MIRION Connect 26

AMERICAS

Annual Users' Conference

Reactor Simulation & Operator Training Solutions for New Nuclear

Multi-reactor digital twin with hardware-in-the-loop

HTGR | LWR | Molten Salt | Fast Reactor

Point kinetics reactor model • 1D-CFD thermodynamics • HIPS / CoreVision / ProTK / RMS in the loop • DCS-agnostic integration

TRAIN THE PLANT BEFORE THE PLANT EXISTS

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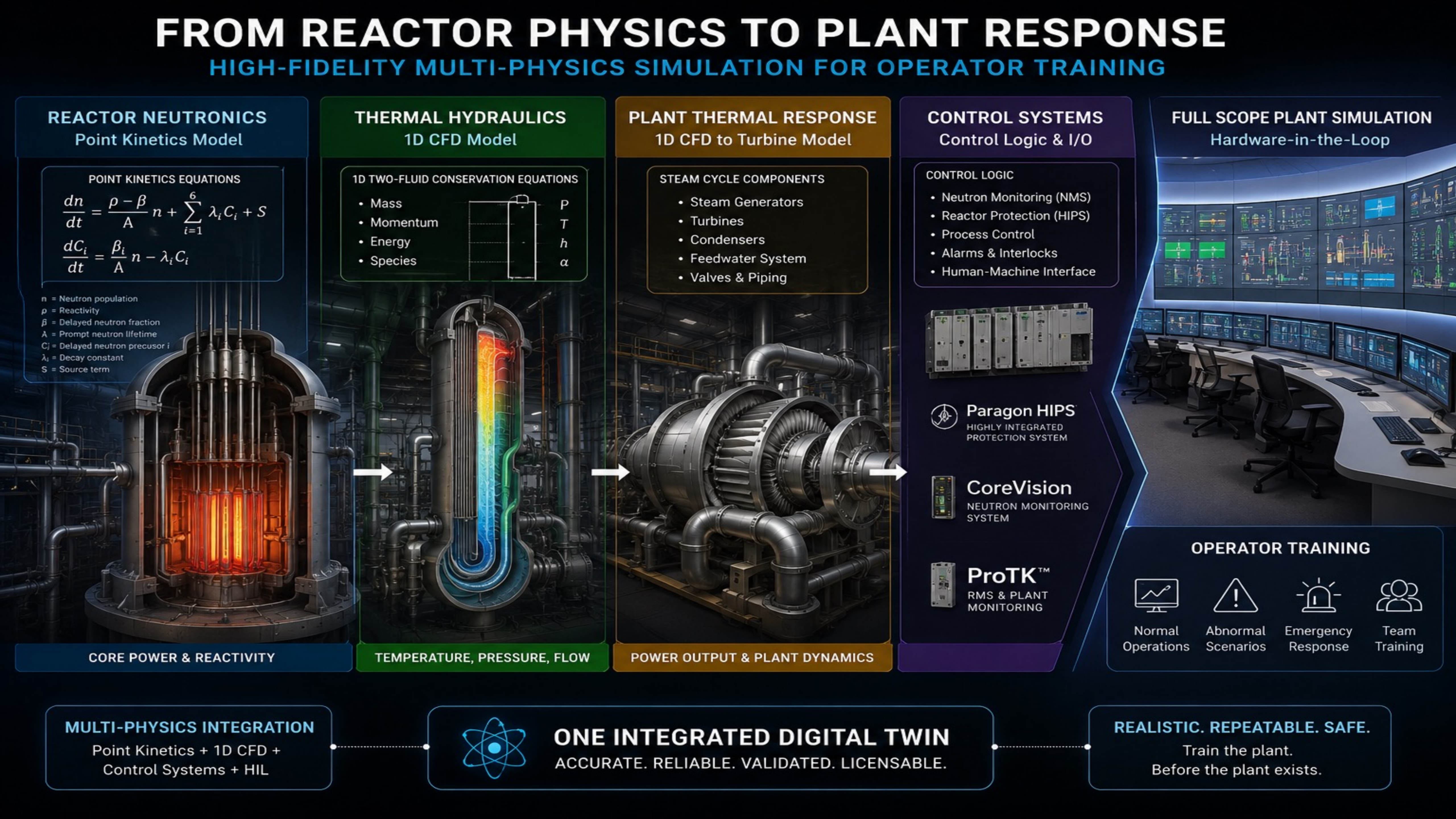
Yvotte Brits

Chief Reactor Technology Officer



FROM REACTOR PHYSICS TO PLANT RESPONSE
HIGH-FIDELITY MULTI-PHYSICS SIMULATION FOR OPERATOR TRAINING
REACTOR NEUTRONICS
Point Kinetics Model
POINT KINETICS EQUATIONS
$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{6} \lambda_i C_i + S$$
$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i C_i$$
n = Neutron population
ρ = Reactivity
β = Delayed neutron fraction
Λ = Prompt neutron lifetime
Cj = Delayed neutron precusor i
λ_i = Decay constant
S = Source term
CORE POWER & REACTIVITY
THERMAL HYDRAULICS
1D CFD Model
1D TWO-FLUID CONSERVATION EQUATIONS
• Mass
• Momentum
• Energy
• Species
P
T
h
α
TEMPERATURE, PRESSURE, FLOW
PLANT THERMAL RESPONSE
1D CFD to Turbine Model
STEAM CYCLE COMPONENTS
• Steam Generators
• Turbines
• Condensers
• Feedwater System
• Valves & Piping
POWER OUTPUT & PLANT DYNAMICS
CONTROL SYSTEMS
Control Logic & I/O
CONTROL LOGIC
• Neutron Monitoring (NMS)
• Reactor Protection (HIPS)
• Process Control
• Alarms & Interlocks
• Human-Machine Interface
Paragon HIPS
HIGHLY INTEGRATED PROTECTION SYSTEM
CoreVision
NEUTRON MONITORING SYSTEM
ProTK™
RMS & PLANT MONITORING
FULL SCOPE PLANT SIMULATION
Hardware-in-the-Loop
OPERATOR TRAINING
Normal Operations
Abnormal Scenarios
Emergency Response
Team Training
MULTI-PHYSICS INTEGRATION
Point Kinetics + 1D CFD + Control Systems + HIL
ONE INTEGRATED DIGITAL TWIN
ACCURATE. RELIABLE. VALIDATED. LICENSABLE.
REALISTIC. REPEATABLE. SAFE.
Train the plant.
Before the plant exists.

170+ new nuclear reactor designs and concepts can be grouped into four main technology families

This creates a huge need for simulator-based design validation, training and licensing readiness.

170+
new nuclear reactor designs & concepts

4
main technology families

HTGR
High temperature gas-cooled
TRISO fuel • high outlet temp

LWR
Pressurized / boiling / integral
Most familiar licensing basis

Molten Salt
Low pressure salt systems
High temperature heat applications

Fast Reactor
Sodium / lead / lead-bismuth
Fast spectrum advanced designs

IAEA ARIS and industry tracking show a broad and growing advanced reactor pipeline. Paragon focuses on the four families most relevant to near-term commercialization.

One simulator platform across all four reactor families

Paragon has already modeled HTGR, LWR, Molten Salt and Fast Reactor configurations on a common simulation platform.

HTGR
High-temperature gas-cooled

LWR
Light water reactor

Molten Salt
Primary/secondary salt systems

Fast Reactor
Sodium / fast spectrum

From Reactor to Turbine — a true digital twin

Paragon and SimGenics model the physics, thermodynamics, operator interface and balance-of-plant behavior together.

1 Reactor physics

Point kinetics model for core power, reactivity feedback, delayed neutron response and trip behavior.

2 Thermodynamics

1D-CFD based thermal-hydraulic model from reactor through heat transport and steam generation.

3 Real Time Plant response

Reactor-to-turbine dynamic behavior including major plant systems and balance-of-plant interactions. (ANSI 3.5)

4 Controls layer

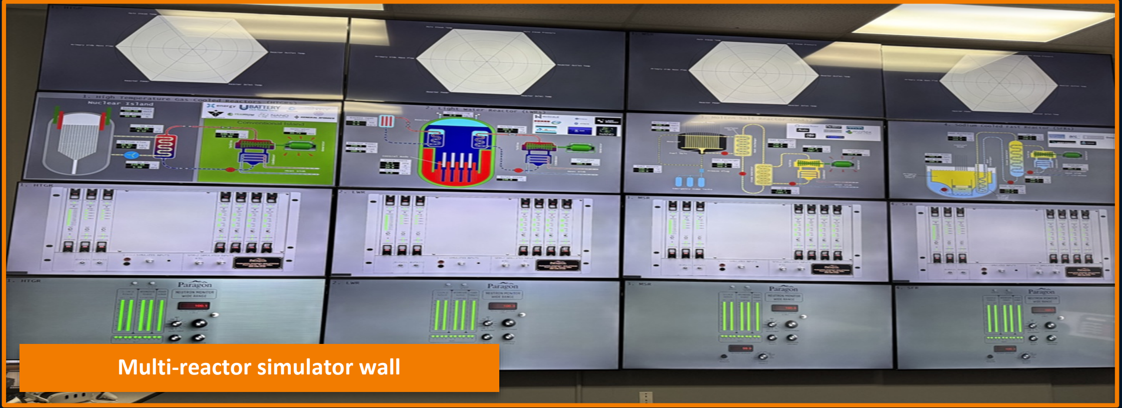
Any DCS / HSI architecture can be represented on top: ABB, Siemens, Ovation, Rockwell or customer-specific.

SimGenics partnership: full-scope simulator environment from reactor to turbine

Hardware-in-the-loop — not just a software demo

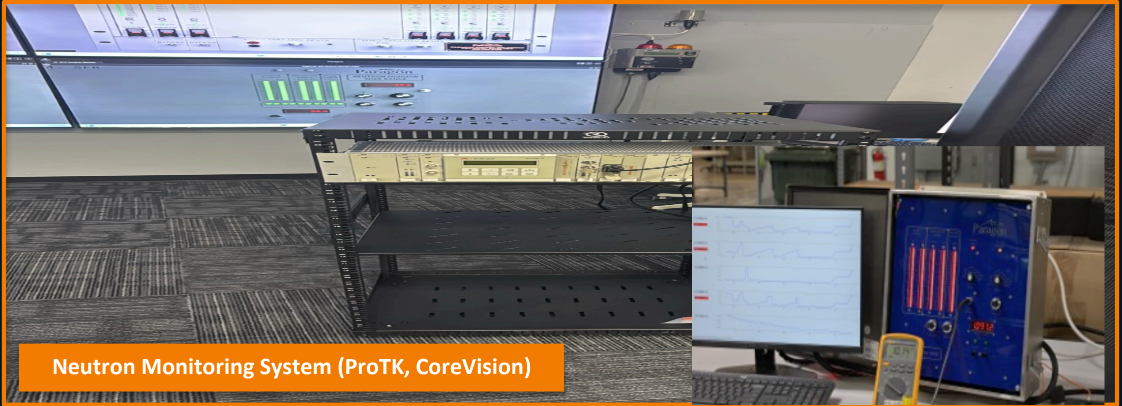
The platform ties simulation to real equipment, real operator stations and real interfaces.

HIPS RPS hardware



Multi-reactor simulator wall

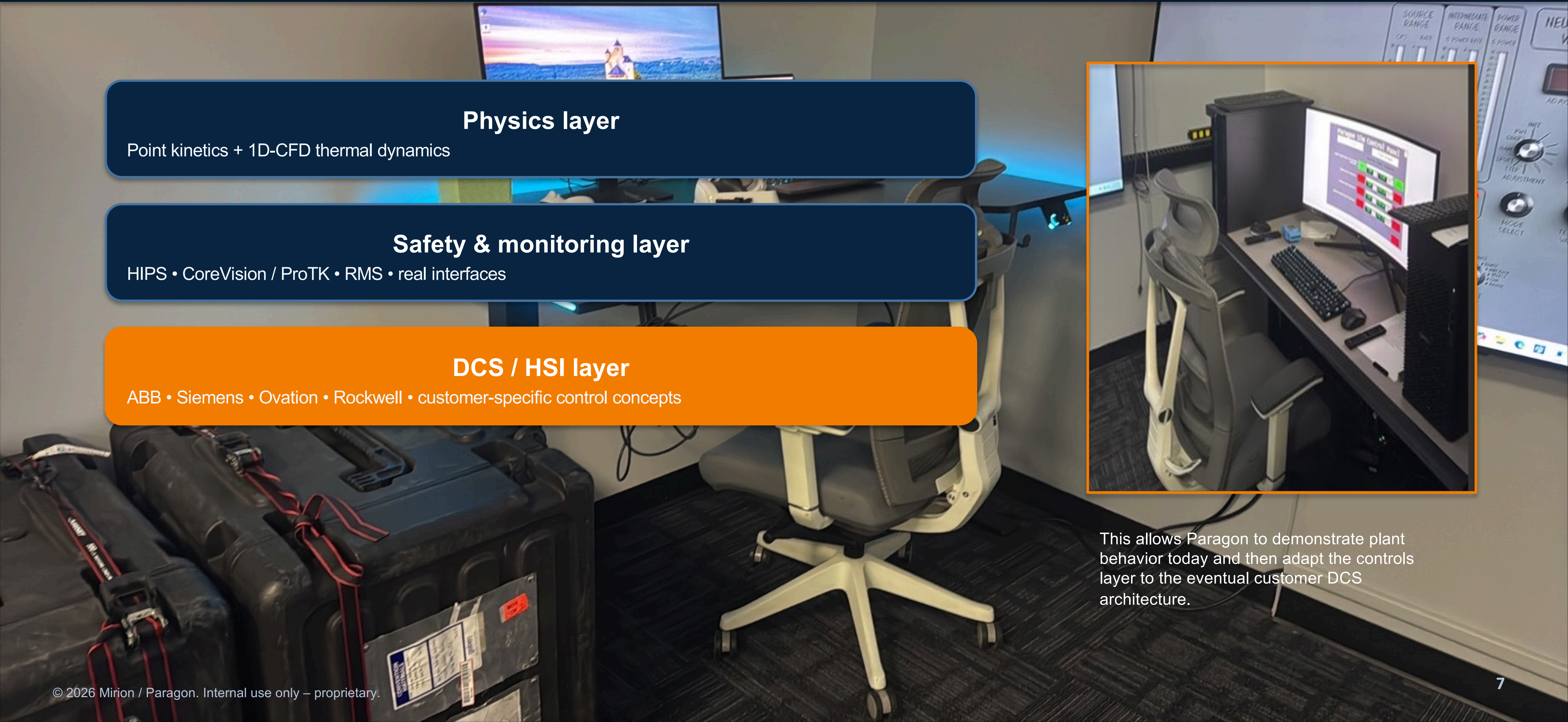
Operator console / HSI



Neutron Monitoring System (ProTK, CoreVision)

DCS-agnostic — model the plant, then put the customer’s controls on top

The plant and protection model stay the same while the control room concept is tailored to the customer.



Physics layer

Point kinetics + 1D-CFD thermal dynamics

Safety & monitoring layer

HIPS • CoreVision / ProTK • RMS • real interfaces

DCS / HSI layer

ABB • Siemens • Ovation • Rockwell • customer-specific control concepts

This allows Paragon to demonstrate plant behavior today and then adapt the controls layer to the eventual customer DCS architecture.

Train the operator before the plant exists

The simulator is a high-value training environment across normal, abnormal and emergency conditions.

- **Startup & approach to criticality**
- **Heatup, synchronization and power ascension**
- **Power maneuvering & load following**
- **Sensor failure, alarms and trip response**
- **Abnormal & emergency procedure validation**

Repeatable realistic scenarios build operator confidence, validate procedures and expose design issues before fuel load.

Paragon + SimGenics = a practical reactor-to-turbine simulator solution

This is cutting-edge because it combines plant models, real hardware and operator training in one environment.

Paragon brings

Advanced reactor integration, HIPS protection systems, CoreVision / ProTK neutron monitoring, RMS and system integration expertise.

SimGenics brings

Full-scope simulation capability, control room environment, scenario development and operator training tools.

Outcome

A customer-ready digital twin platform for demonstrations, licensing support, HFE, FAT/SAT, commissioning and operator training.

Simulator Path: Build, Commission and Gain NRC Acceptance

For operator licensing applications, the key regulatory anchor is 10 CFR 55.46 for simulation facilities.

1 Define reference plant
Reference plant, scope, training objectives and licensing use case.

2 Build simulator
Reactor model, 1D-CFD thermodynamics, HSI, DCS and equipment-in-the-loop.

3 Commission & test
Factory/site testing, scope & fidelity verification, performance testing and issue tracking.

4 Establish basis
Plant-referenced simulator or request Commission approval under 10 CFR 55.46(b).

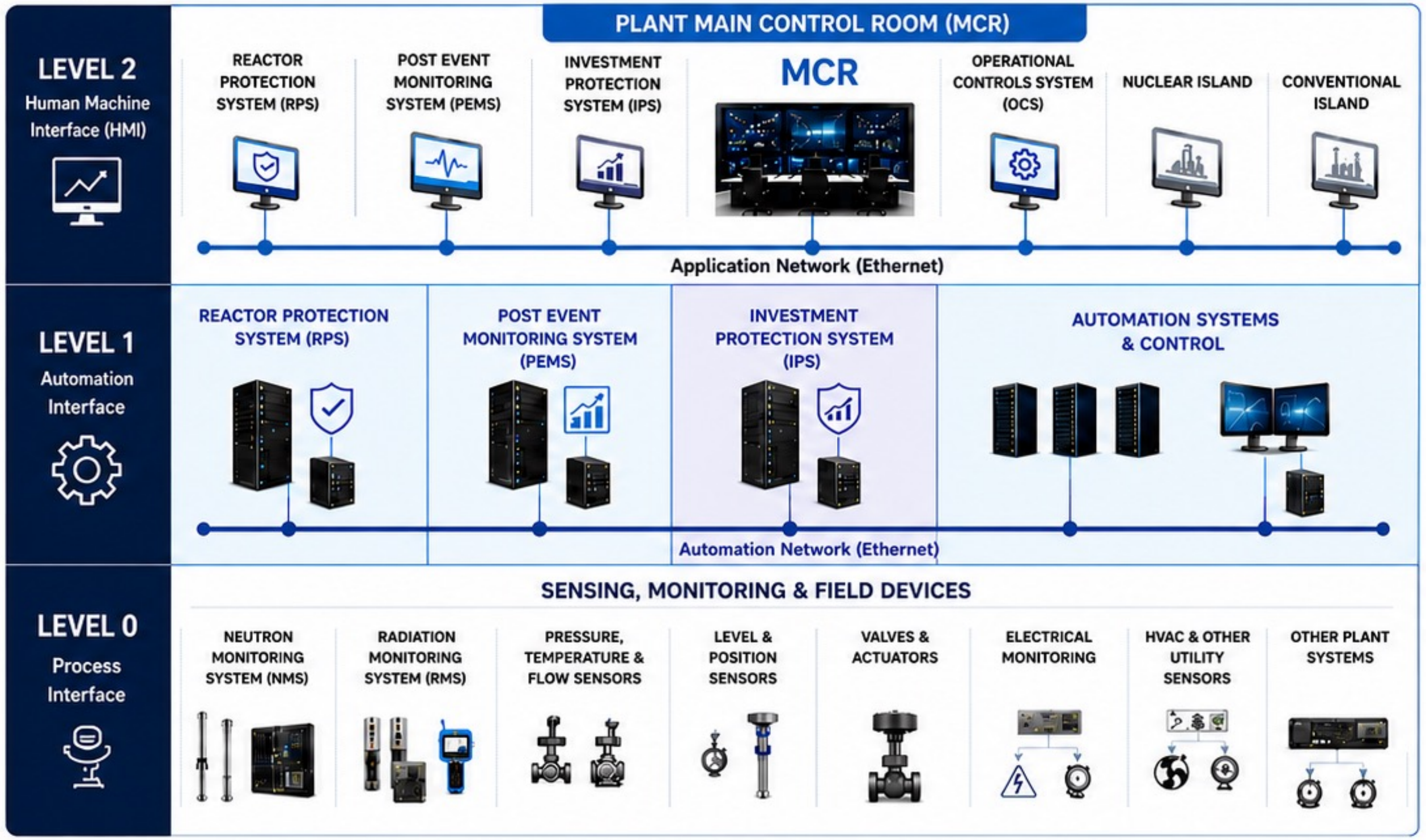
5 NRC review / inspection
Demonstrate suitability for operating tests and experience requirements.

6 Use in program
Initial license exams, experience prerequisites, training and requalification.

Key point: a simulator used for operator licensing must show expected plant response to operator input and to normal, transient and accident conditions for which it is designed.

GENERIC SMR I&C ARCHITECTURE
DEVELOPMENT OVERVIEW

Integrated. Secure. Scalable. Delivered Across Every Level.



I&C SYSTEMS & SAFETY CLASSIFICATION (NEI 18-04)

I&C System	Safety Classification (NEI 18-04)
Reactor Protection System (RPS)	Safety-Related
Post Event Monitoring System (PEMS)	Non-Safety-Related with Special Treatment
Investment Protection System (IPS)	Safety-Related with Special Treatment
Automation Systems & Control	Non-Safety Related
Main Control Room & Training Simulator	Non-Safety Related
Sensing, Monitoring & Field Devices	Safety / Non-Safety Related

MIRION I&C & NUCLEAR TECHNOLOGY SOLUTIONS

DELIVERING VALUE ACROSS THE PLANT LIFECYCLE

- **INTEGRATED ARCHITECTURE** — Seamless system integration across all levels
- **SAFE & RELIABLE** — Defense-in-depth with proven nuclear I&C solutions
- **SCALABLE & FLEXIBLE** — Designed for SMR deployment and future expansion
- **OPTIMIZED PERFORMANCE** — Improved operability, availability and reduced lifecycle cost
- **ONE PARTNER. ONE SOLUTION.** — Complete peace of mind across the plant lifecycle

Additional Mirion Offerings

- Neutron Detectors
- Gamma Detectors
- Environmental Monitors
- Area & Process Monitors
- Cybersecurity Solutions
- Services & Support

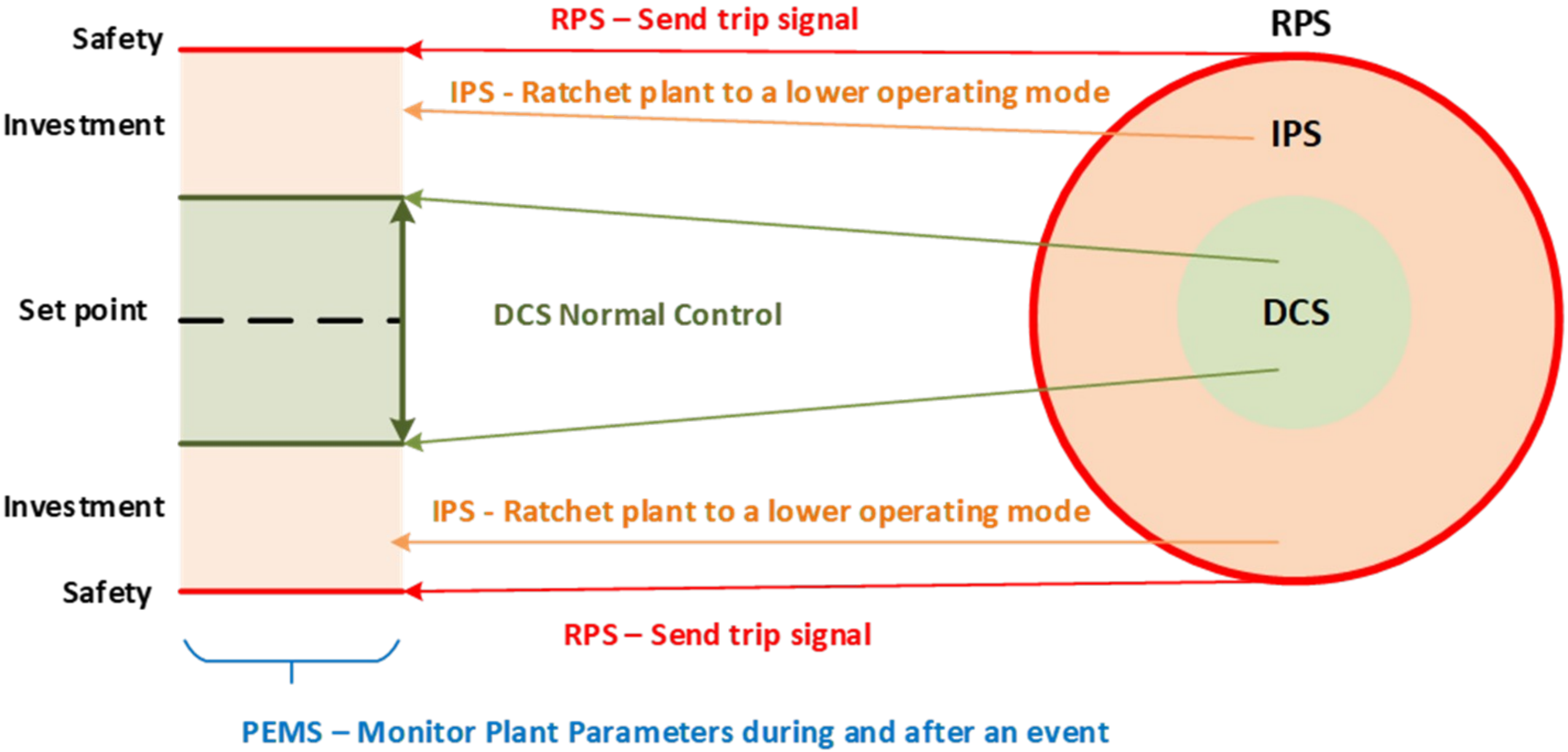
MIRION NUCLEAR SOLUTIONS

I&C Design by Analysis Process

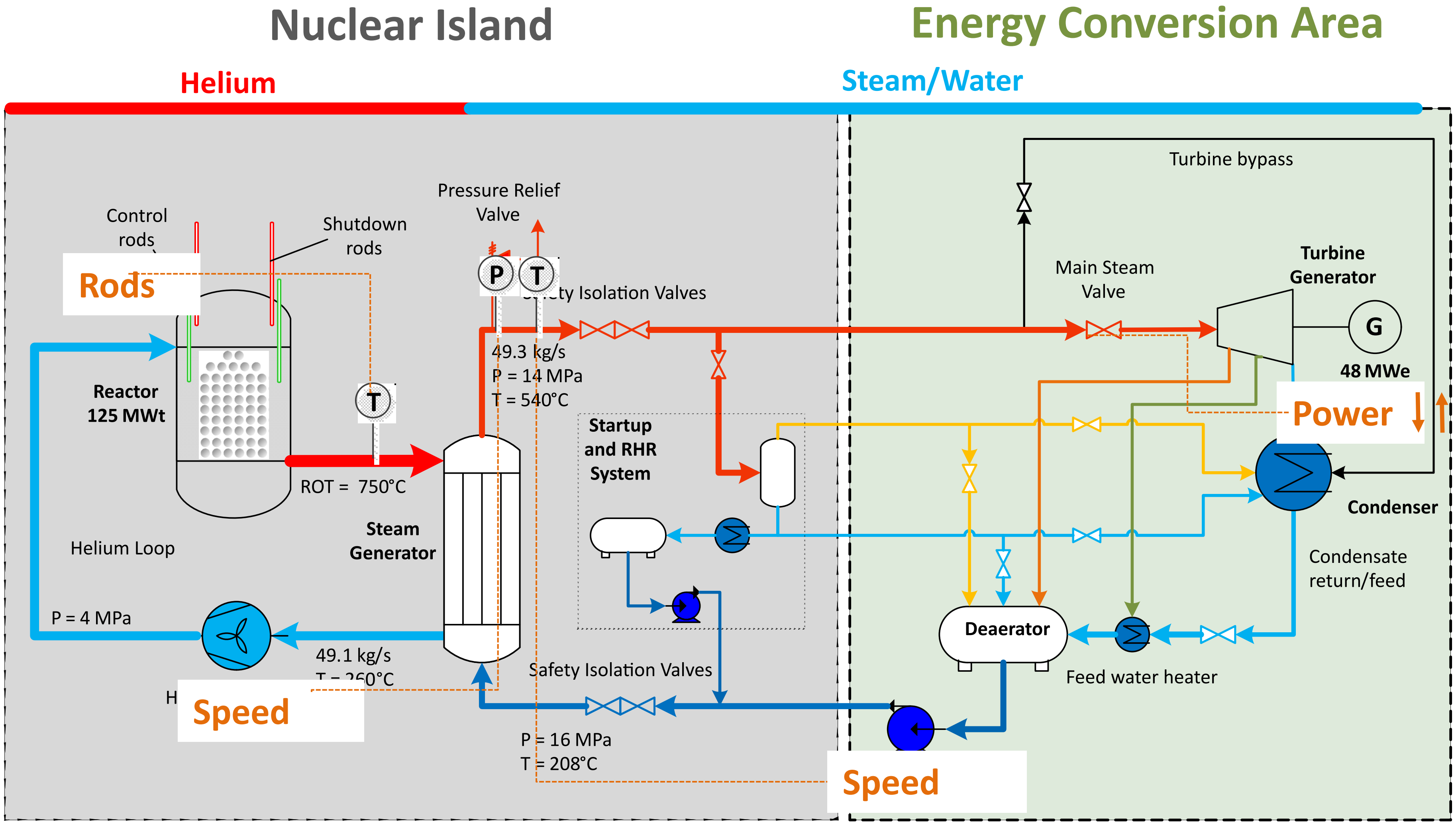
- Develop 1D-CFD SMR Thermal-Hydraulic Model (Reactor to Turbine)
- Control System Design and Implementation
- Design, Implementation and Testing of Protection Systems (IPS, RPS)
- Perform Plant Duty Cycle Transients to test integrated I&C Systems (Start-Up, Shut-Down, Load Following etc.)

1. Open Loop Transients
2. Unprotected Transients
3. Protected Transients
4. Duty Cycle Transients

Generic SMR I&C Architecture: System Synergy Across Plant Operations



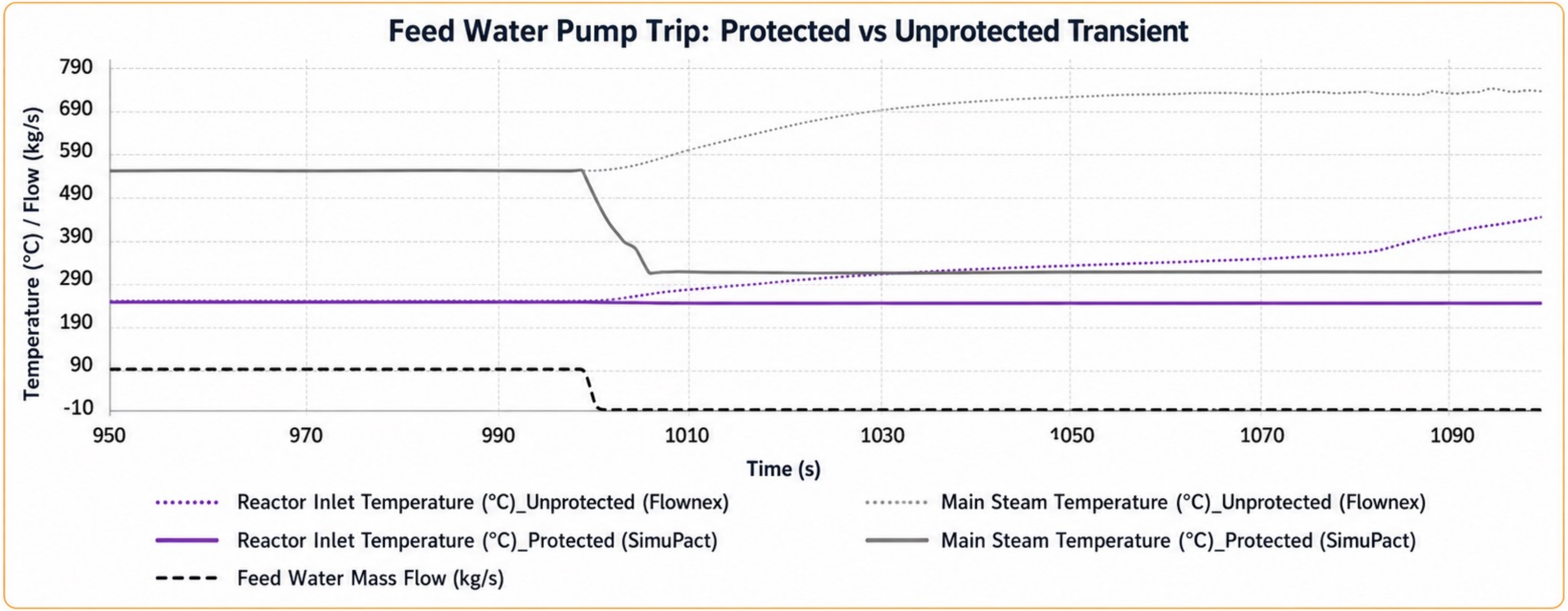
Example Control Approach on a HTGR



Controlled Variable	Set point	Manipulated Variable
Steam Generator Inlet Temperature	750°C	Control Rod Position
Main Steam Pressure	14 MPa	Helium Circulator Speed
Main Steam Temperature	540°C	HP Feed pump Speed
Electrical Load	25 – 100%	Turbine Throttle Valve Position

Example Unprotected, Protected Transient to develop trip actions with setpoints

PROTECTION SYSTEM	PROTECTION SYSTEM INITIATING SIGNAL	PROTECTION SIGNAL & ACTION
Reactor Protection System	• Reactor Inlet Temperature >= 300°C • Main Steam Temperature >= 593°C • Main Steam Pressure >= 19.8 MPa • Reactor Outlet Temperature >= 800°C	Trip Circulators, Insert control rods



Mirion
Nuclear I&C
Paragon

Trip matrix: where the safety case becomes hardware

The trip matrix is the bridge from transient analysis and licensing basis events to RPS logic, actuation, testing, and operator response.

Initiating signal	Condition / setpoint	RPS action	Non-safety response	Traceability
Reactor outlet temp	> high-high limit	Trip reactor / circulators	Alarm + cooldown sequence	LBE-01
Neutron flux	> overpower / rate	Insert rods	Power runback	LBE-02
Primary flow	< low flow	Trip reactor	Pump diagnostics	LBE-03
Steam pressure	> high pressure	Turbine / isolation logic	Bypass / dump controls	LBE-04

Design principle: keep safety-related trip functions short and deterministic; put diagnostics, optimization, and operator aids outside the safety boundary.

Requirements | Setpoint calc | Logic diagrams | Test cases | Operator actions

Operator Pathways: Licensed, Qualified and Application-Specific

Today’s commercial fleet relies on NRC-licensed operators under 10 CFR Part 55. Advanced reactor programs may combine licensed and qualified roles depending on the licensing b

NRC-Licensed Operator (RO/SRO) path

- Candidate selection, education and medical/fitness criteria
- Systems training + procedures + on-shift fundamentals
- Simulator / plant experience and manipulations
- Written exam + operating test
- NRC license issuance
- Continuing requalification

Part 50 / Part 52 — Traditional Commercial Path

Best fit

Reactivity manipulations, control room minimum staffing, established fleet model, highest regulatory certainty.

Potential operating model

- Risk-informed, technology-inclusive approach
- More flexibility to tailor staffing and role definitions to the technology
- Greater opportunity for “qualified operator” / task-qualified roles for some functions
- Final approach remains application-specific and subject to NRC approval

Part 53 Optional Framework — Advanced Reactor Opportunity

Best fit

Highly automated plants, smaller crews, advanced HSI concepts, microreactors and novel operating concepts.

Practical message: new nuclear will likely use a hybrid model — licensed operators where required, qualified operators where that reduces staffing burden without sacrificing safety.

Licensed vs Qualified Operator — What is the Advantage?

A sharp staffing strategy can reduce cost while preserving regulatory confidence and operating discipline.

Advantages

- Clear NRC-recognized authority for RO/SRO functions
- Proven exam and requalification structure
- Supports Part 50 / Part 52 staffing models
- High stakeholder confidence for first-of-a-kind plants
- Best for control room command, reactivity control and shift leadership

Licensed Operator (strongest regulatory position)

Tradeoff

Longer training pipeline and potentially larger staffing footprint.

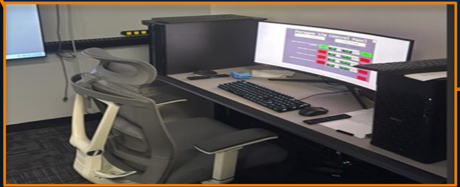
Advantages

- Broader talent pipeline and faster role qualification
- Better alignment to automation and advanced HSI
- Lower staffing burden and lower OPEX
- Strong fit for local operator / system operator / balance-of-plant roles
- Can be tailored to task-specific responsibilities

Qualified Operator (best lever for efficiency)

Tradeoff

Cannot replace NRC-licensed roles where the licensing basis requires licensed operators.



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Human Factors Engineering Program Overview

(According to NUREG-0800 & NUREG-0711)

1. HFE Program Management
Defines scope, responsibilities, and integration of HFE throughout plant design. Develop HFE Style guide.

2. Operating Experience Review (OER)
Analyze relevant OEs to identify human performance issues and design improvements.

3. Functional Requirements Analysis & Function Allocation
Determines what functions are needed and how they're allocated between humans and systems.

4. Task Analysis
Analyze tasks assigned to personnel to ensure compatibility with human capabilities.

5. Staffing and Qualifications (S&Q)
Defines number, roles, and qualifications of staff needed to operate and maintain the plant.

6. Human-System Interface (HSI) Design
Design of control rooms, displays, controls, alarms, and information systems.

7. Procedure Development
Design and validation of normal, abnormal, and emergency operating procedures.

8. Training Program Development
Develop training content based on the analyzed tasks and designed interfaces.

9. Human Factors Verification & Validation (V&V)
Ensure the integrated system supports safe and reliable human performance.

10. Design Implementation
Confirm HFE design features are implemented and integrated as intended.

11. HFE Program Review
Independent review to confirm HFE processes are followed and documented.

Paragon

Operator Training Simulator & Control Room Design Program Overview

(In compliance with ANSI 3.5)

1. Needs Analysis & Functional Requirements

Define simulator scope, training objectives, and interface requirements based on plant design.

2. System Modeling & Fidelity Specification

Develop plant process models (reactor, turbine, I&C) with required fidelity levels for training.

3. Control Room Layout & HSI Conceptual Design

Design control room architecture, panel layout, and HMI concepts including ergonomic considerations.

4. Simulator Architecture & Software Integration

Select simulator platform, integrate physics models, I&C logic, and control interfaces.

5. Hardware Setup (Panels, Screens, HMI)

Install displays, panels, switches, and VR/3D components if applicable to mimic real operations.

6. Scenario Development & Instructor Tools

Create representative normal/abnormal scenarios, configure instructor stations and recording tools.

7. Testing & Validation (V&V)

Verify simulator behavior against reference plant data and validate training scenarios.

8. Operator Training & Certification

Use simulator for licensed operator training, retraining, and NRC evaluation activities.

9. Control Room Final Design & Implementation

Finalize hardware/software layouts, procure control panels, and support installation.

10. Sustainment & Configuration Management

Maintain simulator accuracy with plant changes, updates to models, and control room upgrades.

Mock-Up Control Room

Full Scale Training Simulator & Control Room

Future Paragon Simulation Center

An immersive, digital environment for advanced reactor operator training, HSI validation, and control room design.

USE CASES

- Advanced reactor control room concepts
- Full-wall visualization
- Multi-screen operator interfaces
- Digital procedures and alarm management
- Integrated HIPS / NMS / RMS response

PARAGON VISION

A future-ready simulator environment that helps customers validate the HSI, train operators, and de-risk first-of-a-kind control room design.

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