SIMULATIONS OF SFR NEUTRONIC TRANSIENTS FOR CHOSEN MECHANICAL SCENARIOS.
The aspects studied during my internship in CEA Saclay will be presented.

2 major topics are involved:

- Methodology for coupling of mechanical and neutronic simulations (deformed geometry).
- Selected mechanical excitation scenarios applied to the test fast core model and corresponding neutron responses.

Mechanical part → Cast3M, 
neutronic calculation → Cast3M Neutronic Tool (by Cyril PATRICOT)
Sodium-cooled Fast Reactor is an example of nuclear system operating on neutron flux spectrum and belonging to Gen4 designs.

Compact cores are relatively sensitive to geometrical deformations, that is why tools for neutronic-mechanical coupling are important.

Our attention is focused on the reactor core model which undergoes various mechanical scenarios of short timescale (<1 s).
I. Mechanical calculation
   I.1. Numerical and physical model
   I.2. Mechanical test scenarios

II. Neutronic simulation
   II.1. Description of diffusion neutron solver
   II.2. Results - power evolution in system

III. Summary and prospects for the upcoming studies
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The considered geometry comprises a beam of assemblies located on the diagrid.

The core is surrounded by the lateral neutronic protection (PNL) and immersed in sodium coolant (at rest).
The system is modeled using finite elements method (FEM).

Structures are treated as hexagonal bundle of beams that may collide (+impact stiffness).

The behavior of the structures takes into account behavior of coolant → Fluid-Structure Interaction (FSI).

Perfect fluid + little displacements → Linear Euler Equations

\[ \rho \ddot{X}_L = -\nabla \cdot P \]
\[ P = -\rho c^2 \text{div} \dot{X}_L \]
\[ \dot{V}_L \cdot \vec{n} = \dot{V}_S \cdot \vec{n} \]

Dissipation of fluid energy → Rayleigh damping.

Homogenization of fluid → reduced size of the problem.

Displacements and rotation only in XY direction.
Numerical equations derived in (U,P,φ) formulation.

Introduction of additional variable → symmetrical matrices

\[ \ddot{\phi} = P \]

The final homogeneous equations governing simulation:

\[
\begin{bmatrix}
M + M^* & 0 & -C + JC' \\
0 & 0 & -A(\Omega_L/\Omega_T) \\
-C + JC' & -A(\Omega_L/\Omega_T) & -(1-J)G
\end{bmatrix}
\begin{bmatrix}
\ddot{X}_S \\
\ddot{p} \\
\ddot{\phi}
\end{bmatrix}
+\begin{bmatrix}
K & 0 & 0 \\
0 & A(\Omega_L/\Omega_T) & 0 \\
0 & 0 & P
\end{bmatrix}
\begin{bmatrix}
X_S \\
p \\
\phi
\end{bmatrix}
= \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\]

Acceptable computational cost for whole-core simulation (~several hours)
Injection of 100 L at the bottom of core.

- Injection time 0.05 s
- Located at central fuel assembly
- Simulation time of 0.25 s

Weak seismic excitation

- Frequency of 1 Hz
- Amplitude around ~1 cm or less
- Acceleration applied to all elements
- Simulation time of 0.8 s
Variation of fuel volume

Radial displacements of assemblies (compression – red, departure – green)

Time steps of 0.025s →
MECHANICAL RESULTS: LIQUID INJECTION (2)

- Pressure variation in system

- Displacement of assemblies at the top

![Graph showing displacements with offsets (top of assemblies)]
**MECHANICAL RESULTS: SEISMIC EXCITATION**

- **Variation of fuel volume**

- **Horizontal displacement of assemblies (left – red, right – green)**

  ![Graph](image)

  **Seismic excitation - volume change**

  Time steps of 0.1s →

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MECHANICAL RESULTS: SEISMIC EXCITATION (2)

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CAST3M NEUTRONIC TOOL

- Neutron transport simplified to multigroup diffusion equation (Fick’s law)

\[
- \frac{1}{V_g} \frac{\partial \phi^g(x)}{\partial t} = \nabla (D^g(x) \nabla \phi^g(x)) - \sigma^g_{\text{disp}}(x) \phi^g(x) + \sum_{g' \neq g} \sigma^g_{s' \rightarrow g}(x) \phi^{g'}(x) + \chi_p^g(x)(1 - \beta) \sum_{g'} v\sigma_{f}^{g'}(x) \phi^{g'}(x) + \sum_l \chi_l^g \lambda_l C_l^l.
\]

- Time evolution
- Transport/diffusion
- Removal
- Transfer/arrival
- Fission production
- Delayed neutrons

- Equation above for each energy group of neutrons

- Set of equations for precursor concentrations
The novelty of the CNT concerns direct treatment of geometry displacements.

The CNT has been validated with static Monte Carlo simulations using TRIPOLI4 and for $k_{eff}$ differences up to several hundreds pcm.

Comparable simulations for full-core models were done using APOLLO3.

Set of parametric studies suggest generally correct behavior of result
One way coupling with mechanical simulation

End-of-step displacements are transferred to neutron diffusion calculations.

Parametric study helped to optimize the length of time step for CNT.
Power evolution during neutronic transient...

... strongly correlated with variation of active volume
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SUMMARY

- Structure mechanics models were used together with neutronic models in Cast3M.

- New methodology for neutron-mechanics linking for Sodium Fast Reactors was established, validated and tested.

- Cast3M Neutronic Tool stands as a general tool for a large variety of mechanical excitations and short scenarios.

- CNT is useful for current and upcoming safety assessments concerning Gen4 systems and framework of ASTRID Project.

- Code is currently intensively applied to model various scenarios for better understanding of core behavior.
FSI:
- Taking into account steady state movement of the fluid
- Applying turbulent flow models for the liquid sodium

Structure mechanics:
- Adding vertical (Z) degree of freedom to mechanical model of solid

Neutronics
- Improving neutron diffusion model
Thank you for attention