INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

Welcome to this Engagement & Review Workshop

Thursday, 3rd May, London EC2A 1AG

R&D on Digital Nuclear Reactor Design

Virtual Engineering, Modelling and Simulation

John Lillington, Chief Technologist, Wood

Partners

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

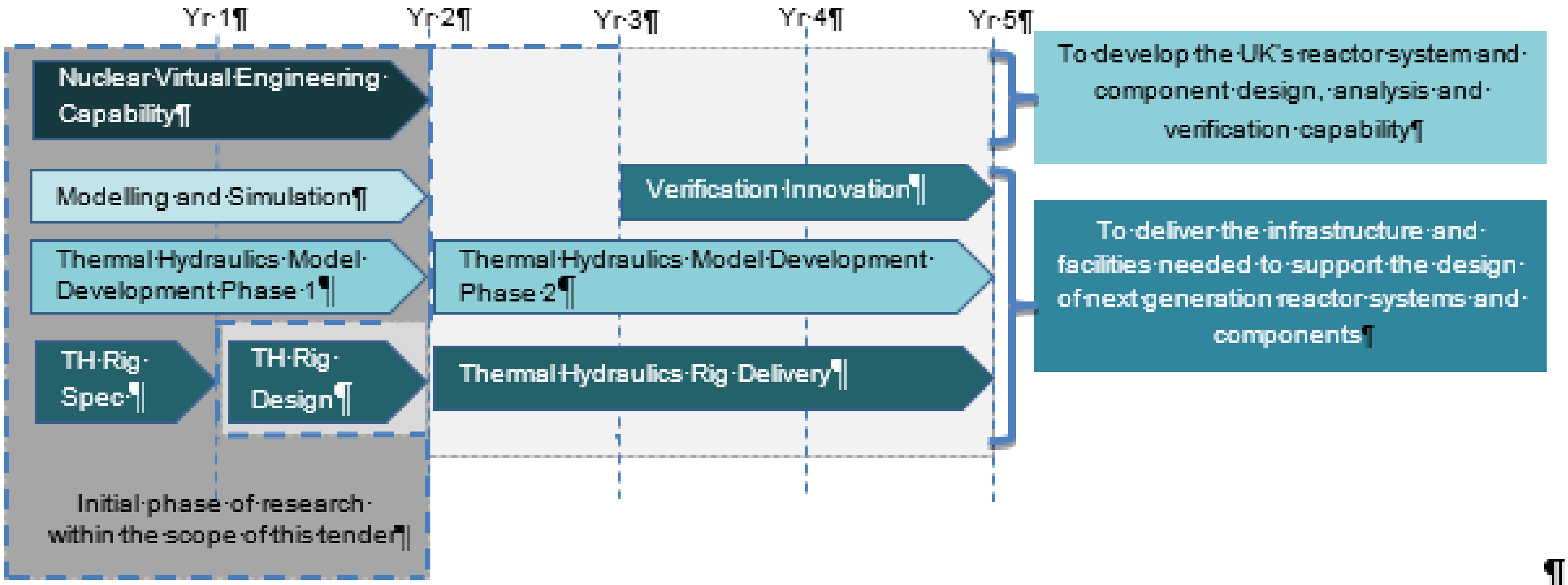
Working together to make the UK a world-leader in nuclear science and technology.

wood.	VIRTUAL ENGINEERING CENTRE	NATIONAL NUCLEAR LABORATORY
ROLLS ROYCE	EDF ENERGY	Hartree Centre Science & Technology Facilities Council
UNIVERSITY OF LIVERPOOL	Imperial College London	UNIVERSITY OF CAMBRIDGE

Six key programme areas:

- Advanced manufacturing and materials
- Advanced fuels
- **Reactor design – digital**
- Reactor design – safety
- Recycle and waste management
- Nuclear facilities and strategic toolkit

Reactor Design - Digital



BEIS Requirements

- **World-leadership!** VE, HPC, 'big data' management & eScience needed to promote UK nuclear science & technology in the UK and globally; UK to become a world-leader?
- **Energy Security.** To support UK infrastructure, framework and tools to support industry in providing UK future energy supply security.
- **Joined-up industry.** To enable the whole of UK nuclear industry, including supply chain & SMEs to have easy access to innovation, expertise, facilities and capabilities, including access to HPC, data and computer visualisation facilities i.e. an Integrated Nuclear Digital Environment (INDE).
- **Cross-discipline benefits.** To bring together expertise from industry and academia to combine the latest digital techniques with advanced multi-scale, multi-physics modelling and simulation expertise.
- **Informed decision making.** Develop VE and associated technologies to inform, underpin and assist Government policy as well as to support informed decision making by all stakeholders.

Industry Requirements

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

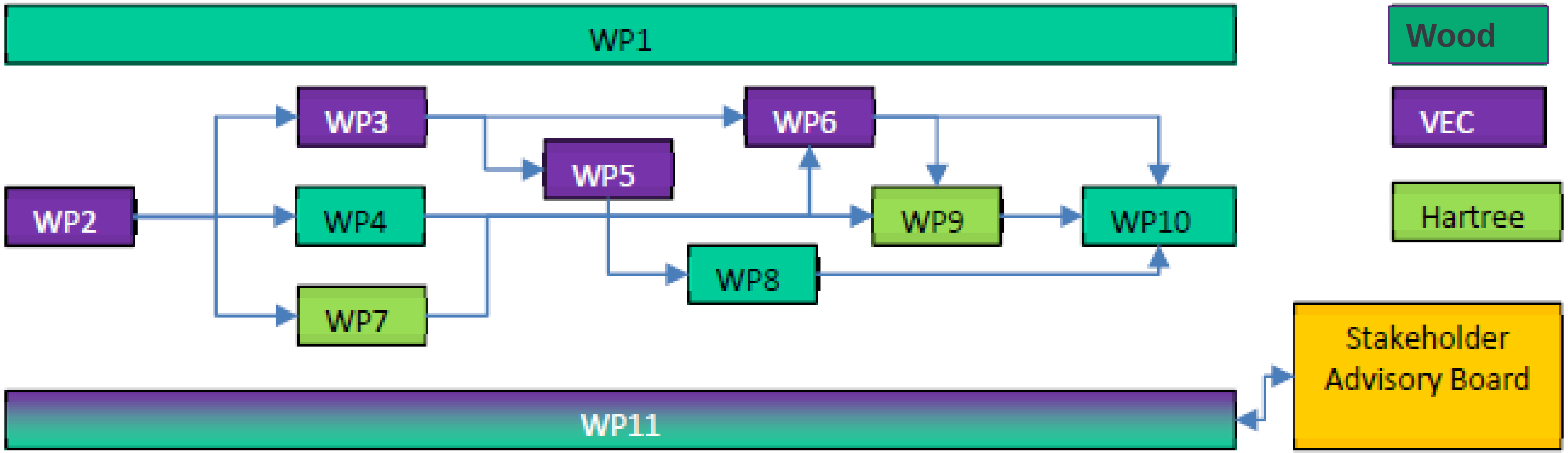
- **Keeping pace with other Industries.** VE & associated technologies are widespread and developed across other high technology industries. There is a requirement to bring these into the nuclear sector to enhance similarly design and development throughout the nuclear lifecycle.

- **Managing operational risks.** Modelling and simulation using VE and associated technologies are crucial to understanding technical risks, therefore lowering costs, reducing the probability of delays, overspends etc.

- **Improved connectivity.** An INDE will allow digital twins to be generated for individual nuclear plants. This will enable connectivity and seamless data transfer between design authorities and CAD models, manufacturers, operators, decommissioning authorities and regulators over the life cycle of the nuclear system.

- **Improved operation and safety.** The advantages of an INDE specifically include reduced development timescales and costs, higher standards of safety, reliability and operability.

Project Organisation



- WP1 Project Management
- WP2 Requirement Capture & Management
- WP3 Capability Mapping
- WP4 Defining Pilot Projects/Use Cases
- WP5 Architecture Design
- WP6 Integration of VE Capabilities
- WP7 Integration/Access to HPC
- WP8 Development of Radiation Simulation Models
- WP9 Security Strategy & Safety Assurance Roadmap
- WP10 Multi-physics, Multi-scale Use Cases
- WP11 Dissemination & Supply Chain/User Engagement

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

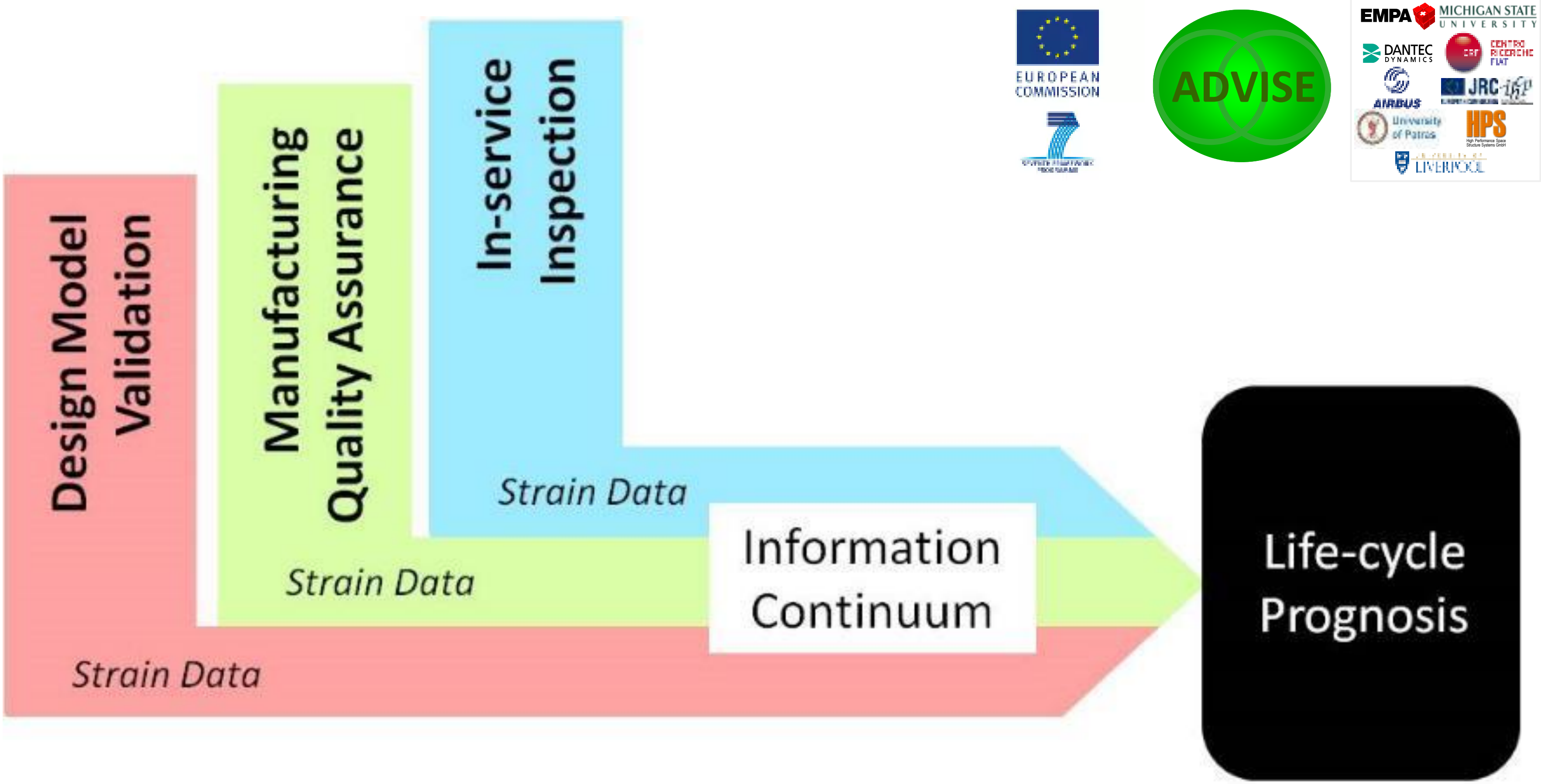
A Simulation Framework: INDE

Sharing Knowledge|Tackling Challenges|Connecting People

Eann A Patterson
A. A. Griffith Chair of Structural Materials & Mechanics, University of Liverpool
&
Senior Visiting Fellow, National Nuclear Laboratory

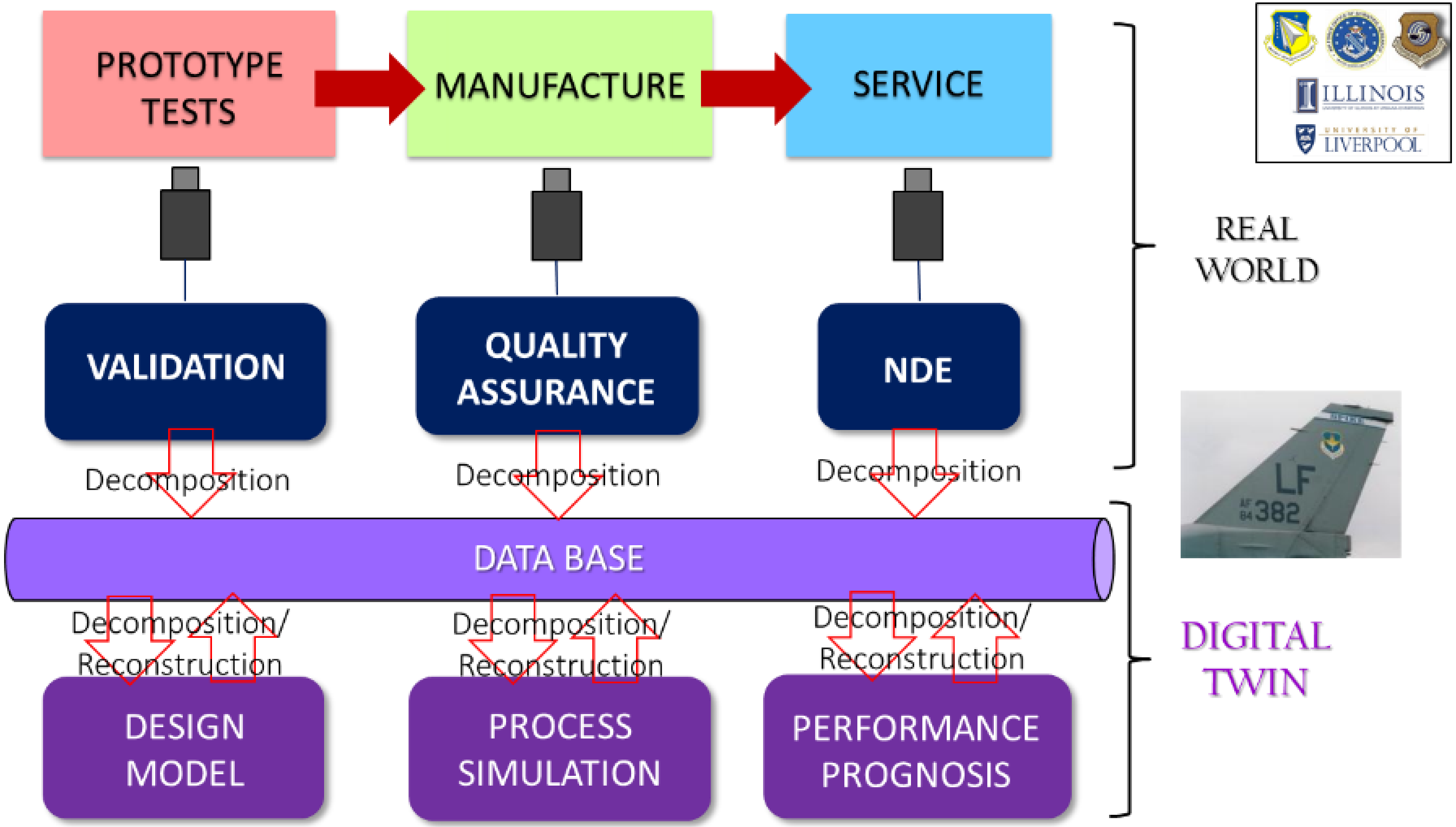
Information continuum

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME



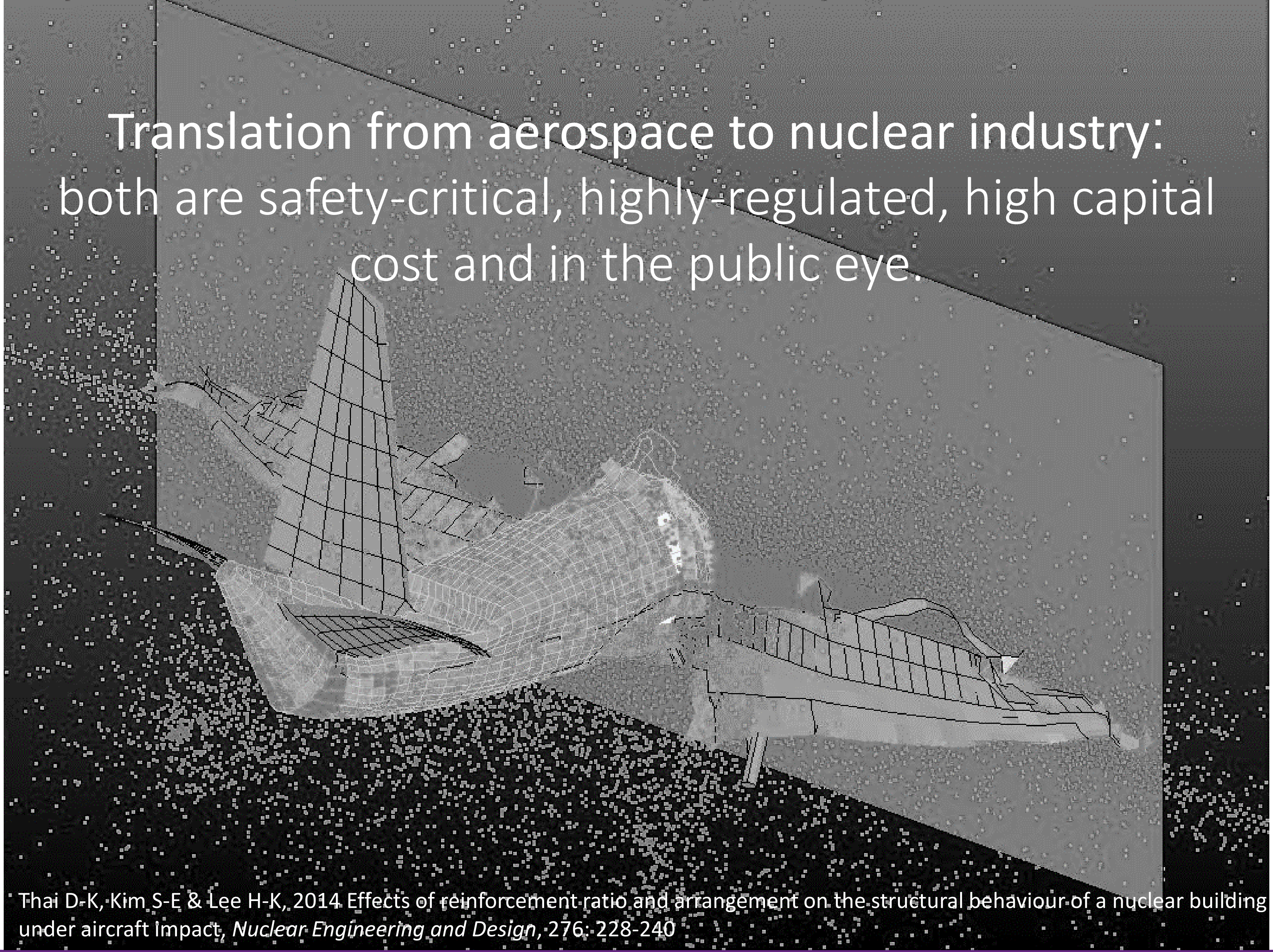
Patterson E.A., Feligiotti, M. & Hack, E., 2013, On the integration of validation, quality assurance and non-destructive evaluation, *J. Strain Analysis*, 48(1):48-59.

Digital String



Glaessgen EH & Stargel DS, 2012, The digital twin paradigm for future NASA and US Air Force vehicles, *Proc 53rd AIAA/ASME/ASCE Structures, Struct. Dyn. & Maters Conf.*, AIAA #2012-2018, NF1676L-13293.

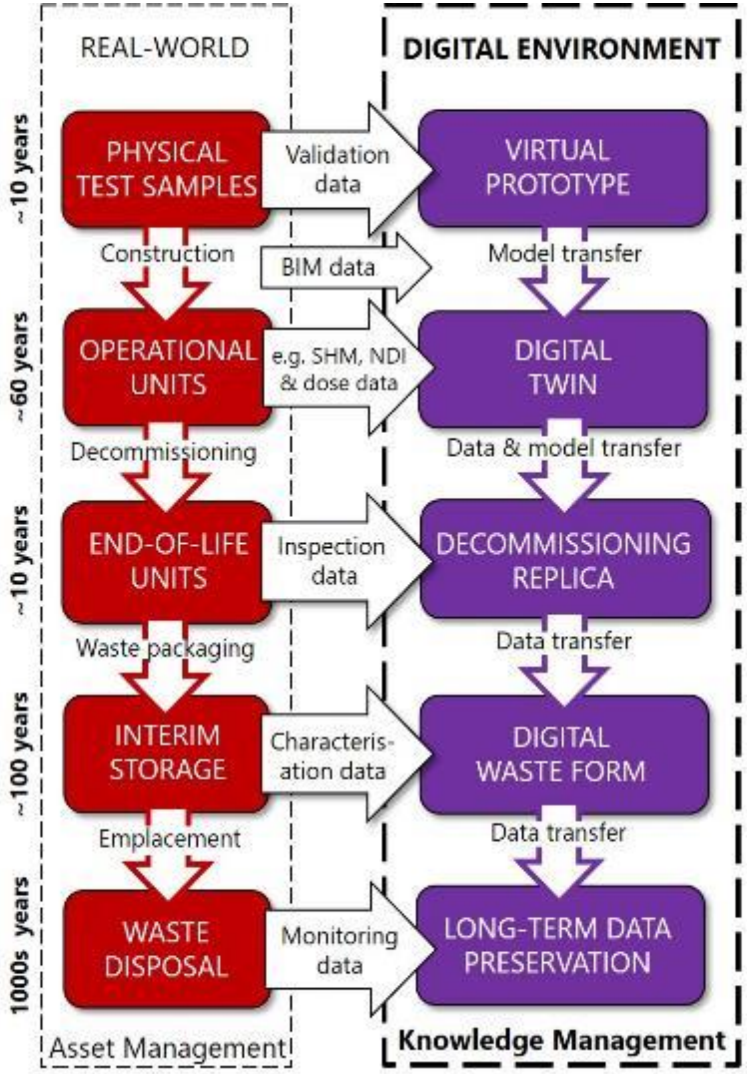
Translation from aerospace to nuclear industry:
both are safety-critical, highly-regulated, high capital cost and in the public eye.



Thai D-K, Kim S-E & Lee H-K, 2014 Effects of reinforcement ratio and arrangement on the structural behaviour of a nuclear building under aircraft impact, *Nuclear Engineering and Design*, 276: 228-240

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

Integrated Nuclear Digital Environment

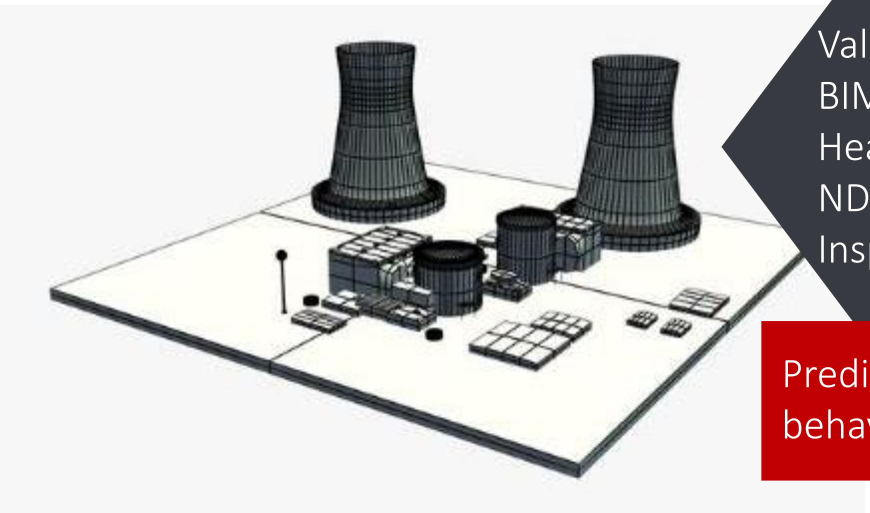


Patterson EA, Taylor RJ & Bankhead M, A framework for an integrated nuclear digital environment, *Progress in Nuclear Energy*, 87:97-103, 2016

Digital Environment

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

- ‘a series of interconnected, multi-scale, multi-physics computational models’



Validation data
BIM data
Health monitoring data
NDI data
Inspection data

Predictive performance / behaviour / outcomes

- Implementation dependent on closing technology gaps in
  - HPC developments in exascale
  - Innovation in measurement technologies
  - Development of data & model credibility, connectivity & integration

Advantages

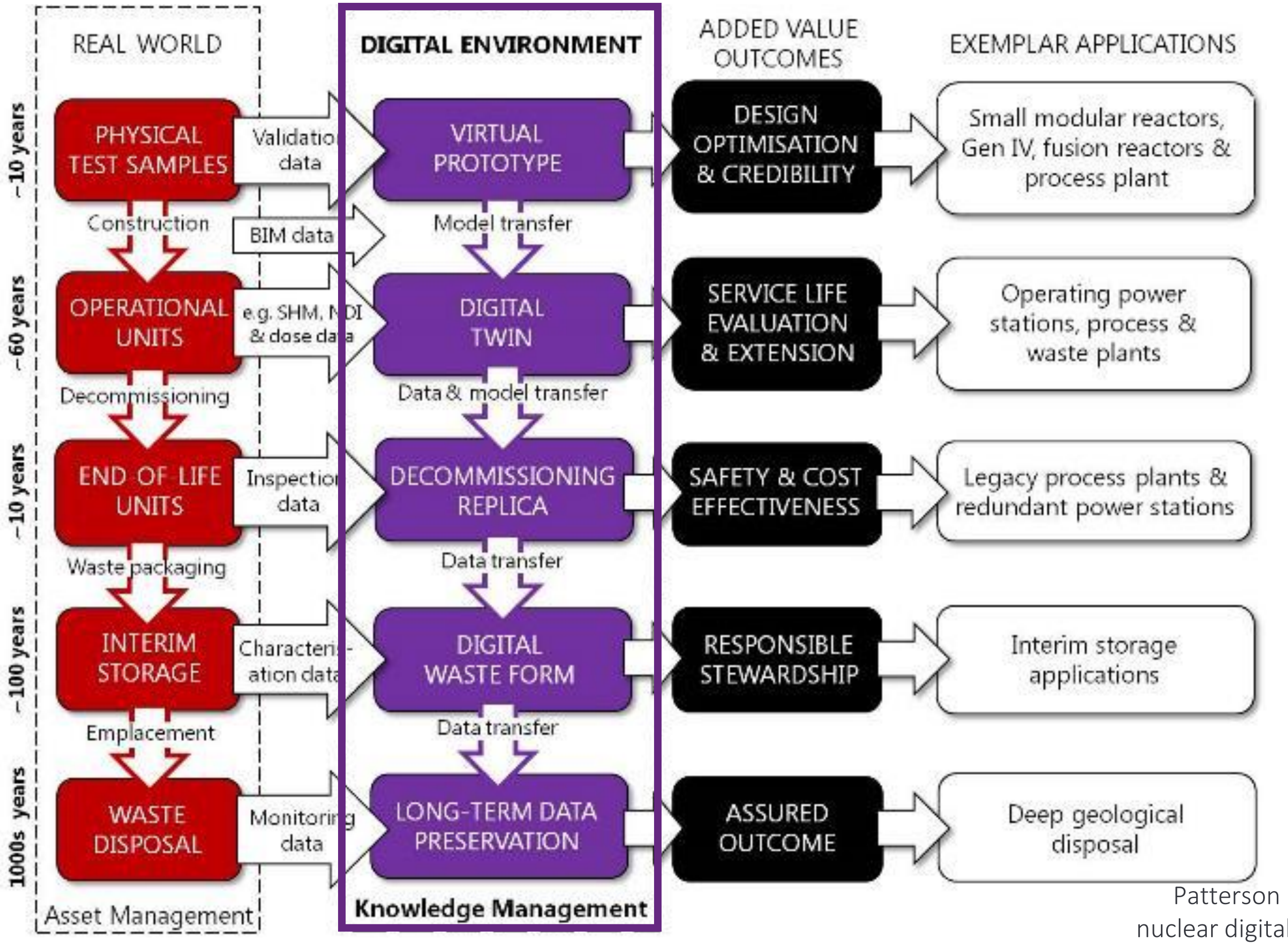
- Shortened development times
  - More reliable prediction of development times, allowing better synchronisation
  - Reduced risk and perception of risk

- Increased credibility, operability, reliability & safety
  - Directly & through enhanced training & skills development
  - Reduced risk and perception of risk

- Reduced costs
  - Shorter timescales for preliminary tests, development & licensing
  - Increased return on investment through efficient operation & maintenance
  - Limiting decommissioning costs to budget
  - Lower risk leading to reduction in financing costs
  - Improved public perception leading to more friendly operating conditions

Integrated Nuclear Digital Environment

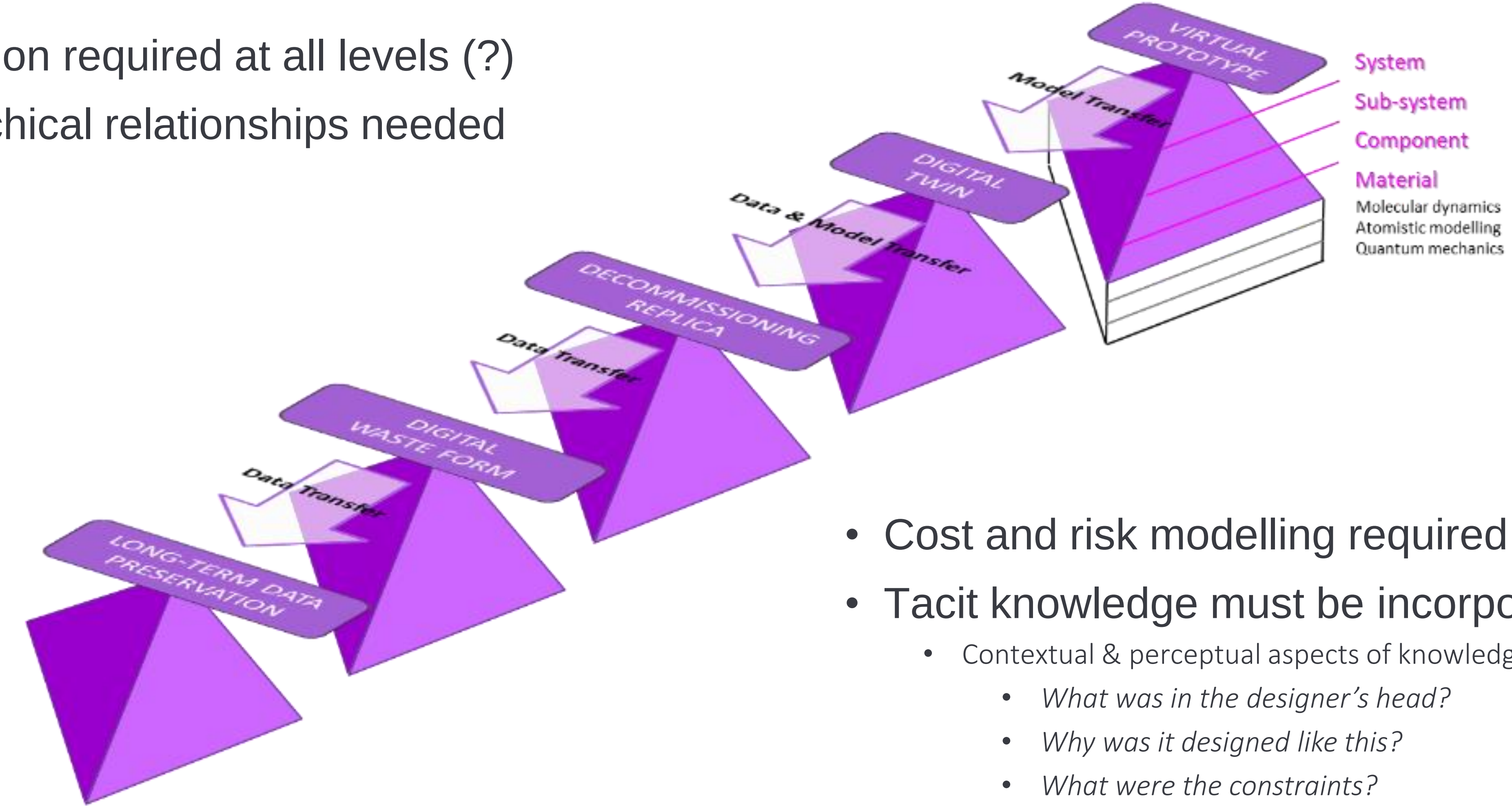
INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME



Patterson EA, Taylor RJ & Bankhead M, A framework for an integrated nuclear digital environment, *Progress in Nuclear Energy*, 87:97-103, 2016

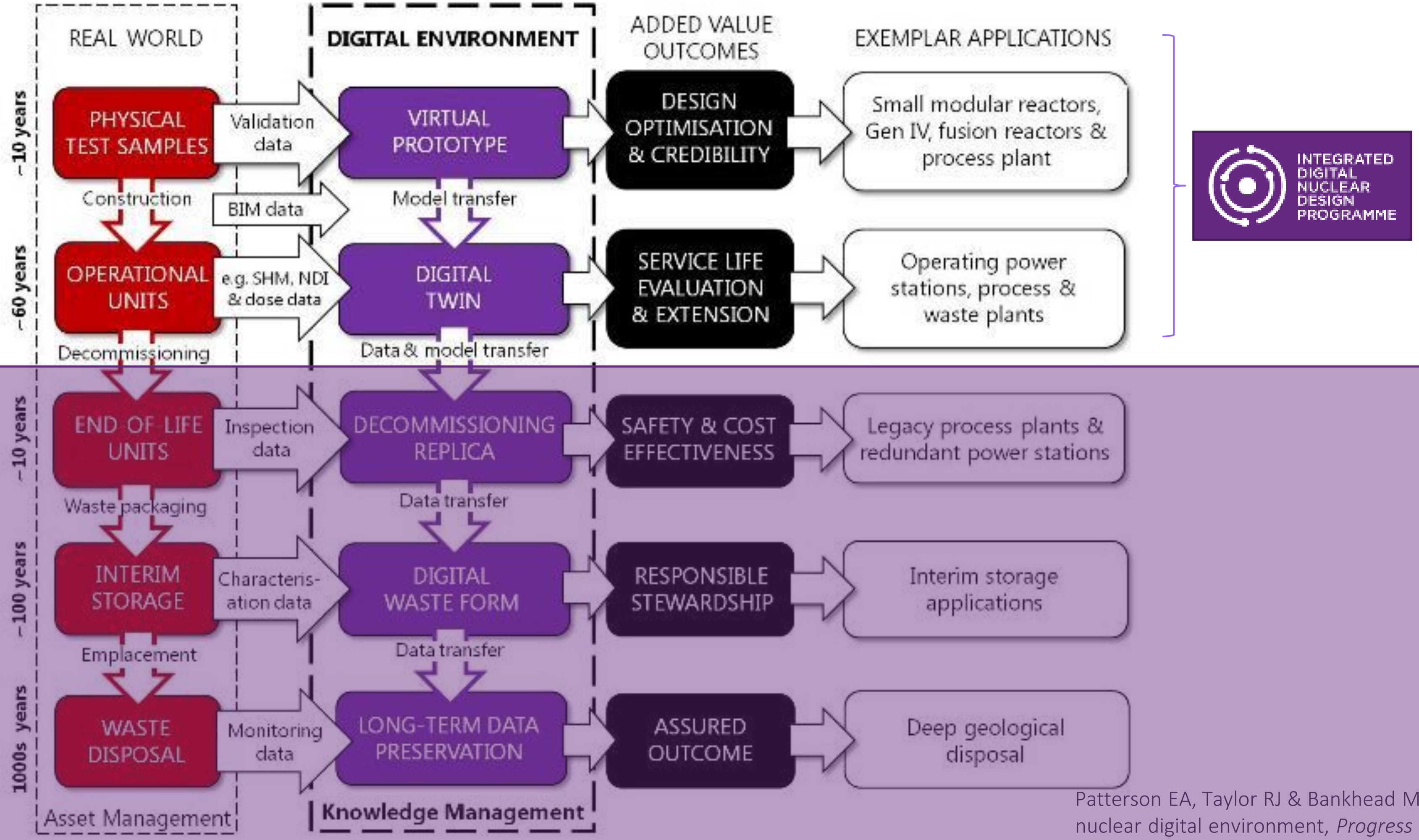
Interconnected hierarchical models

- Validation required at all levels (?)
- Hierarchical relationships needed



- Cost and risk modelling required
- Tacit knowledge must be incorporated
  - Contextual & perceptual aspects of knowledge & understanding
    - *What was in the designer's head?*
    - *Why was it designed like this?*
    - *What were the constraints?*

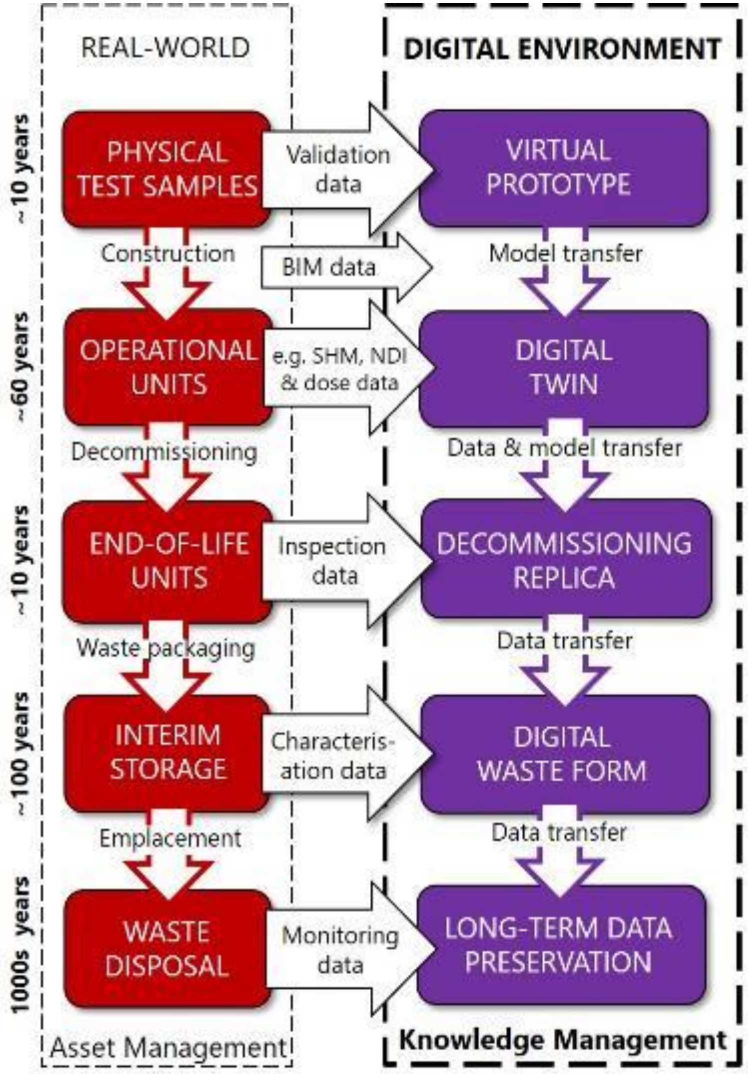
Integrated Nuclear Digital Environment



Patterson EA, Taylor RJ & Bankhead M, A framework for an integrated nuclear digital environment, *Progress in Nuclear Energy*, 87:97-103, 2016

INDE relationship to other work

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME



- Current efforts in nuclear industry include FAST and CASL (Lu et al, 2011)
  - not comprehensive digital environment that is multi-scale in both spatial & temporal domains
- BIM available for new build (Volk et al 2014)
  - Implementation via augmented reality (Wang et al 2014)
- Slow adoption of SHM in nuclear industry
  - Recent first reported use of fibre monitoring system (Mikel et al 2014)
- More advanced in use of NDE
  - particularly concrete structures (Wiggenhauser & Naus 2014)
- Decommissioning processes frequently simulated without continuity of virtual representation (Jeong et al 2014)
- Long-term data preservation implemented over 3 decades in JET (Layne et al 2012)
  - Need to achieve two order of magnitude longer preservation times

Patterson EA, Taylor RJ & Bankhead M, A framework for an integrated nuclear digital environment, *Progress in Nuclear Energy*, 87:97-103, 2016

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

Potential Benefits of an Integrated Nuclear Design Environment

The point of view of the end user based on three “Proofs of Concepts”

Erwan Galenne – Head of R&D Nuclear, EDF Energy R&D UK Centre

Nuclear lifecycle

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

EDF Energy and EDF Group are involved in all phases of the lifecycle

➔ *3 examples to illustrate the value of an Integrated Digital Nuclear approach*

Design | Procurement | Manufacturing / Construction | Operation | Decommissioning

AGR Boiler Spine Digital Twin

Containment Building Digital Twin

HPC 3D/ 4D models

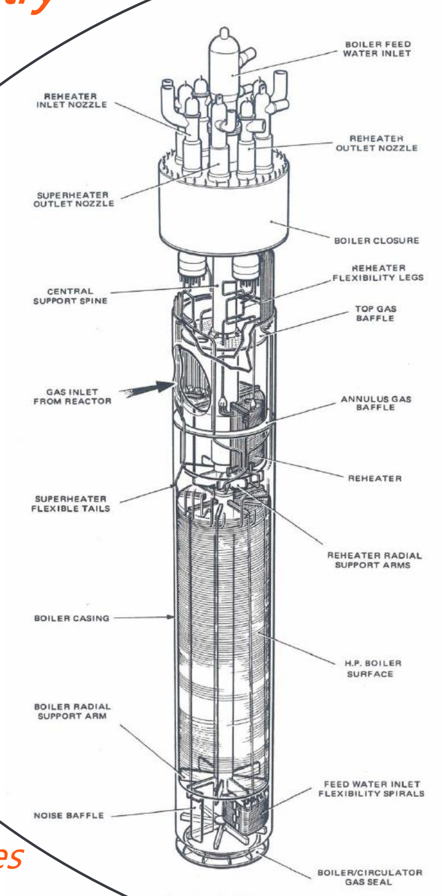
AGR Pod Boiler Spine Digital Twin (EDF Energy)

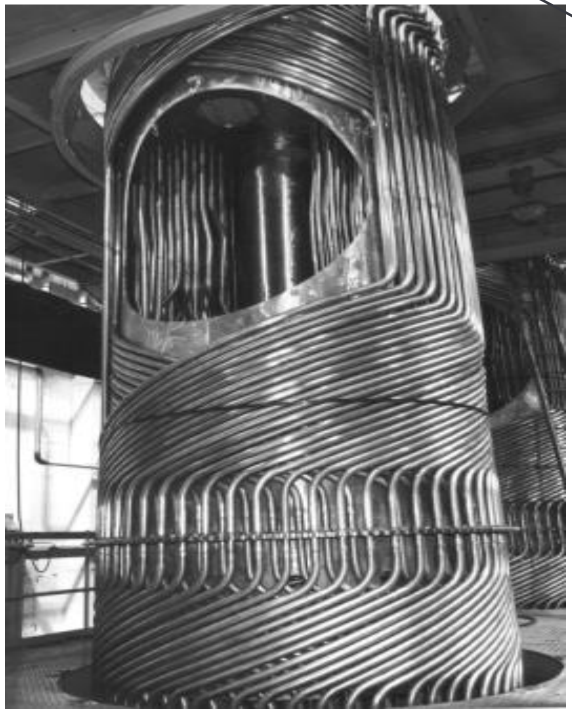
INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

Complex Geometry
- *10m structure*
- *>700 pipes*

Multi-scale
e.g. manufacturing imperfections, turbulent boundary layer flow around tubes

Multi-Physics
- *Primary Gas flow*
- *Secondary steam flow*
- *Heat transfer with structures*





Multi-tools
- *Legacy engineering tool (1D)*
- *Advanced CFD tool*
- *Thermal tool*

Different parameters of interest
- *Temperature at welds (creep, stress corrosion cracking)*
- *Impact of carbon deposition*
- *Impact of tube blanking*

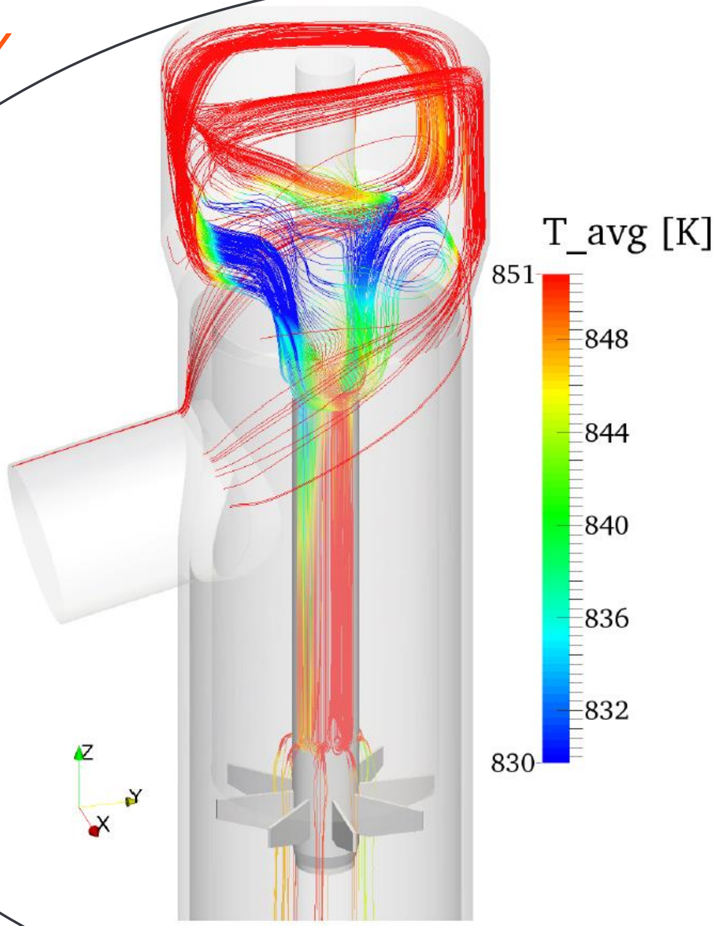
AGR Pod Boiler Spine Digital Twin (EDF Energy)

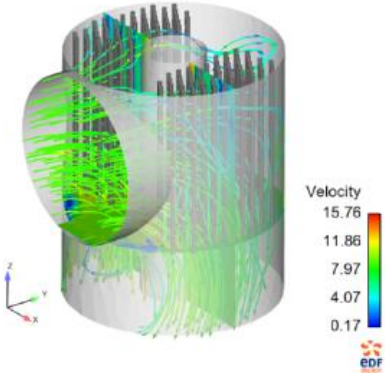
INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

Complex Geometry
- *10m structure*
- *>700 pipes*

Multi-scale
e.g. manufacturing imperfections, turbulent boundary layer flow around tubes

Multi-Physics
- *Primary Gas flow*
- *Secondary steam flow*
- *Heat transfer with structures*





Multi-tools
- *Legacy engineering tool (1D)*
- *Advanced CFD tool*
- *Thermal tool*

Different parameters of interest
- *Temperature at welds (creep, stress corrosion cracking)*
- *Impact of carbon deposition*
- *Impact of tube blanking*

AGR Pod Boiler Spine Digital Twin (EDF Energy)

- Value of the approach
  - By a multi-scale / multi-physics approach (validated against plant data), it gives access to parameters that were not known previously (scarce instrumentation)
  - Uncertainty quantification
  - Support to safety cases for life extension

- Gap (i.e. what is missing / what INDE could bring)
  - Increasing speed to development with an integrated platform rather than ad-hoc approach (5 years for a full-time expert engineer for this project)
  - Quality Assurance

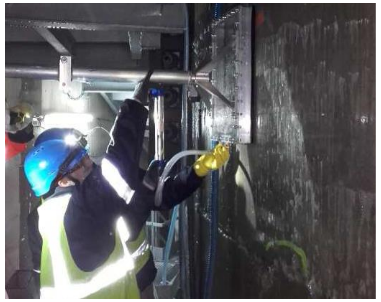
Containment Building Digital Twin (EDF France)

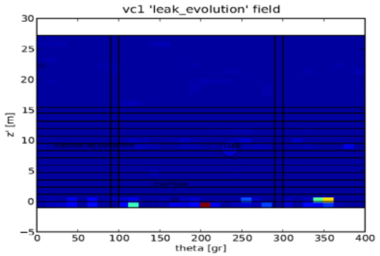
Vercors mock-up (Scale 1:3)

+

Monitoring data (500 sensors, 2km of fiber optic)

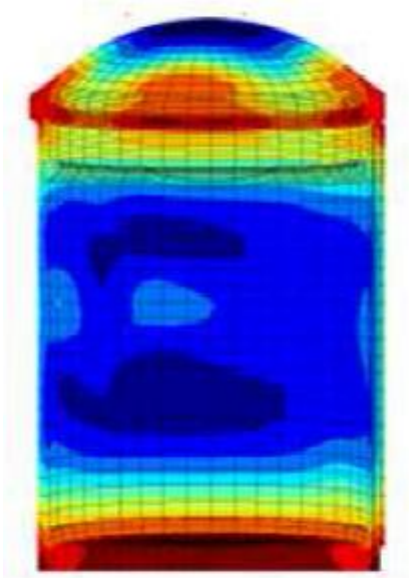
+





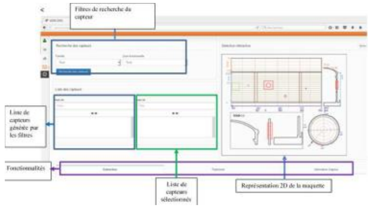
Surveillance data (leak rates during pressure tests)

+



Numerical models
Creep, drying of the concrete, cracks…

+



User-friendly interface

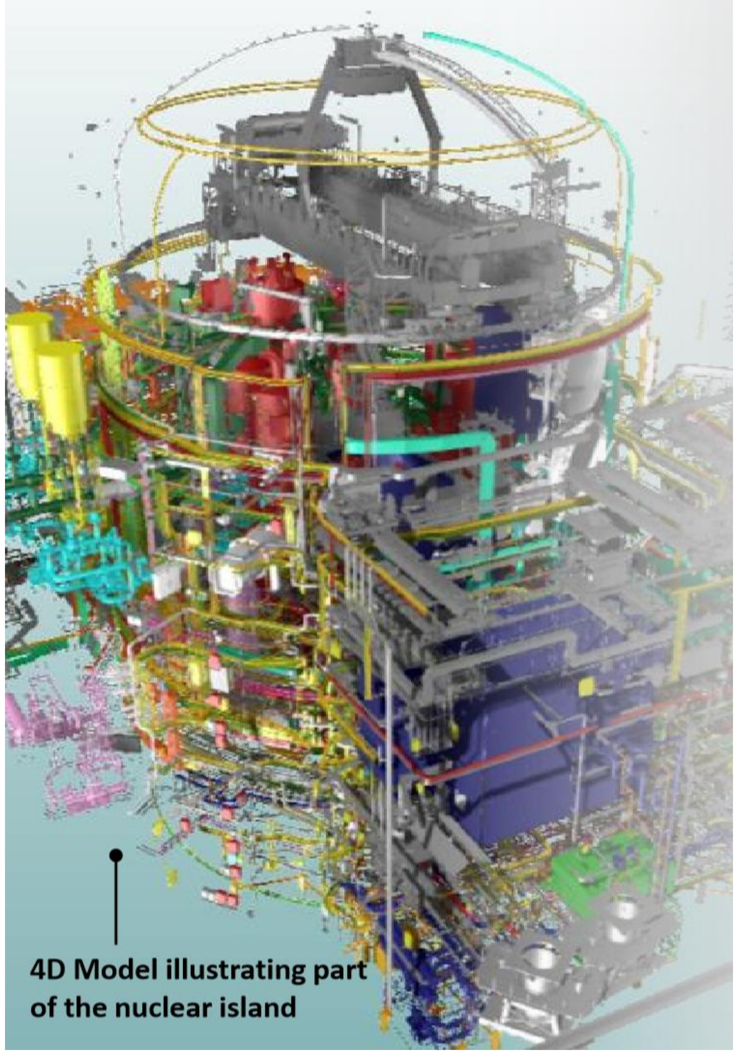
Containment Building Digital Twin (EDF France)

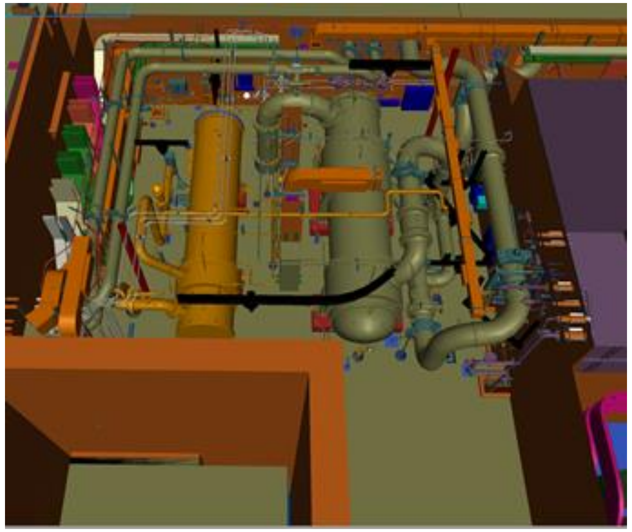
- Value of the approach
  - Bring different communities together (modelers, material, NDE…)
  - User-friendly interface, accessible both to researchers and engineers
  - Knowledge management / knowledge transfer tool
  - Communication

- Gap (i.e. what is missing / what INDE could bring)
  - This project has been developed in a research context
  - Extension to more complex environment: more stakeholders, more partners…
  - Extension of the principles to other physics of interest for 'real' reactors

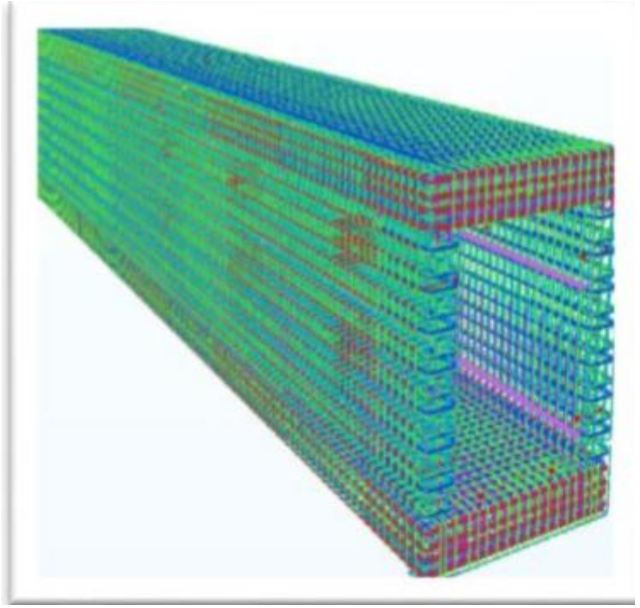
Hinkley Point C 3D / 4D Models

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME





Bespoke MEH (Mechanical, Electrical, HVAC) 4D modelling



3D modelling for rebars (design, identification of clash, procurement)

Hinkley Point C 3D / 4D Models

- Value of the approach
  - Early identification of clash, reduction of the risk in construction
  - Common tools for the Responsible Designer / Licensee / Contractors
  - Communication tool
  - Knowledge capture

- Gap (i.e. what is missing / what INDE could bring)
  - Extension from CAD / BIM to numerical models
  - Evolving the tool from as designed to as built and as operated

Project Aims and Concept

Dave Bowman – Technical Lead, Virtual Engineering Centre

Aims

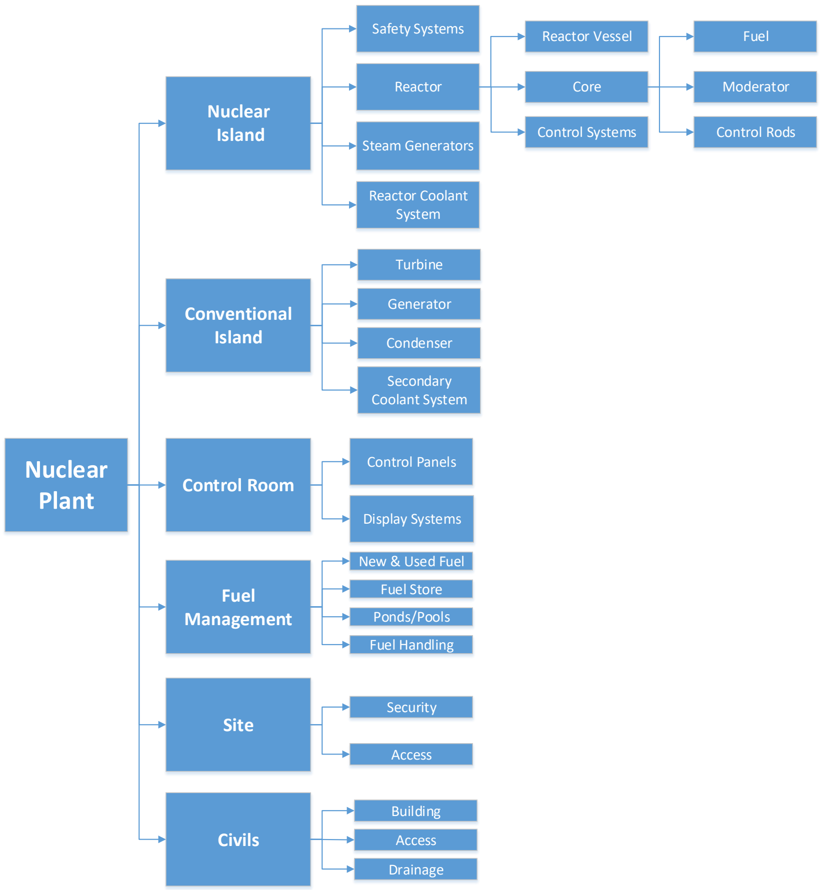
INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

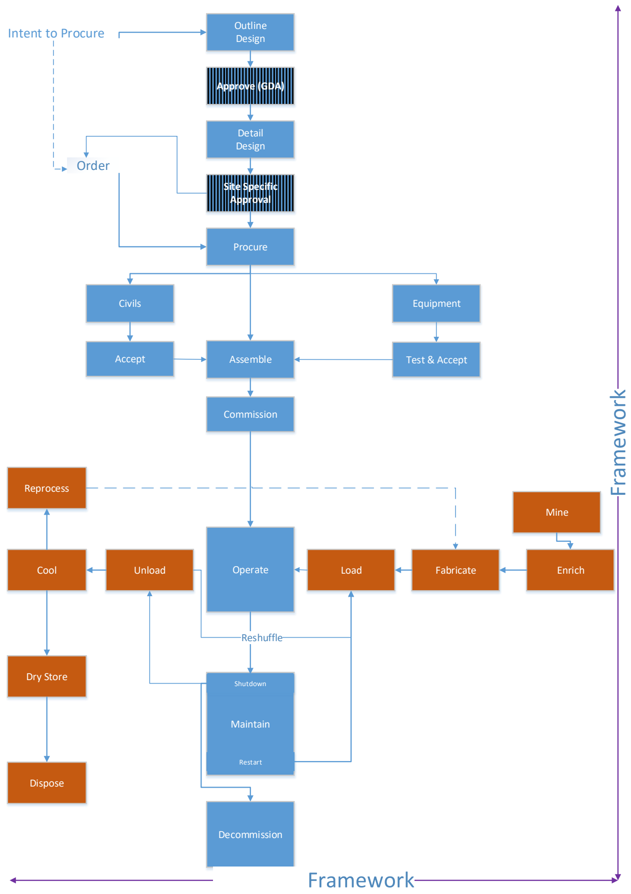
- Improve Reactor Design Process by using Digital Tools Effectively
    - Define and establish a ‘Framework’
    - Whole Plant
    - Iterate faster and/or more frequently
- Reduce Risk and Cost
    - Credibility
    - Communication
- Take Integrated View – Systems and Organisations
    - Communication
    - Knowledge Retention
    - Optimisations

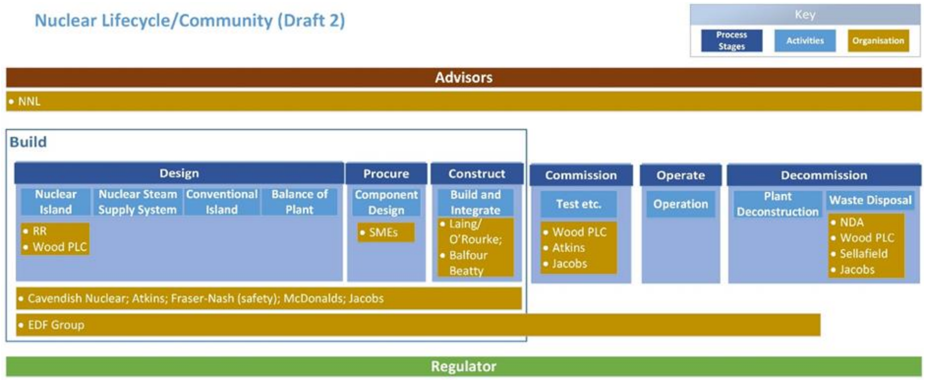
Calculations, Analyses and Data

- Current process
  - Prepare Data/ **Set up Calculation**
  - Run **Calculation**
  - Review
  - Pass all data to next calculation
  - Repeat until end calculation set (=analysis)
- Project approach
  - Understand **Analyses**
  - Understand Data
  - Define common and static data
  - Define variable data
  - **Set up Analysis**
    - Use common and static data once as initial conditions
      - Run **Analysis** with variable data
      - Review
      - Repeat
- Use HLA and toolkit to
  - Establish federation set
  - Pass and record data
  - Manage timings
  - Etc.

Base Diagrams



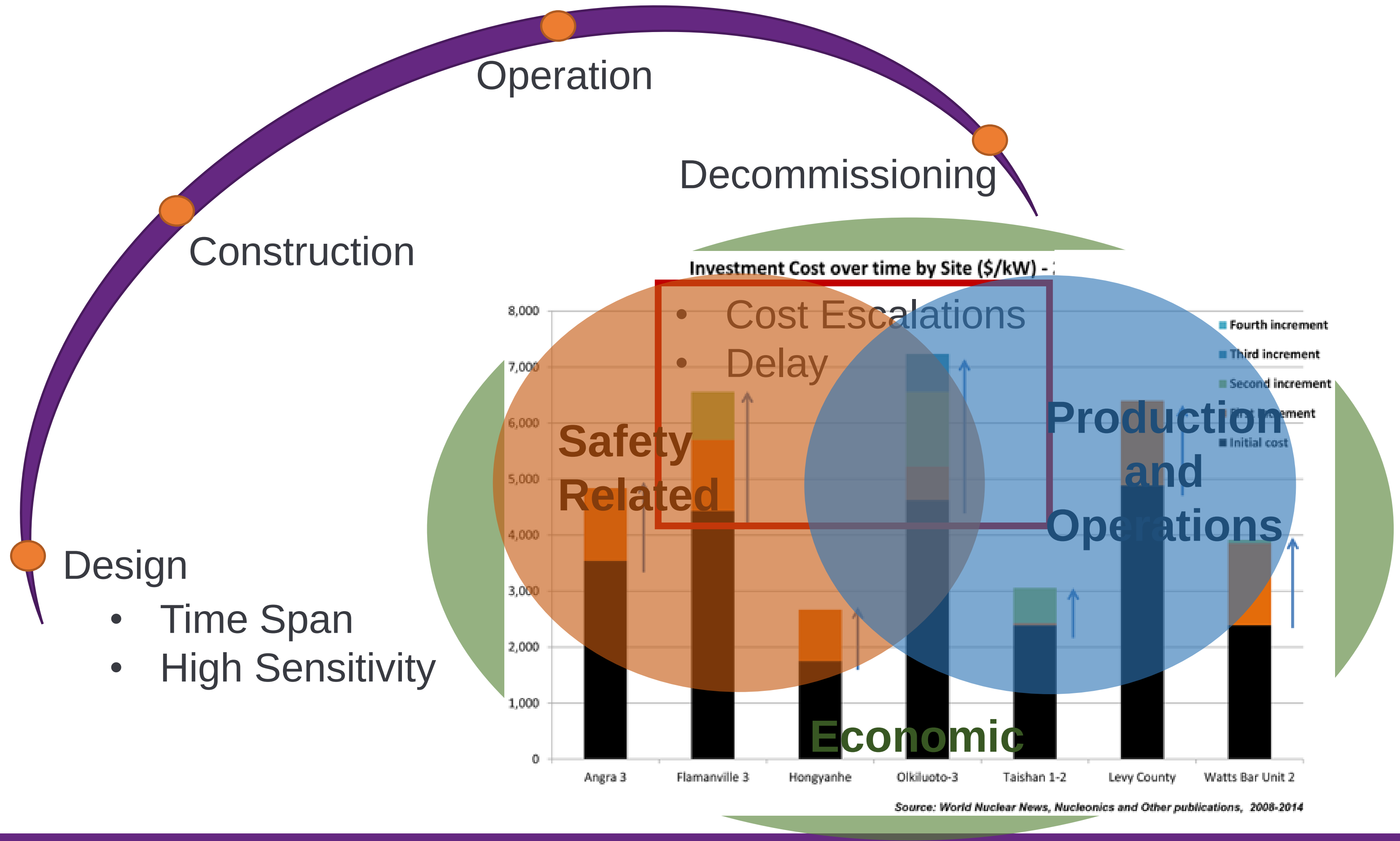




Risk and the Nuclear Industry

Silvia Tolo – University of Liverpool

Risk and the Nuclear Industry



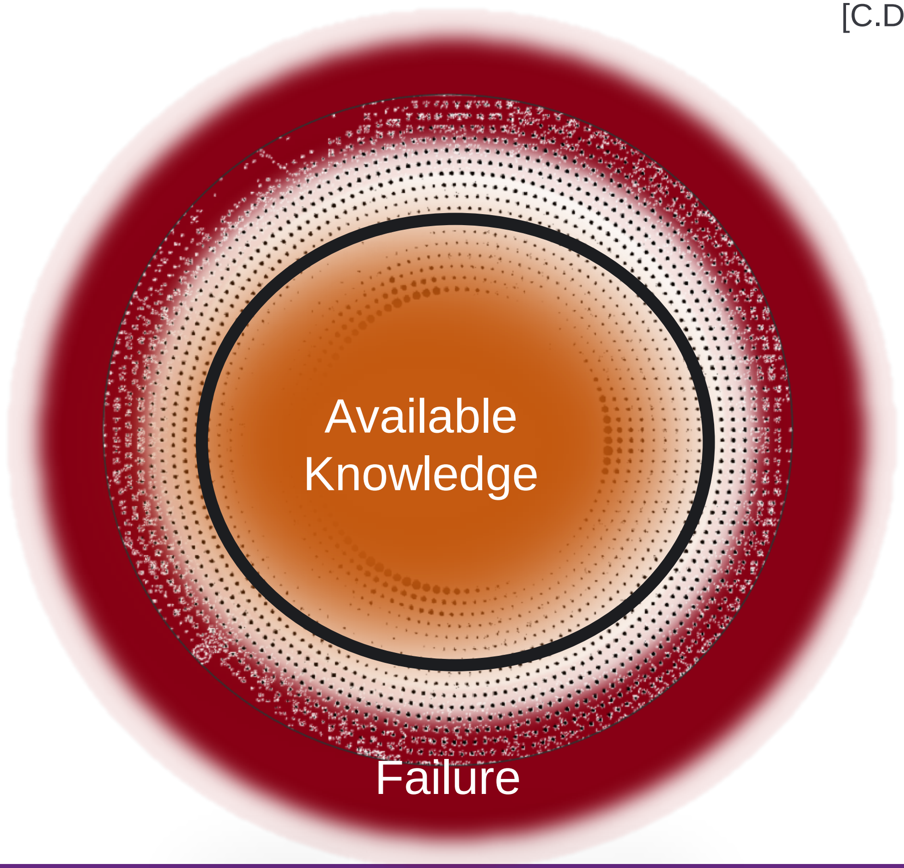
Measuring Risk

*“The question of nuclear power risk acceptability can only be answered in an economic context where the potential benefits of the technology are clearly weighed against the risks, both financial and otherwise, in an **unbiased**, **rational manner**”*

[C.D. Heising and V.P. George, 1986]

RISK

CONSEQUENCE X LIKELIHOOD

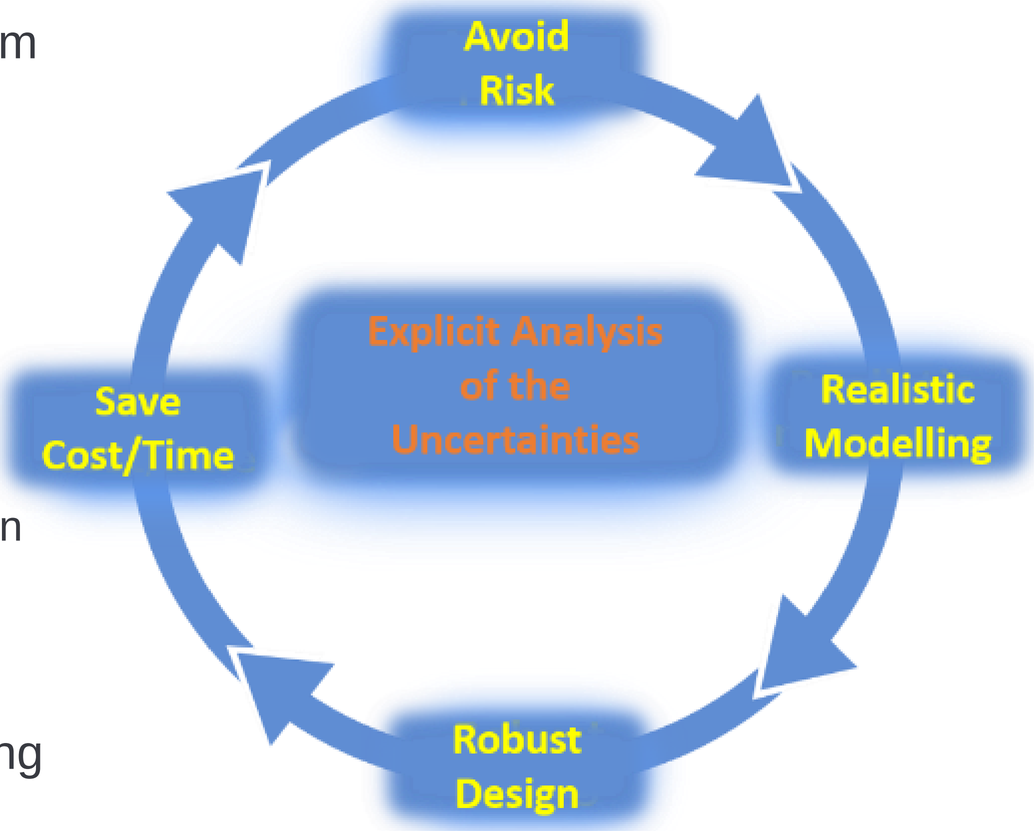


- Conservative Approach
- Minimum assumptions
- Strong Assumptions
- **Unknown level of conservatism**

- Realistic Representation
- Precise Models
- (Unbiased) Assumptions
- Quantification of accuracy

Uncertainty Quantification Tool

- Better understanding of the system
  - How much robust is it?
  - Can we enhance it (in the most efficient way)?
- Increase model credibility
  - What accuracy can I have in output given what I know?
- Fully risk-informed decision making
  - How much can I trust the response?
  - How uncertain is it?



Integrated UQ cutting-edge tool:

Uncertainty Characterization

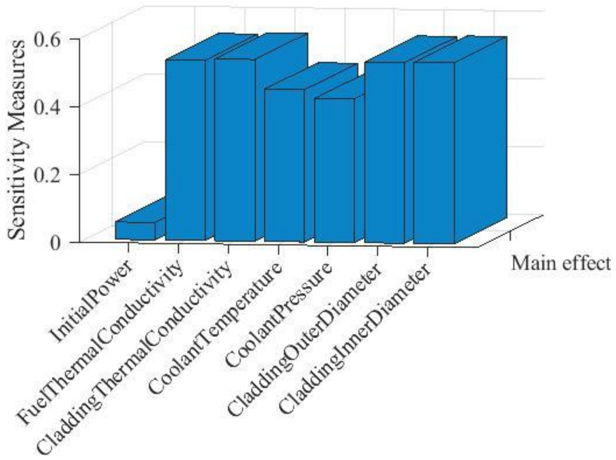
Sensitivity Analysis

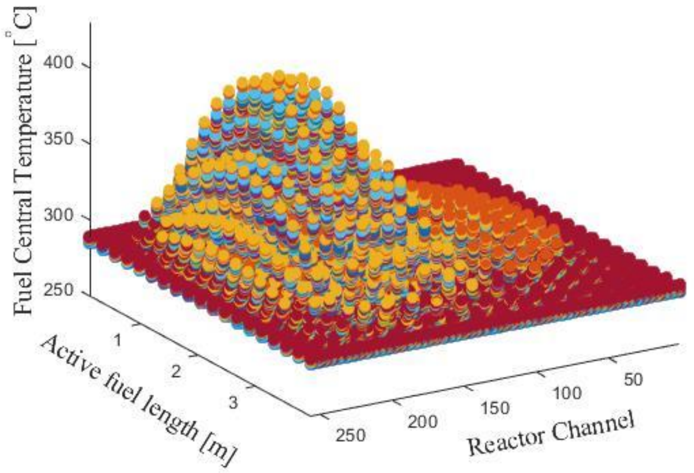
Reliability Analysis

Surrogate Model Implementation

Model Validation

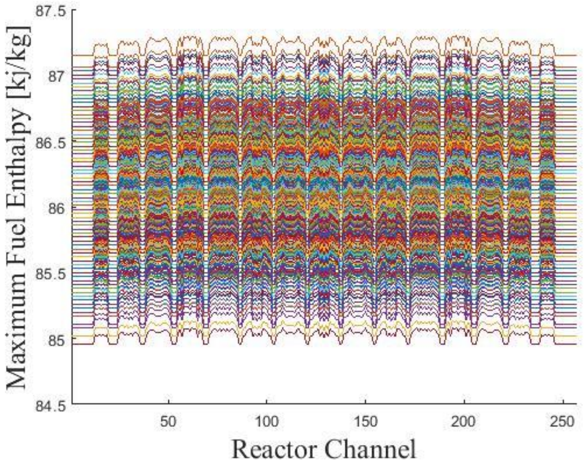
Application

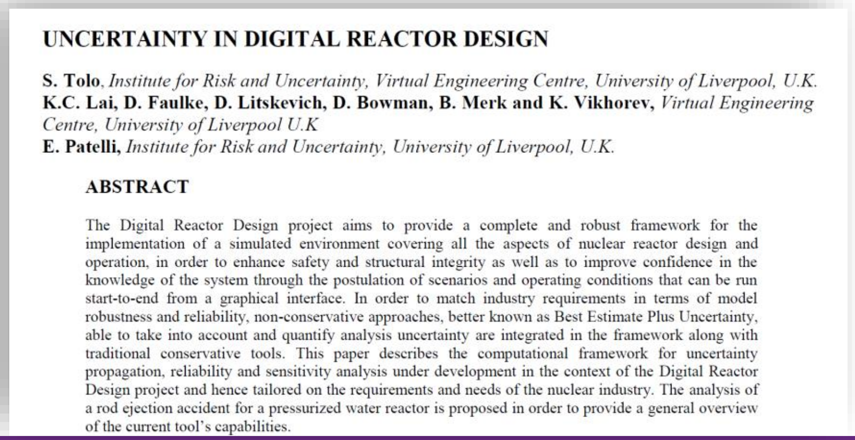




Random Variables	Mean	STD
Initial Power [MW]	3.565	0.02
Coolant Temperature [°C]	286.85	1.15
Coolant Pressure [MPa]	15.5	0.075

Interval Variable	Lower Bound	Upper Bound
Cladding Outer Diameter [mm]	9.146	9.186
Cladding Internal Diameter [mm]	7.820	8.220
Fuel Thermal Conductivity [W/m*K]	3.9	10.1
Cladding Thermal Conductivity [W/m*K]	12.7	18.1




UNCERTAINTY IN DIGITAL REACTOR DESIGN

S. Tolo, *Institute for Risk and Uncertainty, Virtual Engineering Centre, University of Liverpool, U.K.*
K.C. Lai, D. Faulke, D. Litskevich, D. Bowman, B. Merk and K. Vikhorev, *Virtual Engineering Centre, University of Liverpool U.K*
E. Patelli, *Institute for Risk and Uncertainty, University of Liverpool, U.K.*

ABSTRACT

The Digital Reactor Design project aims to provide a complete and robust framework for the implementation of a simulated environment covering all the aspects of nuclear reactor design and operation, in order to enhance safety and structural integrity as well as to improve confidence in the knowledge of the system through the postulation of scenarios and operating conditions that can be run start-to-end from a graphical interface. In order to match industry requirements in terms of model robustness and reliability, non-conservative approaches, better known as Best Estimate Plus Uncertainty, able to take into account and quantify analysis uncertainty are integrated in the framework along with traditional conservative tools. This paper describes the computational framework for uncertainty propagation, reliability and sensitivity analysis under development in the context of the Digital Reactor Design project and hence tailored on the requirements and needs of the nuclear industry. The analysis of a rod ejection accident for a pressurized water reactor is proposed in order to provide a general overview of the current tool's capabilities.

Digital Reactor Design: Delivery Strategy and Progress

Integrated Nuclear Digital Environment (INDE)

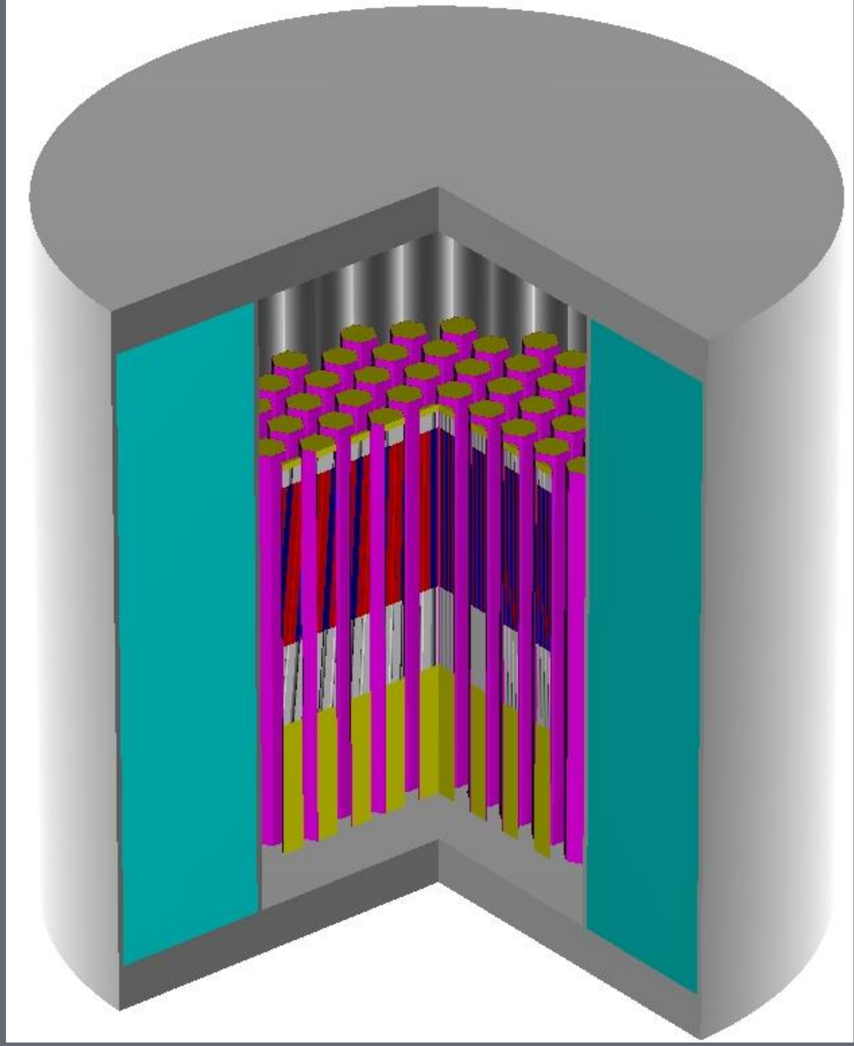
Dr Ahmed Aslam,

Project Technical Lead.

Wood

Mark Bankhead, NNL

Technology Manager for Modelling & Simulation and HPC

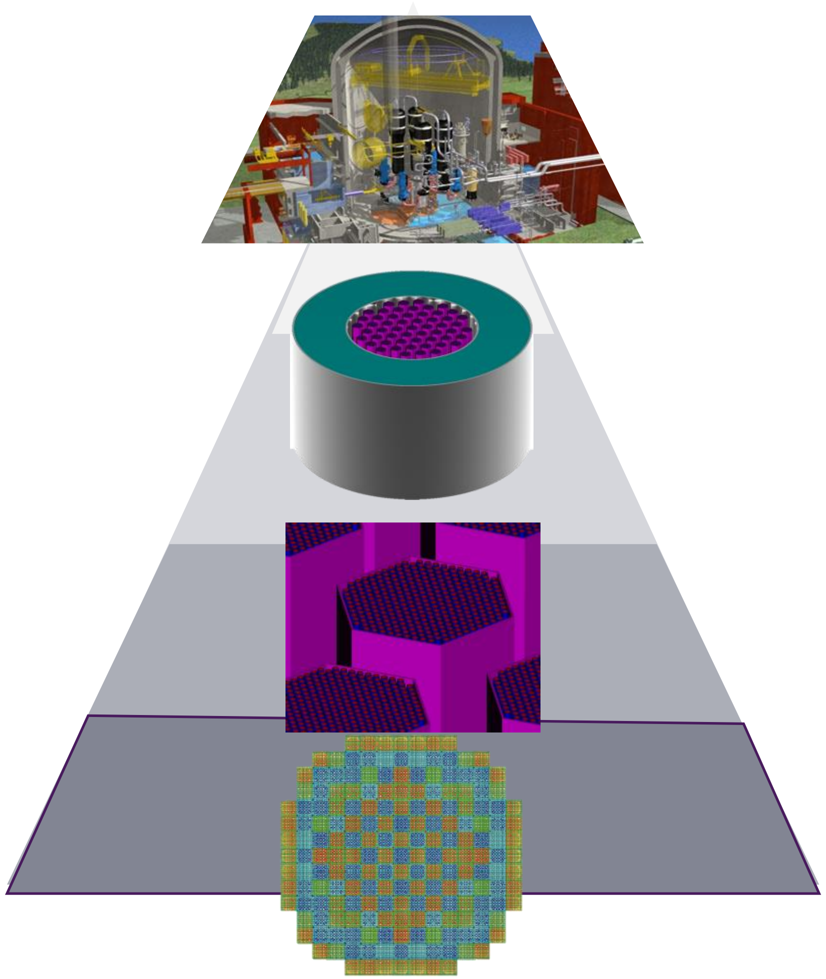


Commercial

Integrated Nuclear Digital Environment (INDE)

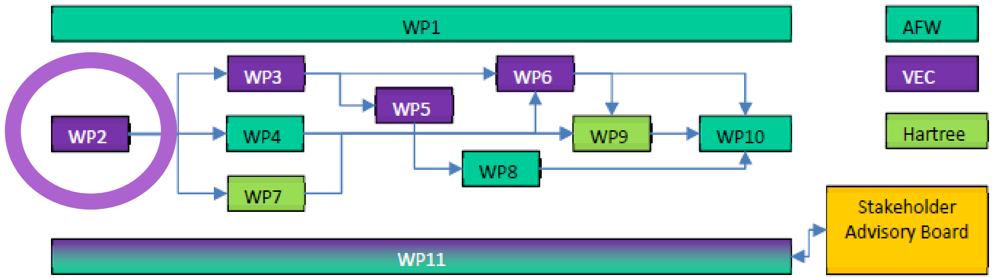
INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

- Multi-scale, multi-physics computational models
- Distributed simulation network
- Integration of HPC, Virtual Reality, simulation codes
- Visualization of simulation results (local and remote)
- Real-time collaboration between participants



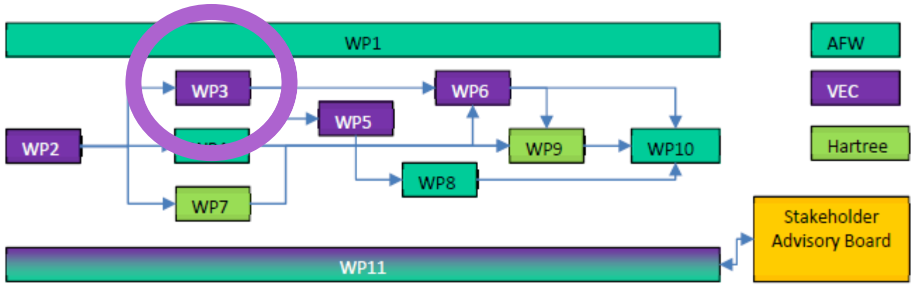
Workshops (WP2)

- Workshop 1: consortium partners only; discussion of Use Cases
- Workshop 2: ONR, SL and NDA; interface with industry and the GDA process
- Workshop 3: representatives from the wider nuclear industry



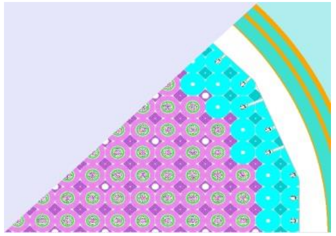
WP3 Capability mapping

- Understanding of current industry position + capabilities of international partners
- Key Outputs – Requirements specification
  - Be capable of being used across the whole lifecycle of a nuclear plant and cover all systems (not just core)
  - Enable proprietary computer codes to be used without loss of IP or data security
  - Open to allow for collaboration (industry, academia and SME's)
  - Flexible in terms of codes and methods
  - Support many reactor types
  - Ease of use



Use Cases (WP4)

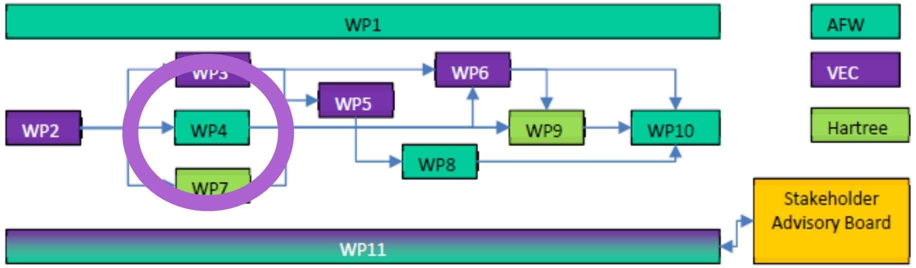
- Proof of concept to be demonstrated with ‘Use Cases’



Core slice model of neutron damage of graphite

- AGR Case: Whole life cycle graphite weight loss and structural analysis

- PWR Case: reactor system response to the ejection of a control rod



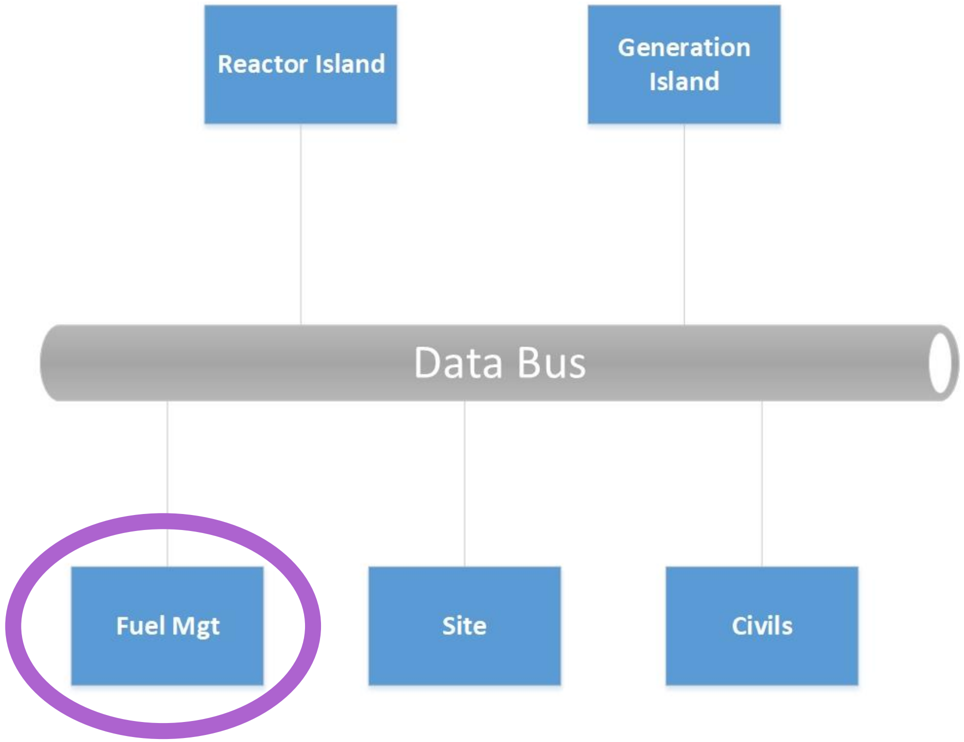
Ongoing activities: Development and Testing

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

- Demonstration of integration of diverse codes and data transfer between modules
  - On-going development on the framework to implement initial requirements
  - Integration of AGR Use case initiated
  - PWR Use case under development and close to completion
- Demonstration of current visualisation capabilities

Ongoing Activities: International Collaboration

- International collaboration is an important aspect of the programme
  - LFE to accelerate development of UK codes
  - Opportunity to exploit UK IP in international markets
- Collaboration with CASL through ORNL
  - Workshop planned for September 2018 to discuss collaboration themes
- Engagement with EDF on SALOME platform



CASL VERA / SALOME

Commercial

INTEGRATED DIGITAL NUCLEAR DESIGN PROGRAMME

Culture - a “new to industry” perspective

Lynn Dwyer - Head of Commercial, Virtual Engineering Centre

Our Learning

- Common language, organisational specific meaning
- Anticipated more process alignment with other domains
- Demographic impact on sector knowledge
- Communication
- Industry structure
- Siloed approach to “collaboration”
- Positive safety culture, risk averse – implications
- An appetite for increased digital adoption and innovation
- Open approach of regulator

Potential framework benefits

- Interoperation will enhance communication and meaning
- Greater opportunity for more alignment across sector
- Skills and knowledge retention enhanced, new training methods
- A common platform to enhance communication
- Necessitates understanding of process as well as output
- Earlier awareness of impact of decisions to other process stages
- Reduced risk through better optimisation, whilst maintaining sufficient levels of safety
- Promotes innovation by offering flexibility of operation and throughout supply chain
- Supports the regulatory environment

Keep in touch

- Planned open industry event – Sci Tech Daresbury - potentially 5th July

- Website www.digitalnucleardesign.com

- Direct