Artificial intelligence for
Simulation of Severe Accidents
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ERMSAR 2024

CAN MACHINE-LEARNING MAKE FAST AND ACCURATE SEVERE ACCIDENT SIMULATORS A REALITY?

INSTITUT DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Version 1 – 13/05/2024

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Summary

1. General objectives of ASSAS
2. Specifications of the simulator
3. Optimisation of ASTEC
4. Machine-learning approaches

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A basic-principles SA simulator

Desktop simulator (Westinghouse)

Need for severe accident (SA) simulators

- Education & training
- Accelerating the learning curve for SA codes
- Importing plant data from existing simulators: data-centric approach

A prototype simulator for a Western-type PWR

- Close to best-estimate accuracy
- Interfacing ASTEC and TEAM_SUITE®
- Prepare the path for more realistic simulators & other designs & other SA codes

Summary

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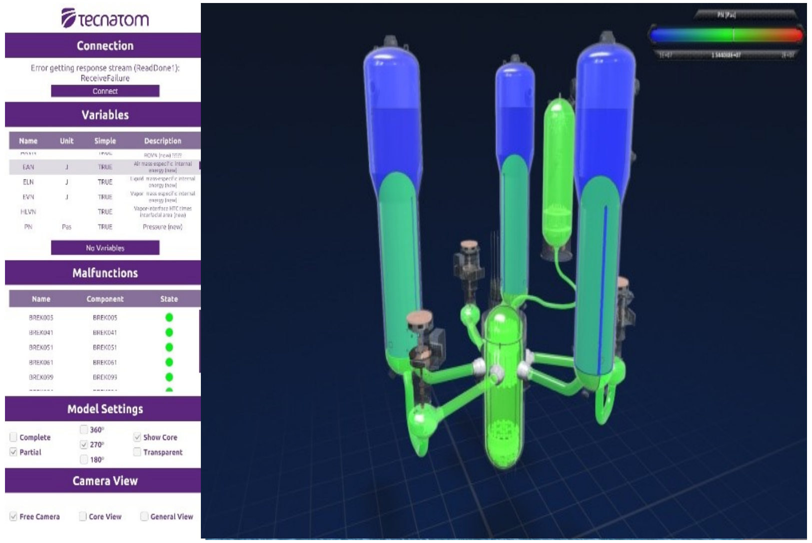
Specifications of the simulator

Showing SA phenomenology

- 2 scenarios:
  - LB-LOCA with SI failure
  - SBO with AFW failure
- Synthetic screen + virtual reality display
- Deterministic answer (no uncertainty)

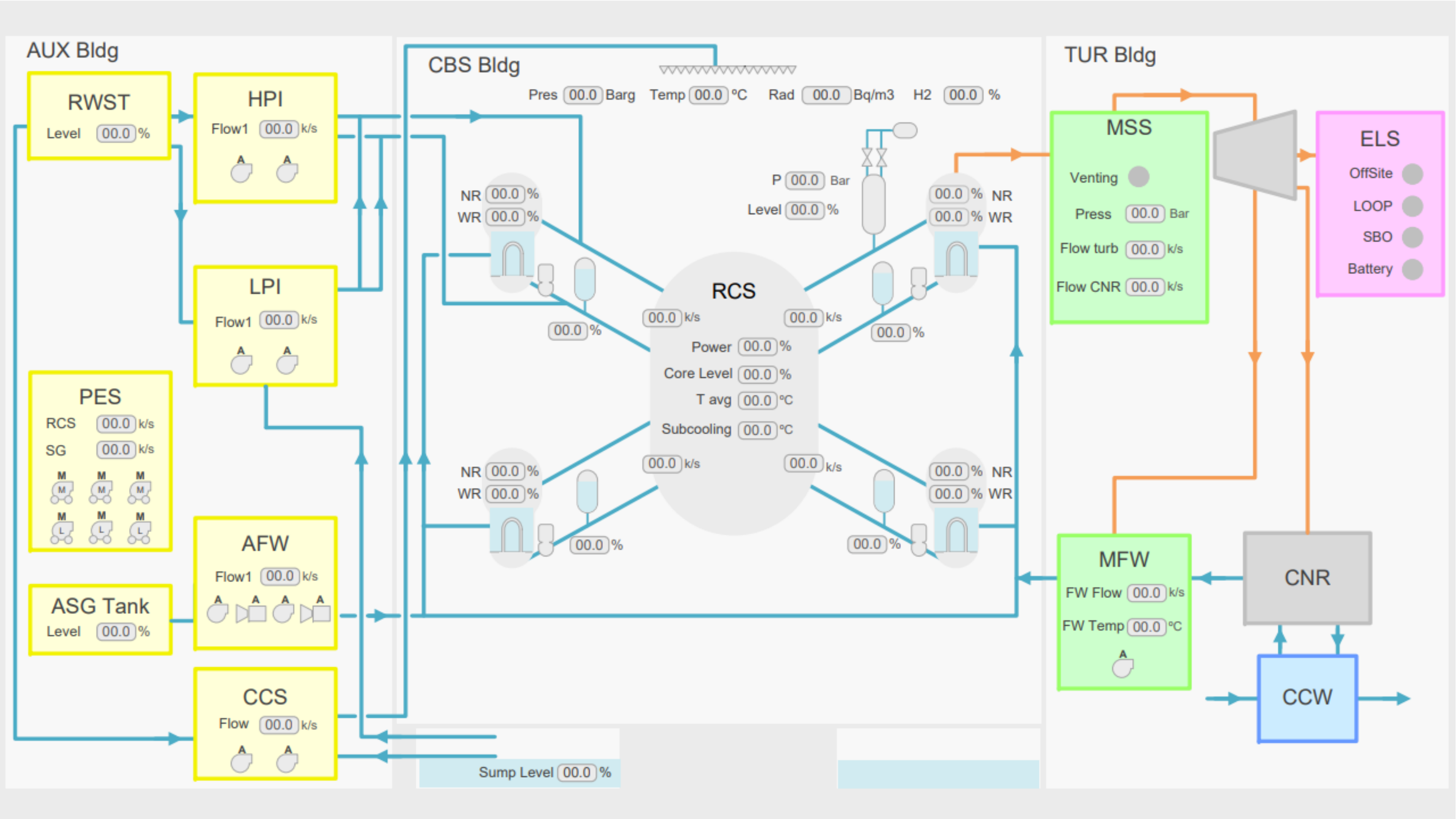


Example of virtual reality display (Westinghouse)

Running in real time or faster

- A challenge for SA codes… an opportunity to use machine-learning!
- Perspectives for fast running tools after the end of the project: uncertainty propagation, emergency response, PSA…

Specifications of the simulator



Simulator overview *SA screen* *Alarm display*

All phases of a SA:

- From initiating event to SA
- Core degradation
- Release and transport of FPs
- Vessel rupture and MCCI
- Containment pressurisation up to the filtered release of FPs
- Some phenomena are excluded: steam explosion, direct containment heating...

Ergonomic interface:

- Simulation control (speed-up factor, freeze, load...)
- Main control room sensors + pedagogical information
- Plot variables & extract data

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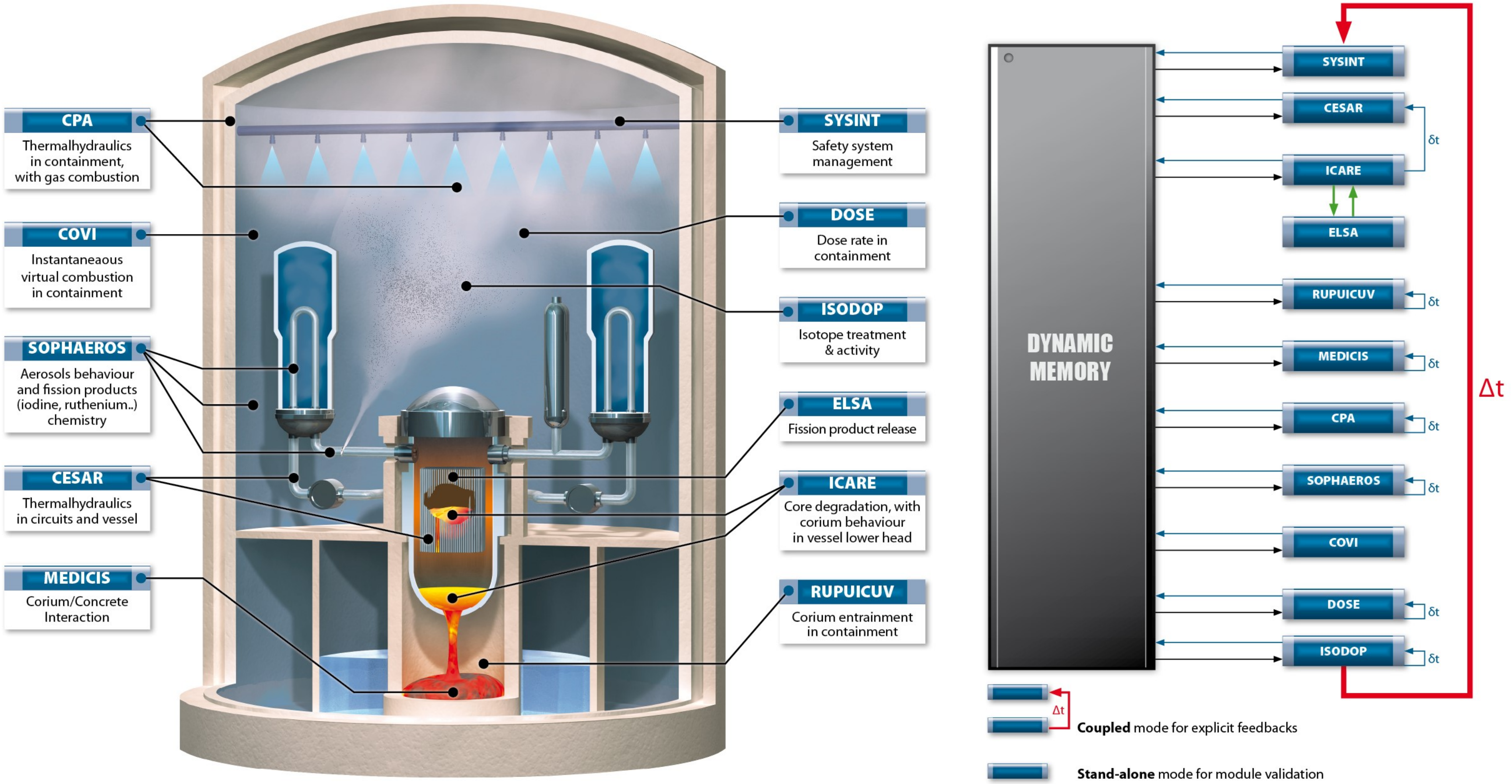
ASTEC structure



Efficient programming

Improving performances without impacting accuracy

Algorithmic improvements:

- Low-level optimisations (memory access, data management...)
- New solvers to be tested

Parallelisation:

- Sequential structure of ASTEC optimised for batch calculations (more sequences than processors) → Run only one sequence but faster
- Results obtained with OpenMP will be delivered to users in 2024

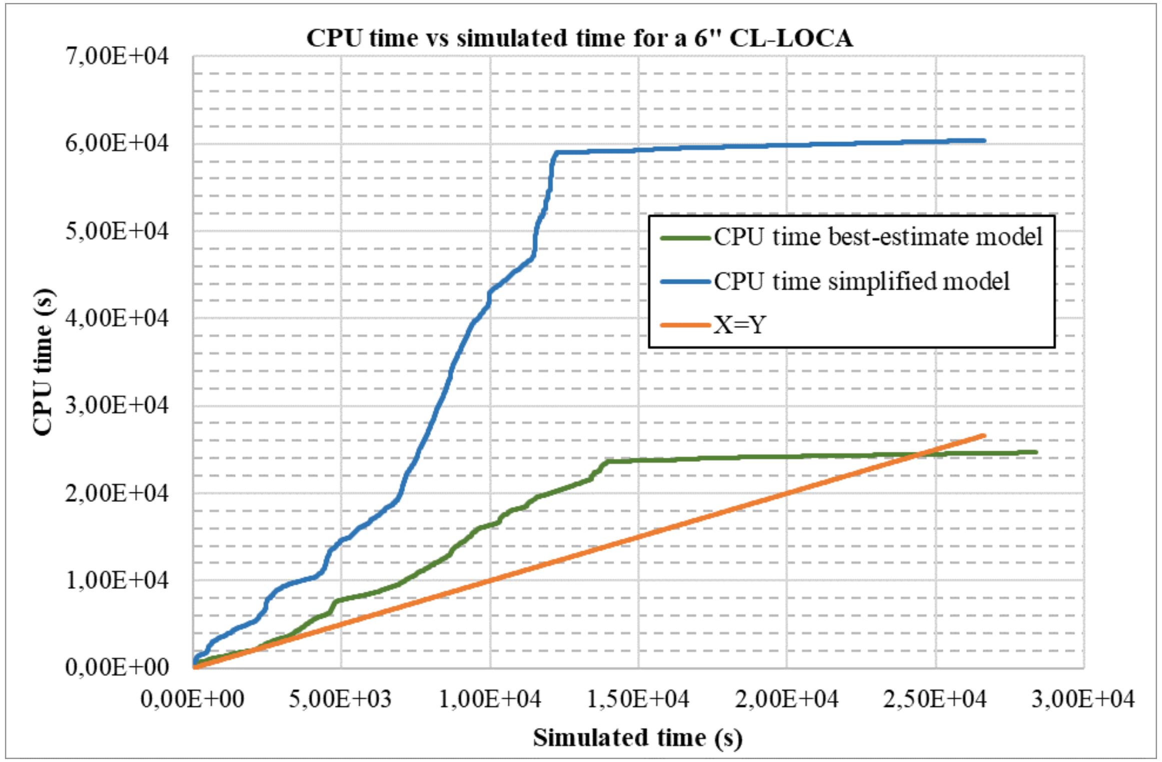
Simplification of the input deck

Simplified models

- ICARE+CESAR stop at vessel rupture
- Limited list of incondensable gases in the RCS

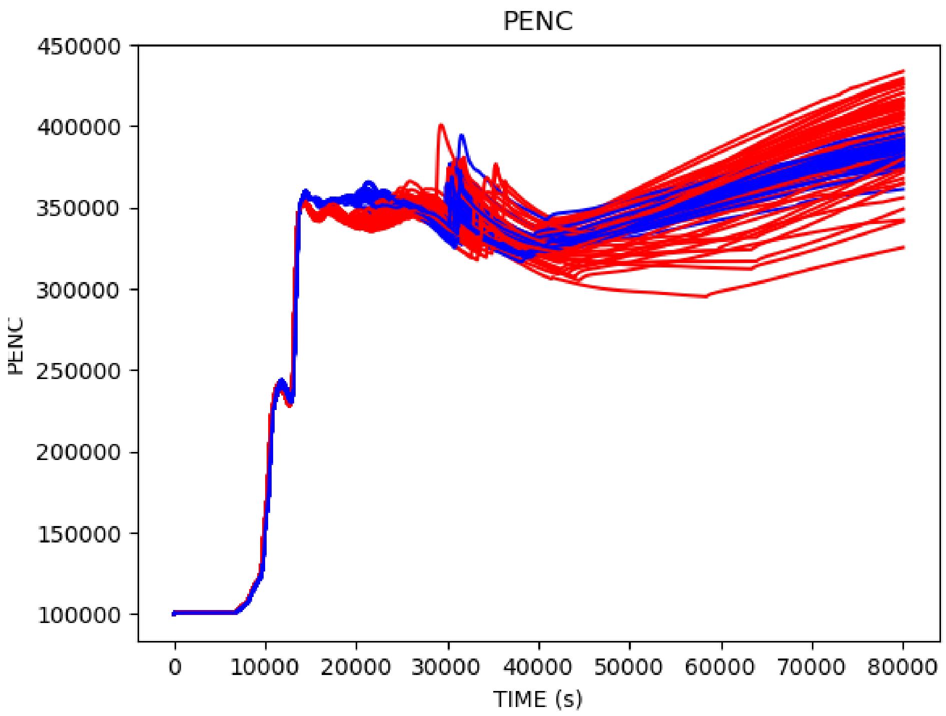
Simplified discretization

- Circuits + containment
- Acceptable results
- Higher numerical sensitivity

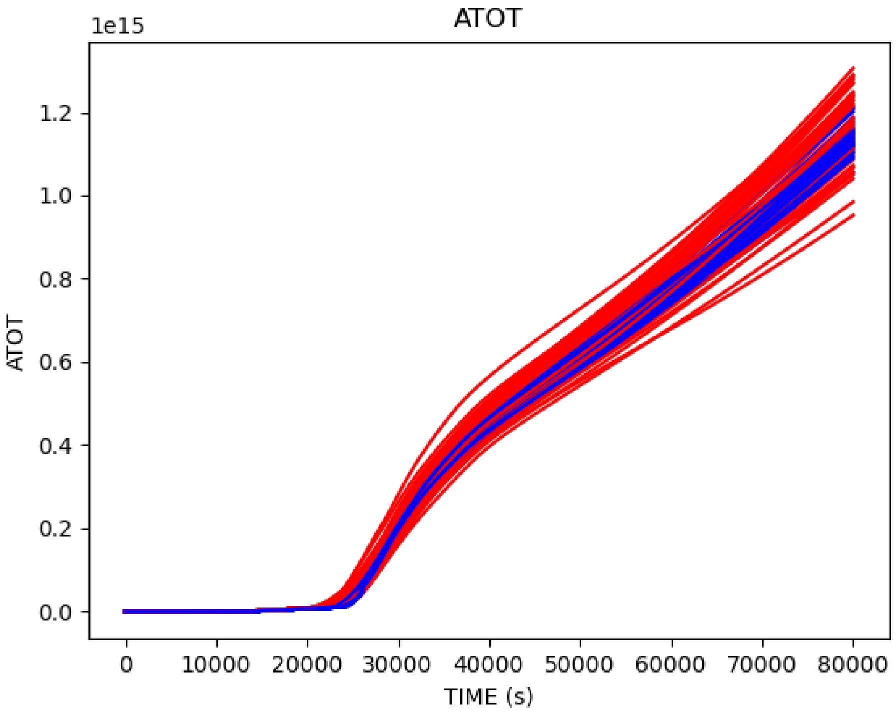


Numerical sensitivity

Numerical noise propagation with the best-estimate (blue) and simplified (red) input decks for a SBO sequence (higher sensitivity)



Containment pressure (Pa) versus time



Total activity (Bq) released to the environment versus time

Summary

Data-driven surrogate models

Machine-learning (ML) for scientific calculation

- ML can emulate complex models, like weather models
- ML learns from data: in our case, precalculated sequences
- Neural networks calculate fast, especially with GPUs

Requirements

- Computational resources to train the models
- Representative data: the amount increases with the complexity of functions and number of degrees of freedom
  - → Necessary to have trustworthy results
  - → Models will be specific to the considered design & scenarios

Global models

Replacing the SA code completely:

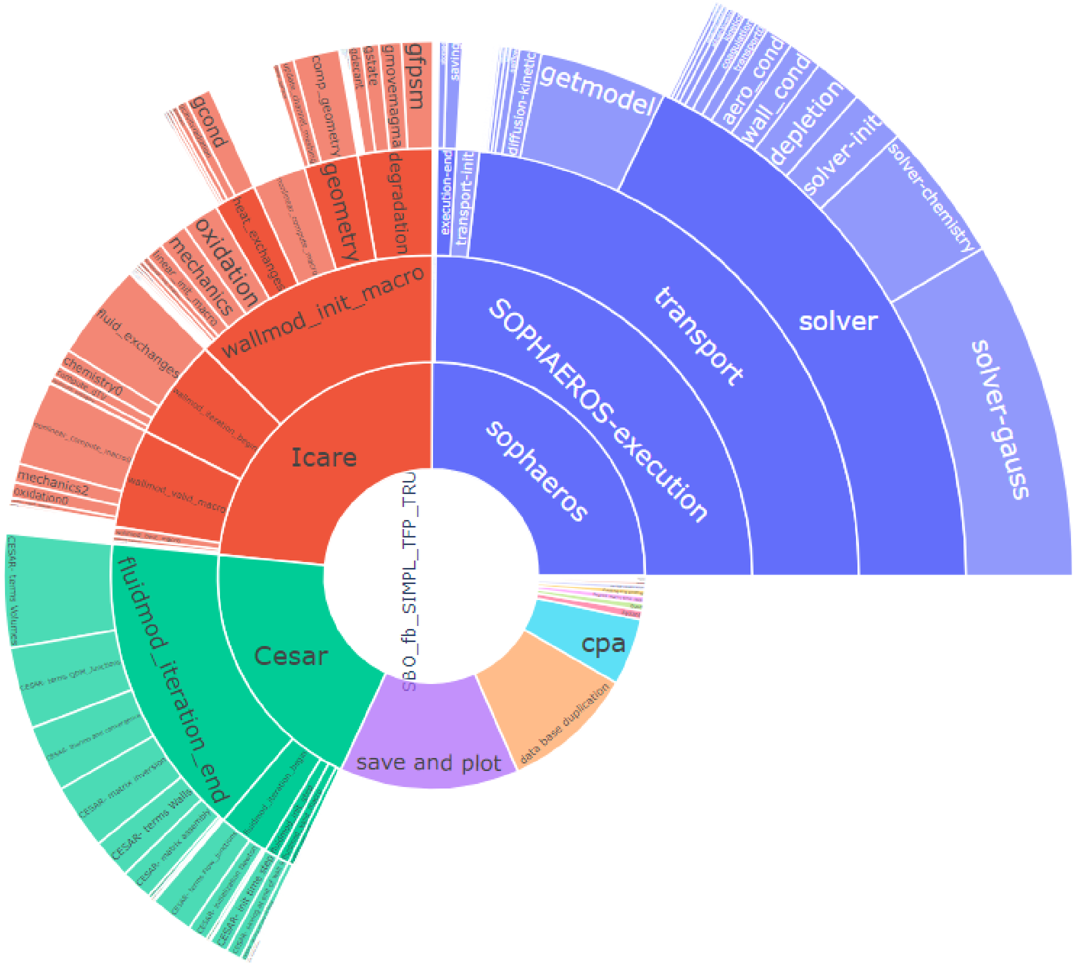
- Faster but more complex

Global containment model after the vessel rupture

- Few actions are possible during the MCCI phase
- Large variety of initial conditions after the vessel rupture
- Preferred option: time-series prediction with bifurcations at operator actions
- JSI & Energorisk for PWR-1300 and VVER-1000 designs

Melcor surrogate model: explored by KTH (BWR)

Hybrid models



Share of the CPU time required by different models of ASTEC during the degradation phase (SBO, simplified input deck)

Replacing only a part of the code

- Data exchange with physical models at each ASTEC macro time-step

→ time-stepping methods are required: error accumulation must be controlled

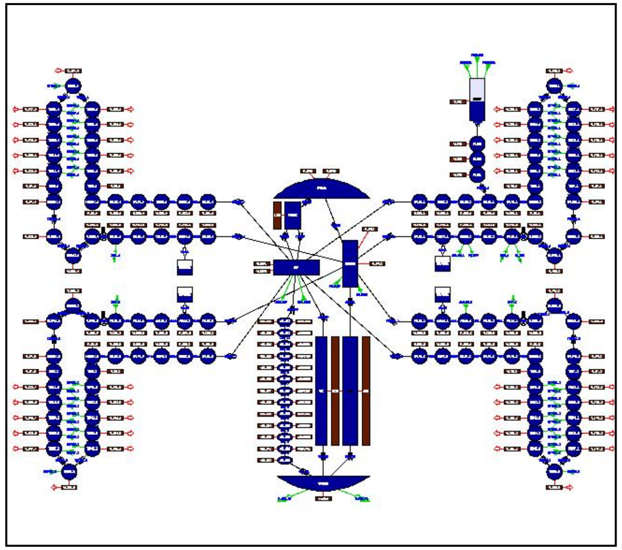
- Interface with the native code to be developed
- Speed-up factor limited to the share of the replaced model to the global CPU time

→ Worth-case scenario illustrated by the chart: 3 modules have the same computational cost

3 options illustrated in the next slides

Local thermal-hydraulic models

CESAR discretization



Objective:

- replace (part(s) of) the primary and secondary circuits by a surrogate model

Advantages

- Thermal-hydraulics is computationally intensive
- Relatively few variables to predict (flow conditions + wall temperature)

Challenges

- Smaller time resolution than the native model (macro time-step vs. CESAR micro time-step)
- Numerous combinations of operator actions on safety systems

CESAR solver initialisation

Accelerate the Newton-Raphson algorithm of the solver

- A gradient descent is used to solve the non-linear system of equations.
- The algorithm is initialised with the converged solution of the previous timestep.
- The ML model should predict a first guess of the solution, to reduce the number of iterations to reach convergence.

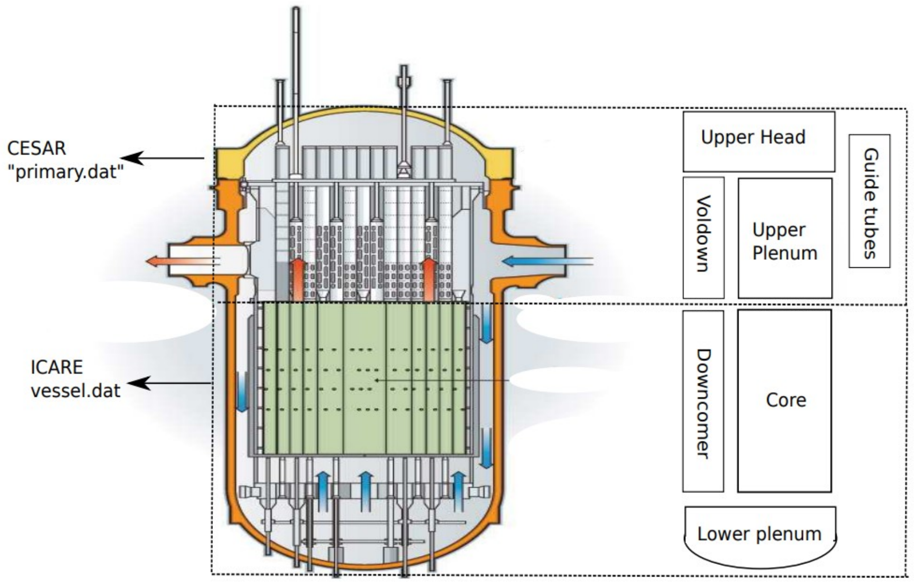
Advantages:

- Same accuracy as physical models
- Easy implementation

Challenges:

- Few examples in literature using ML
- Impact on the computational time to be evaluated

Primary vessel model



ASTEC Vessel model

Replacing ICARE + CESAR in the vessel

Advantages

- Modelling thermal-hydraulics and core degradation together to account for their strong coupling
- Possibly a higher generalisation capacity since no safety system is directly connected to the vessel

Challenges

- Number of variables and number of meshes to consider: high dimensionality
- Complexity of physical models

Conclusion

A simulator to make SA knowledge more accessible

Improving ASTEC's performances for a real time execution

Explore different ML strategies (possibly in combination) to reach higher acceleration factors

Share a high-quality database for future collaborative work

- The ASSAS training database will be openly accessible for reuse:

→ International nuclear ML benchmark

→ Applications for emergency response

List of authors

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assas

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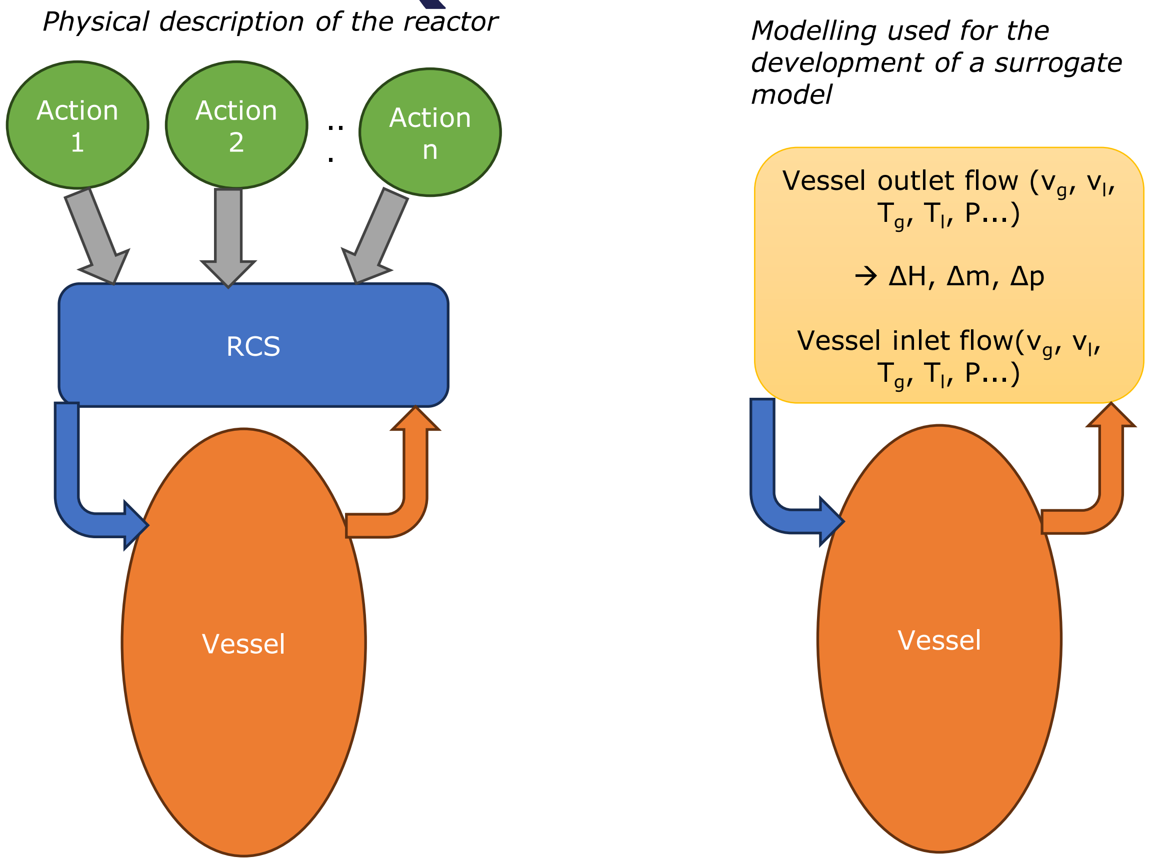
Primary vessel model (alternative slide)



Schematic description of the modelling strategy: The RCS is considered as a black-box modifying mass, momentum and enthalpy of the fluid, whatever the operator actions are.

Replacing ICARE + CESAR in the vessel

Advantages

- Consider the coupling between thermal-hydraulics and core degradation
- Possibly a higher generalisation capacity

Challenges

- Number of variables and number of meshes to consider: high dimensionality
- Complexity of physical models