Neutronics computations in support of the CABRI core safety analysis

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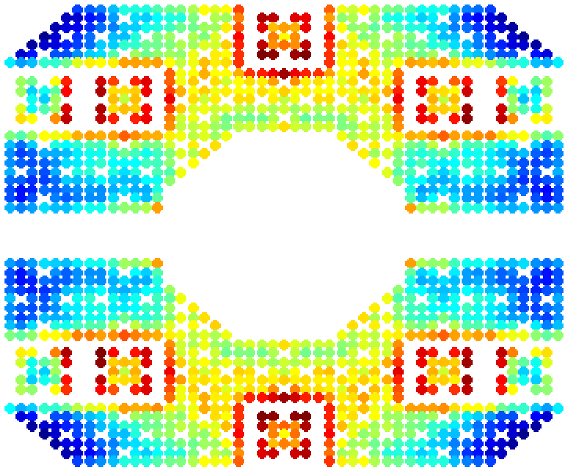

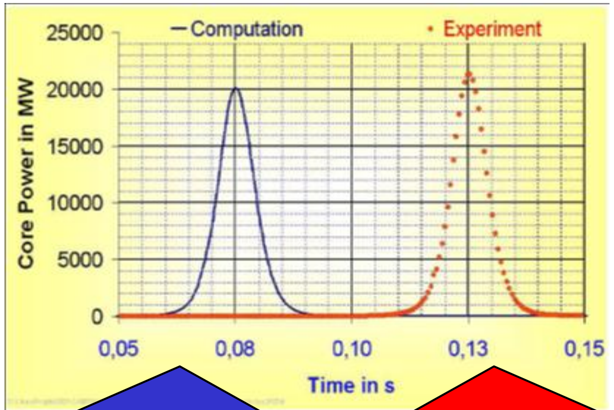

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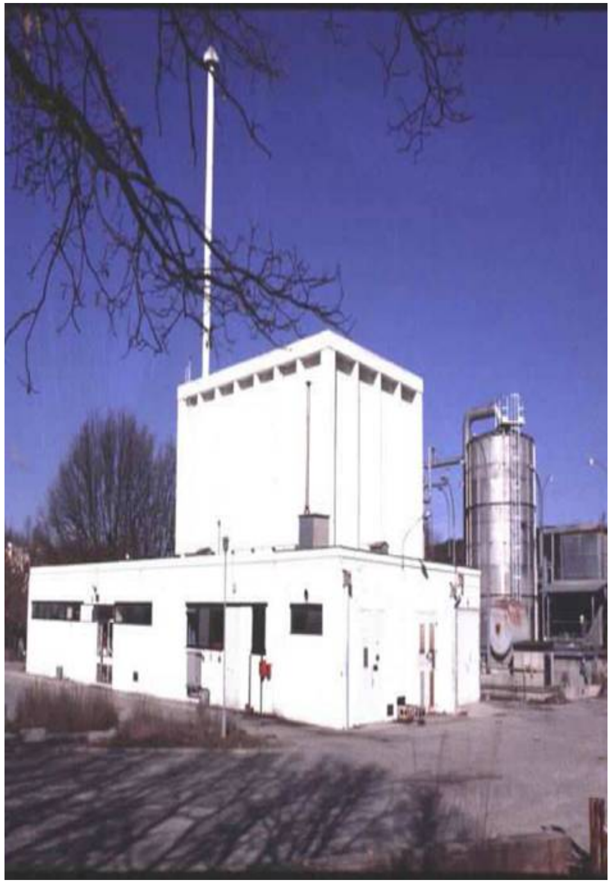
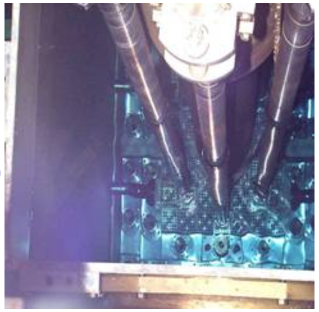
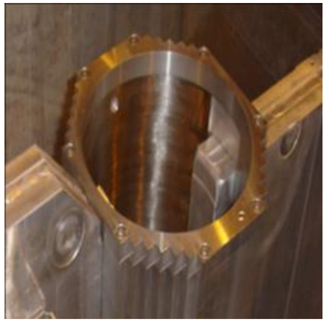


Economic and Safety issues

CABRI is an experimental reactor, operated by the CEA and devoted to safety programs.

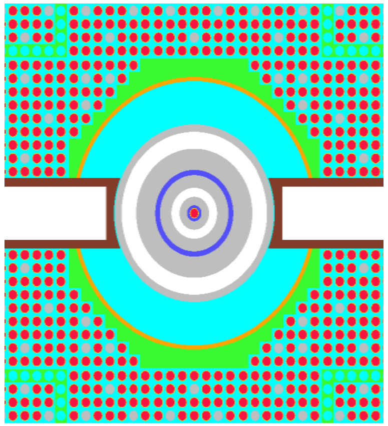


- **Historically:** Improve the fuel behavior knowledge (RIA&LOCA)
  - **Most of the experiments were dedicated to fast reactors**



- **2003:** Installation shut down for renovation
  - **Sodium cooled experimental loop → pressurized water loop: The main goal is to meet thermal hydraulics parameters identical to LWR.**

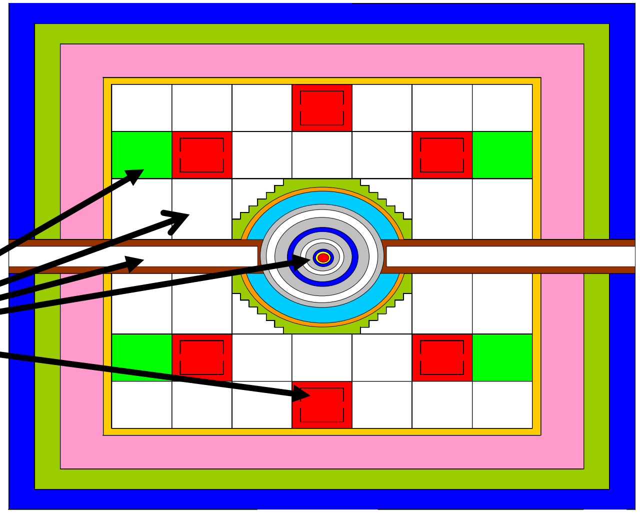
- **2008:** Safety report for the new configuration

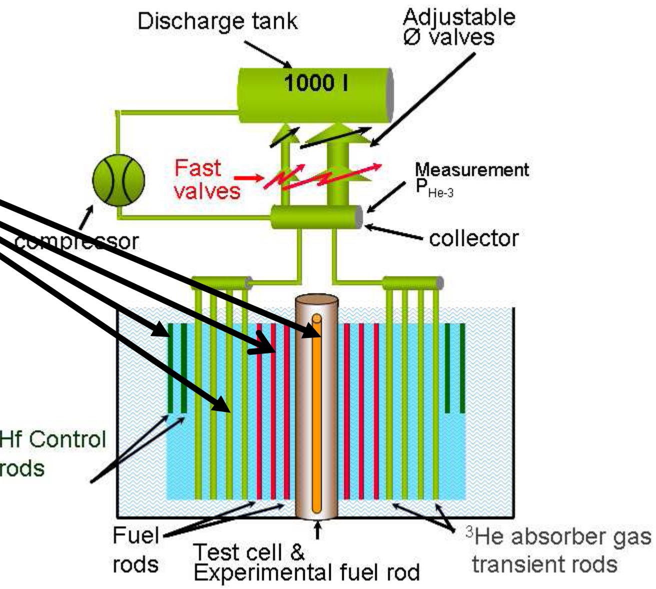


- **2010:** Commissioning tests & start-up

CABRI is a pool-type reactor.

[illegible]





Pressurized Helium tubes
(maximum allowable pressure is 15 bars)

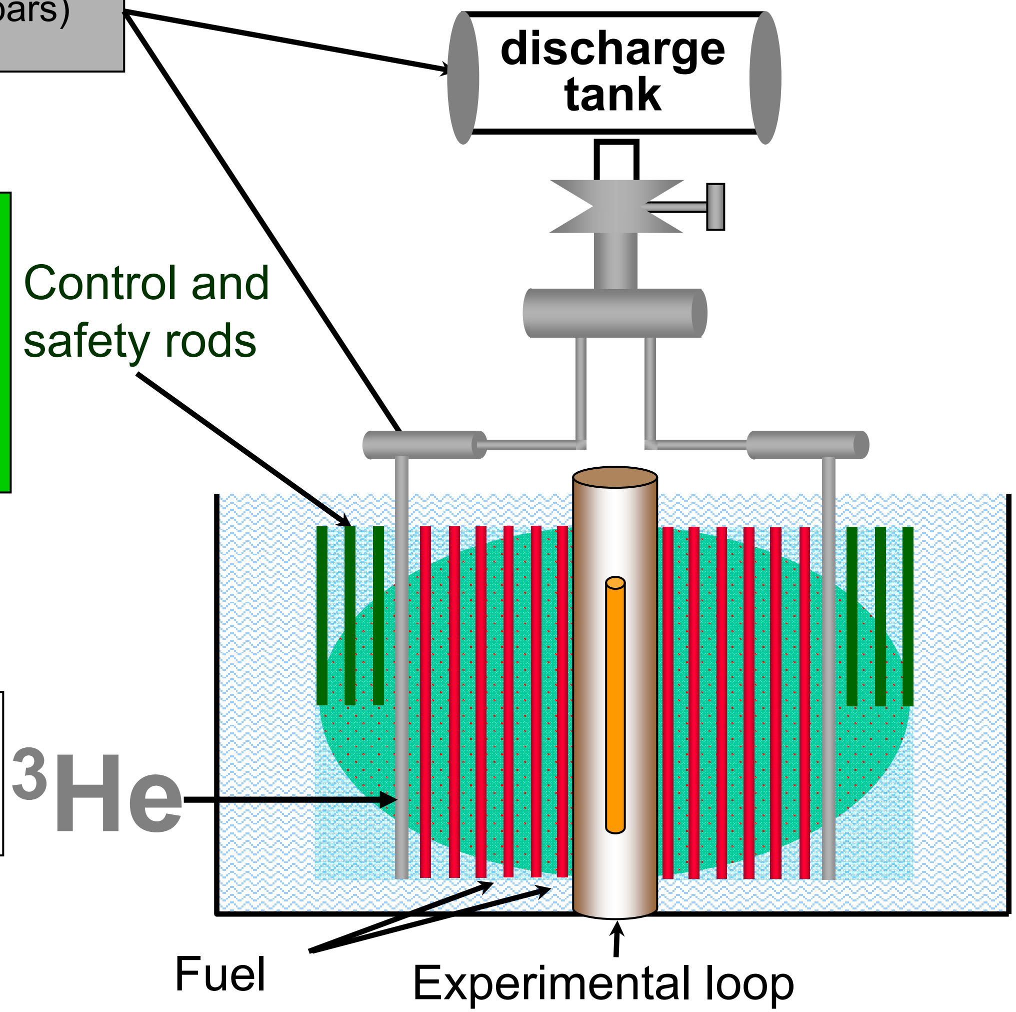
Control rod (Hf) withdrawal

The critical state is obtained by control rod withdrawal to compensate the 3He antireactivity.

For different helium pressures, TRIPOLI4 predicts the critical position with a good accuracy

Fast ejection of 3He

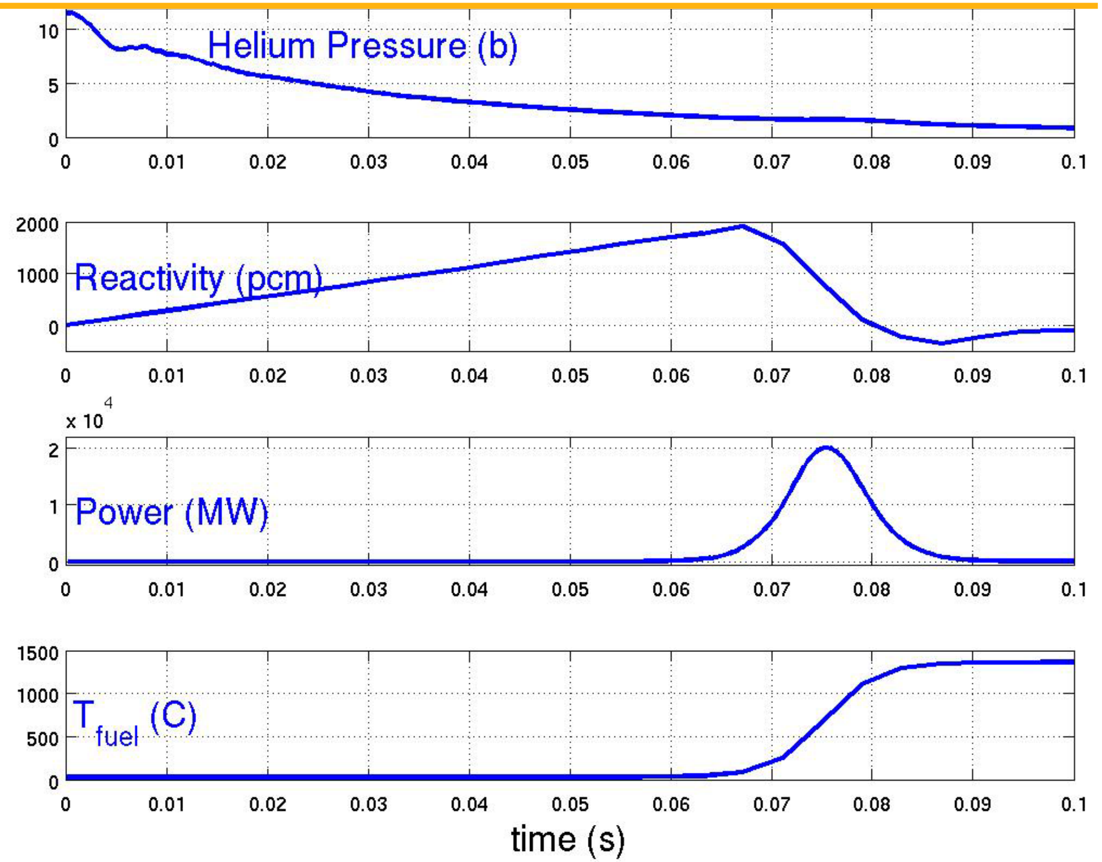
after opening of the circuit valves



Phenomenology of the experiments

t < 0.1 s. (adiabatic)

- Valves opening
- ^{3}He depressurization
- ↑ reactivity (3-4 $)
- ↑ Power (0.1 à 20000MW)
- ↑ T_{fuel} (> 1500 °C)
- Doppler Feedback
- New equilibrium state
  (reactivity = 0 , new fuel T°)



t > 0.1s.

- T°clad, T°coolant increase
- Minor "Delayed" feedback

Neglected

Automatic shutdown ~0.1 – 0.2 s.

by dropping all the control rods

→ End of the transient

What was the problematic in the safety report (2008)?

Evolution of the installation (Na loop replaced)

The last characterization of the core was made 30 years ago

FNSA

Model validation to predict the energy release for future experiments

CEA

Transient consequences are connected to:

- kinetics parameters (β_{eff},Λ_{eff})
- Doppler coefficient

Re-evaluation with 3D reference code

Neutronics characterizations in CABRI core by MC calculation

Doppler coefficient

Using the reactivity determined at different fuel temperatures by the TRIPOLI4 code:

$$\Delta\rho^{\text{doppler}}(t) = A_D.\sqrt{\Delta T} \approx 103\ pcm.K^{-0.5}$$

Effective generation time (Λ_{eff})

Using a method based on perturbation theory with MC calculations.

The results are compared with experimental measurements and deterministic computations.

	Expected values	MCNP results
MASURCA (MUSE4 experiment)	56 ± 5 μs	53 ± 5 μs
OSIRIS (deterministic calculation)	34.7 ± 2 μs	34.0 ± 1.1 μs
JHR (deterministic calculation)	36.0 ± 2 μs	38.7 ± 1.4 μs

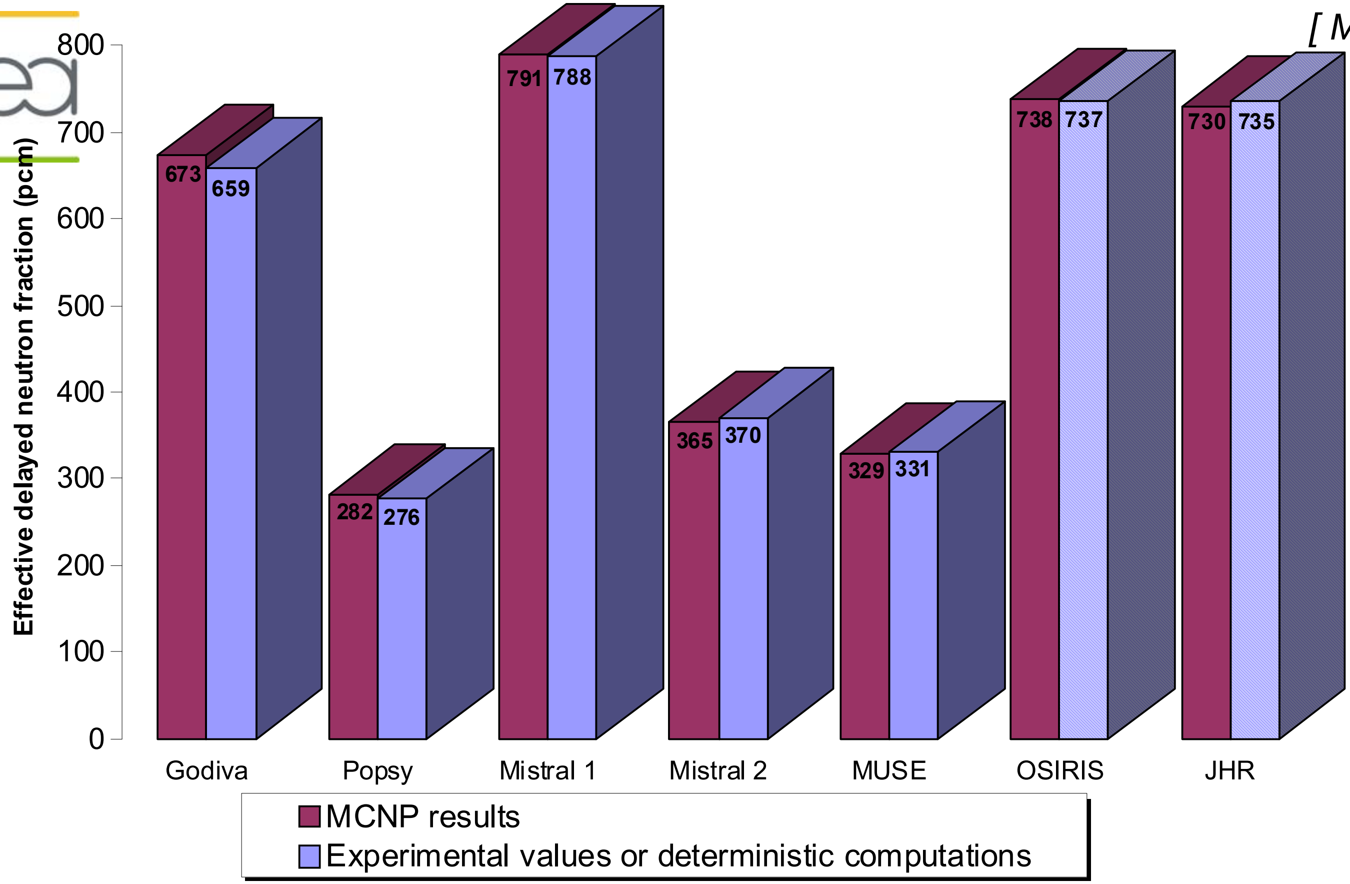
Agreement MCNP results / expected values allows us to trust this method

The application to CABRI core (JEFF-3.1 library) : $\Lambda_{eff} = 27.7 \pm 2\,\mu s$

Effective delayed neutron fraction (β_{eff})

Using a method based on iterated fission probability and available in a MCNP patch

[Meulekamp, Van Der Mark NSE vol. 152 – 2006]

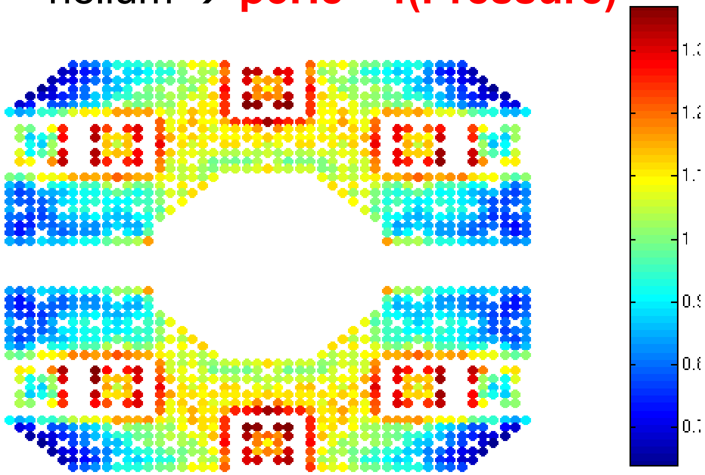


Consistent with deterministic computations & Experimental results C/E < 1.022 ± 0.004

The application to CABRI core (JEFF-3.1 library) : $\beta_{eff} = 758 \pm 2\,pcm$

A test is characterized by the injected Helium reactivity

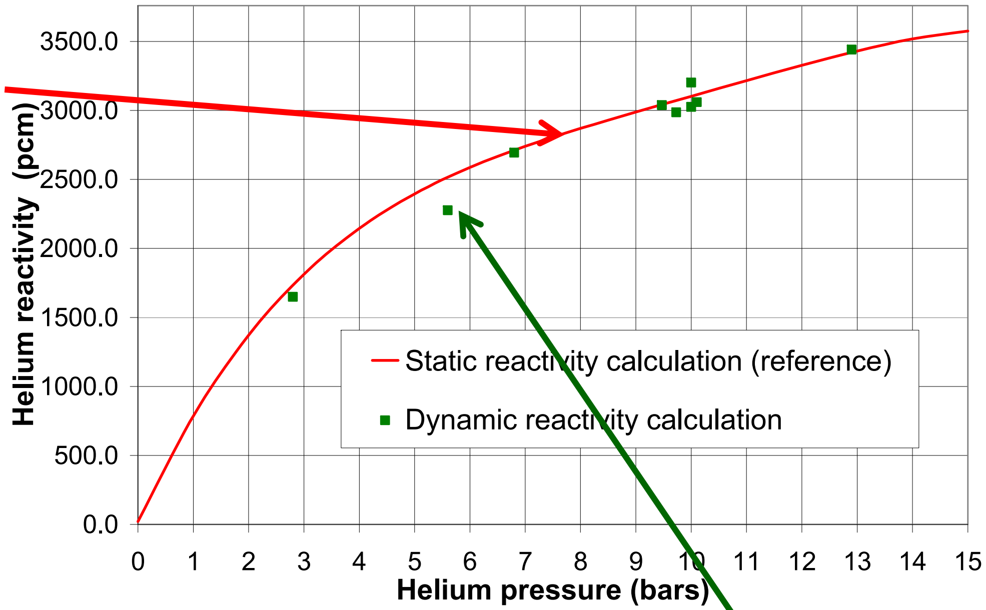
Static calculations with and without helium → **ρ3He = f(Pressure)**



Confident in this result because:

✓ TRIPOLI4 is a reference code and helium 3 cross section are well known

✓ TRIPOLI4 reactivity calculations are validated (for different helium pressure, the predicted critical position by the code is always consistent with the experimental data)



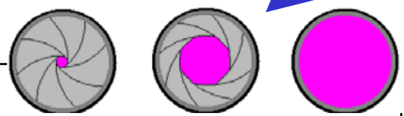
Dynamic Calculations (using β_{eff}, Λ_{eff}, Doppler)

Experimental power bursts obtained in the past can be interpreted by inverse kinetics. One can determine the injected helium reactivity for different tests (performed at different helium pressure) → ρ^{3He} = f(Pressure)

The 2 independent methods are consistent → the kinetic model is validated

Predictive methodology definition

- Problem: to simulate the pulse power, the model need an input data: Reactivity (t).
- Principle: To evaluate $\rho(t)$ the phenomena are decoupled: $\rho(t)$ is dependent on



The valve aperture

determines the kinetics of depressurization (sonic flow): $P(t) \propto 1/(1+Bt)^5$

Initial pressure

determines the integral reactivity (Static computations)

β, l, Doppler feedback

$P_{He\text{-}3}(t) \otimes \rho(P_{He\text{-}3}) \Rightarrow \rho(t)$

Kinetic model

Power(t), Energy(t)

Prospective methodology validation

To assess the accuracy of the predicted energy values, the methodology is applied to the simulation of several tests performed in the past

Test	Energy Measurement (MJ)	Energy Prediction (MJ)	Discrepancy (%)
Test 1	209	195	-6
Test 2	204	197	-3
Test 3	212	199	-6
Test 4	213	203	-4
Test 5	224	227	1
Test 6	172	176	2

Maximum Discrepancy ~ 6%

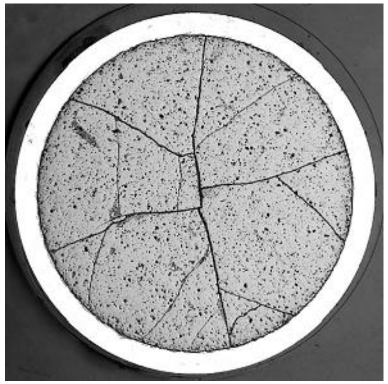
Good agreement between measured and predicted energy better than 6%.

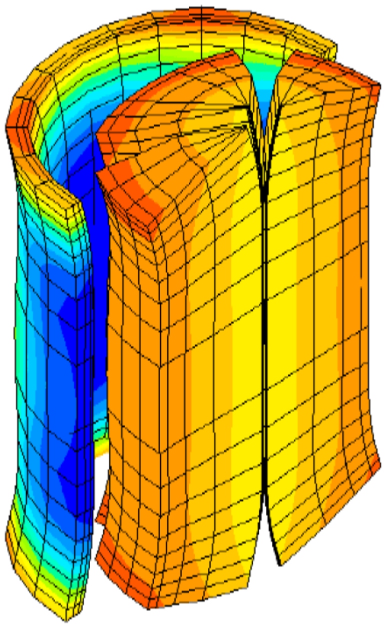
The same predictive approach is used to characterize the energy release during the most severe possible accident

	Peak Power (GW)	Energy release (MJ)
Reference Accident 15 bars-valves at full aperture	38.6	382 *+6% → 403*

Thermo-mechanical computations

SCANAIR code (provided by IRSN)





• attests that the consequences are acceptable to both fuel and cladding.

Conclusion

Reevaluation

✓ **The main neutronics parameters driving a power pulse were re-evaluated by 3D Monte Carlo reference codes.**

Validation

✓ **The code including thermal and point kinetics models is validated.**

Predictive methodology

✓ **The comparison between predictions and experimental results shows the model predictions are better than 6%.**

Safety assessment

✓ **This model is used to assess the power and energy release during the reference accident of the CABRI facility: computations attest the fuel and cladding integrity during the transient.**

Thank you for your attention

ANNEXE 1 : Calcul du β_{eff}

$$\beta_{eff} = \frac{\langle \Phi^* \chi_d \nu_d \Sigma_f \Phi \rangle}{\langle \Phi^* \chi \nu \Sigma_f \Phi \rangle}$$

Dans un calcul Monte-Carlo : Pas de modèle physique, pas d'équation : la notion de flux adjoint Φ^* (ou d'importance neutronique) n'existe pas.

Alternatives :

- On supprime Φ^* → on calcule β_0 (~ environ 10 % inférieur à β_{eff})
- Méthode prompte : approximation $\Phi = \Phi_p$ et $\Phi^* = \Phi^*_p$ → $\beta_{eff} \cong 1 - \frac{k_p}{k}$

  avec $k_p = k_{eff}$ si $\chi = \chi_p$ et $\nu = \nu_p$.
- Méthode NRG→ on estime Φ^* par IFP ou plus précisément NFP : MCNP stocke la « longueur d'histoire » afin de restituer la notion d'importance.

Calcul MCNP CABRI – bib. JEFF3.1	
β_0	716 pcm
β_{eff} (méthode prompte)	762 pcm
β_{eff} (méthode NRG)	758 pcm

Calcul du temps de génération (l_{eff})

$$\Lambda_{eff} = \frac{\left\langle \Phi^*, \frac{1}{v}\Phi \right\rangle}{\langle \Phi^*, F\Phi \rangle}$$

Théorie des perturbations : $\Delta\rho = \frac{\langle \Phi_0^*, [\lambda_0 \Delta F - \Delta K]\, \Phi_1 \rangle}{\langle \Phi_0^*, F_1 \Phi_1 \rangle}$

Cas particulier : ajout uniforme d'un poison de section efficace microscopique de capture en c/v

- $\Delta K = c/v$: l'absorption se rajoute aux causes de disparitions des neutrons ;
- $\Delta F = 0$: pas de modification de l'opérateur production.

$$\Delta\rho = \rho_c - \rho_0 = -\frac{\left\langle \Phi_0^*, \frac{c}{v}\Phi_c \right\rangle}{\langle \Phi_0^*, F_0 \Phi_c \rangle}$$

$$\left(\frac{\partial\rho}{\partial c}\right)_{c=0} = \lim_{c \to 0} \frac{\rho_c - \rho_0}{c} = \lim_{c \to 0} \frac{1}{c} \frac{\left\langle \Phi_0^*, \frac{c}{v}\Phi_c \right\rangle}{\langle \Phi_0^*, F_0 \Phi_c \rangle} = \frac{\left\langle \Phi_0^*, \frac{1}{v}\Phi_0 \right\rangle}{\langle \Phi_0^*, F_0 \Phi_0 \rangle}$$

$$\Lambda_{eff} = -\frac{\Delta\rho}{c}$$

Compromis : c doit tendre vers 0 tout en permettant une précision statistique sur $\Delta\rho$ suffisante. « Verboomen et al. » préconisent $\Delta\rho$ ~ 300 pcm

Rq :le temps de génération est accessible avec T4 (conforme à MCNP)

Doppler coefficient

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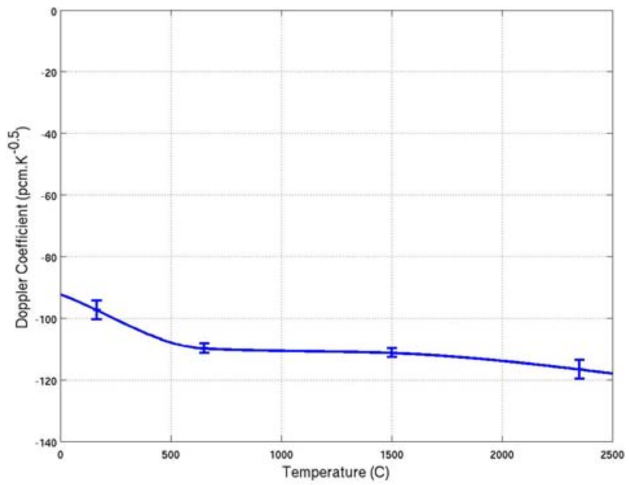

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