Integrated Digital Twin Framework for Breeding Blanket Systems:

Coupling Plasma, Fuel Cycle, and Thermal Hydraulic dynamics

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BACKGROUND: 2025 ACHIEVEMENTS

PROOF OF CONCEPT FOUNDATIONS ESTABLISHED

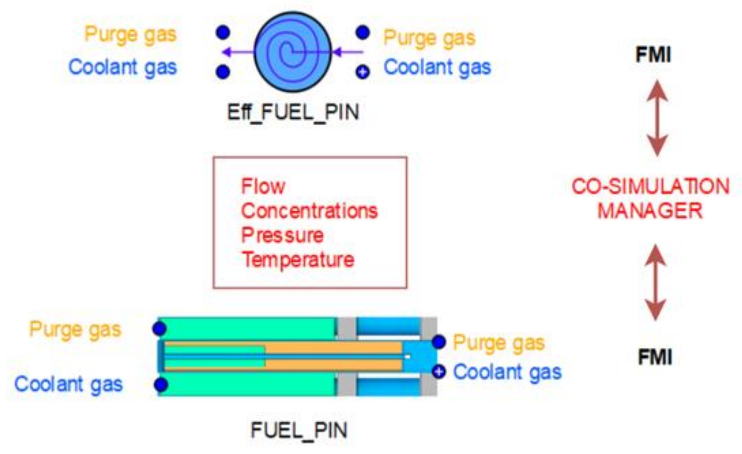
The 2025 project (AC-DTE.DT.CIEMAT-T001) successfully laid the groundwork for developing a Digital Twin of the Breeding Blanket (BB) and its ancillary systems:

Exchanged Variables Identification:

- Tritium Extraction System (TES) → Inner fuel cycle
- Coolant Purification System (CPS) → Inner fuel cycle
- First Wall → Plasma scrape-off layer (SOLPS/EIRENE)
- Pipe forest → Exhaust detritiation system
- Steam generators → Environmental impact systems

Mathematical interfaces defined:

- Heat transport models (RELAP5)
- Hydraulics models
- Balance of Plant models



OPC-UA co-simulation structure used for demonstration

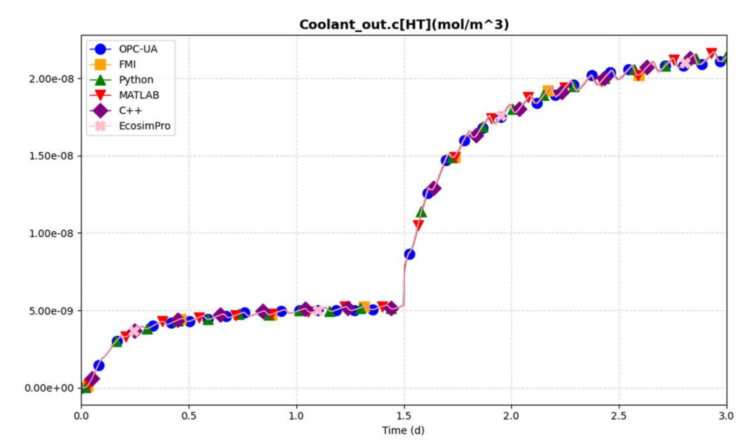
COMMUNICATION PROTOCOLS DEMONSTRATED

Five standardized communication interfaces successfully validated between EcosimPro® models:

- **OPC-UA** (Open Platform Communications - Unified Architecture)
- **FMI** (Functional Mock-up Interface)
- **Python-based** communication scripts
- **MATLAB** integration
- **C++ program** interfaces

Proof of Concept Validation

- Coupled fuel pin model with simplified TES/CPS model
- All protocols showed excellent numerical consistency
- Real-time data exchange demonstrated via UA
- Expert OPC-UA client
- Dynamic modification of extraction efficiencies (TES: 80%→50%, CPS: 90%→60%)validated



Results of the proof-of-concept validation runs

DIGITAL TWIN FRAMEWORK FOR BREEDING BLANKET SYSTEMS (2026-2027)

OBJECTIVES

Main Objective

Develop a dynamic, integrated simulation framework for tritium transport, coupling EcosimPro® models with fuel cycle and incorporating thermal-hydraulic temperature profiles from RELAP5/mod3.3, while preparing the plasma-edge interface.

Specific Objectives

Domain	Objective
Fuel Cycle Integration	Develop dynamic interface between EcosimPro® and fuel cycle simulators (Julia-based TFV code or ASPEN); exchange tritium partial pressures and extraction fluxes at every simulation timestep
Thermal Integration	Implement two-way coupling between EcosimPro® and RELAP5/mod3.3; enable dynamic feedback of temperature distributions to update tritium transport parameters (diffusion coefficients, solubility, release rates)
Plasma-Edge Interface	Consolidate and validate exchange variables at plasma-facing first wall; ensure compatibility with plasma-edge codes (TRIM, SOLPS)
Validation & Demonstration	Apply framework to realistic DEMO breeding blanket scenarios; benchmark against standalone simulations
AI/ML Enhancement	Explore surrogate modelling approaches; develop reference surrogate model for system element; establish computational/accuracy criteria for surrogate model usability

Parallel AI/ML PHASE

- Study surrogate model types applicable to tritium transport
- Define selection criteria between surrogate and first-principles models
- Export datasets from EcosimPro® models
- Train and validate surrogate models for specific system elements
- Benchmark computational performance vs. accuracy

METHODOLOGY

PHASE 1: Interface Specification & Protocol Definition:

- **Review BB, fuel cycle, and thermal system interfaces**
- **Consolidate variable exchange requirements**
- **Define data exchange protocols and synchronization strategy**

PHASE 2: Fuel Cycle Integration

- **Develop modular interface (EcosimPro® ↔ Julia/ASPEN)**
- **Implement timestep-based exchange (co-simulation)**
- **Test with simplified extraction/purification loop models**

PHASE 3: Thermal Integration

- **Establish coupling routines (EcosimPro® ↔ RELAP5/mod3.3)**
- **RELAP5 provides temperatures → EcosimPro® updates**
- **Validate with simplified BB geometries under transient heat loads**

PHASE 4: Plasma-Edge Interface Preparation

- **Define exchange variables at first wall**
- **Ensure TRIM/SOLPS compatibility**
- **Test data exchange with synthetic inputs**

PHASE 5: Integrated Demonstration & Validation

- **Execute co-simulations for representative DEMO pulses**
- **Compare integrated vs. standalone simulation results**
- **Analyse multi-physics coupling impact**

EXPECTED OUTCOMES

TECHNICAL DELIVERABLES

Year	Deliverable
2026	**D1:** Interface Specification Report – Analysis of exchanged variables between tritium implantation (plasma) ↔ tritium transport ↔ fuel cycle ↔ thermal systems
2027	**D2:** Prototype Systems Integration: Fuel cycle (EcosimPro®↔Julia/ASPEN), Plasma-edge (EcosimPro®↔TRIM/SOLPS), Thermal profiles (EcosimPro®↔RELAP5/mod3.3)
2027	**D3:** AI/ML Exploration Report – Surrogate model development for specific system element with selection criteria and results analysis

SCIENTIFIC & TECHNICAL IMPACT

- Working prototype of integrated framework allowing dynamic co-simulation between tritium transport, fuel cycle, and thermal profiles
- Improved predictive accuracy for tritium inventories and permeation
- First demonstration of integrated Pulse Design Tool (PDT)–plasma–BB workflow
- Foundation for future extensions to plasma-edge interactions and predictive operational tools for DEMO
- Preliminary surrogate models embedded in EcosimPro® or FMUs for real-time execution

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