

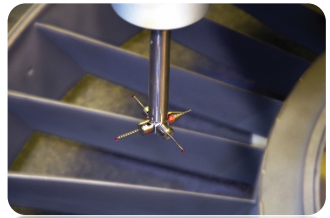

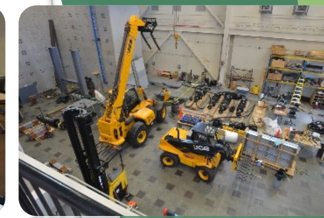

Managing Regulated Change: An Enterprise-Level Digital Twin for the Nuclear Industry

Michael Mazzola, Robert Cox, Jeffrey Hawkins
Energy Production and Infrastructure Center (EPIC)
UNC Charlotte, NC, USA
mmazzola@uncc.edu EPIC.UNCC.EDU

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Energy Production and Infrastructure Center

Outline

- Introduction to EPIC
- Consensus on Nuclear Energy has Changed
- Construction Best Practice has Yet to Change (Enough)
- Translating Enterprise Digital Twin Culture to Construction
- Leveraging the Single Source of Truth for JIT Regulation

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EPIC’s Mission

- Education for Engineers in Energy
- Research and Development
- Economic Development

www.epic.uncc.edu

Albert and Freeman
Energy Production and Infrastructure Center

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Practical Nuclear Experience through Partnerships with SMR Developers

- EPIC expertise is being applied to inspection techniques and construction sequencing for SMR's
- EPIC is supporting the development of a construction-related LTR for the NRC
- Digital Twin Pilot Projects include
  - Structural health monitoring (Dr. Tim Kernicky presented on Thursday)
  - Adapting Enterprise DT's from Advanced Manufacturing to Construction (partnership with Siemens)
- "Single Source of Truth" for structural and geotechnical models during construction (partnership with EPRI and Purdue)
- EPIC nuclear industry advisor is Mr. Jeff Hawkins, retired Vice President – Project Director Fluor Nuclear Power

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Consensus on Nuclear Energy has Changed

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The message is we need new nuclear…

A carbon-free future is a nuclear future

by Rep Michael Burgess & Bud Albright

> “Contrary to what Hollywood might have you believe, nuclear power is one of the safest and most reliable sources of energy in the world, producing approximately 20% of our nation's electrical power, and more than half of our nation's carbon-free energy.“

- **The environmental emergency of the second decade is climate change.**
- **Zero emission sources that work 24 hours a day are important again.**

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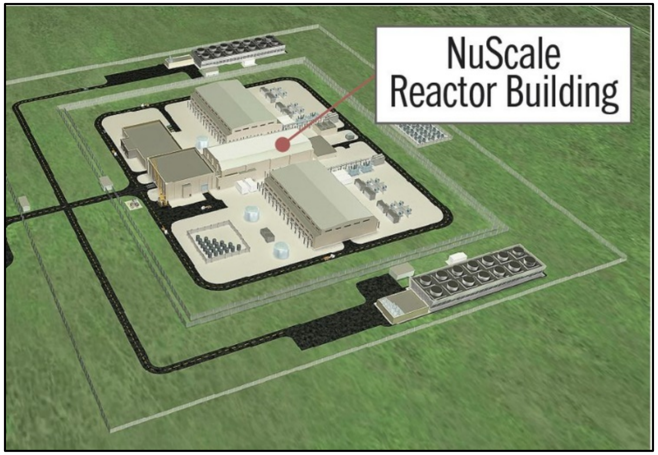
If it is affordable and in time…



Is next generation nuclear technology destined to serve Utah?
by Amy Joi O'Donoghue, DeseretNews, Nov. 11, 2020

"UAMPS spokesman LaVarr Webb said the power association will not move forward with the project unless costs per megawatt hour remains at $55 or lower and the current timeline for licensing and permitting is preserved."

- **Acceptance for new nuclear energy depends on cost and schedule.**
- **"More than 50% of costs are civil works."**

  Tim Schmitt, Engineering Supervisor for Civil Analysis,
  and Carl Fisher, VP for Products and Engineering,
  Framatome, meeting at EPIC, Nov. 1, 2018

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Construction Best Practice has Yet to Change “Enough”

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What do experienced nuclear construction professionals say?

January 28, 2019 Workshop on Large Energy Plant Construction hosted by EPIC.
Industry contributors: EPRI, Framatome, Atkins SNC Lavalin and Duke Energy

- Planning, scheduling, and sourcing optimized by and connected to the design.
- Fully 3D digital representation of complete design that remains trusted.
- Avoid "over the wall" design strategy – artificial separation between designer and construction—Reduce the cascade of ECO's!
- Consider how the regulator will interpret as-built construction—Is it to license or not?

What does the Construction Industry Institute say?

CII analyzed the performance of 975 light and heavy industrial projects.*

- Only 5.4% met "best in class" predictability in cost and schedule.
- Owners and contractors constructing large capital projects have resisted full-scale adoption of integrated digital tools and platforms to drive project performance.
- Nuclear plant construction is the most expensive example.

*www.pwc.com/us/en/industries/capital-projects-infrastructure/library/digital-twin-platform-capital-projects.html

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NEI | TECHNICAL REPORT

NEI 20-08

Strategic Project Management Lessons Learned & Best Practices for New Nuclear Power Construction

Prepared by the Nuclear Energy Institute
April 2020 Rev 0

nei.org

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Translating Enterprise Digital Twin Culture to Construction

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Aerospace and Nuclear - Both regulated for safety and economics

Commercial Aerospace Regulatory Hierarchy

- Accountable entity for the Type Design Certificate: Aircraft manufacturer (e.g., Boeing)
- Safety Regulator: Civil Aviation Authority (e.g., Federal Aviation Administration)
- Economic Regulator: Owner/operator (e.g., Airlines)

Nuclear Energy Regulatory Hierarchy

- Accountable entity for the License: Owner/operator (e.g., Utility)[†]
- Safety Regulator: Nuclear Safety Authority (e.g., Nuclear Regulatory Commission)
- Economic Regulator: Rate Setting Authority (e.g., Public Utility Commissions)

- In the Commercial Aerospace Industry, airliner OEM leads the integrated product team for the entire life cycle of the product (airliner).
- In the Nuclear Energy Industry, the owner of the plant should lead the integrated project team during the construction project[†] (planning, construction, handoff) and thence for the life cycle of the plant (operation, maintenance, and decommissioning).

[†] NEI Technical Report 20-08 *Strategic Project Management Lessons Learned & Best Practices for New Nuclear Power Construction*, pp. 15-16.

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Build the airplane, not the airport.

Characterized by:

- All digital design
- Automated component production by supply chain
- Repeatable component dimensions
- Reliable assembly by OEM
- Cost competitive
- High production rates
- Achieved in a regulated environment designed for safety

Characterized by:

- Single design (no two airports alike)
- Local fabrication
- No complete digital design
- Diminishing supply chain

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Methods to improve the work culture to one of "finish on-time and within budget"

Digital Twin for New Nuclear Construction

- Includes **enterprise** level program management support throughout construction.
  - A programmatic approach to cost saving with clear leadership, responsibility, and organization for project management.
  - Information technology and data analytics leveraged to simplify workflow, to make shared information current and consistent, and to automate administrative tasks.
  - IT based actionable spend analytics for improved decision-making strategies.
  - IT based actionable data analytics for improved procurement.
- Trusted model of what is built or modified for the life of the project.
- Design for construction and assembly. (Similar to DFMA)
- Incorporate details about fabrication processes so components can be produced by any vendor in the supply chain.

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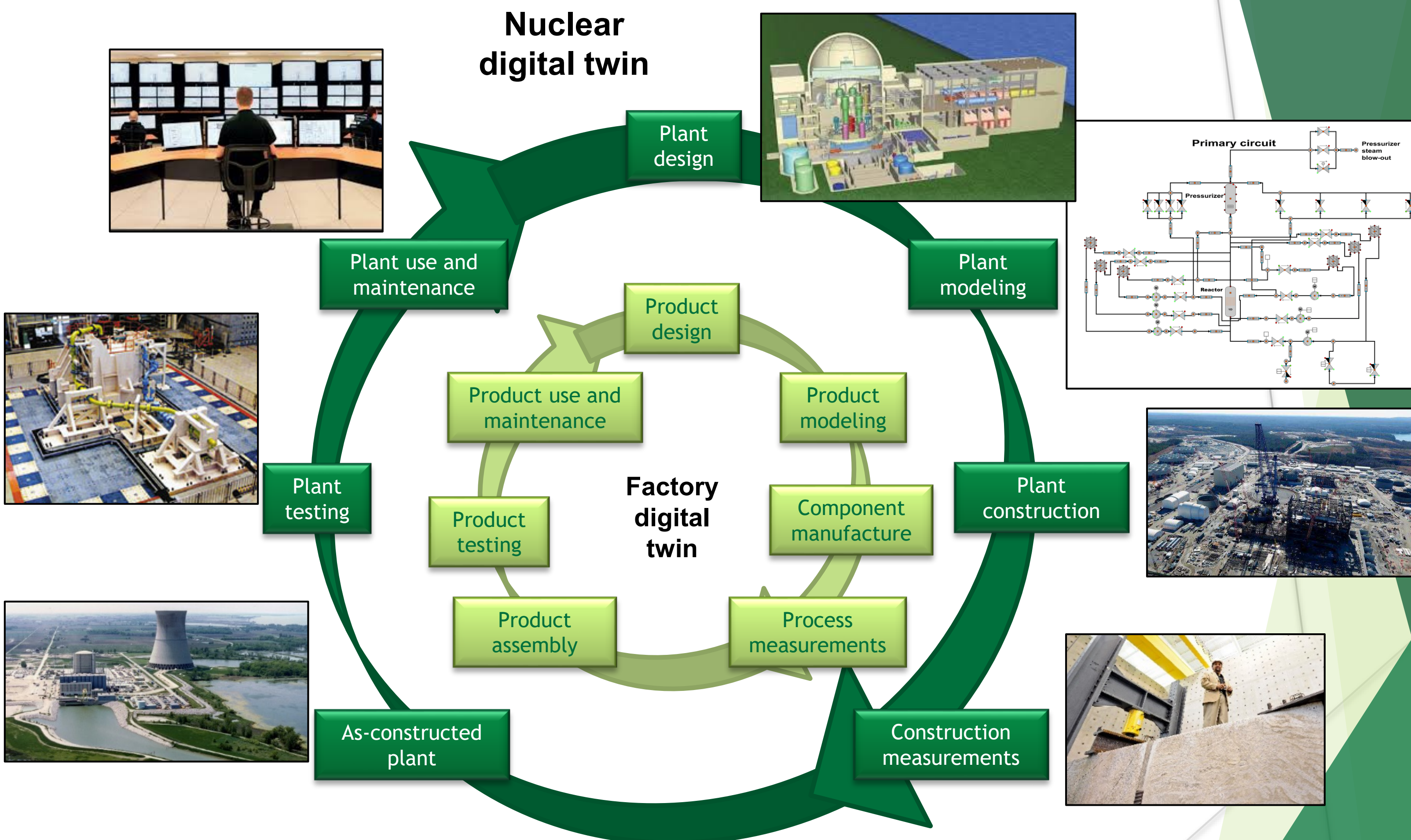
Analogy to Advanced Manufacturing



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Leveraging the Single Source of Truth for Just In Time Regulation

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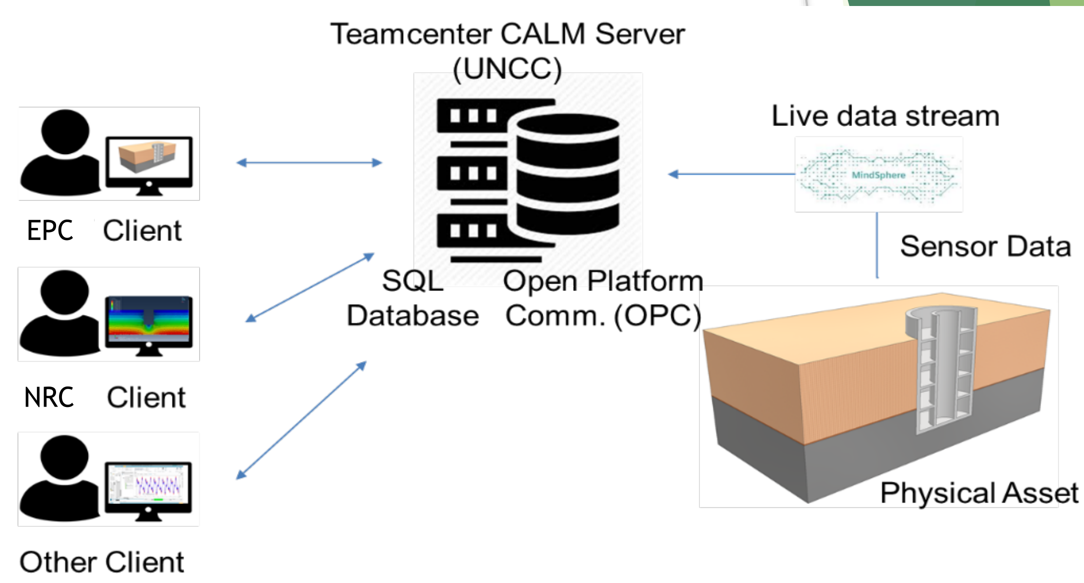
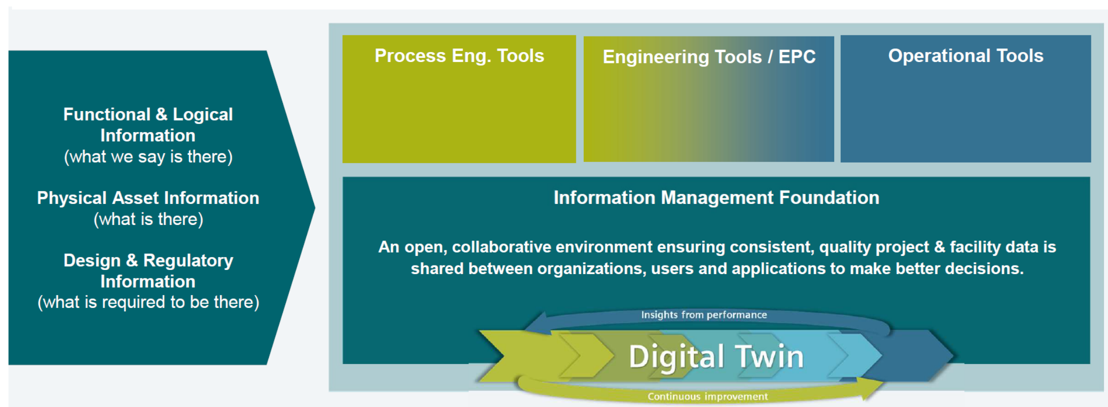
Part 52 Current Rules

- Part 52 licensees may proceed with construction departing from licensing basis only after:
- 1) the licensee, with collaboration from the NRC, determines that a License Amendment Request (LAR) is not required; or
- 2) the licensee submits a LAR and the NRC reviews and approves it; or
- 3) the licensee receives Preliminary Amendment Request (PAR) "no objection" letter from NRC.
- The PAR "no objection" letter is provided only after the associated LAR is developed, submitted and accepted for review by the NRC.

Project Management and Regulator Have Access to the Same Single Source of Truth

- Interfaces to different clients and project, technical, or regulatory software systems available in Teamcenter.
- Consideration of phases of the project and how the Part 52 restrictions should be applied.
- Projects could be allowed to advance specified phases prior to the final COL being issued.
- The phased approach allows parallel project execution to occur.
- Risk should be well defined and understood by management and regulator.





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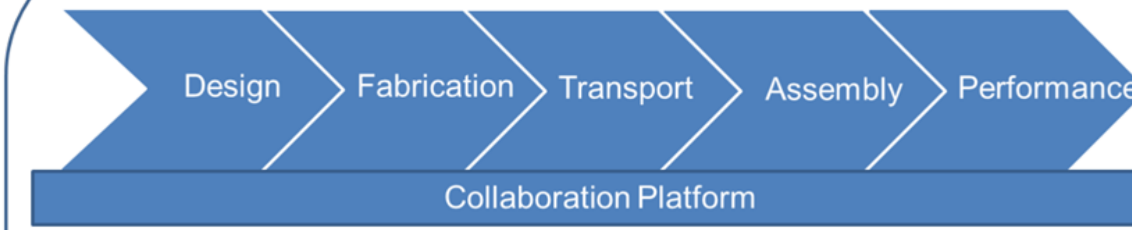
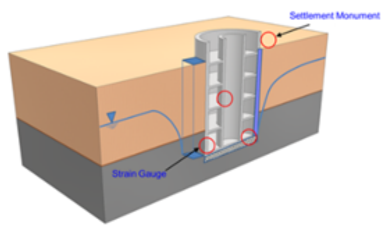
Maintaining Single Source of Truth during Construction - Example

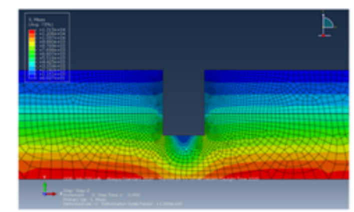
- Structures constructed using innovative technologies
- Structures tracked through design, fabrication, transport, assembly, and in-service life
- E.g., Finite-element structural and geotechnical models can be integrated application domains





Building Information Modeling & RT Sensor Data

Discrete Event Simulation for Planning



FEA Models

The Digital Twin: End-to-end solution to acquire and stream data and augment it using simulation models

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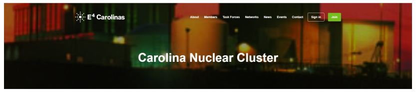
2020 External Partnerships



advanced energy

CCOG Centralina Council of Governments

CHARLOTTE.

CLEMSON UNIVERSITY

Dominion Energy

DUKE ENERGY

EPRI ELECTRIC POWER RESEARCH INSTITUTE

EnergyUnited YOUR LOCAL CONNECTION A Touchstone Energy Cooperative

framatome

GE

HITACHI

INL Idaho National Laboratory

Joules Accelerator

KIT Karlsruhe Institute of Technology

LS Energy Solutions

NREL NATIONAL RENEWABLE ENERGY LABORATORY

NC Environmental Quality

STATE OF NORTH CAROLINA DEPARTMENT OF TRANSPORTATION

NC Electric Cooperatives Your Touchstone Energy Cooperatives

NC STATE UNIVERSITY

NC SUSTAINABLE ENERGY ASSOCIATION

NEI NUCLEAR ENERGY INSTITUTE

OAK RIDGE National Laboratory

Piedmont Natural Gas

pillsbury

POWER ENGINEERS

RESEARCH TRIANGLE CLEANTECH CLUSTER™ » Transformation Through Collaboration

Sandia National Laboratories

sas

SRNL SAVANNAH RIVER NATIONAL LABORATORY OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

SIEMENS energy

SOS Reliability Matters

TVA

TERRESTRIAL ENERGY

DEPARTMENT OF DEFENSE UNITED STATES OF AMERICA

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

DEPARTMENT OF TRANSPORTATION UNITED STATES OF AMERICA

United States NIC Nuclear Industry Council

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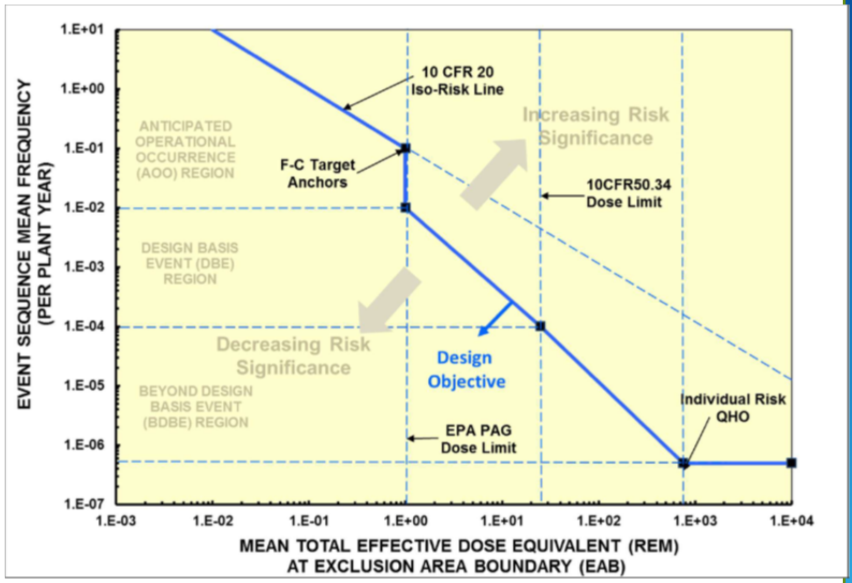


EMRALD

SAPHIRE

DIAMOND

December 4, 2020

Mike Calley

Department Manager, Regulatory Support

Including Risk in Digital Twins

Idaho National Laboratory

Nuclear Safety and Regulatory Research Division

Let’s start with the punchlines

- Many next generation reactors will use digital twin technology (DT) for design and operation
- “Risk” in terms of performance shortfalls is a powerful way to characterize and understand complex systems
- Risk, in terms of a “public health” frequency-consequence idea, is a key part of the next-gen risk-informed approach (e.g., in NRC’s SECY-19-0117)
- For completeness in design and operation, we must consider uncertainties
- When we put these together, we can realize a major efficiency if we design, operate, and license advanced reactors using a digital twin approach that includes a risk element

Outline

- **Risk**
  - What does it mean to use the word “risk” in the context of a DT?
- **Context**
  - Why is context important for operation of a reactor?
- **Framework**
  - How would we include risk when using a DT?

“Risk” tends to be used to describe one of two contexts

Risk represents a measured impact to safety

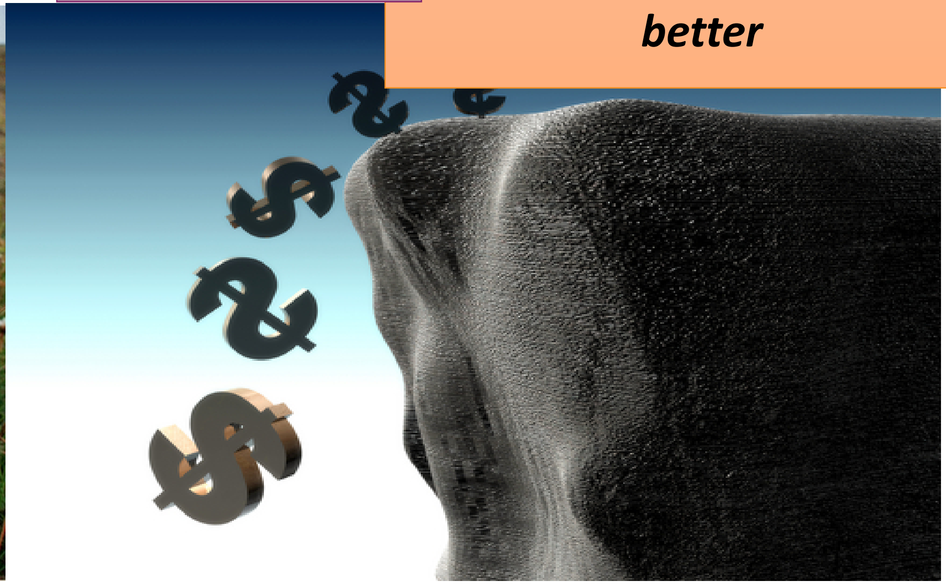
Risk Analysis → science-driven way to make things *safer*

PRA or PSA

Uncertainty Quant. or Risk Analysis

Risk represents a performance shortfall

Risk Analysis → science-driven way to make things *better*



For a DT, risk can be addressed for different metrics

Risk represents a measured impact to safety

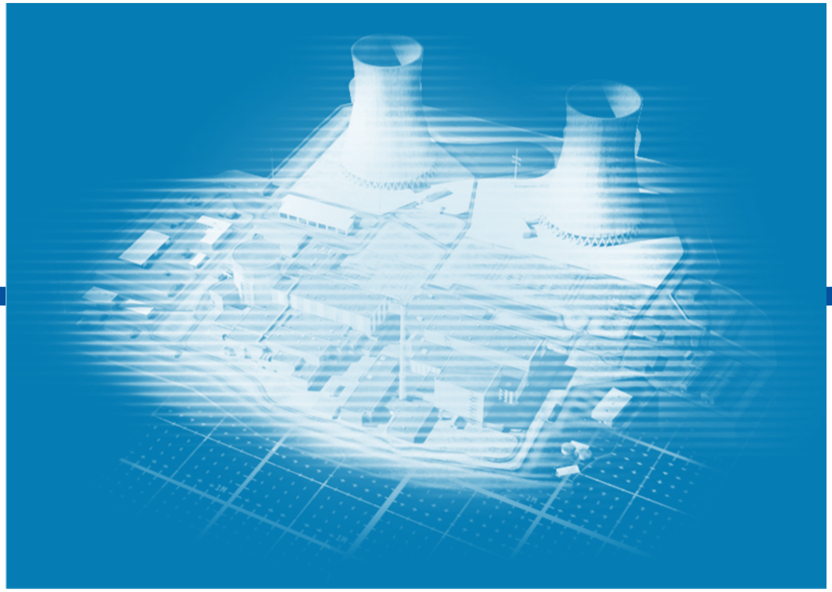
Risk Analysis → science-driven way to make things *safer*

PRA or PSA

Uncertainty Quant. or Risk Analysis

Risk represents a performance shortfall

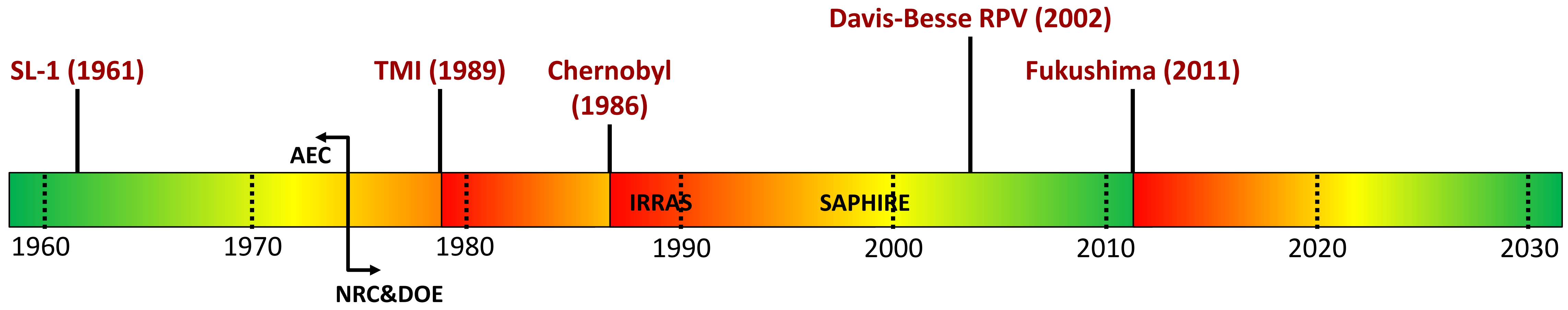
Risk Analysis → science-driven way to make things *better*

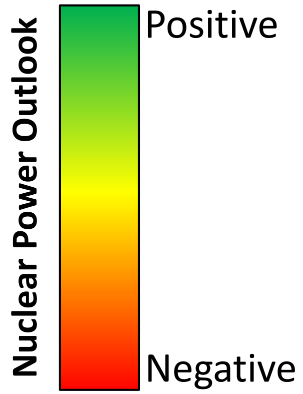


Core Damage
Fuel Damage
Material Release
Public Dose
Etc.

Costs
Availability
Reliability
Etc.

Context is important to understand off-normal events

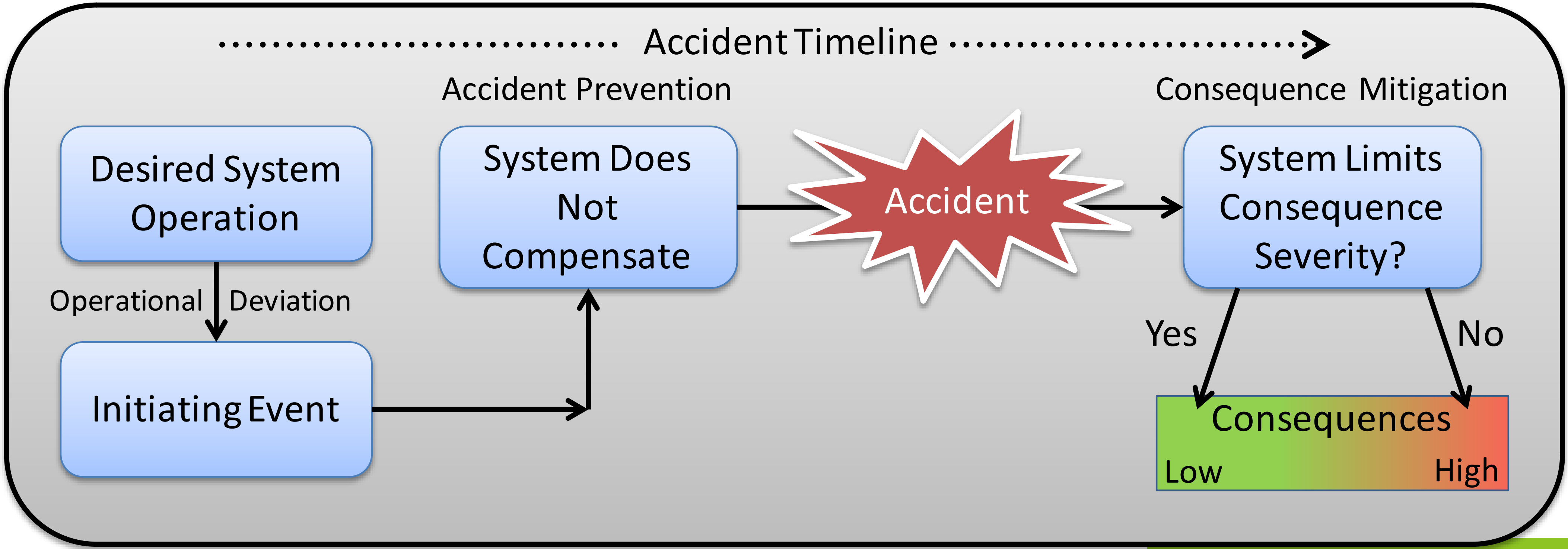




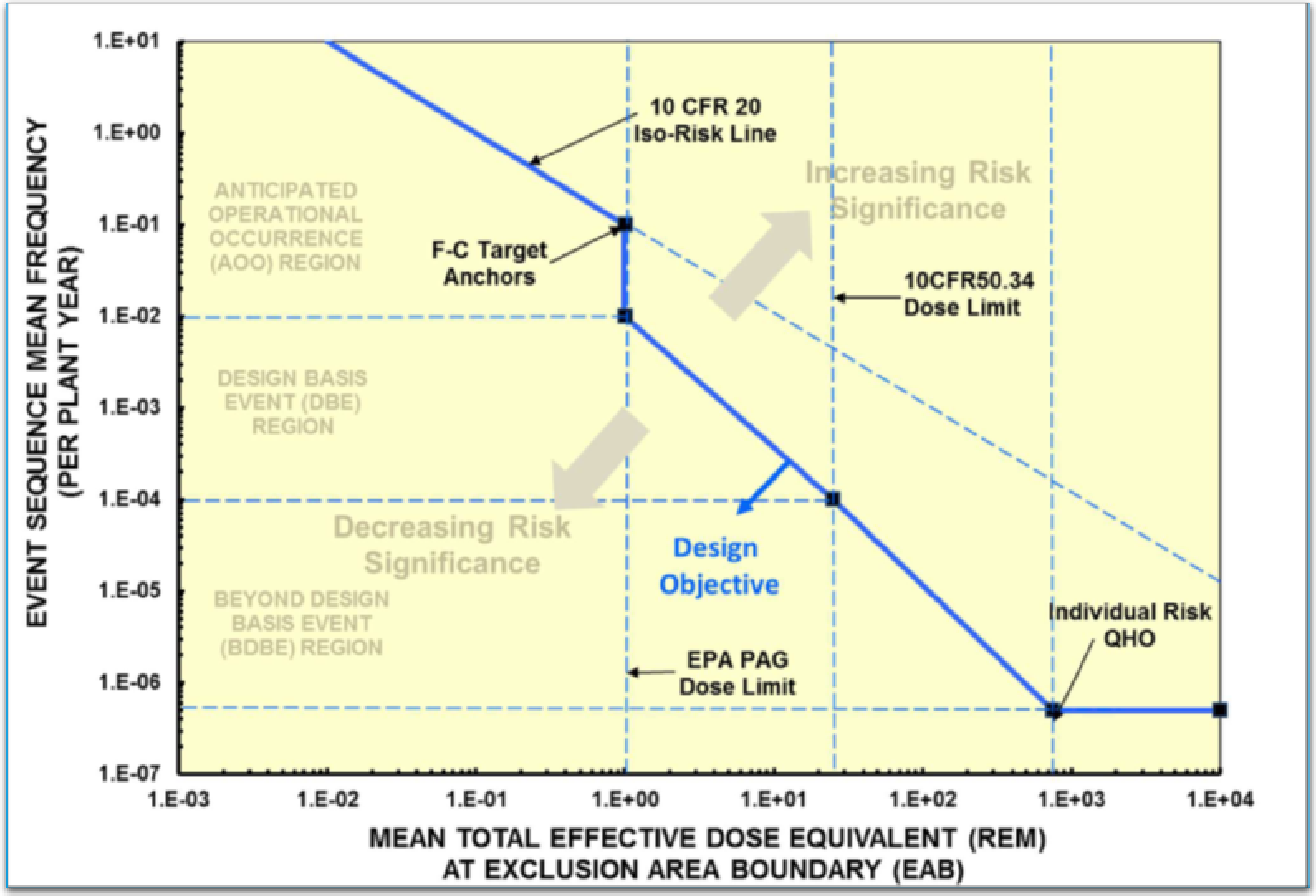
- **Understanding what is going on with, and around, a nuclear reactor is vital to capturing possible off-normal scenarios**
  - Off-normal events can be triggered by human actions, plant degradations, external events, or …
- **Having a model of the reactor physics (e.g., thermal-hydraulics, neutronics, materials) only captures part of the scenario story**

A scenario depicts off-normal behavior

- **Context for a facility includes and understanding of possible hazards**
- **For hazards that may impact a DT, context sets the scenario**
  - Scenario = initiating event + enabling conditions + undesired events/actions



From risk concepts & models comes risk-informed decisions



Frequency-consequence target (derived from NEI 18-04)

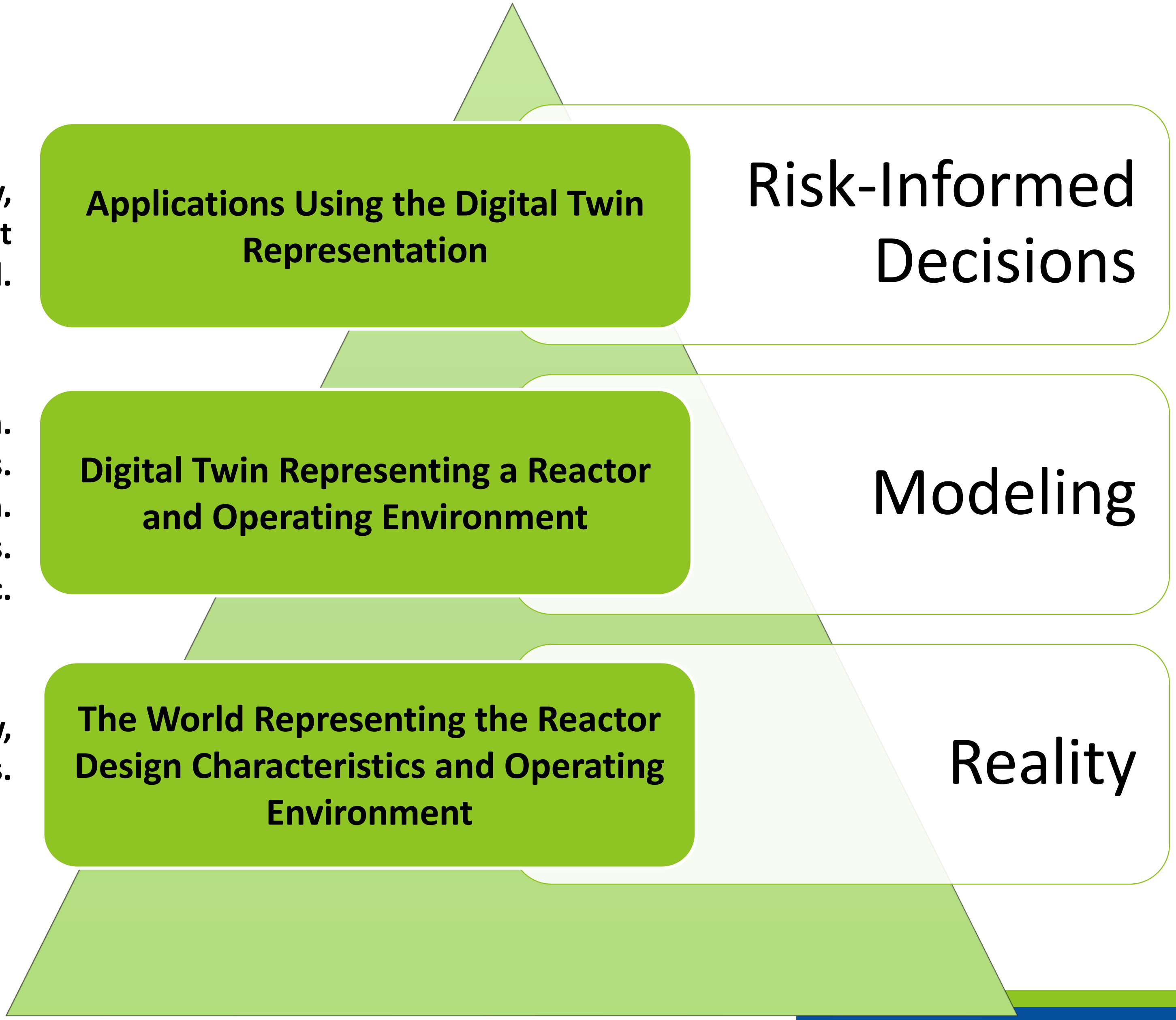
DT framework

Design, operation, safety, reliability, economics, and regulatory questions that are answered via the digital twin model.

Models for physical phenomena.
Models for probabilistic outcomes.
Models for reactor operation.
Models for reactor physical properties.
Etc.

The actual reactor including how, when, and where it operates.

Uncertainty



DT modeling, including risk, implies usage of computational risk assessment

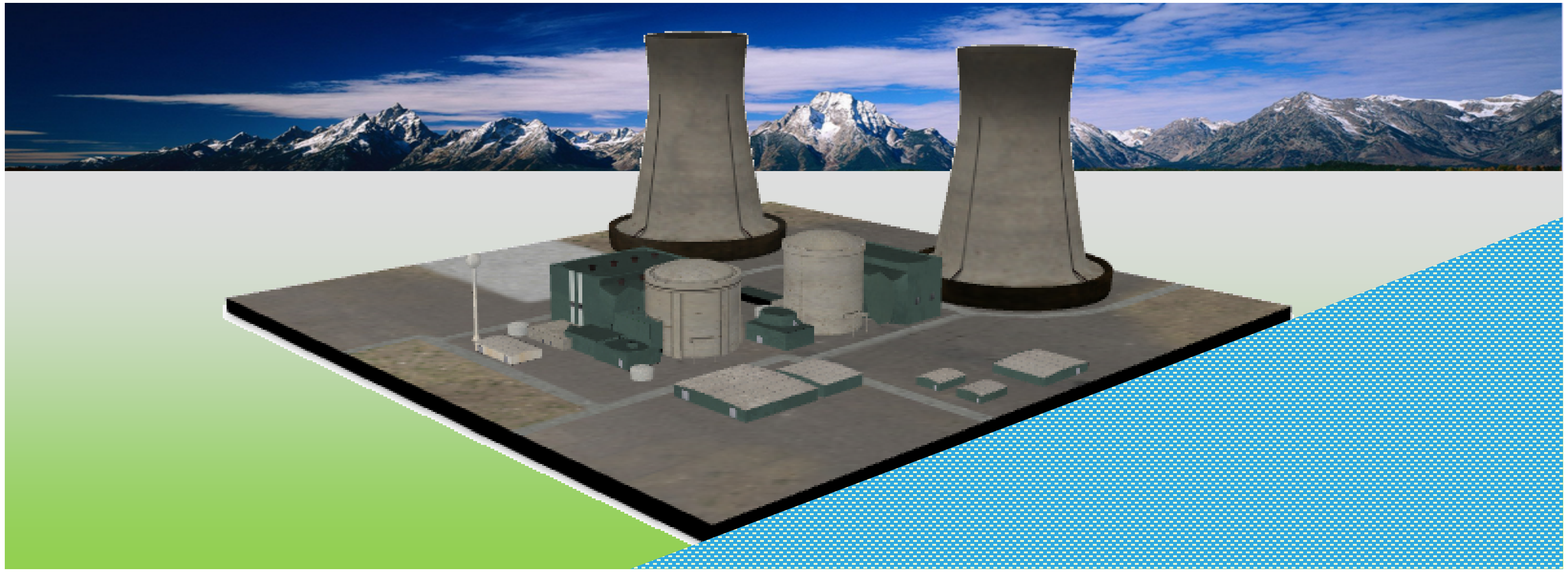
- **Computational Risk Assessment integrates risk and physics models**
- **CRA is a combination of**
  - Probabilistic scenario creation where scenarios unfold (in the computer) and are not defined a priori
  - Mechanistic analysis representing physics of the unfolding scenarios
- **CRA is not simply solving traditional PRA models faster or with higher precision**
  - It is a different way of approaching a safety analysis or a performance-shortfall evaluation

Integrating the worlds of physics and probability leads us to predictions based upon an approach called "computational risk assessment"

CRA Steps for Scenario Generation

Enabling Conditions → Initiating Event → Plant SSC Response to Initiator → SSC Failures & Successes → Scenario Simulation

3D Models for the DT including Systems, Structures, & Components (SSC)



Computational Layers Used for the Analysis

Probabilistic events

These tend to be stochastic models (but could be load/capacity)

Seismic

Flooding

These tend to be physics models

. . .

Thermal-hydraulics

In summary

- **DT for design and operation**
  - Helps us understand the facility, and how it will operate, before and during actual operation
- **Performance shortfall to characterize and understand complex systems**
  - Helps us to focus on the strengths and weakness of these systems
- **Public health risk is a part of the next-gen licensing**
  - Helps us license advanced reactors in an efficient manner
- **We must consider uncertainties**
  - Helps us characterize our knowledge about the operation- and safety-cases
- **These points imply we should include risk for our advanced reactor DTs**

Michael.Calley@inl.gov

Thank you!

Defense Nuclear Nonproliferation Research & Development

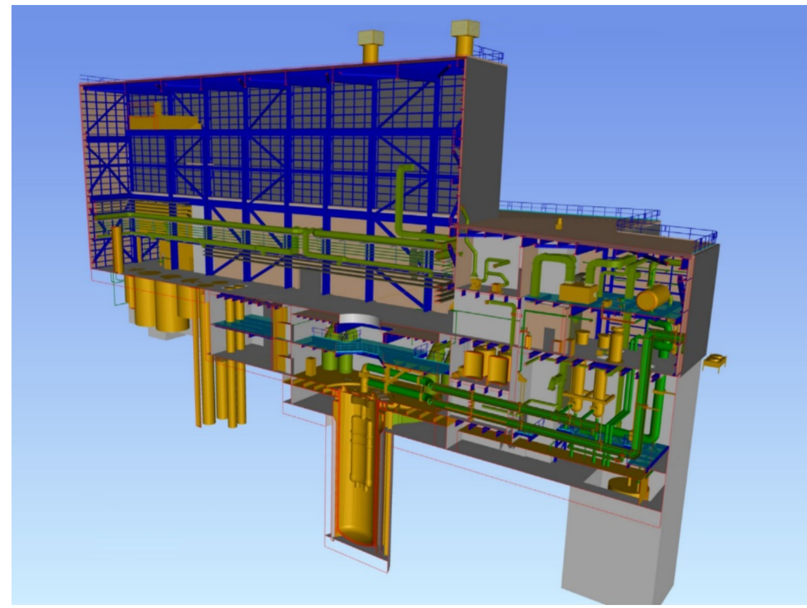
Towards a Digital Twin to Detect Nuclear Proliferation Activities

NA-22 Office of Data Science

Christopher Ritter (PI), Sam Bays, Eric Bohney, Ross Hays, John Koudelka, Ross Kunz, Gustavo Reyes, Mark Schanfein

Current Limits of Practice

- State of the Art:
  - Safeguards analysis is typically SME based without models
  - When models exist, they are disconnected, have no AI/ML integration, and no digital twin capabilities
- Problem: Development of new advanced reactors (Gen IV) increases importance of new methods to understand diversion and misuse scenarios and determine mitigation pathways



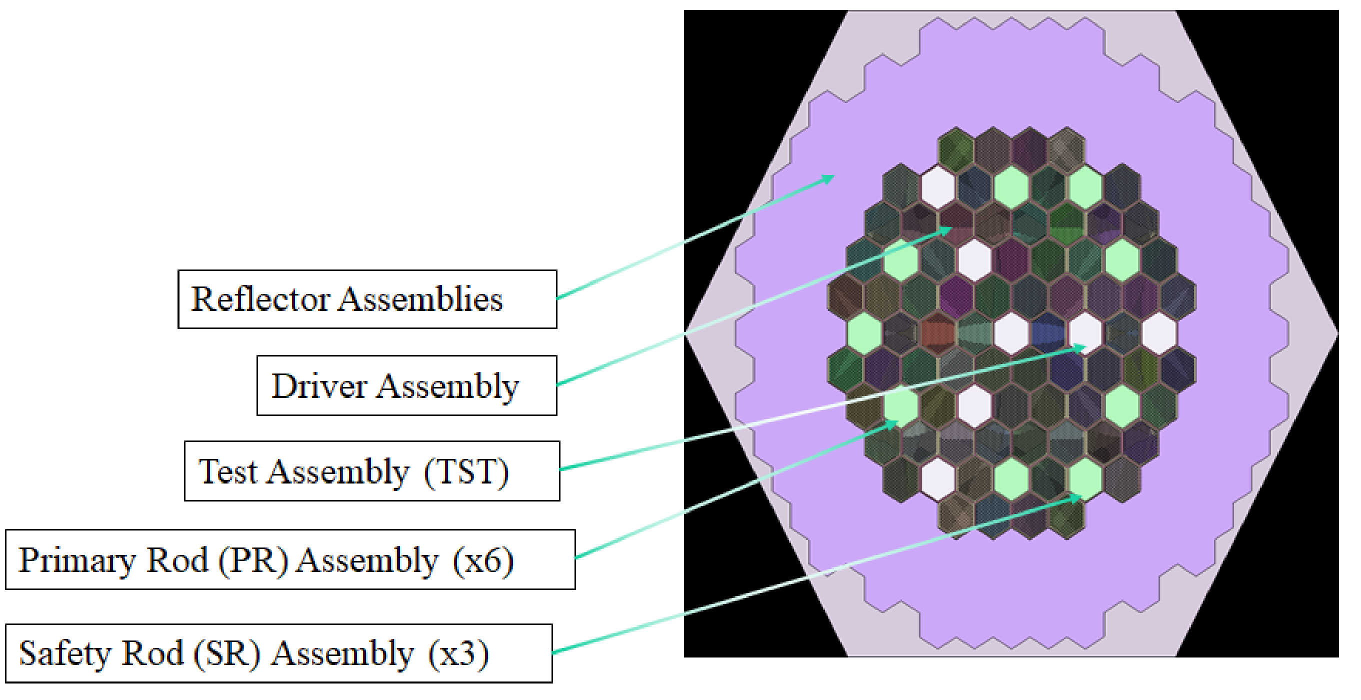
Versatile Test Reactor: Gen IV Sodium Cooled Fast Reactor (scheduled for operation in 2026)

Diversion / Misuse Definitions

- **Diversion**: The special fissionable nuclear material (Pu239, U233, U enriched in U233/235) that has been declared to the International Atomic Energy Agency is removed surreptitiously either by taking small amounts of nuclear material over a long time (known as protracted diversion) or large amounts in a short time (known as abrupt diversion)
- **Misuse**: The undeclared source material (material that can be transmuted into special fissionable nuclear material: depleted uranium, natural uranium, and thorium) is placed in the core uses the neutron flux for the transmutation

Nuclear Physics Overview

- Thermal Output: 300 MWth
- Cycle Length: 400 days
- Outage Length: 20 days
- Three batches of fuel in the core
  - (Fresh, 1st burned, 2nd burned)



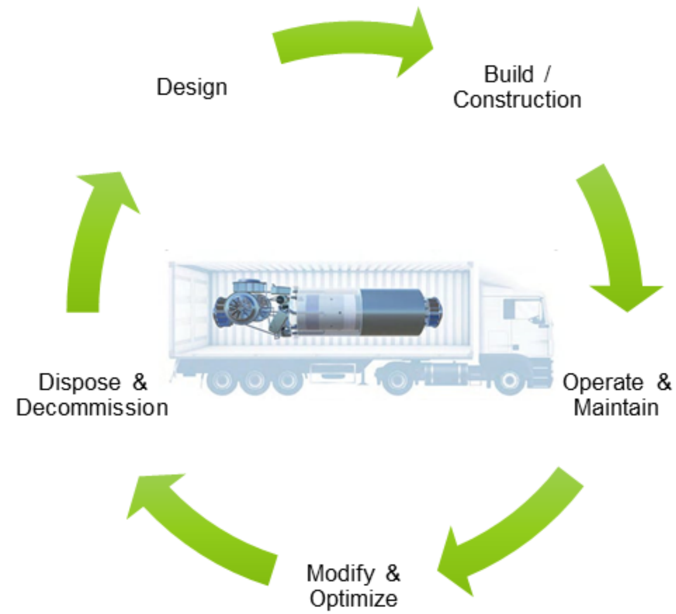
Diversion / Misuse Scenarios

- **Target**: *Obtain 1 Significant Quantity (SQ) of Plutonium (Pu = 8 kg) for a clandestine weapons program, ideally in 1 year*
- <u>Diversion</u> - diverting 1, 2, 4, 8, or 12 fuel pins per 217 pin *declared* assembly and substituting with either lead (Pb), stainless steel (SS), or natural uranium pins. Thereby immediately obtaining the fissionable Pu intended for the fresh fuel.
- <u>Misuse</u> - placement of a whole *undeclared* assembly(s) (referred to as a target) of fertile natural uranium in an experiment test location(s) within the reactor. Thereby transmuting the NU to Pu over time.

Key Technologies

DIAMOND Ontology

- **Project Objective(s):** This ontology allows for a generic, common framework to enable digital engineering programs. Like previous successful Idaho National Labs initiatives (ex. MOOSE), this data ontology will allow for a common framework to be shared, allowing for more complex energy projects to be undertaken and utilize a plug and play model.
- **Technical Challenges**: (1) Ontological compatibility with other domain ontologies: Mitigated through BFO use (2) Right sized ontology development to ensure the ontology is deep enough to be useful but flexible enough to support multiple designs (3) Verification of the ontology to ensure that functional specifications are executable; this is mitigated by the use of the Monterey Phoenix event trace system
- **Approach**: (1) analysis and selection of top level meta models (BFO/LML) (2) development of lower ontological decompositions for nuclear design using subject matter input to create an easily extendable ontology framework (3) validation and verification of the DIAMOND ontology for nuclear reactor behavior models using Monterey Phoenix (MP)



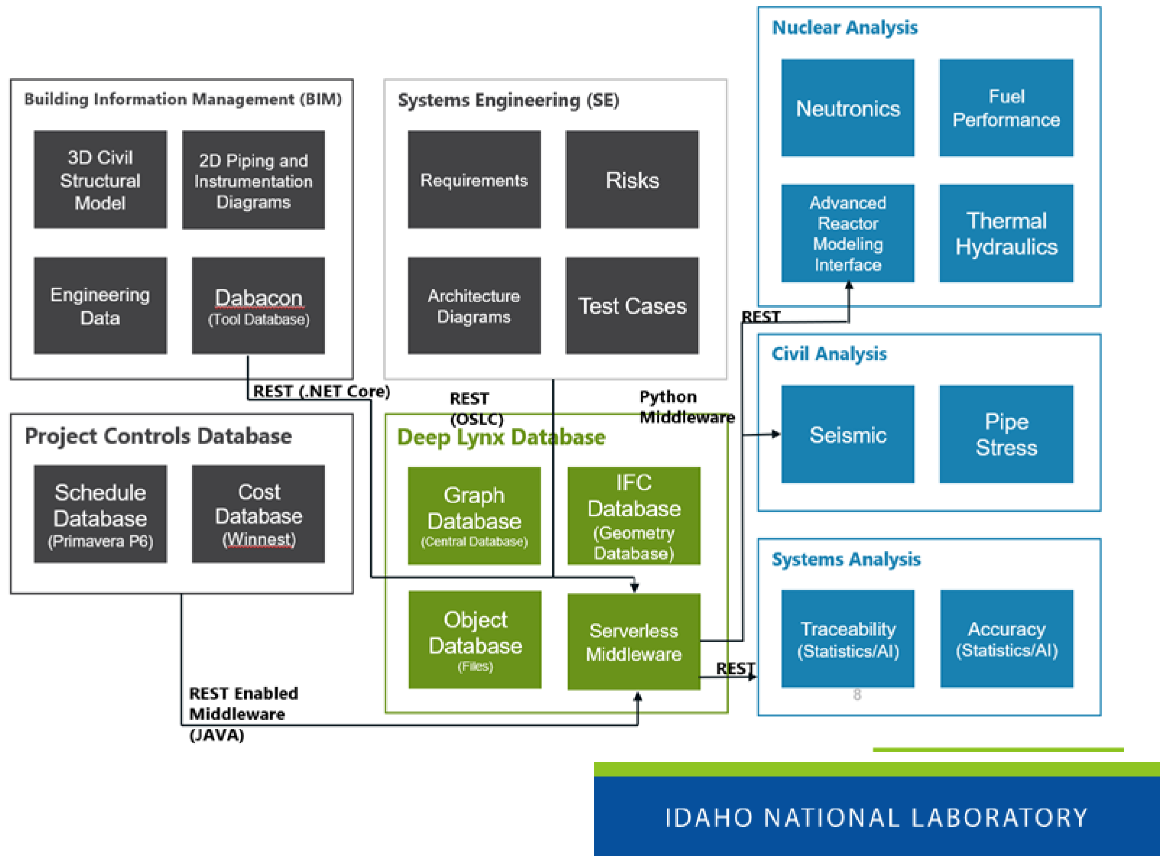
Connection across asset lifecycle

IDAHO NATIONAL LABORATORY

Key Technologies

Deep Lynx Datawarehouse

- **Ontology**: Utilizes ontology for a standardized, common data model to enable a generic framework independent of tool/solution
- **Central Software Framework**: This allows for a common software framework to be shared, allowing for code re-use and minimal point-to-point integrations
- **Central Datastore**: This is utilizing the Microsoft Azure Postgres Hyperscale Database which allows a balance between scalability and historical stability



Digital Twin Data Model

- **Model Input:**
  - List of selected parameters (fuel design, location, operations, etc.)
  - SERPENT input generating scripts (utilize above parameters)
  - SERPENT version, installation, runtime data
  - Output data extraction script
- **Model Output:**
  - SERPENT data is passed through extraction script to yield selected parameters
  - Parameters stored in HDF5 archive, passed to DeepLynx.
  - DeepLynx extracts archive, converts to DIAMOND type

Digital Twin Data Model

- **Current Status**
  - Defining and converting input parameters within generation scripts
  - Defining output parameters of current and future interest, creating DIAMOND type classes and relationships
  - Establishing automated linkages, authentication methods between cloud data host, local SERPENT installation
- **Future Work**
  - Expand DIAMOND type mappings
  - Automate creation, execution of SERPENT inputs
  - Automate extraction, ingestion of data to DeepLynx.

Questions

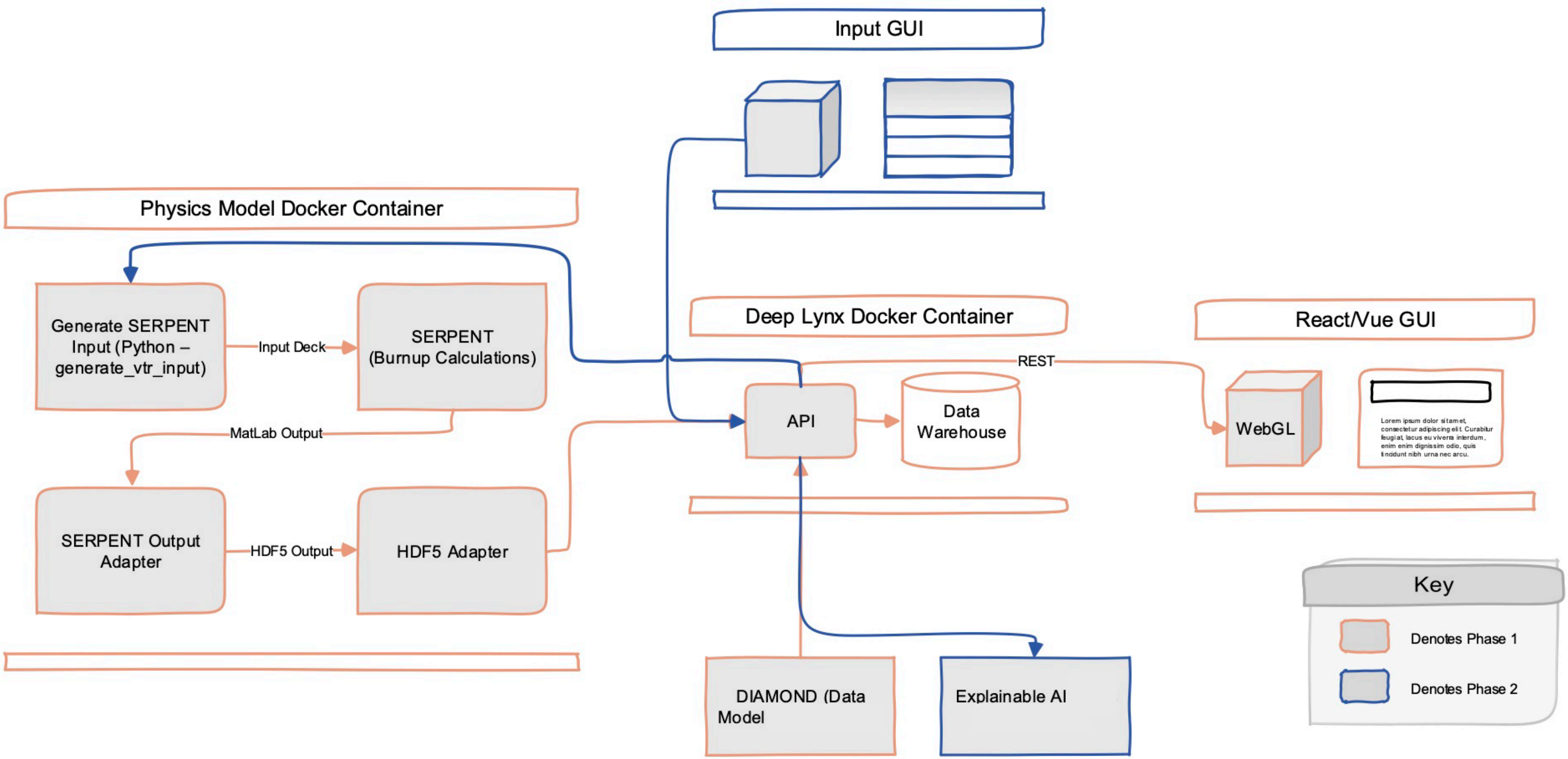
Digital Twin Software Overview

National Nuclear Security Administration
Defense Nuclear Nonproliferation

- **INL HPC (High Performance Computing) hosting:**
  - Serpent: burnup calculations
  - Serpent output adapter and HDF5 to JSON converter (python) for ingestion to Deep Lynx
- **Deep Lynx data warehouse**
  - NodeJS
  - PostgreSQL
  - DIAMOND data model
- **Input and Output GUIs**
  - Input[2]: Visual selection to create input to Serpent
  - Output: WebGL app that provides 3D model of reactor

2: Phase 2

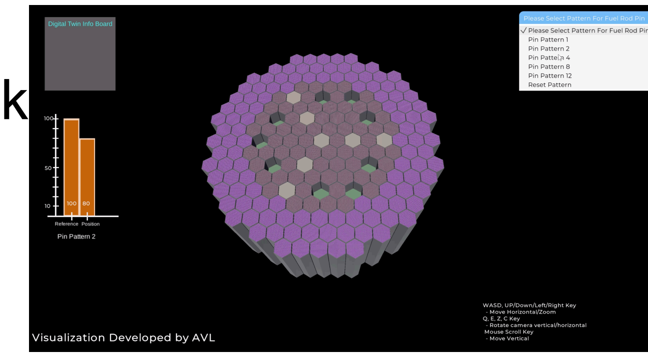
Digital Twin Data Pipeline

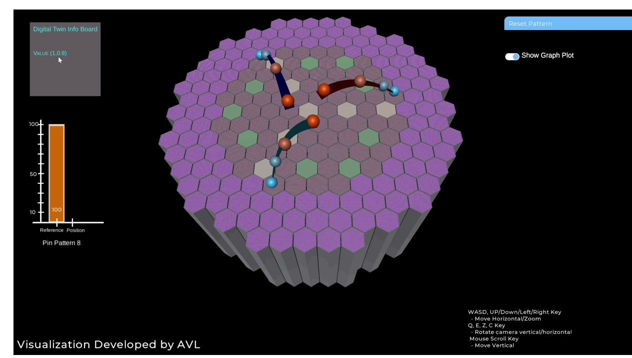


Questions

Digital Twin Visualization Technology

- **Web-based, Virtual Reality environment**
  - Reactor model developed in Autodesk Inventor and 3DS Max
  - WebGL 3D environment
    - Visual Analytics
    - Integration of 2D & 3D
    - RESTful API calls for data
    - Scalable (desktop, laptop, tablet)
  - Dynamic Interaction
- **Data Connection**
  - Calls to Deep Lynx for data
  - Digital Twin is controlled by the result

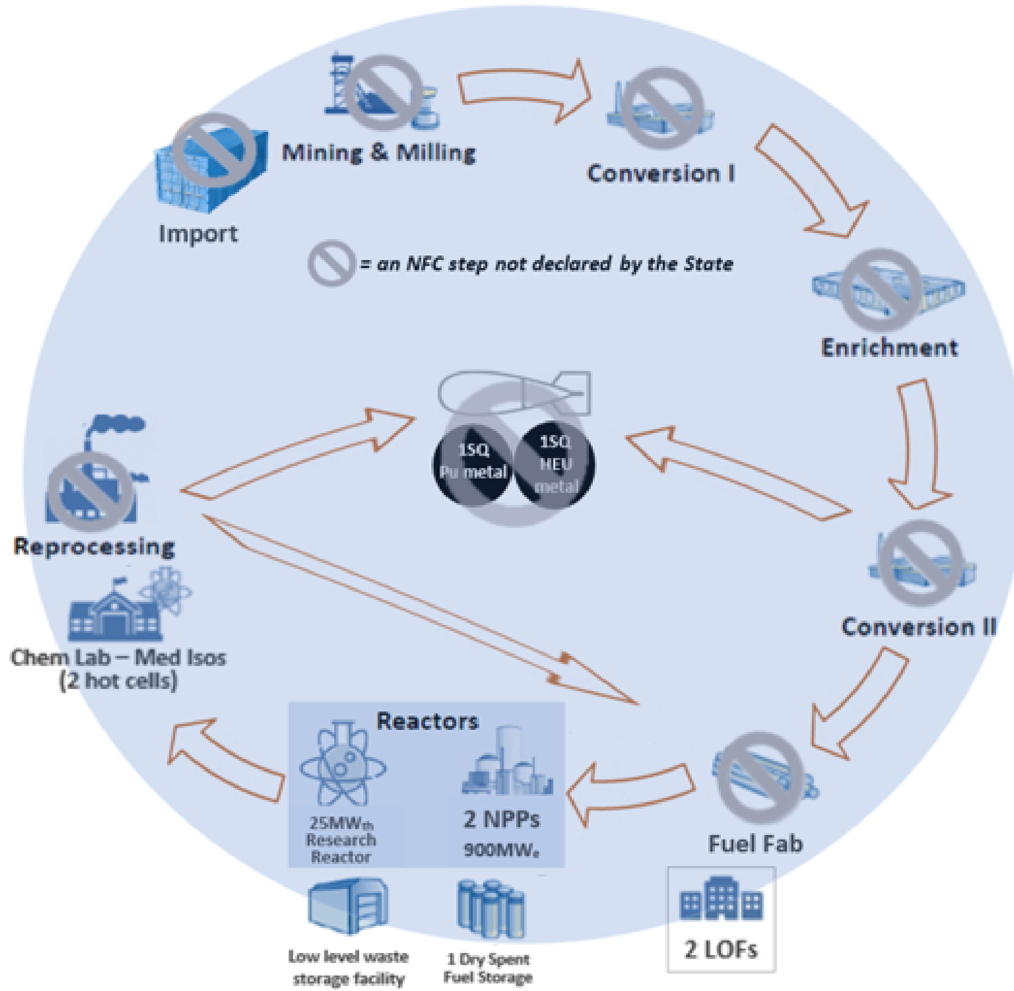




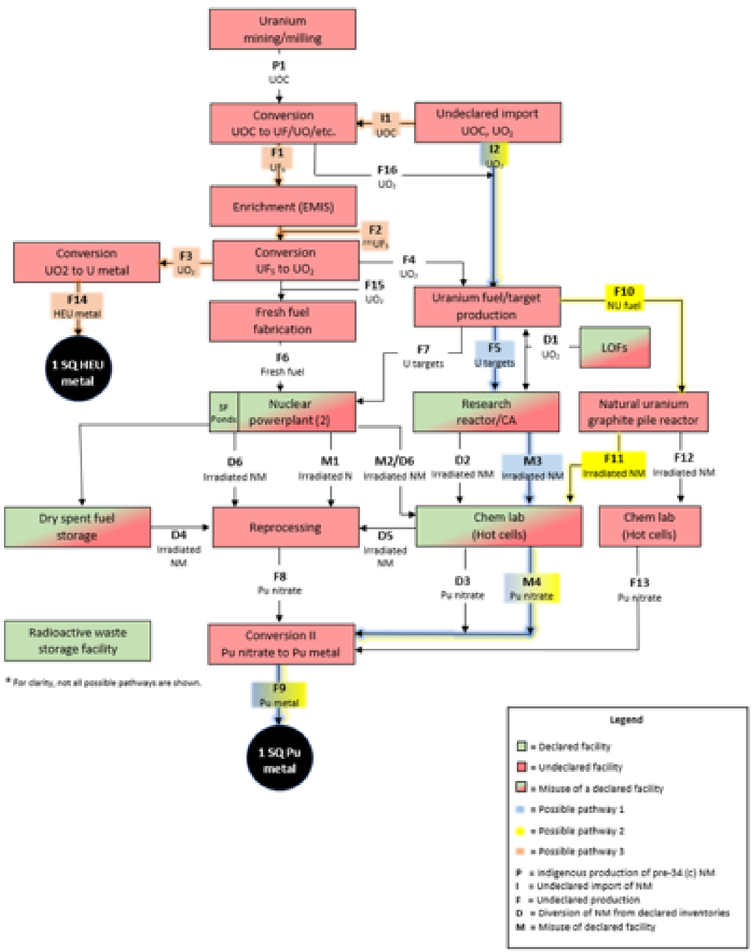
Questions

Realizing DT's Full Potential

- *Diversion* & *Misuse* at <u>declared</u> facilities may indicate <u>undeclared</u> facilities & activities
- NPP a great place to start…
- The value of DT applies to the entire NFC



Using DT in IAEA's Maturing State Level Concept



Questions

- SLC is applied holistically in a State based on its declared NFC, technical capabilities, etc.
- Safeguards activities driven by acquisition path analysis (APA)
- DT can point to misuse/diversion at other NFC steps in the State
- DT informs IAEA's AP Complementary Access activities
- This can lead to a more effective International Safeguards program

Expected Results

- Complete and demonstrated digital twin framework for safeguards by design
- Opportunity for comprehensive understanding of nuclear fuel cycle facility operations to significantly strengthen nuclear safeguards and nonproliferation regime
- Future opportunity to support diversion/misuse detection for both item (LWR) and bulk (MSR) type advanced reactors. As well as indicators for clandestine reactors