DE LA RECHERCHE À L'INDUSTRIE

cea den

Direction d l'Energie Nucléaire
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Shapley indices estimation in multi-physics nuclear transient modeling

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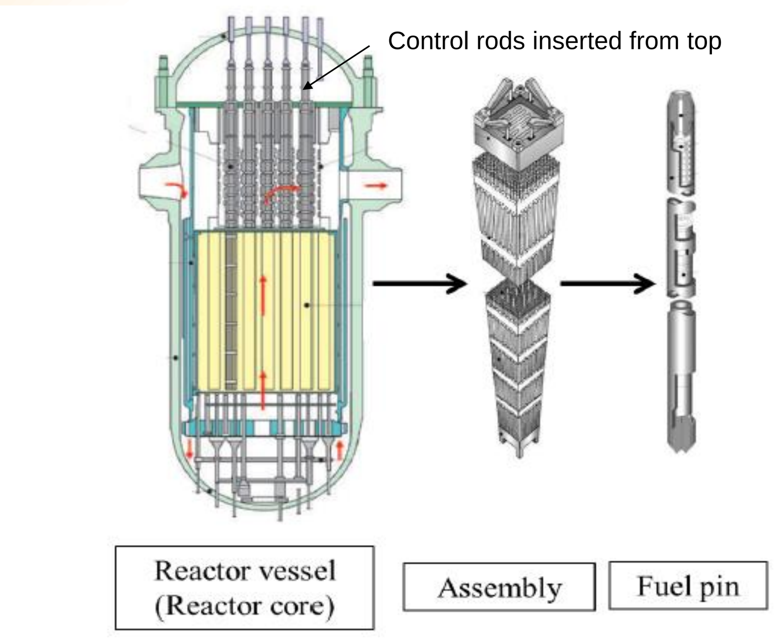
GENERAL CONTEXT

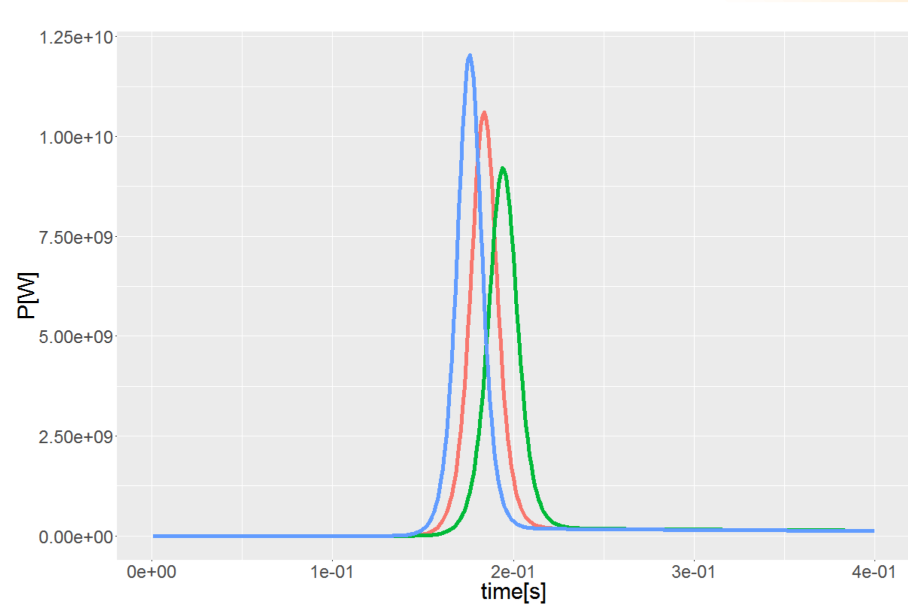
1 Pressurized Water Reactor



- Power generation: 1300MWe
- Lifetime: 40-60 years
- Pressure: 155 bar
- Fuel: 3-5% enriched UO_2
- Water temperature: 290-325 ^oC
- 200 fuel assemblies of 264 fuel pins and 25 control rod guides

2 Rod Ejection Accident (REA)

- Mechanical failure → control rod ejection in 0.1s
- Peak creation due to Doppler thermal and moderator feedback
- Strong multi-physics effects that can lead to severe reactor damage



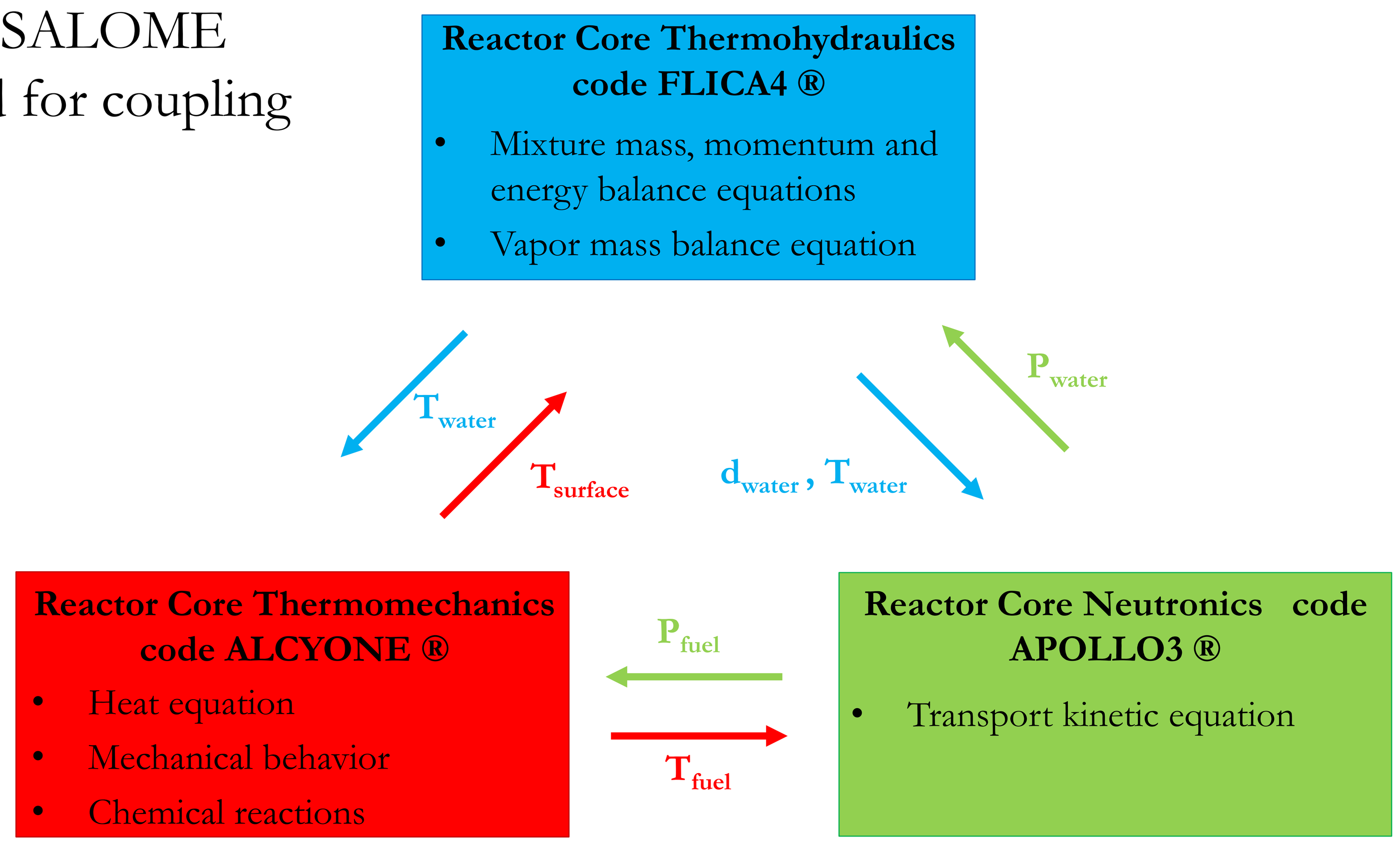
3 Academic Core Design

REFL	REFL	REFL	REFL	REFL
REFL	UO2	UO2	UO2	REFL
REFL	UO2	UGD12	UO2	REFL
REFL	UO2	UO2	UO2	REFL
REFL	REFL	REFL	REFL	REFL

- Uncertainty analysis on an academic core to capture the main phenomena
- 3x3 fuel assemblies core at zero power
- Control rod ejection in central assembly
- Homogenization at assembly level
- Axial power deformation due to Xe concentration (penalized scenario)

4 Coupling Modelling

- CORPUS/SALOME tool is used for coupling



EXERCISE

5 Exercise details

- APOLLO3® –FLICA4 coupling with 2 group diffusion approximation in APOLLO3® and simplified thermal model in FLICA4

NEUTRONICS		FUEL-THERMAL		THERMAL-HYDRAULICS	
Inputs	Output	Inputs	Output	Inputs	Output
Total cross-sections (T_1, T_2)	Maximum local linear power during REA (P_{max})	Fuel specific heat capacity (Cp_f)	Maximum local stored enthalpy in fuel during REA (h_{max})	Convective heat transfer coefficient (CT)	Minimum local DNBR during REA ($DNBR_{min}$)
νxFission cross-sections (NF_1, NF_2)		Cladding thermal conductivity (λ_c)		Recondensation model (RT)	
Diffusion coefficients (D_1, D_2)					
Scattering cross-sections ($S_{1\to1}$, $S_{2\to1}$, $S_{1\to2}$, $S_{2\to2}$)					
Neutronic inputs are correlated , while the rest inputs are independent					

- Monte Carlo uncertainty propagation and sensitivity analysis using Shapley indices

6 Shapley Indices

- For model: $Y = F(X)$, $X \in R^d$
- $K = \{1,2\ldots d\}$, π a permutation of the indices in K and $P_i(\pi)$ the set containing all the variables preceding i in π
- For $J \subseteq K$ the cost function is defined as the expected remaining variance of the output if all variables except the ones in J are fixed

$$c(J) = E[Var(Y|X_{\sim J})]$$

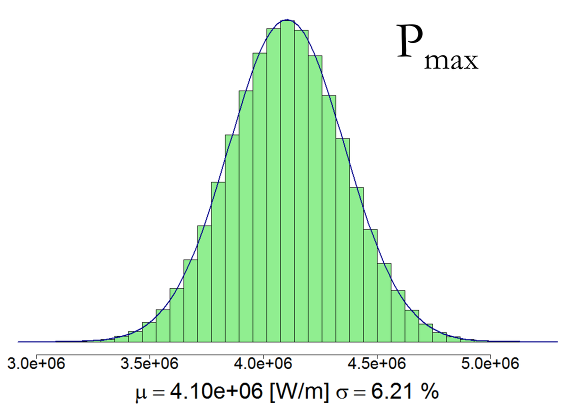
- The cost function is estimated by two loop Monte Carlo simulations
- N permutations are randomly generated

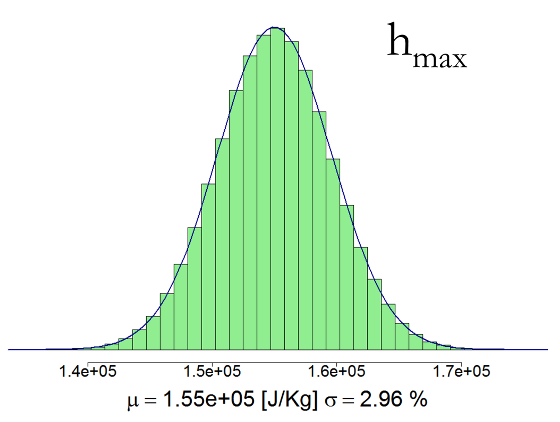
$$\widehat{Sh}_i = \frac{1}{N}\sum_{r=1}^{N} \hat{c}(P_i(\pi_r) \cup \{i\}) - \hat{c}\big(P_i(\pi_r)\big)$$

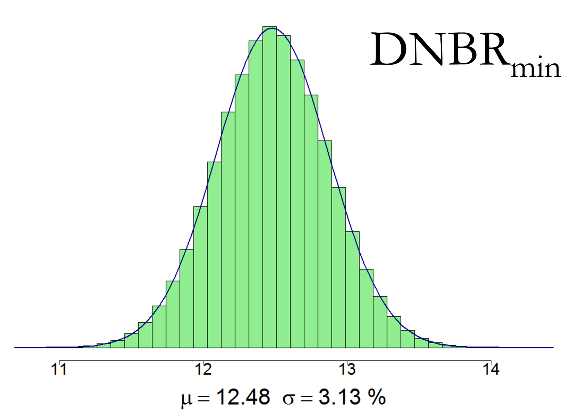
RESULTS

7 Uncertainty propagation

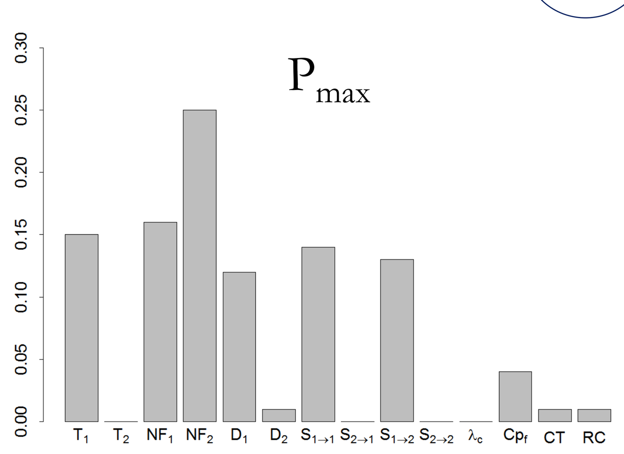
- Model close to linear, something expected by the simplifications in the coupling
- Relative standard variations of 6.21% , 2.96% and 3.13% for P_{max} , h_{max} and $DNBR_{min}$ respectively



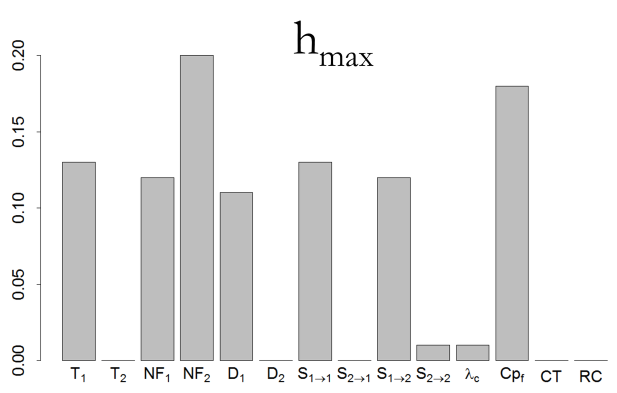


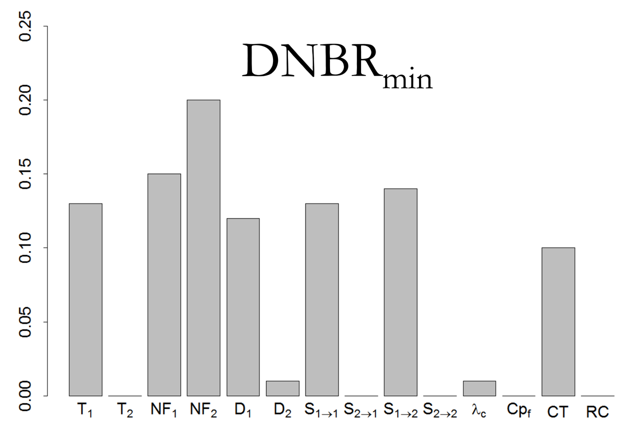


8 Sensitivity analysis



- T_1, NF_1, NF_2, D_1, $S_{1\to1}$, $S_{1\to2}$ are important for all outputs
- Cp_f is important for h_{max} and P_{max}
- CT is important for $DNBR_{min}$





PERSPECTIVES

- Study full coupling using ALCYONE code for Fuel-Thermal modeling (very time consuming) with all the uncertain input variables
- Use larger core design, with possibility of spatial cross-sections correlations
- Create a methodology to perform uncertainty analysis on transient nuclear calculations

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