Qualification of the Pickering A Test Facility

Workshop on Digital Twin Applications for Advanced Nuclear Technologies

Richard Henry (OPG), John Sladek (CNSC) | 1-4 December 2020

ONTARIO POWER GENERATION | Where a brighter tomorrow begins.

Overview

1 | What is the Pickering A Test Facility (PATF) and how is it used?

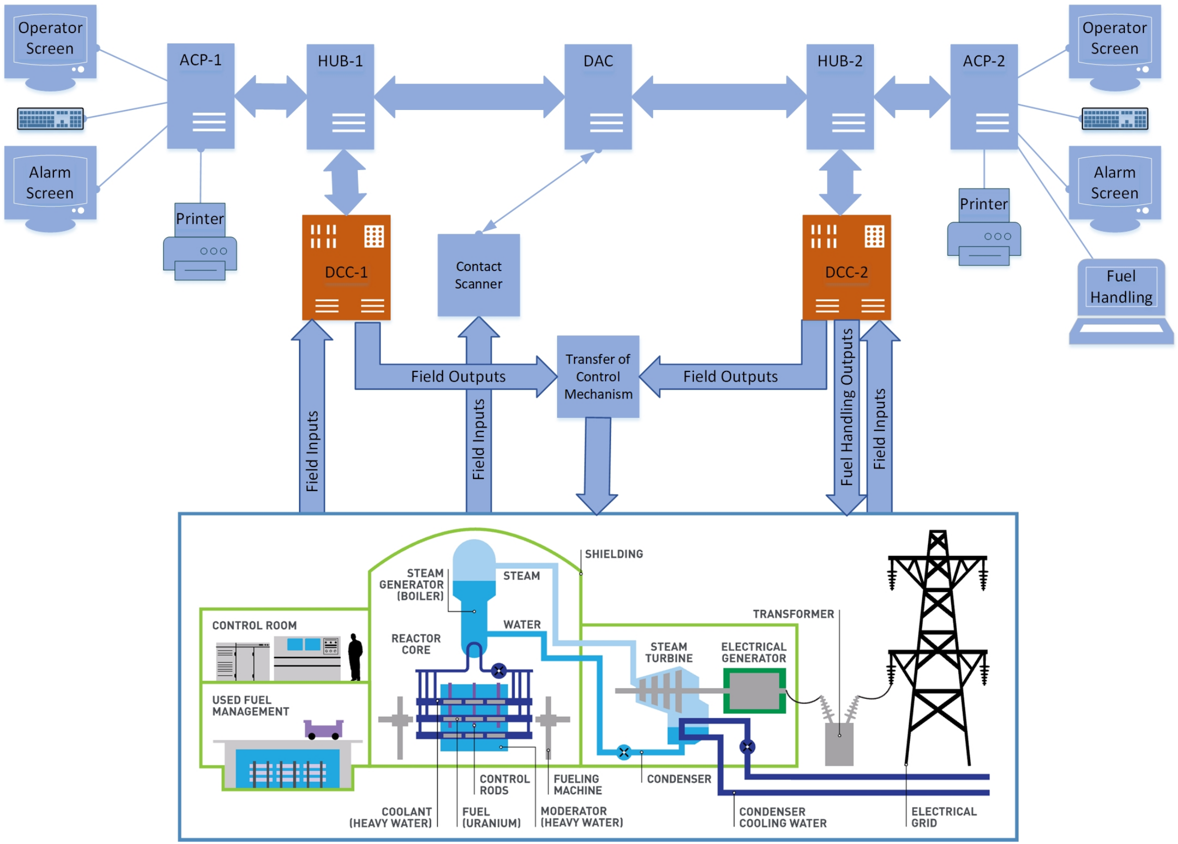
2 | What are the regulatory requirements and process for qualification of Software Tools?

3 | How was the PATF qualified?

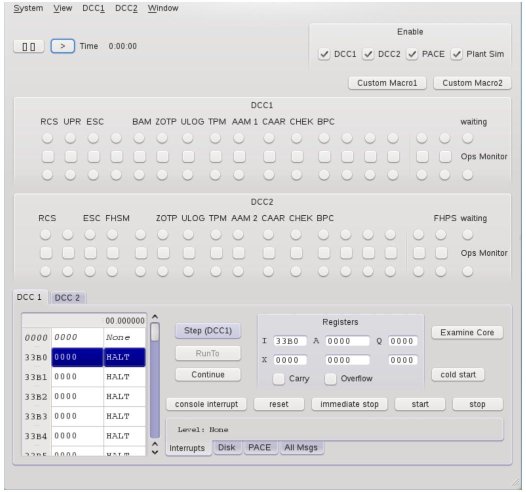
Context

- Pickering A 4x540 MW CANDU Pressurized Heavy Water Reactors
  - Placed in service 1971-73. Currently two units in service. Two units in safe store.
- Digital Control Computers (DCC) control major plant processes (Reactor power, Boiler pressure, Online fuel handling)
- Obsolescence issues with legacy test facilities used for software Verification and Validation testing.
- A software-based test facility (digital twin) was developed.
- Qualified September 2011
- Followed existing qualification processes
- No new processes required

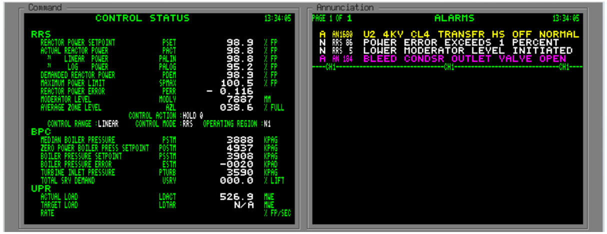
DCC System Context

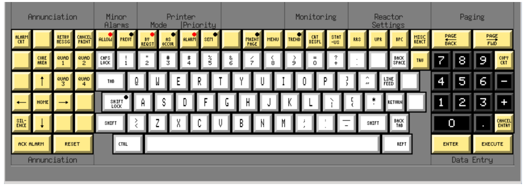


Pickering A Test Facility Overview

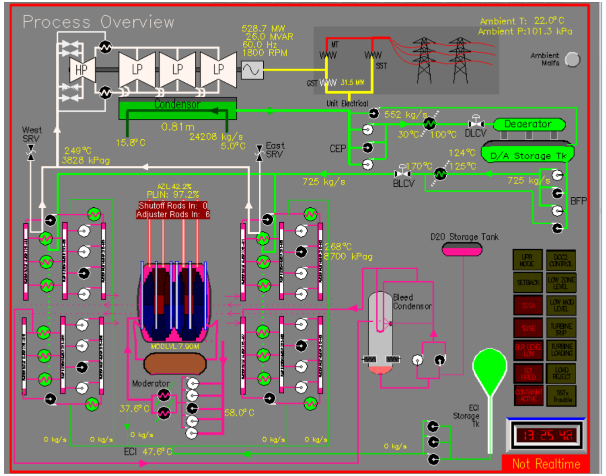


- High-fidelity DCC **Emulation**
  - Function and timing
  - Instructions, peripherals, process input/output, interrupts





- **Simulated** Operator Human Machine Interface
  - Annunciation computer, keyboard and displays
  - Control room panels
- Contact alarm scanner



- Plant **Simulation**
  - Process models
  - Simulated relay logic
  - Simulated stand-alone devices (e.g., PLCs, digital meters)

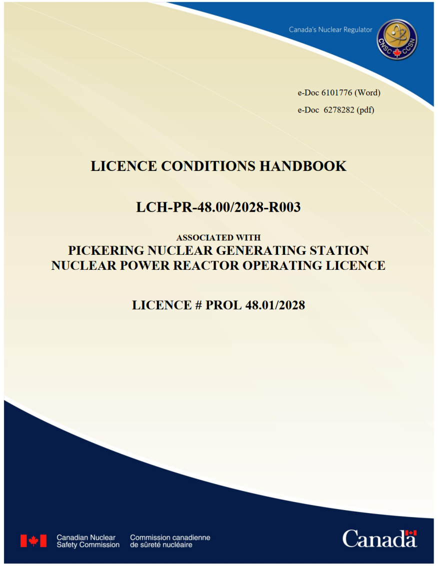
Test Execution for V&V Activities

- **Software engineering tool** used within the development lifecycle
- Test execution controlled by scripting language (Python)
  - Able to control DCC, simulation, etc.
  - Can simulate operator actions (keyboard, panel switches)
  - Can override simulation with substitute values
  - Observe/record process parameters or internal DCC states
- Save and restore "storepoints"
  - Available for all major plant modes of operation (0%-100%FP)
  - Process model state
  - Internal DCC state (memory, disk, registers)
- Allows for development of fully-automated repeatable tests
- Useful for training new staff in DCC fundamentals
- Scenario based analysis of control algorithm changes

```
# Restore 100% full power storepoint
restore('/home/patf/storept/FPSS_ibm1800.stp')
# Set Digital Input 0x41, bit 10 on DCC1 off
# Set Digital Input 0x41, bit 10 on DCC2 off
dcc1.di[0x41].b10=0
dcc2.di[0x41].b10=0
# Print simulated reactor neutron power
print "Starting Power: ", getcdb ('RNTPOW')
# On ACP1, pull up the RRS display and
# decrease reactor power by 10% at rate 3
pace.acp1.keypress("<RRS>")
pace.acp1.keypress("RD3<ENTER><EXECUTE>")
# Run for 30 seconds
run_for (seconds=30.0)
# Print simulated reactor neutron power
print "Ending Power:", getcdb ('RNTPOW')
# Print DCC1 Analog Input @Address /1D01
# in ADC counts and eng. units
print dcc1.ai[0x1D01], dcc1.ai[0x1D01].eng
# Display core location 0x1800
print dcc1.core [0x01800]
# Print dcc registers A, Q and I
print dcc1.a, dcc1.q, dcc1.i
```

Regulatory Requirements for Software QA

- The Pickering Nuclear Generating Station License and Condition Handbook (Effective 17 April 2020):
  - "The licensee shall implement and maintain a **management system**"
    - Licensing basis publication: CSA N286, NPP **QA Program Requirements.**
    - Compliance Verification Criteria include:
      - OPG N-CHAR-AS-002, *Nuclear Management System,*
      - OPG N-PROG-MP-0006, ***Software***
  - "The licensee shall implement and maintain a **design program**."
    - Guidance: N290.14, ***Qualification of Digital Hardware and Software*** *for Use in Instrumentation and Control Applications for Nuclear Power Plants*
  - "The licensee shall implement and maintain a **safety analysis program.**"
    - Guidance: N286.7, *Quality assurance of analytical, scientific and design computer programs for nuclear power plants*



Software Qualification

- N-PROG-MP-0006, *Software*, defines processes for all types of software including,
  - Software Engineering Tools follows OPG N-STI-69000-10002, *Qualification of Software Engineering Tools*
    - This is key to the qualification of PATF for the use case for V&V of software
    - Testing requirements based on categorization of **Target** software (RTPC or SESA)
  - Real Time Process Computing (RTPC). QA Requirements based upon software classification:

Organizations or Countries	Safety Classification of I&C Functions and Systems in nuclear plants			
United States	Systems Important to Safety			(not specified)
	Safety-Related	5		
Canada	Category 1	Category 2	Category 3	Category 4

http://www.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/safety-classification-for-iandc-systems-in-npps.pdf

- Scientific, Engineering and Safety Analysis (SESA) software follow CSA N286.7 QA requirements

N-STI-69000-10002

- Qualification requirements for software engineering tools:

  *Software engineering tools are those used to **<u>support any aspect of the software engineering lifecycle</u>**, including: requirements gathering and specification; design and code production; review and static verification of requirements, design and code; **<u>test case generation, execution, and results analysis</u>**; configuration management and change control; and training.*

- Method

1. Identify target software classification and categorization
2. Select tools
3. **Determine impact severity of tool failure**
4. **Determine mitigating circumstances**
5. **Select a qualification approach**
6. Perform qualification activities
7. Configuration management of software engineering tools
8. Software engineering tool qualification report

Determine Severity of Tool Failure

- Guidance: "Consider the failure modes for **each use** of the **software engineering tool**, and identify the relevant failure effects on the target software. Classify each failure effect based on its potential impact on the safety, functional, reliability, performance or security requirements of the target software."
- Classification Scheme:

Failure Type	Description
Direct	the tool is incorporated in the target application. Tool is to be considered pre-developed software and qualified to the same degree of rigor as the target software.
Indirect-Causal	Tool failure can introduce errors in the target software which if undetected could result in the target software failing to meet the above requirements.
Indirect-Preventive	A tool failure effect can result in the non-detection of errors in the target software which could result in the failure of the target software to meet the above requirements.
Minimal	A tool failure could have an impact on the target software but no mechanism has been identified that could result in the target software failing to meet the above requirements.
No Impact	A tool failure can have no impact on the target software in meeting the above requirements.

Identify and Classify Mitigations

- Identify any mitigations that eliminate or reduce the impact of the failure effect.
- Classify mitigations as one of the following:

Class	Description
None	
Single	**Single** reliable mitigating activity or procedure which defends against impact. Must be independent of the failure effect (efficacy of mitigation not diminished or nullified by the failure effect). **Examples**: Testing, review, checksum comparison
Multiple	**Multiple** reliable mitigating activities or procedures which defend against impact. Must be independent of the failure effect. Must be independent of each other (having no other common failure mechanism) **Example**: Review of outputs by two independent individuals using different methods.

Determine Qualification Approach

- Qualification grade is determined based upon:
  - **Target** software classification and categorization
  - Impact severity of tool failure
  - Mitigations
  - Result is: **NSR2, NSR3, O,** and **A**
- Qualification method is based on grade
  - **NSR2 / NSR3**: Follow RTPC Category II/III qualification method (e.g., CSA N290.14)
  - **A**: Follow SESA qualification method (e.g., CSA N286.7)
  - **O**: Select qualification method from. For example:
    - Acceptance testing
    - Widespread industry usage (for same purpose)
    - Operating history from third party

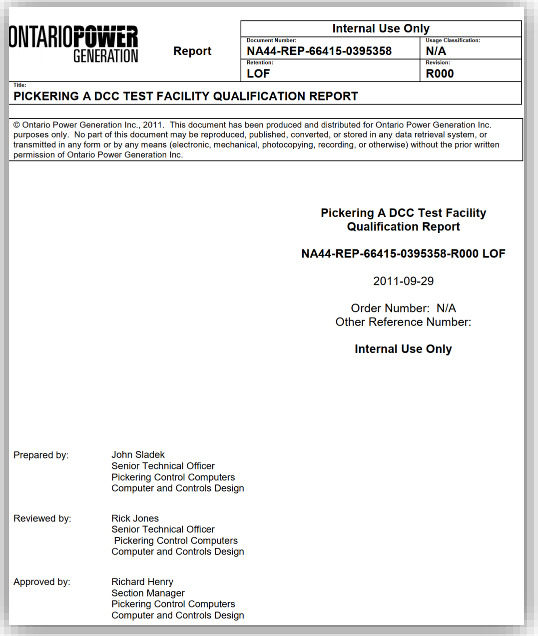
Results for PATF

- Target Software Classification and Categorization: System is used for testing of DCC software which is Categorized. → **Category 2**.
- Impact: failure of the software test tool could result in non-detection of errors in the target software. → **Indirect-Preventive**
- Mitigation:
  - Several sets of tests are performed by independent individuals (e.g., unit testing, subsystem testing, integration testing and validation testing)
  - However, some of these tests could all potentially make use of the PATF, so there could be a common failure in the mitigating activities. → **Single**
  - Qualification approach is "**O**" (as per lookup table)
  - Qualification method selected to be "Acceptance Testing"

Table 3.5-1 Qualification Grade				
Software Categorization and Classification	Impact of Failure Effect	Mitigating Circumstances		
		None	Single	Multiple
Nuclear Safety Related Category I	Direct	See Note below		
	Indirect-Causal	NSR2	NSR3	O
	Indirect-Preventive	NSR3	O	O
	Minimal	O	O	O
Nuclear Safety Related Category II	Direct	See Note below		
	Indirect-Causal	NSR3	O	O
	Indirect-Preventive	O	O	O
	Minimal	O	O	O
Nuclear Safety Related Category III	Direct	See Note below		
	Indirect-Causal	O	O	O
	Indirect-Preventive	O	O	O
	Minimal	O	O	O
Scientific, Engineering and Safety Analysis	Direct	See Note below		
	Indirect-Causal	A	O	O
	Indirect-Preventive	A	O	O
	Minimal	O	O	O
Common Grade	Direct	See Note below		
	Indirect-Causal	O	O	O
	Indirect-Preventive	O	O	O
	Minimal	O	O	O

Acceptance Testing of PATF

- PATF development team had extensive experience with qualification of DCC hardware and with the software QA processes
  - DCC's previously replaced with hardware emulators (1995-2001)
- Qualification tests focused on:
  - Quality of emulation:
    - Included execution of all OEM diagnostics
    - Test cases for DCC features, based on OEM documentation
  - Test cases to test all features of scripting language
  - Testing of integration of Emulated DCC with plant simulation
  - Testing of transfer of control mechanism
- Qualification tests were implemented using scripting language
  - Simplified qualification testing of a new release of PATF in 2014


ONTARIOPOWER GENERATION Report

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Title: PICKERING A DCC TEST FACILITY QUALIFICATION REPORT

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Pickering A DCC Test Facility Qualification Report

NA44-REP-66415-0395358-R000 LOF

2011-09-29

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NUCLEAR VIRTUAL ENGINEERING CAPABILITY

Department for Business, Energy & Industrial Strategy

NATIONAL NUCLEAR LABORATORY

Rolls-Royce

Jacobs

VIRTUAL ENGINEERING CENTRE

EDF ENERGY

NUCLEAR AMRC

Nuclear Virtual Engineering Capability

Dr. Albrecht Kyrieleis

Jacobs Challenging today. Reinventing tomorrow.

Agenda

- Context for NVEC
- NVEC elements
- Case studies
- Future developments

The Nuclear Innovation Programme

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	~£30M		~£150M	
	Apr 18	Apr 19	Apr 20	Apr 21

	Research Theme
Advanced Fuels	Accident Tolerant Fuels
	Coated Particle Fuels
	Pu containing fast reactor fuels
	Reactor physics
	Nuclear Data
Reactor Design	Thermal hydraulic model development
	Thermal hydraulic facility development
	Reactor safety and security
	Virtual engineering
	Modelling and simulation
Spent fuel recycle	Development of proliferation resistant spent fuel recycle technology
Materials and Manufacturing	Materials testing and development
	Advanced component manufacturing
	Large scale manufacturing / assembly
	Prefabrication module development
	Codes and standards
Nuclear facilities and strategic toolkit	Strategic assessments
	Fast reactor knowledge capture
	Regulatory engagement
	Access to irradiation facilities
Advanced Modular Reactors	Feasibility Study
	Design Development

Challenge

- Innovative nuclear power plants needed to meet the UK Government commitment of net zero carbon emissions by 2050
- By 2030 deliver
  - Cost savings of 30% on new build, 20% on decommissioning
  - £2bn domestic and international contract wins

- ‘Silo’ practices
- Information sharing
- Innovation
- Cost management

The NVEC Partnership

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- Jacobs Lead
- Wider partners include: Digital Catapult, University of Bangor, University of Bristol, EvoMetric
- Collaboration includes: UKAEA, Fraser-Nash, Sellafield Ltd, Menai Science Park

NVEC Elements

- Develop collaborative digital environment to support the nuclear life cycle
  - Use existing technology where possible
  - Open and highly flexible
- Develop operating model, standards and guidance
- Demonstrate benefits of digital environment in various case studies
- Involve stakeholders
- Early adoption

- Develop 'community' which can assume responsibility for
  - issuing **guidance**, maintaining **standards**,
  - discussing and **resolving common technological issues**
  - ensuring a **common approach** across the sector

NVEC Phase 2 Environment

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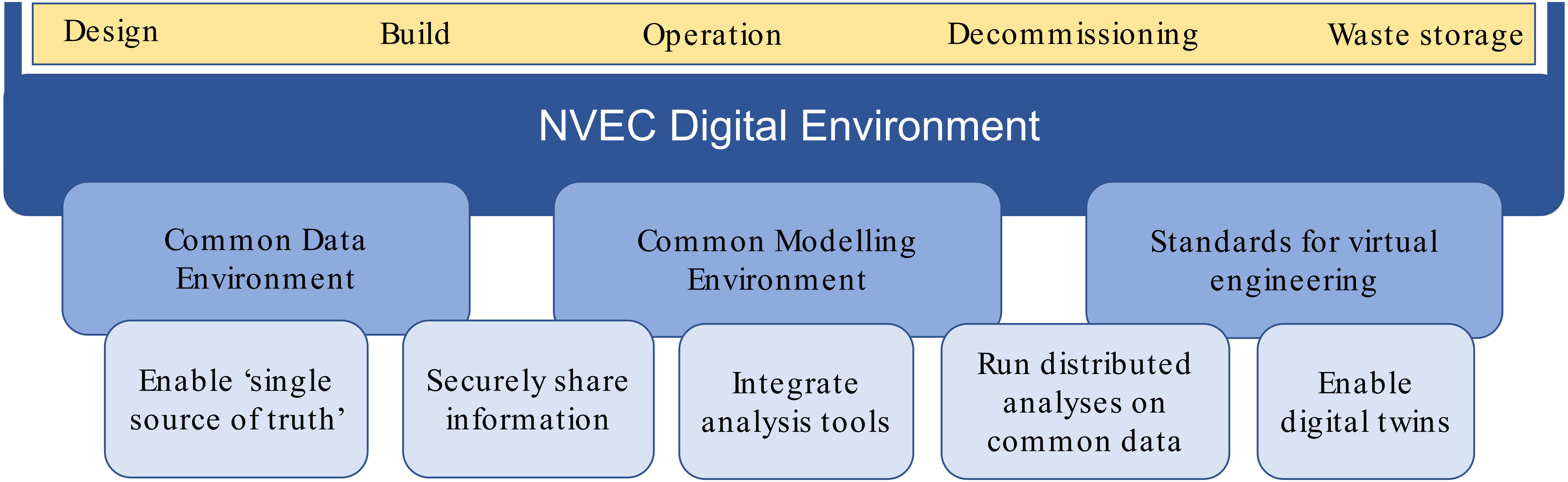

Benefits

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- Reduced costs
  - Single source of design data; collaborative environment
  - Increased return on investment through efficient operation & maintenance
  - Lower risk leading to reduction in financing costs

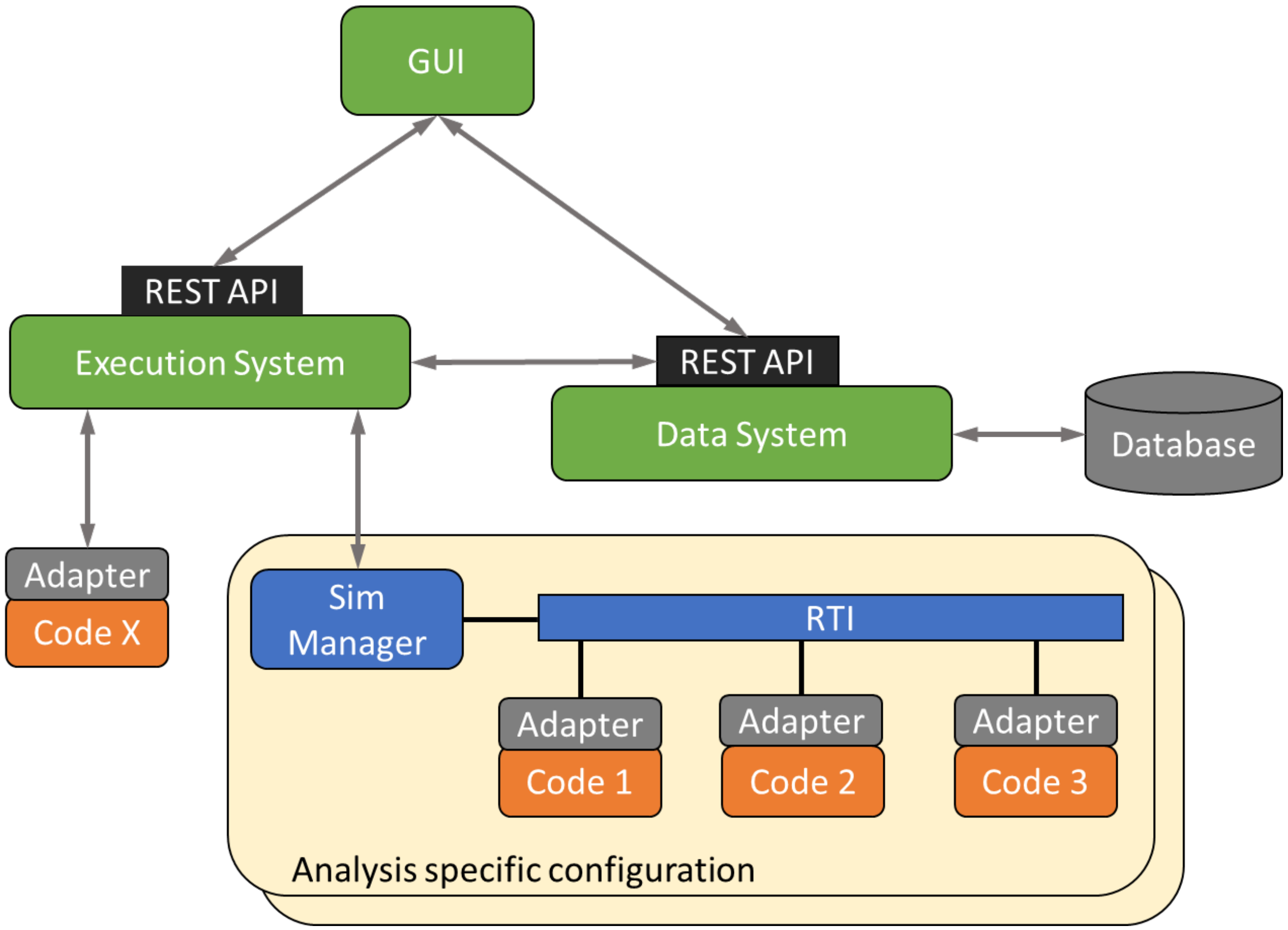
- Shortened development times
  - Efficient Design & licensing ; Integrated multi-physics approach
  - More reliable prediction of development times, allowing better synchronisation

- Enhanced credibility, operability, reliability & safety
  - Real time understanding of plant, better planning and predictive maintenance
  - Enhanced training & skills development
  - Reduced risk and perception of risk

- Cross-discipline transfer of expertise; joined-up industry

- Enables innovation and new technology adoption; diverse users

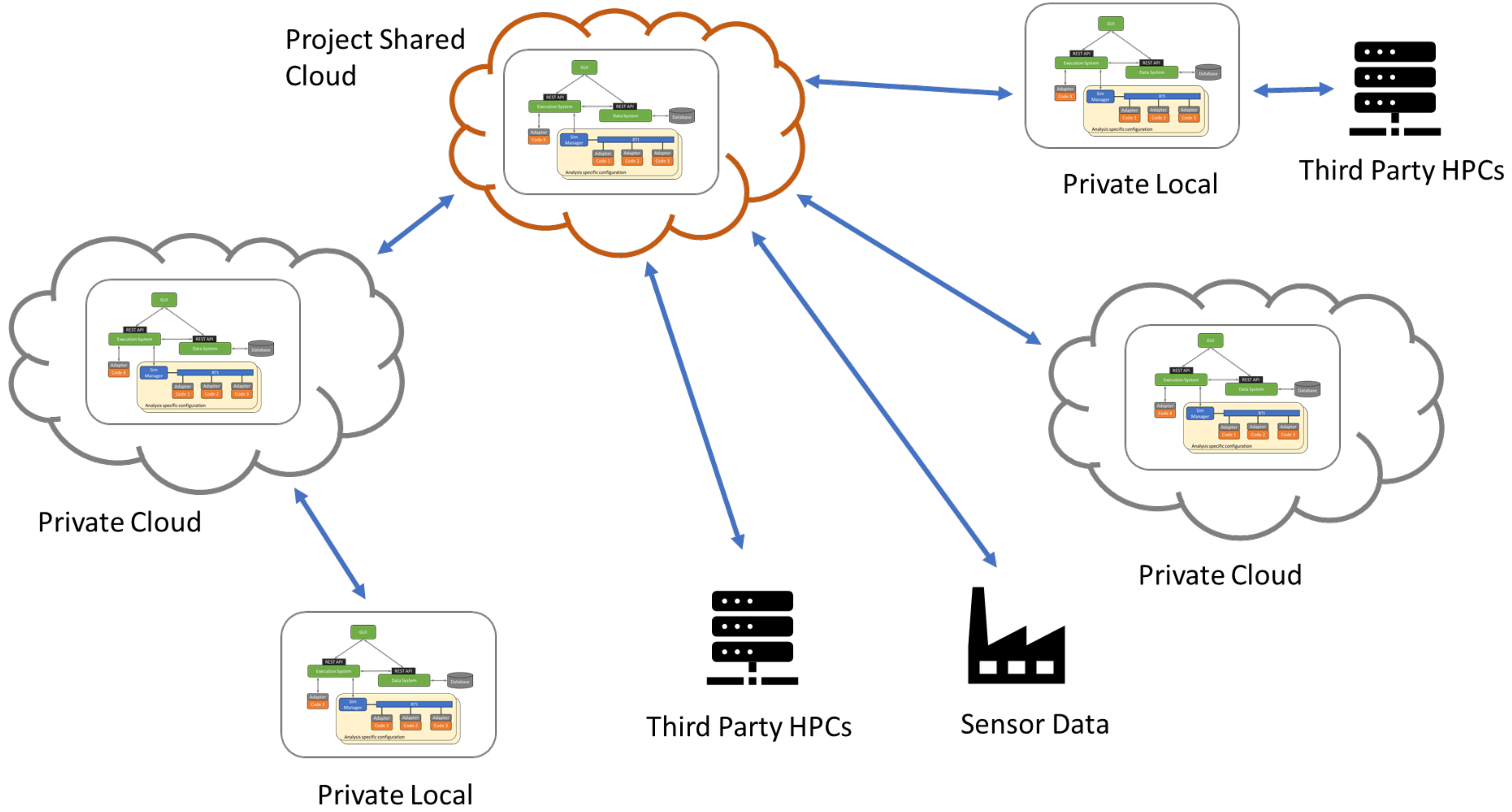
Architecture



Status

- Initial implementation of all components complete
- Continuous improvement
- Deployed on different systems
- Application to various cases on-going

Networked Architecture



Change Control using the Data System

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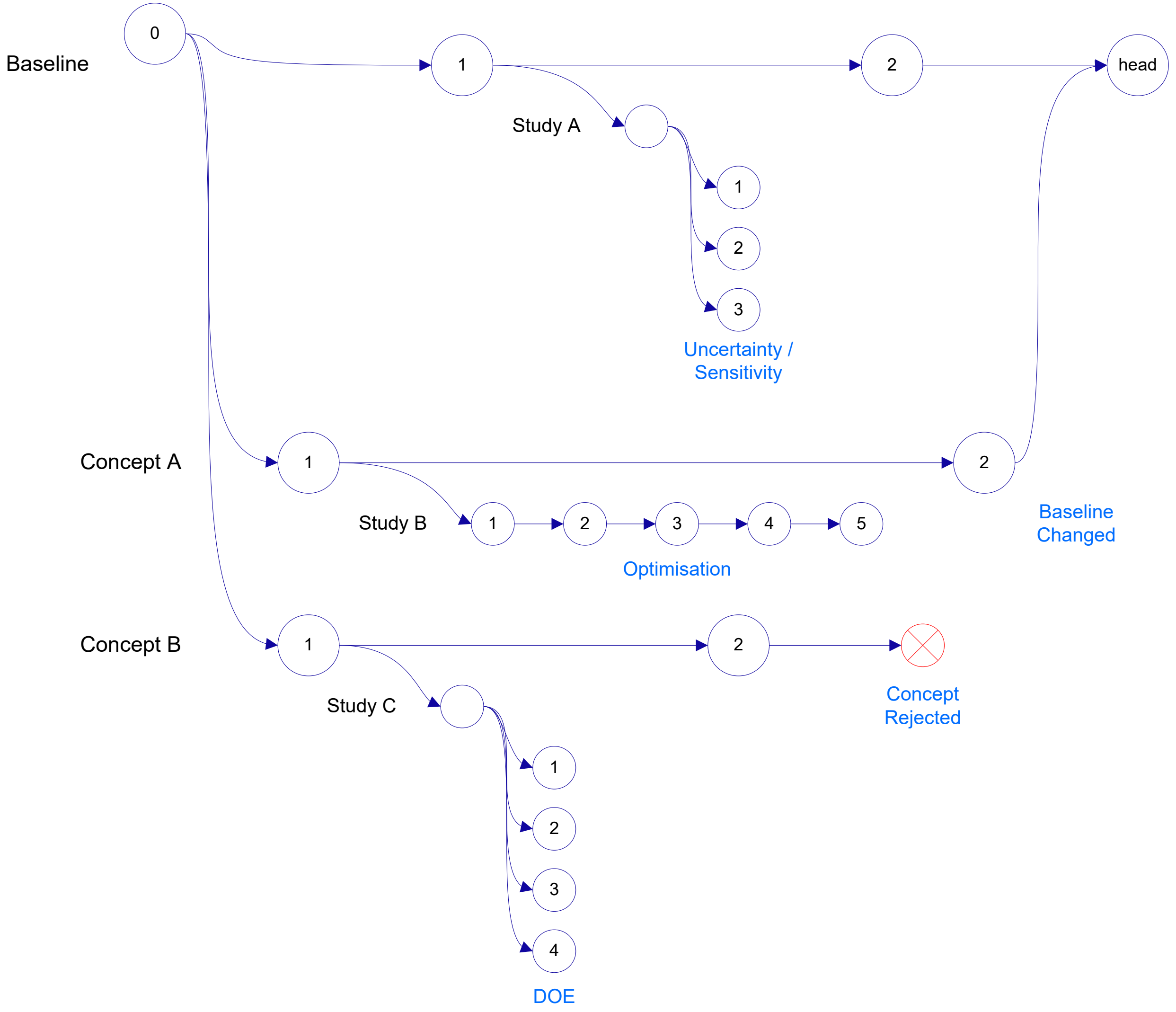
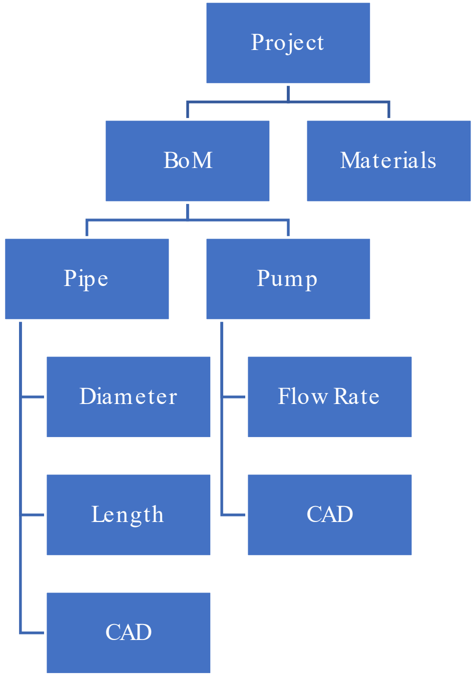
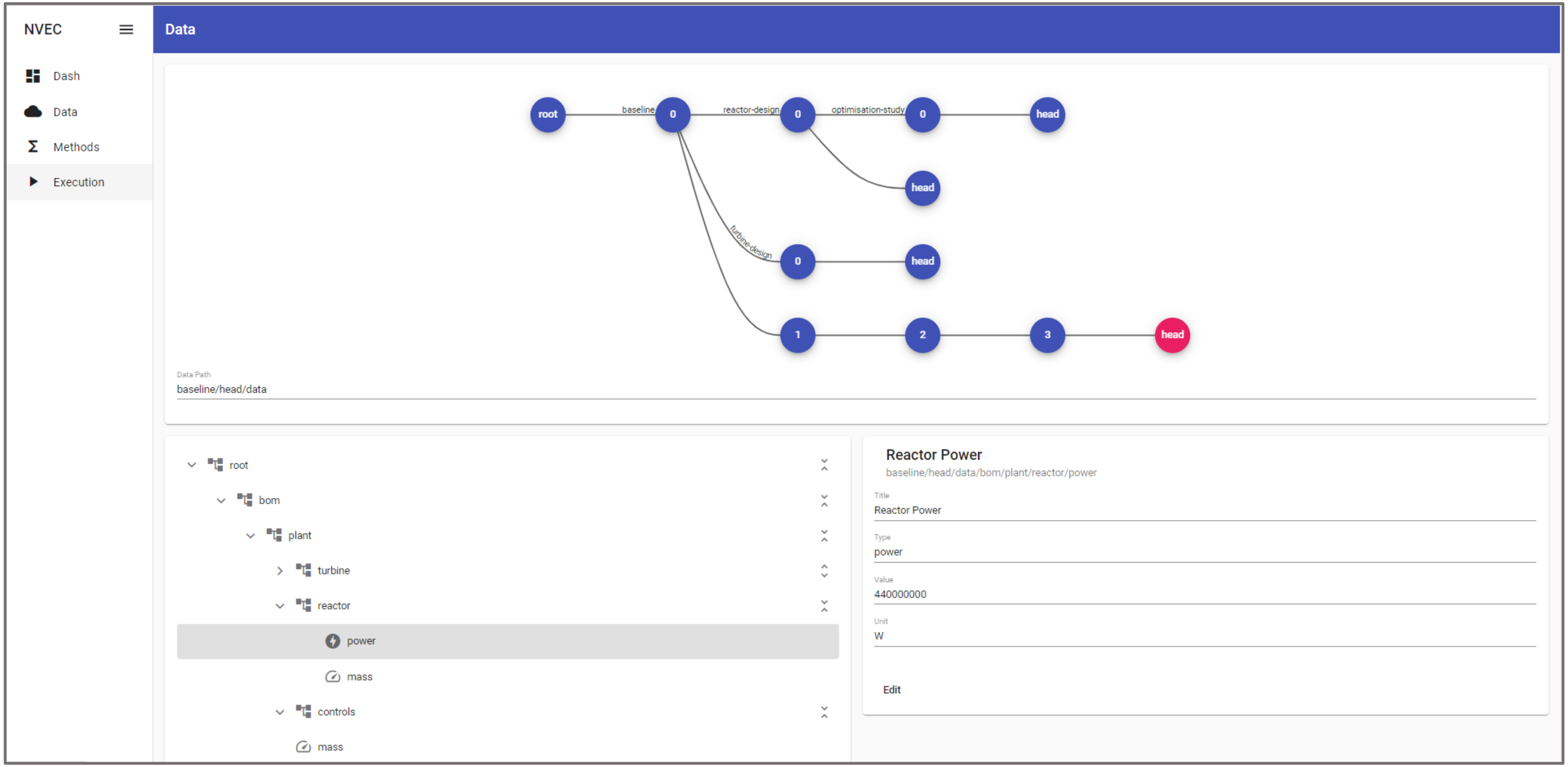




Graphical User Interface



NVEC Multi-Scale Simulation

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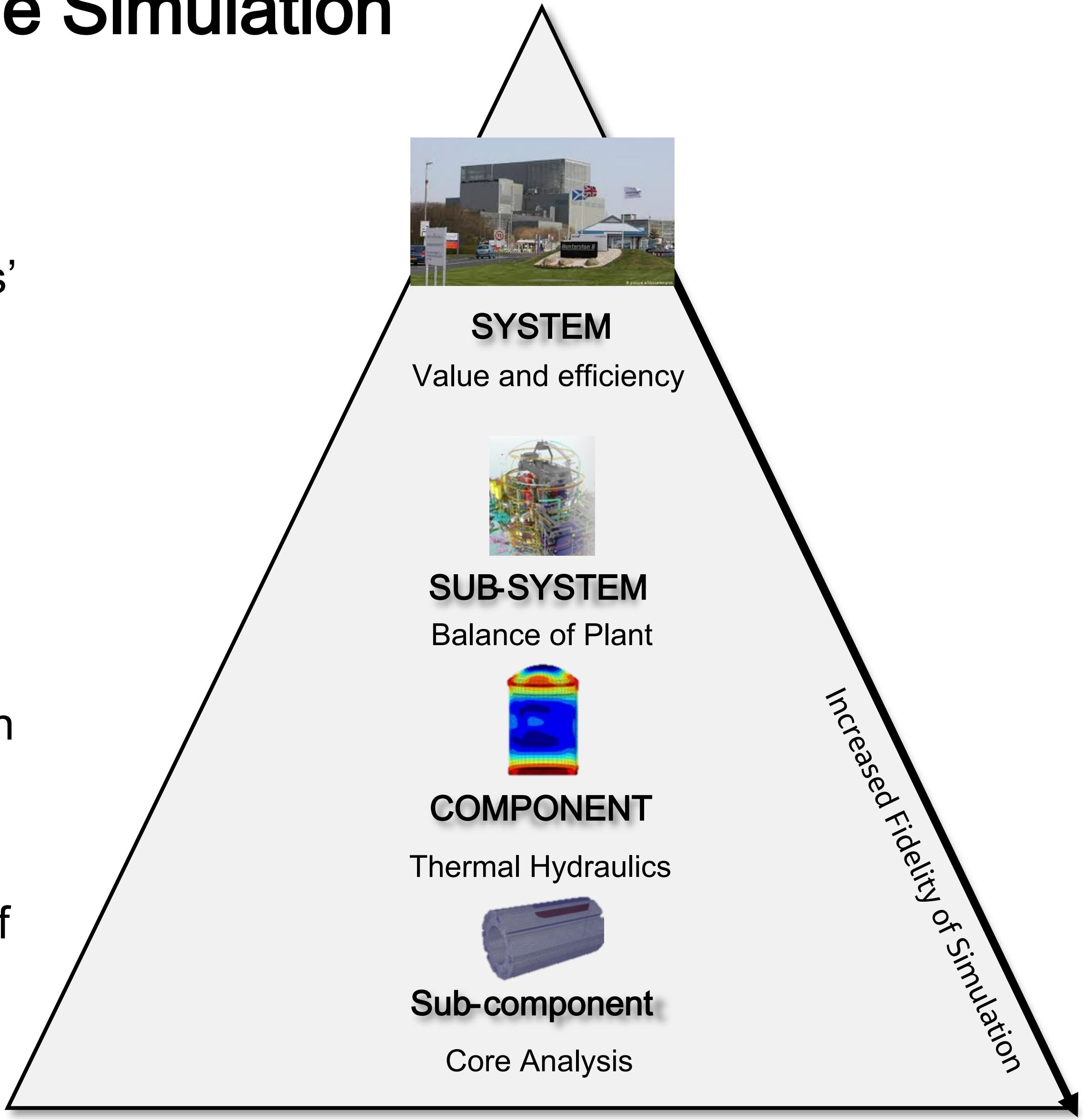
Features

Break down 'model into hierarchy of components'

'Equation Orientated' modelling approach or dedicated code

Code coupling via 'plug and play' modular design

Scalable to allow deployment in a range of applications



Benefits

Single tool can analyse many different designs with few changes

Rapid turn-around from concept to outcome from an analysis

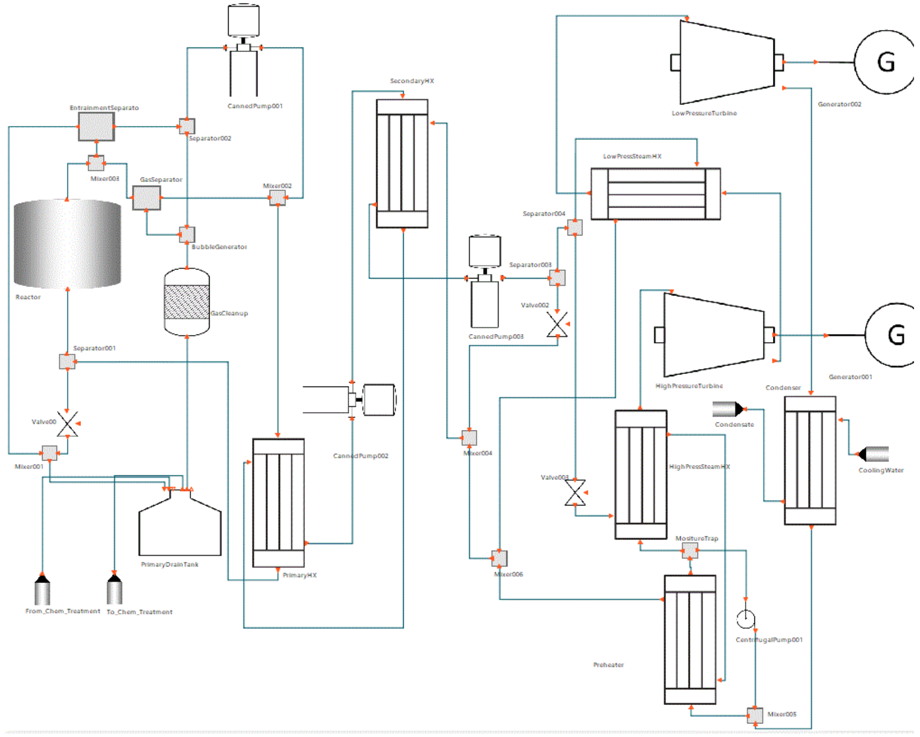
Detailed component analysis via dedicated code where required

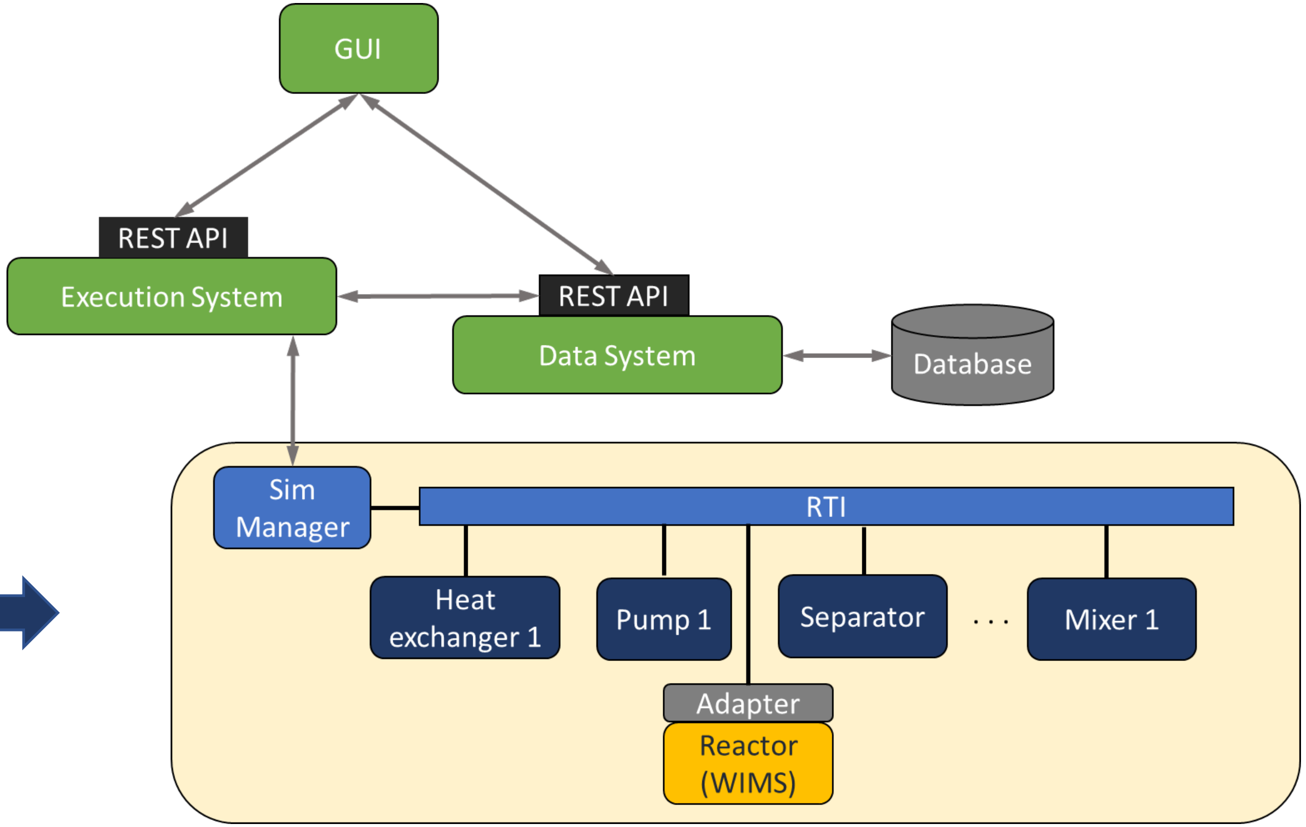
Analyse faults faster as plant simulator and control system can have common features

Case Study: System Level Modelling

- Component libraries can be re-used
- Simulation of operational sequences

- Complex system model of Molten Salt AMR developed and implemented
- Reactor analysis optionally using WIMS code





Multi -Scale Simulation GUI

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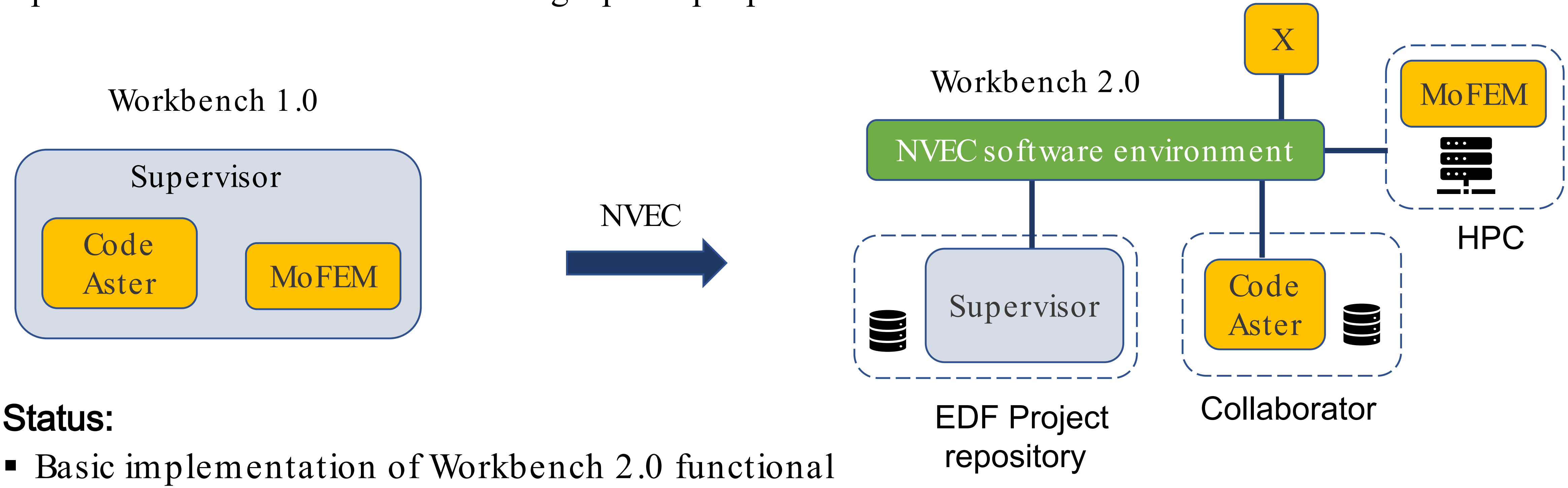
- [Screen shot Sys Lev Sim GUI]

Case Study: AGR Graphite Workbench

Comprehensive simulation of reactor graphite properties over time



Status:

- Basic implementation of Workbench 2.0 functional

Benefits of integration with NVEC

- Enables sharing of computational infrastructure / increased fidelity / inclusion of future modules
- Improved collaboration between sub-contractors
- Standardisation of analyses: less QA effort and training

Integration with IIoT

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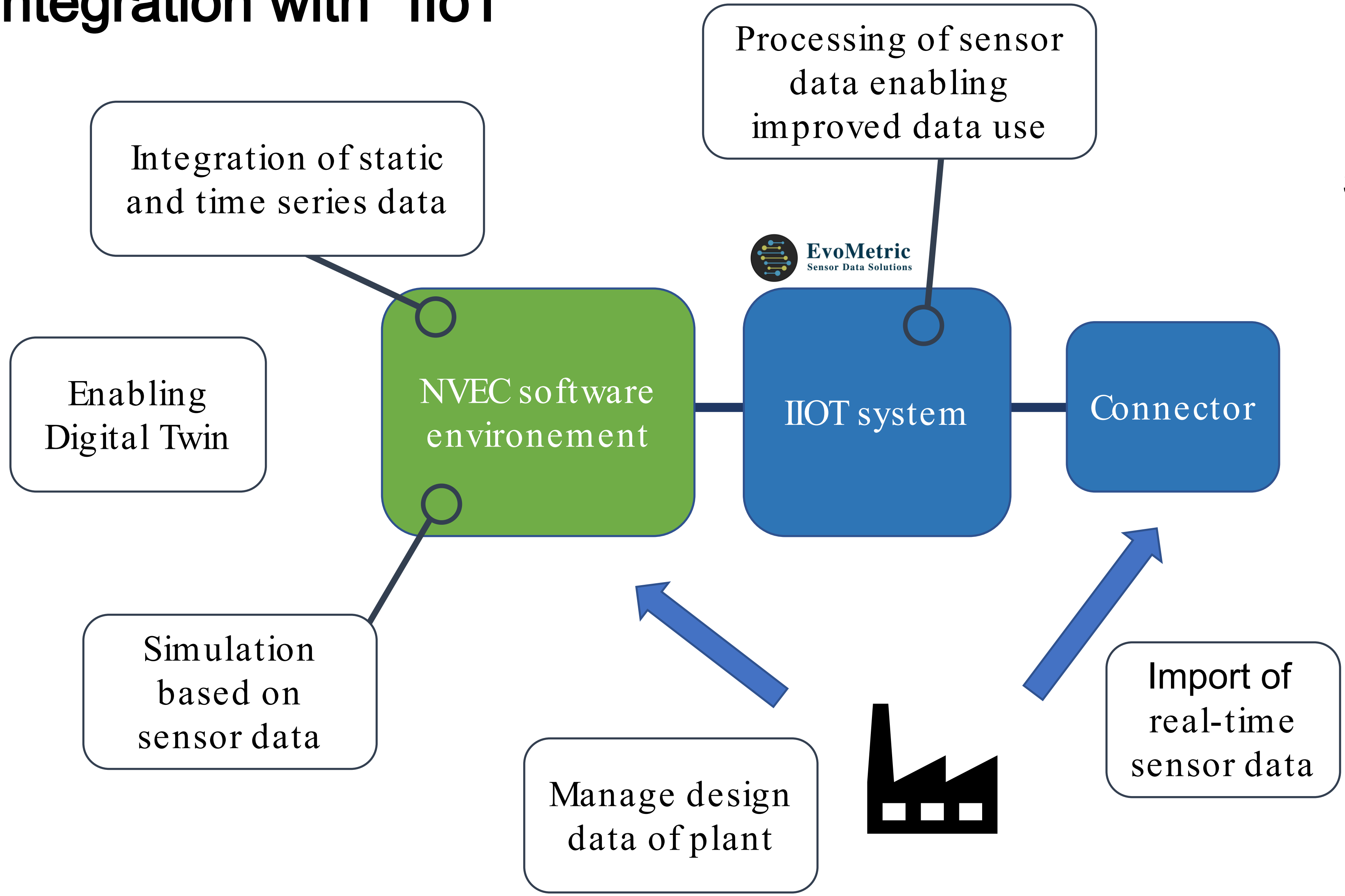

Status:

- Design in progress
- Plant at NAMRC setup to export sensor data
- Model of plant sub-system developed (Frazer-Nash)
- Collaboration with Digital Catapult / SMEs on related methods/technologies

Further Applications

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- **Decommissioning**
  - Integration of simulations with point cloud data from innovative decommissioning project (IIND)

- **Reactor Physics**
  - Completed design of coupling of codes for key workflow (WIMS-ENIGMA) in NVEC

- **THOR** (Thermal Hydraulic Open-Access Research Facility), University of Bangor
  - Collaboration started aiming at involving NVEC from design stage onwards
  - Data Model for THOR developed

- **FAITH**
  - Application of NVEC approach and tools on-going

SME Discovery Workshop (held in Sept ’20)

- Exploring opportunities for collaboration
- NVEC enabling innovation through SMEs

Future Developments

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- SMR
  - Use NVEC for key requirements: e.g. engineering data management, design, change control
  - Initial NVEC evaluation version in development for Rolls-Royce SMR
- Fusion (STEP, CHIMERA)
  - Develop requirements / information model
- System level digital representations enabling optimisation strategies
  - e.g. AMR, process heat, Hydrogen-Nuclear combinations
- Implementation of operational Digital Twins for existing facilities
- Further development of application for FAITH and THOR/ THUNDER

Future Developments

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- Advanced Materials & Manufacturing: more effective structural integrity management
- Increased effectiveness of safety case support
- Social factors study of benefits/obstacles of digitalisation in nuclear
- Develop working practices to support an information management strategy between disciplines
- Develop standards/guidance aiming at a 'NVEC Community'
- Link to the Construction Sector Deal

Summary

- NVEC to help deliver UK Government net zero carbon emissions target by 2050
- Key challenges: 'Silo' practices, information sharing, innovation, cost management
- Development of collaborative digital environment along with standards/guidance
- 'NVEC community': responsible for issuing guidance, maintaining standards, ensuring a common approach across the sector
- Various case studies on-going demonstrating benefits of NVEC
- Broad range of future opportunities

Acknowledgments

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- S. Marr (NAMRC)

Thank you

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Challenging today.
Reinventing tomorrow.

Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

NRC&INL&ORNL 2020 – December 3rd

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tecnatom

CONTENTS

Who we are

Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

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Who we are

TECHNOLOGICAL CAPABILITIES

- Training
- Simulation
- Control Rooms
- Operation Support
- Emergency Support
- Engineering
- Inspection
- Tests
- NDT Systems
- NDT Products

MARKETS

ENERGY			INDUSTRIAL
REACTORS IN OPERATION	NEW REACTORS	COMBINED CYCLE THERMAL RENEWABLE	AEROSPACE PETROCHEMICAL RAILWAY

Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

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Who we are

group tecnatom

tecnatom

tecnatom Mexico

tecnatom Abu Dhabi

tecnatom France

tecnatom brasil

CITEC

tecnatom china – 中国

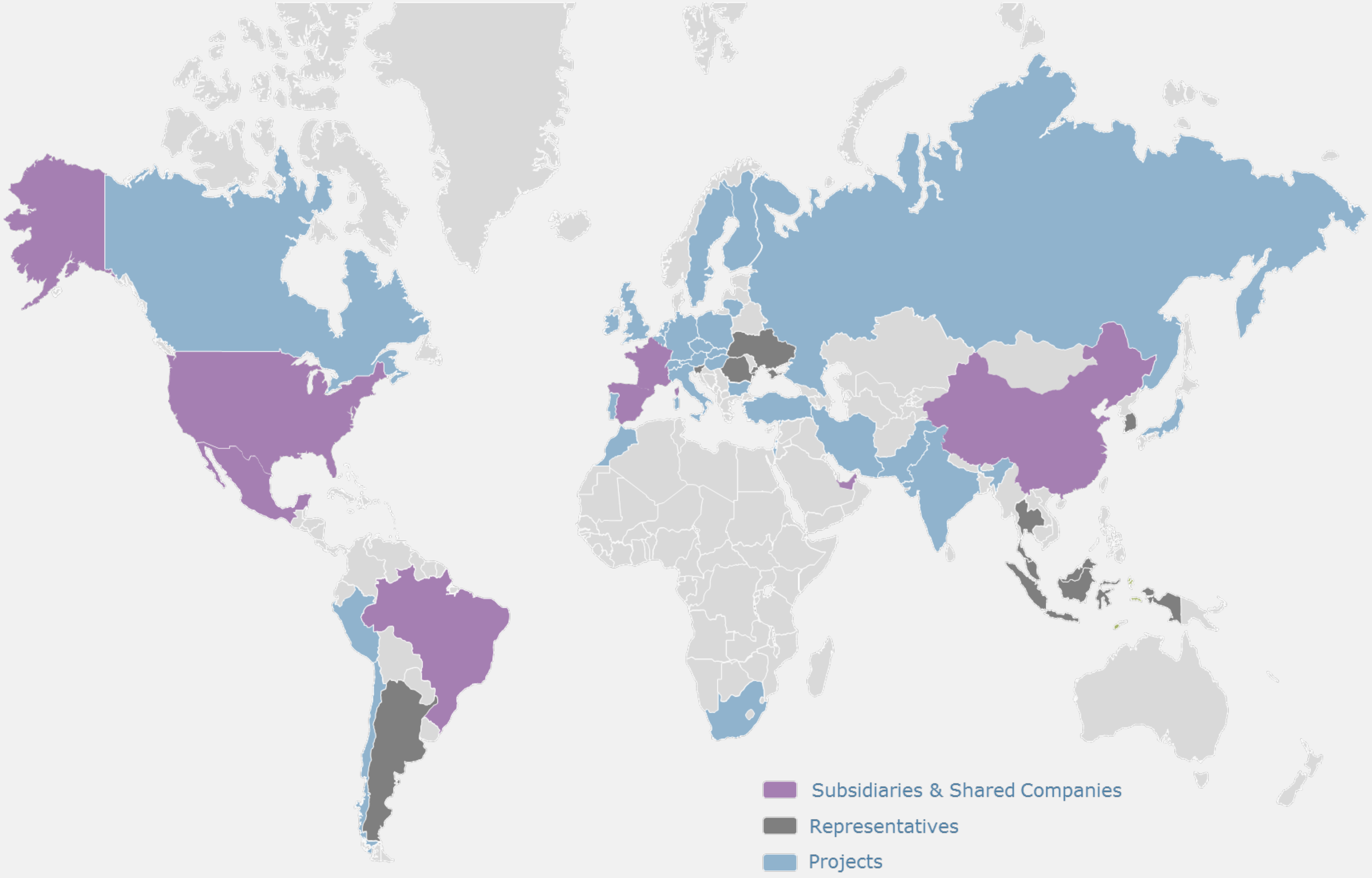
ibercal

sertec

tecnatom USA

FarField

SNGC



The concern

The concern

BWR/6 manufactured by General Electric
Electrical power 1,092.02 MW
Located in Spain

Key facts

- 1st coupling: 14 October 1984
- Commercial operation: 11 March 1985

BOP DCS

- Honeywell TDC 3000 since 1988
- Installed in Full-scope simulator in 2002
- Migrated to Experion in 2005
- Design modifications: control room digitalization

Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

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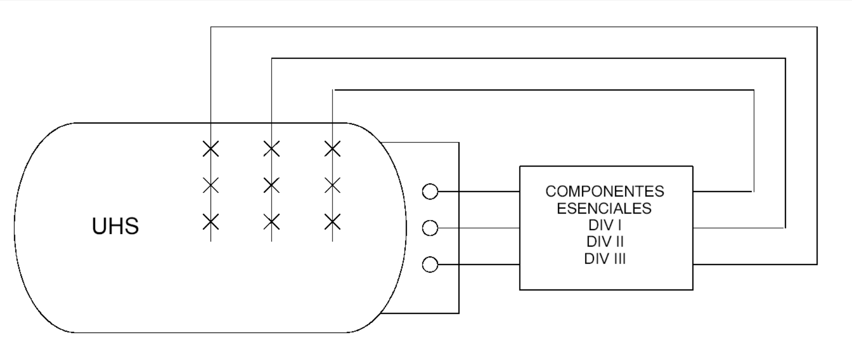
The concern : BWR NPP heat sinks

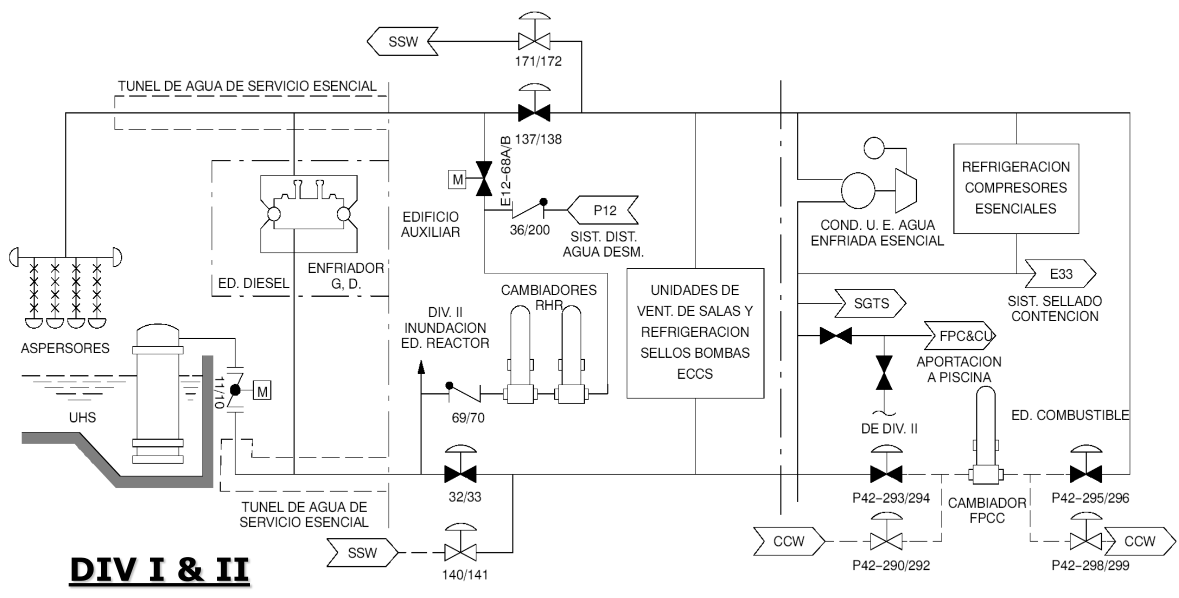
Normal Operation: Main Sink

- 2 natural draught cooling towers (Main condenser)
- Forced draught towers (Auxiliary systems)

Alternative: Ultimate Heat Sink (UHS)

- Pond: 30 days autonomy
- ESW: 3 cooling water pumping and distribution sub-systems
- LOCA or LOOP





The concern: Essential Services Water pipes effective section

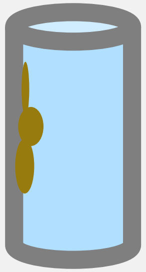
Carbon Steel Pipes

+

Chemically pretreated water

→

Iron Oxide accumulation



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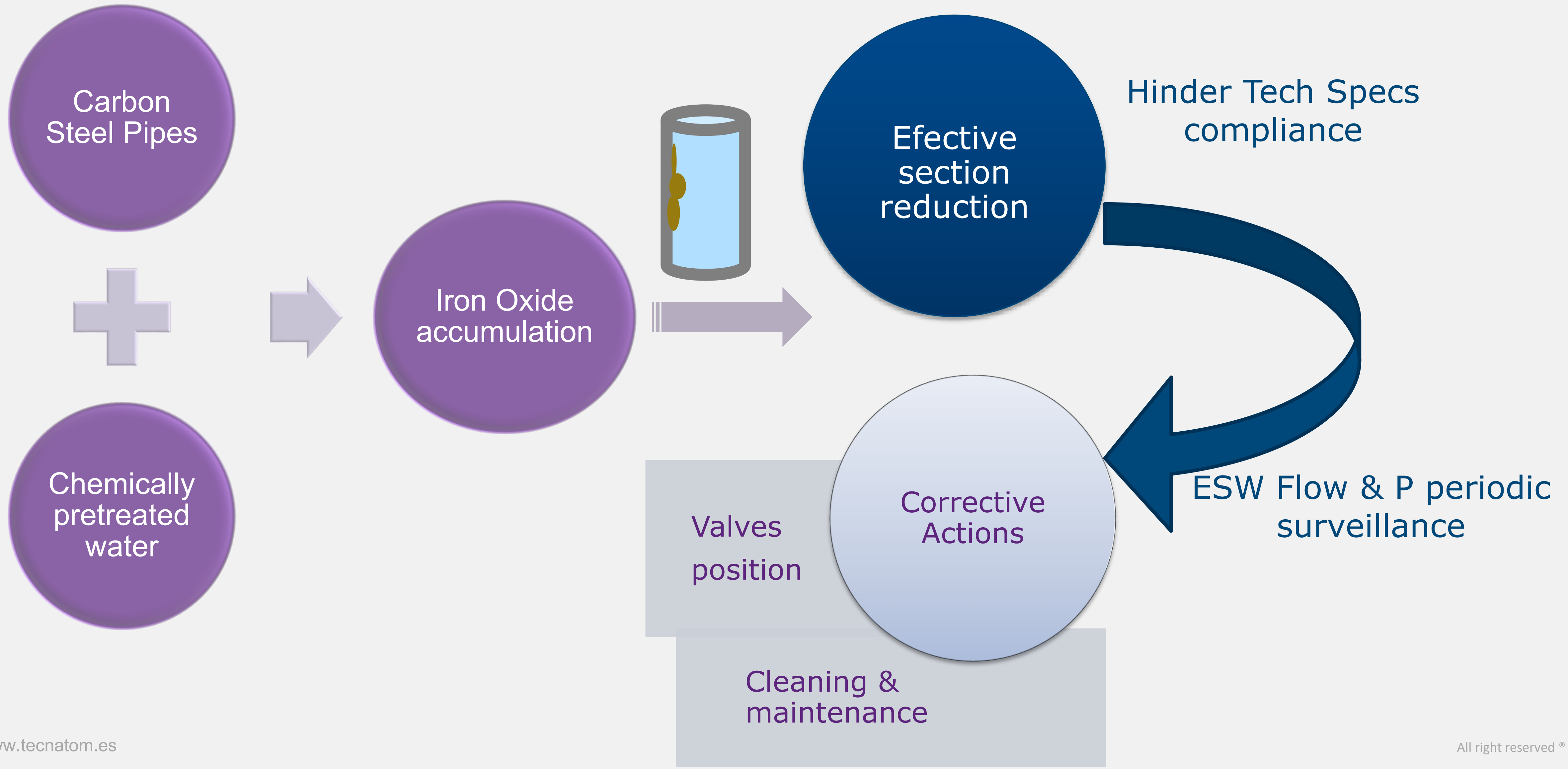
The concern: Essential Services Water pipes effective section



The concern : the solution

Digital Twin to ensure compliance with Technical Specifications

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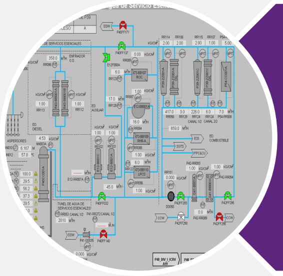
Success story DT P40

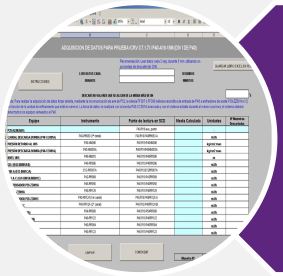
Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

tecnatom

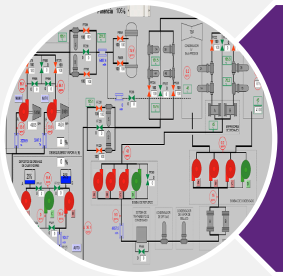
Project DT P40



ESW integration into DCS



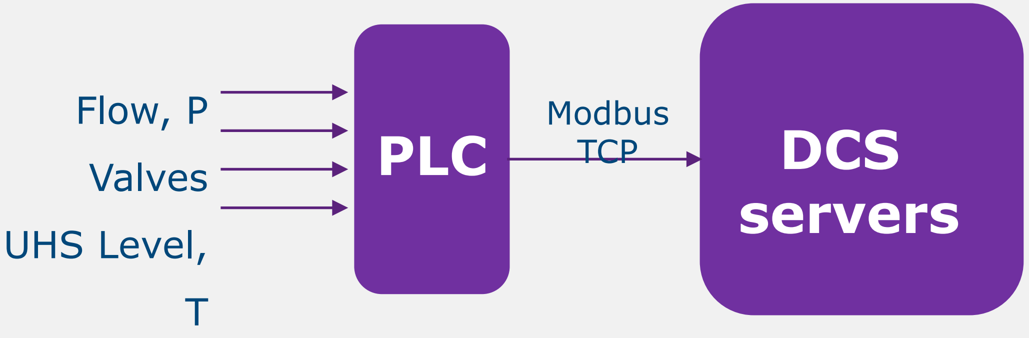
Tools for the automated fulfillment of surveillance reports.



Digital Twin

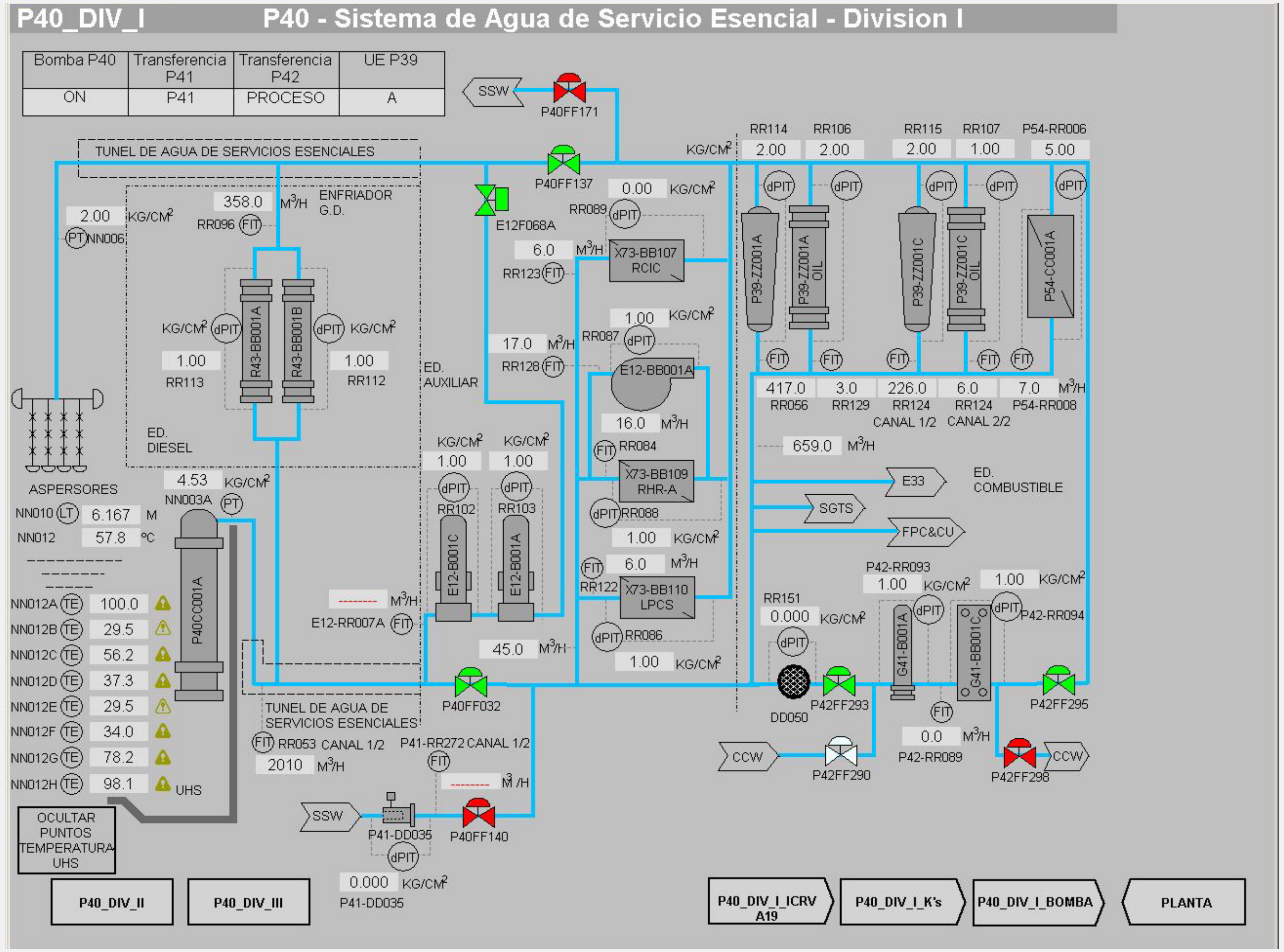
Project DT P40 : ESW integration into DCS

ESW Data Acquisition

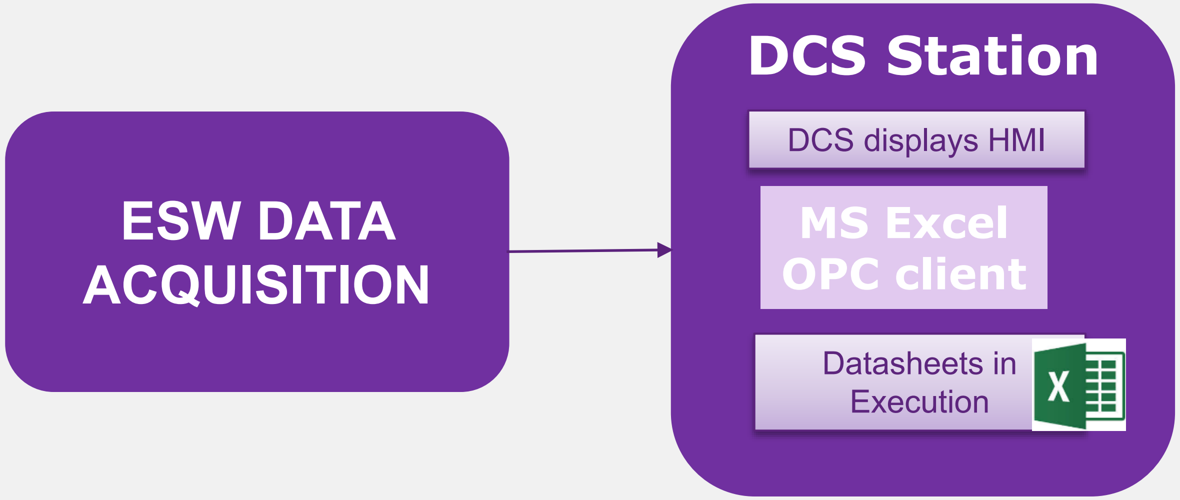


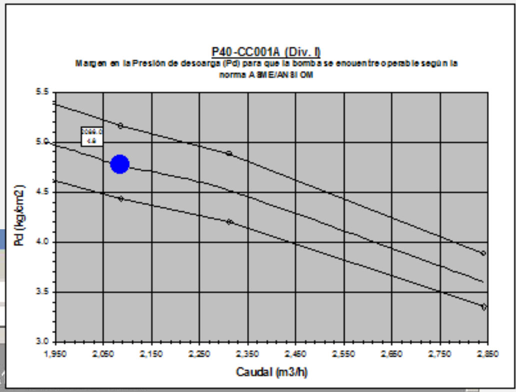
HSI displays:

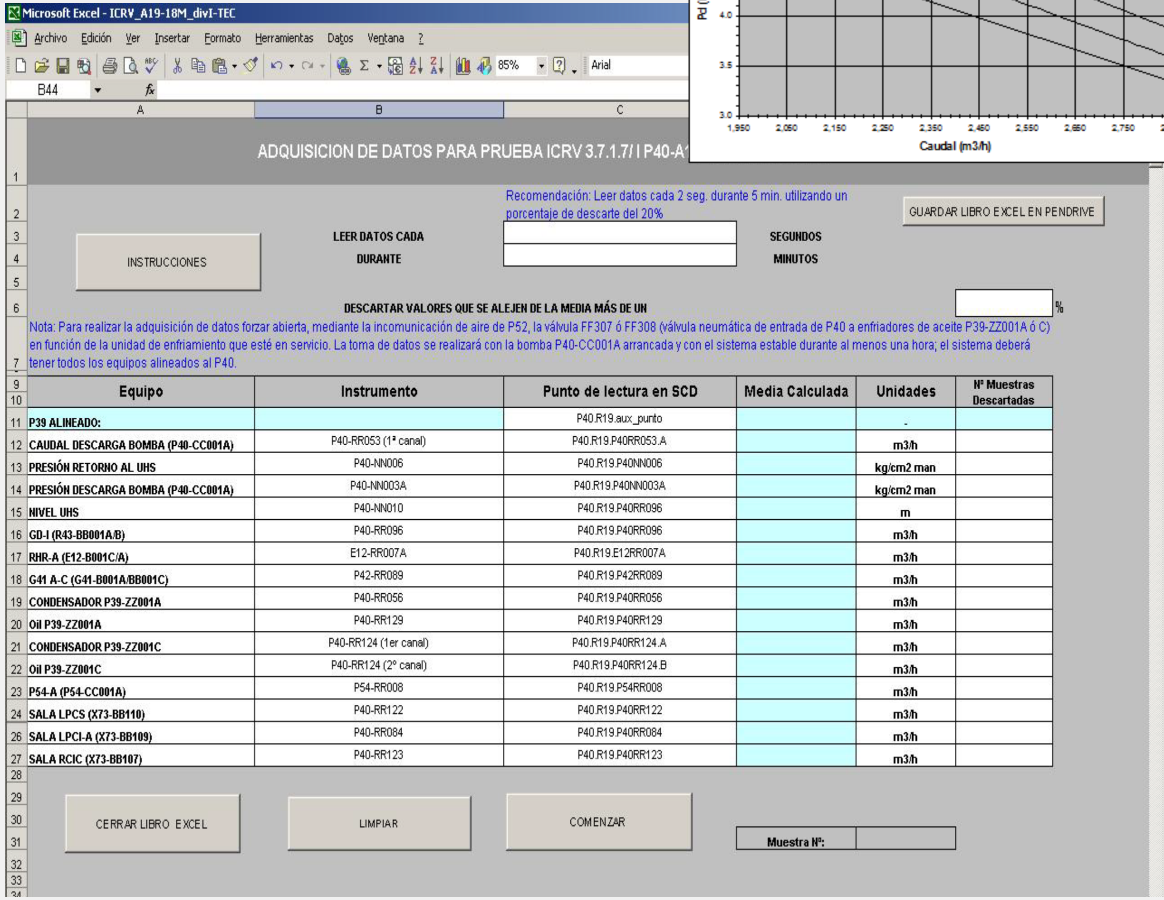
- Division I, II, III
- Heat exchangers pressure drop (K factor)



Project DT P40 : Tools for automatization of surveillance reports





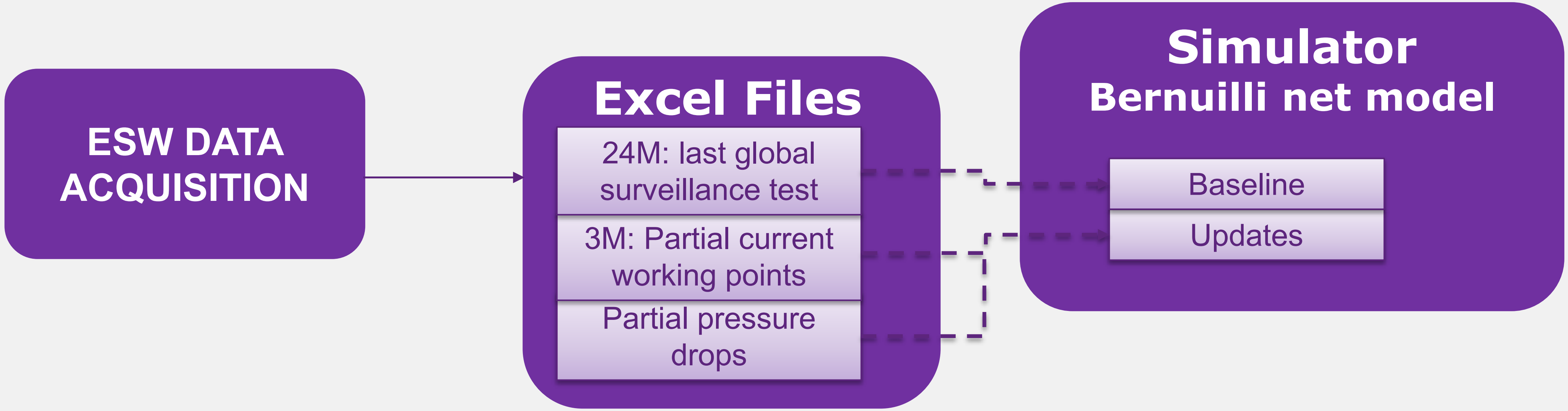


Equipo	Instrumento	Punto de lectura en SCD	Media Calculada	Unidades	Nº Muestras Descartadas
P39 ALINEADO:		P40.R19.aux_punto		-	
CAUDAL DESCARGA BOMBA (P40-CC001A)	P40-RR053 (1ª canal)	P40.R19.P40RR053.A		m3/h	
PRESIÓN RETORNO AL UHS	P40-NN006	P40.R19.P40NN006		kg/cm2 man	
PRESIÓN DESCARGA BOMBA (P40-CC001A)	P40-NN003A	P40.R19.P40NN003A		kg/cm2 man	
NIVEL UHS	P40-NN010	P40.R19.P40RR096		m	
GD-I (R43-BB001A/B)	P40-RR096	P40.R19.P40RR096		m3/h	
RHR-A (E12-B001C/A)	E12-RR007A	P40.R19.E12RR007A		m3/h	
G41 A-C (G41-B001A/BB001C)	P42-RR089	P40.R19.P42RR089		m3/h	
CONDENSADOR P39-ZZ001A	P40-RR056	P40.R19.P40RR056		m3/h	
Oil P39-ZZ001A	P40-RR129	P40.R19.P40RR129		m3/h	
CONDENSADOR P39-ZZ001C	P40-RR124 (1er canal)	P40.R19.P40RR124.A		m3/h	
Oil P39-ZZ001C	P40-RR124 (2º canal)	P40.R19.P40RR124.B		m3/h	
P54-A (P54-CC001A)	P54-RR008	P40.R19.P54RR008		m3/h	
SALA LPCS (X73-BB110)	P40-RR122	P40.R19.P40RR122		m3/h	
SALA LPCI-A (X73-BB109)	P40-RR084	P40.R19.P40RR084		m3/h	
SALA RCIC (X73-BB107)	P40-RR123	P40.R19.P40RR123		m3/h	

Each division surveillance books:

- **24M: Minimum flow surveillance (all components)**
- **03M: Pumps functional capacity (current and historical working point)**
- **Pressure drop factor (K= dP/Q2)**
  - **Heat exchangers & filters**
  - **Graph over time**

Project DT P40 : Digital Twin



Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

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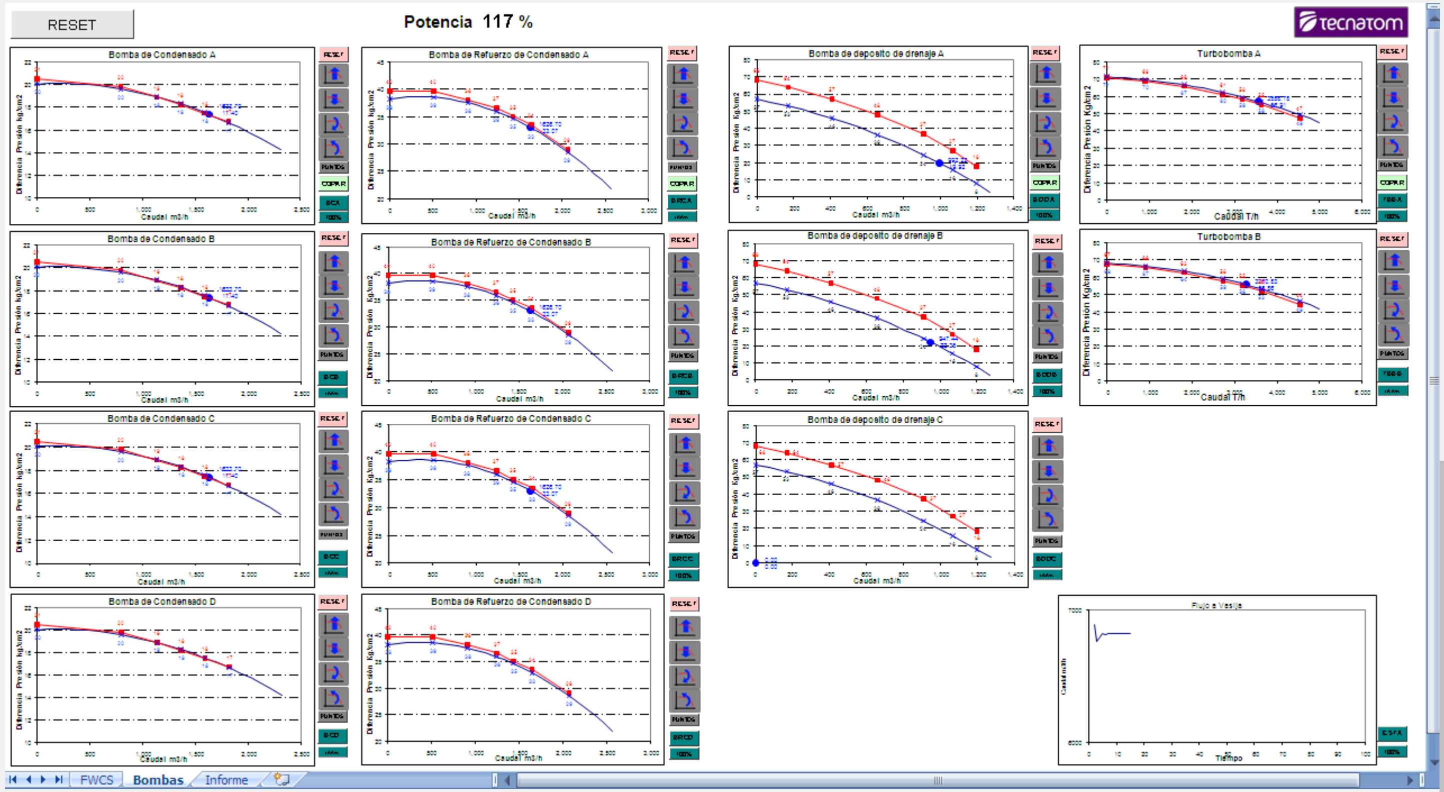
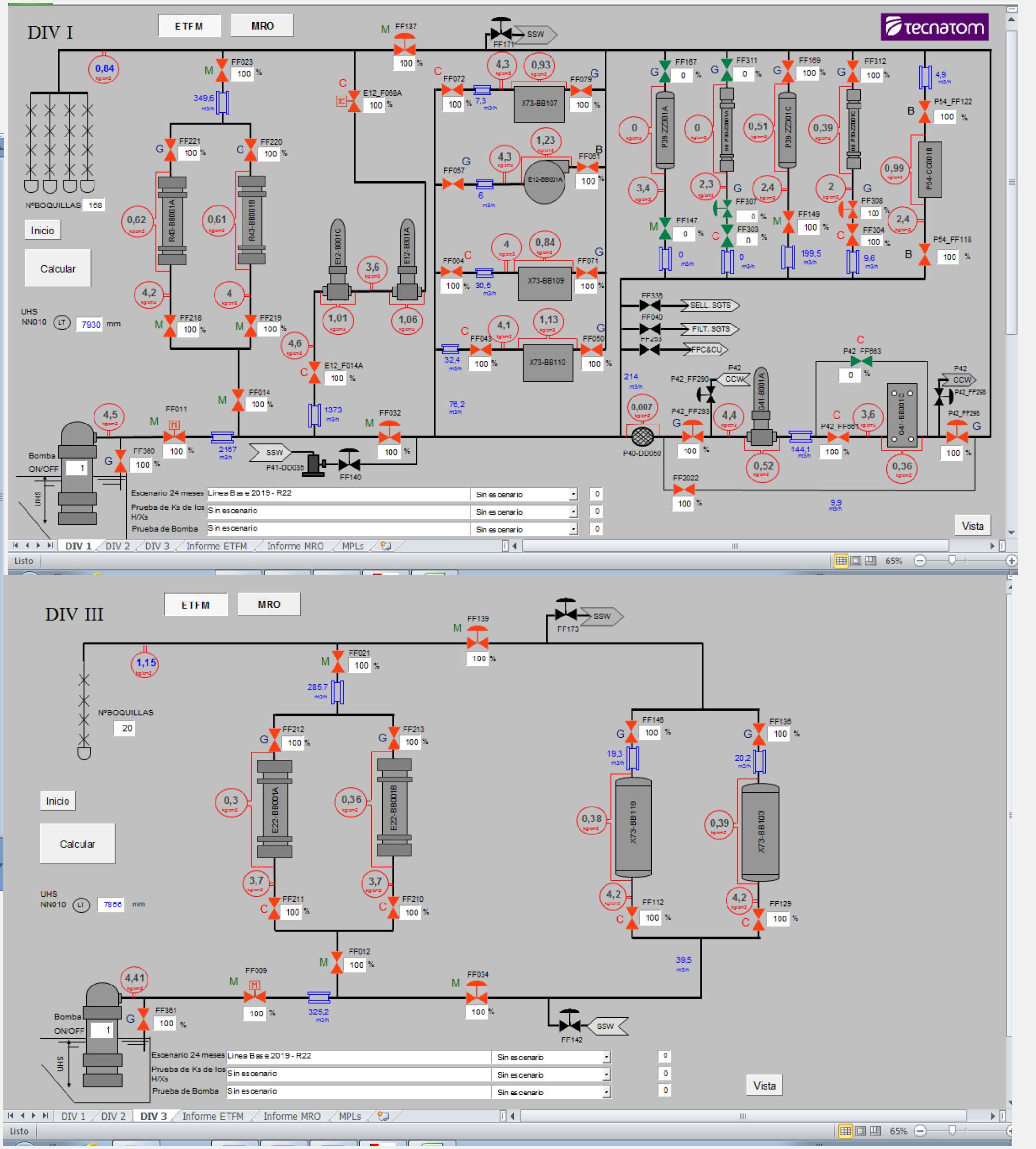
Project DT P40 : Digital Twin

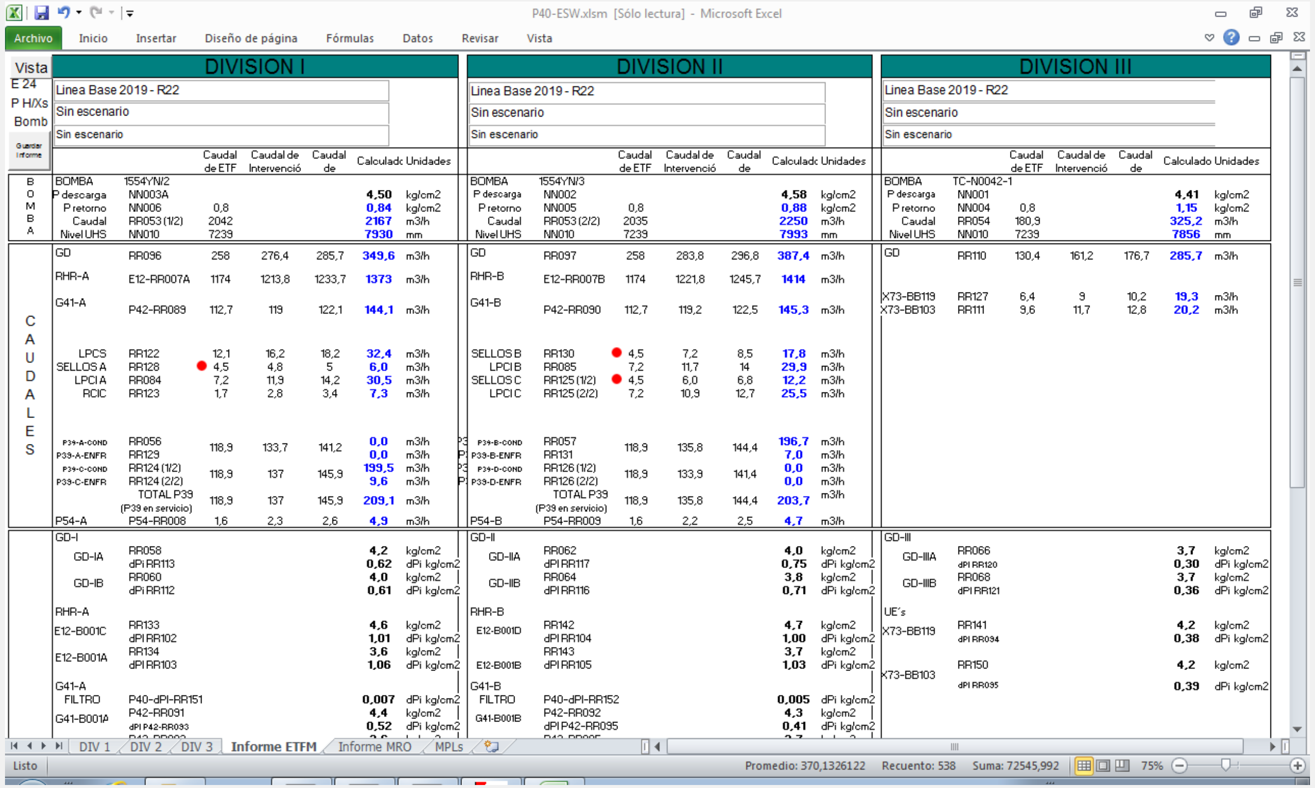




Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

Project DT P40 : Digital Twin

RESULTS



P40-ESW.xlsm [Sólo lectura] - Microsoft Excel

Archivo | Inicio | Insertar | Diseño de página | Fórmulas | Datos | Revisar | Vista

Vista / E 24 / P H/Xs / Bomb / Guardar Informe

DIVISION I

Linea Base 2019 - R22
Sin escenario
Sin escenario

		Caudal de ETF	Caudal de Intervenció	Caudal de	Calculado	Unidades
BOMBA	1554YN/2					
P descarga	NN003A				4,50	kg/cm2
P retorno	NN006	0,8			0,84	kg/cm2
Caudal	RR053 (1/2)	2042			2167	m3/h
Nivel UHS	NN010	7239			7930	mm
GD	RR096	258	276,4	285,7	349,6	m3/h
RHR-A	E12-RR007A	1174	1213,8	1233,7	1373	m3/h
G41-A	P42-RR089	112,7	119	122,1	144,1	m3/h
LPCS	RR122	12,1	16,2	18,2	32,4	m3/h
SELLOS A	RR128	● 4,5	4,8	5	6,0	m3/h
LPCI A	RR084	7,2	11,9	14,2	30,5	m3/h
RCIC	RR123	1,7	2,8	3,4	7,3	m3/h
P39-A-COND	RR056	118,9	133,7	141,2	0,0	m3/h
P39-A-ENFR	RR129				0,0	m3/h
P39-C-COND	RR124 (1/2)	118,9	137	145,9	199,5	m3/h
P39-C-ENFR	RR124 (2/2)				9,6	m3/h
TOTAL P39 (P39 en servicio)		118,9	137	145,9	209,1	m3/h
P54-A	P54-RR008	1,6	2,3	2,6	4,9	m3/h
GD-I						
GD-IA	RR058				4,2	kg/cm2
	dPi RR113				0,62	dPi kg/cm2
GD-IB	RR060				4,0	kg/cm2
	dPi RR112				0,61	dPi kg/cm2
RHR-A						
E12-B001C	RR133				4,6	kg/cm2
	dPI RR102				1,01	dPi kg/cm2
E12-B001A	RR134				3,6	kg/cm2
	dPI RR103				1,06	dPi kg/cm2
G41-A						
FILTRO	P40-dPI-RR151				0,007	dPi kg/cm2
G41-B001A	P42-RR091				4,4	kg/cm2
	dPI P42-RR093				0,52	dPi kg/cm2

DIVISION II

Linea Base 2019 - R22
Sin escenario
Sin escenario

		Caudal de ETF	Caudal de Intervenció	Caudal de	Calculado	Unidades
BOMBA	1554YN/3					
P descarga	NN002				4,58	kg/cm2
P retorno	NN005	0,8			0,88	kg/cm2
Caudal	RR053 (2/2)	2035			2250	m3/h
Nivel UHS	NN010	7239			7993	mm
GD	RR097	258	283,8	296,8	387,4	m3/h
RHR-B	E12-RR007B	1174	1221,8	1245,7	1414	m3/h
G41-B	P42-RR090	112,7	119,2	122,5	145,3	m3/h
SELLOS B	RR130	● 4,5	7,2	8,5	17,8	m3/h
LPCI B	RR085	7,2	11,7	14	29,9	m3/h
SELLOS C	RR125 (1/2)	● 4,5	6,0	6,8	12,2	m3/h
LPCI C	RR125 (2/2)	7,2	10,9	12,7	25,5	m3/h
P39-B-COND	RR057	118,9	135,8	144,4	196,7	m3/h
P39-B-ENFR	RR131				7,0	m3/h
P39-D-COND	RR126 (1/2)	118,9	133,9	141,4	0,0	m3/h
P39-D-ENFR	RR126 (2/2)				0,0	m3/h
TOTAL P39 (P39 en servicio)		118,9	135,8	144,4	203,7	m3/h
P54-B	P54-RR009	1,6	2,2	2,5	4,7	m3/h
GD-II						
GD-IIA	RR062				4,0	kg/cm2
	dPI RR117				0,75	dPi kg/cm2
GD-IIB	RR064				3,8	kg/cm2
	dPI RR116				0,71	dPi kg/cm2
RHR-B						
E12-B001D	RR142				4,7	kg/cm2
	dPI RR104				1,00	dPi kg/cm2
E12-B001B	RR143				3,7	kg/cm2
	dPI RR105				1,03	dPi kg/cm2
G41-B						
FILTRO	P40-dPI-RR152				0,005	dPi kg/cm2
G41-B001B	P42-RR092				4,3	kg/cm2
	dPI P42-RR095				0,41	dPi kg/cm2

DIVISION III

Linea Base 2019 - R22
Sin escenario
Sin escenario

		Caudal de ETF	Caudal de Intervenció	Caudal de	Calculado	Unidades
BOMBA	TC-N0042-1					
P descarga	NN001				4,41	kg/cm2
P retorno	NN004	0,8			1,15	kg/cm2
Caudal	RR054	180,9			325,2	m3/h
Nivel UHS	NN010	7239			7856	mm
GD	RR110	130,4	161,2	176,7	285,7	m3/h
X73-BB119	RR127	6,4	9	10,2	19,3	m3/h
X73-BB103	RR111	9,6	11,7	12,8	20,2	m3/h
GD-III						
GD-IIIA	RR066				3,7	kg/cm2
	dPI RR120				0,30	dPi kg/cm2
GD-IIIB	RR068				3,7	kg/cm2
	dPI RR121				0,36	dPi kg/cm2
UE´s						
X73-BB119	RR141				4,2	kg/cm2
	dPI RR094				0,38	dPi kg/cm2
X73-BB103	RR150				4,2	kg/cm2
	dPI RR095				0,39	dPi kg/cm2

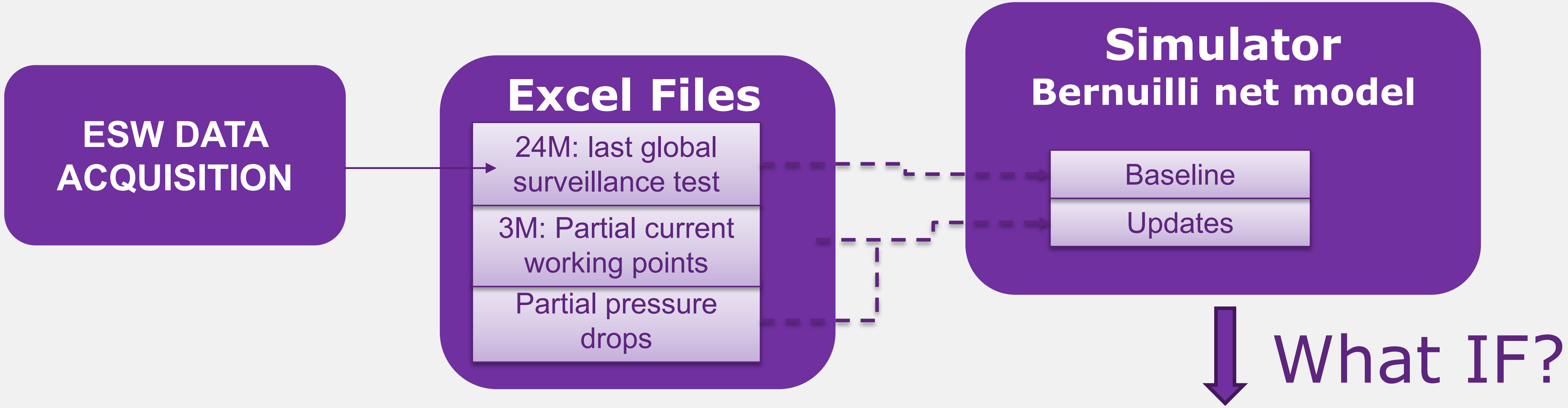
DIV 1 | DIV 2 | DIV 3 | Informe ETFM | Informe MRO | MPLs

Listo | Promedio: 370,1326122 | Recuento: 538 | Suma: 72545,992 | 75%

GD	RR110	155	182.2	195.7	291.8	m3/h
UEs	TOTAL	30			41.5	m3/h
X73-BB119	RR127	11	13	13.9	21.8	m3/h
X73-BB103	RR111	18.6	19.4	19.8	19.7	m3/h

GD	RR110	155	182.2	195.7	292.0	m3/h
UEs	TOTAL	30			41.2	m3/h
X73-BB119	RR127	11	13	13.9	22.0	m3/h
X73-BB103	RR111	18.6	19.4	19.8	19.2	m3/h

Project DT P40 : Digital Twin



Prediction

- Quantitative result of eventual system use or complete test

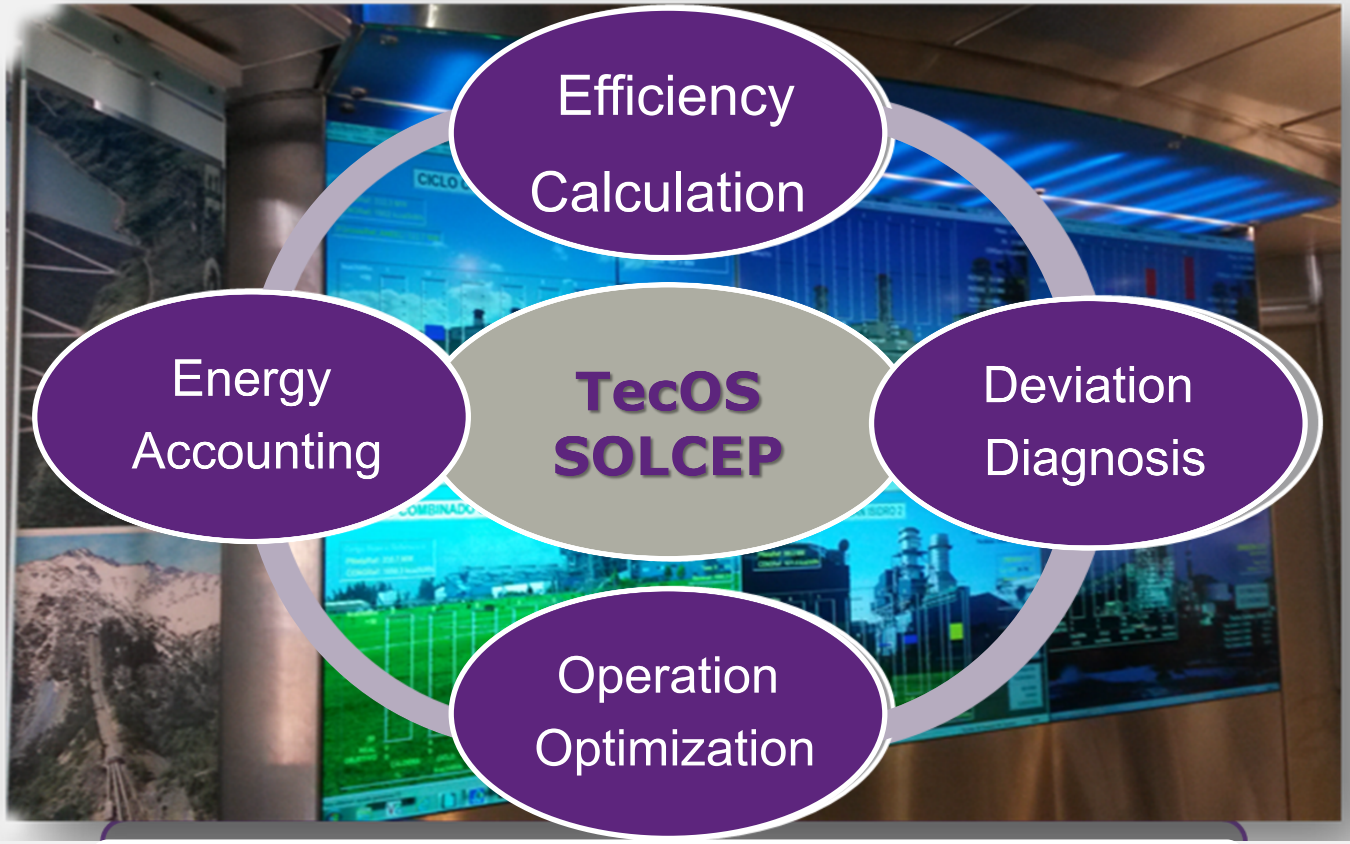
Best system configuration

- Simulate valves and pumps operation

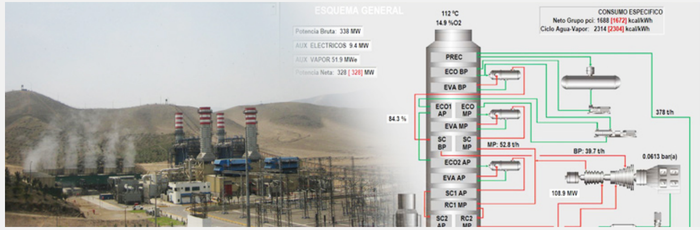
Other success stories

Project DT TecOS SOLCEP

ASME PTC PM 1993(2010). Performance Monitoring Guidelines for Power Plants



Assisted Diagnostic (Tecnatom Engineers)



Benefits of Digitalizing and Employing Simulation to Increase Plant System Performance and Ensure Compliance with Technical Specifications

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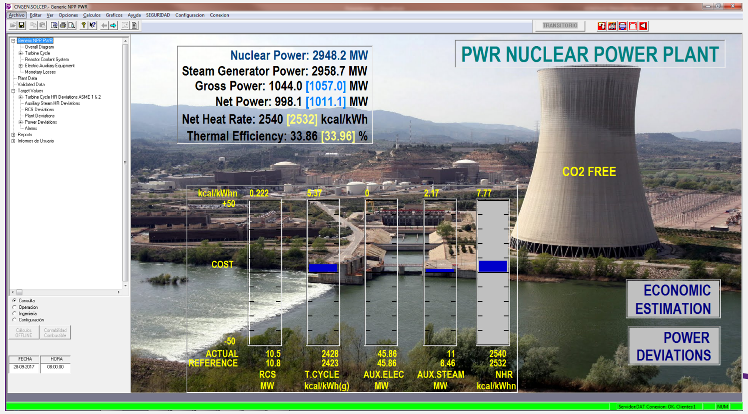
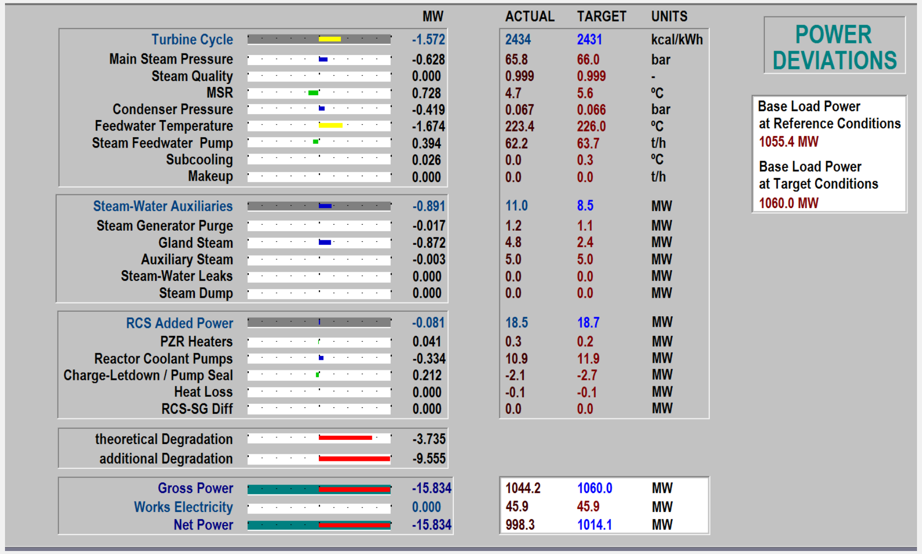
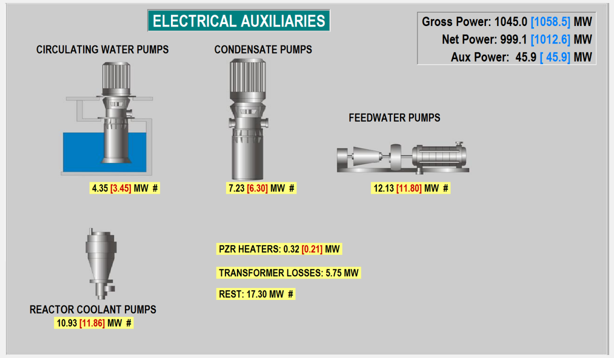
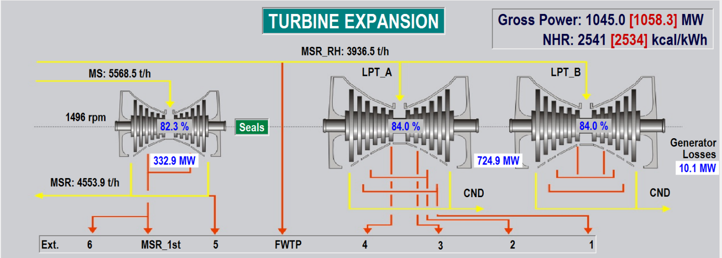
Project DT TecOS SOLCEP

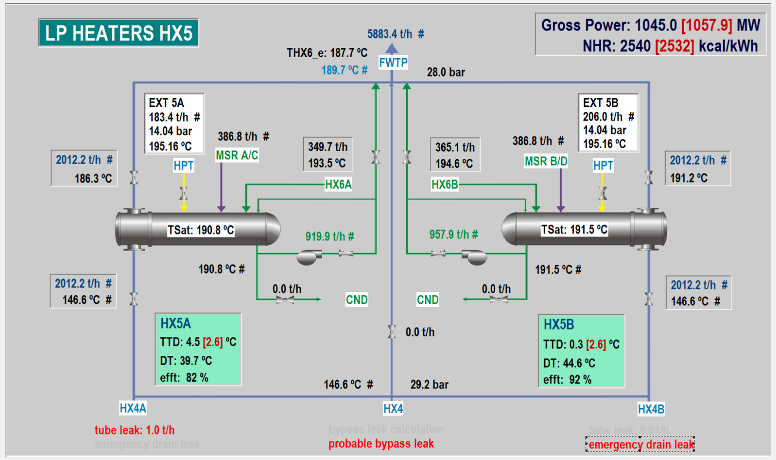








	6	MSR_1st	5	FWTP	4	3	2	1
P (bar)	30.43	28.89	14.04	13.60	4.44	2.17	0.66	0.28
T (ºC)	234.63	234.63	195.18	275.84	164.42	118.63	88.58	67.94
X (-)	0.92		0.88			0.98	0.90	0.87
F (kg/s)	57.51	27.49	50.66	8.64	33.87	29.68	13.83	27.17
byp (kg/s)	2.35		0.00		0.00	0.00	0.00	0.00
P (bar)	30.43	29.30	14.04	13.60	4.44	2.40	0.61	0.30
T (ºC)	234.63	234.63	195.18	275.84	161.17	119.66	86.51	68.90
X (-)	0.92		0.88			0.99	0.90	0.87
F (kg/s)	60.31	27.49	56.92	8.64	32.51	30.85	16.61	26.13
byp (kg/s)	0.00		0.00		0.00	0.00	0.00	0.00



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Conclusions

Conclusions

Benefits:

- Maximizing operation increasing safety margins
  - No need for maintenance shutdown
- Eases the evaluation of blockages and soiling
  - On-line information (digitalization)
- Optimizes preventive maintenance tasks (cleaning)
- Optimizes operator workload:
  - Automates calculations and surveillance and test requirements reports

Key Factors:

- Integrated approach for design modifications
  - Simulation, I&C, HFE, Operation

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European Commission

THE EU FRAMEWORK PROGRAMME
FOR RESEARCH AND INNOVATION

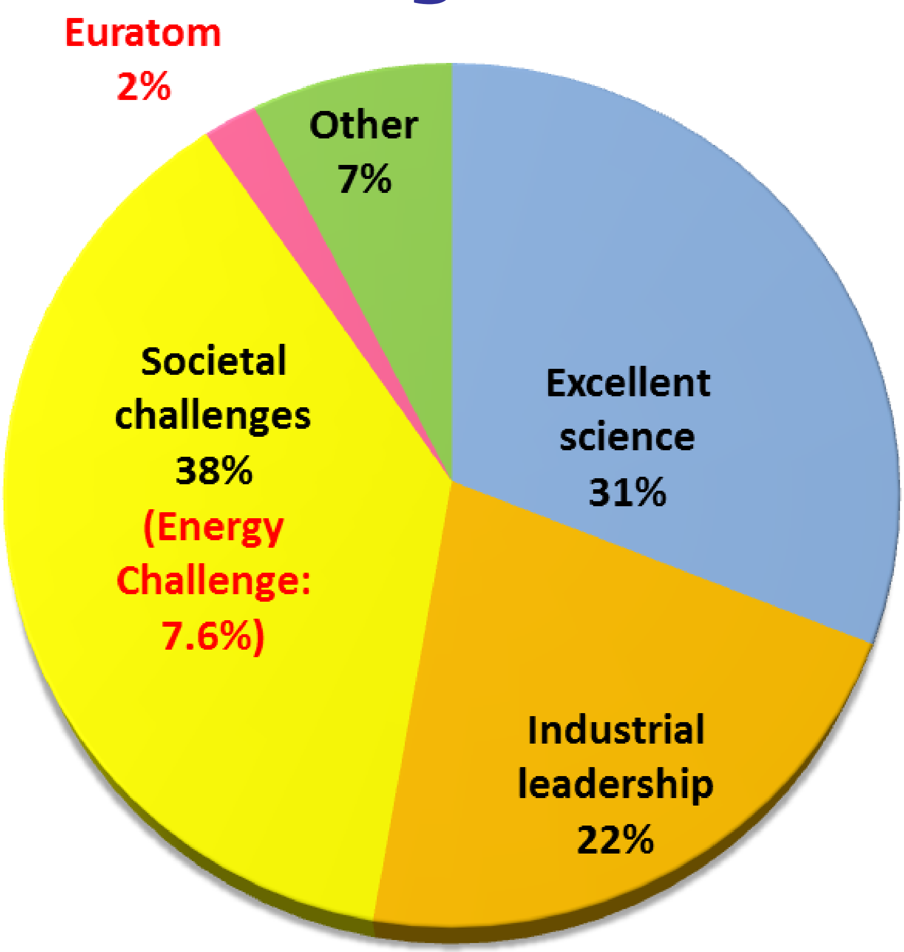
EURATOM RESEARCH AND TRAINING PROGRAMME
FISSION RESEARCH

Panagiotis MANOLATOS
DG RTD
Clean Planet
panagiotis.manolatos@ec.europa.eu

DIGITAL TWIN
4-5 December 2020

HORIZON 2020

Challenges – Overall budgets

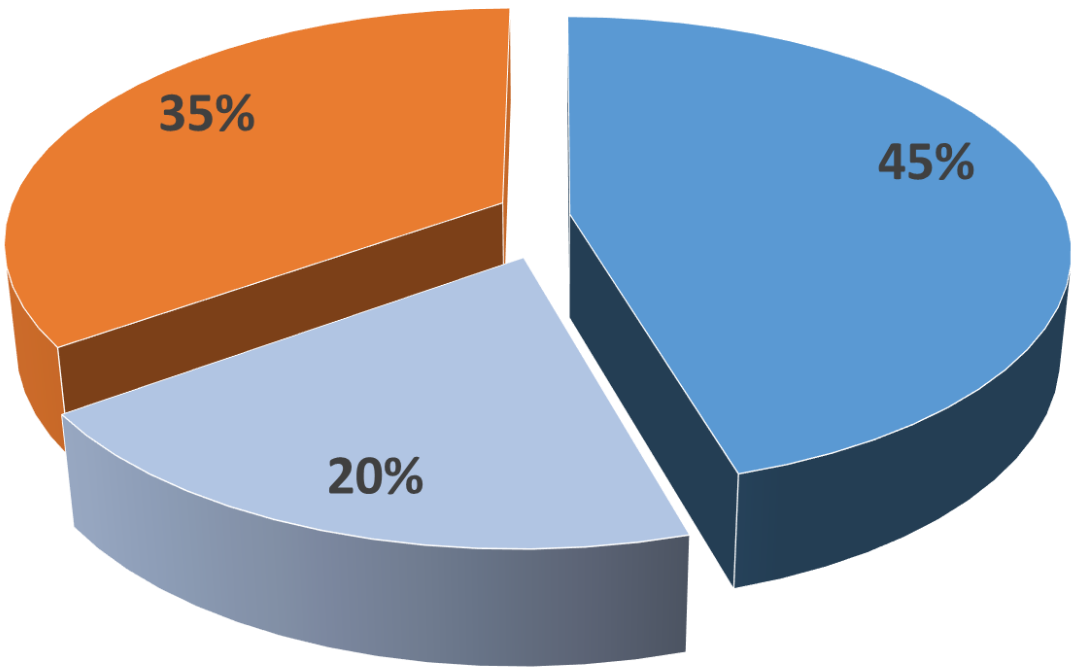


Total budget H2020:
EUR 74,83 billion

Budget of the
Energy Challenge:
EUR 5,69 billion

Euratom Research & Training Programme 2019 - 2020

Total Budget: € 770 million



- DG RTD
  Indirect actions
  Fusion R&D Programme
  € 350 million
- DG RTD
  Indirect actions
  Nuclear Fission, Safety & Radiation Protection
  € 152 million
- DG JRC
  Direct Actions
  Nuclear Safety & Security
  € 269 million

European Commission

Council Regulation

Euratom indirect actions specific objectives:

(a) supporting **safety** of nuclear systems;

(b) contributing to the development of safe, longer term solutions for the management of ultimate **nuclear waste**, including final geological disposal as well as partitioning and transmutation;

(c) supporting the development and sustainability of **nuclear expertise** and excellence in the Union;

(d) supporting **radiation protection** and development of medical applications of radiation, including, inter alia, the secure and safe supply and use of radioisotopes;

European Commission

Council Regulation

Euratom indirect actions specific objectives:

(e) moving towards **demonstration of feasibility of fusion** as a power source by exploiting existing and future fusion facilities;

(f) laying the **foundations for future fusion** power plants by developing materials, technologies and conceptual design;

(g) promoting **innovation** and industrial competitiveness;

(h) ensuring availability and use of **research infrastructures** of pan-European relevance.

European Commission

Current Euratom Nuclear Fission and Radiation Protection budget share

~ 40%	**Reactor systems** • Safety of existing nuclear installation (Gen-II-III) • Safety of Advanced nuclear systems (Gen-IV) • Partitioning, Transmutation and closing the fuel cycle • Cross-cutting aspects (e.g. fuels, materials, simulation, nuclear data) • Other applications (e.g. cogeneration, support to Research Reactors)
~ 20%	**Radiation protection**
~ 20%	**Geological disposal**
~ 20%	**Research infrastructures; Training and mobility; Cross-cutting**

Source: EC

Types of Actions – Research/Innovation

Research and Innovation Actions

They are actions with Research and Development activities as the core of the project intending to establish new scientific and technical knowledge and/or explore the feasibility of a new or improved technology, product, process, service or solution

- may include basic and applied research, technology development and integration, testing and validation on a small-scale prototype in a laboratory or simulated environment

- may contain closely connected but limited demonstration or pilot activities aiming to show technical feasibility in a near to operational environment

- 100% funding rate

"Pure" Innovation Actions

*"'Innovation action' means an action primarily consisting of activities **directly aiming** at producing plans and arrangements or designs for new, altered or improved products, processes or services. For this purpose they may include prototyping, testing, demonstrating, piloting, large-scale product validation and market replication"*

- 70% funding rate (100% for non-profit legal entities)

Types of Actions – Coordination and Support

Coordination and Support Action

Actions consisting primarily of accompanying measures such as standardisation, dissemination, awareness-raising and communication, networking, coordination or support services, policy dialogues and mutual learning exercises and studies, including design studies for new infrastructure and may also include complementary activities of strategic planning, networking and coordination between programmes in different countries.

Nuclear Fission & Radiation Protection Research (NRFP)

Call 2019-2020 Calendar

WP Adoption: *14 December 2018*
Call Open: *15 May 2019*

Submission deadline: *25 September 2019*
Evaluation: *November 2019*

62 proposals received

EC requested : EUR 265 million
EC budget : EUR 134 million

Signature of GAs: ***May 2020***

European Commission

Research and Innovation Actions (RIA)

Topic	Budgets (EUR million)
Nuclear safety - NFRP-01: Ageing phenomena of components and structures and operational issues	16
Nuclear safety - NFRP-02: Safety assessments for LTO upgrades of Generation II and III reactors	12
Nuclear safety - NFRP-03: Safety margins determination for design basis-exceeding external hazards	8
Nuclear safety - NFRP-05: Support for safety research of Small Modular Reactors	8
Nuclear safety - NFRP-06: Safety Research and Innovation for advanced nuclear systems	7.6
Nuclear safety - NFRP-07: Safety Research and Innovation for Partitioning and/or Transmutation	6

European Commission

Coordination and Support Actions (CSA)

Topic	Budgets (EUR million)
Nuclear safety - NFRP-08: Towards joint European effort in area of nuclear materials	1.1
Education and Training - NFRP-11: Advancing nuclear education	5
Research Infrastructure - NFRP-16: Roadmap for use of Euratom access rights to JHR experimental capacity	1.1
Research Infrastructure - NFRP 17: Optimised use of European research reactors	1.1

Innovation Action (IA)

Nuclear safety - NFRP-04: Innovation for Generation II and III reactors	12

Topic	Acronym	Title	Duration (Months)	Max EC contribution (M€)	Total cost (M€)
NFRP-01	**ACES**	Towards improved assessment of safety performance for long-term operation of nuclear civil engineering structures	48	4	5,5
	ENTENTE	European database for multiscale modelling of radiation damage	48	4	5
	INCEFA-SCALE	Increasing safety in npps by covering gaps in environmental fatigue assessment - focusing on gaps between laboratory data and component SCALE	60	4	6,8
	STRUMAT-LTO	Structural materials research for safe long term operation of LWR npps	48	4	4,8
NFRP-02	**AMHYCO**	Towards an enhanced accident management of the hydrogen/co combustion risk	48	4	4
	APAL	Advanced PTS analysis for LTO	48	4	4,6
	CAMIVVER	Codes and methods improvements for VVER comprehensive safety assessment	36	4	4

Abstracts, coordinator, and further info is published as soon as the Grant Agreements are signed and can be found at :

https://cordis.europa.eu/projects/en

International Cooperation

- **Multilateral**
  - **International Energy Agency (IEA)**
  - **Nuclear Energy Agency (OECD-NEA)**
  - **International Atomic Energy Agency (IAEA)**
- **Bilateral**
  - **Association Agreements with Switzerland and Ukraine**
  - **Cooperation with Japan, Canada, US, China, Korea, Brazil, Argentina…**

International Cooperation

Participation

Open for all legal entities established in third countries and for international organisations.

Restrictions only possible if introduced in the work programme.

- ✓ **For reciprocity reasons**
- ✓ **For security reasons**

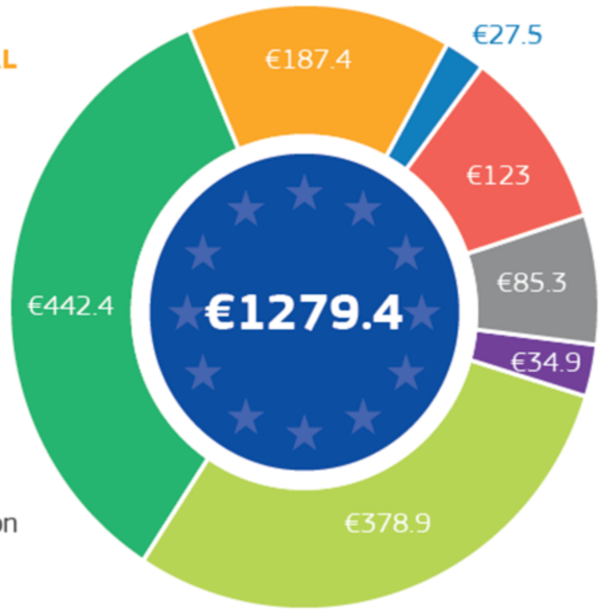
Funding

- ✓ **Third country identified in the Work Programme or**
- ✓ **participation deemed by the Commission essential in the action or**
- ✓ **when provided under a bilateral scientific and technological agreement**

European Commission

EU priorities: 2021-2027 MFF proposal

In billion euro, current prices



I. SINGLE MARKET, INNOVATION AND DIGITAL
€187.4

1 Research and Innovation
2 European Strategic Investments
3 Single Market
4 Space

II. COHESION AND VALUES
€442.4

5 Regional Development and Cohesion
6 Economic and Monetary Union
7 Investing in People, Social Cohesion and Values

III. NATURAL RESOURCES AND ENVIRONMENT
€378.9

8 Agriculture and Maritime Policy
9 Environment and Climate Action

IV. MIGRATION AND BORDER MANAGEMENT
€34.9

10 Migration
11 Border Management

V. SECURITY AND DEFENCE
€27.5

12 Security
13 Defence
14 Crisis Response

VI. NEIGHBOURHOOD AND THE WORLD
€123

15 External Action
16 Pre-Accession Assistance

VII. EUROPEAN PUBLIC ADMINISTRATION
€85.3

17 European Public Administration

Source: EC

European Commission

Commission proposal for

Horizon Europe

THE NEXT EU RESEARCH & INNOVATION PROGRAMME (2021 – 2027)

Research and Innovation

Horizon Europe budget proposal (2021-2027)

€ billion
In current prices

€ 100 B including € 3.5 from InvestEU

Source: EC

Thank you!

#HorizonEU

http://ec.europa.eu/horizon-europe

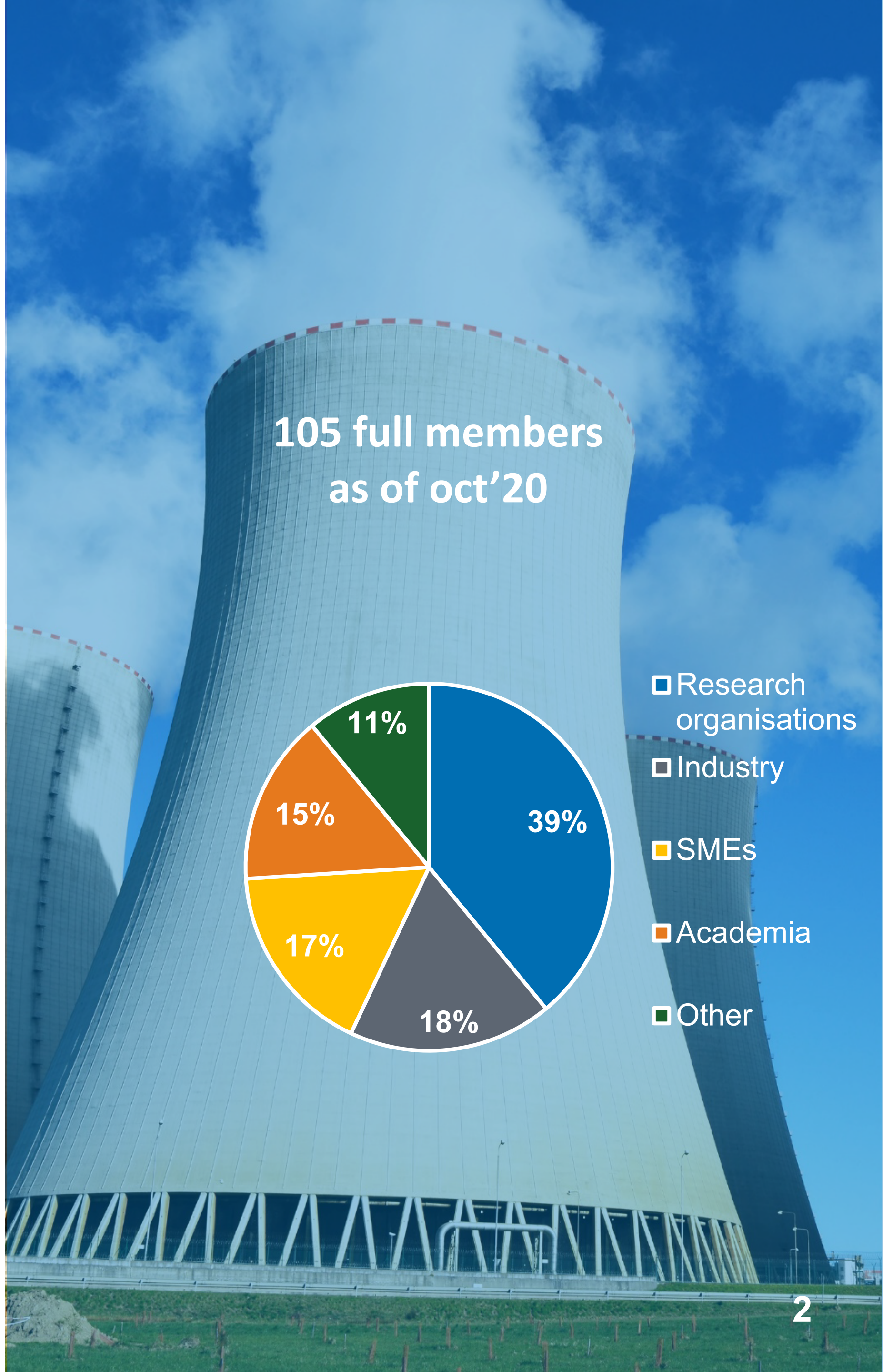
SNETP
Sustainable Nuclear Energy Technology Platform

European R&D&I towards Digital Twins

A. Al Mazouzi (General Secretariat)

SNETP in a nutshell

- SNETP was set up in 2007 under the auspices of the European Commission with the goal to **support technological development for enhancing safe and competitive nuclear fission in a climate-neutral and sustainable energy mix**.
- In line with the objectives of the SET-Plan, SNETP aims to contribute to:
  - ➢ Lowering European greenhouse gas emissions
  - ➢ Assuring security of energy supply for Europe
  - ➢ Stabilizing electricity prices in Europe
- The association gathers various types of stakeholders: industry, research centres, safety organisations, universities, non-governmental organisations, SMEs, etc.



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Objectives

Promoting Scientific Excellence
Agree on, implement and promote common R&I priorities within the SNETP community representing the three pillars

Boosting Innovation
Facilitate industrial-driven and intersectoral innovation (digital, robotics, materials, etc.) in nuclear for current and new applications (non-power, hydrogen, etc.)

Representing nuclear fission R&D in European Affairs
Promote SNETP expertise and research priorities towards European institutions

Strenghtening International Relations
Promote SNETP expertise and research priorities towards international nuclear institutions (IAEA, OECD/NEA, GIF, etc.)

Providing solutions to Industry
Foster industrial-driven research addressing the needs of SNETP industrial members in particular regarding safety, supply chain, licensing and cost-competitiveness

Cooperating closely with Regulators
Reinforce cooperation between SNETP and the different regulatory and standardization bodies.

Supporting R&D infrastructures
Support projects and initiatives aiming at maintaining/refurbishing/building the needed infrastructure to perform R&D&I in the nuclear field.

Sharing Experience with European Associations
Fostering and coordinating interactions with European associations in the field of nuclear, and any other sector with potential mutual interests with nuclear.

Engaging with Civil Society
Engage with civil society and non-nuclear stakeholders to rationalize the debate on the European energy mix and enhance the acceptability of nuclear.

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SNETP-Strategic Research and Innovation agenda

- Establishes long-term research priorities for its members
- Provides a clear research plan for industry, policy makers and research centers
- Provides state of the art analysis on nuclear research & innovation topics in line with European foreseen electricity mix in 2050 and the Green deal
- Prioritizes the topics of added value to the end users
- Create a synergy between various industrial sectors: cross-sectorial innovation (digital, material, space, ocean, robotics, etc.)
- Establish win-win relationship with national/European and international stakeholders
- Initiate and disseminate innovation within the nuclear sector

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Wo is SNETP?

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Current state of Digital Reactor

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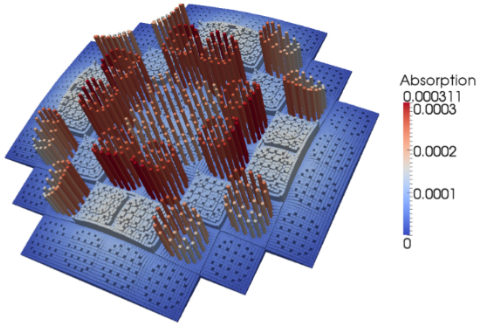
Different uses in Reactor Simulations

Higher representativity

Simulators

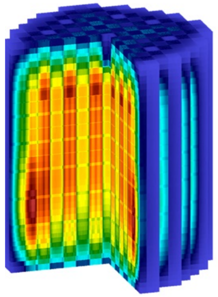
- Operators training
- Driver assistance systems
- Operations studies

Best estimate



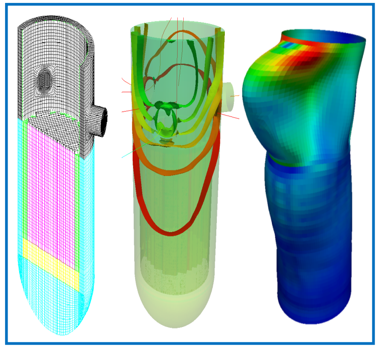
- Design Studies
- Reactor Design
- Accidents and safety studies

Best efforts



- Quantification of simulation biases
- Reference for safety studies

High Fidelity



- Reference calculations
- Studies in extreme situations (accidents…)
- Substitute for experiments where no data are available

The European Nuclear sector has a long standing experience in developing a lot of physics codes including state of the art thanks to the EURATOM support and international collaboration

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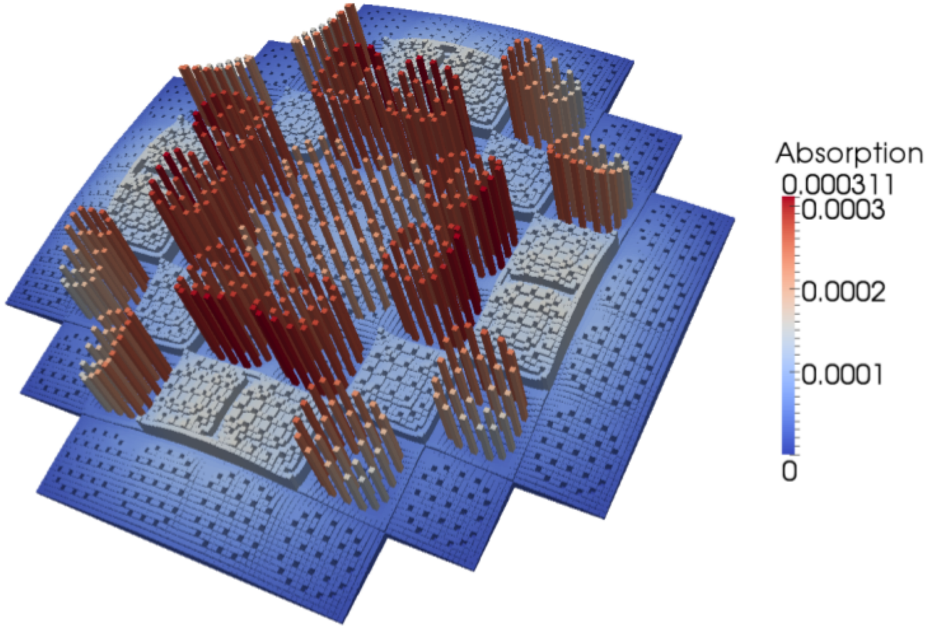
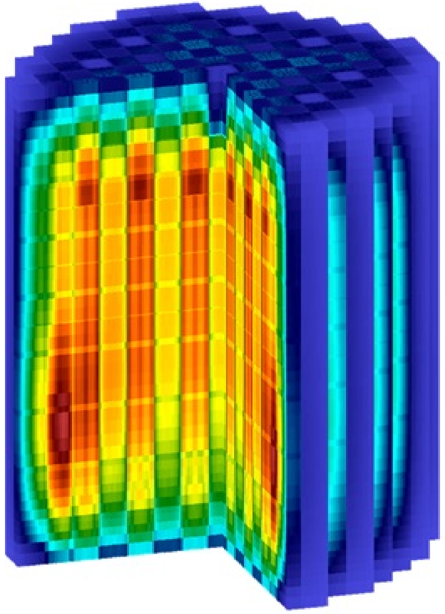
Emphasis on codes – Neutronics



neutronics code

- Both lattice and core calculations
- Transport solvers on unstructured meshes
- Parallelization on thousands of nodes
- Depletion chain with more than a thousand isotopes
- Allows advanced calculation such as direct calculation (on going work)



H2020 projects:
- ARIEL (2019-2023)
- SANDA (2020-2024)

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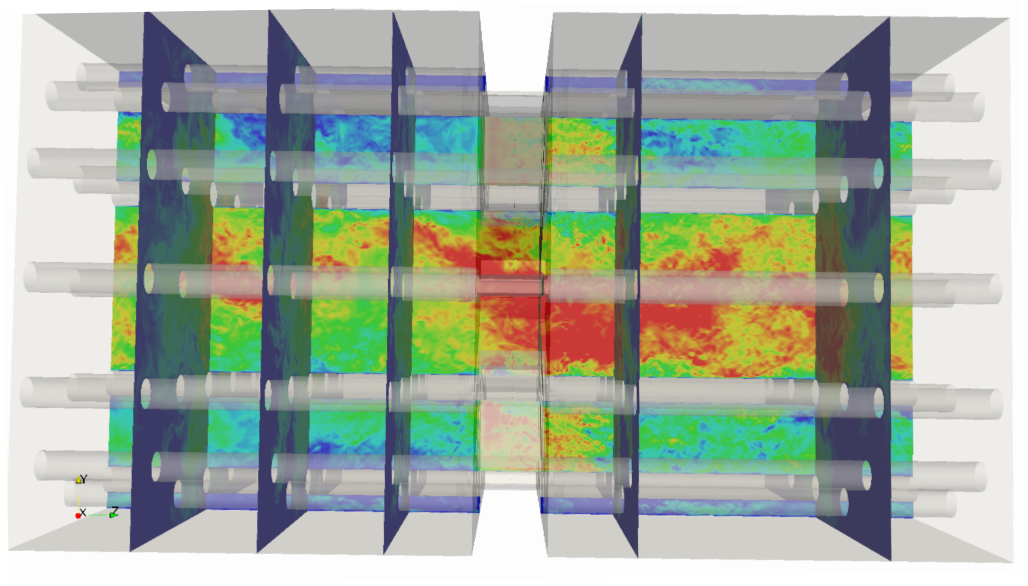
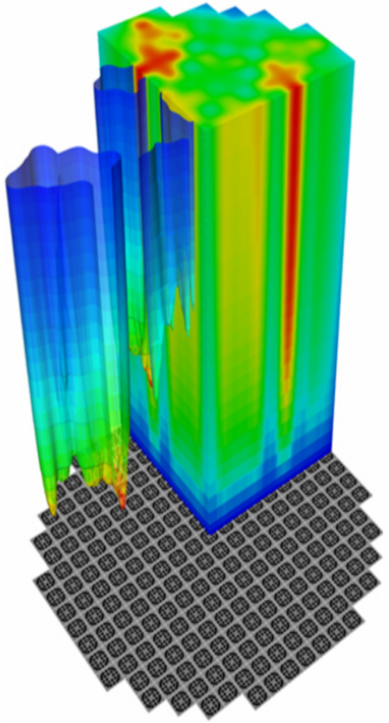
Emphasis on codes – Thermalhydraulics



CFD code

- Single and multiphase flows
- RANS and LES turbulent models
- Unstructured meshes and parallelization on tens of thousands of nodes
- Multiphysics: Fire, Severe Accidents, turbomachinery, ground water flows, …



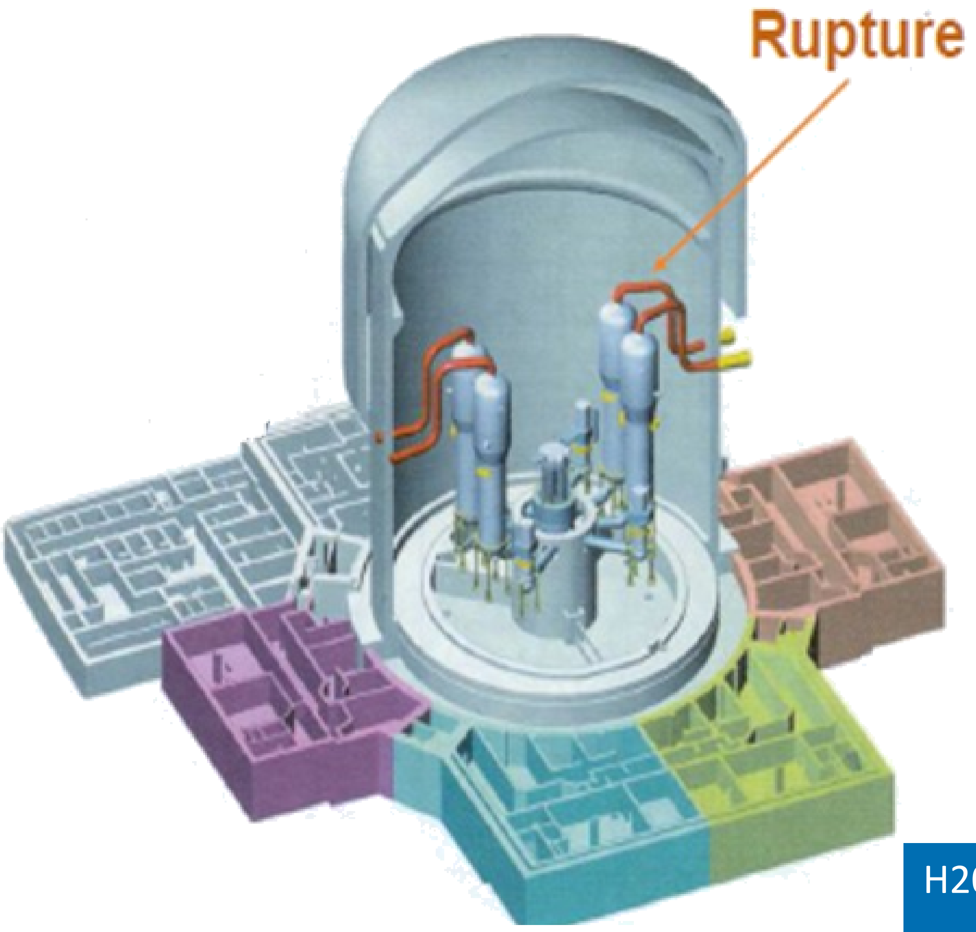
- Single and multiphase flows
- Based on the porous media assumption
- Used for Cores, Steam Generators, Heat exchangers
- used for Safety analysis, Core refueling operations ad R&D studies

H2020 projects (exemples):

- McSafe (2017-2020); McSafer (2020-2024)
- Cortex (2017_2021)
- PIACE (2020-2024)
- CAMVVER (2020-2024)

Advanced Modeling Applications

Typical use case : Steam-line break accident (SLB)



- This transient has been studied for decades by with different simulation tools.
- Very complex situation with strong physics coupling and 3D effects : good candidate for advanced simulation codes (CFD, neutronics transport with unstructured meshes…)
- Allows benchmarking between legacy and new generation of codes (test for code interchangeability)
- Possibility benchmarking with other international software (VERA from CASL,…)
- Good candidate for advanced visualization techniques to help understand the physics.

H2020 projects (examples):
- INCEFA+ & INCEFA-SCALE (2015-2025)
- MEACTOS (2017-2021)
- MUSA (2020-2024)
- APAL (2020-2024)

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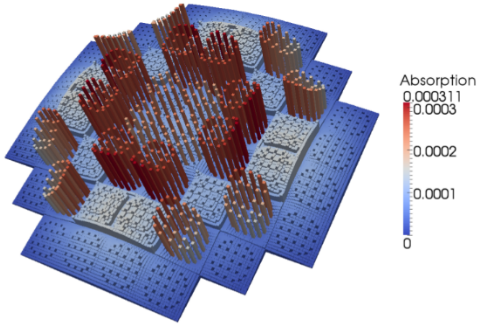
Improvements in Reactor Simulations

Representativity/quality

Simulators

- Operators training
- Driver assistance systems
- Operations studies

Best estimate



- Design Studies
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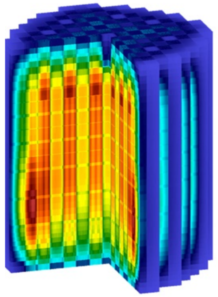

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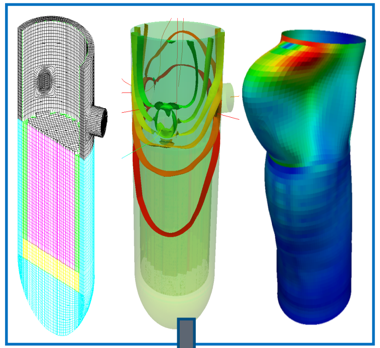
High Fidelity



- Reference calculations
- Studies in extreme situations (accidents…)
- Substitute for experiments where no data are available

Interoperability / Interchangeability

Exploitation

R&D / Expertise

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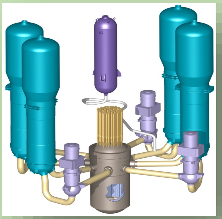
Codes and Data integration

DATA



CAD and Geometries calculation

Operating point

Physical tests and database validation

Validation of ϕ modelling

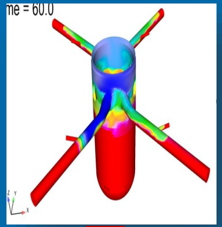
Users Needs

SOFTWARE INTEROPERABILITY & MODULARITY

Data acquisition from physical tests and exploitation

Minimization of experiments tests → **Validation of the Digital Reactor**

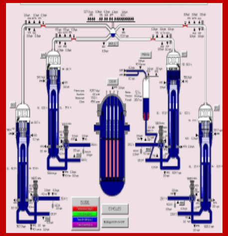
Advanced Modeling of the whole core



Optimization of the number of calculations → **Physics coupling including Uncertainties Quantification**

Models reduction

Real time modeling of the power plant



Improving physics representativity + Automation of the validation → **Visualization of complex physics phenomena**

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Some Scientific and technical challenges

- Goals / Challenges

  - Building a multi-physics (interoperability) and multi-scale (interchangeability) platform where all relevant physics codes should be able to plug in seamlessly.
  - Being able to come together with a common standard (API, data model exchange) for both new and legacy codes.
  - Building bridges to allow *advanced* codes to be used in simulators as well.
  - Using reduction models techniques for *at least* real-time simulation .
  - Taking into account, from the ground up, the possibility to quantify uncertainties.
  - Developing the right methodology for propagating uncertainties when doing multi-physics.
  - Being able to understand the physics involved as complexity increases dramatically.
  - Using advanced, ergonomic, visualization techniques (metaphors, AR, VR…) as a helping tool.
  - V&V of the whole platform when using strongly coupled physics.

Need of collaboration (European and international)

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SNETP added value

- **SNETP is the only European wide association dedicated to collaborative nuclear research.**
  - All major European R&D organisations involved in nuclear are members of the association.
  - Various events are organised and online tools are deployed to facilitate collaboration of the community on new projects proposals. Since its creation in 2007, SNETP has supported discussions on approximately 300 project ideas.
- **The specific European Technology & Innovation Platform (ETIP) status provides an important visibility to SNETP and its members**, with privileged access to relevant high-level managers within EU institutions, international organisations, and member states.
- **SNETP and its members contribute to the shaping of European energy policies**, by exchanging with peers on research priority topics, by producing reference documents (e.g. SRIA) on the state of R&D&I in Europe, by publishing position papers, etc.

Contact us

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October 18, 2020

Chris Spirito
Nuclear Cybersecurity Specialist

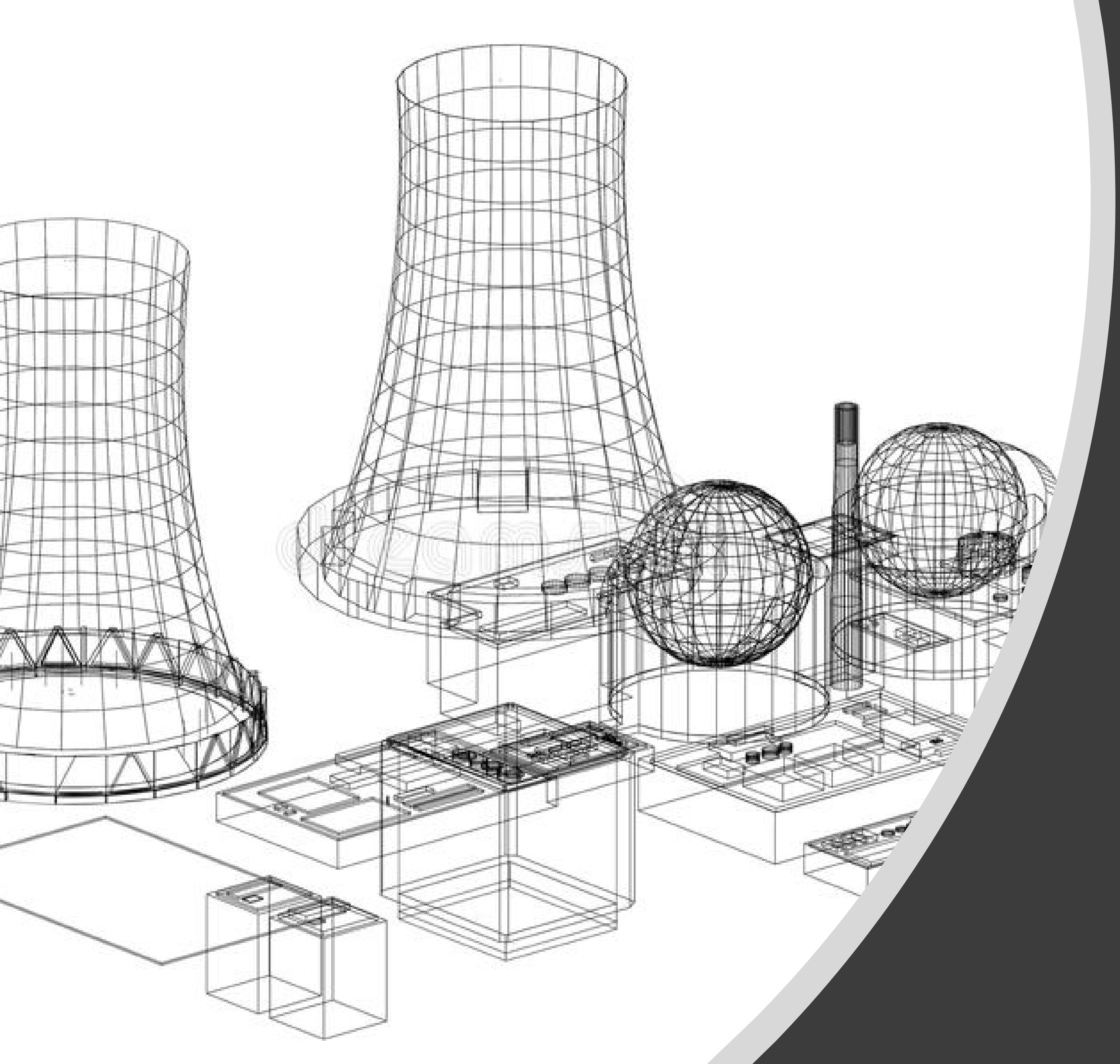
Digital Twins and Cyber Capability Development

Idaho National Laboratory

War Operations Plan Response WOPR (circa 1983)

Simulation Software / AI:
- Joshua

Simulation Models:
- Basic Strategy (Tic-Tac-Toe)
- Complex Strategy (Chess)
- Basic Warfare (Air-to-Ground Actions)
- Tactical Warfare (Theaterwide Biotoxic and Chem)
- Digital Twin (Global Thermonuclear War)



Cyber Capability Development (Digital Twins // Systems)

Reactor Simulators:
- IAEA Asherah, GSE GPWR, …

Digital Twin Targets:
- Systems
  (Pressurizer, Condenser, …)
- Components
  (PLCs, FPGAs, …)
- Comm Mediums
  (Analog, Digital, …)
- Functional Targets
  (Diodes, Proto. Converters)

Cyber Capability Development (Digital Twins / Humans)

Personality Characteristics:
- Curiosity & Relentlessness
- Novelty & Creativity,

Motivation and Ethics:
- Mercenary & Ideology

Strategies
- Weakness Exploitation
- Denial & Deception

Enumerate Interaction Pathways

Cyber Capability Development (Digital Twins / APTs)

Interactive Test Ranges:
- Integrated AI
- Infrastructure Modeling

Attack Library:
- Validation of Capabilities
- Validation of Processes
- Theoretical Testbed

Idaho National Laboratory

WWW.INL.GOV

Cyber Security for Digital Twins

Cynthia DeBisschop and Alan (Al) Konkal

Senior Cyber Security Analysts

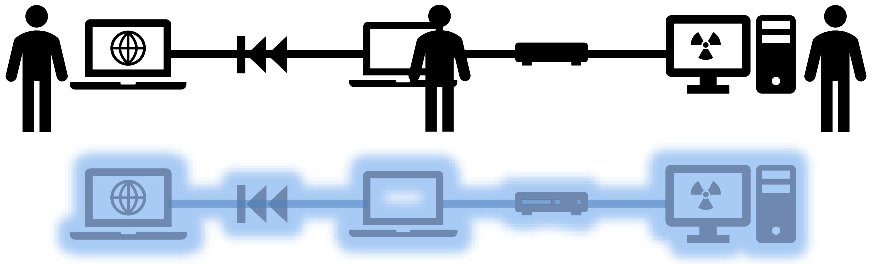
NRC Contractors, Cyber Security Branch (CSB)

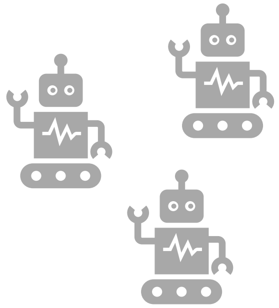
Division of Physical and Cyber Security Policy (DPCP)

Office of Nuclear Security and Incident Response (NSIR)

Overview

- Background
- Motivation
- Considerations for Entire Life Cycle of Digital Assets
- Cyber Security Vulnerabilities and Protective Strategies
- Summary





ICON LEGEND

→ **Real World**
→ **Virtual Model**
→ **Technology Gap**

Collaborative Review

INL DICE Glossary[1] of Terms: What Does Cyber Analyst Hear?

- **Digital Twin.** The computational simulation of a physical process or system that has a live link to the physical system, enabling enhanced verification of the simulation, control of the physical system, and analysis of trends via artificial intelligence and machine learning.
- **Artificial Intelligence (AI).** The simulation of human intelligence in computers or computer-controlled robots, allowing them to perform tasks commonly associated with intelligent beings.
- **Machine Learning.** The application of AI that provides systems the ability to automatically learn and improve from experience without being explicitly programmed.
- **Operational AI.** The application of artificial intelligence (AI) in energy systems to automate expensive and manual human activities and improve the efficiency of asset operations.
- **Next Gen AI.** The simulation of human intelligence in computers or computer-controlled robots, allowing them to perform tasks commonly associated with intelligent beings.

[1] Source: Idaho National Laboratory (INL) Digital Innovation Center of Excellence (DICE) at https://dice.inl.gov/glossary-of-terms

Technology Gap Must Close Safely, If at All

INL DICE Operational Artificial Intelligence[2] Description

The use of artificial intelligence (AI) in energy applications has a game-changing potential in automating expensive and manual human activities in various types of industries. In the energy industry, power plants (especially nuclear) rely on staff performing several types of manual activities on a regular basis. Future energy plants, including advanced nuclear reactors, are designed to reduce the dependence on people for the operations, maintenance, and support activities of a plant. A light water nuclear power plant is typically full of analog gauges and manual actuators. By comparing a nuclear power plant control room to a modern airplane cockpit where the plane can fly itself and the pilot's role can be reduced to simply monitoring the airplane, it is obvious that a significant technology gap exists that needs to be closed. Human intelligence needs to be replaced by machine intelligence in various forms of AI if this vision is to be realized.

- **Comparison of nuclear power plant (NPP) control room to modern self-flying-airplane cockpit**
- **Mention of need to close significant technology gap if this Vision is to be realized for NPPs**
- **Cyber Security Analyst: Technology gap must close safely, if at all**

[2] Source: Idaho National Laboratory (INL) Digital Innovation Center of Excellence (DICE) at https://dice.inl.gov/operational-artificial-intelligence

Motivation

Pop Quiz[3] from October 2019 Forbes Article "How to Protect Your Digital Twin"

Q. "Which of the following is more valuable: a Boeing 777 or the digital twin of a Boeing 777?"

A. "The first option, the physical plane, is an expensive item – buying a new one will cost you around $344 million. Yet, the digital twin of a 777 is far more valuable. It's the digital simulation of the plane that constantly collects situational awareness data and is used to understand and improve the ongoing performance of various parts and systems. If you control the digital twin, you control every 777 on (and above) the planet."

BONUS. Fill in the Blank.

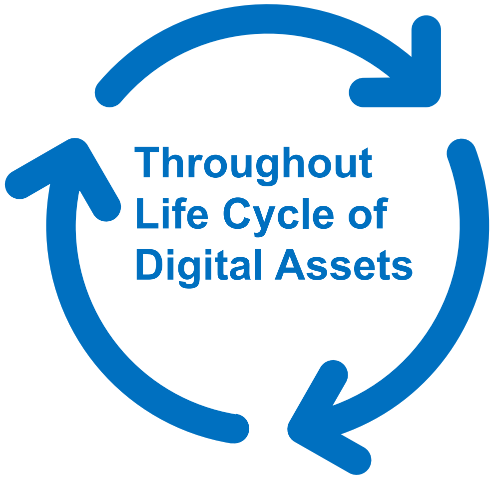
Cyber Security Analyst: To effectively _protect_, think carefully throughout the evolution. Keep the vision in mind. Evaluate protections with every step along the road!

[3] Source: Kawalec, Andrzej, ''How to Protect Your Digital Twin,'' Forbes Technology Councill Post, October 21, 2019, at https://www.forbes.com/sites/forbestechcouncil/2019/10/21/how-to-protect-your-digital-twin

Need to Understand/Consider

(Now, Throughout Evolution, and Before Procurement or Use)

- Technology Itself
- Security Gaps
- Threat You Are Designing Against
- Changes to Environment of Digital Assets
- Attack Surfaces of Digital Assets
- Cyber Risk
- Consequences of Cyber Attacks
- Defense-in-Depth Protective Strategies



Cyber Security Vulnerabilities

- **Data Exfiltration.** Plant sensors and data streams need to be connected to virtual model to realize concept. Digital twin is intended to be near-perfect blueprint of its real twin. Potential exists for monitoring and exfiltration of information about types of systems and sensors used by plant.
- **Man in the Middle Attack.** Early component failures may result due to alternated maintenance cycles based on faulty data after a compromise, if data is used for predictive maintenance. Scenarios that involved predictive component failure were used in the now famous Stuxnet attack. Untimely failure of a key component could be used as an element of a kinetic attack.
- **Supply Chain Attack.** Digital twins can be used to model new components, testing how they will perform under real-world conditions. Data obtained from components of digital twin models can be used in manufacturing. Compromised components data could lead to manufacturing faulty components.

Protective Strategies

Fully Implement a Sound Cyber Security Framework

- NEI 08-09, RG 5.71, NIST 800-53, and NIST 800-82
- Implement security patches and remediate vulnerabilities quickly
- Harden digital twin platforms
  - Utilize hash code-based allowlisting
  - Remove all unnecessary files and services
  - Implement Anti-Virus and Host Intrusion Detection Systems
- Identify security and remediate gaps between the twin and the physical hardware

Protective Strategies

Secure Software Development Environments

- Develop in secure isolated environment
- Verify all Third Party and Open Source Code
- Test for language conformance, known vulnerabilities and flaws
- Conduct peer code reviews
- Use a secure repository control
- Utilize security testing techniques, fuzzing and penetration testing

Protective Strategies

Implement Software Hardening

- Harden software to make the binary resistant to hacking
- Use coded cyclic redundancy checks (CRC) or embedded hash codes checks, binary runtime encryption
- Utilize inline coding and merge functions to minimize modular code, and altered code flow to make reverse engineering difficult
- Implement glass box techniques
(Binary code can only run on designated hardware)

Protective Strategies

Supply Chain and Intellectual Property

- Supply Chain Protection
  - Audit vendors for compliance with cyber security best practices
  - Test and verify third-party code releases prior to introducing them into your environment
  - Purchase hardware and software from trusted sources
- Protection of All Intellectual Property
  - Secure all digital twin artifacts, documents, schematics, etc.
  - Protect all information flow to and from the digital twin platform
  - Minimize access to source code and critical design elements

Summary

- This presentation offers considerations from a regulatory perspective while digital twin technology is in development.
- Before procurement or use of technology and throughout its evolution, there is a need to understand the attack surfaces and environments associated with digital assets.
- Nuclear power plant operators maintain the following throughout the life cycle of digital assets: a security defensive architecture to address the attack surfaces and environments, and multiple layers of cyber security protections to establish sufficient defense-in depth. Defense-in-depth protective strategies are maintained to ensure the capability to detect, respond, and recover from cyber attacks.
- Such an objective depends on understanding and careful consideration of technology before procurement or use.

Asherah NPP Simulator Cybersecurity in a Digital Closed-Loop Environment

The 2020 Workshop on Digital Twin Applications in the Nuclear Industry

Rodney Busquim e Silva
December 3, 2020

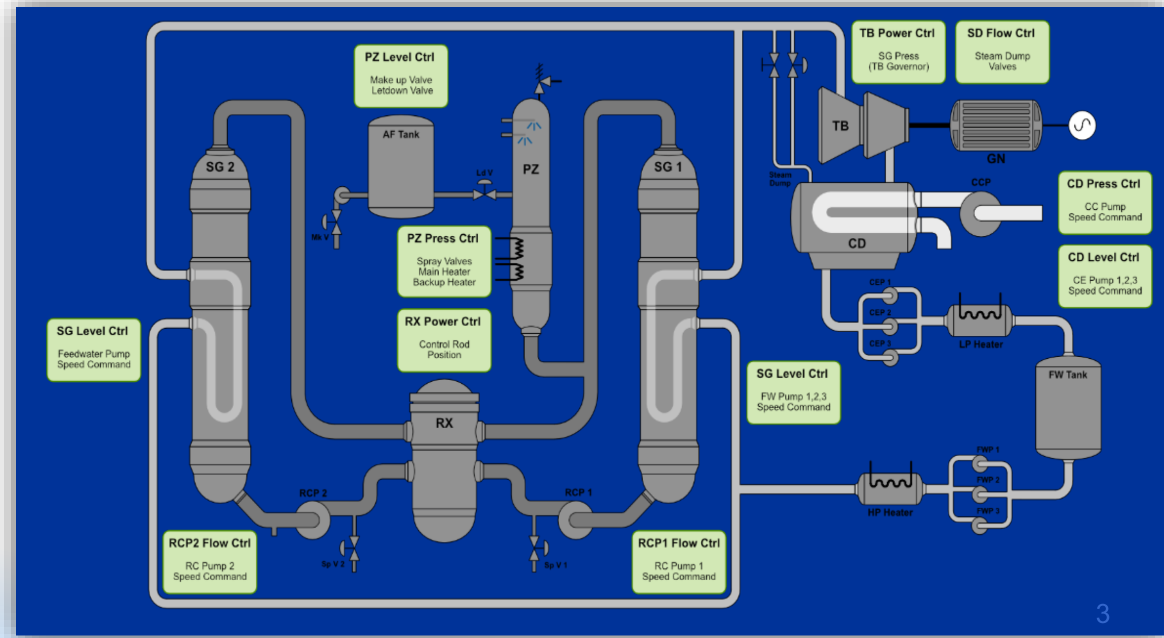
Nuclear Power Plants Rely on Digital-based Systems

- NPPs are among the most complex energy systems ever built.
- NPP functions and processes rely on a myriad of digital IT and I&C systems.

- NPPs' capital cost and the radioactive nature of nuclear fuel demand computational tools for licensing, operation and accident analysis.
- NPPs are among the most emblematic examples of critical infrastructure cyber-targets.

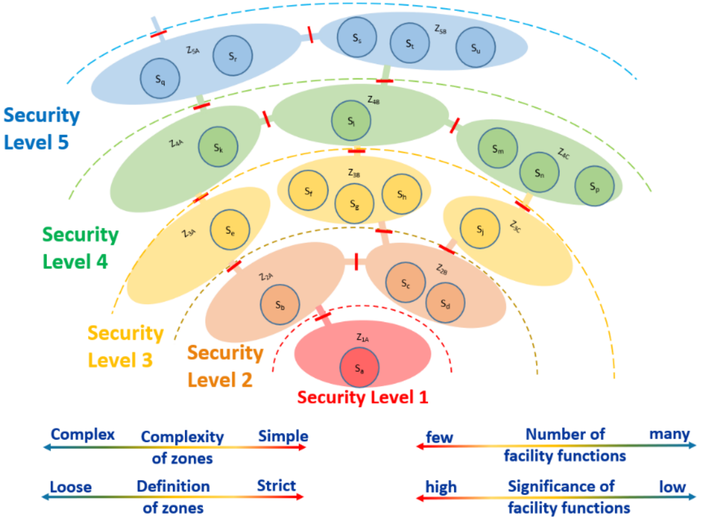
The Challenge

How can we improve cybersecurity capabilities, conduct IT and I&C research, increase awareness, and perform training and hands-on exercises in an integrated nuclear power plant environment?



In a NPP environment, how do we:

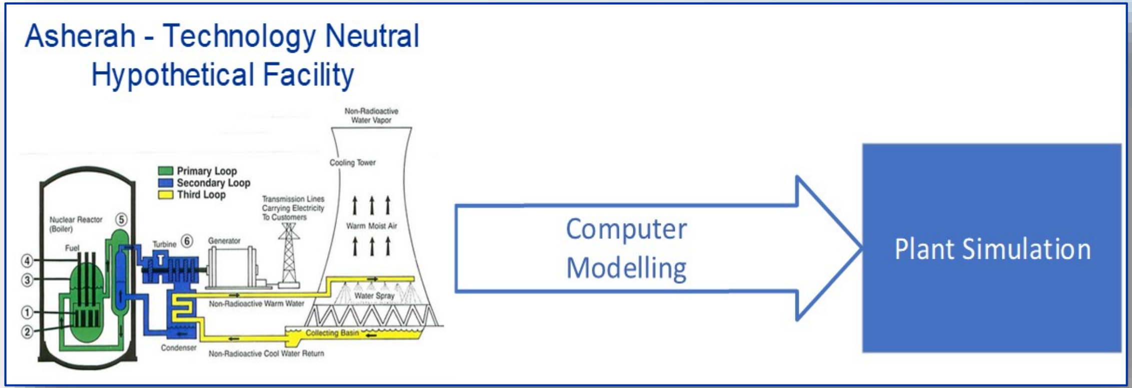
- assess the facility impact of a system being compromised?
- evaluate the effectiveness of segregating facility functions?
- assess computer security (CS) vulnerabilities in the systems that perform functions?
- evaluate the use of de-coupling mechanisms?
- test the effectiveness of firewall rules?
- … and assess many other CS related issues?



NST047 Fig 9

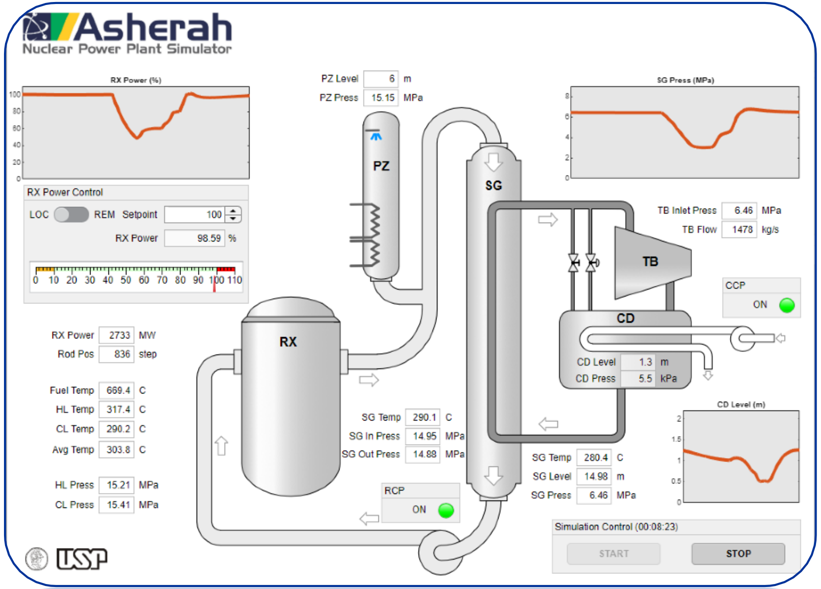
IAEA CRP: Asherah NPP Simulator (ANS)

A hypothetical/neutral PWR named "Asherah" was defined based upon several NPP existing designs.



- The results were combined to produce a technological neutral facility.
- USP developed ANS model to be the heart of a cyber security assessment test bed.
- The simulator was designed specifically for the simulation of cyber-attacks.

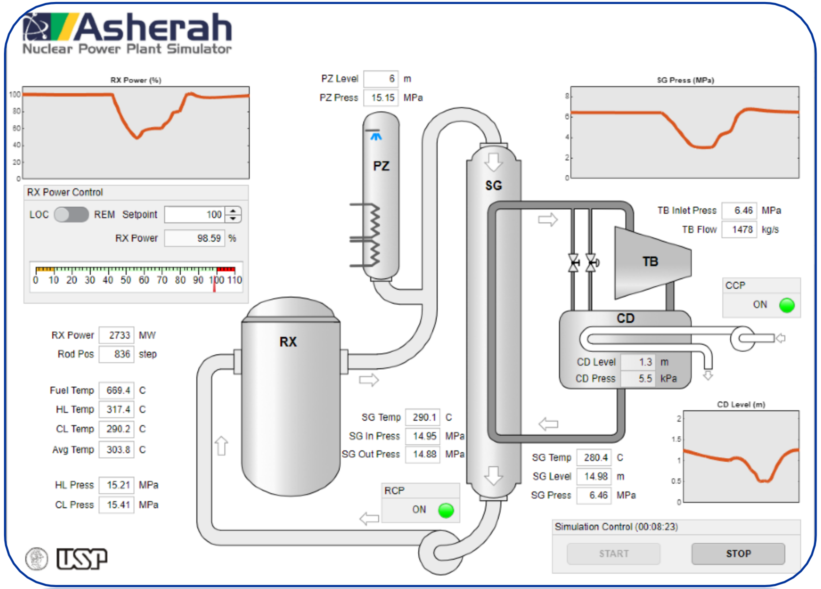
IAEA CRP: Asherah NPP Simulator (ANS)

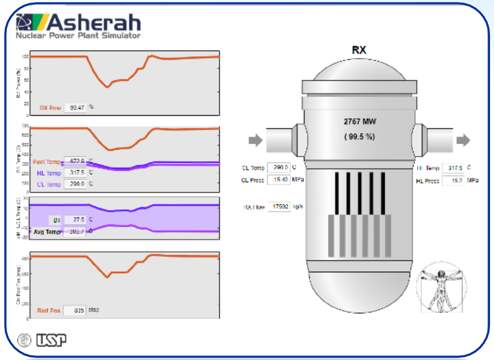


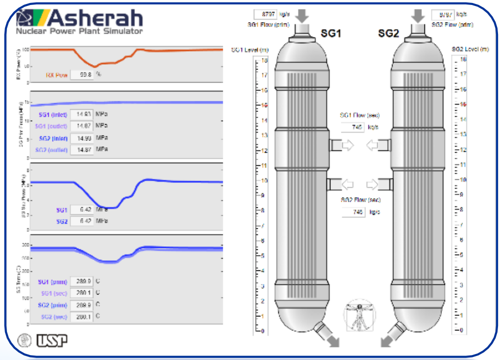
Local HMI & Simulation Control

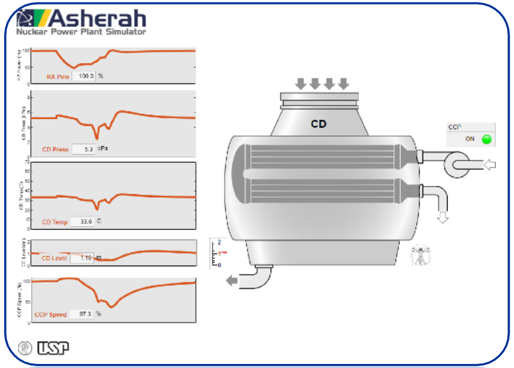
- ANS reproduces the Asherah NPP behavior using dynamic models.
- It is based on:
  - The TMI core.
  - Typical industry systems and equipment.
  - Standard control logic.
- It has been implemented using the Matlab/Simulink environment.
- It has the capability to interface with IT/OT equipment for cyber security assessment.

IAEA CRP: Asherah NPP Simulator (ANS)









Local HMI & Simulation Control

WATCH THE VIDEOS

ANS Interfaces

- ANS has been connected to physical and virtual controllers - and other equipment.
- USP developed I/O interfaces for Modbus and OPC-UA & DA communication.
- USP has also developed a light OPC UA Server & client, i4BrSrv, for ANS communication.

ANS Deployment Modes

Abstract & Portable

Standalone — ANS (plant processes & controllers) running in one VM

Model-Based — ANS plant processes & controllers running in many VMs

CLDT-Based — ANS plant processes & controllers running in a Closed-Loop Digital Twin (CLDT) test bed

HIL-Based — ANS plant processes & controllers running in a Hardware-In-the-Loop (HIL) test bed

Concrete & Complex

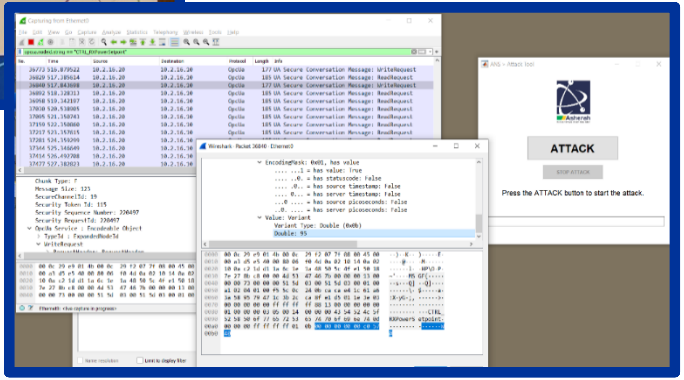
IAEA ICONS 2020 DEMO: HIL and Model-based Run

Easy to run by any user

Model & HIL based setups

4 Virtual machines per setup

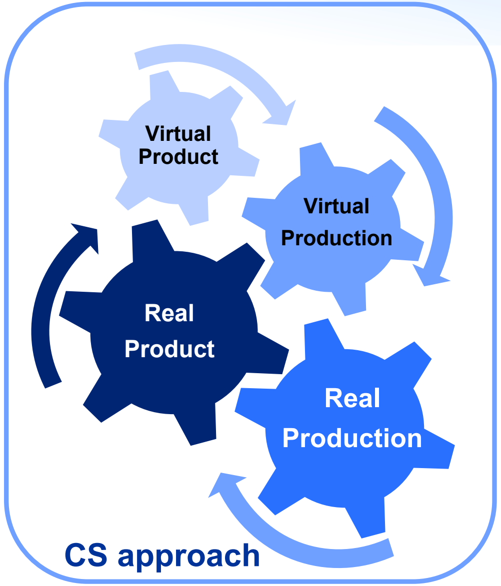
Easy to analyze the network



Closed-Loop Digital Twin (CLDT)

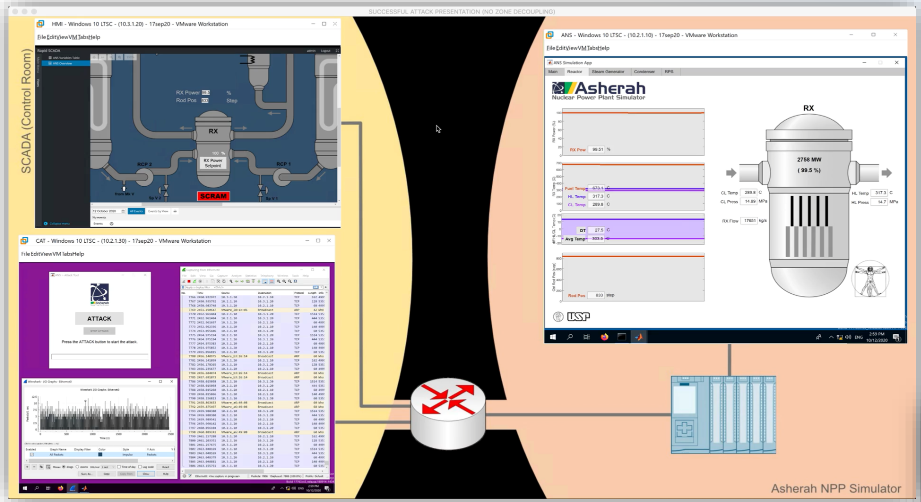
- A DT is a simulated/emulated device/system that replicates in detail their physical counterparts on the logic and network layer.

- A DT may be leveraged for CS purposes in two ways:
  - Simulation mode
  - Replication mode



- CS can be introduced during the **product design** and production phases.
- CS can be seamlessly integrated in the entire digital-based systems **lifecycle**.

ANS PLC CLDT: Successful Attack Example



- Attack scenario where a PLC is compromised from outside the I&C controllers network.
- A PLC DT integrated with the ANS CLDT test bed allows for assessment of the network indicator of compromise and of the facility impact.

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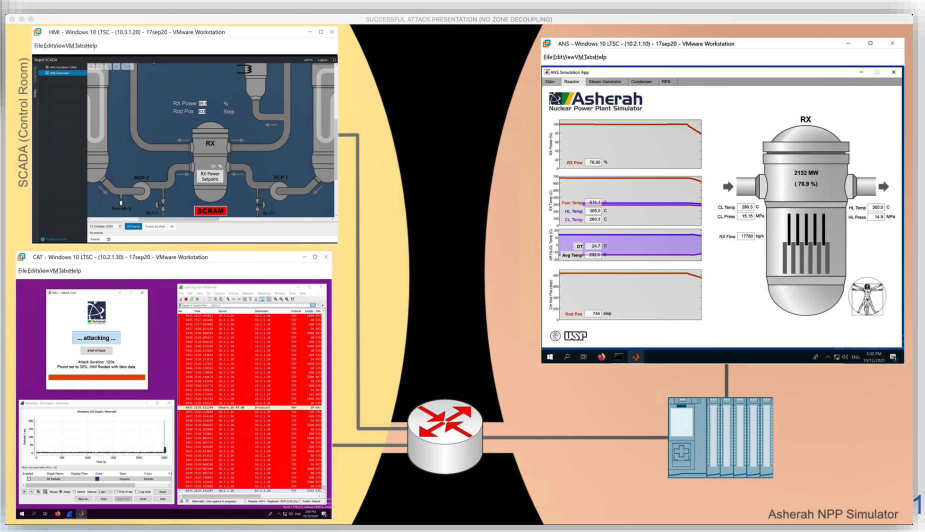
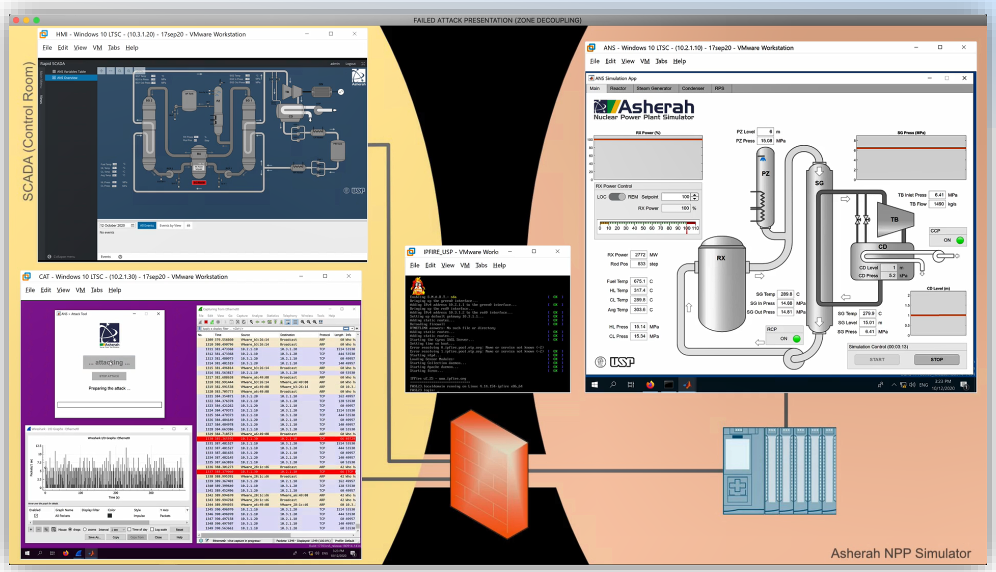


ANS PLC CLDT: Unsuccessful Attack Example

The ANS PLC CLDT Simulation mode test bed allowed for:

- Monitoring of NPP facility functions.
- Assessment of the effectiveness of a computer security strategy.
- Monitoring I/O tags at the PLC (process).
- Checking integrity and availability of PLC I/O tags and HMI tags (network).
- Introduction of CS from the design phase.



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Final Remarks

- DTs create new possibilities for monitoring, simulating, estimating and assessing states of real systems.
- ANS was developed for an IAEA CRP (17 teams of 13 MS) for computer security research and it has been supporting graduate and postdoctoral studies.
- ANS has been integrated in test beds, applied in CS exercises and demonstration in Austria, Brazil, Canada, China, Germany, ROK and USA.
- DTs can be leveraged for computer security purposes when integrated with nuclear simulators like the ANS.

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Thank you!

Advanced Modeling and Simulation and its Future Role in Nuclear Systems Digital Twin Technology

Dave Kropaczek
Oak Ridge National Laboratory

Technical Session: Multiphysics Modeling
Digital Twin Applications for Advanced Nuclear Technologies
December 1-4, 2020

Digital Twin – Role of Modeling and Simulation

"The digital twin is the virtual representation of a physical object or system across its life-cycle. It uses real-time data and other sources to enable learning, reasoning, and dynamically recalibrating for improved decision making." *

In Nuclear Systems, the digital twin may be characterized by:

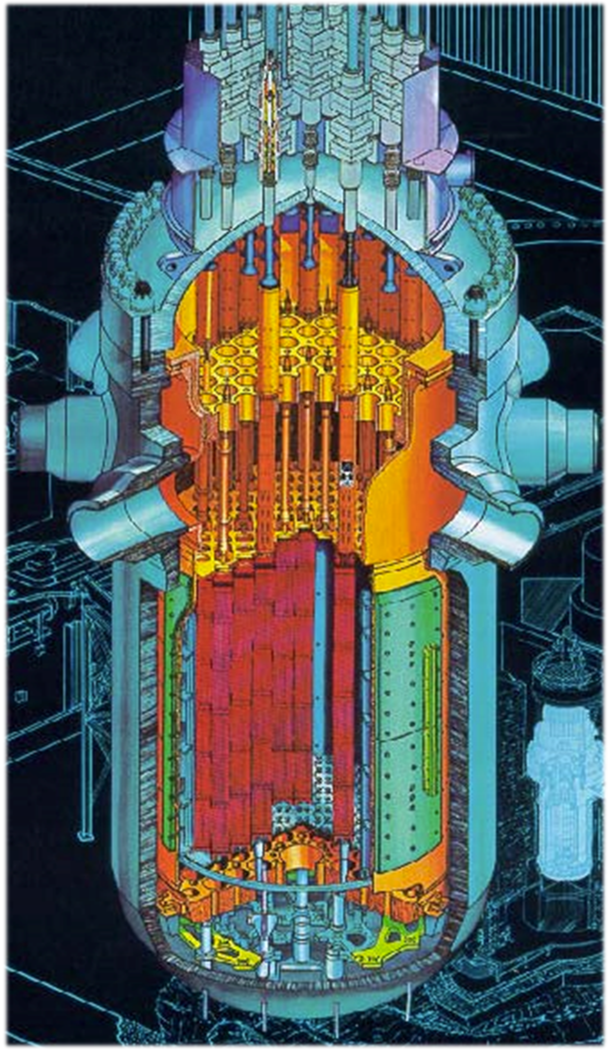
- Virtual simulator for the plant systems and subsystems, including the reactor core and fuel
- Use of a wide-range of sensors (in-core/ex-core detectors, thermocouples, pressure, flow, etc.)
- Mapping of sensor data onto the virtual model through update of the simulator model parameters
- Recalibration of the virtual simulator based on real-time data
- Use of the virtual simulator to monitor operational limits (e.g. core, fuel)
- Use of the virtual simulator to make future projections regarding reactor behavior under "what if" scenarios
- Use of the virtual simulator as part of the reactor control system (human or autonomous)

By these definitions, the digital twin for nuclear systems has existed for decades in the form of on-line core monitoring systems. What has changed are the advances in modeling, sensors, calibration techniques, and predictive analytics to enable a step change in decision-making capabilities for reactor operation.

* *https://www.ibm.com/blogs/internet-of-things/iot-cheat-sheet-digital-twin/*
with credit to Josh Kaizer, NRC

Digital Twin - Virtual Simulator

- High fidelity predictive simulation for quantities of interest
  - Safety parameters (temperatures, power deposition)
  - Operational parameters (power response, energy output)
  - Component behavior (lifetime analysis)
- Physics-based modeling for key phenomena
  - First-principles based (elimination of correlations)
  - Multi-physics response for coupled physics
  - Includes neutronics, thermal-hydraulics, chemistry, and materials modeling
- High geometrical resolution
  - Sufficient resolution to make use of real-time sensor data
  - Modeling across length scales – atomistic to engineering scale
- Comprehensive, usable and extensible software system
  - Verified software – code and solution verification
  - Validated software – single and integral effects tests
  - Quantified uncertainties for model parameters and input data



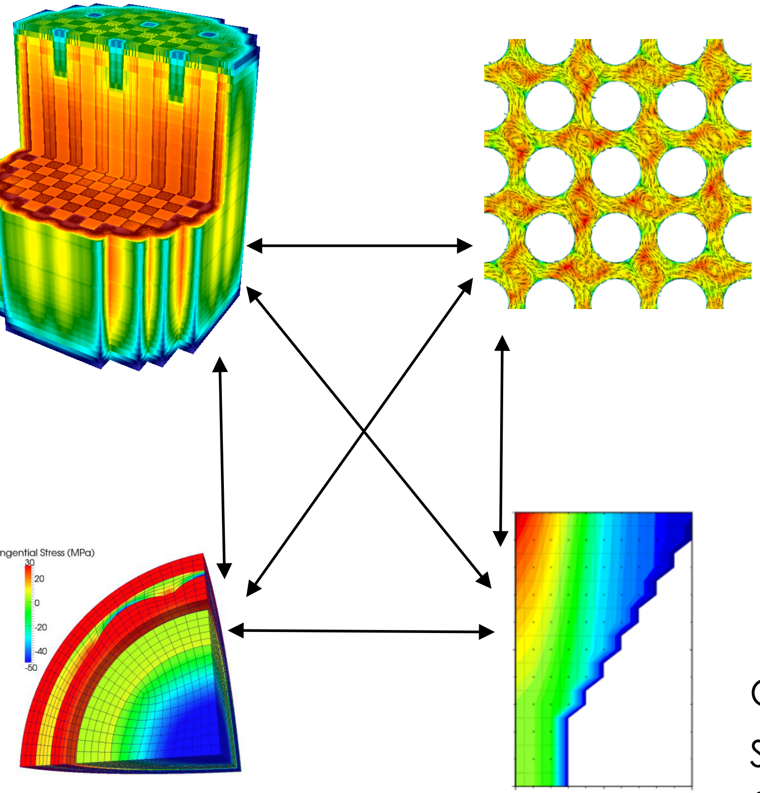
Multi-Physics Coupled Simulation

Reactor Physics

- (n + γ) Transport
- Nuclear XS Feedback
- On-the-fly XS Processing
- Isotopic Transmutation

Thermal Hydraulics

- Mass, Momentum, and Energy Transport
- Whole-core flow field resolution
- Multi-phase flow

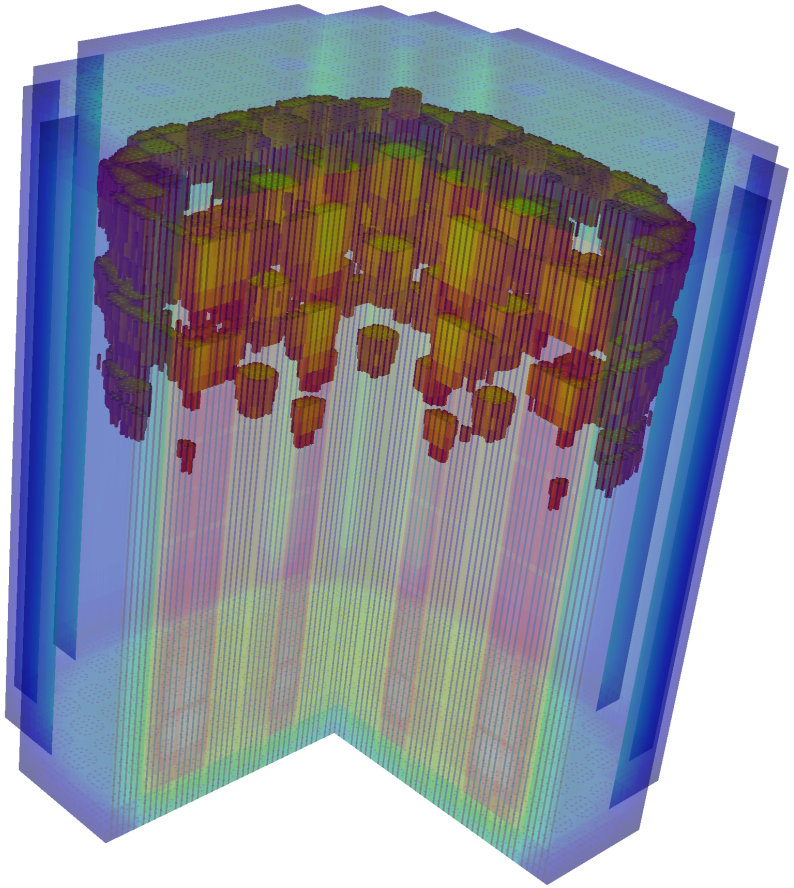


Fuel Performance

- Thermal Transport
- Fuel Evolution (relocation, swelling)
- Clad Evolution (creep)
- Mechanical Contact

Coolant Chemistry

- Crud source term
- Surface deposition and growth
- Equilibrium thermodynamics
- Chemical Kinetics



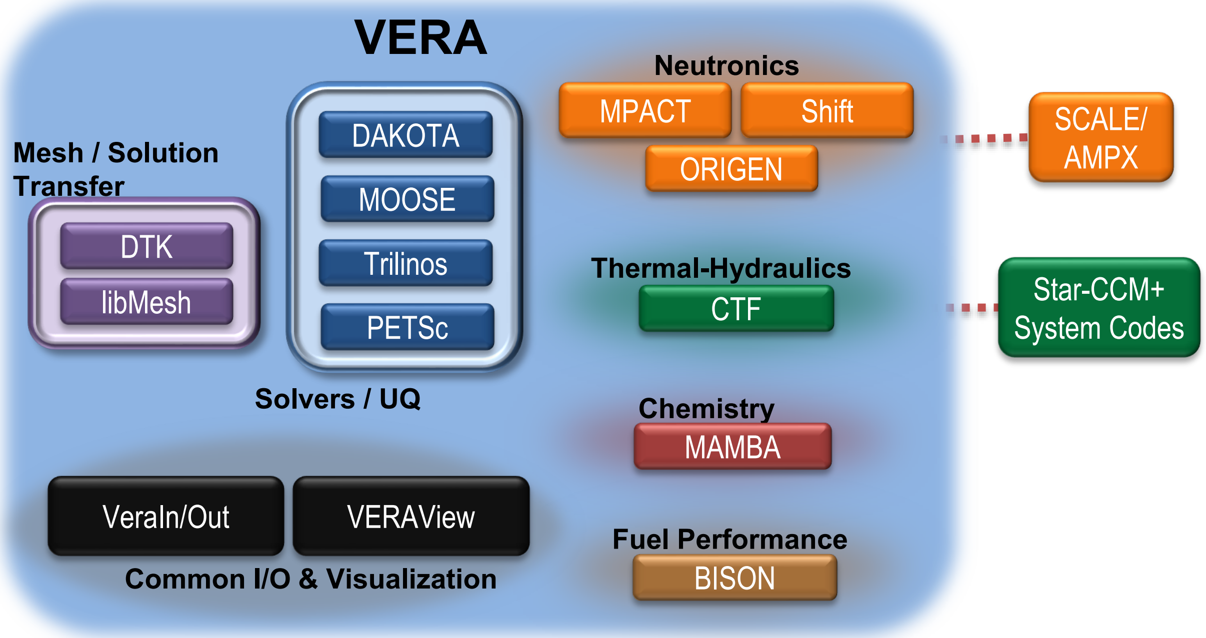
Crud distribution in a PWR

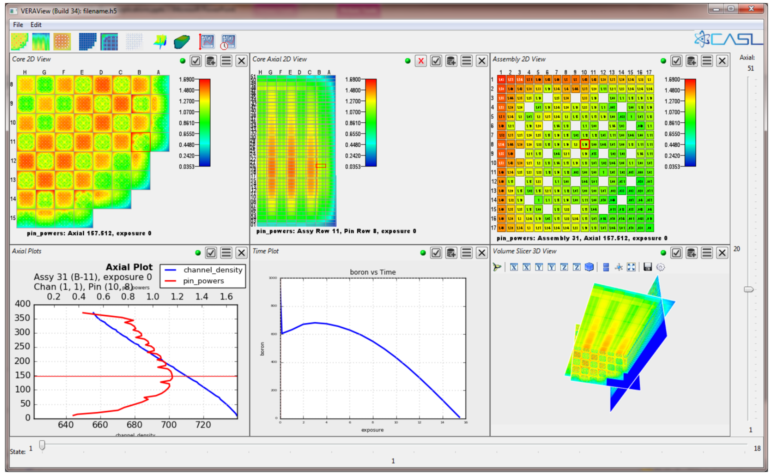
Physics Phenomena of Interest are Common to All Reactor Types

VERA – A Fully Integrated Capability for Reactor Analysis

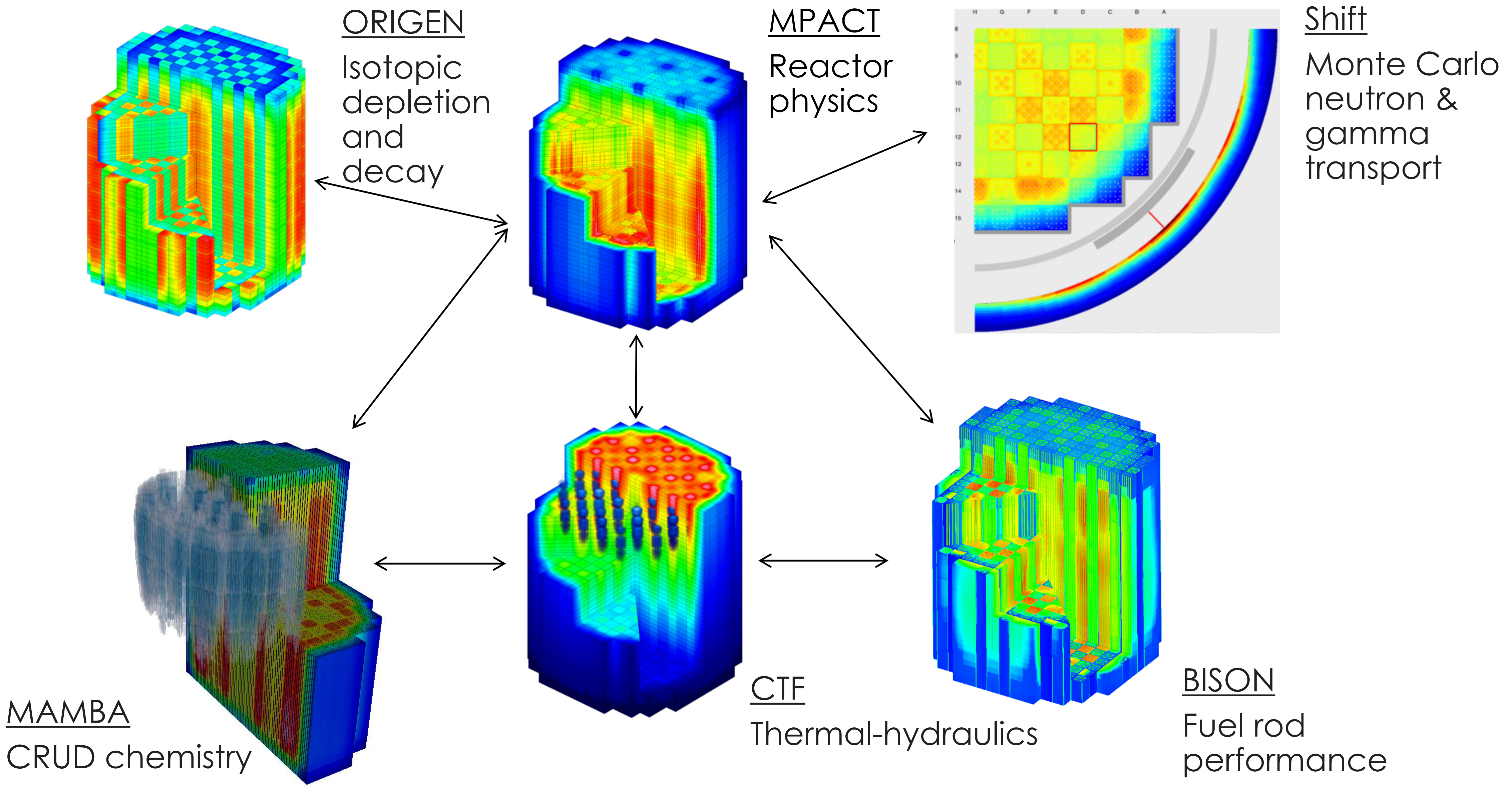
Virtual Environment for Reactor Applications

- High Resolution:
  - Fully coupled and pin-resolved neutronic, T/H, and crud growth physics
  - Detailed rod-wise fuel performance analyses
- Integrated Applications:
  - Modeling in-core and ex-core detector prediction of axial offset (AO) due to CRUD deposition
  - Identification of PCI failure risk during load follow operation with accident tolerance fuel and cladding
  - Accumulation of radiation damage in the reactor vessel due to neutron fluence
  - Prediction of cladding integrity during reactivity-initiated transient using coupled neutronics and T/H with offline fuels analysis
- Performance & Usability:
  - User-friendly I/O (e.g. automated mesh generation and data transfers)
  - Integrated visualization tools



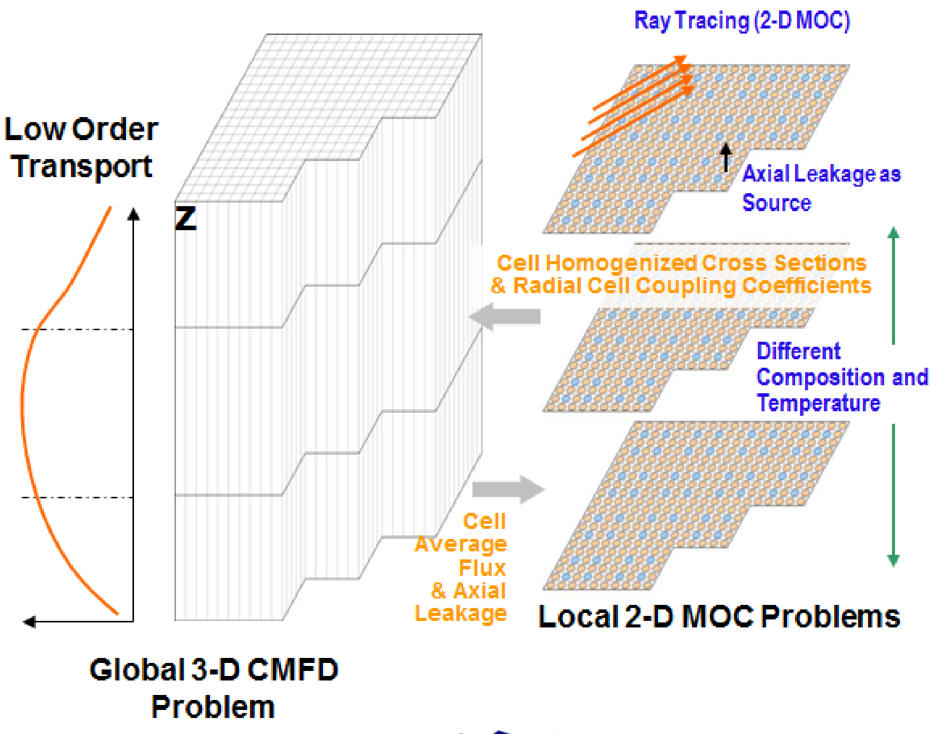


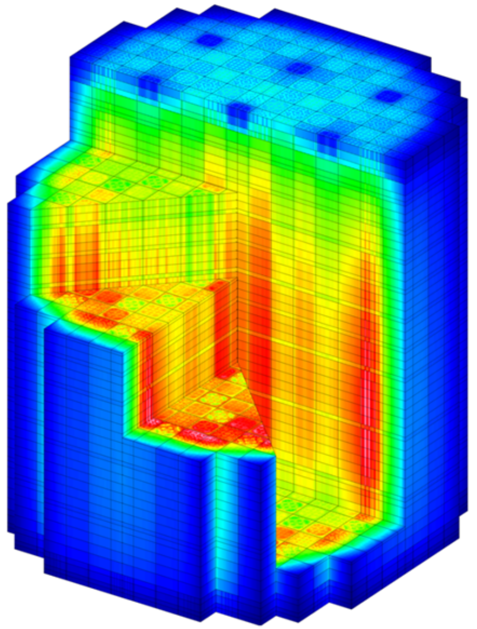
VERA Key Physics Codes



MPACT

- Advanced 3D Neutronics
  - Method-of-Characteristics
  - 51 energy group nuclear data library
  - Whole pin-wise resolution, including intra-pellet power and isotopic distributions
- Steady-state and transient capability
- Integrated explicit isotopic depletion and decay with ORIGEN
- 3D accuracy comparable to continuous-energy Monte Carlo methods, including Shift and MCNP
- Core shuffling and control rod movement
- In-core detector responses
- Validated against critical experiments and over 150 fuel cycles

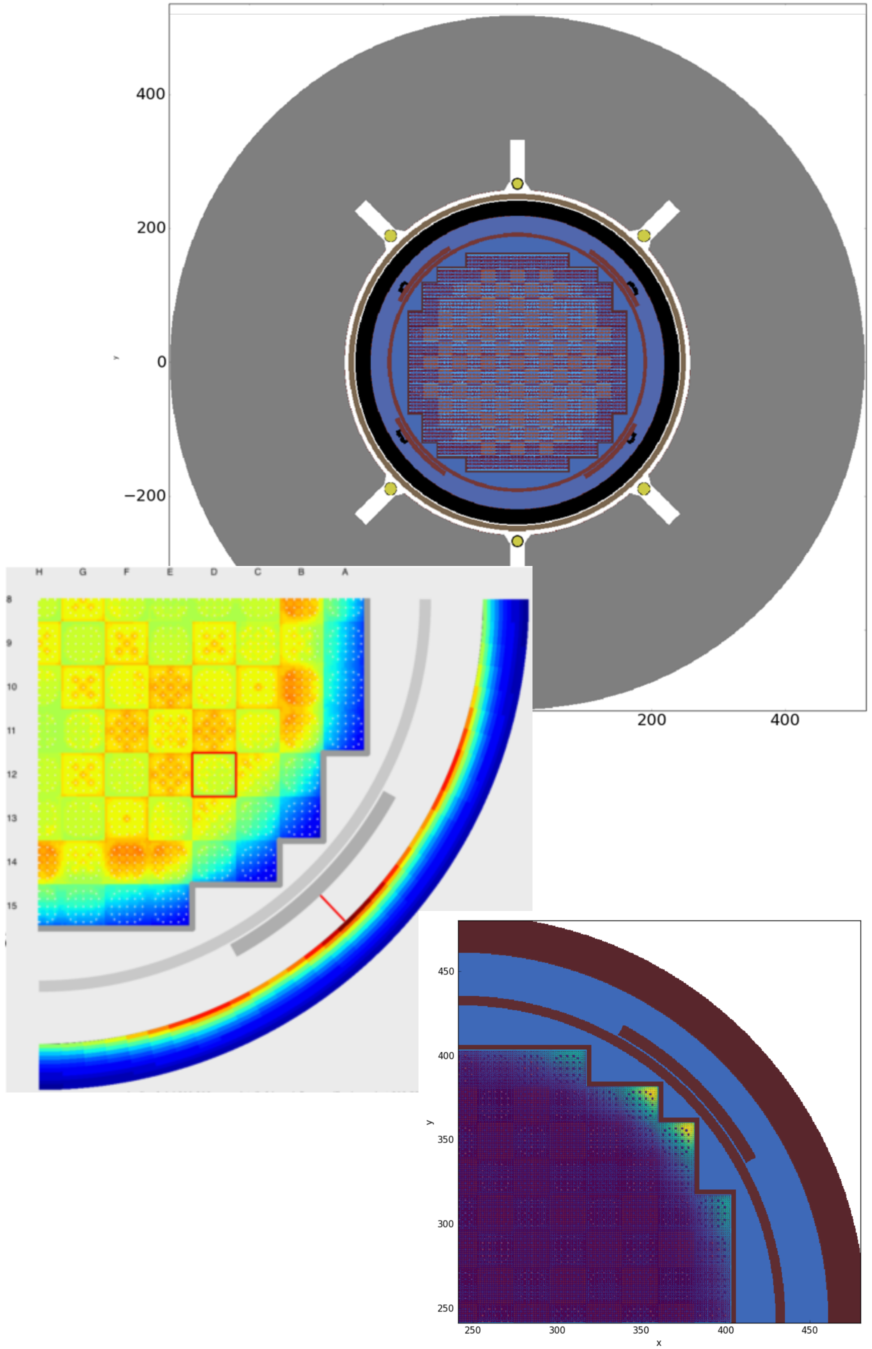




OAK RIDGE National Laboratory

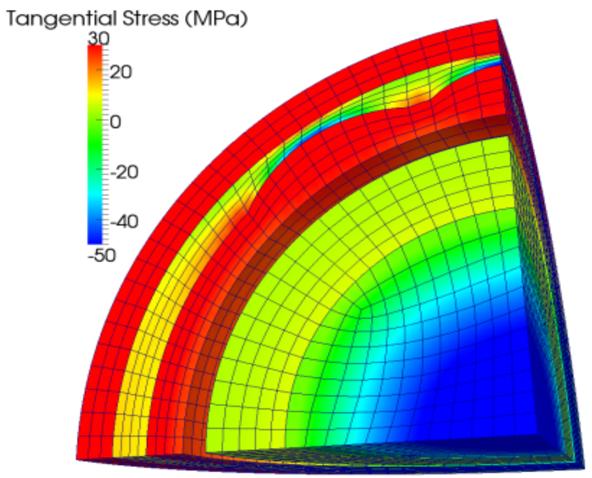
Shift

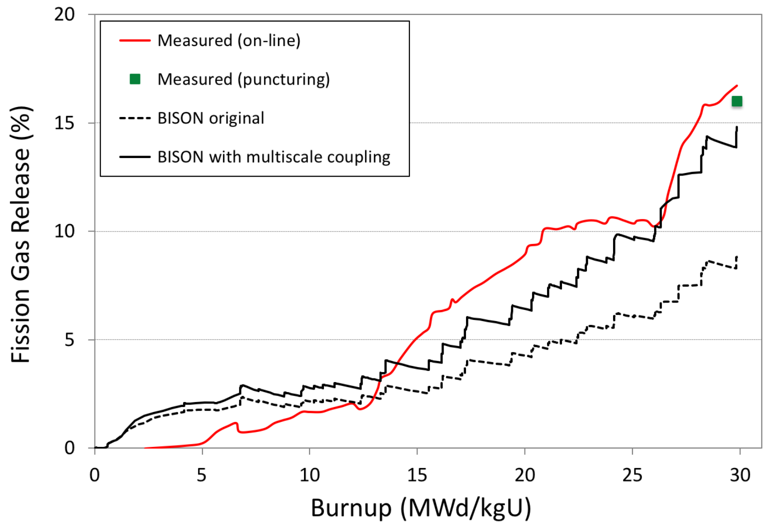
- Accurate and efficient neutron and gamma transport
  - Continuous-energy Monte Carlo neutron & gamma transport to any region outside of the reactor core
  - State-of-the-art hybrid methods focus particles toward the regions of interest
- General geometry capability for ex-vessel region
- MPACT provides accurate 3D fission source & isotopics
- Enables best-estimate vessel fluence analysis and coupon irradiation
- Ex-core detector response calculations and weighting factor generation
- Coupling with materials models allows for calculation of concrete degradation and core structure embrittlement



BISON

- VERA can be used to perform detailed fuel rod performance analysis with BISON
  - Finite element-based engineering scale fuel performance code
  - Solves the fully-coupled thermo-mechanics and species diffusion equations in 1D symmetric, 1.5D, 2D axisymmetric or generalized plane strain, or 3D
- Lower length scale and mechanistic models for key physics phenomenon (e.g. fission gas release, thermal conductivity) applicable to existing and future ATF fuel forms and clad
- Fuel rod geometry and power histories used to automatically create BISON inputs for any or all fuel rods in a reactor core
- BISON results are collected into VERAOut format for whole-core fuel rod performance analysis or screening





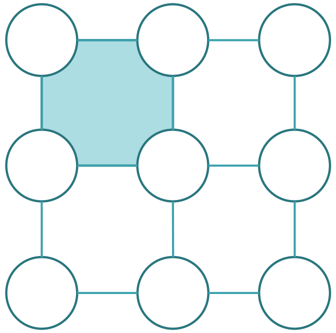
Ref. K. Gamble, G. Pastore, M. Cooper, D. Andersson, ATF material model development and validation for priority fuel concepts, CASL-U-2019-1870-000, July 2019.

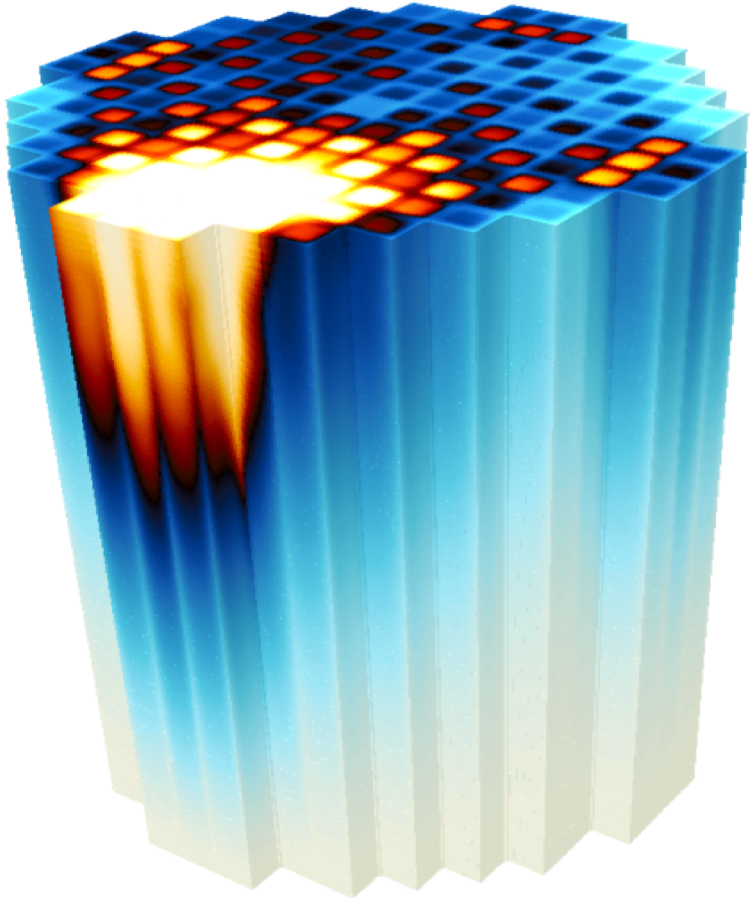
OAK RIDGE National Laboratory

CTF

- Whole-Core Two-Phase Subchannel Thermal-Hydraulics
  - Three-field representation of two-phase flow
  - Continuous vapor (mass, momentum and energy)
  - Continuous liquid (mass, momentum and energy)
  - Entrained liquid drops (mass and momentum)
  - Non-condensable gas mixture (mass)
  - Native, transient fuel temperature model
- Cross flow between channels
- Coupling with Systems Codes (TRACE, RELAP) via inlet and exit boundary conditions
- Spacer grid pressure loses and blockages and intra-grid form losses
- Use of higher resolution computational fluid dynamics (CFD) simulation to improve the subchannel modeling

Sub-Channel Discretization for the entire core

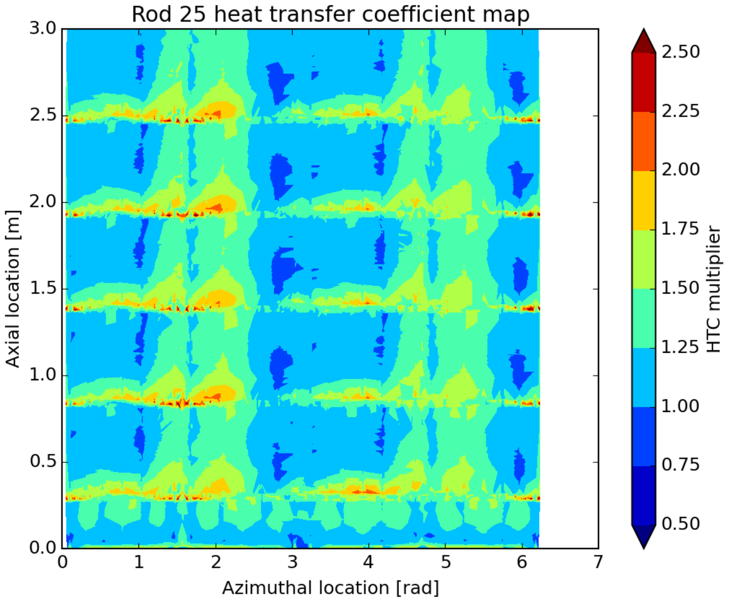




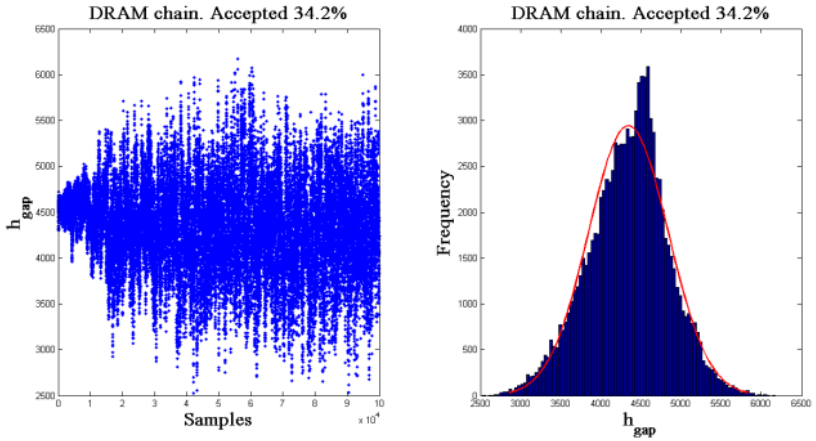
Addressing Modeling Gaps

- Use of high resolution, high fidelity methods to improve lower resolution model for key System Response Quantities (SRQs)
  - STAR-CCM+ informs CTF
  - SRQs include azimuthal heat flux and TKE

- Use of integral experiments and system level data to calibrate fundamental model parameters where Single Effects Tests (SETs) data does not exist
  - Bayesian calibration allows for establishment of uncertainty bounds on calibrated parameters



Ref. Salko, R., S. Slattery, T. Lange, M. Delchini, W. Gurecky, E. Tatli, and B. Collins, Development of Preliminary VERA-CS Crud-Induced Localized Corrosion Modeling Capability, CASL-U- 2018-1617-000, June 2018.



Ref. B. Kuwaileh and P. Turinsky, Data Assimilation and Uncertainty Quantification Using VERA-CS for a Core Wide LWR Problem with Depletion, CASL-U-2016-1054-000, April 2016.

Watts Bar Unit 2 Power Ascension

TVA

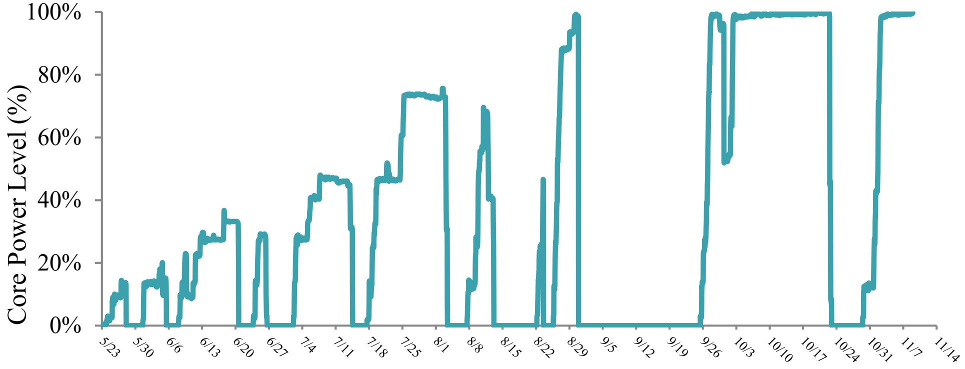
First US reactor startup in over two decades modeled in near real time as a 'blind prediction'

- 4,130 hourly state-points
- 13.5 days of runtime on 2,784 cores
- 892,837 core-hours
- 16,605 fully-coupled neutronics/TH iterations

Accurate comparison to measurement, including a new Vanadium-wire, in-core flux map system (± 2.4%)

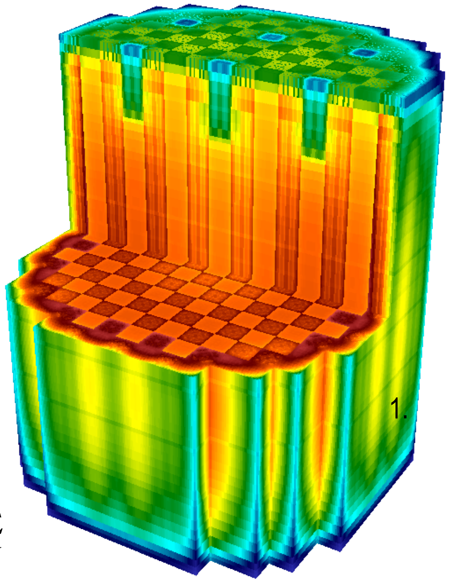
Pin-by-pin spatial detail of 'non-measurable' quantities of interest (e.g. Xe-135)

Watts Bar Unit 2 Power Ascension



Measured Power Distribution (M/P)
(Full Power, 5.6 GWD/T Exposure)

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							1.03			1.03					
2			1.03			0.99		0.99							
3								1.01		1.02		1.02		1.01	
4		1.03	1.01					0.99							
5					0.99				0.98		0.99		0.98		
6	1.03		1.02			0.98		0.96						0.97	
7				1.02			0.97			1.00			0.97		
8	1.04		1.02		1.00		1.00			0.97		0.98	1.00	0.98	
9		1.04							0.98		0.98				1.00
10					1.01		1.01					0.97			
11	1.02				0.99			1.01			0.98				1.00
12						0.99			1.02			0.98			
13			1.05		0.99			1.02						1.01	
14			1.03				1.04			0.98		1.02			
15					1.00			1.03							

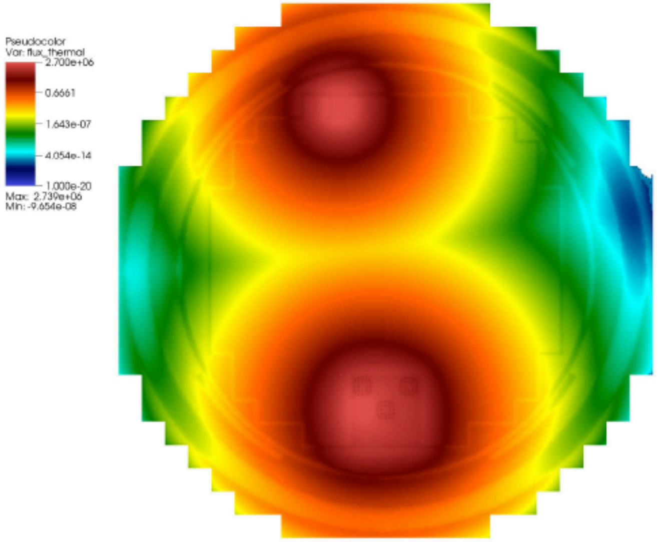


Watts Bar 2 predicted, transient Xenon-135 distribution at 28% power level

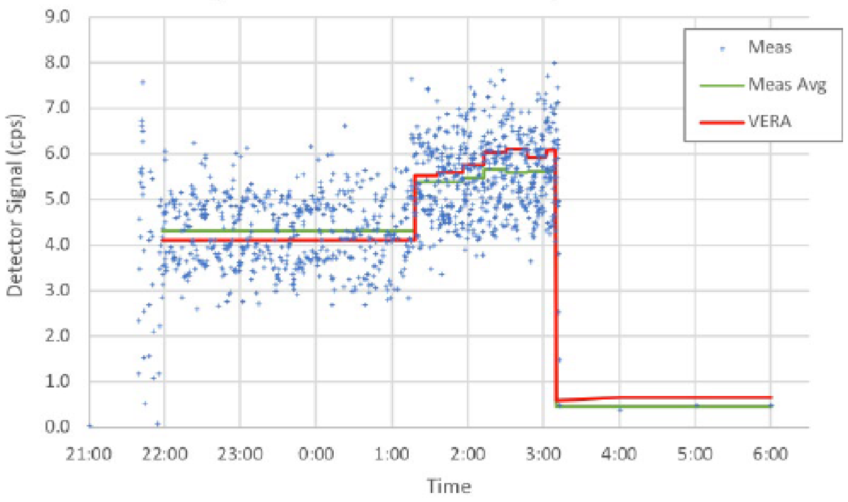
1. Ref. A. Godfrey, B. Collins, C. Gentry, S. Stimpson, J. Ritchie, Watts Bar Unit 2 Startup Results with VERA, CASL-U-2017-1306-000, March 2017.

VERA Simulation of Signal Response

- First-of-a-kind capability demonstrated for VERA-Shift applied to coupled in-core/ex-core calculations
- Addresses a concern over secondary source signal strength as seen by the source range detectors (SRD) during refueling
- In this application, virtual detector signals were generated for the refueling shuffle sequence with direct comparison against measured count rates
- Excellent agreement between measured and predicted signal



WBN1 C8 Thermal Flux with 9 Assemblies Loaded for Southern SRD

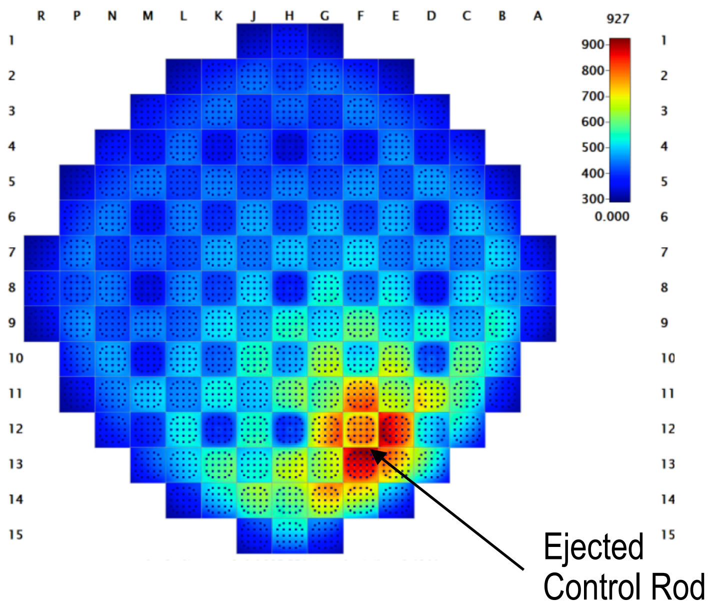


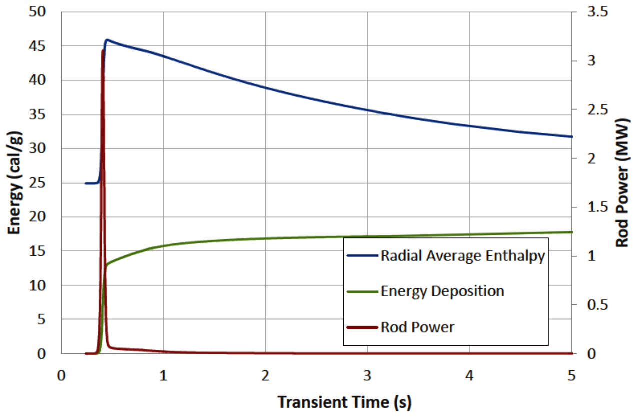
Ref. Godfrey, E. Davidson, G. Wolfram, B. Collins, C. Gentry, G. Ilas, S. Palmtag, T. Pandya, K. Royston, Watts Bar Unit 1 Source Range Detector Response Validation During Refueling, CASL-U-2018-1561-000, December 2018.

DOE-NE Advanced Modeling Simulation

Light Water Reactors - Near-term focus

- Provide support for advanced LWR nuclear technologies and target areas for which current LWR modeling and simulation capabilities cannot be used
- Areas include:
  - Accident tolerant fuels
  - High burnup, high enrichment fuel
  - Materials fabrication and performance, including advanced manufacturing
  - Two-phase fluid flow, including flow regime transitions
  - Reactor operational performance
  - Reactor safety performance





AP1000® RIA fuel rod enthalpy and energy deposition evolution (ATF fuel form)

Ref. S. Ray, V. Kucukboyaci, Y. Sung, P. Kersting, R. Brewster, Industry Use of CASL Tools, CASL-U-2019-1739-000, September 2018.

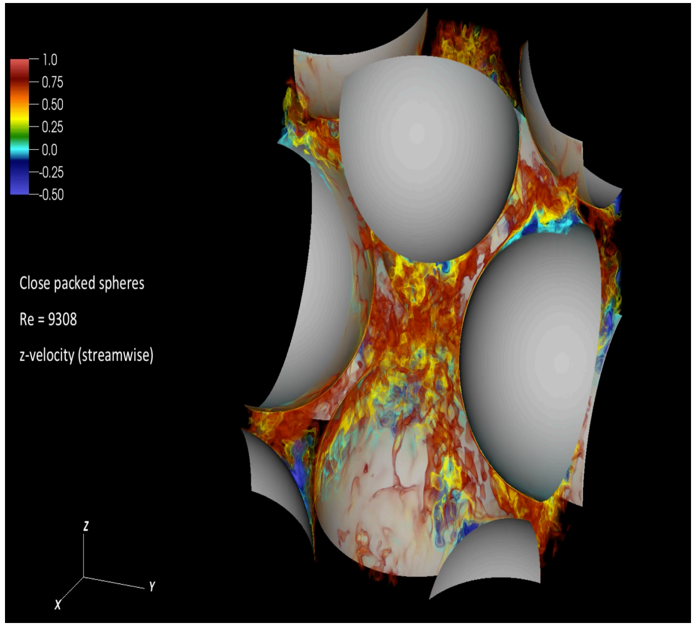
DOE-NE Advanced Modeling Simulation

Advanced Non-Light Water Reactors - Near-term focus

- Target areas identified by industry, GAIN Technical Working Groups, and the US NRC to support their activities including molten salt, HTGR, and fast reactor technologies

- Support industry and the NRC for the rapid development and demonstration of microreactors in the 3-5 years time frame

- Areas include:
  - Fuels
  - Materials fabrication and performance, including advanced manufacturing
  - Chemistry
  - Reactor systems

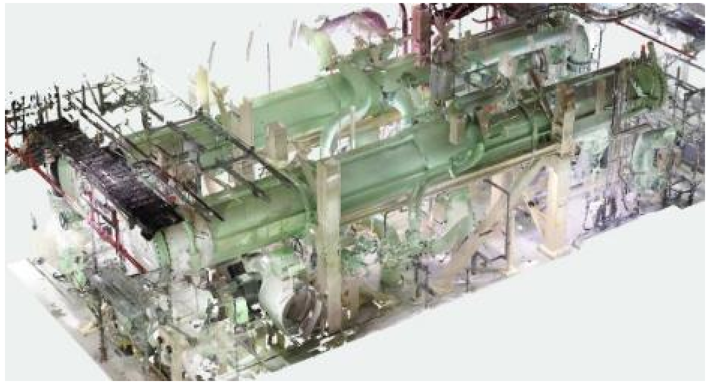


Turbulent Heat Flux – Nek5000/BISON

Summary

- The virtual reactor simulator is one aspect of the Digital Twin for Nuclear Systems
- High fidelity, high resolution virtual simulator technology has rapidly evolved to the level of high predictability for reactor quantities of interest based on coupled, multi-physics modeling
  - First principles combined with multi-scale approach can capture the relevant physics phenomena
- Uncertainties in input parameters and closure relations may nevertheless be an issue for a particular reactor configuration (fuel form, coolant).
  - Model gaps can be addressed through use of formal calibration methods
  - Such methods benefit from availability of measured data required for calibration
- Integration of high fidelity, high resolution simulation with advanced sensors result in unprecedent detailed of reactor behavior

Modeling and Simulation to Support Digital Twins



Dr. Jeffrey W. Lane
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919-903-6763

Digital Twin Applications for Advanced Nuclear Technologies
Online Workshop
December 1-4, 2020

ZACHRY

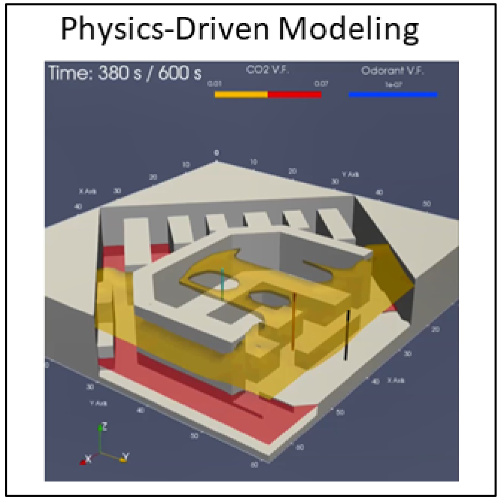
INTRODUCTION

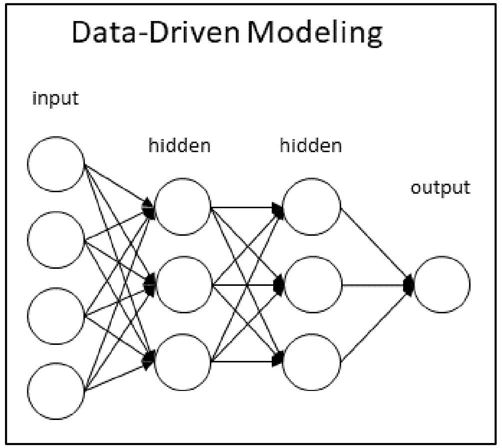
Digital Twin is a virtual replica of a physical asset

- Can be a plant, system or specific component
- Enhanced understanding of physical asset integrating data + simulation
- Can use Machine Learning (ML) & Artificial Intelligence (AI) to identify causal relationships and produce reduced-order models (ROM)
- Predict performance and expected response of the asset
- Identify vulnerabilities

Types of Digital Twins

- Design – identify issues before construction and optimize system
- Construction – support scheduling and evaluate as-built deviations
- Operations – monitor performance degradation and maintenance
- Others





ZACHRY

EXAMPLE - DESIGN DIGITAL TWIN

Design by simulation

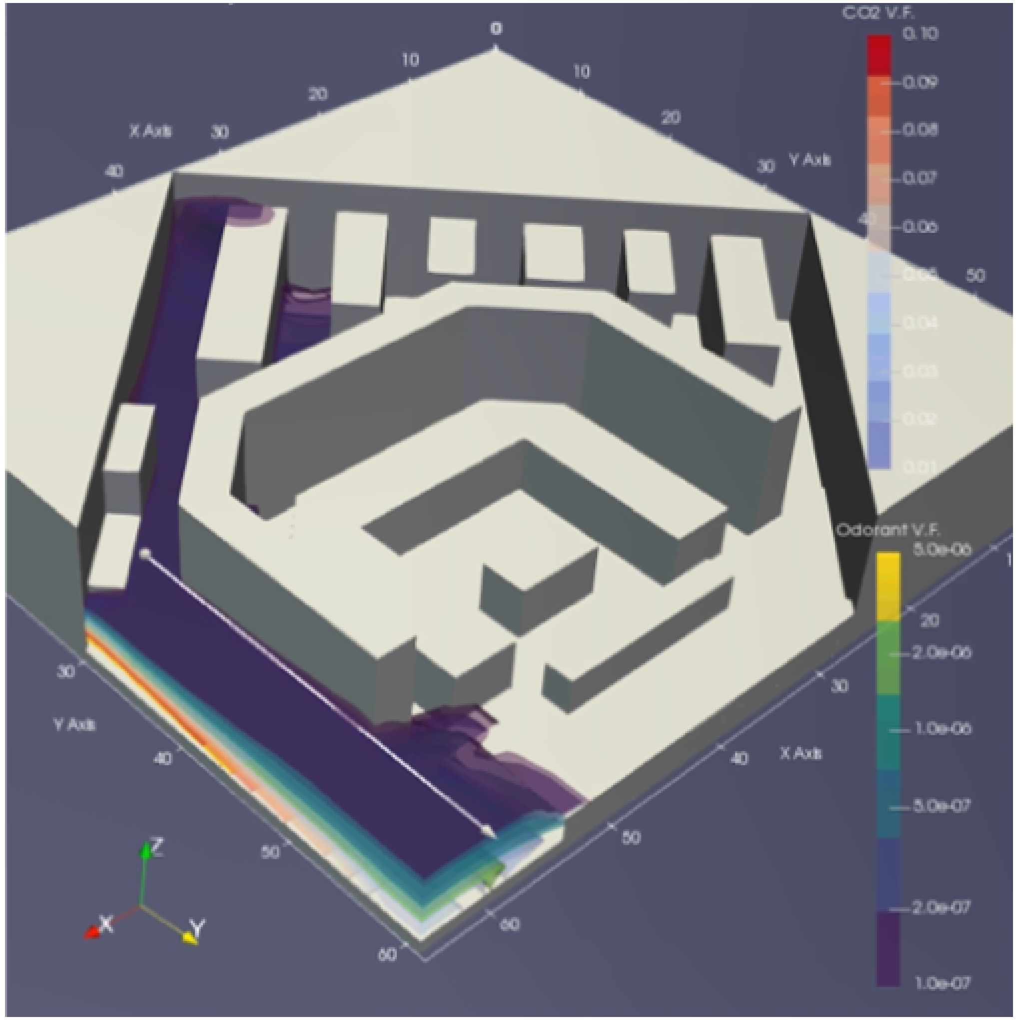
- Physics based modeling provides access to a wealth of data, including unmeasurable quantities
- Can be more cost effective than testing

Attributes:

- Identify system faults before the system is built
- System optimization

Example – Ventilation System

- Toxic gas and room habitability assessments
- Location and sizing of HVAC and filtration
- Complex geometry and recirculation patterns
- Simulation identified local pockets of higher concentration for original design



ZACHRY

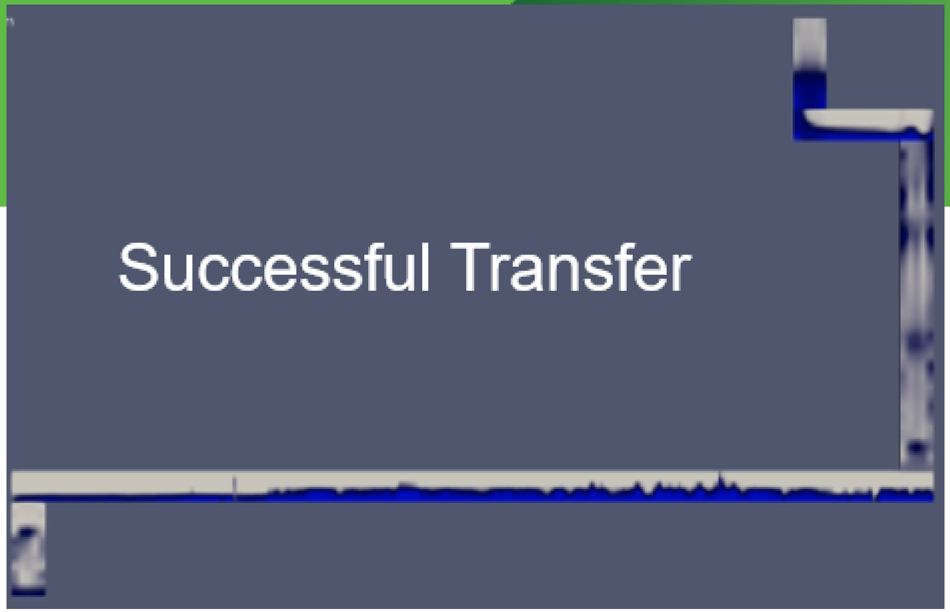
EXAMPLE - OPERATIONS DIGITAL TWIN

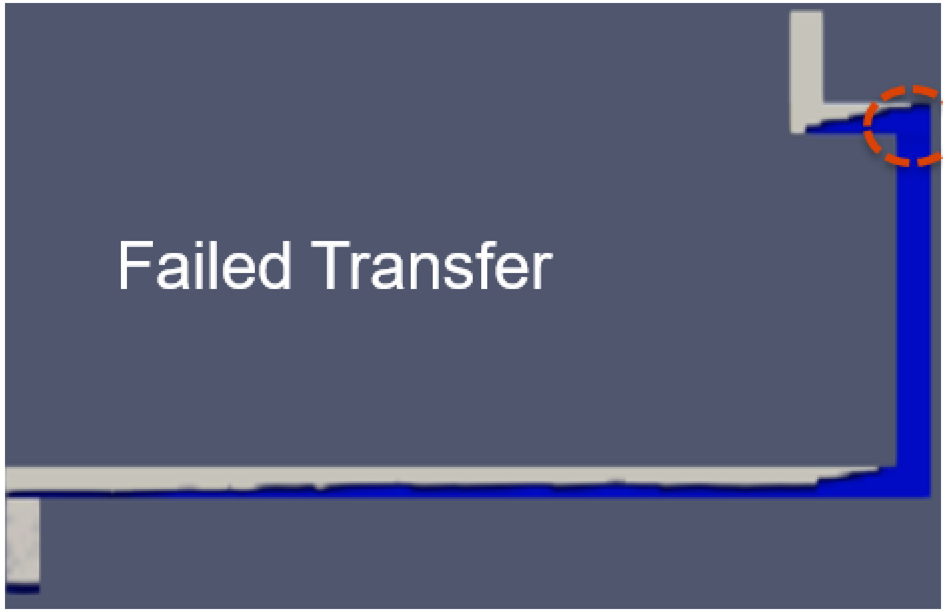
Attributes:

- Connected to the physical asset by continuously monitoring and collecting information
- Continuously learning and dynamically updating
- Simulation used to fill in knowledge gaps (e.g., non-existent data for fault scenarios)

Example - Vacuum transfer system

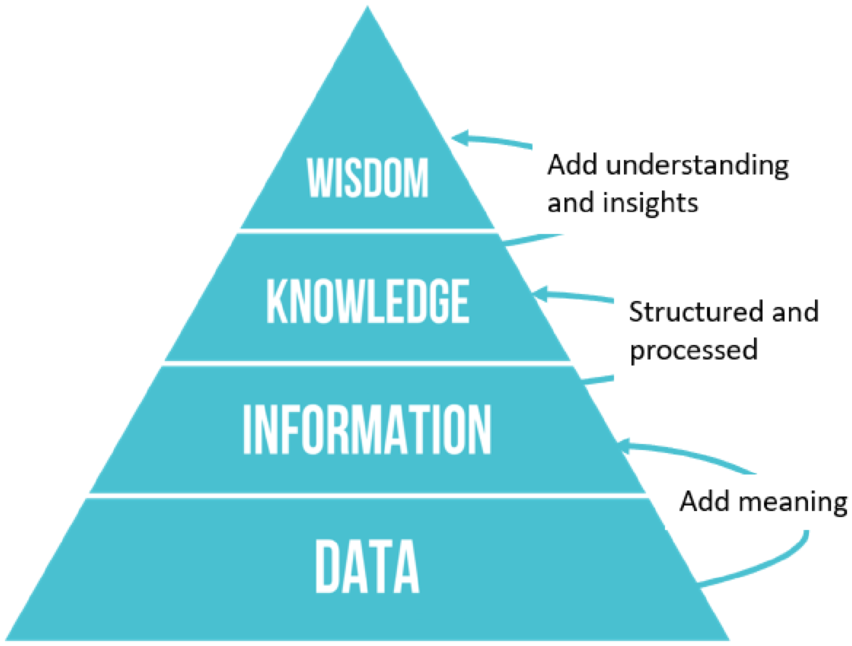
- Time critical transfer of fluid
- Performance degradation of seals and vacuum system
- Elongate time between maintenance and minimize downtime
- Pre-emptively schedule maintenance before failure





REQUIREMENTS

- Modeling & Simulation (M&S) plays an important role in digital twins to:
  - Fill in knowledge gaps or lack of available data
  - Provide access to unmeasurable quantities
- However, the M&S results must be **obtainable** and **meaningful**
  - Design by simulation requires VVUQ of M&S tool
  - Will need to assimilate M&S results with information obtained directly from the asset (I&C signals) and resolve discrepancies
- The following must be considered with respect to applying M&S for digital twins
  - Establish Applicability
  - Data Assessment
  - Software Requirements
  - Computational Requirements



From - J. Rowley, "The Wisdom Hierarchy: Representations of the DIKW hierarchy", Journal of information Science, pp. 163-180, 2006

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APPLICABILITY OF M&S TOOLS

- Just like any other application of M&S, one must establish the credibility and applicability of the evaluation model (code + inputs) for the intended application
  - Provides confidence that the simulation includes the **necessary physics** and **produces accurate results** throughout the application domain
  - Establish the **uncertainty** and **trustworthiness** of the results

- Established methods for assessment
  - US NRC Code Scaling, Applicability and Uncertainty (CSAU) using Phenomena Identification and Ranking Table (PIRT)
  - Evaluation Model Development and Assessment Process (EMDAP) from Reg. Guide 1.203

- *Provide good frameworks for evaluating the adequacy and sufficiency of a result; however, in practice many applications of these methods tend to rely heavily on engineering judgement.*

ZACHRY

APPLICABILITY OF M&S TOOLS

- Need quantitative approaches to assess
  - Accuracy of results, including uncertainty and effects of scale
  - Domain coverage – where are the holes?
  - Adequacy – what level of agreement is sufficient?

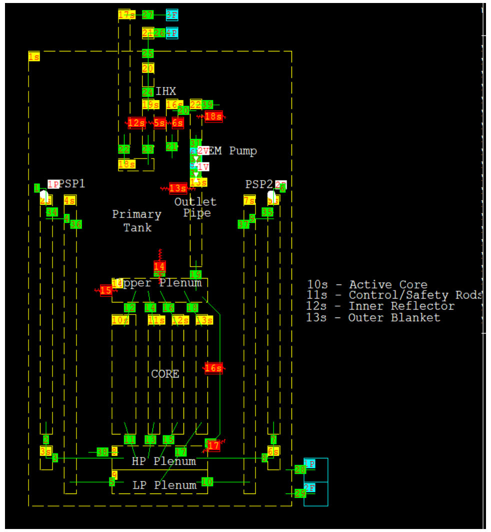
- Quantitative approaches
  - Reduce reliance on engineering judgement
  - Rank and prioritize areas for improvement both in the simulation and experimental needs

- Example:
  - Predictive Capability Maturity Quantification (PCMQ)

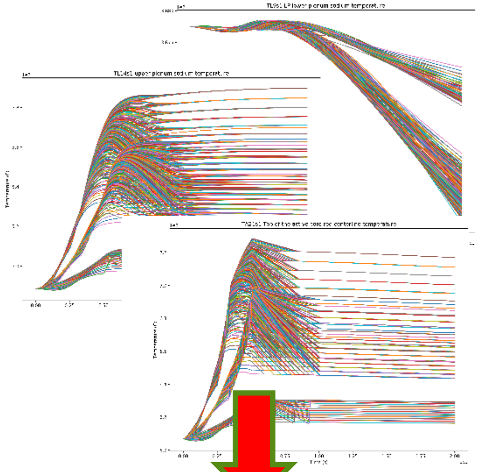
DATA ASSESSMENT

- Must assess the quality and trustworthiness of M&S data prior to training ML algorithms.
  - Establish confidence or identify unexpected results
- Automated tool to parse results
  - Search against multiple criteria and types
  - Limits (>,<), logical (AND/OR), inflection points, etc.
- Scanning tool and criteria developed to identify unexpected or anomalous behavior in simulation results
  - Reinforces that samples and training data cannot be treated as a “black-box”

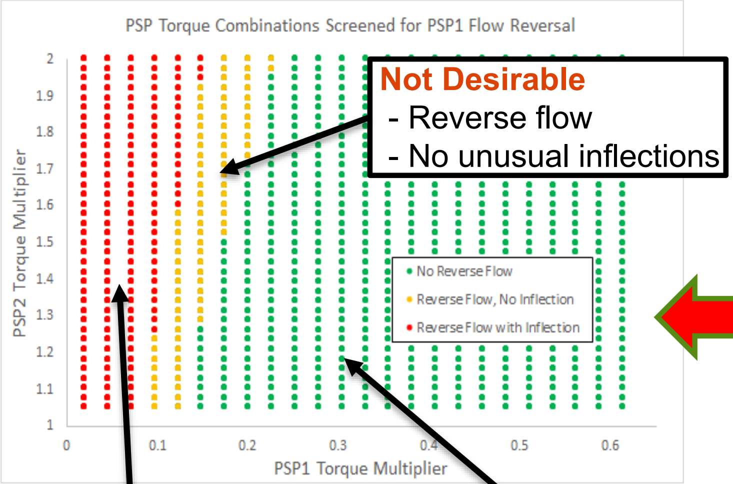
Model of EBR-II

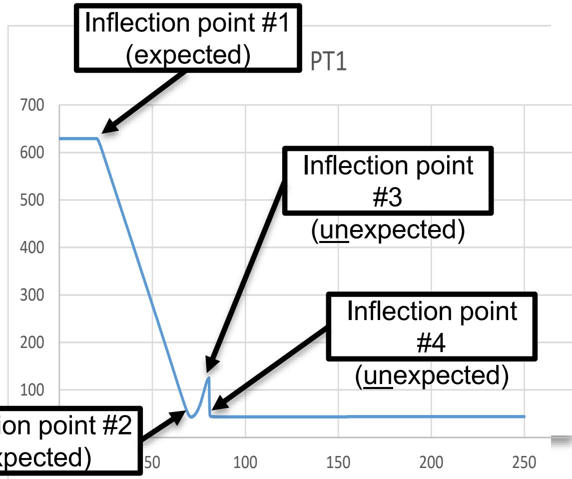


Simulation results from range of transients



Unexpected behavior in simulation results?





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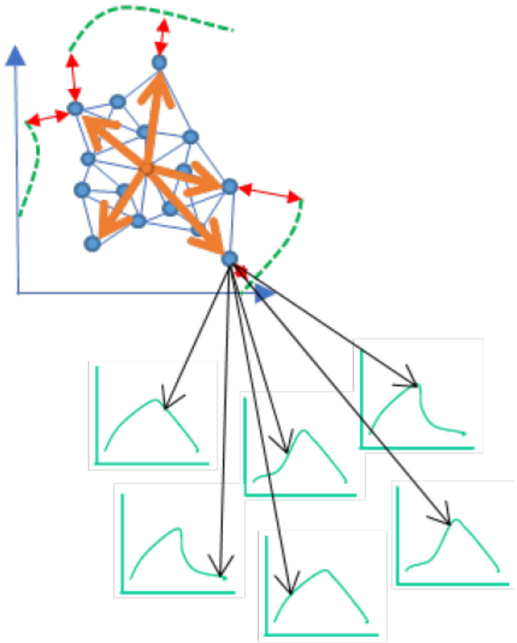
DIGITAL TWINS AS SOFTWARE



- Digital twin functionality is similar to M&S
  - Stores prototypical conditions, physics, and closures to make inferences and predictions for real systems
  - But, generally able to provide results much faster than M&S
- Digital twins include different types of software
  - Computational Engine or simulator
  - Training of ML/AI algorithms
  - Digital twin itself
- ML/AI are new paradigms relative to existing nuclear SQA standards (e.g., 10 CFR 50 Appendix B, ASME NQA-1)
  - Not static and continuously learning, but must be able to verify results
  - Must provide transparency & traceability to gain confidence in these technologies
- Depending on functionality or role of the digital twin, may also need to consider software reliability, hazard analysis and cybersecurity.

COMPUTATIONAL REQUIREMENTS

- Several different considerations for “computational performance”
  - Effectiveness of process for generating training data
    - Adaptive sampling and coverage assessment
    - Assisted using other available knowledge bases
  - Digital Twin Training Process
    - Balance accuracy with potential for overfitting
    - Hyperparameters represent an additional sensitivity/uncertainty
  - Execution time for Digital Twin
    - Depends on the time scale for the event, but initial response must be real-time
    - Potential for recommendations to change during processing time

- Need a general purpose, validated and robust simulation engine to generate training data
  - Can involve $O(10^4\text{-}10^6)$ or more simulations, so even a small fraction of simulations that fail to run to completion can be problematic.
  - Requires a 3-D, coarse-grid CFD code that can model all facets of the plant (reactor vessel, piping systems and containment) using a variable mesh and is applicable to both LWR and non-LWRs
  - GOTHIC is an industry trusted multi-physics, multi-scale M&S tool that supports digital twin development

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CONCLUSIONS

Digital twin solutions support decision making and provide a variety of benefits.

Modeling & simulation plays an important role in digital twins

- Must establish the credibility of M&S results as it directly impacts the credibility of digital twins
- Therefore, this is a critical element to the adoption, and regulatory approval, of ML based technologies for nuclear applications

- Cost Savings
- Increased Safety
- Equipment Reliability & Loss Avoidance
- Operations Flexibility
- Reduced Reactive Maintenance
- Higher Efficiency
- Optimized Design/Construction

ZACHRY

WORKSHOP ON DIGITAL TWIN APPLICATIONS FOR ADVANCED NUCLEAR TECHNOLOGIES
December 1–4, 2020

MULTI-PHYSICS MODELING FOR ADVANCED REACTOR SAFETY

RUI HU
Nuclear Science and Engineering Division
Argonne National Laboratory

Safety Characteristics of Advanced Reactors

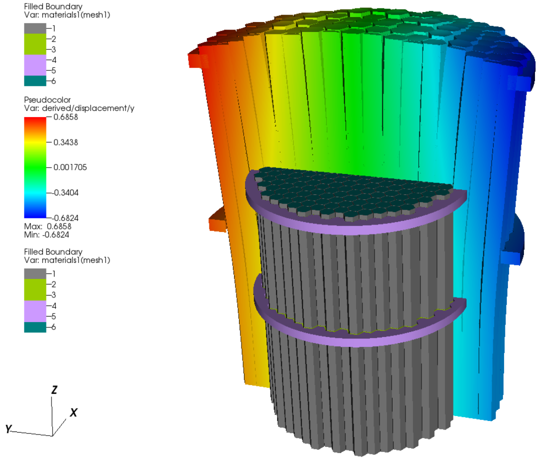
Pursuing high levels of inherent (walk-away) safety

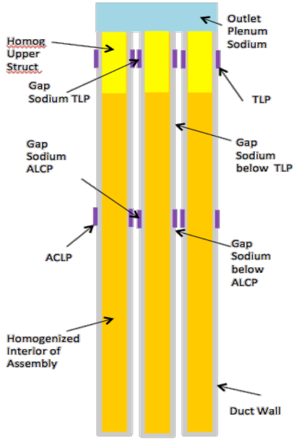
- Inherent reactivity feedback
- Passive decay heat removal
- Ultimate heat sink (ambient air)
- Advanced fuel
  - TRISO, metallic, liquid
- SMR and Micro-Reactor
  - Small nuclear fuel inventories
  - Large surface to volume ratio

- Multi-physics calculation for unprotected transients?
- Accurate modeling of in-vessel heat transport (from the core to vessel wall)
- Detailed simulation vs. lumped parameter approach
- Integrated modeling of reactor cavity cooling system or vessel cooling system

Needs for Multi-scale Multi-physics Capability (1)

- Analysis of the transient behavior of a nuclear reactor requires coupled simulation of reactor kinetics and thermal-hydraulics of the reactor core
- In advanced nuclear reactors, e.g. Sodium-cooled fast reactor, the reactivity feedback due to core radial and axial thermal expansion are important
- The coupled simulation of thermal-hydraulics and thermal-mechanics is important for the multi-physics simulations of advance reactors for accurate prediction of thermal reactivity feedbacks



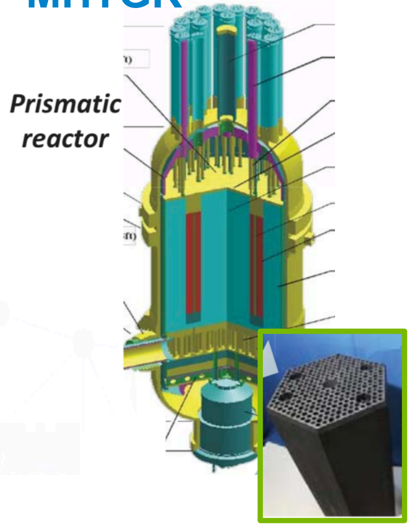


Needs for Multi-scale Multi-physics Capability (2)

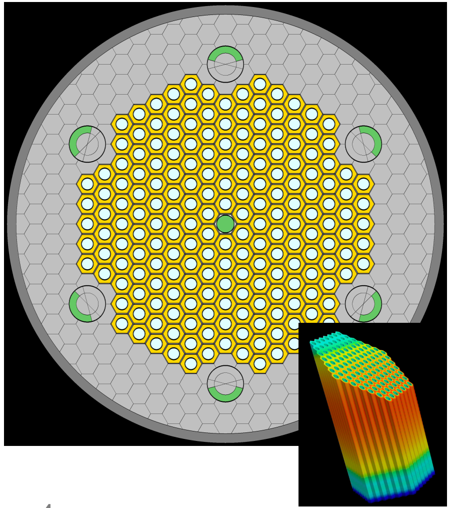
- Decay heat removal
  - Most advanced reactor designs rely on passive safety system, such as RCCS
  - Decay heat must be conducted from core to surface: fuels/structures are strongly thermally-coupled, and requires multi-dimensional modeling and simulation capabilities

PB HTGR

MHTGR

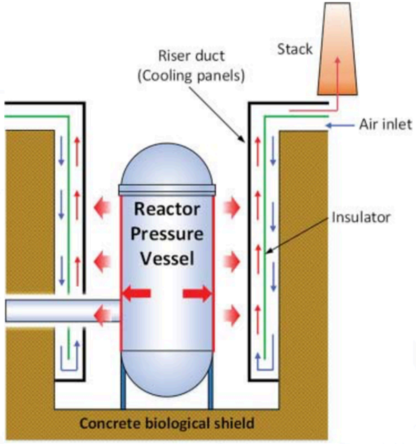


Heat-pipe Reactor



RCCS

Reactor Cavity Cooling



Sources: High Temperature Gas-cooled Reactor Technology Training Curriculum; ANL/NSE-19/25; UCBTH-14-009

MULTI-PHYSICS SIMULATION OF HEAT PIPE MICRO-REACTOR

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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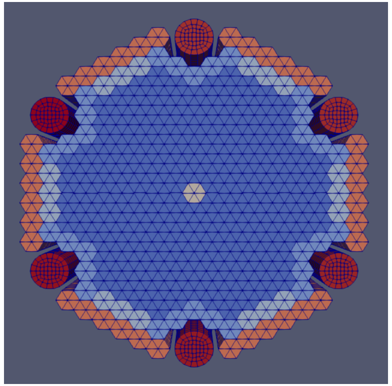
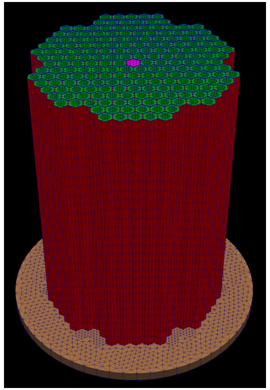
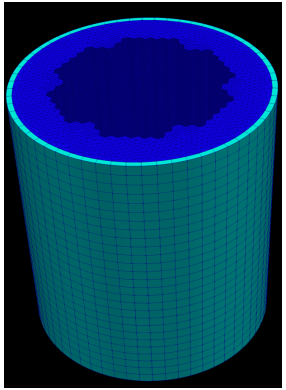
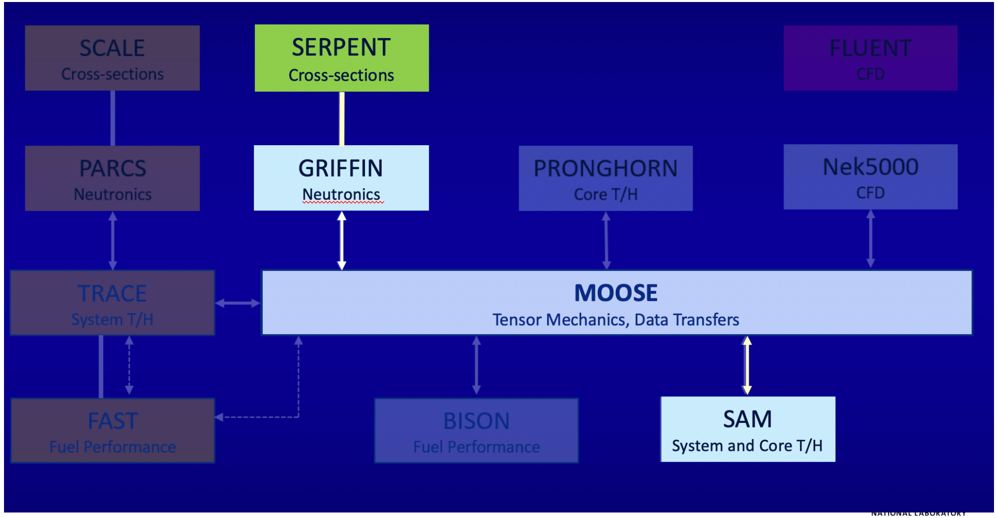
COUPLED CODE SIMULATIONS

- Joint Argonne-INL-NRC efforts using BlueCRAB
- Coupled codes in reference heat pipe microreactor model
  - Reactor Kinetics (MAMMOTH/Rattlesnake)
  - Thermomechanics (MOOSE Tensor Mechanics)
  - 3D Heat Transfer (SAM)
  - Heat Pipe Heat Exchanger (SAM)
  - Reactor Cavity Cooling System (SAM)
- MOOSE: multi-physics framework
- MAMMOTH: INL neutronics code
- SAM: ANL system code



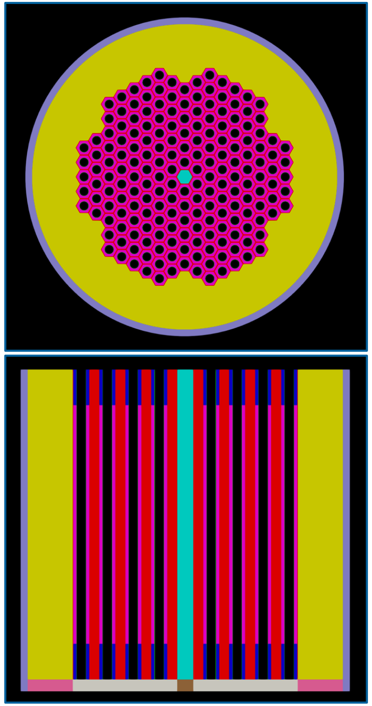




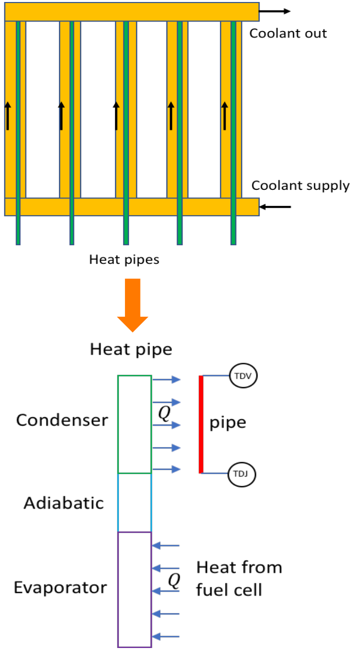


SAM MODELS

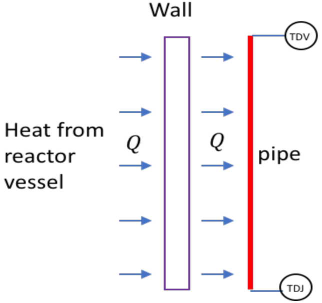
Reactor core

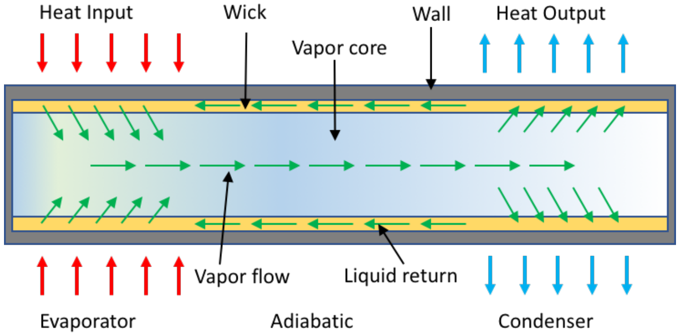


Heat pipe heat exchanger



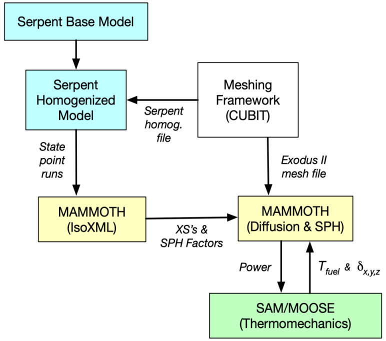
RCCS

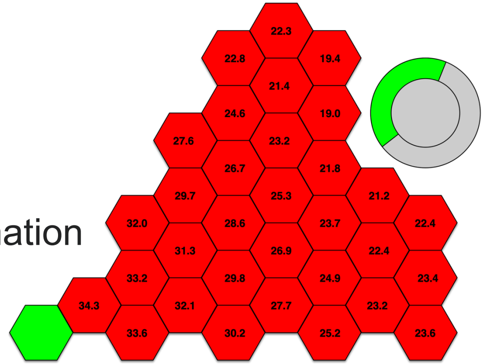


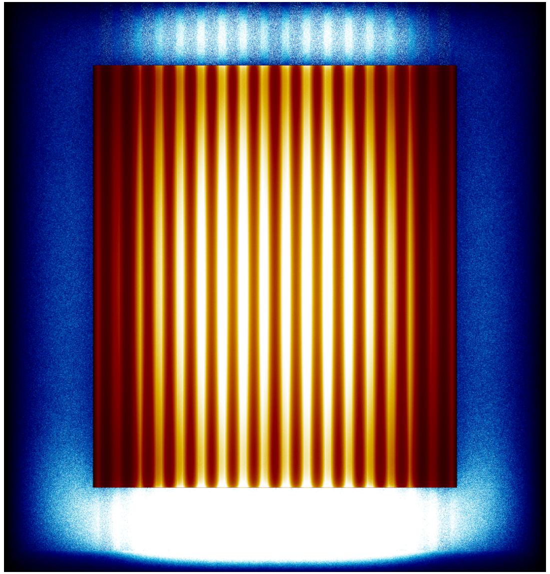


MAMMOTH REACTOR PHYSICS MODEL

- Beginning-of-life (BOL) conditions
- Multi-group diffusion solver with MAMMOTH/Rattlesnake
- Correction with the super-homogenization (SPH) equivalence scheme
- Cross-section preparation with SERPENT Monte Carlo code
- Reactivity feedback effects
  - Doppler effect: fuel temperature
  - Radial expansion: radial core mesh deformation
  - Axial expansion: fuel axial mesh deformation



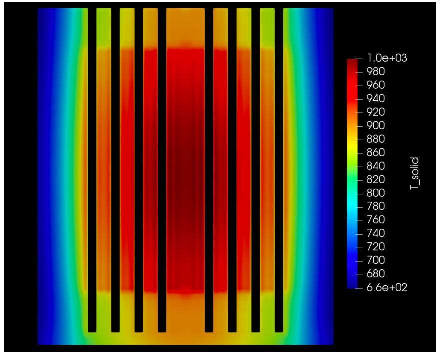




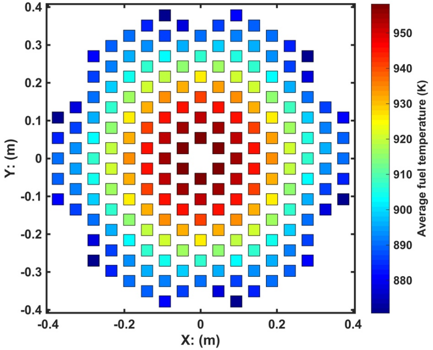
STEADY STATE

- The model works very well for the steady state operation analysis
- Average fuel temperature keeps very well the symmetry of the reactor core
- Heat pipe near the center removes roughly 1.5 times heat compared with heat pipe near the periphery of the core (average 26 kW)

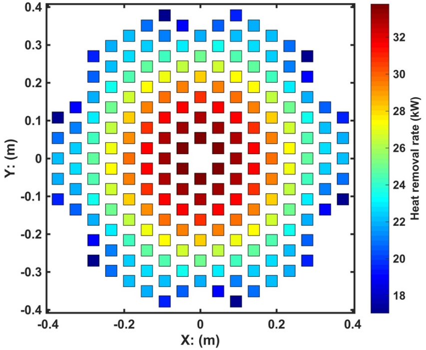
Parameters	Value
Eigenvalue	0.99990492
Total power	5.0 MW
Power to heat pipes	4.8942 MW
Power to RCCS	0.05291 MW
Average fuel temperature	914.7 K
Average hex can temperature	912.8 K
Average bottom/top reflector temperature	866.9 K
Average side reflector temperature	765.6 K
Average plate temperature	803.6 K
Average vessel wall temperature	674.5 K



Reactor core temperature



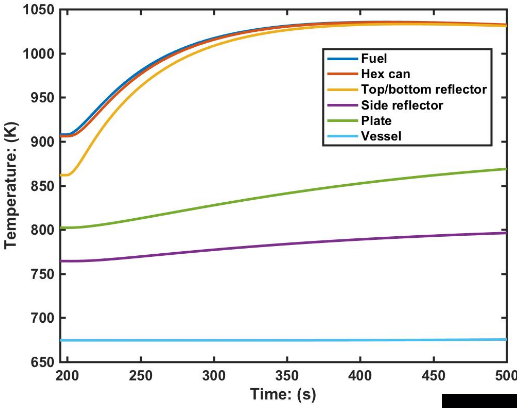
Average fuel temperature



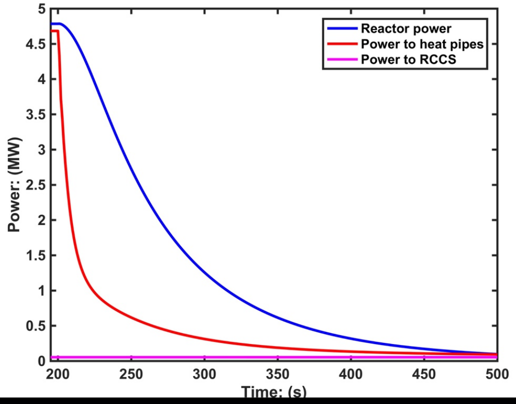
Heat pipe heat removal rate

LOSS OF HEAT SINK

- Heat pipe heat removal rate drops quickly to a lower level
  - Flow rate drops to 0.1% of steady-state value
  - Slow decrease due to the thermal inertial of the heat pipes
- Reactor power drops quickly due to the strong negative reactivity feedback
- Decay power was not considered yet in the reactor physics model



Average solid temperature



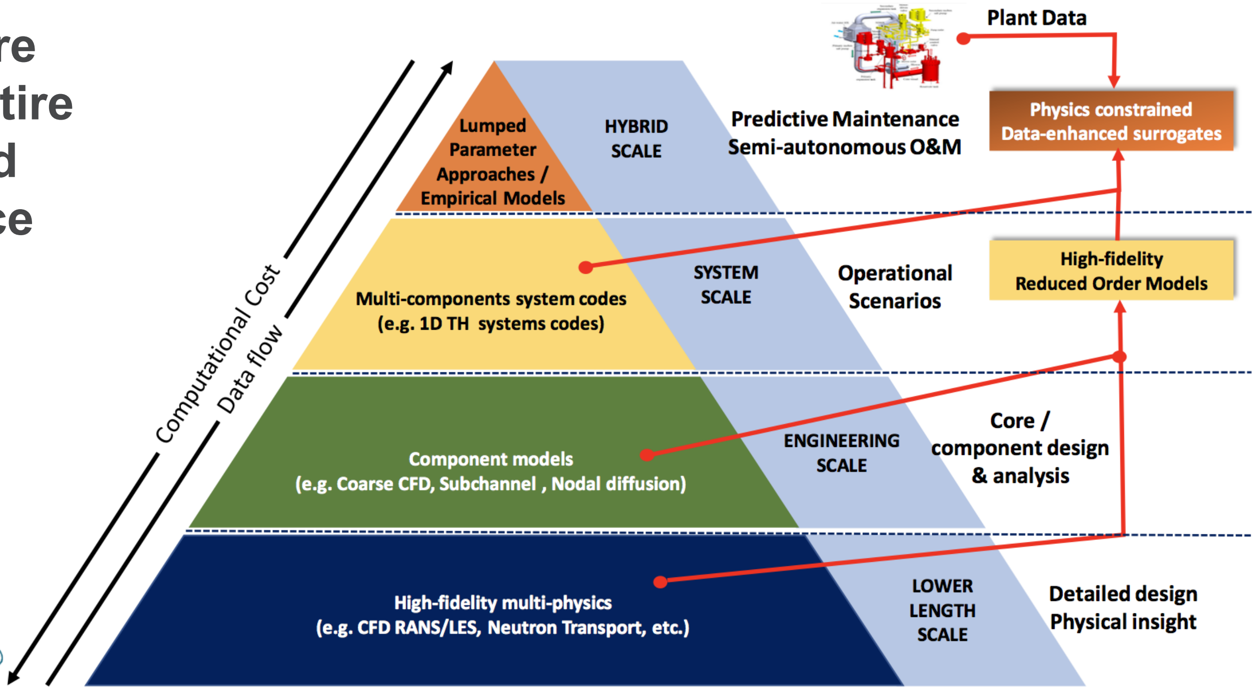
Fuel average temperature

MULTI-PHYSICS MODELING FOR DIGITAL TWIN DEVELOPMENT

SCALABLE DIGITAL TWIN IN SAFARI PROJECT

Physics-based to ensure robustness over the entire range of operations and data-enabled to enhance predictive capabilities.

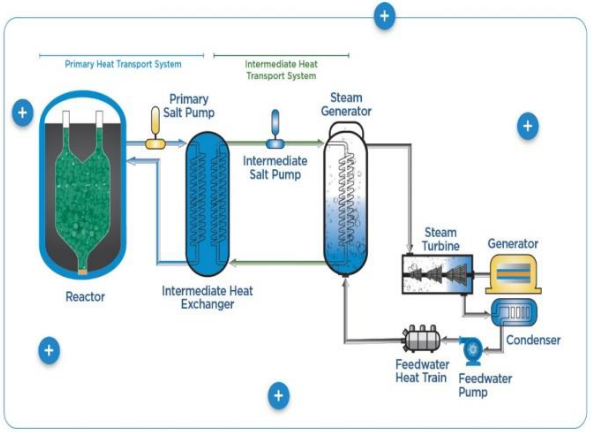
SAFARI: Secure Automation for Advanced Reactor Innovation, ARPA-E GEMINA Award



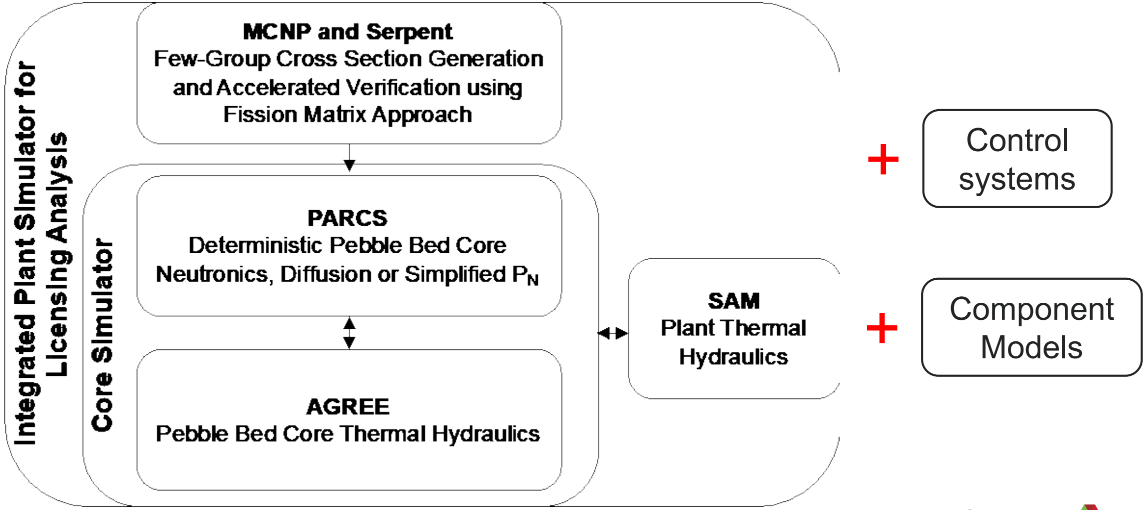
(Courtesy of A. Manera, UM)

MULTI-PHYSICS MODELING FOR DIGITAL TWIN DEVELOPMENT

- Multi-physics simulations including plant control and protection systems
- To build the ML-augmented, physics-based reduced order models of the FHR
- To demonstrate the accuracy of the digital twin and the commercial benefit



https: //kairospower.com



MULTI-SCALE MULTI-PHYSICS MODELING CAPABILITY NEEDED FOR ADVANCED REACTOR SAFETY AND SCALABLE DIGITAL TWIN DEVELOPMENT

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Mechanical and Aerospace Engineering
UCF
UNIVERSITY OF CENTRAL FLORIDA

Hybrid Physics-Informed Neural Networks, Cumulative Damage Models, and Digital Twins

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Assistant Professor

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University of Central Florida

Prognosis and digital twins

Maintenance costs

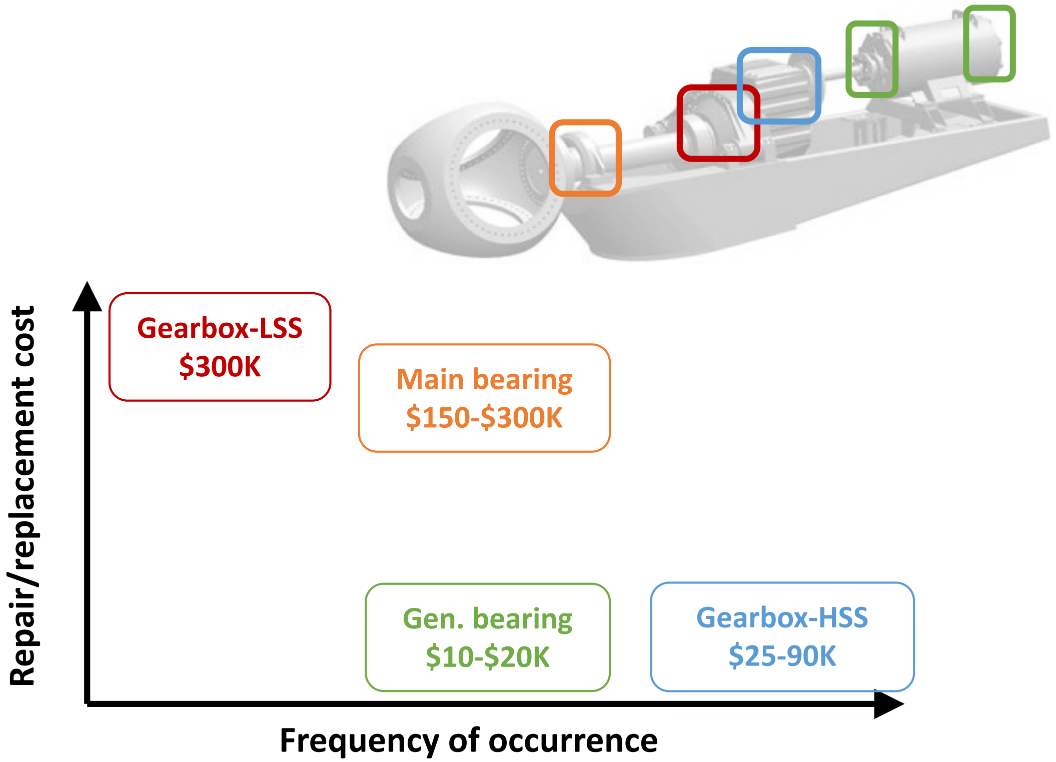
- Production lost
- Component
- Equipment rent, labor, etc.

Prognosis and digital twin challenges:

- Physics not fully understood
- Data is highly unstructured
    - Operation/controls vastly available (?)
    - Poor inspection and failure data

1. Digital twins must bridge the gap between model predictions (understanding) and observations (reality)
2. Hybrid models can be really helpful

(a) Onshore wind turbine example



Sethuraman, L., Guo, Y., & Sheng, S. (2015). Main bearing dynamics in three-point suspension drivetrains for wind turbines. American Wind Energy Association Conference & Exhibition, May 18–21, Orlando, FL.

Physics-informed neural networks are not new…

JOURNAL OF COMPUTATIONAL PHYSICS **91**, 110–131 (1990)

Neural Algorithm for Solving Differential Equations

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AND

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Received August 17, 1988; revised October 6, 1989

Finite difference equations are considered to solve differential equations numerically by utilizing minimization algorithms. Neural minimization algorithms for solving the finite difference equations are presented. Results of numerical simulation are described to demonstrate the method. Methods of implementing the algorithms are discussed. General features of the neural algorithms are discussed.

2018 Advances in Neural Information Processing Systems
(NeurIPS 2018 – Best paper)

Neural Ordinary Differential Equations

Ricky T. Q. Chen*, Yulia Rubanova*, Jesse Bettencourt*, David Duvenaud
University of Toronto, Vector Institute
{rtqichen, rubanova, jessebett, duvenaud}@cs.toronto.edu

Abstract

We introduce a new family of deep neural network models. Instead of specifying a discrete sequence of hidden layers, we parameterize the derivative of the hidden state using a neural network. The output of the network is computed using a black-box differential equation solver. These continuous-depth models have constant memory cost, adapt their evaluation strategy to each input, and can explicitly trade numerical precision for speed. We demonstrate these properties in continuous-depth residual networks and continuous-time latent variable models. We also construct continuous normalizing flows, a generative model that can train by maximum likelihood, without partitioning or ordering the data dimensions. For training, we show how to scalably backpropagate through any ODE solver, without access to its internal operations. This allows end-to-end training of ODEs within larger models.

How can we leverage this concept to build digital twins?

Cumulative damage models and uncertainty quantification

Fatigue crack growth

$$\frac{da}{dN} = C\Delta K^m$$

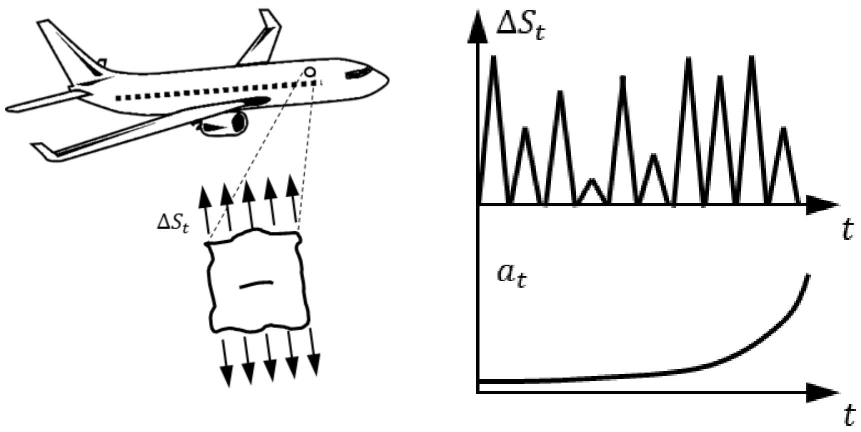
where:

- N: number of cycles
- C and m: material properties (coupon tests)
- $\Delta K = F\Delta S\sqrt{\pi a}$
- ΔS: engineering analysis (e.g., FEM)

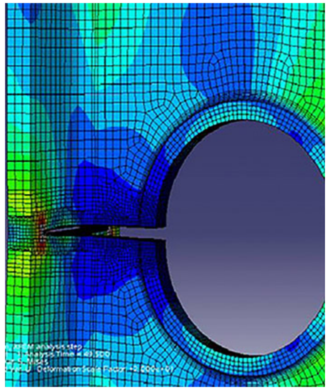
What if ΔK or ΔS are not accurate?

We propose using hybrid models for uncertainty quantification

(a) Fatigue crack growth at fuselage panel



(b) Finite element modeling

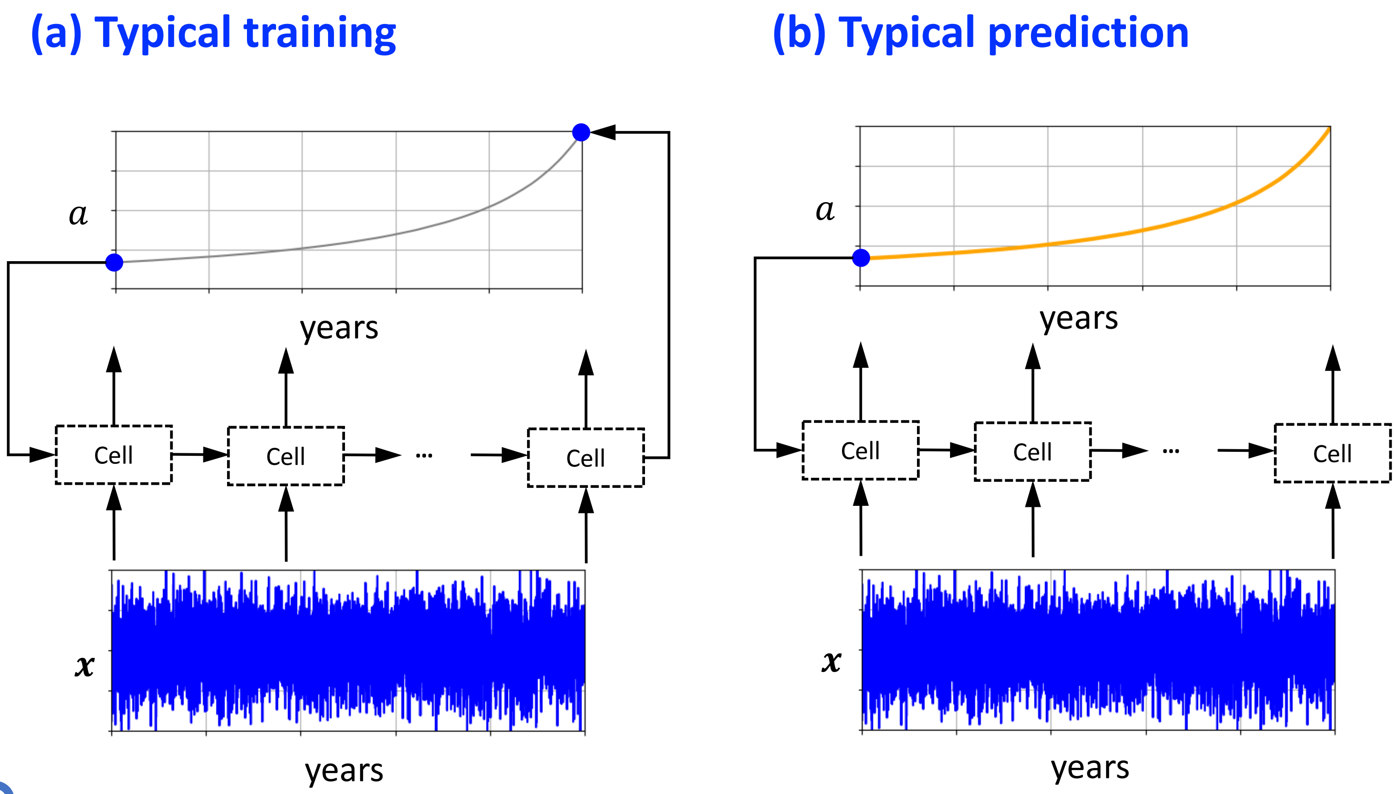


Physics-informed neural networks are perfect for prognosis digital twin

Use case:
- Very few output observations
- Inputs observed throughout
- Sequences are VERY long
- Cell models transition never observed

If output is observed throughout, data-driven **recurrent neural networks** (LSTM, GRU, etc.) might be useful, otherwise…

Very hard (impossible) without physics

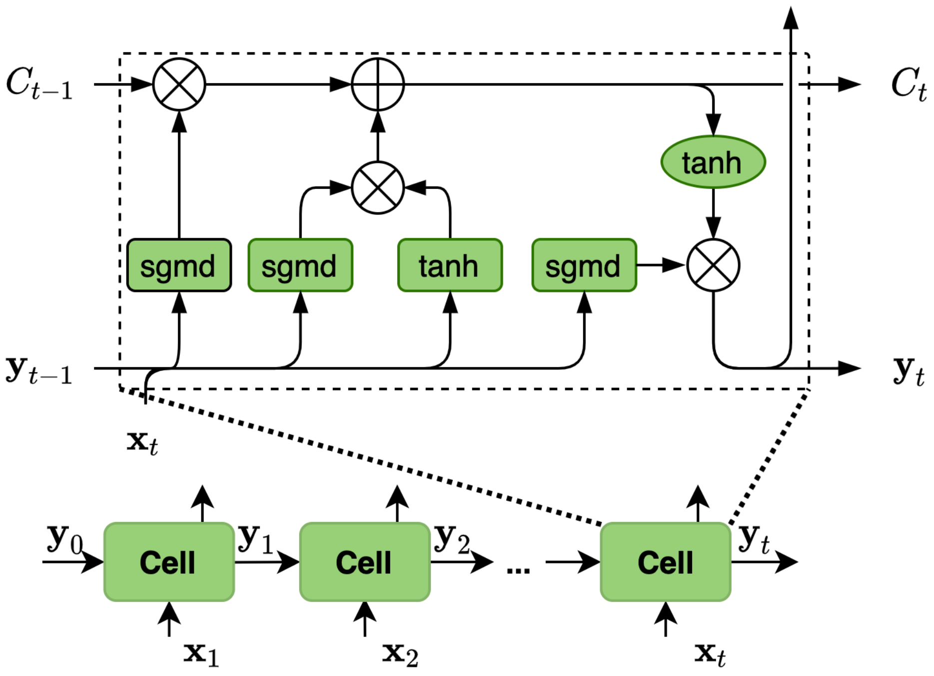


Blue: observed data
Gray: desired output (never fully observed)
Orange: Recurrent neural network prediction

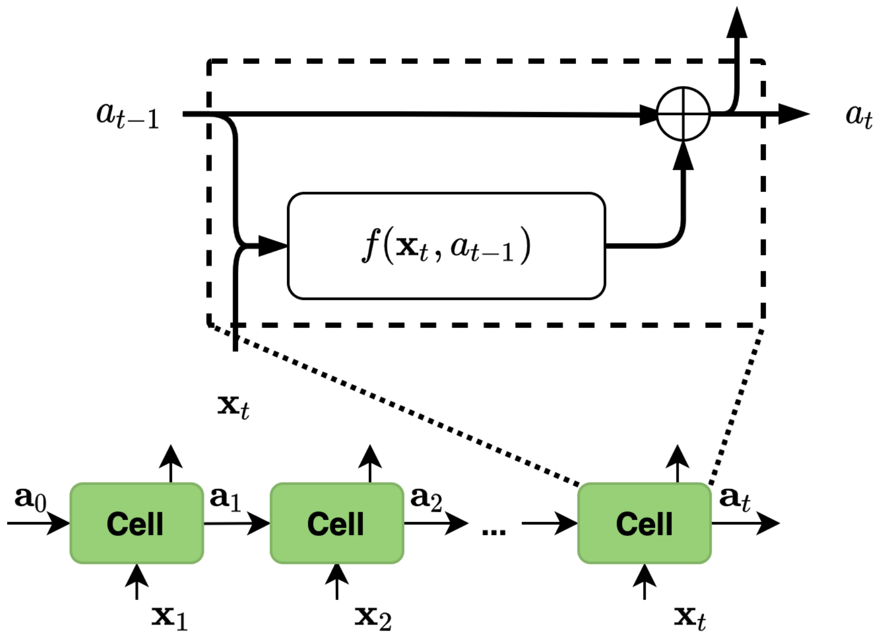
R. G. Nascimento and F. A. C. Viana, "Cumulative damage modeling with recurrent neural networks," AIAA Journal, Online First, 13 pages, 2020, DOI: 10.2514/1.J059250.

Cumulative damage model with recurrent neural networks

(a) Long short-term memory (LSTM) cell



(b) Euler integrator cell (cumulative damage)



$$\frac{da}{dN} = C\Delta K^m \quad \Longrightarrow \quad f(\boldsymbol{x}_t, a_{t-1}) = C\Delta K^m$$

- **RNNs are perfect fit for damage accumulation,**
- $f(x_t, a_{t-1})$ **can be customized.**

R. G. Nascimento, K. Fricke, and F. A. C. Viana, “A tutorial on solving ordinary differential equations using Python and hybrid physics-informed neural network,” Engineering Applications of Artificial Intelligence, Vol. 96, 2020, 103996, DOI: 10.1016/j.engappai.2020.103996.

Wind turbine main bearing fatigue

Model-form uncertainty:

- Bearing fatigue: relatively well-understood
- Grease degradation: difficult to model with physics

Damage inspection:

- Bearing: not always measurable
- Grease:
    - Laboratory: accurate but expensive
    - Visual: large uncertainty but affordable

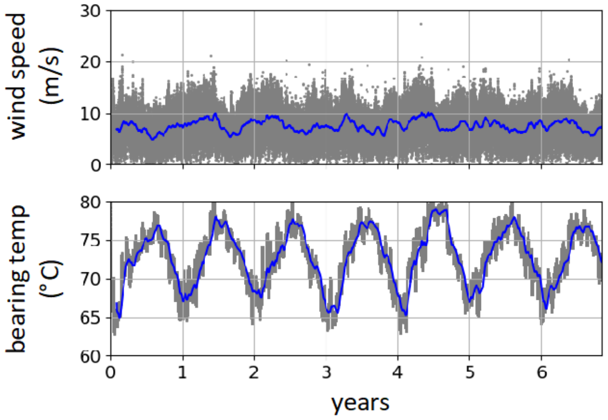
Unbalanced data:

- Supervisory control and data acquisition (SCADA) system (per 10 mins)
- Inspection depends on operator inspection policy

Y. A. Yucesan and F. A. C. Viana, "A physics-informed neural network for wind turbine main bearing fatigue," International Journal of Prognostics and Health Management, Vol. 11 (1), 2020.

Y. A. Yucesan and F. A. C. Viana, "Hybrid physics-informed neural networks for main bearing fatigue prognosis with visual grease inspection," Computers in Industry, Accepted.

(a) SCADA data



(b) Visual grease inspection ranking (high variability)

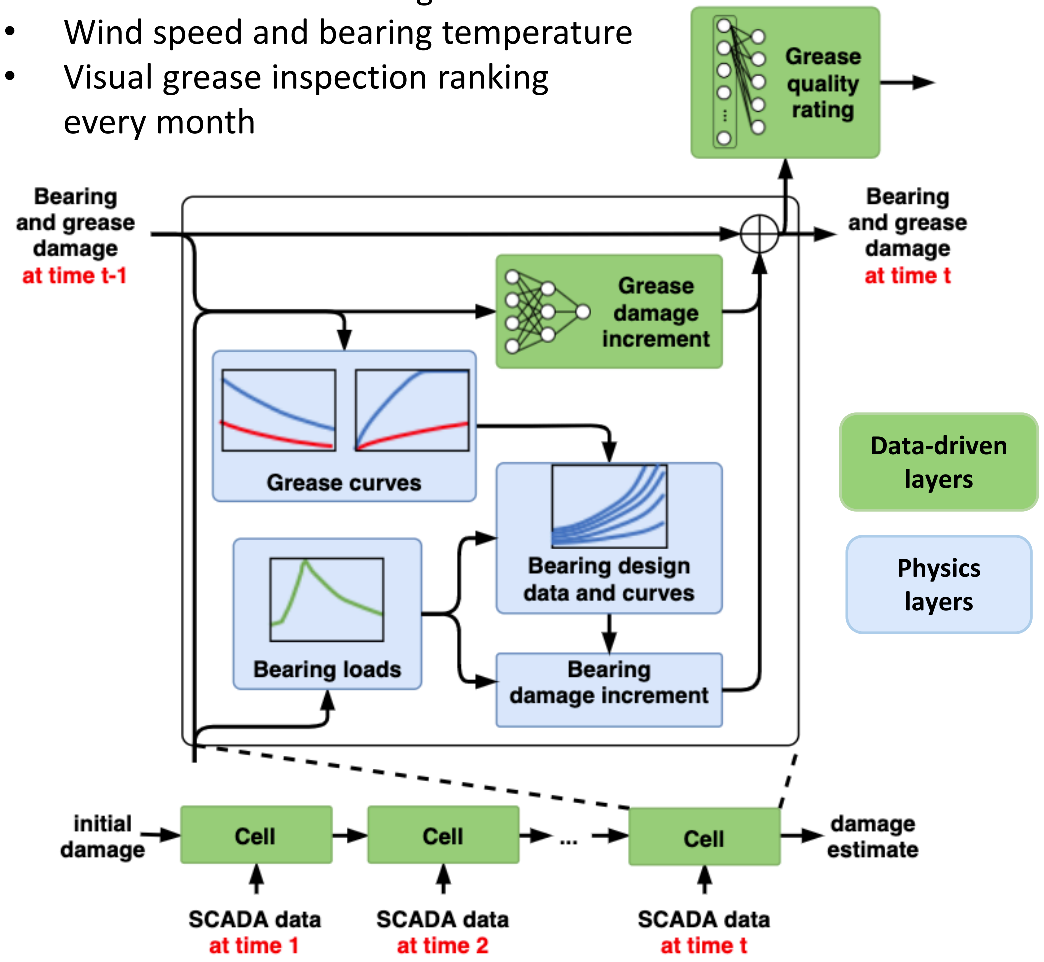
Example of ranking

Hybrid physics-informed neural network

(a) Hybrid model

10 turbines used for training

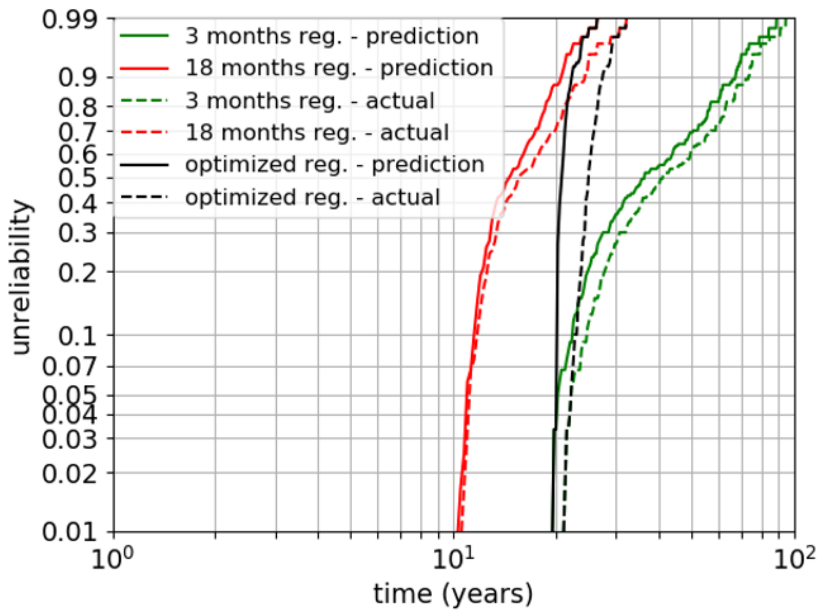
- Wind speed and bearing temperature
- Visual grease inspection ranking every month



(b) Turbine-level service optimization

Regreasing optimization @ 120 turbines

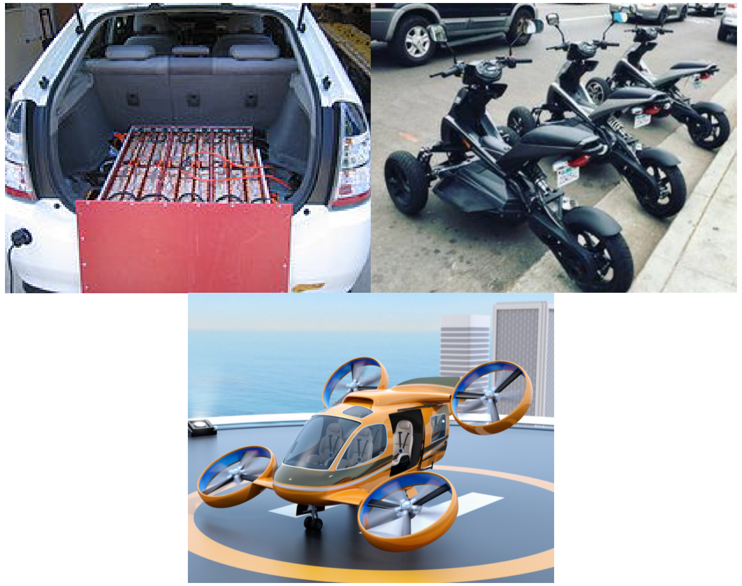
- Wind speed and bearing temperature



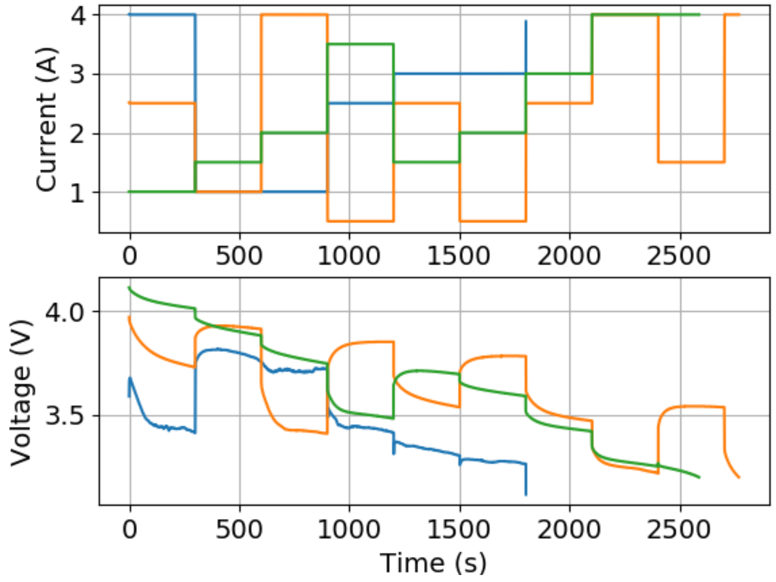
We optimized service intervals on a turbine-by-turbine basis

Lithium-ion battery aging modeling

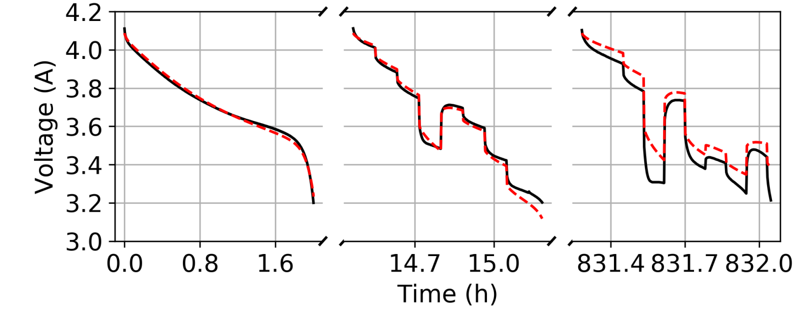
Key technology for electric vehicles



(a) Example of random loading conditions



(b) Aging can cause models to diverge from observations



Challenges:

- Prognosis models depend on a number of empirically adjusted factors
- Hard to account for aging

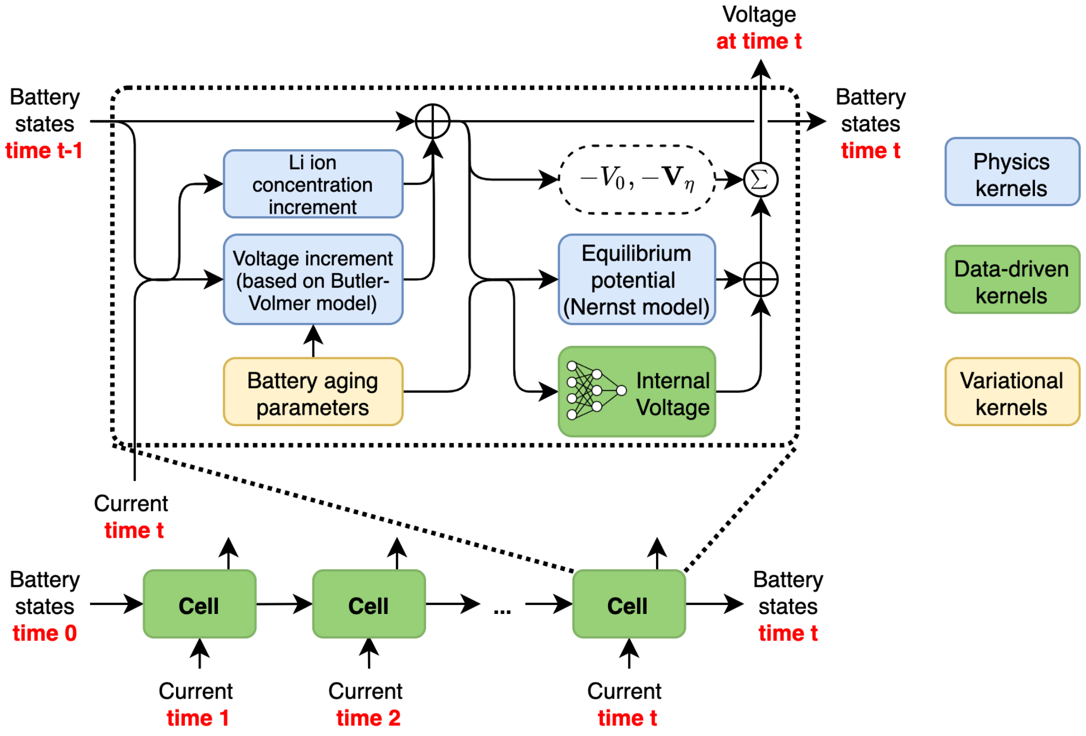
R. G. Nascimento, M. Corbetta, C. S. Kulkarni, and F. A. C. Viana, "Hybrid Physics-Informed Neural Networks for Lithium-Ion Battery Modeling and Prognosis," Applied Energy, submitted.

Hybrid physics-informed neural network

(a) Hybrid model

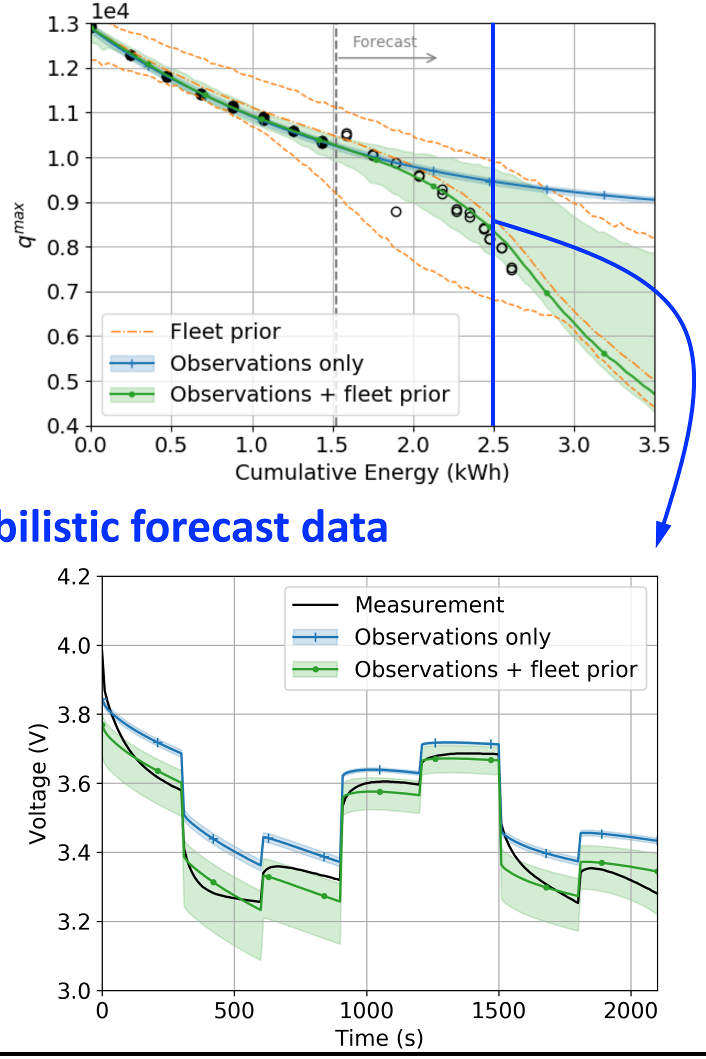
8 batteries used for training

- Current and voltage time histories
- Internal voltage adjusted with constant discharge
- Battery aging is a probabilistic model adjusted using hundreds of hours worth of data



(b) Aging model

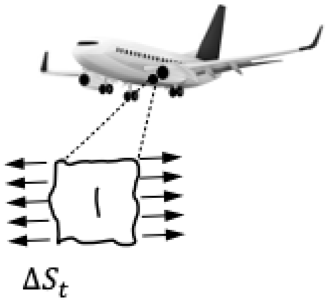
(c) Probabilistic forecast data



Model-form uncertainty in corrosion fatigue

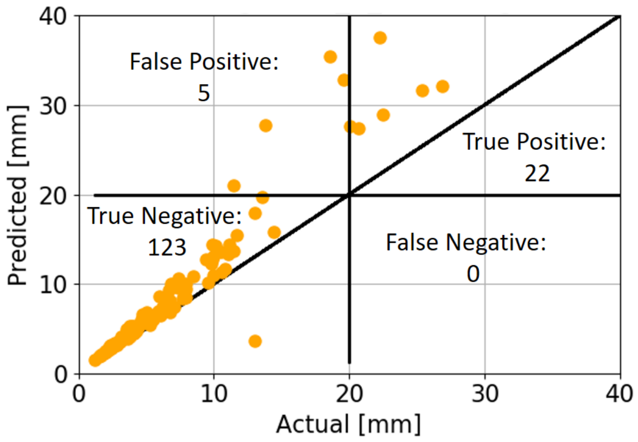
Challenge
- Assumed: pure mechanical fatigue
- After 5 years: corrosion-fatigue

Data
- Load history of 5 years: 150 aircraft
- Crack length: 15 aircraft at end of 5th year.

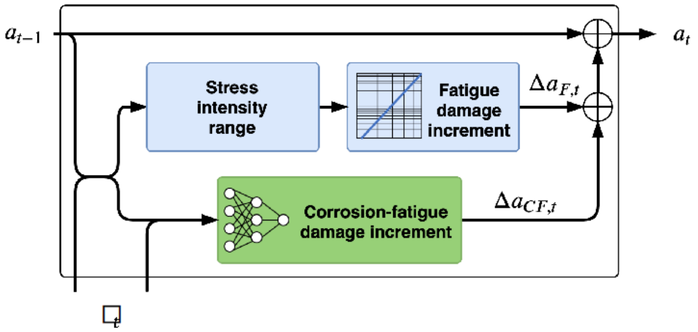


Damage accumulation grossly underestimated!!!

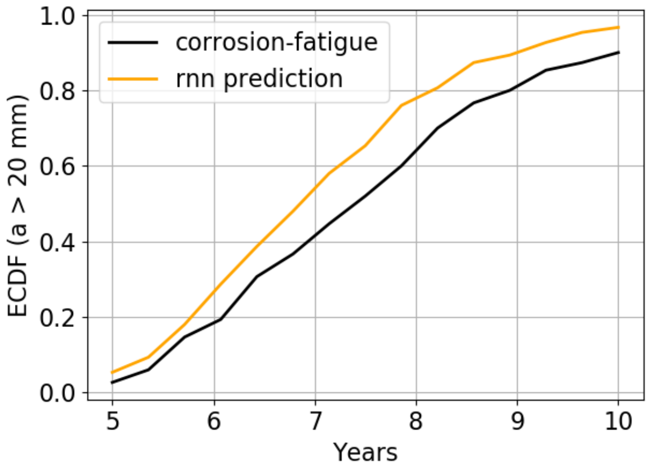
(b) Fleet prediction at the end of 5th year.



(a) Hybrid physics-informed neural network cell



(c) Probability of failure forecast



A. Dourado and F. A. C. Viana, “Physics-informed neural networks for missing physics estimation in cumulative damage models: a case study in corrosion fatigue,” ASME Journal of Computing and Information Science in Engineering, Vol. 20 (6), 10 pages, 2020.

Probabilistic Mechanics Laboratory

Publications:

pml-ucf.github.io/publications

GitHub

Physics-informed neural networks package
github.com/PML-UCF/pinn

Ordinary differential equation solver:
https://github.com/PML-UCF/pinn_ode_tutorial

Wind turbine main bearing fatigue
github.com/PML-UCF/pinn_wind_bearing

Corrosion-fatigue prognosis
github.com/PML-UCF/pinn_corrosion_fatigue

Credit really goes to my PhD students

Andre Von Zuben

Arinan Dourado

Kajetan Fricke

Renato Nascimento

Yigit Yucesan

Sponsors and Collaborators

BakerHughes

NASA

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

INSA
INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

Probabilistic Mechanics Laboratory

A Quantitative Framework to Assess Tradeoffs in Alternative Models and Algorithms for Prognostics and Health Management

Saikath Bhattacharya and Lance Fiondella

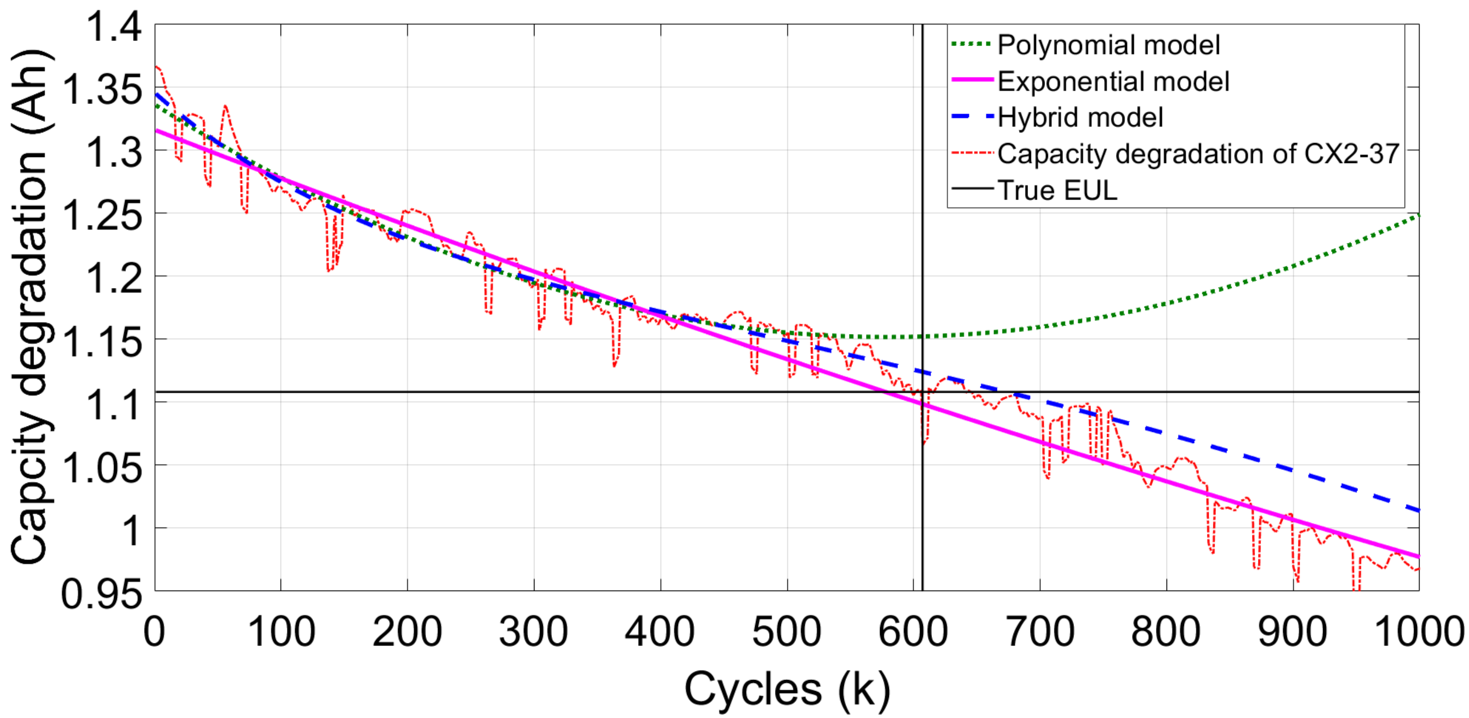
Introduction

- Prognostics and health management
  - Modernizing system reliability engineering with sensing, models, and algorithms to accurately estimate remaining useful life
  - Promotes nonfunctional RAM+C (reliability, availability, maintainability, and cost) requirements

Motivation

- Previous studies
  - Emphasize development of
    - Degradation models
    - Algorithms to estimate model parameters
  - Typically
    - Restricted to single maintenance cycle and focused on enhancing prediction
    - Do not assess long term performance of competing methods

Limitations of Academic Modeling Studies



Number of cycles used to fit models (500)
Often hand-picked to make a proposed model appear favorable

Motivation (2)

- Fewer studies
  - Assess impact of PHM decisions on cost and other derived reliability measures
  - Restricted to simulation and analytical techniques (not data-driven)

Proposed Approach

- Objective framework to assess
  - Performance decisions made by alternative combinations of models and algorithms
  - Adapts analytical methods from maintenance theory to data-driven approach
    - Average cost per unit time
    - Utilization
    - Safety
    - Availability

Capacity (Battery) Degradation Models

Some parametric models

- Polynomial model
  - $y_k = x_1 k^2 + x_2 k + x_3$ (1)
- Exponential model
  - $y_k = x_1 e^{x_2 k} + x_3 e^{x_4 k}$ (2)
- Hybrid model
  - $y_k = x_1 e^{x_2 k} + x_3 k^2 + x_4$ (3)

Filtering for Battery Degradation Models

- Unscented Kalman filter
  - Recursively updates degradation model parameters ($\mathbf{x}$) based on capacity in past and present cycles (y_k) to estimate RUL
- Particle Filtering
  - Based on Bayesian Monte Carlo simulation with importance sampling to update parameters

Preventive Maintenance

- Based on present model parameter estimates
- Recommends maintenance
  - If remaining useful life (RUL) prediction less than prognostic distance
- Continues operation otherwise

Reliability, Availability, and Maintainability Measures

- Given unit lifetime τ and maintenance interval T, inter-renewal time $Z = \min(\tau, T)$ such that

$$E[Z] = \int_0^T (1 - F(t))dt$$

  - $R(t) = 1 - F(t)$ - Unit reliability (complement of CDF)

Age Replacement Maintenance Model

- Average cost per unit time

$$\eta_{age}(T) = \frac{F(T)C_{ER} + \big(1 - F(T)\big)C_{PM}}{\int_0^T \big(1 - F(t)\big)dt}$$

  - $F(T)$ - Probability of failure before maintenance
  - C_{ER} - Cost of emergency repair
  - C_{PM} - Cost of preventive maintenance

Age Replacement Maintenance Model (2)

- Average cost per cycle

$$C(\theta) = \frac{\sum_{i=1}^{l}\{C_{PM} I(k_i) + C_{ER}[1 - I(k_i)]\}}{\sum_{i=1}^{l}\{k_i^{\theta} I(k_i) + EUL_i[1 - I(k_i)]\}}$$

  - θ – Prognostic distance
  - l – Number of units
  - $I(k_i)$ - Indicator function of i^{th} unit
  - k_i^{θ} - Cycle at which preventive maintenance performed on i^{th} unit with prognostic distance θ

ILLUSTRATIONS

Data and Methodology

- Utilized Li-ion battery data set ($n = 4$)
  - Performed least squares estimation on battery exhibiting most cycles prior to failure and used as initial estimates for UKF and PF (also considered battery with fewest cycles)

Data and Methodology (2)

- Ratio of emergency and preventive repair costs

$$\frac{C_{ER}}{C_{PM}} = 1{,}000$$

- Mean times to repair

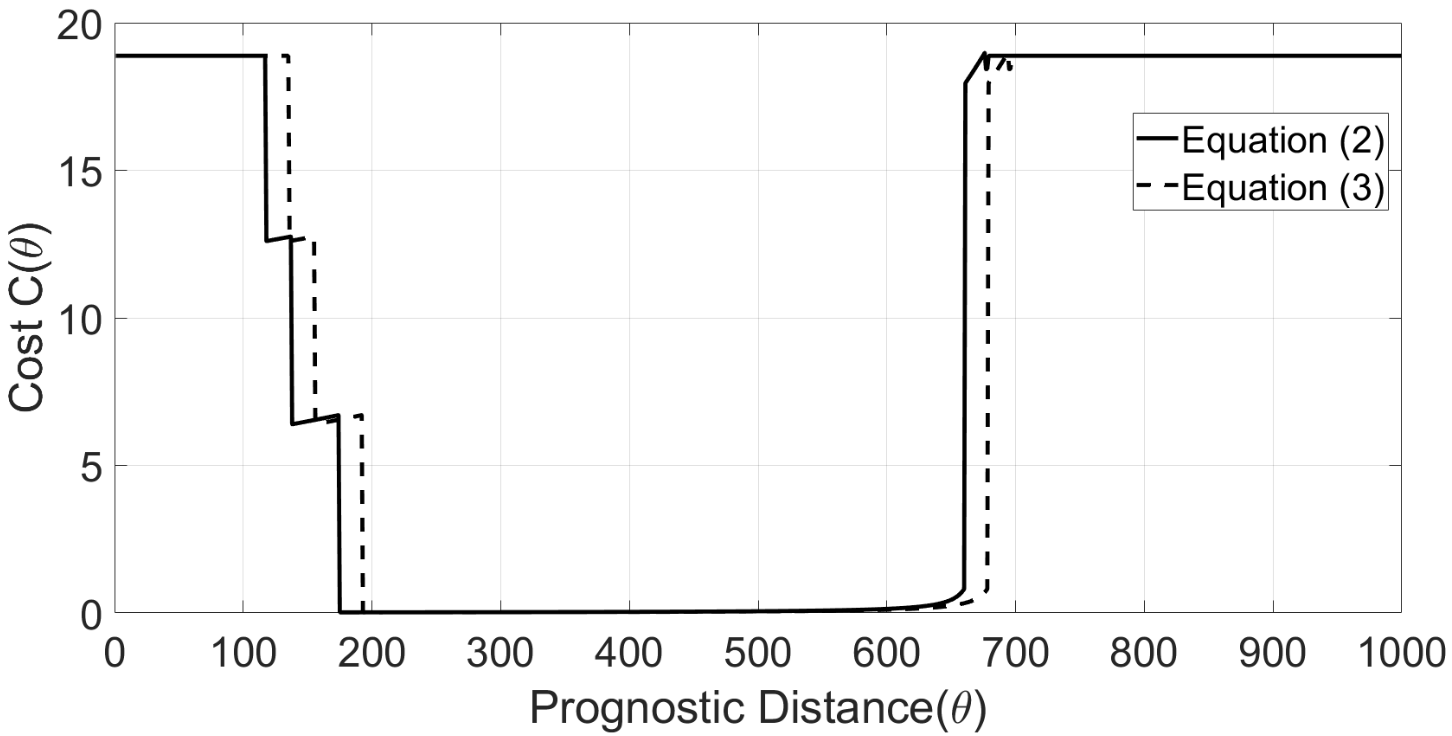
$$MTTR_{PM} = 3 \text{ and } MTTR_{ER} = 8$$

Point Example: Equation (2) under UKF with $\theta = 150$

Measure	CX2-34	CX2-36	CX2-38
True EUL (cycles)	505	560	524
Maintenance (k_i^θ)	505	527	511
Predicted EUL (cycles)	679	677	661
Unused life (cycles)	0	33	13
Cost $C(\theta)$	10,000	10	10
Safety $S(\theta)$	0	1	1
Time to repair (cycles)	8	3	3

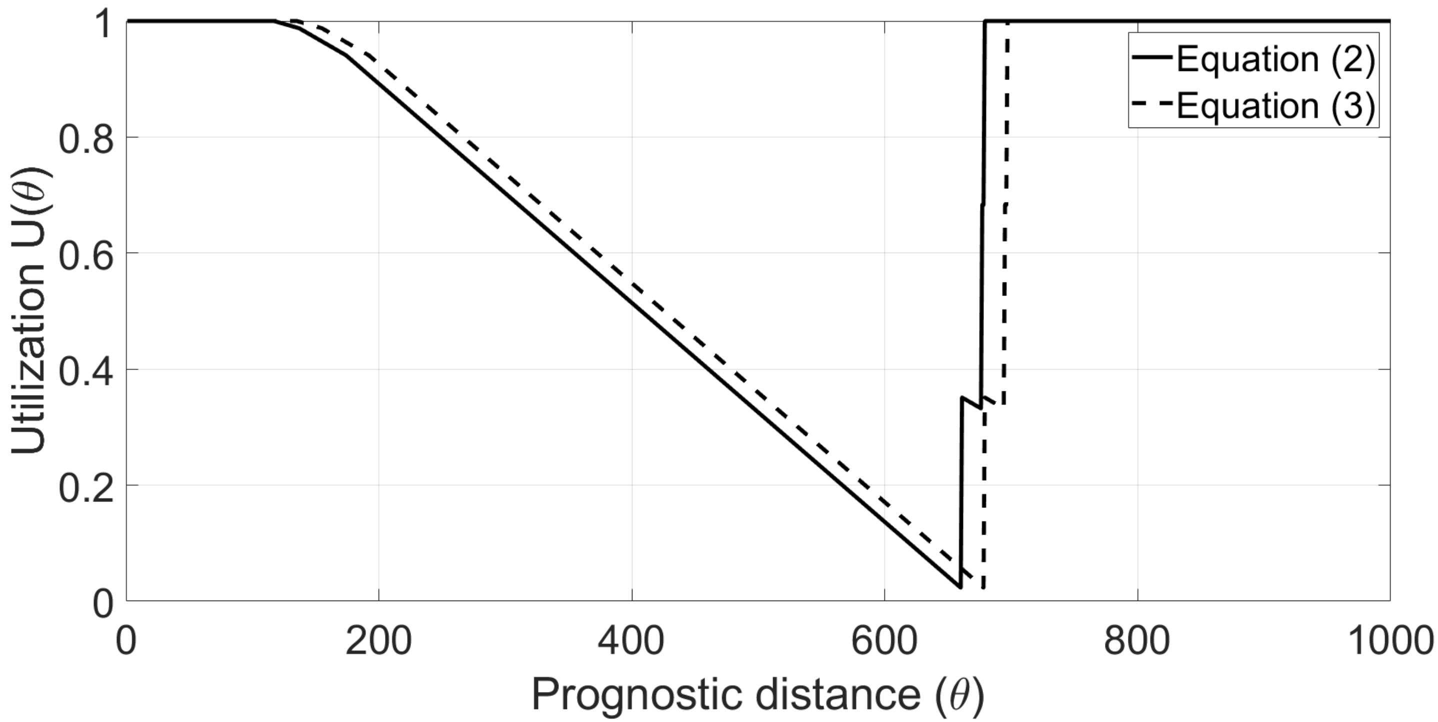
$C(150) = \frac{10{,}020}{1{,}543} = 6.494$, $U(150) = \frac{1{,}543}{1{,}589} = 97.11\%$, $S(150) = \frac{2}{3}$, $A(150) = 99.1\%$

Average Cost per Cycle (UKF)



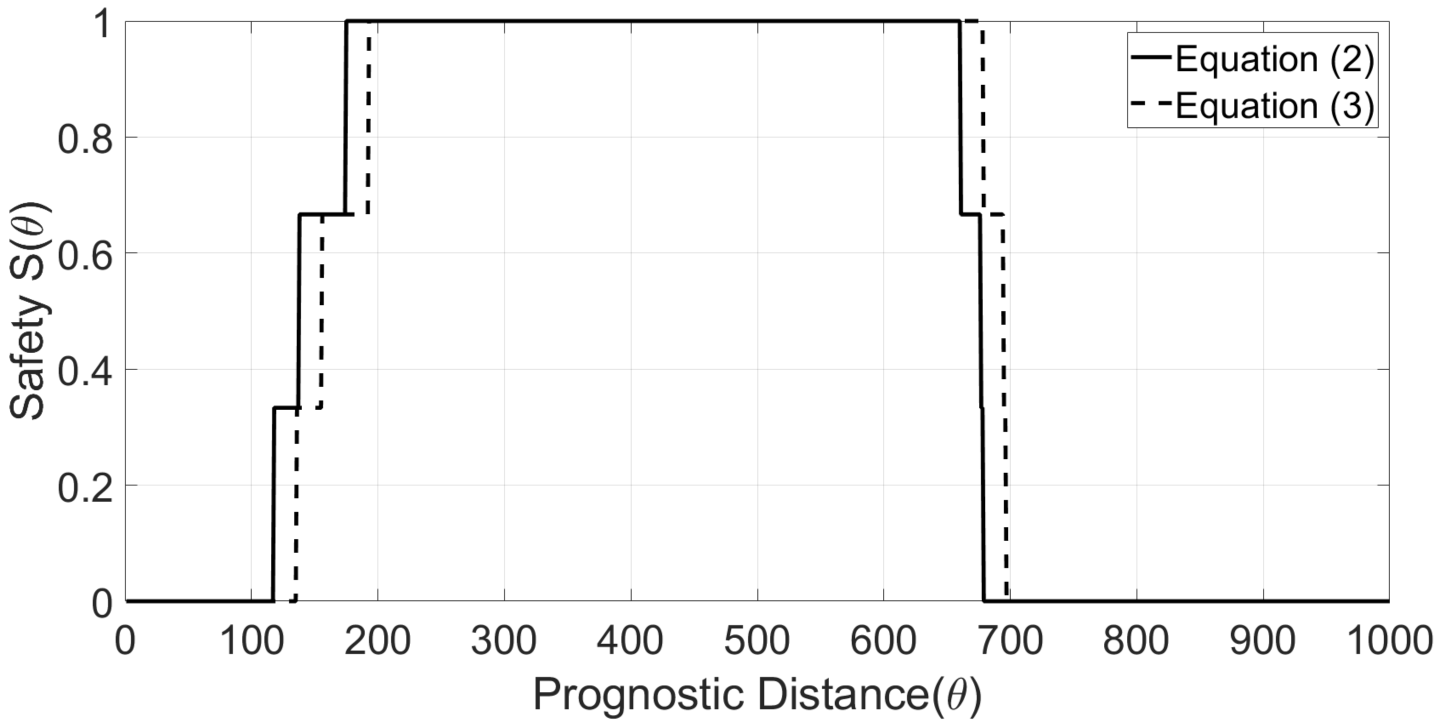
Prognostic distance $\theta \in (175,678)$ minimizes cost

Utilization (UKF)



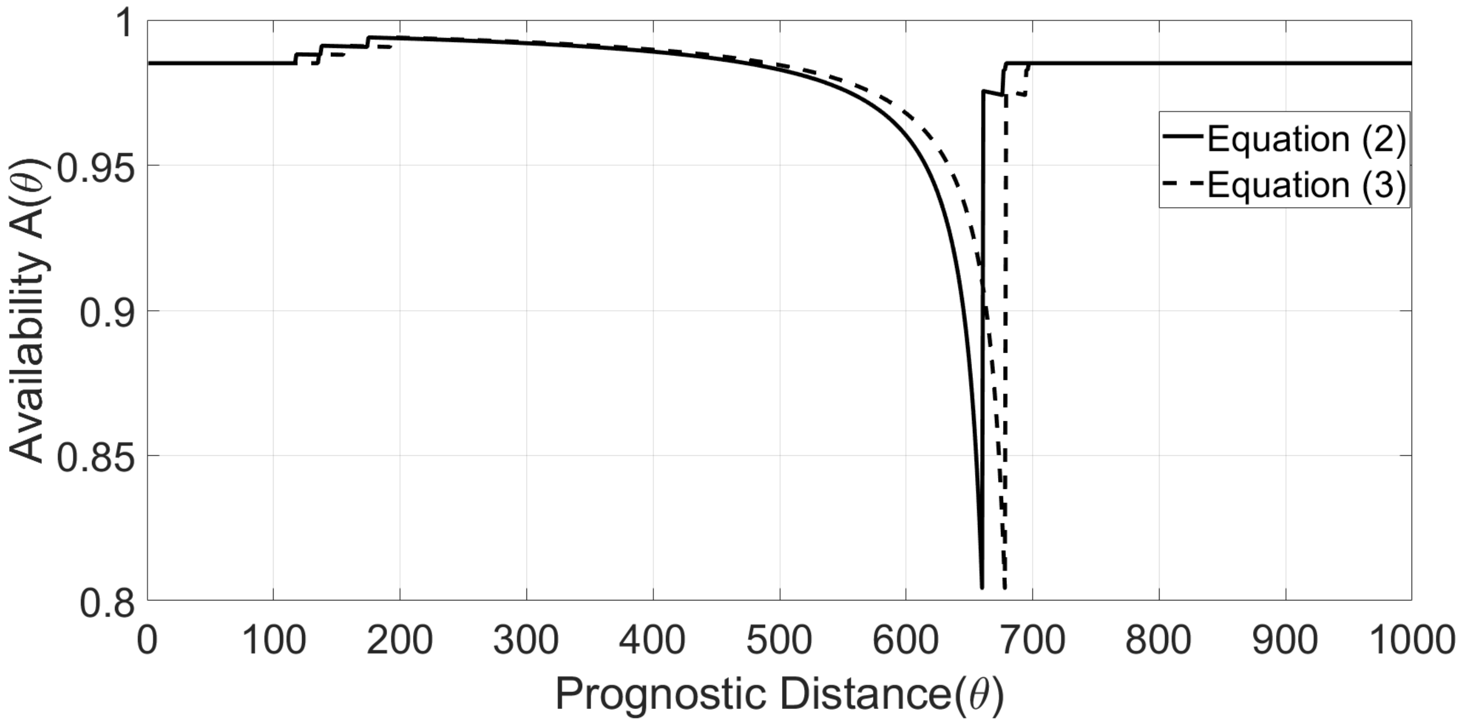
Utilization decreases monotonically as larger prognostic distance initiates earlier maintenance

Safety (UKF)



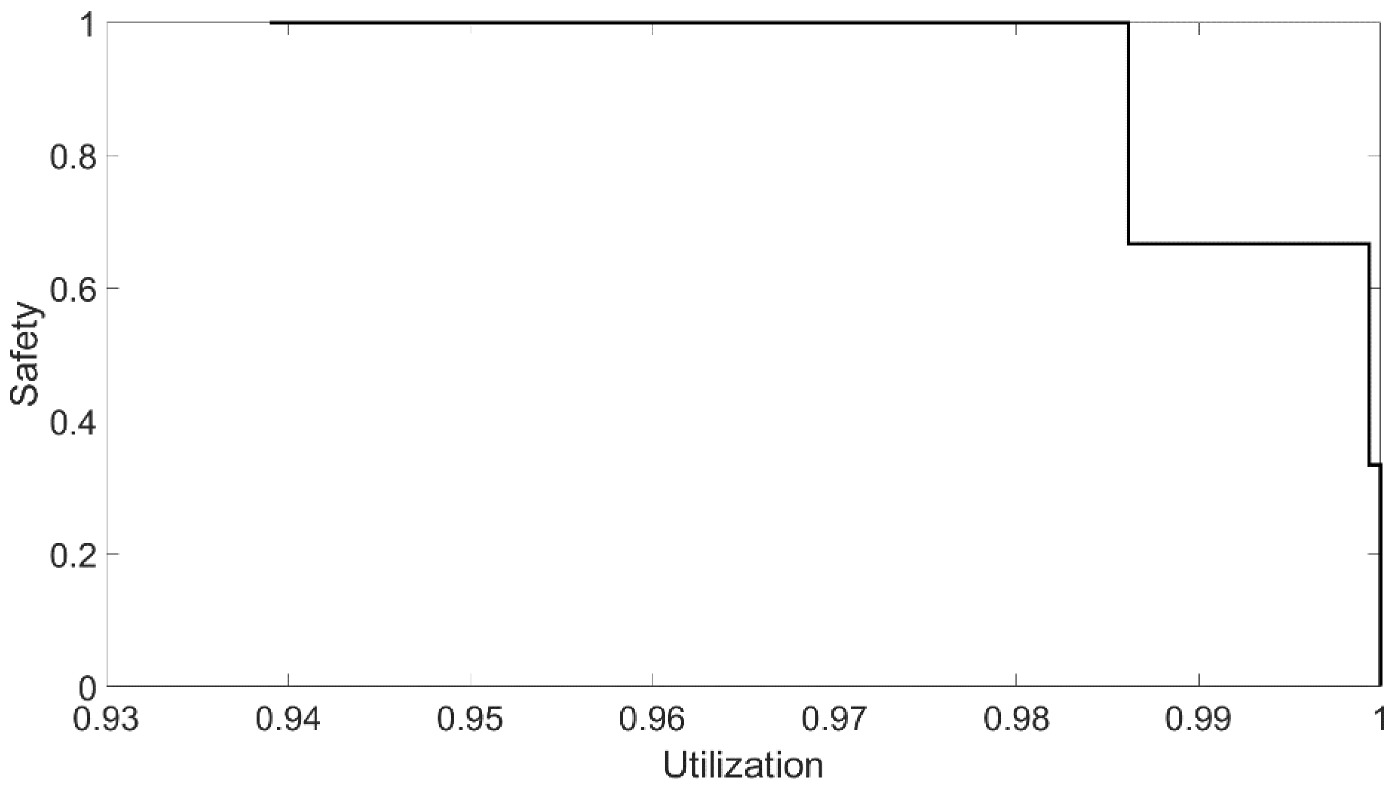
Safety and average cost per cycle exhibit inverse trends

Availability (UKF)



Low utilization corresponds to low availability

Example tradeoff (UKF)



Safety and utilization competing constraints

Summary and Conclusions

- Proposed framework to assess
  - Quantitative performance of PHM decisions made by alternative combinations of models and algorithms
- Developed RAM+C measures for PHM
  - Average cost per unit time, utilization, safety, and availability

Summary and Conclusions (2)

- Applied to combinations of three degradation models and two filtering methods with Li-ion data set
- Proposed approach
  - Offers method to select prognostic distance to balance stakeholder needs
  - Can be applied to other domains, degradation models (physics of failure), and algorithms (deep learning)

Future work

- Open source framework
  - Crowdsource contribution of
    - Models
    - Algorithm
    - Datasets/Challenges
  - Raise academic standards for comparison
  - Promote collaboration between academic, industry, and government stakeholders

- Formulation of additional quantitative measures
- Performance of particle filtering on quantitative measures
- Comparison of quantitative measures in window minimizing cost

BACK UP SLIDES

Additional Measures

- Utilization

$$U(\theta) = \frac{\sum_{i=1}^{l}\left(k_i^{\theta} I(k_i) + EUL_i\left(1 - I(k_i)\right)\right)}{\sum_{i=1}^{l} EUL_i}$$

  - EUL_i - End of useful life of i^{th} unit

- Can take values in interval $(0,1)$
- Poses competing objective with cost and safety

Additional Measures (2)

- Safety

$$S(\theta) = \frac{\sum_{i=1}^{l} I(k_i)}{l}$$

  - Fraction of units that undergo preventive maintenance

- Minimizing cost corresponds to maximizing safety

Additional Measures (3)

- Availability

$$A(\theta) = \frac{MTTF}{MTTF + MTTR}$$

- Mean time to failure (MTTF)

$$MTTF = \frac{1}{l}\sum_{i=1}^{l}\left(k_i^{\theta} I(k_i) + EUL_i(1 - I(k_i))\right)$$

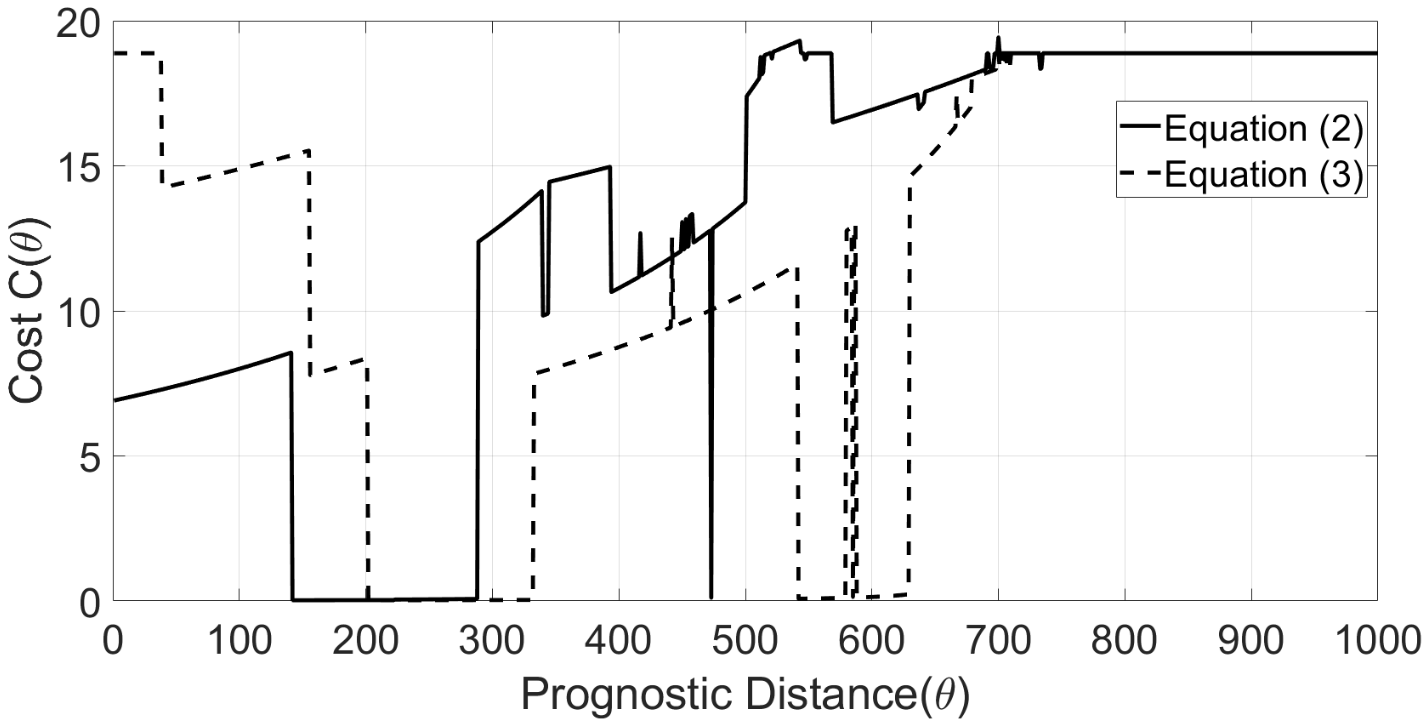
Additional Measures (4)

- Mean time to repair (MTTR)

$$MTTR = \frac{1}{l}(l_{PM}MTTR_{PM} + l_{ER}MTTR_{ER})$$

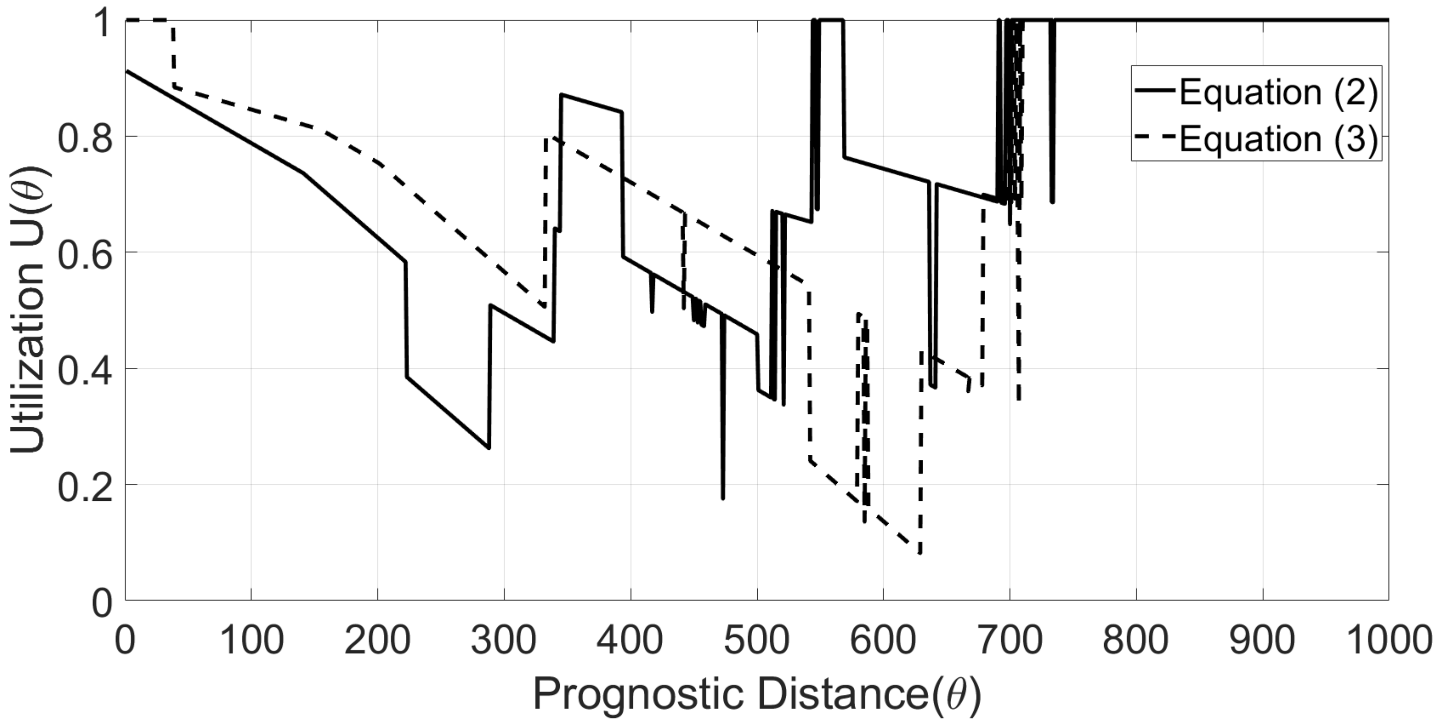
  - l_x - Number of units subject to $x \in (PM, ER)$
  - $MTTR_x$ - Mean time to repair given that unit underwent $x \in (PM, ER)$

Average Cost per Cycle (PF)



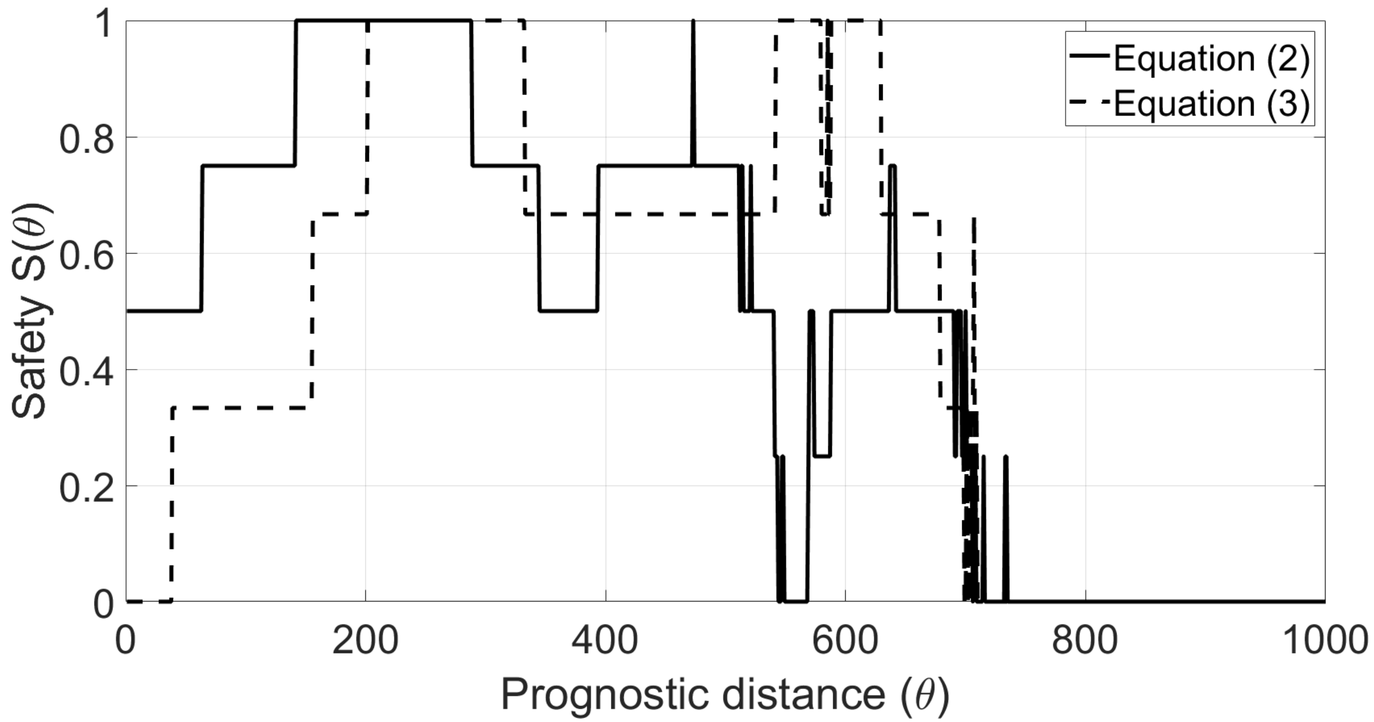
Prognostic distance $\theta \in (202,288)$ minimizes cost

Utilization (PF)



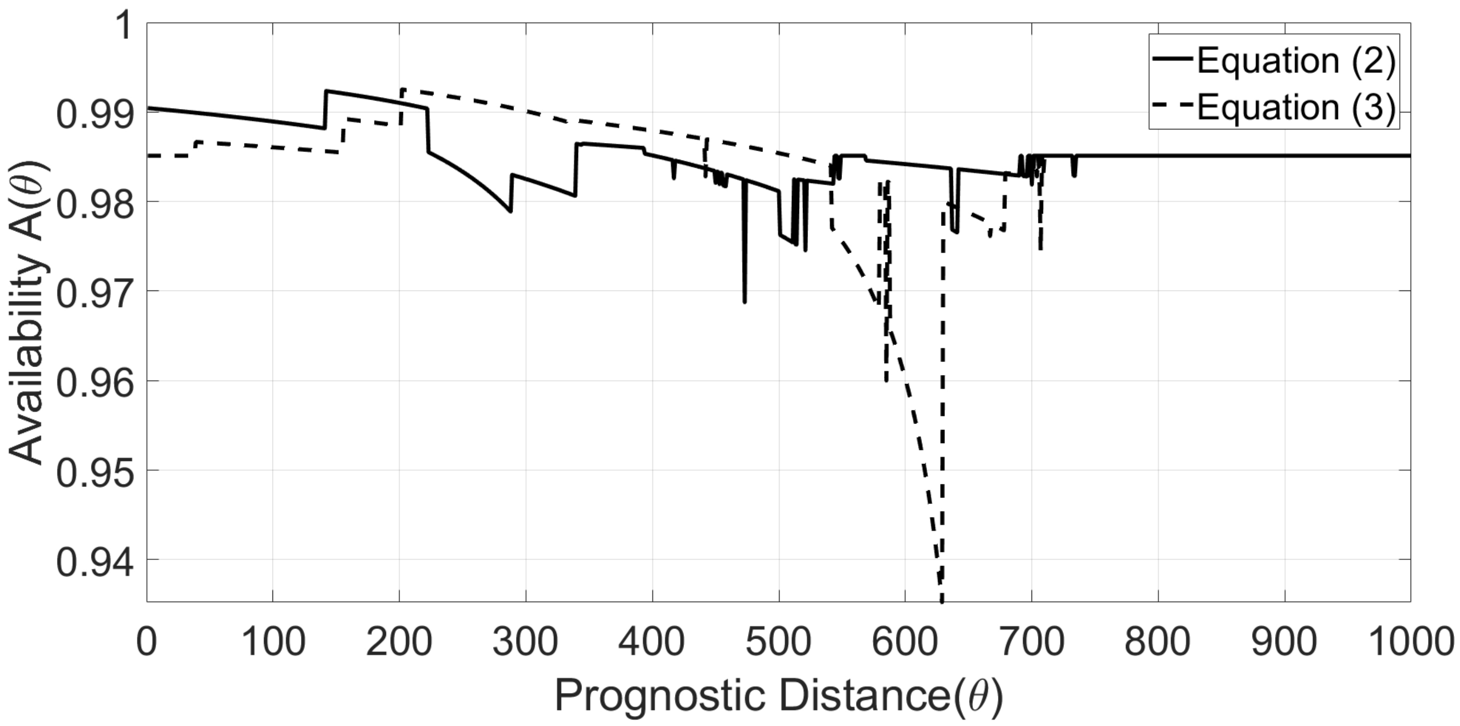
Prognostic distances that produce low utilization correspond to low cost

Safety (PF)



Safety and average cost per cycle exhibit inverse trends

Availability (PF)



Low utilization corresponds to low availability

Measures in Prognostic Window with Cx2-37 (most cycles to failure)

	Unscented Kalman Filter			Particle Filter		
θ	**Left**	**Mid**	**Right**	**Left**	**Mid**	**Right**
Eq (2)	175	412	660	142	215	288
$C(\theta)$	0.020	0.039	0.810	0.025	0.031	0.071
$U(\theta)$	0.939	0.482	0.023	0.734	0.596	0.262
$A(\theta)$	0.994	0.988	0.804	0.992	0.990	0.978

Eq (3)	193	435	678	202	267	332
$C(\theta)$	0.020	0.039	0.810	0.025	0.030	0.037
$U(\theta)$	0.939	0.482	0.023	0.751	0.628	0.500
$A(\theta)$	0.994	0.988	0.804	0.992	0.991	0.988

Conservative strategy selects θ at midpoint

Measures in Prognostic Window with Cx2-34 (most cycles to failure)

	Unscented Kalman Filter			Particle Filter		
θ	**Left**	**Mid**	**Right**	**Left**	**Mid**	**Right**
Eq (1)	101	343	586	330	361	392
$C(\theta)$	0.019	0.035	0.267	0.035	0.039	0.044
$U(\theta)$	0.937	0.503	0.067	0.512	0.456	0.4013
$A(\theta)$	0.994	0.989	0.925	0.989	0.988	0.986

Eq (3)	136	374	613	160	261	362
$C(\theta)$	0.020	0.039	0.576	0.022	0.028	0.044
$U(\theta)$	0.887	0.459	0.031	0.815	0.634	0.401
$A(\theta)$	0.994	0.988	0.852	0.993	0.991	0.986

Equation (3) with UKF stable in both scenarios

Digital Twins in a Nearly Autonomous Management and Control System for Advanced Reactors

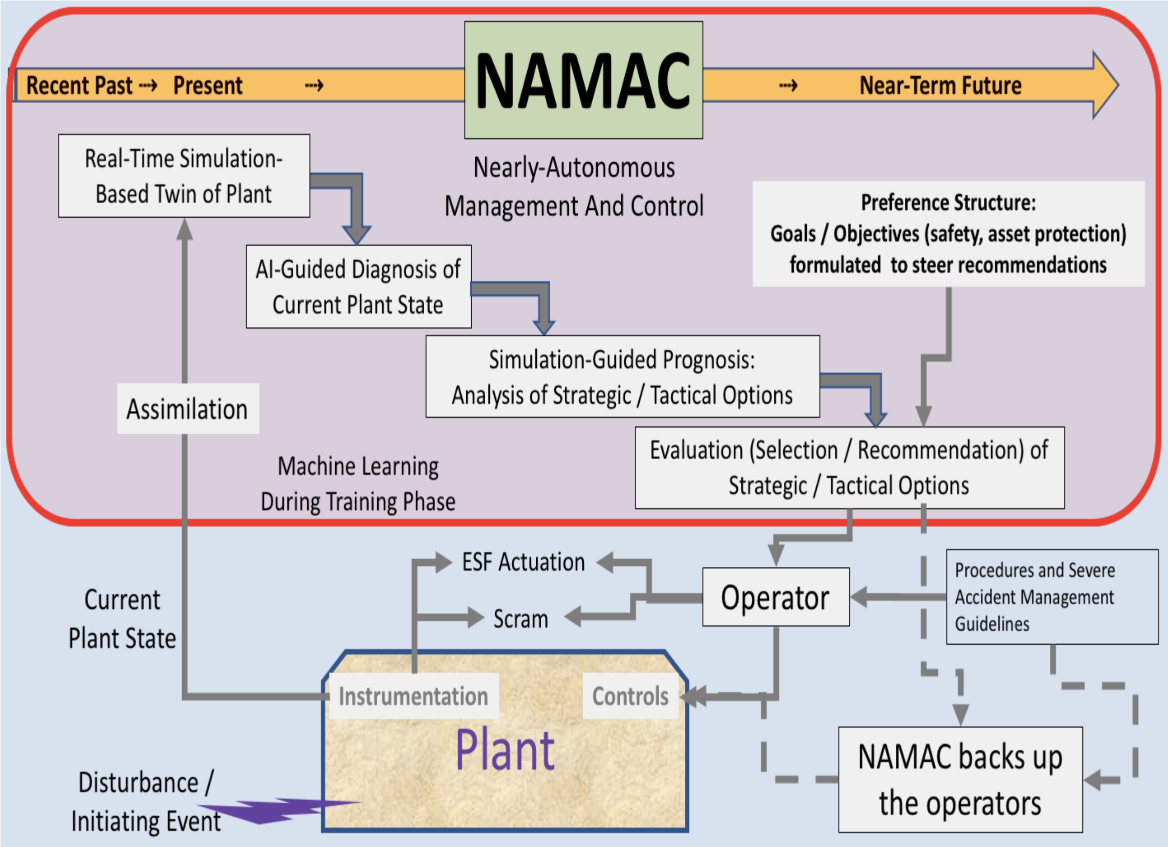
Nam Dinh, Linyu Lin

Department of Nuclear Engineering
North Carolina State University

12/08/2020

Nearly Autonomous Management and Control (NAMAC)

- A comprehensive control system to assist plant operations
  - Knowledge integration
    - Scenario-based model of plant (systems, success paths)
    - plant operating procedures, tech. specs., etc.
    - Real-time measurements
  - Digital twin technology
    - Power of AI/ML



- NAMAC
  - Diagnoses the plant state
  - Searches for all available mitigation strategies
  - Projects the effects of actions and uncertainties into the future behavior
  - Determines the best strategy considering plant safety, performance, and cost.

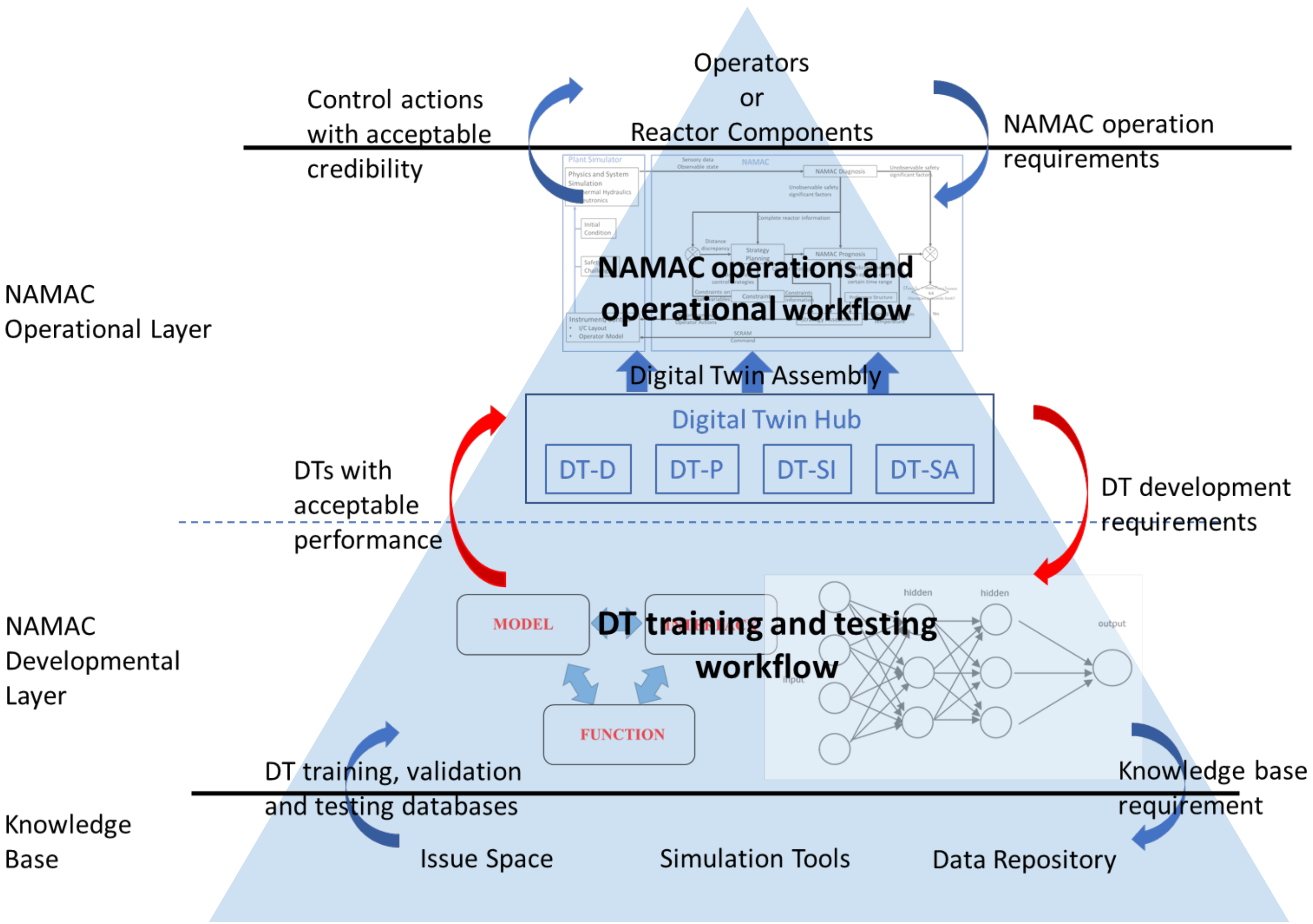
Guiding Principles and Development Philosophy

- High-level requirements
  - Technology neutral
  - Accurate representation (twin) of the plant
  - Dynamic and real-time: diagnosis, prognosis, and evaluation during operations
  - Adaptive (or continuously learning)
  - Explainable: outputs are traceable and justifiable

- Design principles for an intelligent autonomous control system
  - Three-Level Architecture
  - Knowledge Base
  - Digital Twin
  - Digital Twin Development and Assessment Process
  - Trustworthiness Assessment

Three-Layer Architecture

- Individual Digital Twins (DT) are assembled into a DT-Hub to support decisions in operation, maintenance, safety management, etc. in the Operational Layer
- Each Digital Twin (DT) is a knowledge acquisition system to support specific functions
  - Digital Twin for Diagnosis (DT-D)
  - Digital Twin for Strategy Inventory (DT-SI)
  - Digital Twin for Prognosis (DT-P)
  - Digital Twin for Strategy Assessment (DT-SA)
- Developmental Layer extracts useful information from the knowledge base and creates Digital Twins (DT)
- Knowledge base stores data from simulations, operations, documents, procedures, etc.



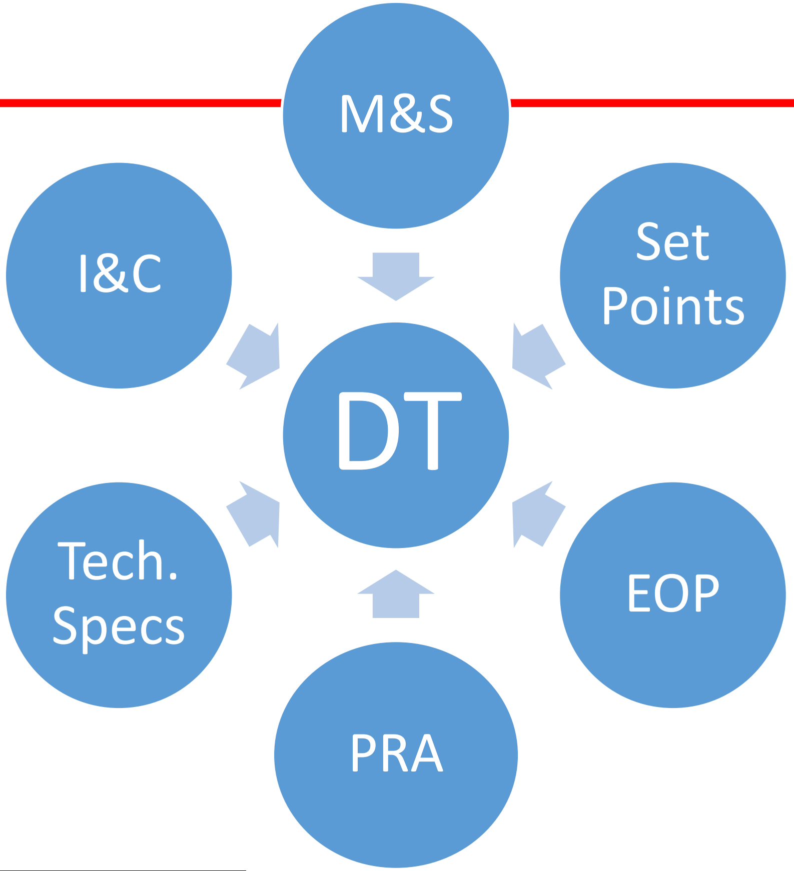
Knowledge Base

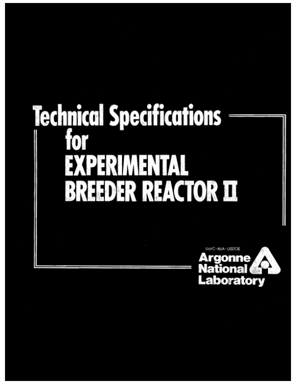
- Knowledge base is the foundation of DTs and NAMAC

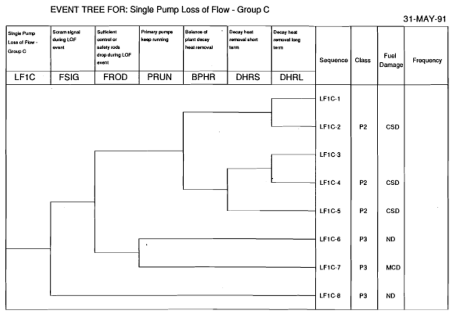
- Integrate knowledge from a variety of sources
  - Plant monitoring systems
  - Scenario based modeling & simulation (M&S)
  - Operating limits and control procedures
  - Probabilistic assessment of the risk
  - Emergency Operating Procedures (EOP)

- Knowledge base will transit from simulation-based data to assimilating sensor data as a new plant comes on-line and operating history becomes available
  - M&S will always be a key contributor to the knowledge base, particularly for accidents and other low frequency events where actual plant data may not be available.

- Not just “raw” data signals, but these sources are vital knowledge bases
  - Leverage existing information
  - Minimize propensity to treat ML and DTs as “black-box”

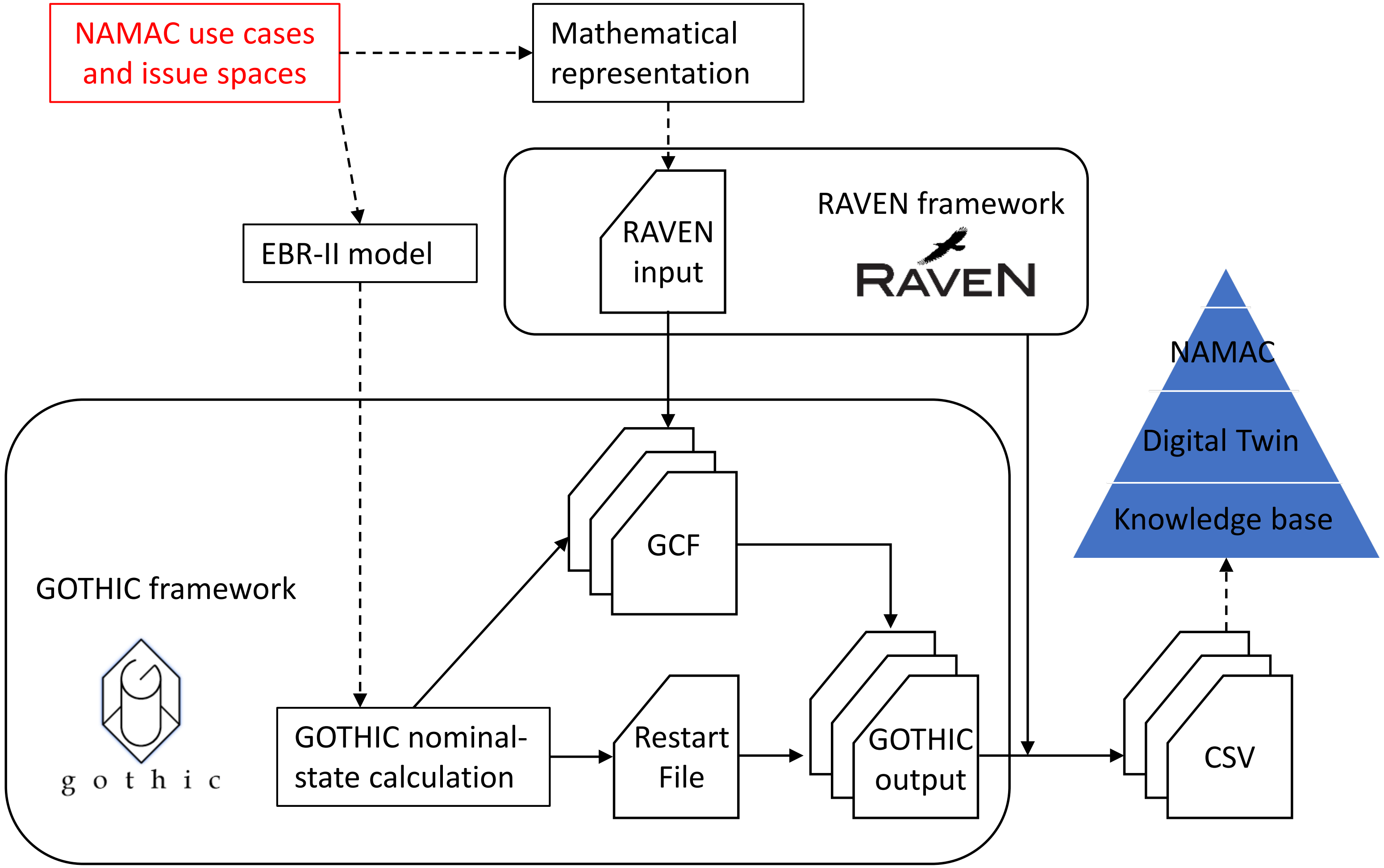






Database Generation in Knowledge Base

- NAMAC Database generation:
  - Training databases are generated by sampling scenarios to populate information in the application domain
  - The Digital Twin are constructed according to the databases for supporting diagnosis, prognosis, etc.



Digital Twin

- Digital Twin technology - construct a digital replica (twin) for the real reactors and transients

- DTs must provide insights equivalent to Modeling and Simulation (M&S), but need to learn and provide those insights much faster than the development and uses of M&S

- But DTs are tightly coupled with operation
  - Assimilating and adapting to real-time information from the operating environment
  - Interacting with user for specific objectives

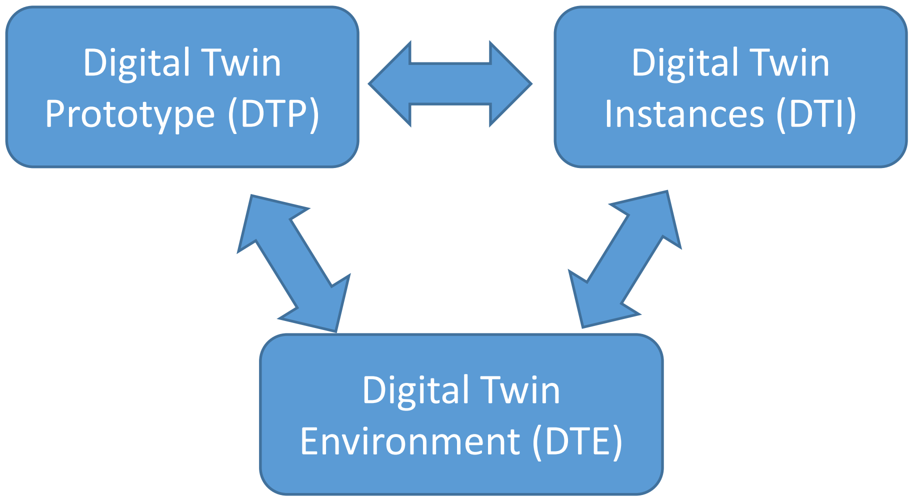
Definitions for DTs [1]

MODEL

- Data-driven model
- Mechanistic model
- Reasoning-based model

INTERFACE

- API
- I/O
- User Interface



FUNCTION

- Use cases
- Objectives
- Output types

[1] F. Kahlen, et al., "Transdisciplinary perspectives on complex systems - new findings and approaches", Springer, 2017

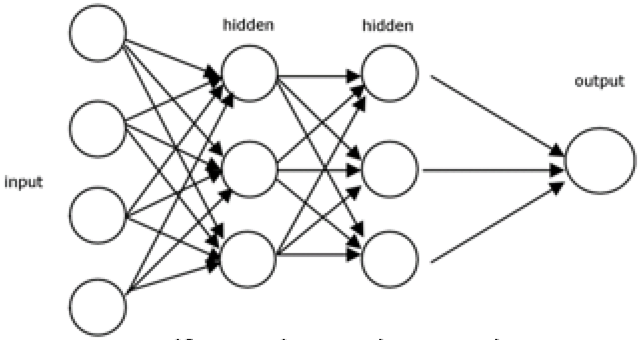
Digital Twin Training and Algorithms

- Artificial Neural Network (ANNs) is currently the major technology in constructing Digital Twins and NAMAC system.

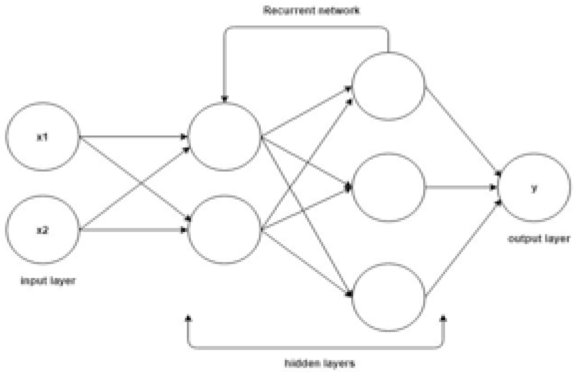
- As complexity of NAMAC case studies increases, advanced algorithms are required to support DTs
  - Modular framework allows for multi-tiered implementation
  - Do not need a single, monolithic solution to cover all conditions

- Two classes of advanced algorithms are being investigated:
  1. *Knowledge/reasoning-based methods*
     - Provide **explainability** and **transparency**
  2. *Model free methods*
     - Deep learning capability that is needed for **diversity** and **complexity**

- Need both types for NAMAC



Feedforward Neural Network

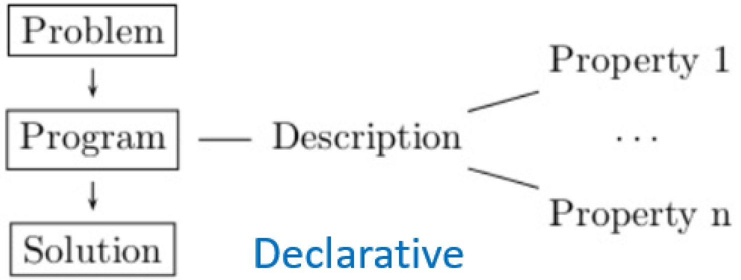


Recurrent Neural Network

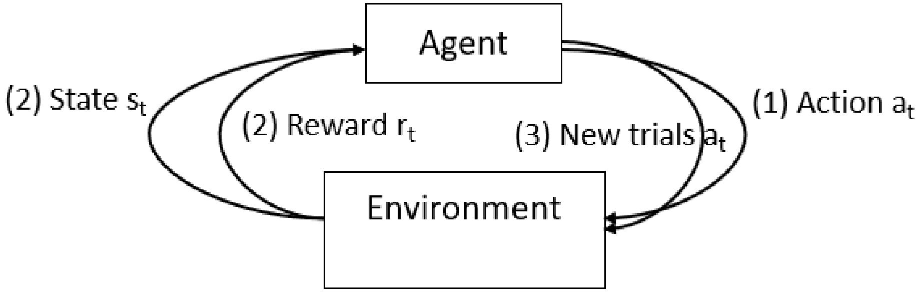
Digital Twin Training and Algorithms

- Advanced Algorithms
  - **Answer Set Programming (ASP)** is a form of declarative programming oriented towards difficult search problems
    - Discrepancy Checker (DC)
  - **Ensemble modeling** employs a voting technique to aggregate/select predictions from a set of base models
    - Digital twin for diagnosis (DT-D)
  - **Reinforcement Learning (RL)** interacts with the environment and is time aware
    - Wholistic NAMAC for furnishing recommendations
  - **Adaptive sampling** techniques for data generation
    - Efficient process to support Strategy Inventory (DT-SI)
  - **Meta-Learning** to accelerate and optimize development

Given descriptions and problem, ASP can find a solution that is consistent with properties



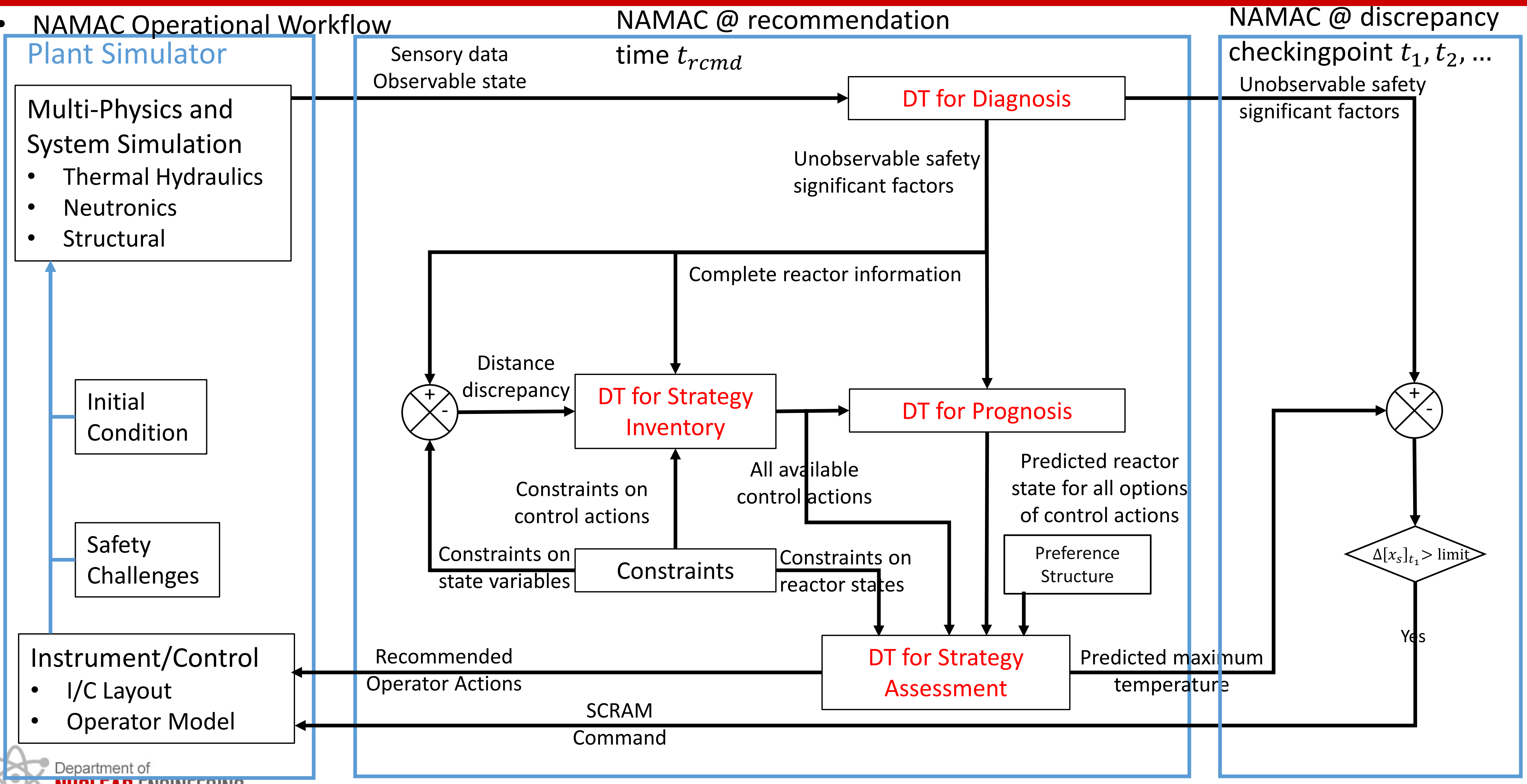
Declarative programming



Modular Framework

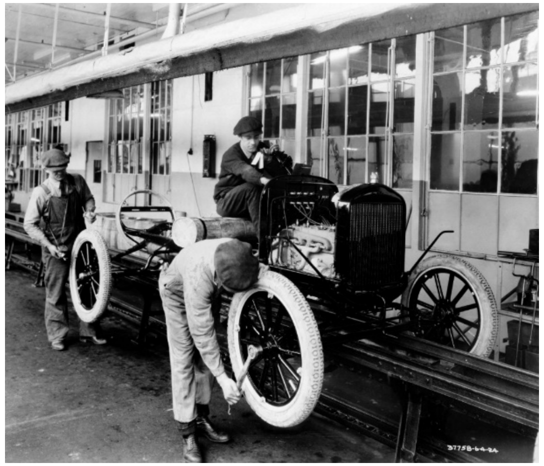
	Function	Modeling
Diagnosis	Recover full reactor states by assimilating plant sensor data with the knowledge base	Neural nets (feedforward & recurrent); Logic programming (Answer Set Programming)
Strategy Inventory	Find all available control/mitigation strategies	Uniform sampling Reinforcement Learning
Prognosis	Predict the transients of state variables over a time range	Neural nets (feedforward & recurrent)
Strategy Assessment	Rank possible mitigations strategies and make recommendations considering preference structure	Safety margin/limiting surface; Expected utility;
Discrepancy Checker	Detect unexpected transient during operations considering DT trustworthiness for current conditions	Distance metrics; Logic programming (Answer Set Programming)

- NAMAC Operational Workflow



The Development and Assessment Process (DAP)

- Instead of claiming to have a perfect autonomous system for a specific reactor during a specific scenario, our objective is to have a "smart" Development and Assessment Process (DAP) that produces NAMAC systems for generic types of reactors based on requirements from all stakeholders.



1924 – Ford assembly line

1965 – Ford assembly line

2019 – Tesla smart factory

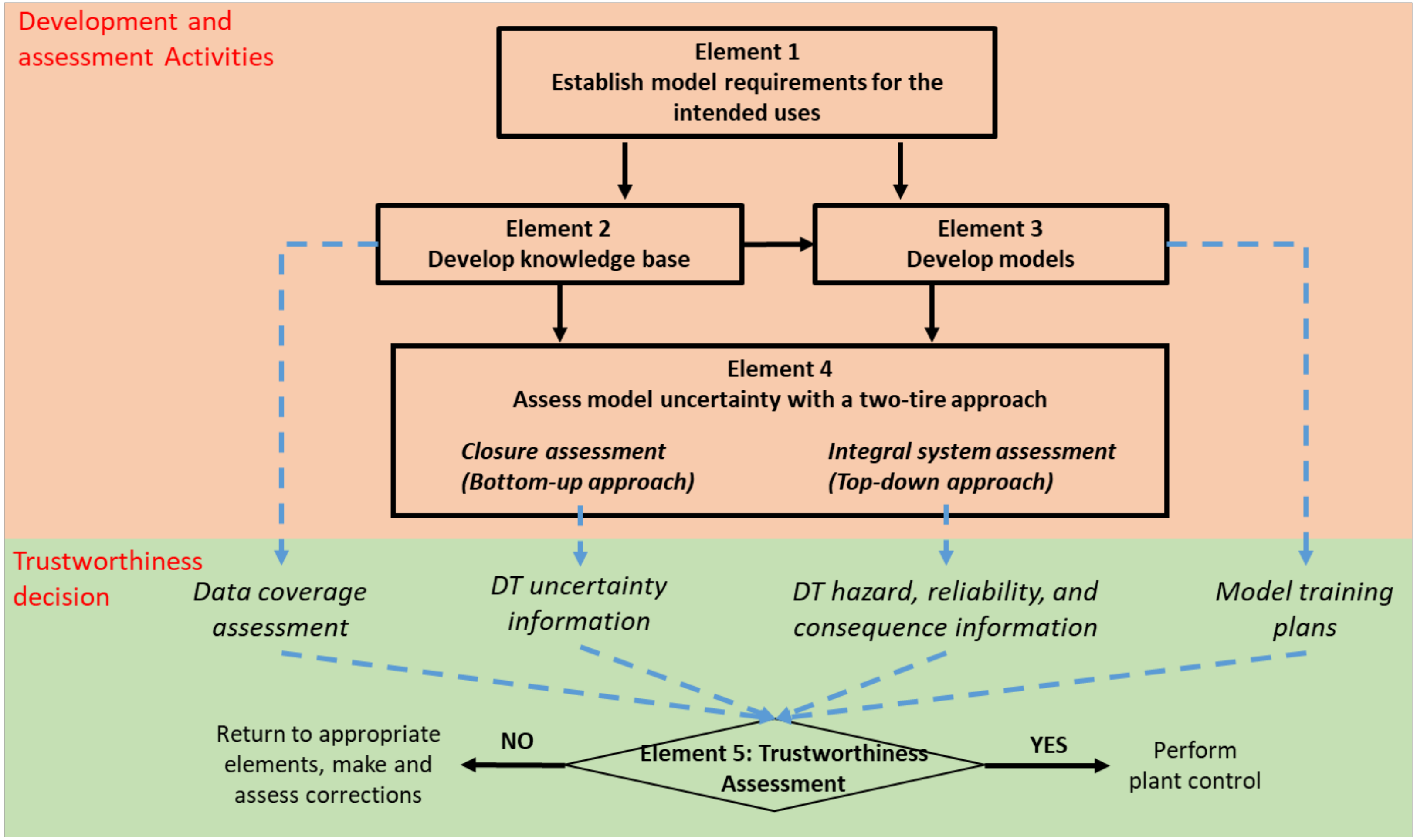
Evolution of "Development and Assessment Process (DAP)" for Automobile

[1] [2] Picture by Ford, "The evolution of assembly lines: A brief history", https://robohub.org/the-evolution-of-assembly-lines-a-brief-history/, 2014
[3] Picture from "Popular Mechanics", https://ottomotors.com/blog/what-is-the-smart-factory-manufacturing, 2019

Digital Twin Development and Assessment Process

- DT-DAP for a scalable and robust application of digital twins and NAMAC concept to generic types of use cases and advanced reactors.

- The DAP is conducted iteratively to deliver a reliable NAMAC with a set of credible DTs
  - *Element 1*: Refined requirements
  - *Element 2*: More complex and realistic knowledge base
  - *Element 3*: Different machine-learning algorithms
  - *Element 4*: ML uncertainty quantification, software reliability analysis
  - *Element 5*: Digital twin trustworthiness assessment



Adopted from U.S. NRC RG 1.203 “Transient and Accident Analysis Methods”

Digital Twin Trustworthiness

- In fundamental, the NAMAC make recommendations by **extracting** knowledge from knowledge base and **assimilating** them with **real-time** sensor signals – Digital Twin
    - Considering the complexity and heterogeneity of knowledge base, we investigate **data-driven models** and **machine-learning algorithms** for

- However, for complex systems and difficult tasks, the uncertainty of the DTs in NAMAC, if being overlooked, could introduce additional risks and degrade the trustworthiness of NAMAC recommendations, especially when the DT itself is complicated and black-box

- As a result, we need a trustworthiness assessment framework for DTs in NAMAC (ongoing)

    (1) monitor uncertainty that could complicate the determination of mitigation strategies

    (2) make uses of information from the DT development and assessment process

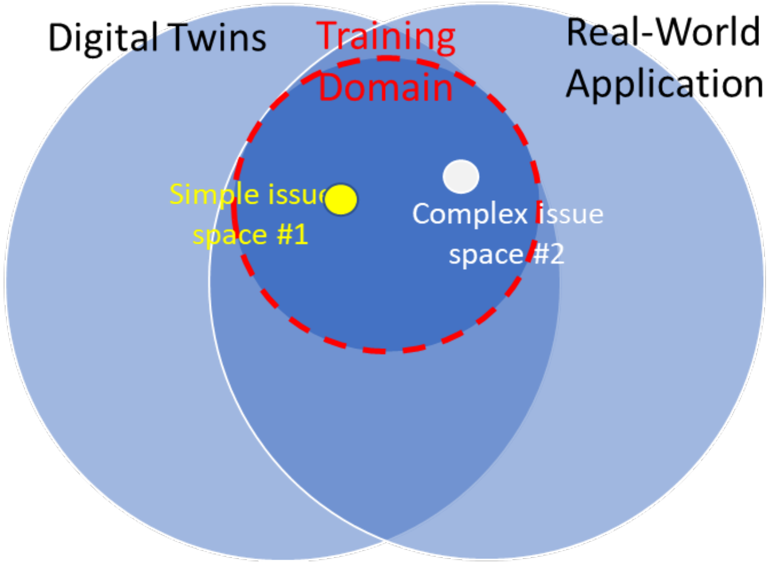
    (3) do this in real time

A gap between

the development & assessment of a digital twin

and

the use & regulation of a digital twin



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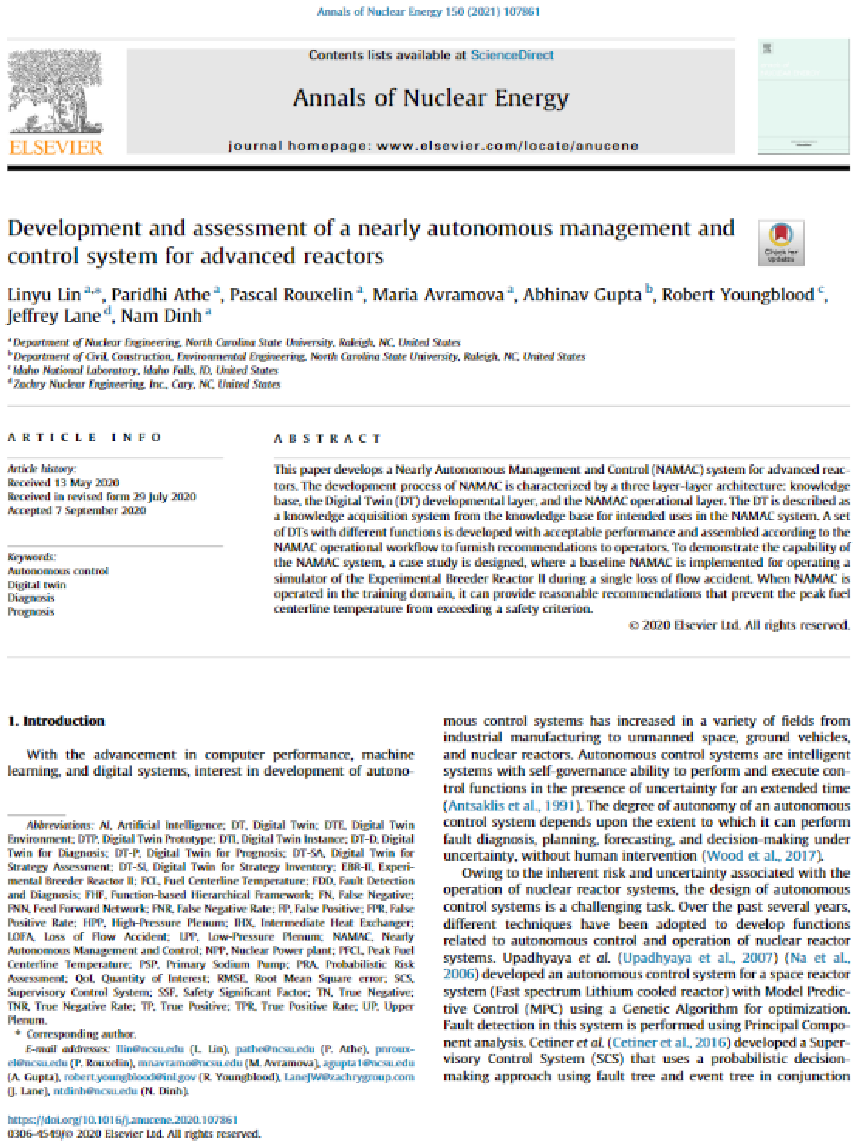
Summary

- Implementation of digital twins for extracting and assimilating the knowledge base with real-time information
- Proof-of-concept of NAMAC for one class of transients
  - Pump malfunction ranging from flow anomaly to complete loss of flow accident
  - NAMAC provides recommendations during the event consistent to human operator norm
- The design of a digital twin development and assessment process (DT-DAP) for implementing, improving, and collecting evidence of a generic types of digital twins in autonomous systems
  - DT-DAP at scoping stage that is driven by user experiences and sensitivity analysis
  - Informed by EMDAP, but necessarily seeks to provide quantitative basis to support NAMAC decision making
  - *Next steps – the trustworthiness and robustness of DTs based on both intrinsic (i.e., uncertainty quantification, reliability) and contextual properties (i.e., confidence, safety-related vs. non-safety related).*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Development and assessment of a nearly autonomous management and control system for advanced reactors

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ABSTRACT

This paper develops a Nearly Autonomous Management and Control (NAMAC) system for advanced reactors. The development process of NAMAC is characterized by a three layer-layer architecture: knowledge base, the Digital Twin (DT) developmental layer, and the NAMAC operational layer. The DT is described as a knowledge acquisition system from the knowledge base for intended uses in the NAMAC system. A set of DTs with different functions is developed with acceptable performance and assembled according to the NAMAC operational workflow to furnish recommendations to operators. To demonstrate the capability of the NAMAC system, a case study is designed, where a baseline NAMAC is implemented for operating a simulator of the Experimental Breeder Reactor II during a single loss of flow accident. When NAMAC is operated in the training domain, it can provide reasonable recommendations that prevent the peak fuel centerline temperature from exceeding a safety criterion.

1. Introduction

With the advancement in computer performance, machine learning, and digital systems, interest in development of autonomous control systems has increased in a variety of fields from industrial manufacturing to unmanned space, ground vehicles, and nuclear reactors. Autonomous control systems are intelligent systems with self-governance ability to perform and execute control functions in the presence of uncertainty for an extended time (Antsaklis et al., 1991). The degree of autonomy of an autonomous control system depends upon the extent to which it can perform fault diagnosis, planning, forecasting, and decision-making under uncertainty, without human intervention (Wood et al., 2017).

Owing to the inherent risk and uncertainty associated with the operation of nuclear reactor systems, the design of autonomous control systems is a challenging task. Over the past several years, different techniques have been adopted to develop functions related to autonomous control and operation of nuclear reactor systems. Upadhyaya *et al.* (Upadhyaya et al., 2007) (Na et al., 2006) developed an autonomous control system for a space reactor system (Fast spectrum Lithium cooled reactor) with Model Predictive Control (MPC) using a Genetic Algorithm for optimization. Fault detection in this system is performed using Principal Component analysis. Cetiner *et al.* (Cetiner et al., 2016) developed a Supervisory Control System (SCS) that uses a probabilistic decision-making approach using fault tree and event tree in conjunction

Abbreviations: AI, Artificial Intelligence; DT, Digital Twin; DTE, Digital Twin Environment; DTP, Digital Twin Prototype; DTI, Digital Twin Instance; DT-D, Digital Twin for Diagnosis; DT-P, Digital Twin for Prognosis; DT-SA, Digital Twin for Strategy Assessment; DT-SI, Digital Twin for Strategy Inventory; EBR-II, Experimental Breeder Reactor II; FCL, Fuel Centerline Temperature; FDD, Fault Detection and Diagnosis; FHF, Function-based Hierarchical Framework; FN, False Negative; FNN, Feed Forward Network; FNR, False Negative Rate; FP, False Positive; FPR, False Positive Rate; HPP, High-Pressure Plenum; IHX, Intermediate Heat Exchanger; LOFA, Loss of Flow Accident; LPP, Low-Pressure Plenum; NAMAC, Nearly Autonomous Management and Control; NPP, Nuclear Power plant; PFCL, Peak Fuel Centerline Temperature; PSP, Primary Sodium Pump; PRA, Probabilistic Risk Assessment; QoI, Quantity of Interest; RMSE, Root Mean Square error; SCS, Supervisory Control System; SSF, Safety Significant Factor; TN, True Negative; TNR, True Negative Rate; TP, True Positive; TPR, True Positive Rate; UP, Upper Plenum.

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- The NAMAC project team
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- GOTHIC license is provided by Zachry Nuclear Engineering, Inc. GOTHIC incorporates technology developed for the electric power industry under the sponsorship of EPRI, the Electric Power Research Institute.

Structural Condition Monitoring with a Digital Twin: Explorations on a Nuclear Containment Vessel Model

Presenter: Dr. Timothy Kernicky, EPIC Research Assistant Professor of Civil Engineering, University of North Carolina Charlotte

Contributors: Dr. Matthew Whelan

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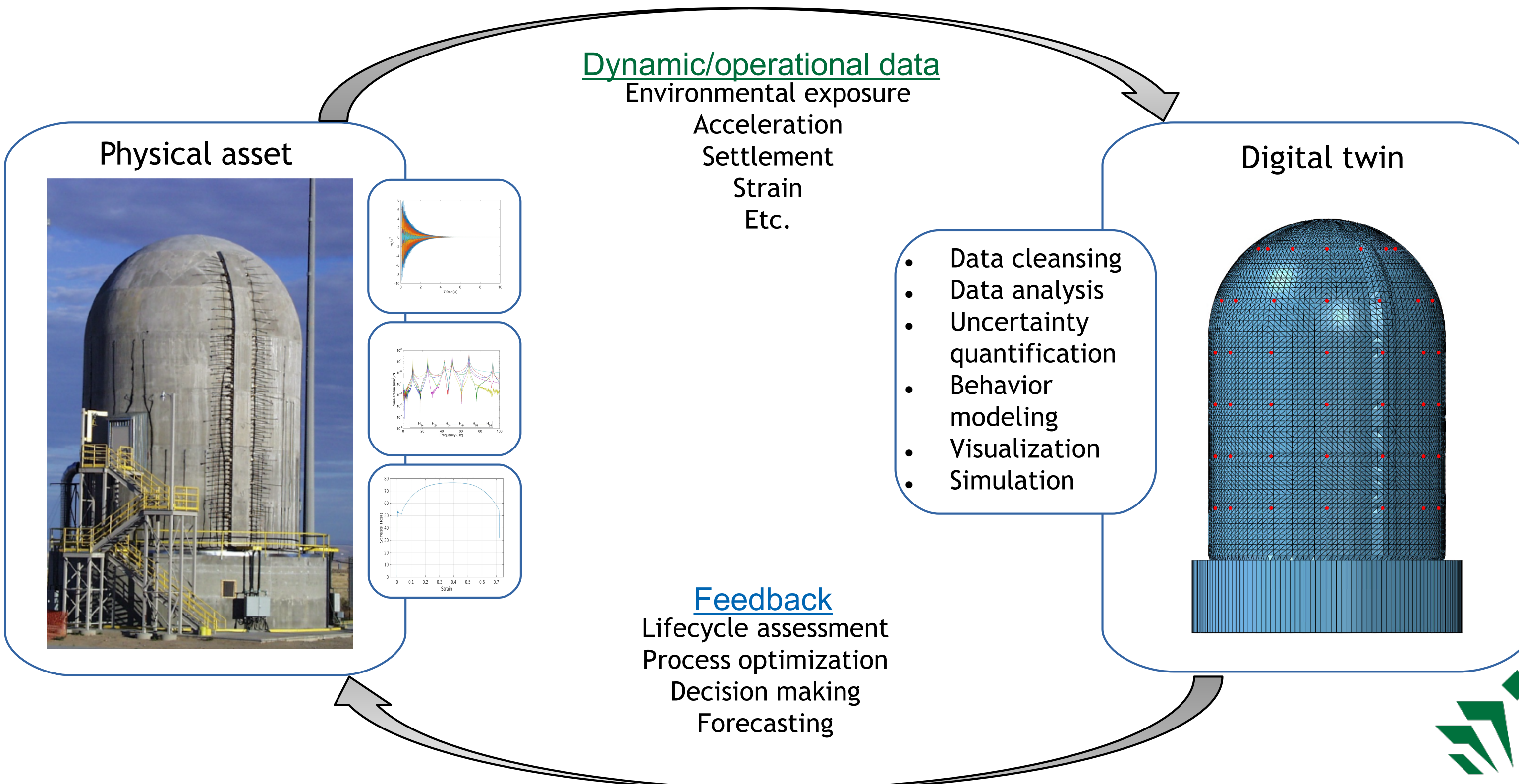
Digital Twin

- A digital twin is more than a digital model that faithfully represents physical assets and processes
- The primary distinguishing feature of a digital twin is its connection to the real-world asset with the ability to inform the state of the physical asset



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First Step: Structural Identification

- The first step towards successful digital twin deployment is the development of a “trusted” model, which faithfully replicates the performance of the physical asset
- This simple study leverages vibration-based structural identification to calibrate a set of uncertain material parameters of the digital twin using synthetic measurement data

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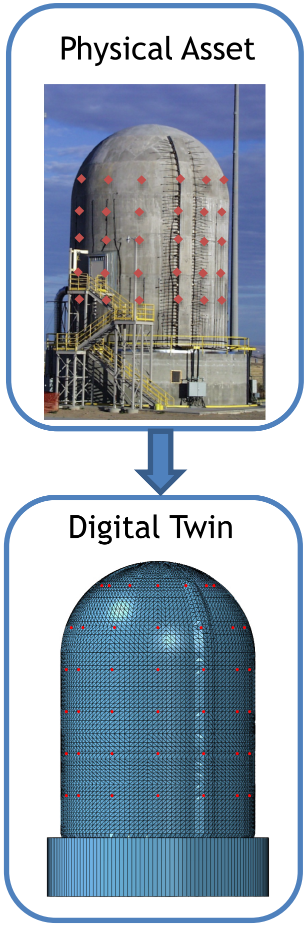
Vibration-Based Structural Identification



- Finite element (FE) model of physical asset created

- Initial model suffers from
  - Parameter uncertainties
    - Geometries
    - Material properties
  - Idealization errors
  - Discretization errors

- FE model may be leveraged to develop appropriate sensor array for physical structure

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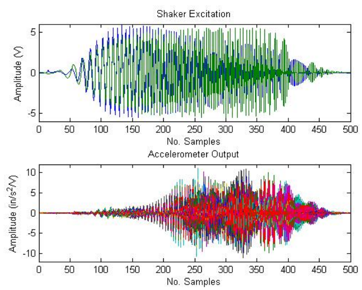
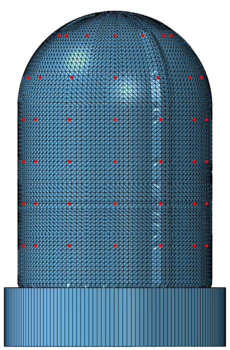
Vibration-Based Structural Identification

Physical Asset

Vibration Testing



Digital Twin



- Vibration data is acquired from sensor array on the physical structure
- Structure excitation can be ambient (operational) or forced

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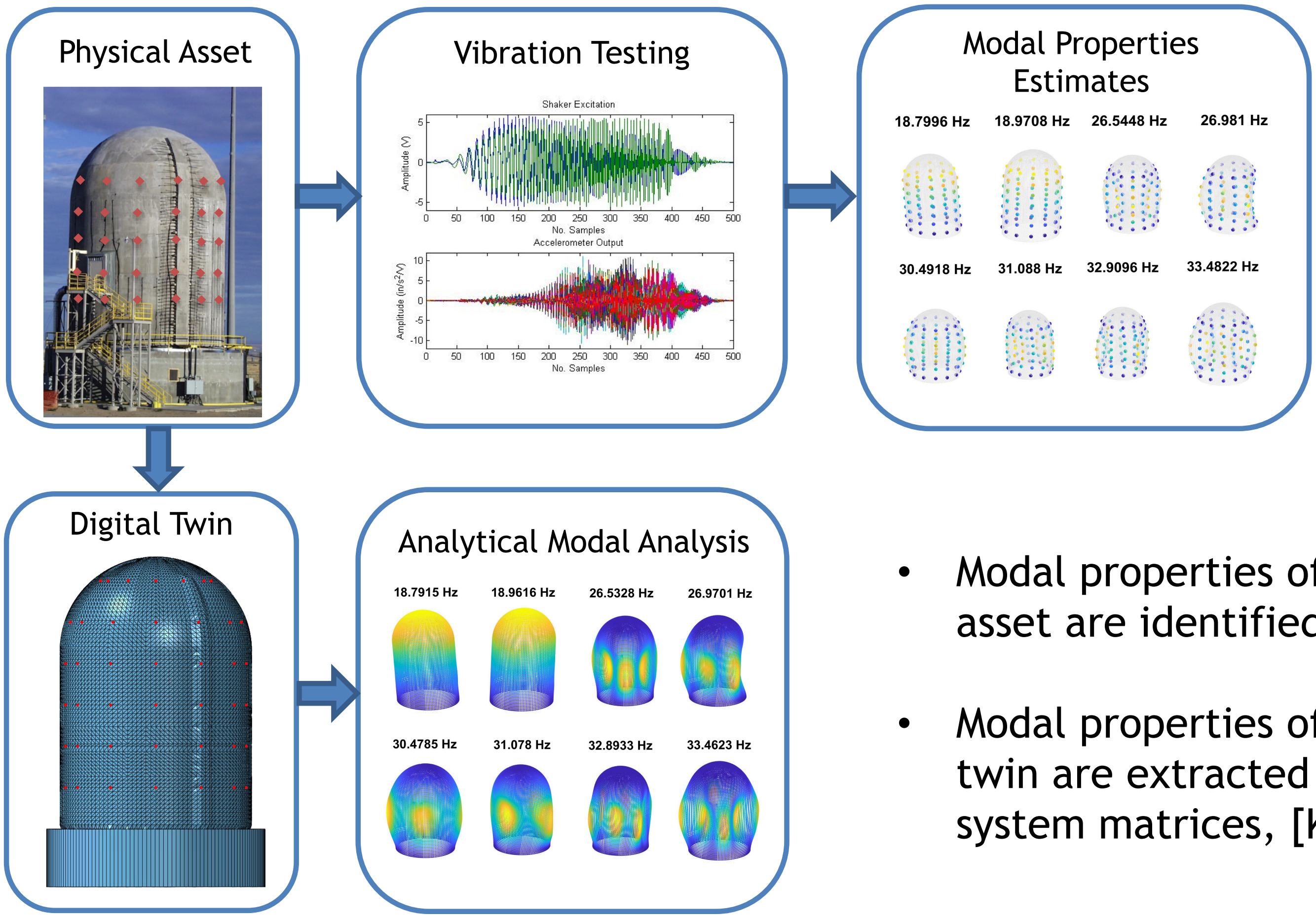
Vibration-Based Structural Identification



- Modal properties of the physical asset are identified
- Modal properties of the digital twin are extracted from the system matrices, [K] & [M]

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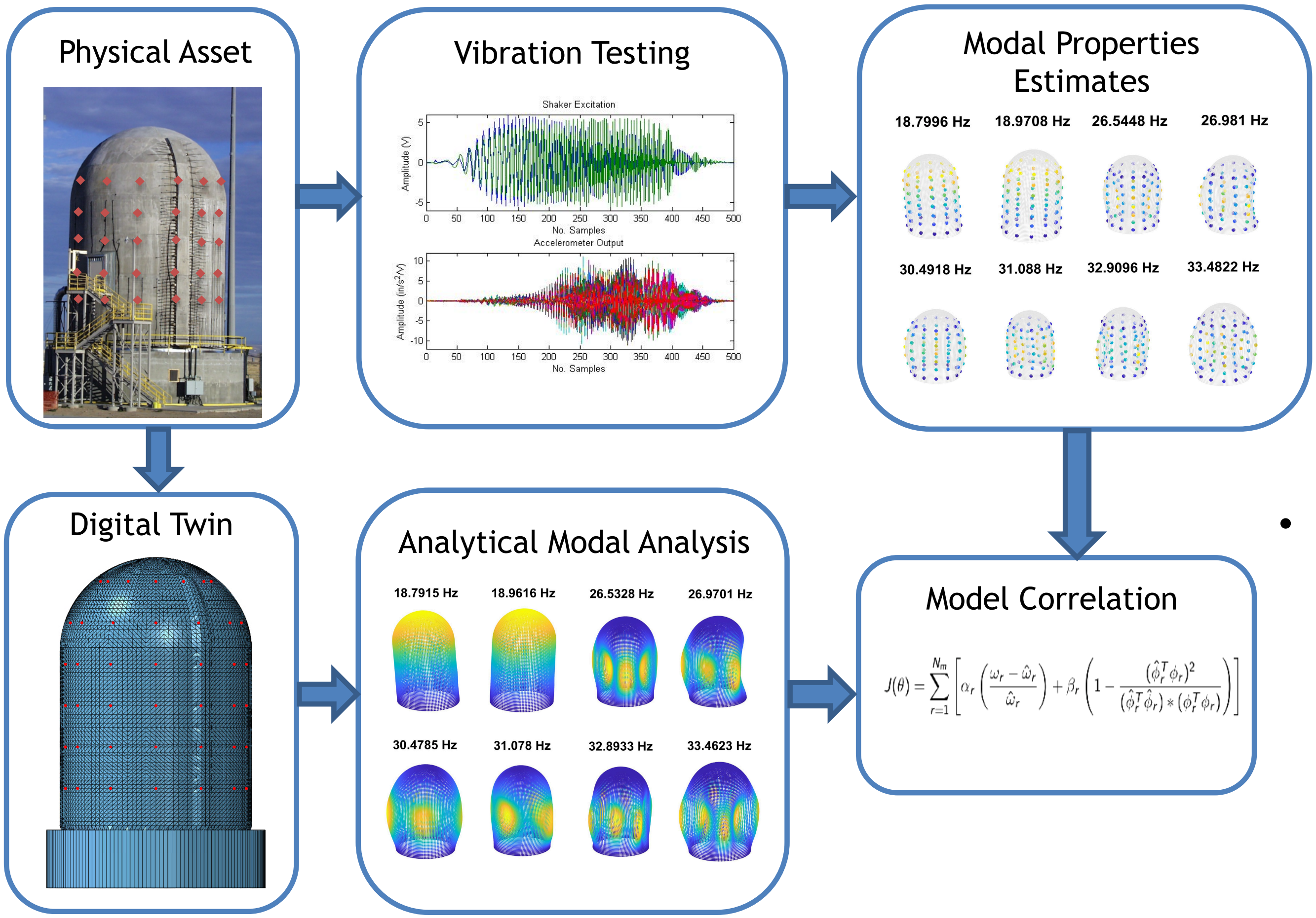
Vibration-Based Structural Identification



- Correlation between the physical and FE modal properties is determined by a modal measure of fit, which accepts natural frequencies and mode shapes as input.

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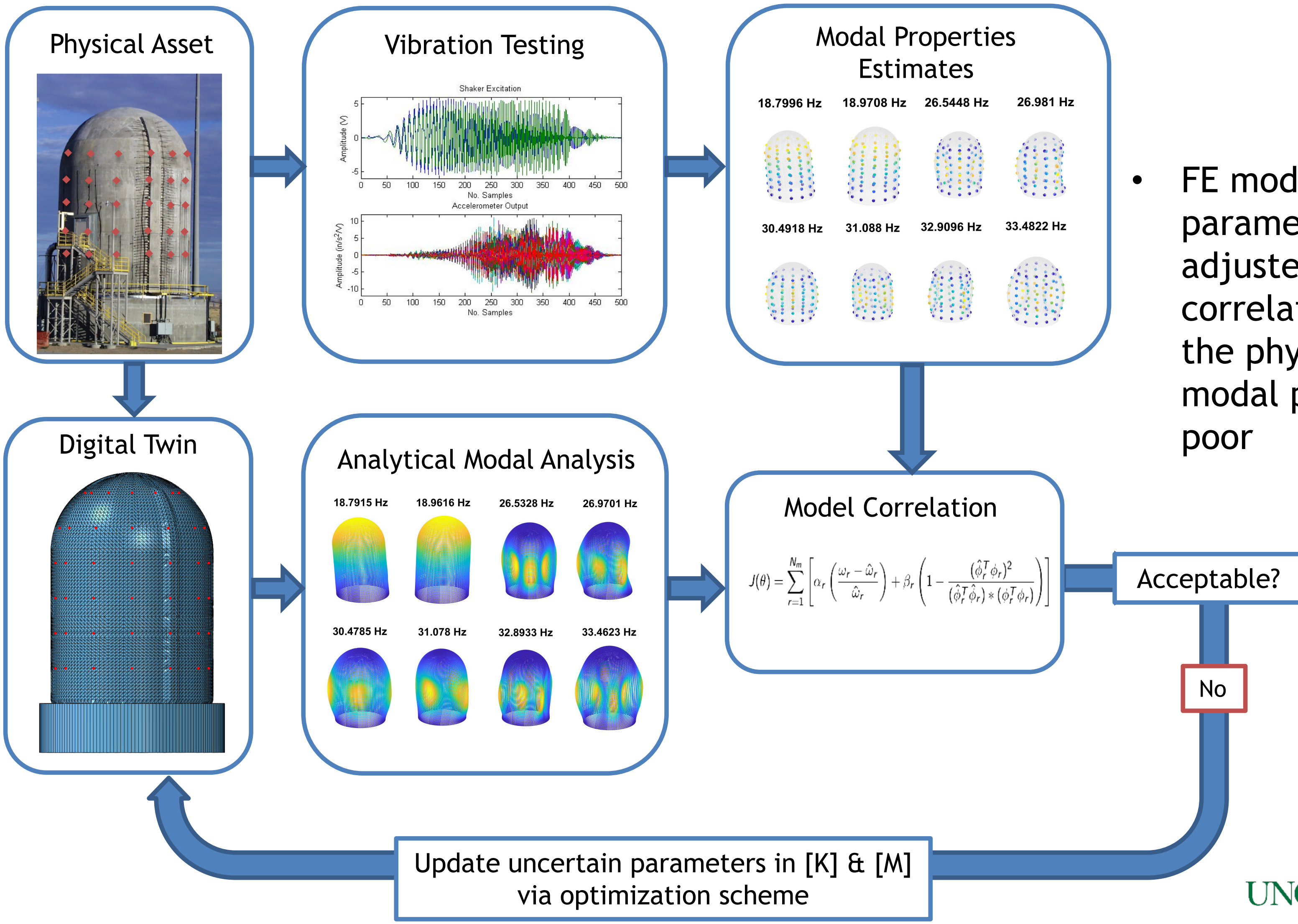
Vibration-Based Structural Identification



- FE model parameters are adjusted if the correlation between the physical and FE modal parameters is poor

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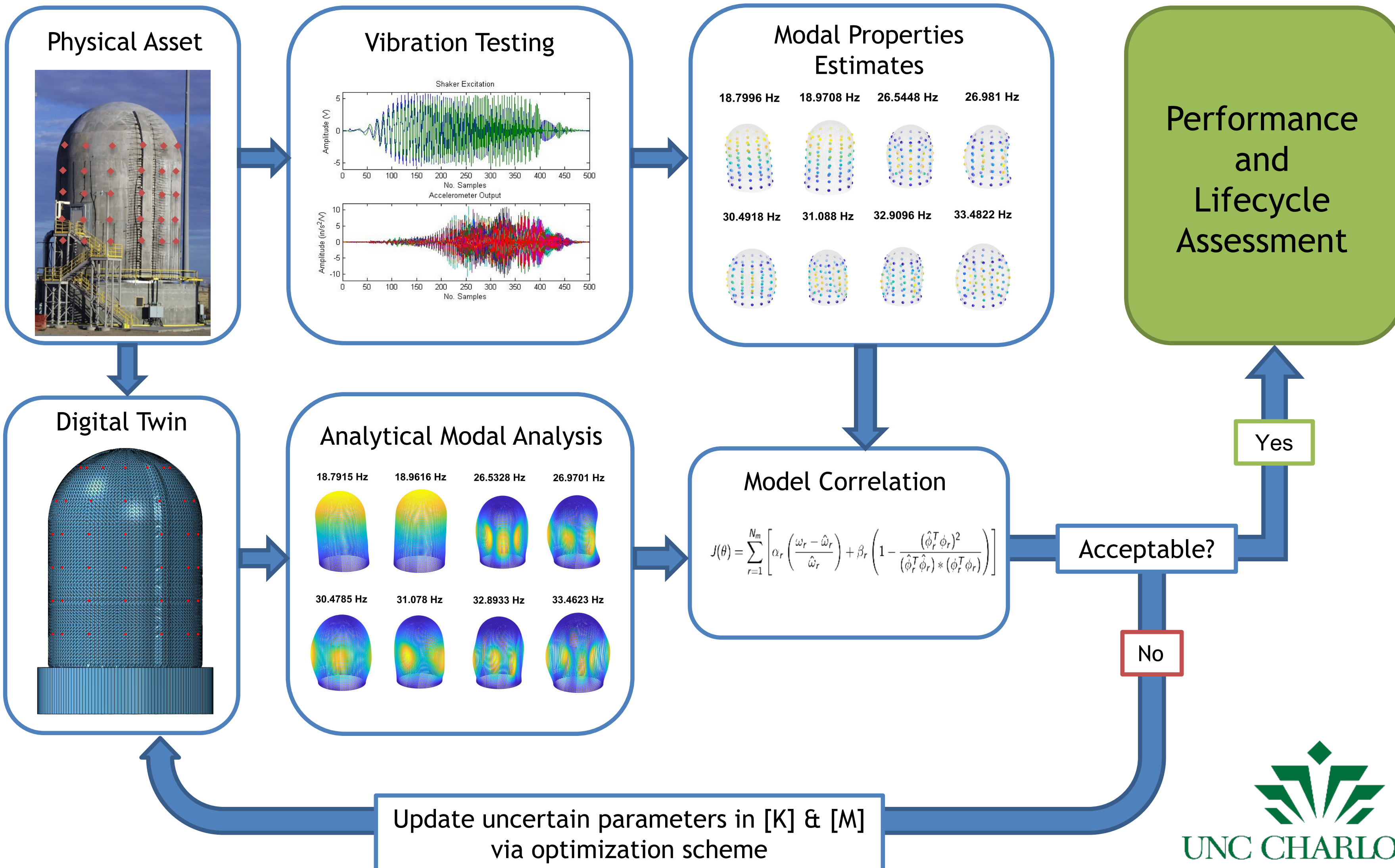
Vibration-Based Structural Identification



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Digital Twin Study of a Containment Vessel

- This study will demonstrate a potential capability to track changes/deterioration in a concrete containment vessel

- The structure explored is based on the 1:4 scale model of the Ohi-3 containment vessel in Japan, which was funded by NUPEC and the NRC and tested by SNL [NUREG/CR-6810, SAND2003-0840P]

- Two FE models will be utilized in this study.
  - One represents the physical asset from which “in-service”, synthetic measurements are obtained
  - The second will serve as the digital twin to be updated

- Measurements of dynamic properties (modal parameters) will be used by the digital twin to inform changes in the structural condition, while synthetic response measurements obtained from the “physical” structure will be used to correct the digital twin

[NUREG/CR-6810, SAND2003-0840P]

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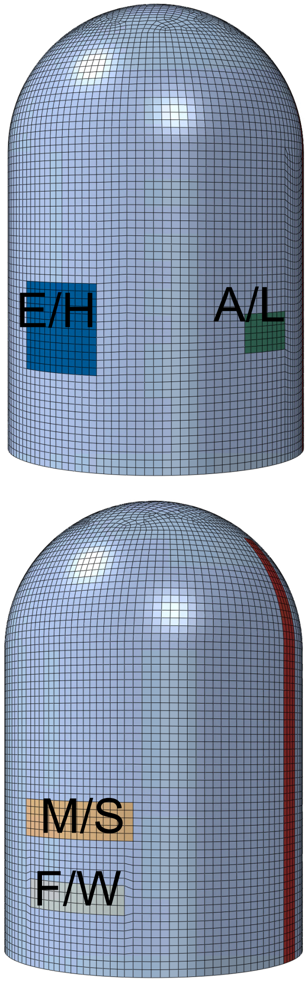
Concrete Containment Model

- A simplified finite element model was created using ABAQUS
- Four locations of interest where penetrations exist in the vessel were chosen as uncertain parameters to identify
  - main steam penetration (M/S)
  - feed water penetration (F/W)
  - equipment hatch (E/H)
  - air lock (A/L)
- The modulus of elasticity of each section of elements was used as the uncertain parameter to be updated
- Four deterioration scenarios were examined to demonstrate the ability of the methodology to identify material degradation

Case	Parameter	Stiffness Change (%)
1	$E_{M/S}$	0
2	$E_{M/S}$	-5
3	$E_{M/S}$	-15
4	$E_{M/S}$	-25



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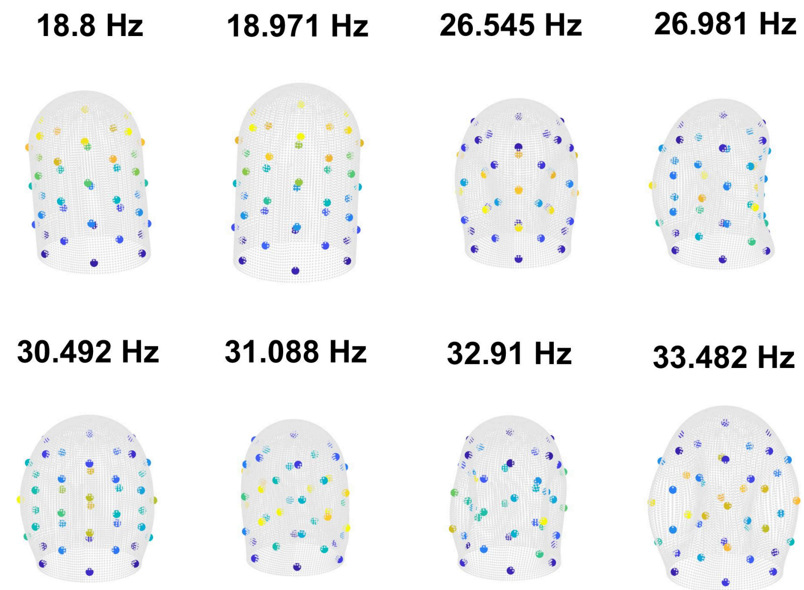
Development of Synthetic Dataset

- Synthetic measurement data was extracted from the finite element model in the form of natural frequencies and mode shapes from 42 biaxial sensors
- Noise was added to the synthetic measurements by adding 0.5% Gaussian noise to generate 10 sets of data



Synthetic natural frequencies and mode shapes for Case 1

	Case 1	Case 2		Case 3		Case 4	
Mode	f_n	$\Delta f(\%)$	MAC	$\Delta f(\%)$	MAC	$\Delta f(\%)$	MAC
1	18.800	-0.033	1.000	-0.108	1.000	-0.200	1.000
2	18.971	-0.041	1.000	-0.135	0.999	-0.250	0.999
3	26.545	-0.038	1.000	-0.122	0.999	-0.218	0.999
4	26.981	-0.031	1.000	-0.100	0.999	-0.183	0.999
5	30.492	-0.035	1.000	-0.115	0.999	-0.212	0.999
6	31.088	-0.025	1.000	-0.080	0.999	-0.148	0.999
7	32.910	-0.045	1.000	-0.141	0.999	-0.248	0.999
8	33.482	-0.048	1.000	-0.149	0.999	-0.258	0.999

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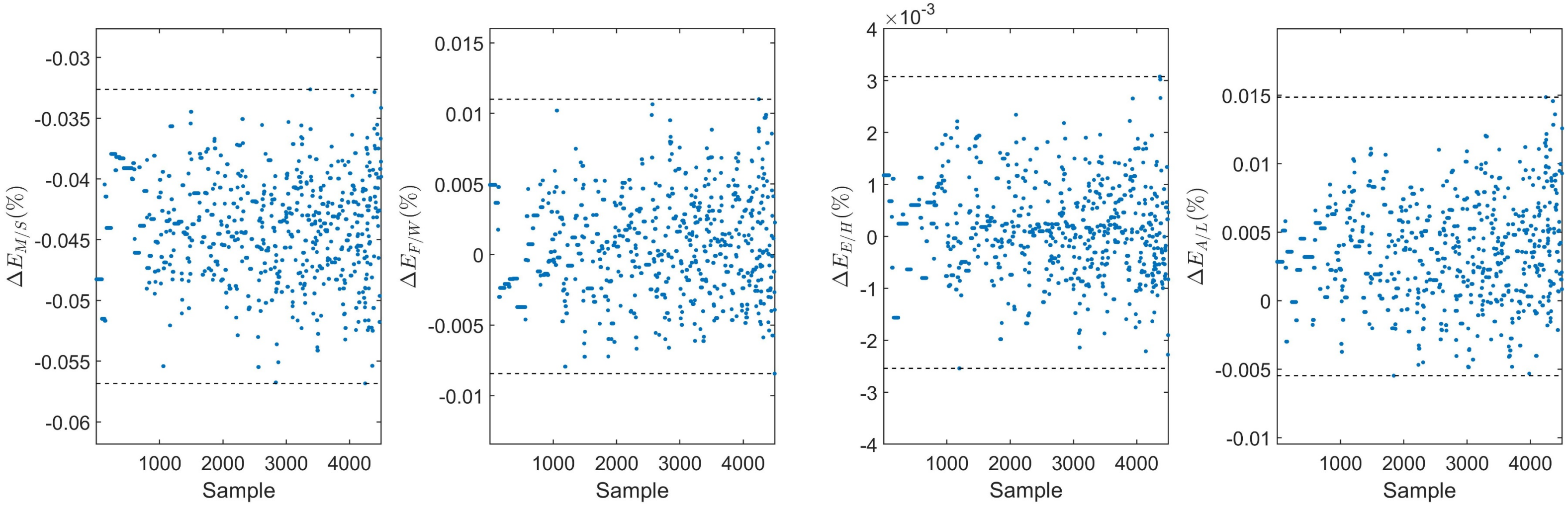
Bayesian Model Updating

- Probabilistic updating was utilized as the model updating method, which accounts for measurement and modeling uncertainties
- Each uncertain parameter was assigned lower and upper bounds to which an adaptive Markov Chain Monte Carlo sampling method was used to generate 5000 posterior probability distributions



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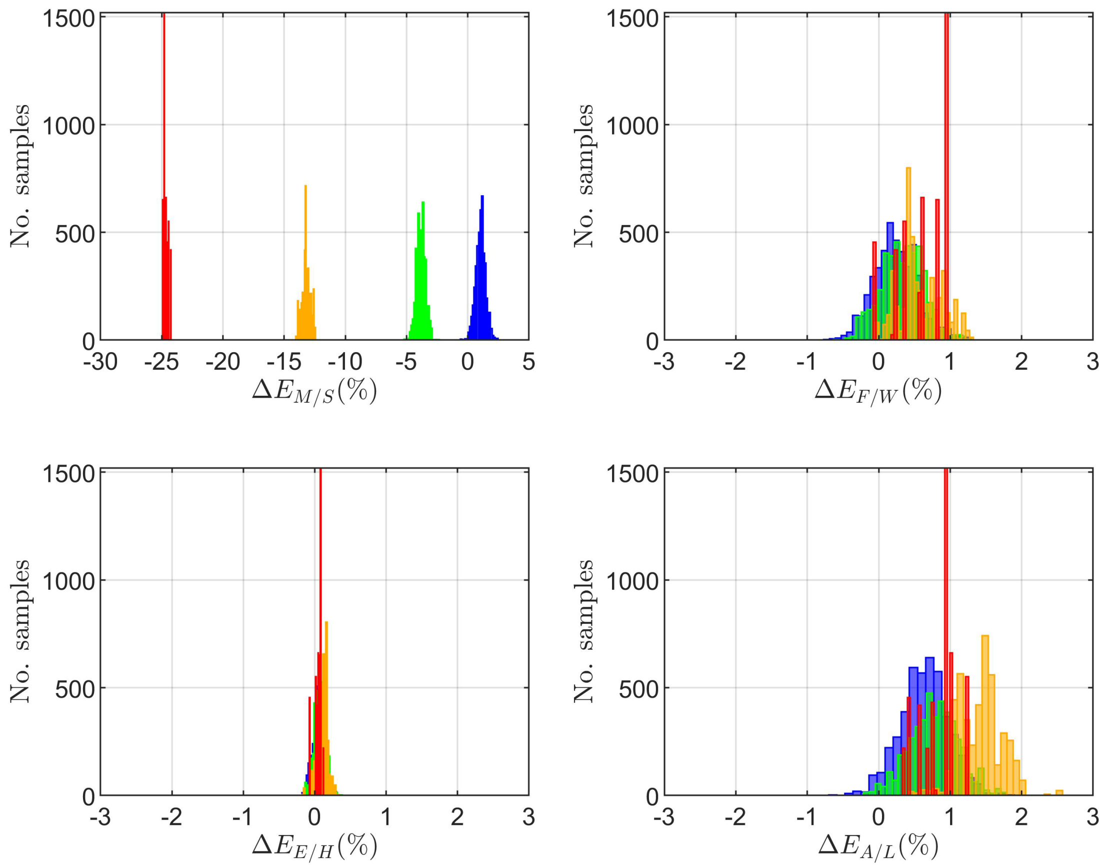
Bayesian Model Updating

- The discrete distributions of the points samples clearly indicate a successful identification of deterioration in the modulus of elasticity of the M/S elements, with negligible changes identified in the other parameters



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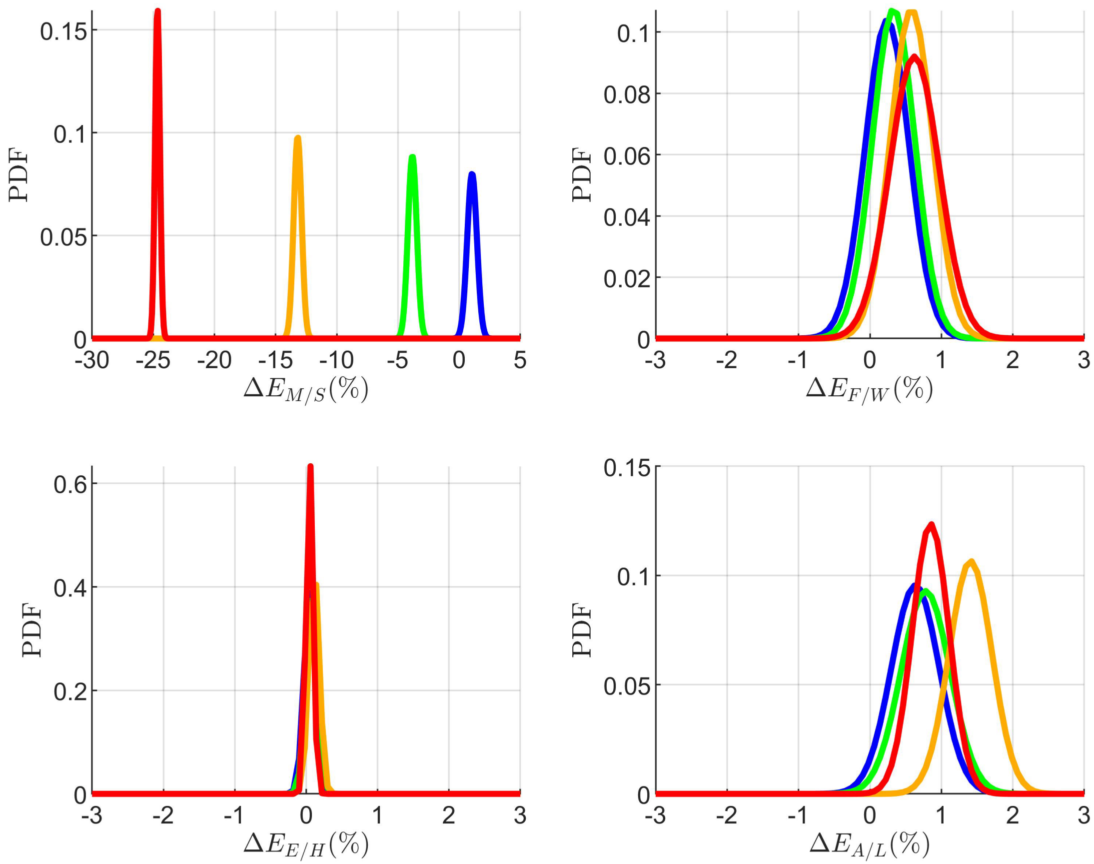
Bayesian Model Updating

- Posterior probability density functions may be analyzed from which confidence bounds may be placed on the parameter identification



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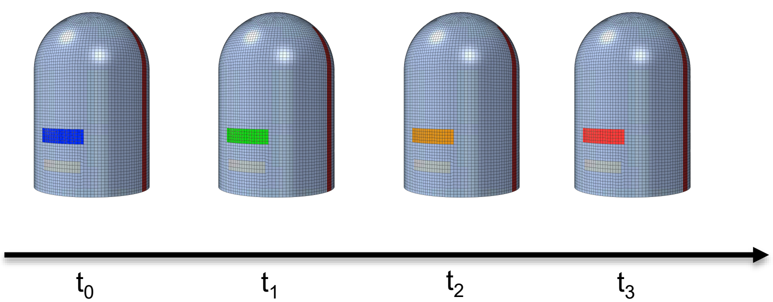
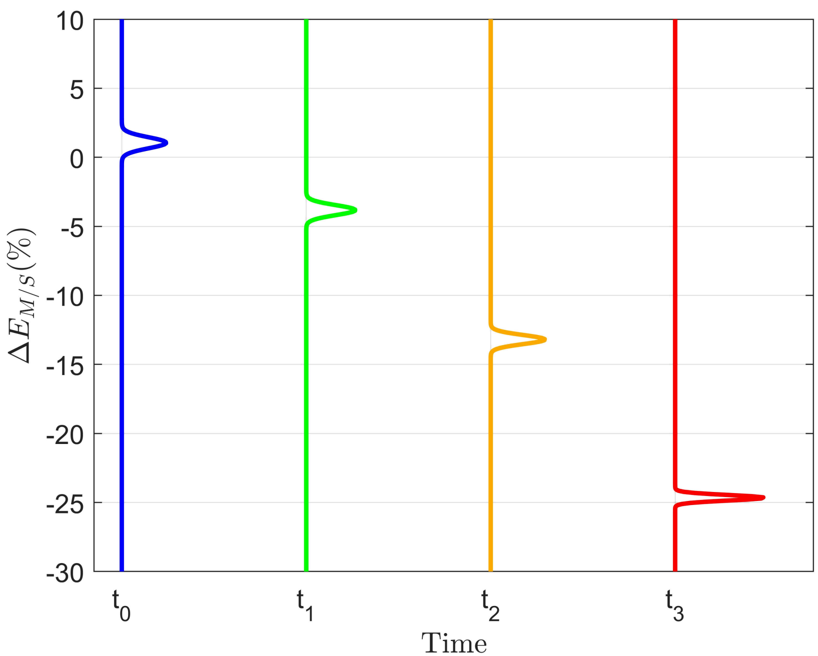
Trusted Model…Now What?

- Once a faithful digital representation of a physical structure has been realized:
  - Performance of the structure may be monitored by using historical and present-day data streams
  - Critical limit states may be evaluated in a digital environment
  - Lifecycle analyses may be performed to inform maintenance outside of routinely scheduled programs





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Trusted Model…Now What?

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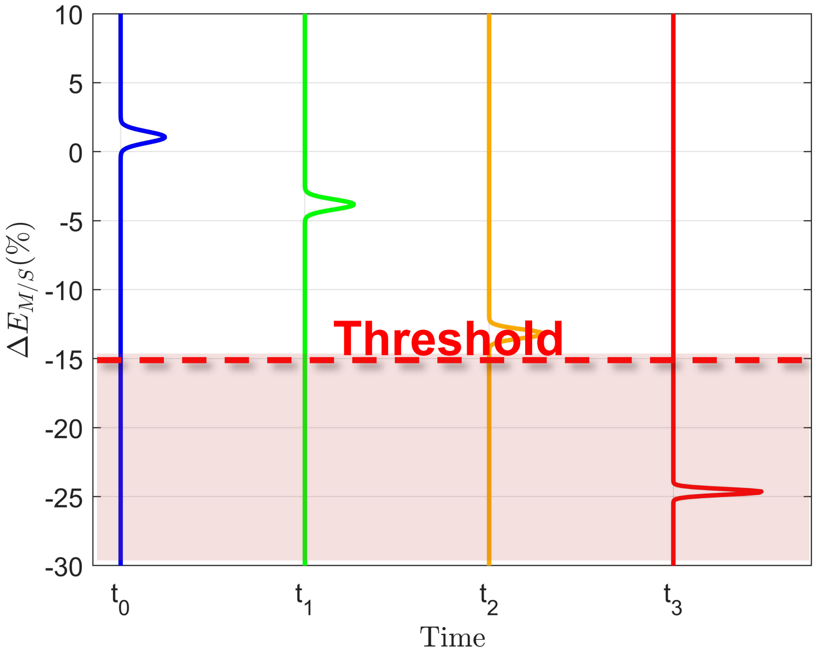

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Challenges

- Physical Asset
  - Development of appropriate performance metrics
  - Deployment of suitable sensor net to capture relevant physical phenomena
- Digital Twin
  - Development of data pipeline to connect physical sensors to digital twin
  - Creation of routines to process and interpret operational data

- Development of end-user application of methodology
- Instruction of end-user knowledge-base

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Advantages of Methodology

- May provide near real-time assessment
- Not inhibited by outages as other periodic inspections
- Can incorporate data from periodic inspections
- Capable of identifying hidden/local deterioration
- Identifies potential areas of preventative maintenance

Digital Twins for Prognostic Health Management (PHM) in Nuclear Energy: Opportunities and Challenges

Pradeep Ramuhalli
Distinguished Scientist

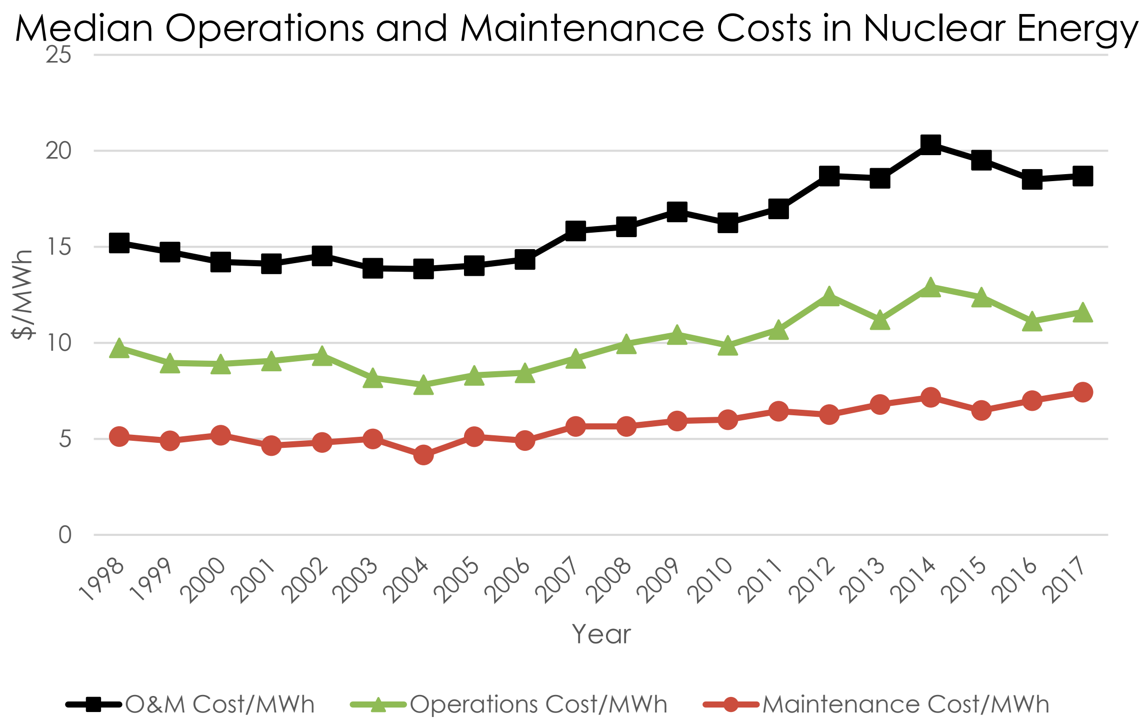
Virtual Workshop on Digital Twin Applications for Advanced Nuclear Technologies

December 3, 2020

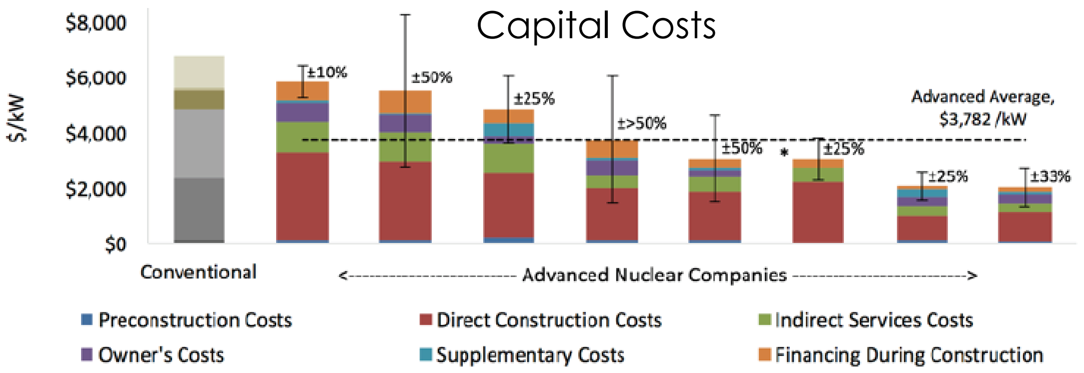
Outline

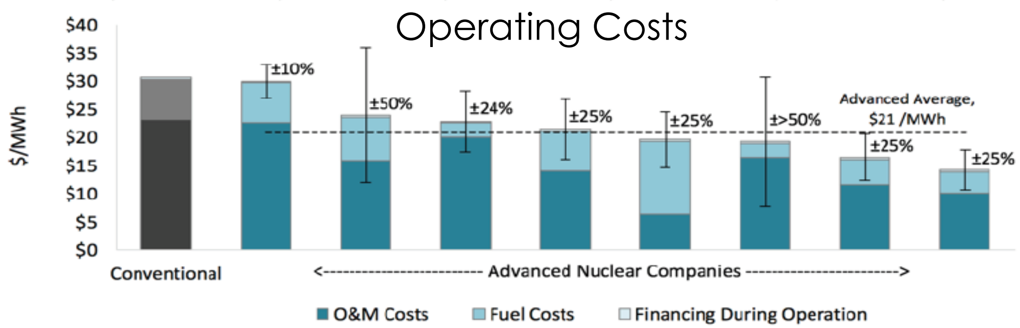
- Background – drivers for prognostics health management in nuclear power
- Diagnostics, prognostics and decision making - An integrated solution using intelligent digital twins
- Examples
- Research Needs and Summary

The Big Picture



Data from: " Broken: Costs to Operate, Maintain Electricity Generation Have Soared Over Two Decades" (uptake.com/energy)





Energy Options Network Report (2019) " What Will Advanced Nuclear Power Plants Cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development"

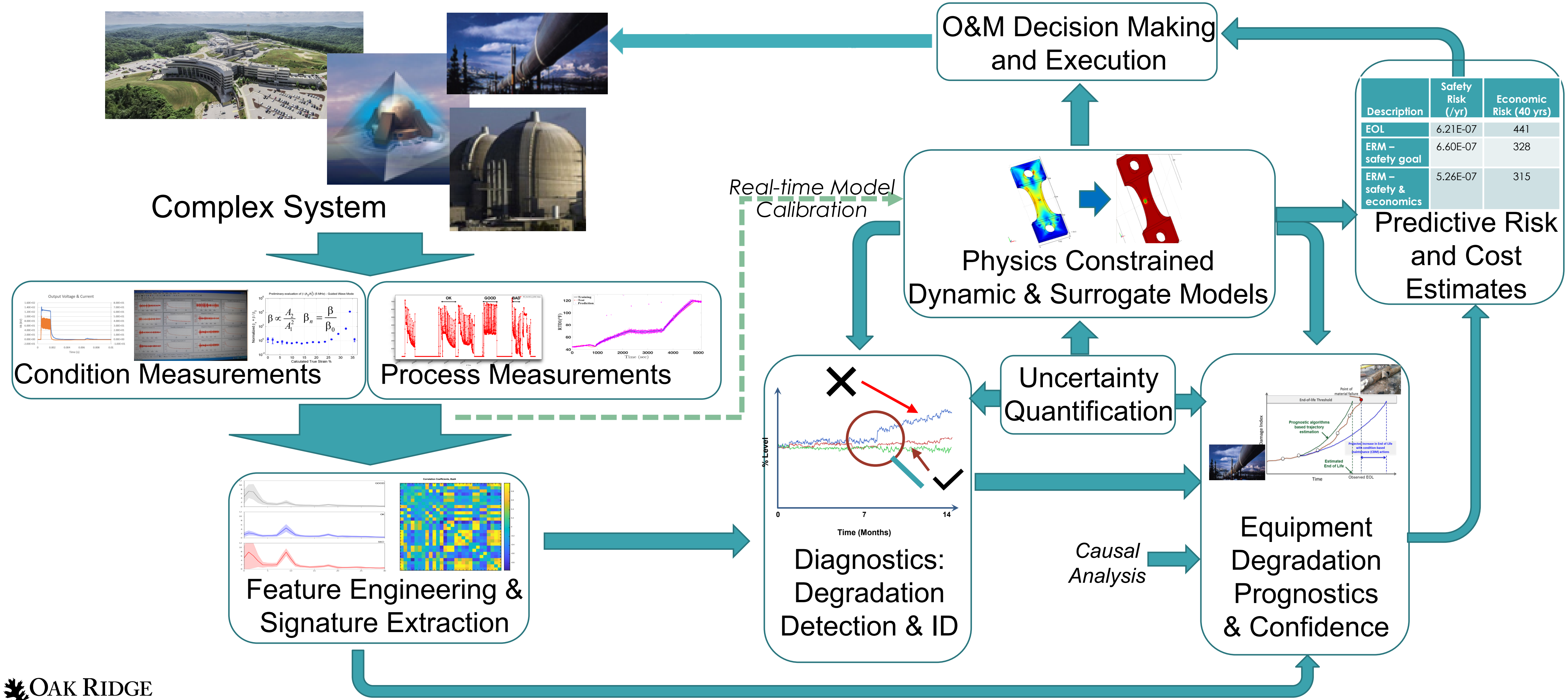
__Operating Plants__

__Advanced Reactors__

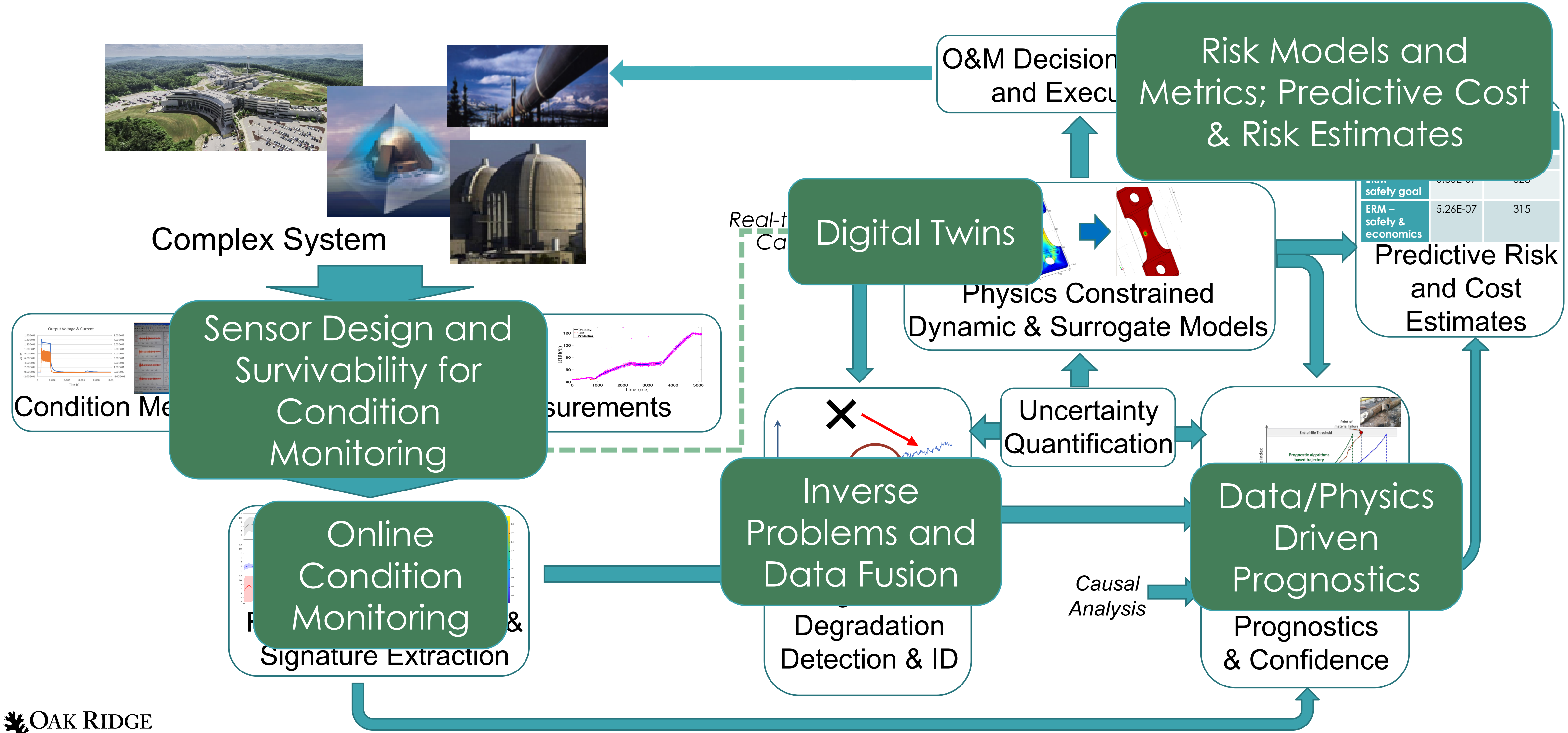
Need: Information-driven Asset Management Technologies and best practices to lower operating and maintenance costs while maintaining safety and reliability

Oak Ridge National Laboratory

Diagnostics and Prognostics Enable Information-Driven Asset Management



Intelligent Digital Twins Enable PHM



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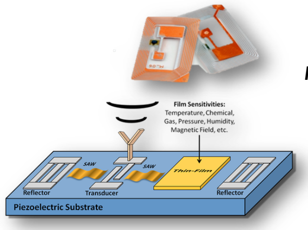
Together with Advances in…

- Sensors and instrumentation
- Modeling and simulation methods and high performance computing
- Data analytics, especially domain-aware data analytics
- Communication technologies
- Advanced manufacturing

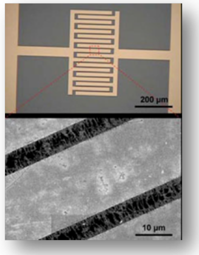


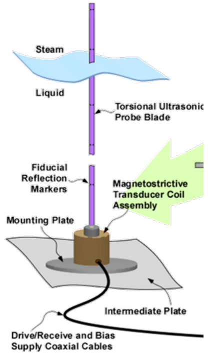
SAW Chemical Sensors

>2Mrad JFET-based Sensor Interface Electronics (DOE NEET)

Acoustic wave resonator

Carbon nano-tubes embedded within inter-digitated structures

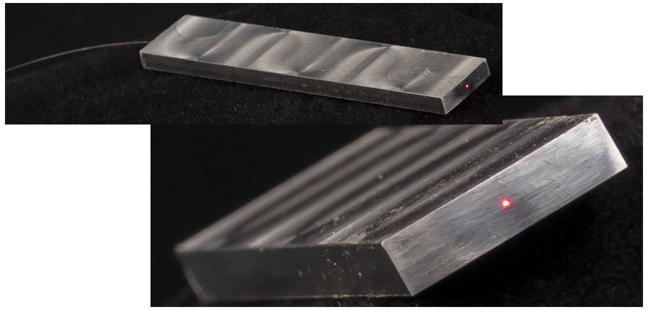


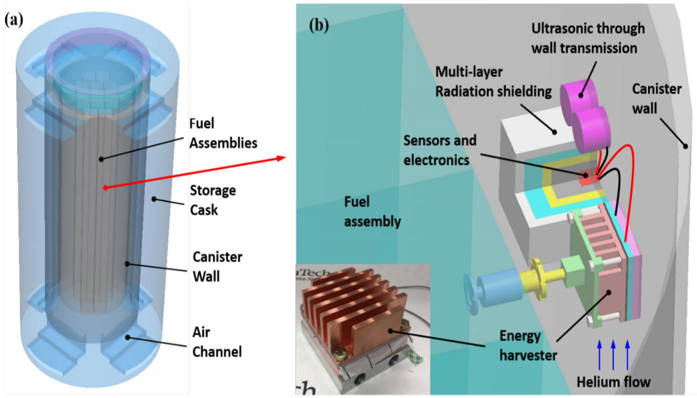


Temperature, Pressure and Level Sensors

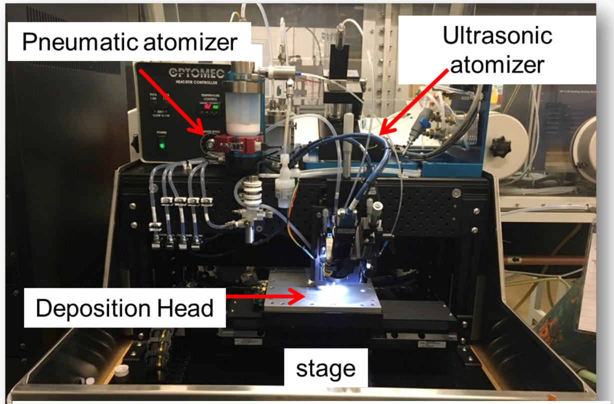

316L sheathed sensor in AM 316L build

Novel Ex-Vessel, In-Vessel, and In-Core Sensors and Electronics


High Temperature Compatible and Embedded Sensors for Nuclear Process and Component Health Monitoring



Self-powered Through-Wall Communication



3D Printing Passive Wireless Sensors

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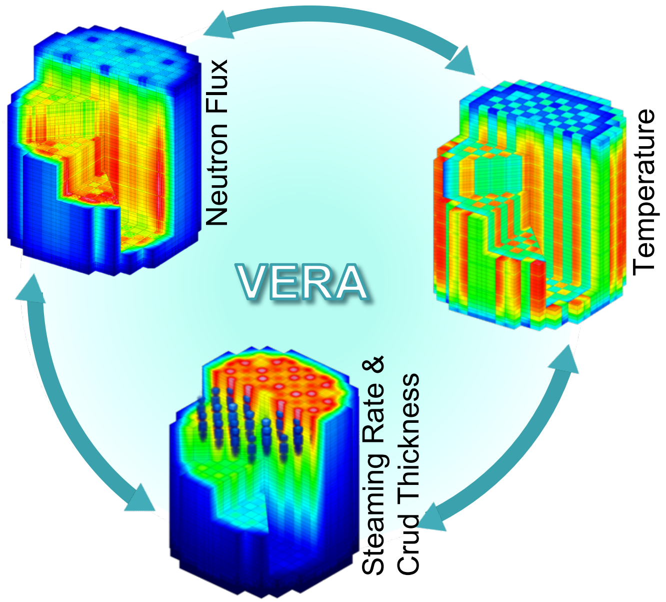
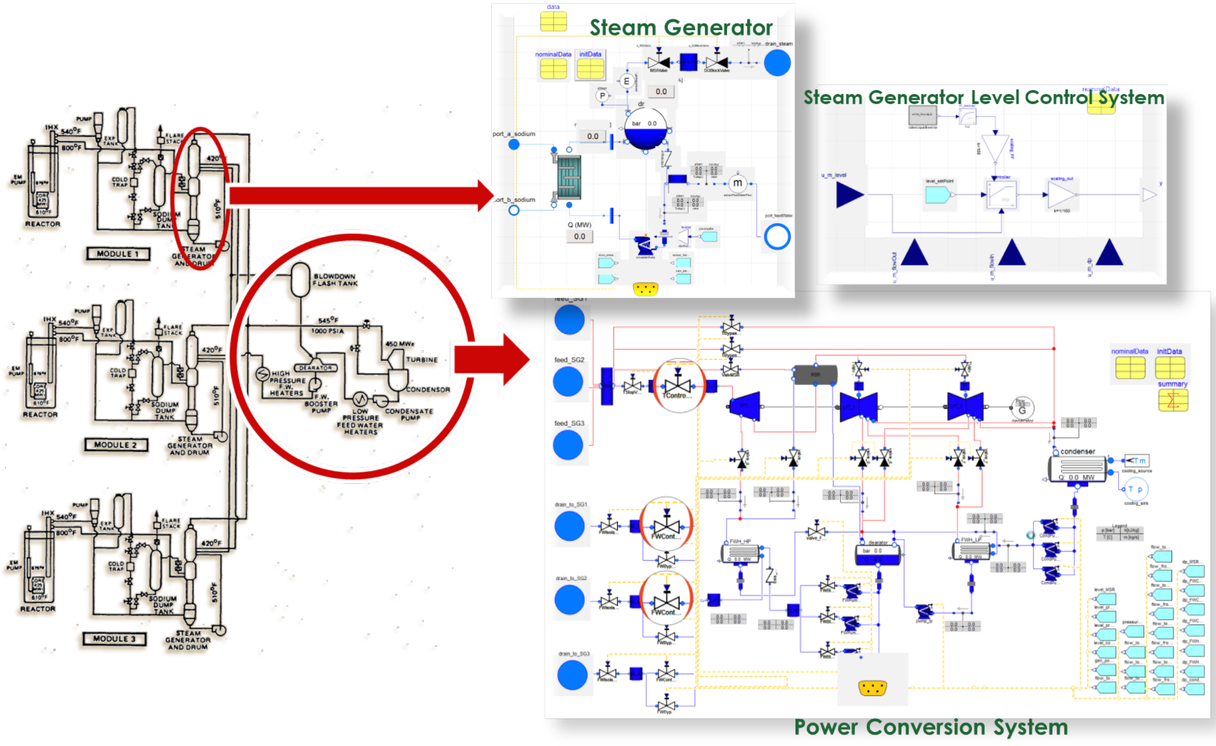
Digital Twin

- A software design pattern that represents a physical object with the objective of understanding the asset's state, responding to changes, improving business operations and adding value (Gartner)
- Potential for different levels of fidelity and for different uses, and spanning the range from fully data-driven to physics-based
  - What is "good enough" for the problem?

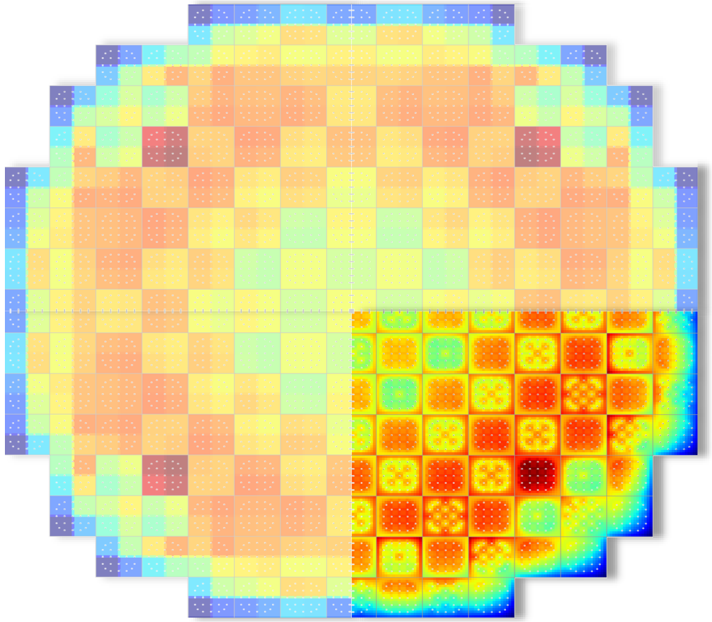




ALMR PRISM Power Block

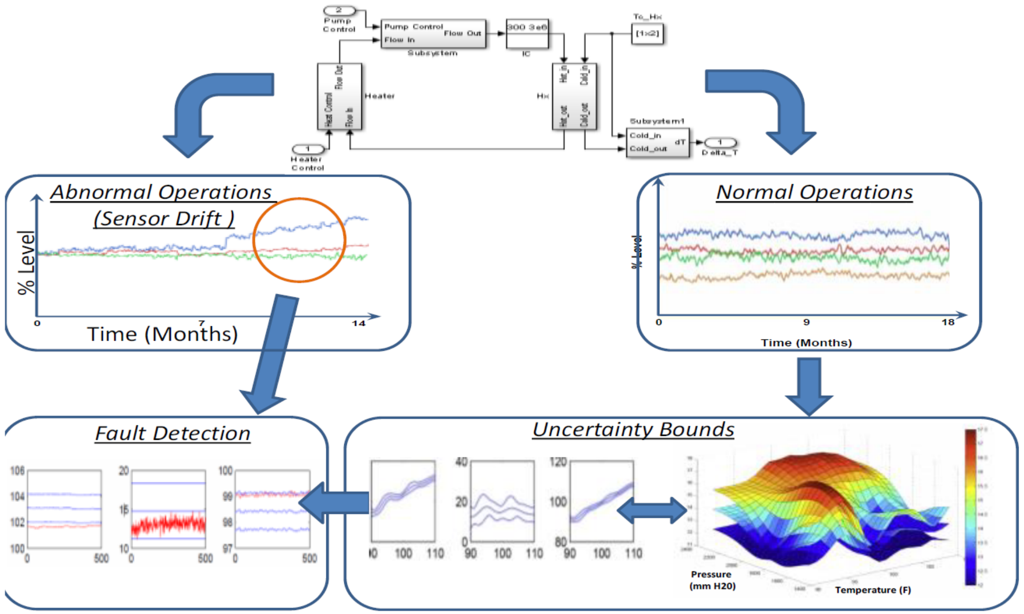
Intelligent Digital Twins for Diagnostics and Prognostics

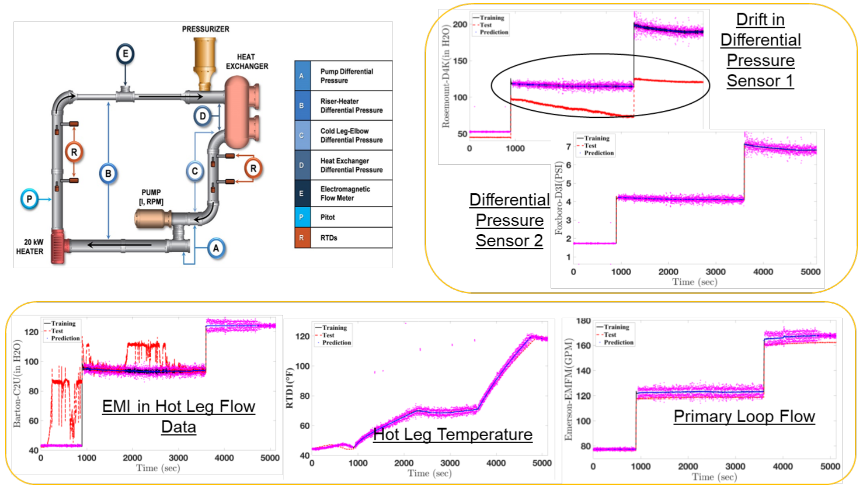
- Hybrid (Data-driven, with domain information) can serve as digital twins for diagnostics and prognostics
- Reliability assessment and prediction
  - Sensors
  - Active components (pumps, valves, etc.)
  - Passive components (piping, vessel, etc.)
  - Sub-system (power conversion unit, etc.)
- Risk-informed operational decision making for autonomous operations
- Risk-informed maintenance decision making for cost reduction



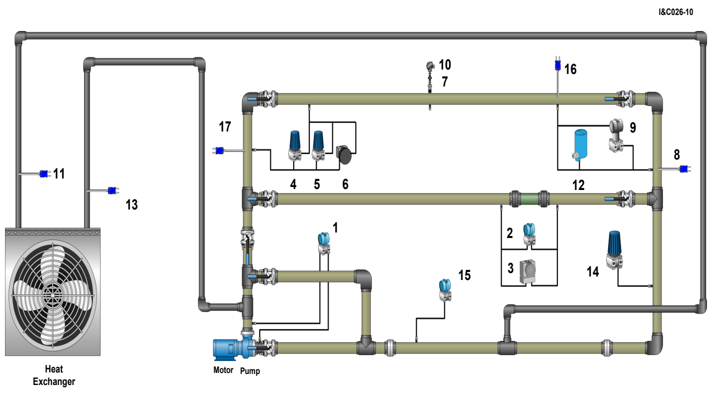
Physics Informed Machine Learning Reduced Order Model

Robust Virtual Sensor Models Can Improve Sensor Drift Detection and Compensation Performance

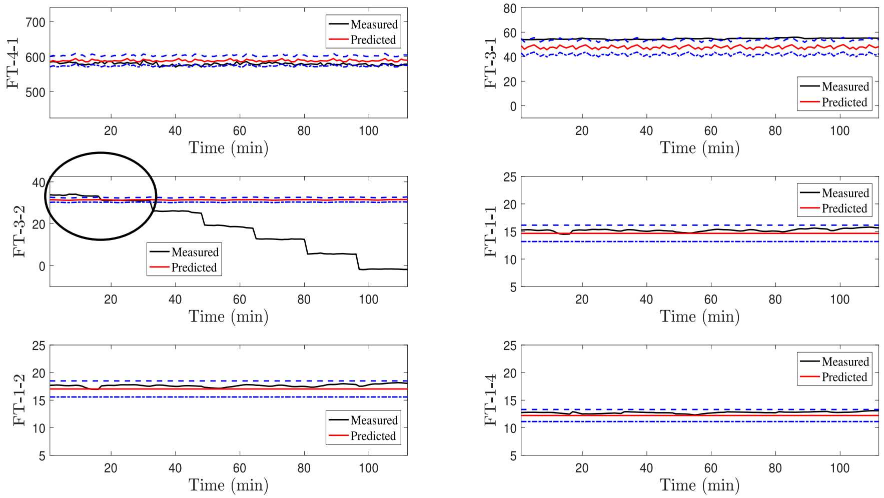




Example of Sensor Calibration Drift Detection and Compensation

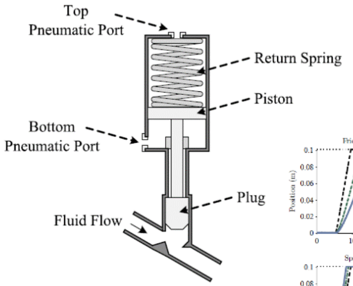


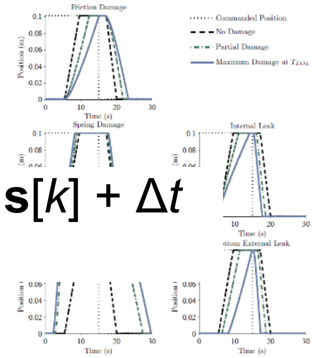
ITEM	ID	SENSOR TYPE	MANUFACTURER
1	FT-4-1	DIFFERENTIAL PRESSURE	ROSEMOUNT
2	FT-3-1	DIFFERENTIAL PRESSURE (SMART)	ROSEMOUNT
3	FT-3-2	DIFFERENTIAL PRESSURE	BARTON
4	FT-1-1	DIFFERENTIAL PRESSURE	FOXBORO
5	FT-1-2	DIFFERENTIAL PRESSURE	FOXBORO
6	FT-1-4	DIFFERENTIAL PRESSURE (SMART)	BARTON
7	TE-1-2	RTD (SMART)	ROSEMOUNT
8	TC-2-1	THERMOCOUPLE TYPE-J (SMART)	ROSEMOUNT
9	FT-2-1	DIFFERENTIAL PRESSURE	SCHLUMBERGER
10	CTRL-TEMP	RTD (SMART)	ROSEMOUNT
11	TC-HX-OUT	THERMOCOUPLE TYPE-J	OMEGA
12	FT-2-3	DIFFERENTIAL PRESSURE	HONEYWELL
13	TC-HX-IN	THERMOCOUPLE TYPE-J	OMEGA
14	CTRL-PSR	GAUGE PRESSURE	FOXBORO
15	PT-2	GAUGE PRESSURE	ROSEMOUNT
16	TC-LOOP-FAR	THERMOCOUPLE TYPE-E	OMEGA
17	TC-PUMP-OUT	THERMOCOUPLE TYPE-K	OMEGA



Tipireddy, Ramuhalli et al, ANS NPIC-HMIT 2017

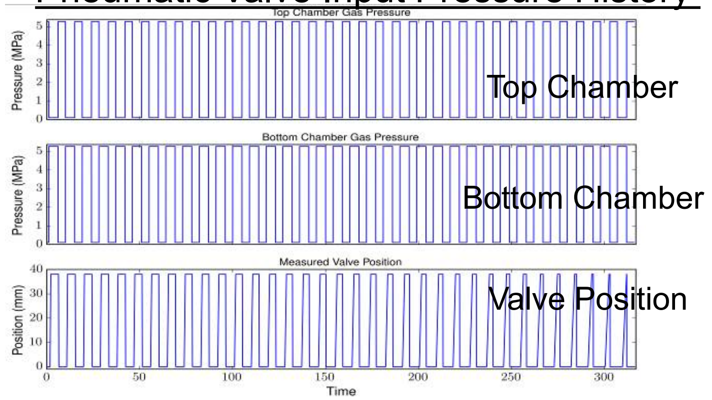
Data-driven, Physics-Inspired Models for Diagnostics and Predictive Maintenance

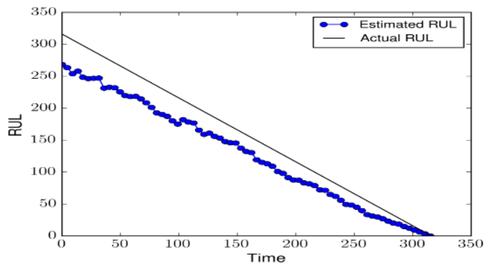




$\mathbf{s}[k+1] = \mathbf{s}[k] + \Delta t\, \dot{\mathbf{s}}[k]$

Pneumatic Valve Input Pressure History





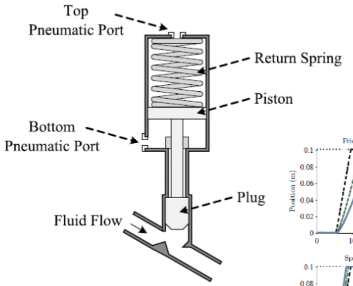
Prognostic Result: RUL

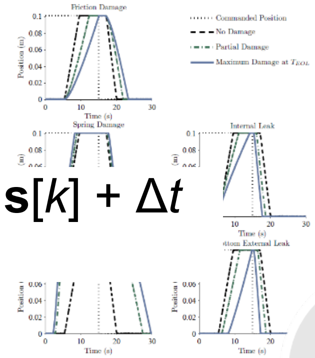
Data shown from Daigle and Goebel, IJPHM, 2008

Roy, Ramuhalli et al, ANS NPIC-HMIT 2015

Dib, Roy, et al, ANS NPIC-HMIT 2017

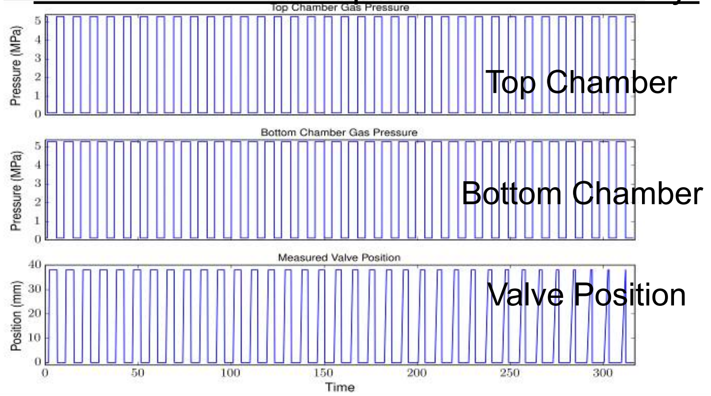
Data-driven, Physics-Inspired Models for Diagnostics and Predictive Maintenance

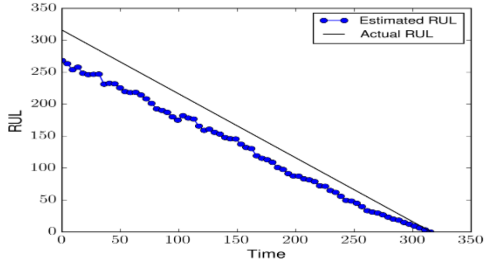




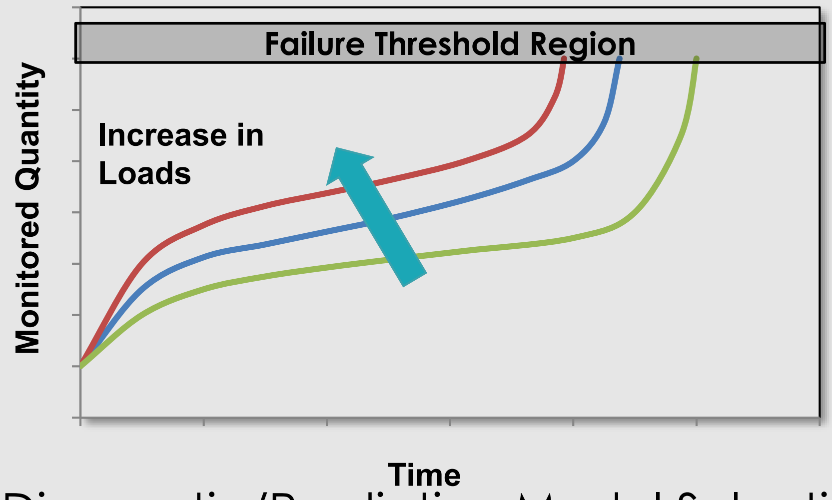
$$\mathbf{s}[k+1] = \mathbf{s}[k] + \Delta t\, \dot{\mathbf{s}}[k]$$

Pneumatic Valve Input Pressure History





Prognostic Result: RUL



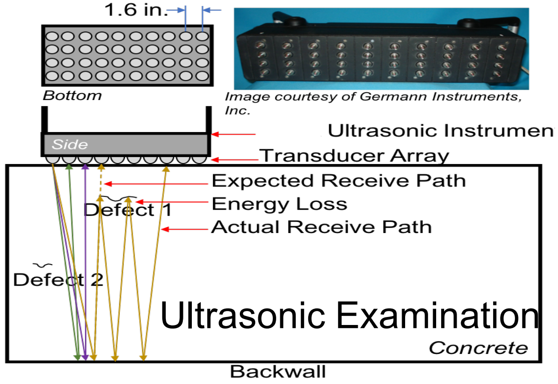
Diagnostic/Predictive Model Selection

Data shown from Daigle and Goebel, IJPHM, 2008

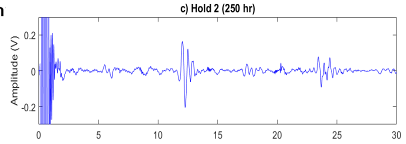
Roy, Ramuhalli et al, ANS NPIC-HMIT 2015

Dib, Roy, et al, ANS NPIC-HMIT 2017

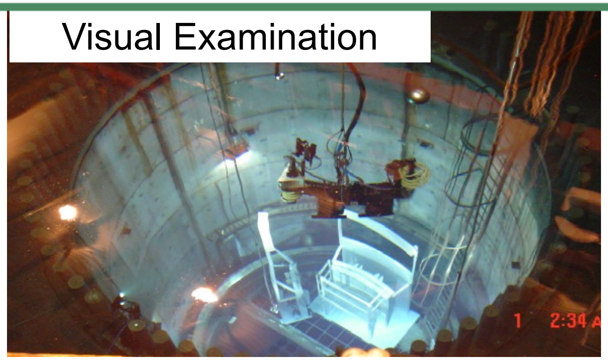
Complex Multi-scale Physics of Failure Models Challenge PHM for Materials Failure; Data-driven Models Show Promise

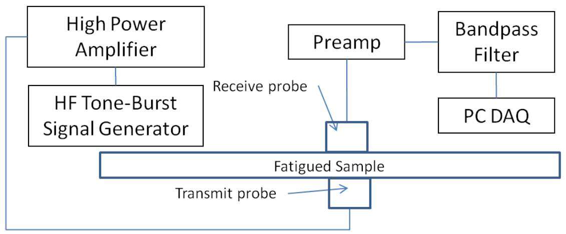


Ultrasonic Examination

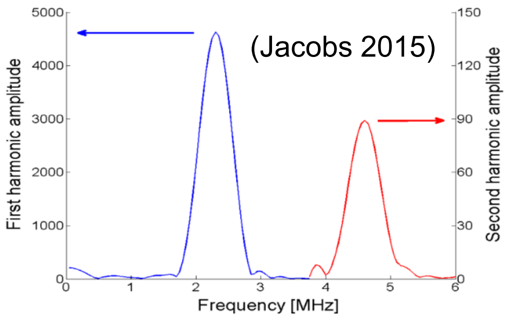


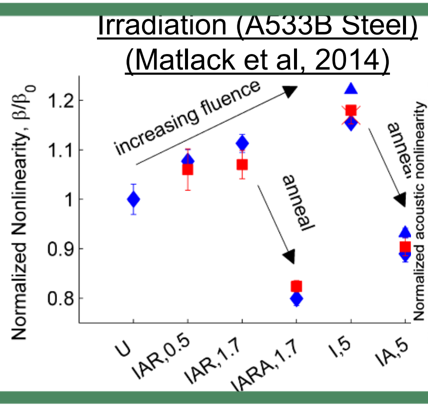
Visual Examination

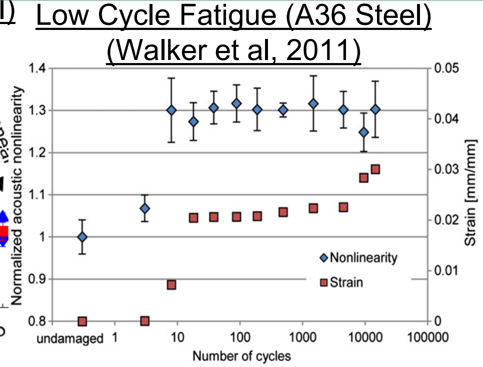


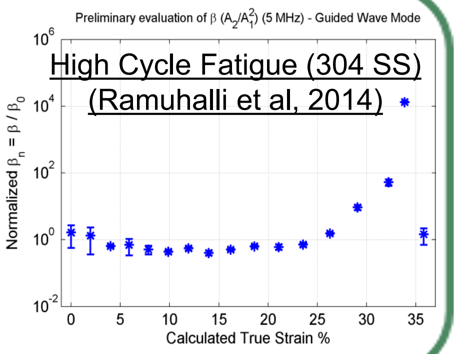


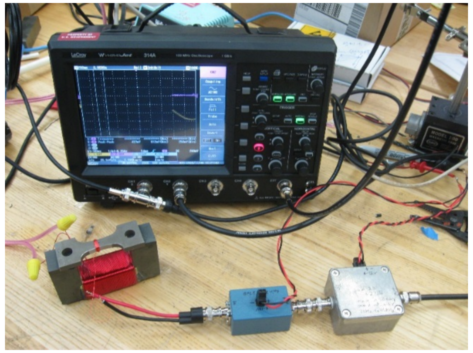
Nonlinear Ultrasonics

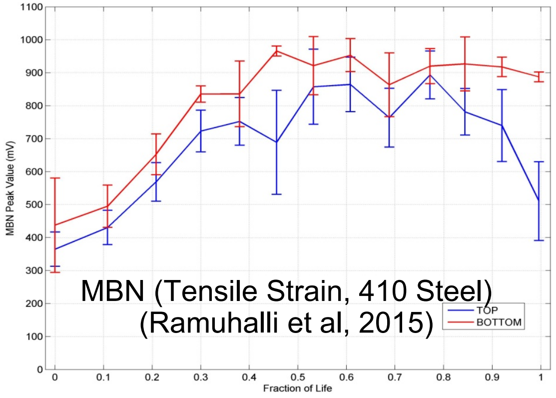


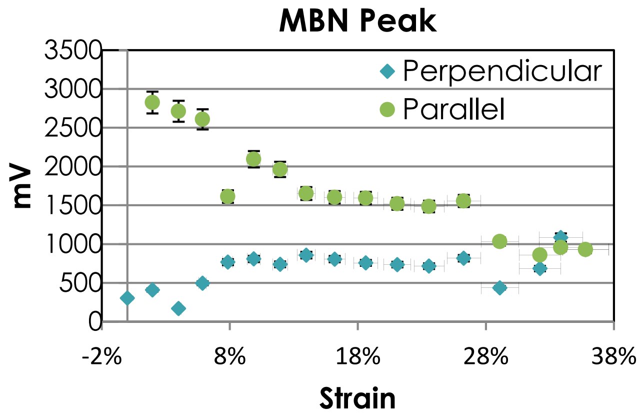








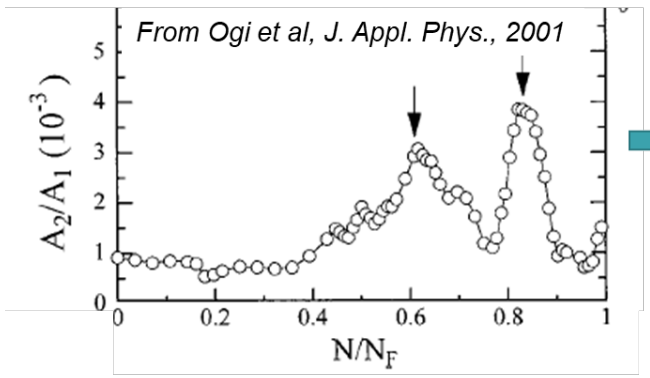


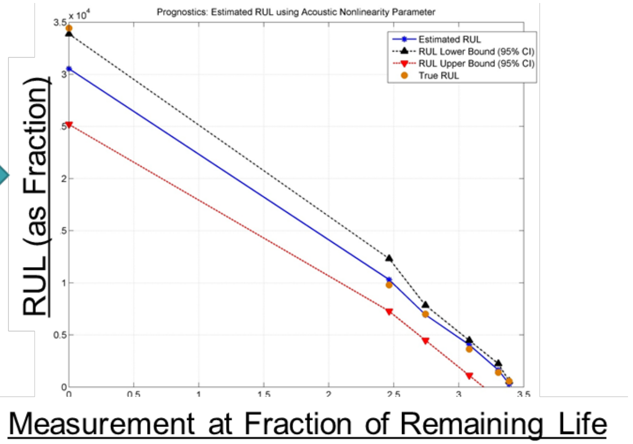


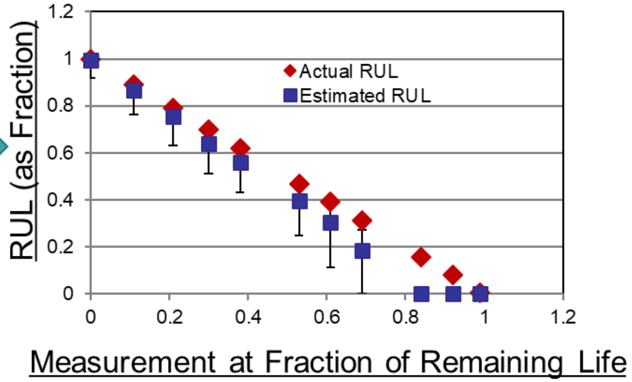
Magnetic Barkhausen Noise

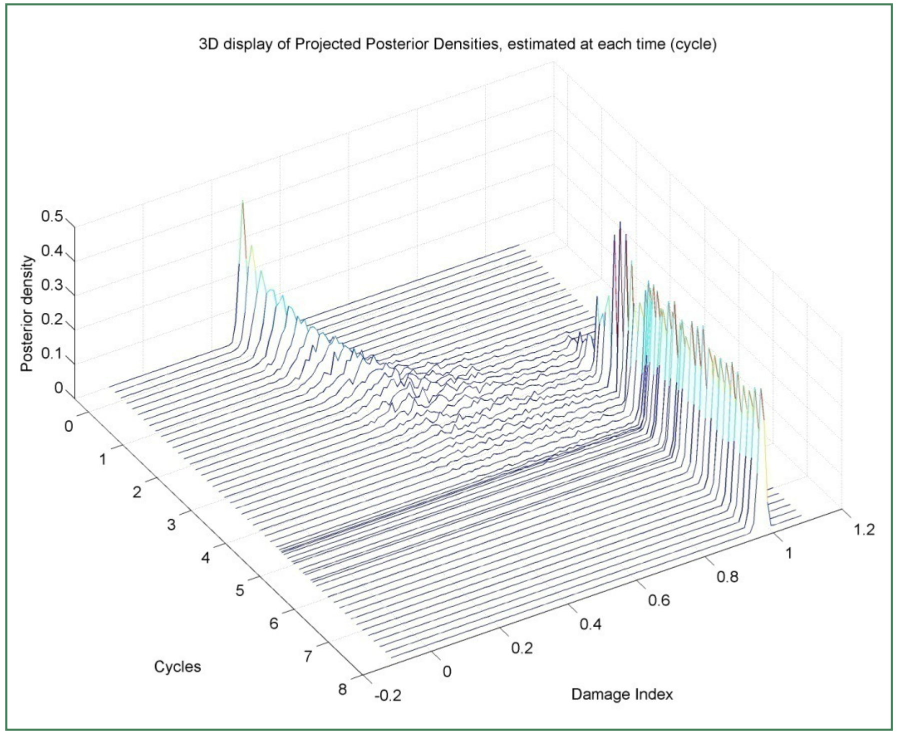
Bayesian Methods Allow Integration of Failure Physics Information, Condition Data, and enable Uncertainty Quantification

- Underlying models can be at desired level of fidelity
- Prediction updates with new measurements
- Model updates over time also possible to reflect reality





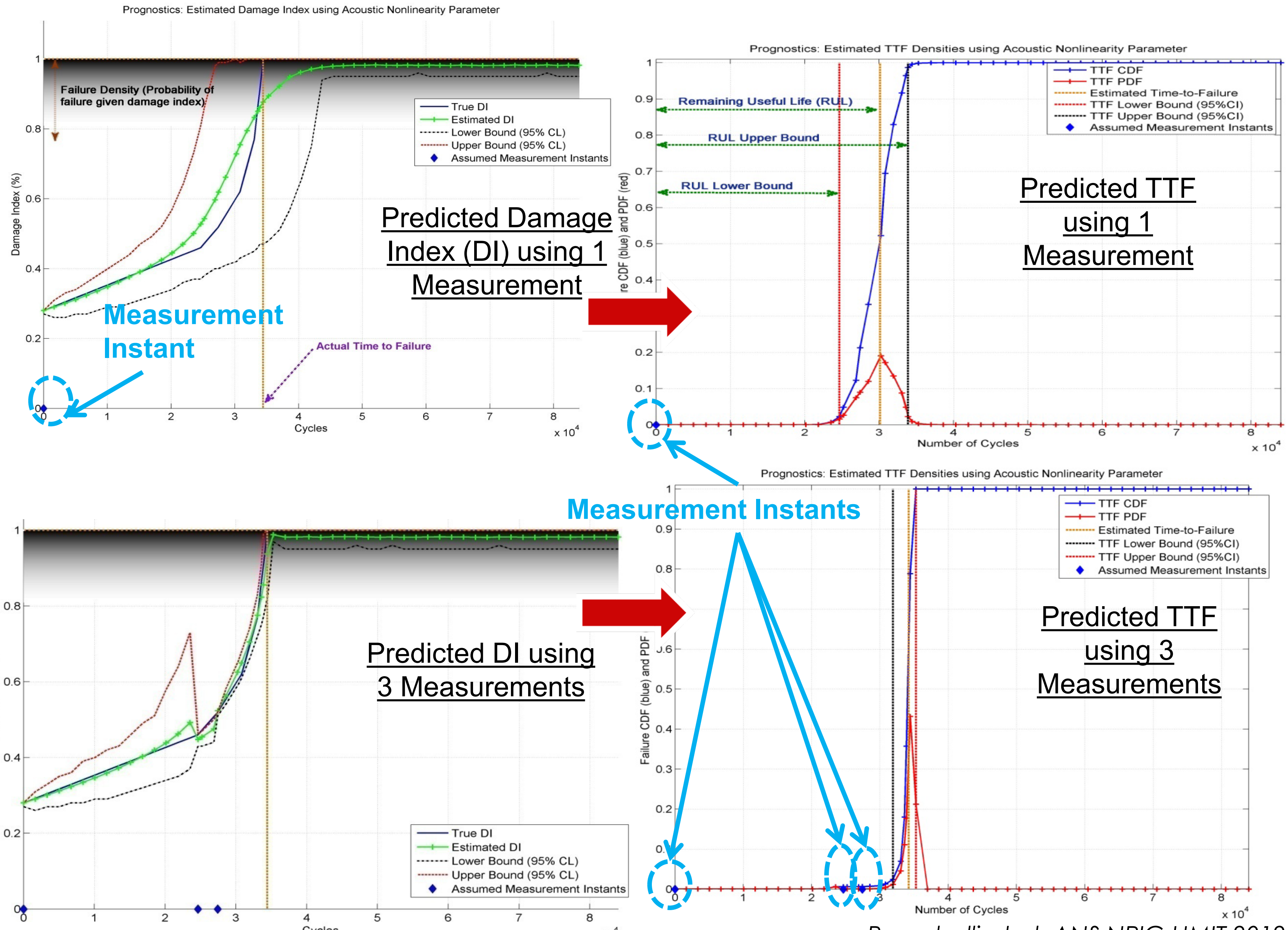




Evolution of Posterior Probability Density with Time

Example: Predicted Time-to-Failure (TTF) for Fatigue Crack Initiation

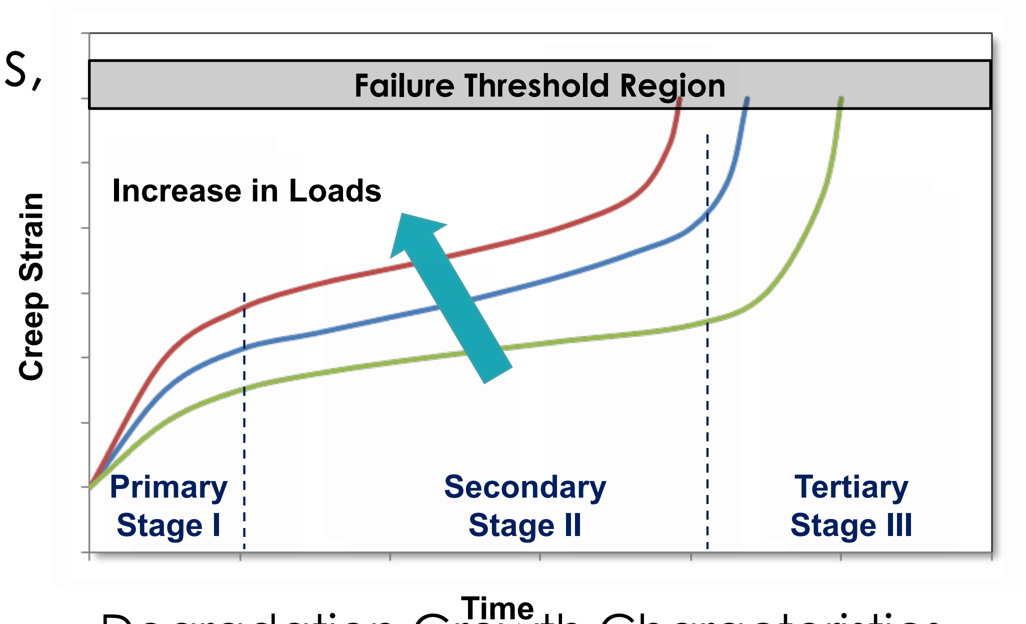
- Diagnostics and prognostics using data-driven models of
  - Damage growth
  - Measurement
- Necessary data may be difficult to acquire
- Physics-inspired models (damage growth and measurement) have been used in other instances with good accuracy



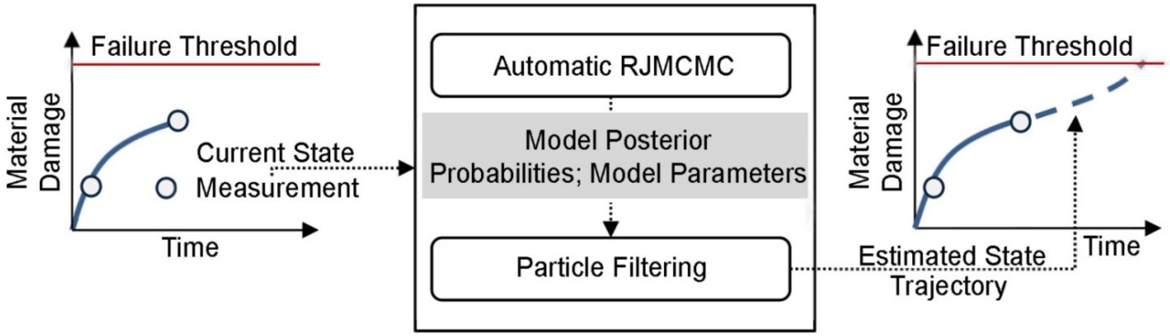
Ramuhalli et al, ANS NPIC-HMIT 2012

Digital Twin Model Updates are Essential for Many Applications

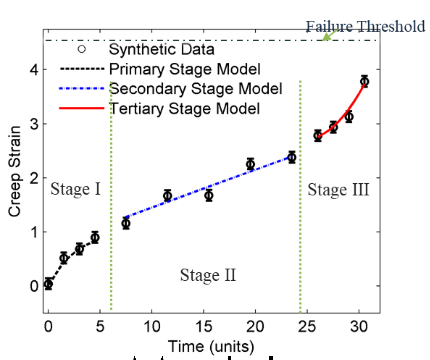
- Limited examples for certain fault conditions, and limited data
- Operational conditions may vary over time
- System or component condition may vary, requiring different models
- New failure modes with longer term operation
- Continuous learning, with model selection, will be necessary



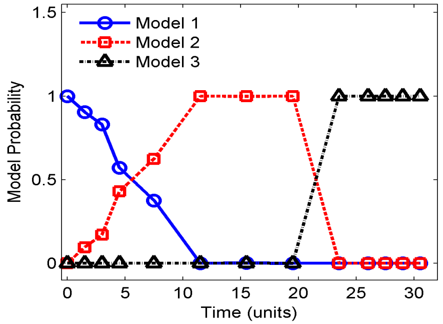
Degradation Growth Characteristics – Function of Time and Load



RJMCMC for Model Selection



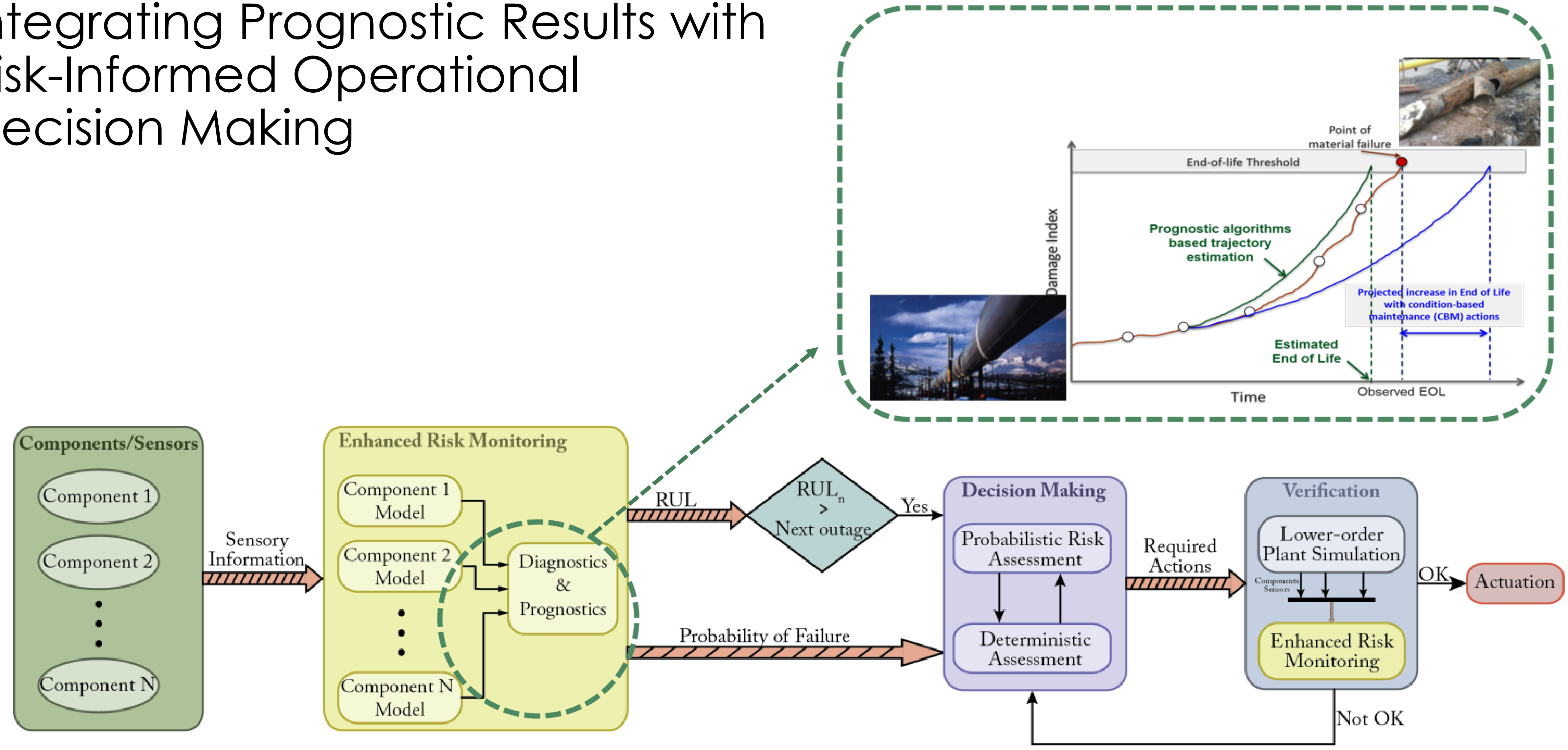
Models



Model Likelihood

Roy, Ramuhalli et al, ANS NPIC-HMIT 2015

Integrating Prognostic Results with Risk-Informed Operational Decision Making



Sensing

Prognostic Health and Risk Assessment

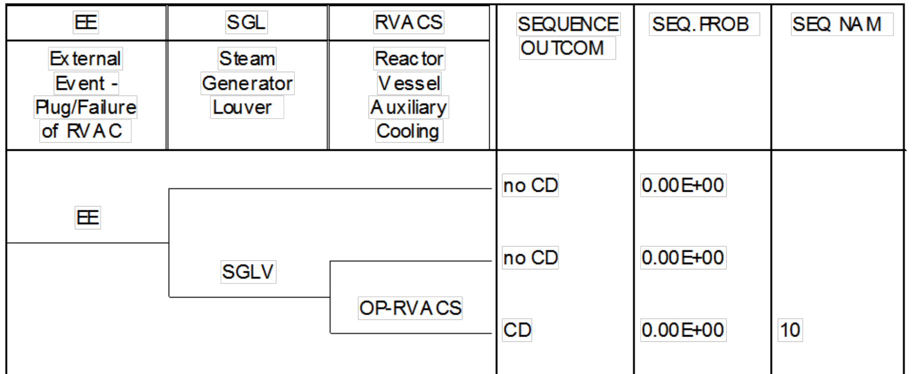
Control Logic Decision Making

Actuation

Cetiner et al, ANS NPIC-HMIT 2017

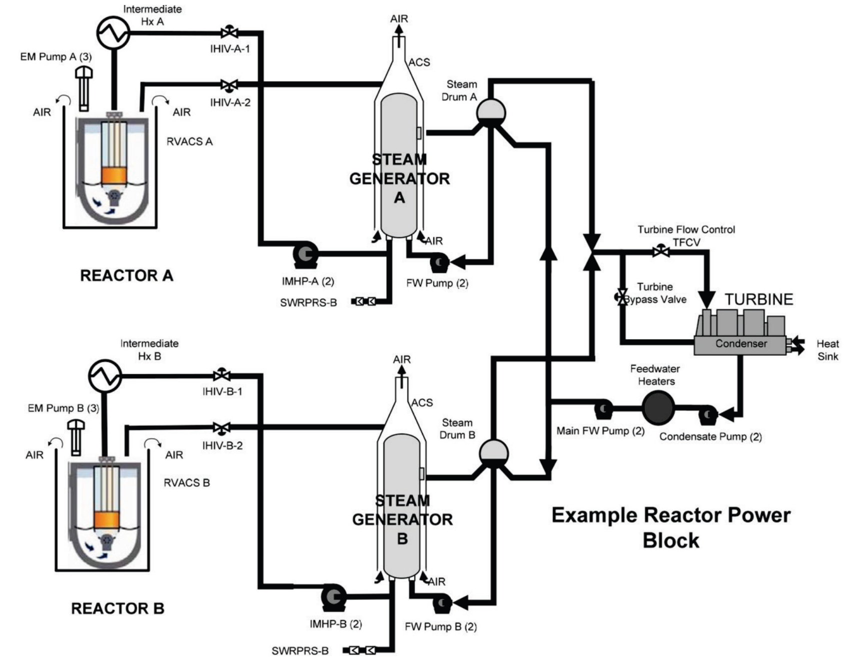
Integrating PHM and Risk Monitors with Plant Control Logic

- Risk: Measure of probability of some undesirable consequence
  - Core damage frequency, large early release frequency, health consequences to the public

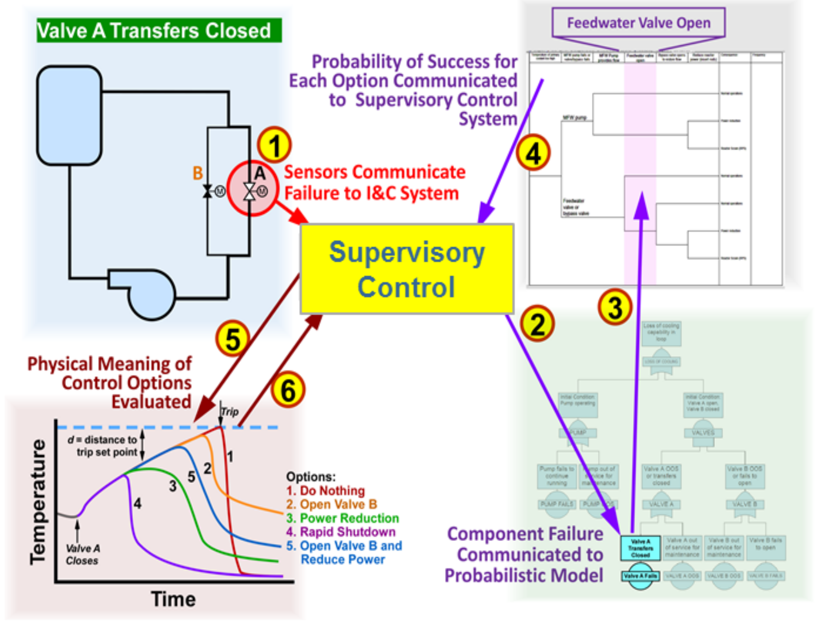


Simplified Reactor PRA Event Tree

- Elements of PHM integration with risk monitors
  - Equipment condition assessment (ECA) and prognostics for predictive health assessment
  - Predictive risk assessment (safety and economic)
  - Uncertainty quantification



Simplified Diagram of Multimodule Reactor



Cetiner, Muhlheim et al, Nuclear News 2015

Risk-informed Decisions: Economics and Safety

- Methodology for using cost metrics for component replacement scheduling
- *Hypothetical cost and failure rates used in analysis*
- Assessment computes safety related risk metric (CDF) and normalized cost over 40 years for three cases
  - Case A: Run to end-of-service-life; replace during scheduled outage.
  - Case B: Use diagnostics/prognostics; replace equipment just prior to plant exceeding safety limit.
  - Case C: Use diagnostics/prognostics; replace equipment if risk of unplanned outage at a future time. Schedule based on optimizing cost metric.

Case #	Description	Expected CDF (/yr)	Reduction in Economic Risk Over 40 yrs (Relative to Case A)
A	Expected end-of-life replacement	6.21E-07	-
B	ERM – safety goal based maintenance	6.60E-07	25.6%
C	ERM – safety and economics based maintenance	5.26E-07	28.6%

Ramuhalli, Veeramany et al, ICONE25, 2016

Summary

- Digital twin solutions for intelligent asset management and autonomous operations
  - Enabled by technology advances in sensing, data analysis, modeling and simulation, and machine learning
- Technical challenges still exist and are targets for ongoing research
  - Research leveraging advances in machine learning
- Resulting technologies enable sustainable nuclear power by improving the reliability and economics of nuclear plants

Looking Forward: Some Challenges

- Data
  - Data access and data quality
  - Optimal sensor type and placement
  - Testbeds for data generation and verification and validation (V&V)
- Technology Development
  - Robust digital twin development
  - Model selection and model updates
  - Robust diagnostics and prognostics in the presence of concurrent mechanisms, influencing factors, interacting subsystems, and measurement drift
  - Methods for semi-autonomous decision making
- Deployment
  - V&V approaches
  - Uncertainty quantification
  - Cybersecurity

Acknowledgments

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- Oak Ridge National Laboratory is operated by UT-Battelle for the US Department of Energy.

Questions?

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