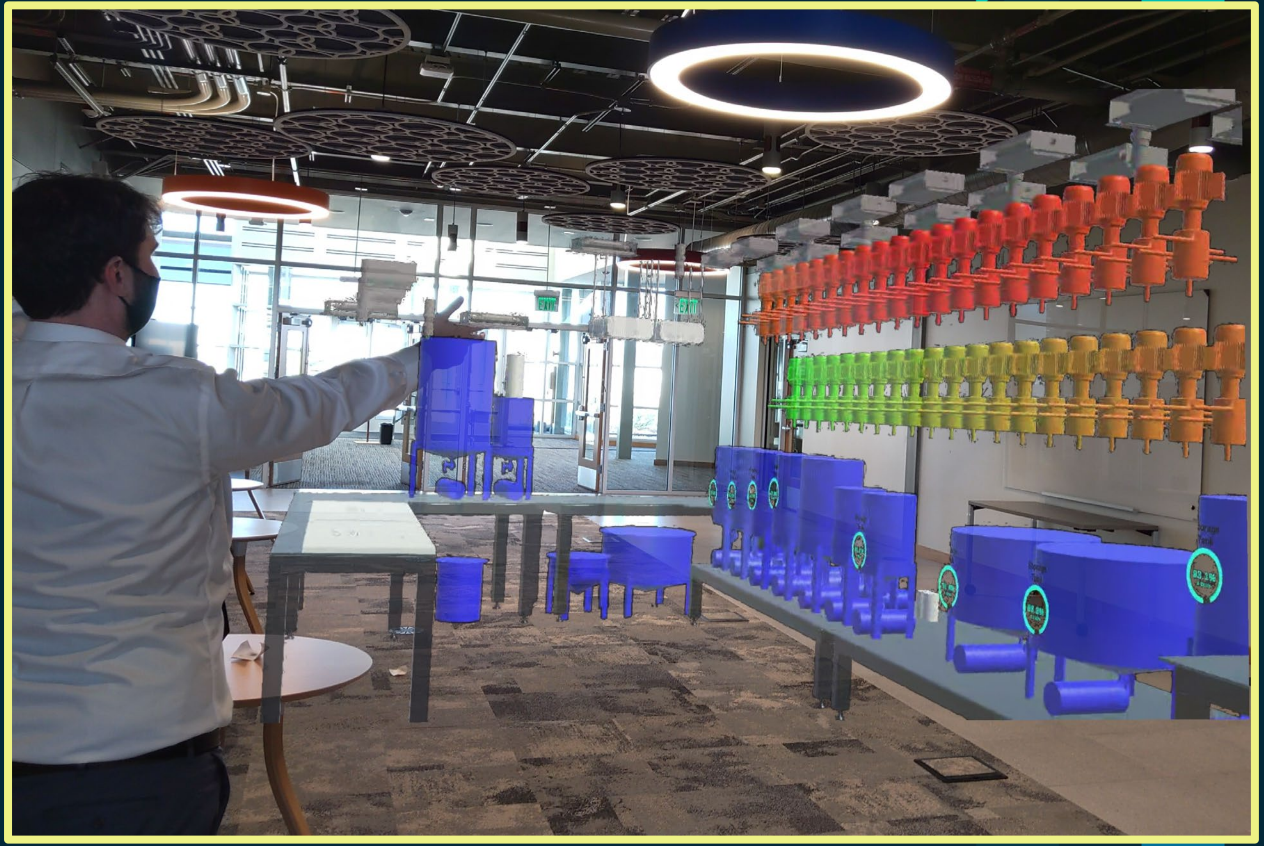
Mixed Reality for Digital Twin Prototyping

- Demonstrated the digital thread platform, DeepLynx, providing real-time data into Beartooth model

- Demonstrate possibilities unique operational and experimental views into testbed



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Configuration Management and Document Control

AnnMarie Marshall

Manager of Configuration Management,
National Reactor Innovation Center

What is Configuration Management

CM is defined as the **process** that controls the activities, and interfaces, among design, construction, procurement, training, licensing, operations, and maintenance to ensure that the **configuration of the facility is established, approved, and maintained.**

CM frequently includes CM as well as Document Management, Records Management, Change Control, and Requirements Management.

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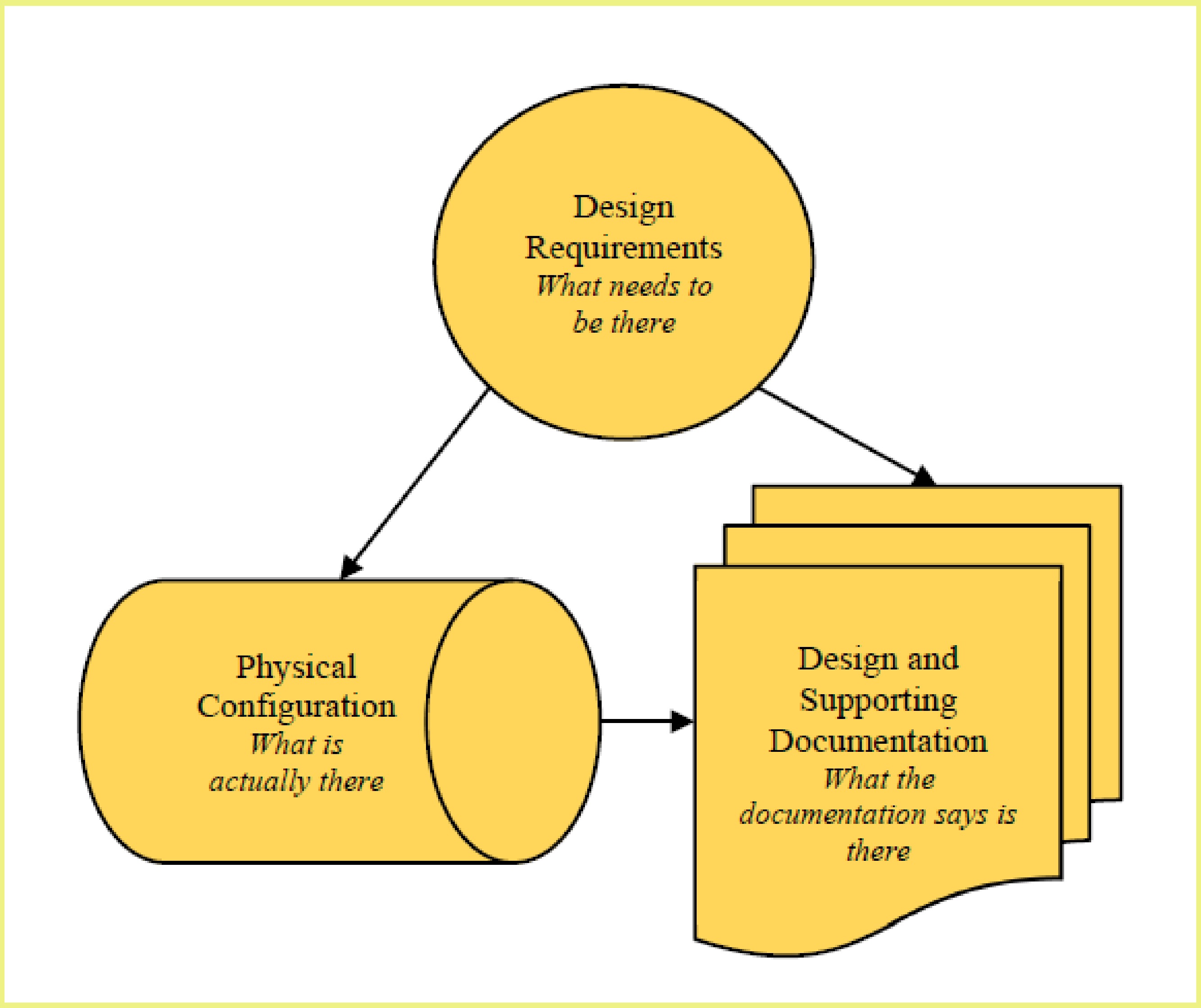
What is Configuration Management

The objective of CM is to establish **consistency** among **design requirements, physical configuration, and the associated documentation** (drawings, analyses, and specifications) and activities. This allows the facility operator to maintain configuration consistency throughout the life of the facility.


Design Requirements
What needs to be there
Physical Configuration
What is actually there
Design and Supporting Documentation
What the documentation says is there

Existing

INL has an established home built EDMS that has been in place for years. This system meets all NQA-1 requirements for change management, but it isn't an industry known CMIS (Configuration Management Information System).

- Document Centric
- Doesn't include structures, systems, or components (SSCs)
- Provides traceability within documents but not to SSCs
- Some metadata but nothing associated with plant, facility, or system
- Requirements are static in documents

Future

NRIC is working to implement a more advanced system that will provide, not all, but more CMIS like functionality

- Includes structures, systems, and components (SSCs)
- Traceability of documentation to SSCs
- Integrated with the requirements which are in the living database of DOORS-NG
- All documents in one system as the single source of truth – One project at a time
- Include functions of document control, records management, and change control.

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NQA-1 Qualification Plans

Ross Hays
Principal Investigator,
Natrium Digital Engineering Collaboration

ASME NQA-1

- Sets out quality assurance **requirements** for nuclear facility applications
- We already support design processes for nuclear facilities that have complex requirements
- **Leverage the existing tools and expertise!**
  - Multiple RM tools available (DOORs, Innoslate)
  - Outreach to existing efforts (MOOSE, MC-21, etc.)
  - System engineering experts
- Requirements to drive software
  - Developmental processes
  - Acceptance test design

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Create Reusable Requirement Hierarchies

- Parse requirements into DOORs identifying
  - Policy decisions
  - Configuration elements
  - Necessary Documentation
  - Necessary Test Cases, results
- Policy decisions may drive certain requirements, e.g.:
  - Use of previously provisioned tools
  - Incumbent workflows
- **By explicitly mapping these decisions, sections of requirement tree may be re-used under different contexts**

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Anticipated Benefits

- Streamlined ability to qualify products under similar independent quality plans (NQA-1-2008 vs NQA-1-2019, or BEA vs GEH, etc.)
- Clear identification of decision impacts
  - When decisions are changed
  - When requirement drivers are updated
- Leverage existing expertise and established tools
- Reduced development effort vs non-integrated approaches

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NetZero at INL

Kaleb Houck

Digital Twin Research Scientist

Paul Plachinda, Ph.D.

Digital Design Scientist

What is the Net Zero Campus?

The ESL-II Complex at INL will provide a one-of-a-kind pioneering-scale complex housing an evolving microgrid supporting various net-negative technologies including an on-campus microreactor. ESL-II will be the advanced energy demonstration epicenter that supports R&D of integrated energy systems including: nuclear, hydrogen/ammonia, electrochemical, solar, wind, batteries, thermal generation and storage, microgrids, and carbon-neutral mass transportation.

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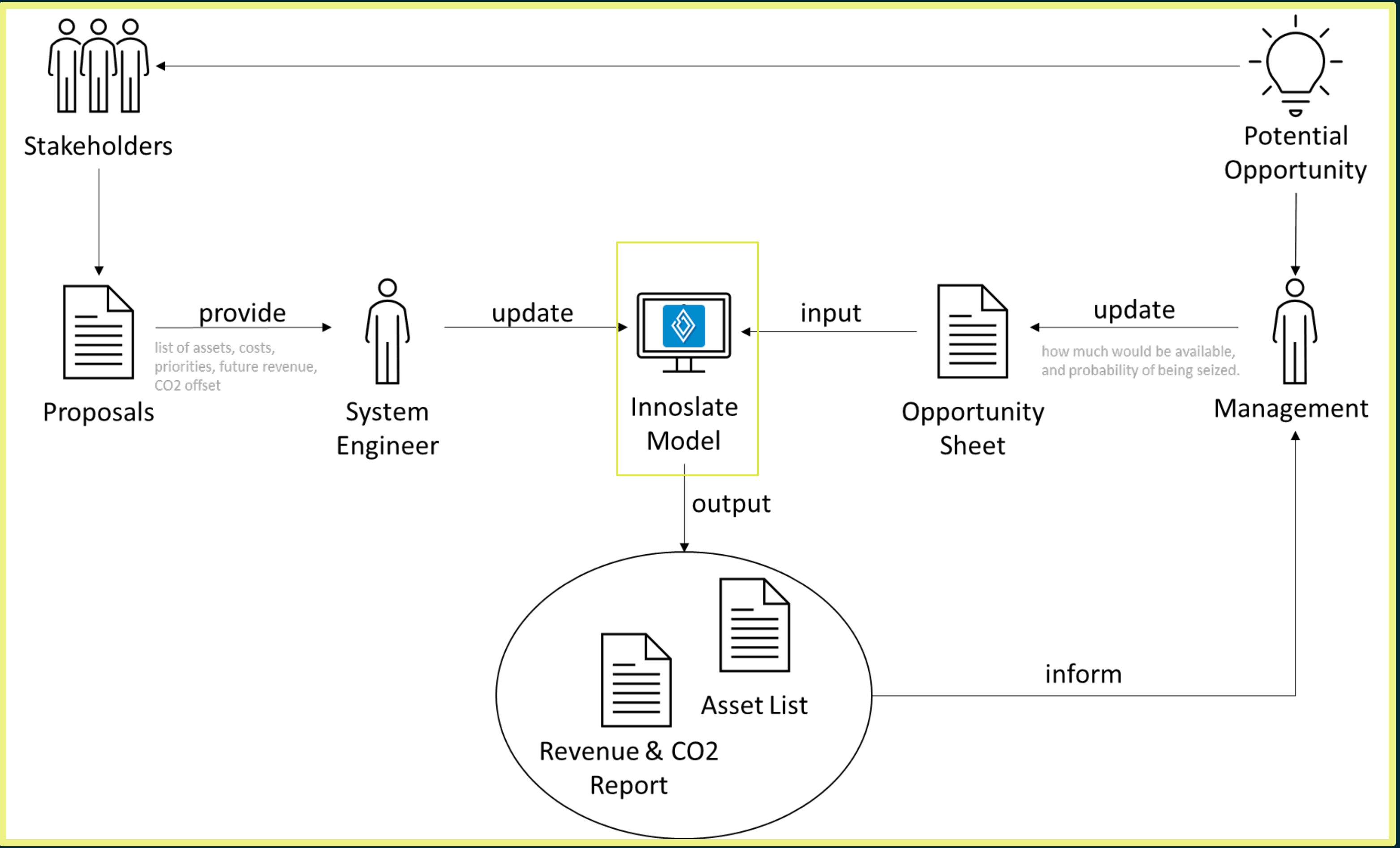
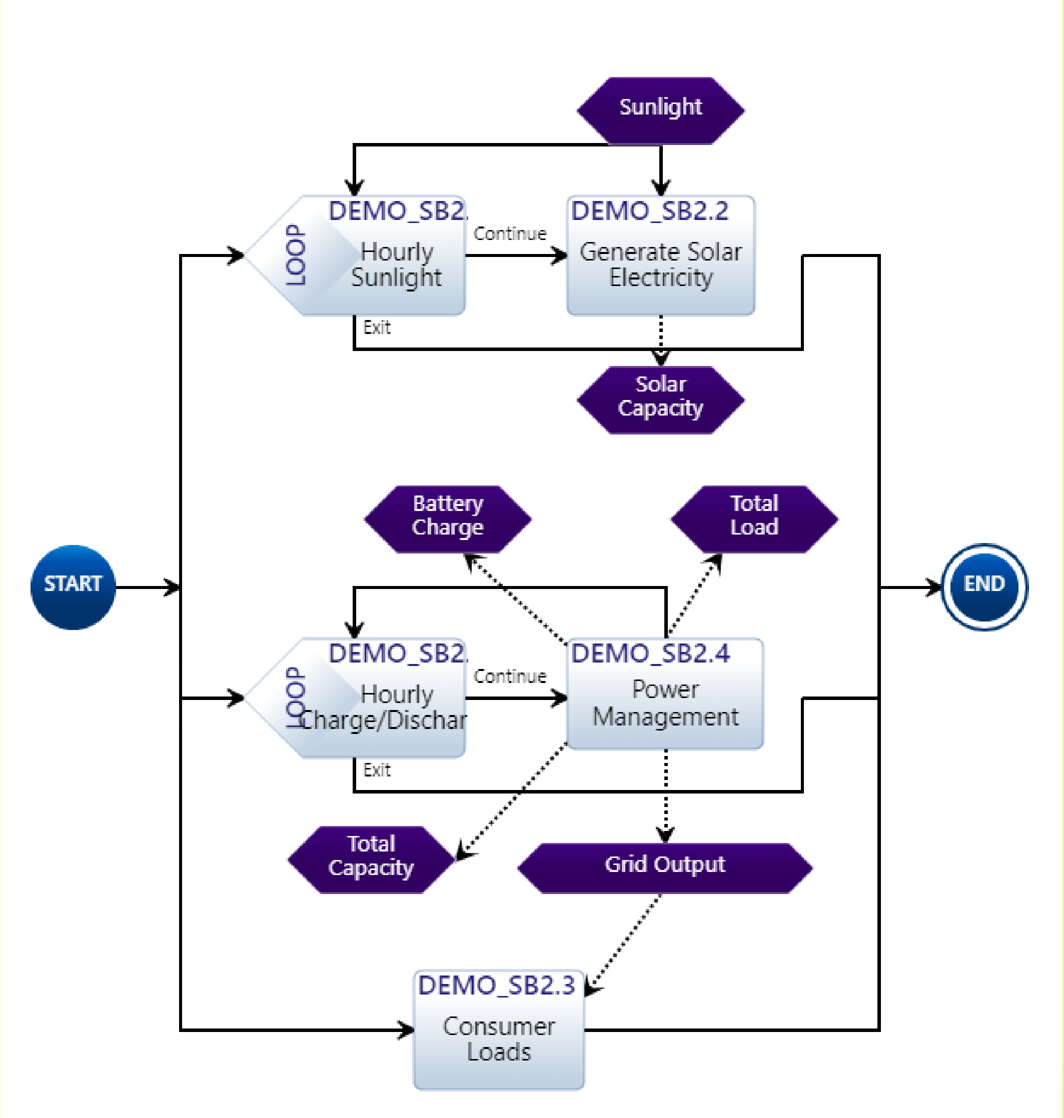
Why is it built?
(Requirements Management Flow)



How is it built?
(Energy and Monetary Flow Modelling)

- Model Based Systems Engineering enables creation of a functional model to simulate interactions and verify assumptions. It can be directly translated to an asset model assuring that all necessary assets are present to fulfil the functional need.
- Simulation can predict energy sources and sinks and their mutual capacity.
- MBSE can also predict the economics of the system.



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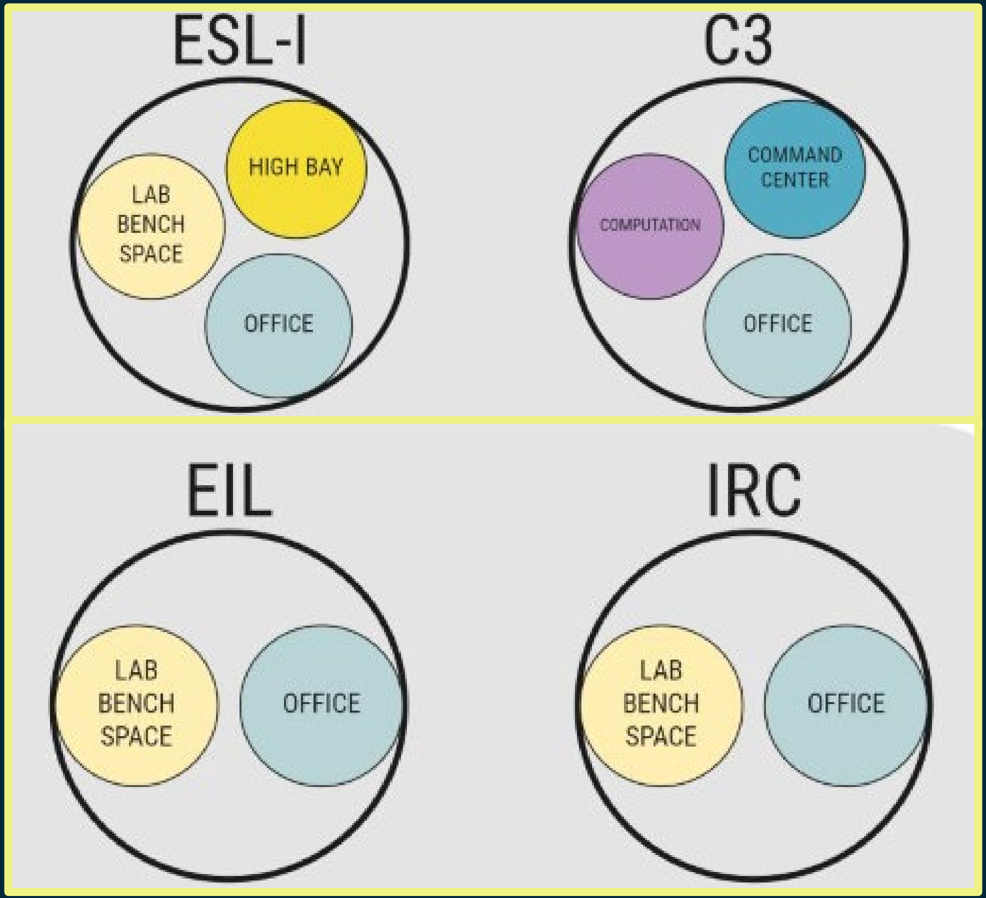
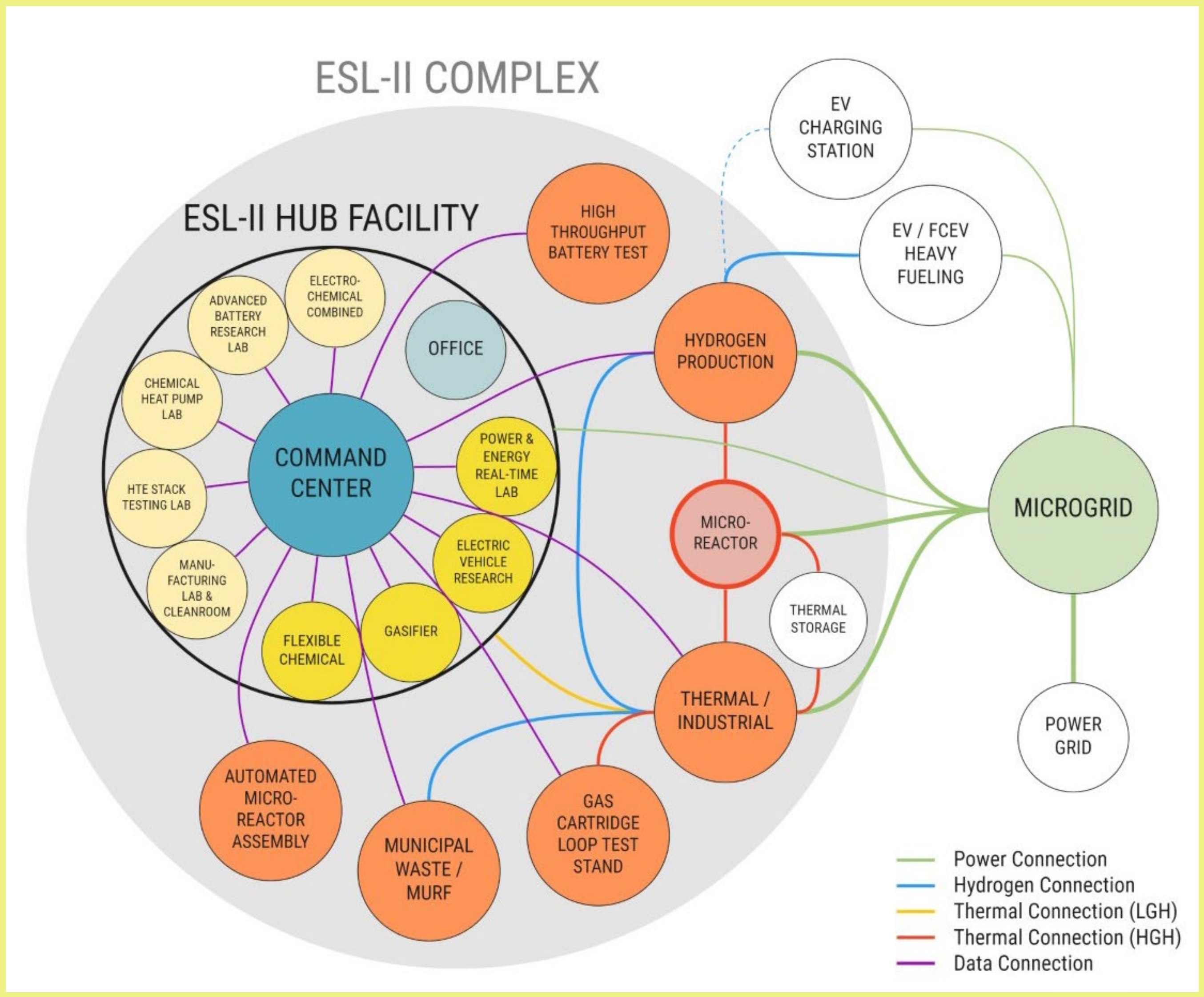
What is it comprised of? (Asset Modelling)





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Digital Twin of a “Hangar”