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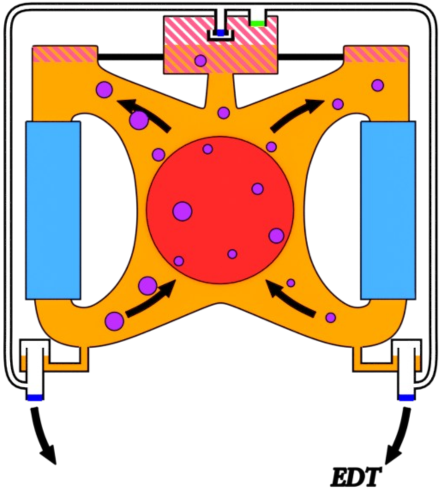
Calculation of reactivity insertion in a generation IV Molten Salt Reactor

Le Meute Thibault, Bertrand Frédéric, Merle Elsa, Seiler Nathalie, Heuer Daniel

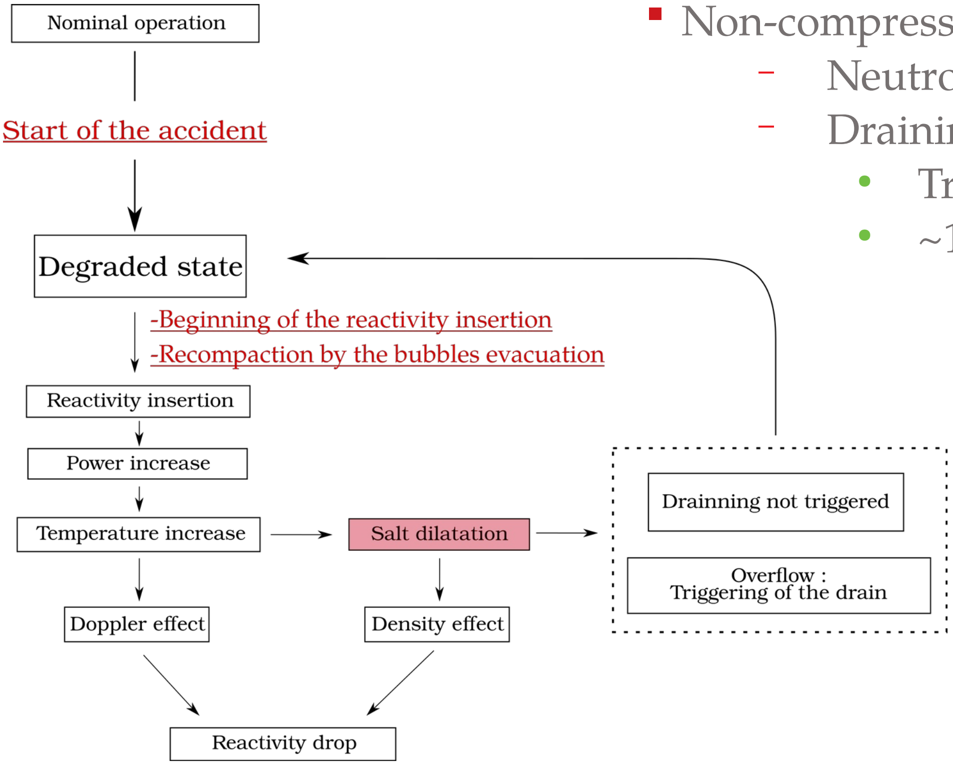
Table of content

Context

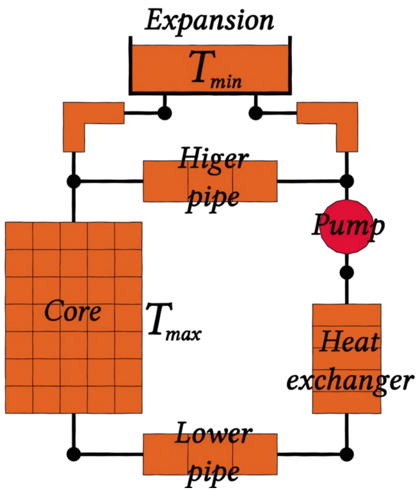
- Reactor specifications
  - Liquid fuel
  - Circulating fuel
- Power generation reactor (3 GW) isogenerator
  - Th/U, fluoride salt (TMFR)
  - U/Pu, chloride salt (PMCR)
- Study of hypothetical reactivity insertion accidents
  - Lead to a power peak
  - Increase of the salt temperature
- <u>Objectives:</u>
  - Feedback on reactor design
  - Volume of the expansion tank
  - Draining upper time



Non-compressible phenomenology (MOSAICS)

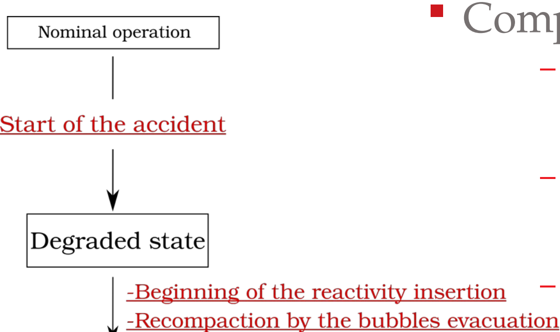


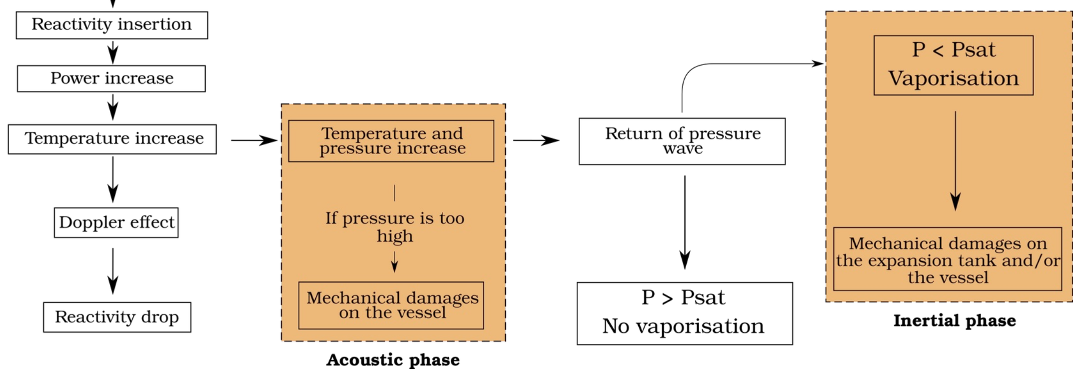
- Non-compressible phase
  - Neutrons precursors transport
  - Draining
    - Triggering by overflow
    - ~100 s

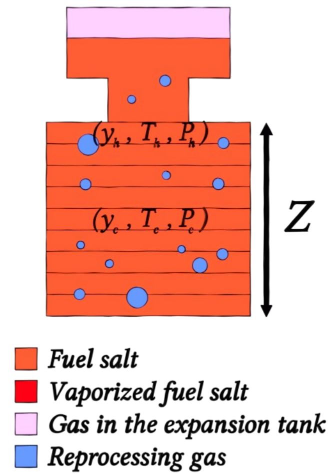


Compressible phenomenology (COCCINELLE)

- Compressible phase
  - Increase of the temperature
    => Increase of pressure
  - Doppler neutronic feedback almost alone
    - Density when salt goes out of the core
  - Inertial phase when vaporization occurs

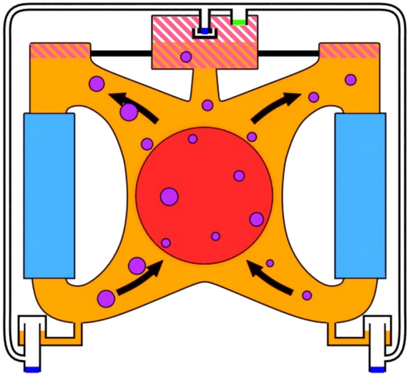






Compressible criterion

- In order to chain both the calculations tools, a criterion has been developed
- Flow is incompressible if:



$$\frac{\delta\rho}{\rho} \ll 1$$

- In MOSAICS, the incompressible hypothesis is considered as wrong if:

$$\frac{\delta P}{\varrho c^2} > 0.01$$

$$\Rightarrow \frac{1}{\varrho c^2} \left| \frac{\alpha}{\beta} \right| \frac{dT}{dt} t_c > 0.01$$

Criterion

Trigger value

- This criterion is calculated at each time step in MOSAICS.

Characterisation of the criterion

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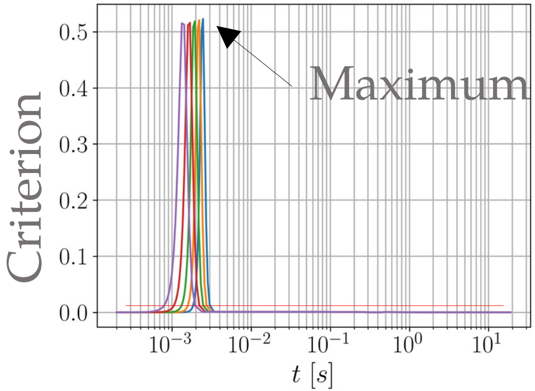
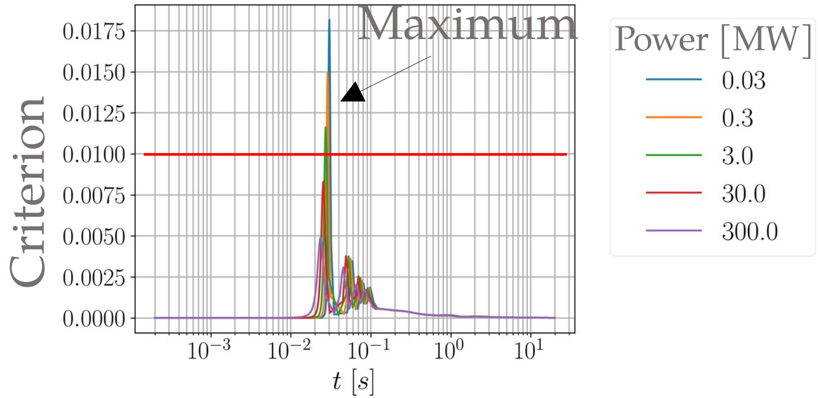
Objective

- The compressible phase is not easy to model
  - Often need a different calculation tool
  - Increase a lot transient calculation time
  - Need more calculation resources to reach the same fidelity than incompressible CFD calculations
- Characterize the developed criterion (MOSAICS alone)
  - What kind of reactivity insertion leads to a compressible phase
  - What reactor characteristic changes the behavior of the core

Objective

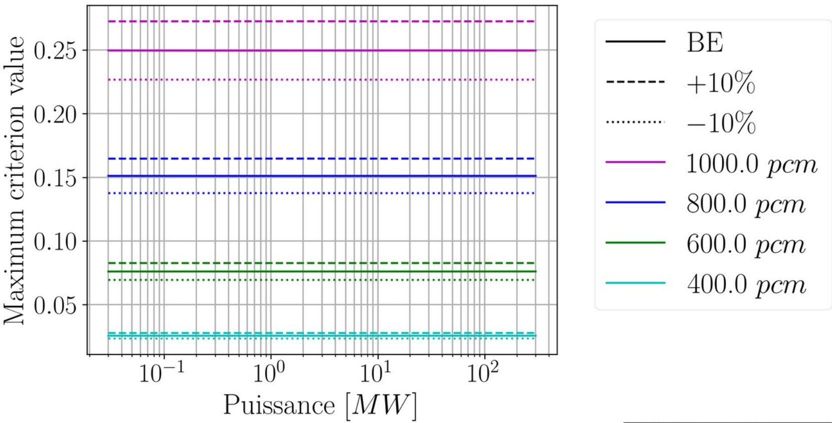
- Two kinds of reactivity transients are studied:
  - Ramp/Step
  - The maximum value of the criterion calculated will be interesting
    - If the maximum is below the trigger : Does not lead to compressible
    - If the maximum is higher : Lead to a compressible phase
  - This will permit to understand in what kind of transient the compressible phase have to be model
  - After this characterization, compressible transient have to be performed to understand the differences in the transient





Results of reactivity insertion, dilatability sensitivity

- Calculation in the fluoride version of the MSFR reactor

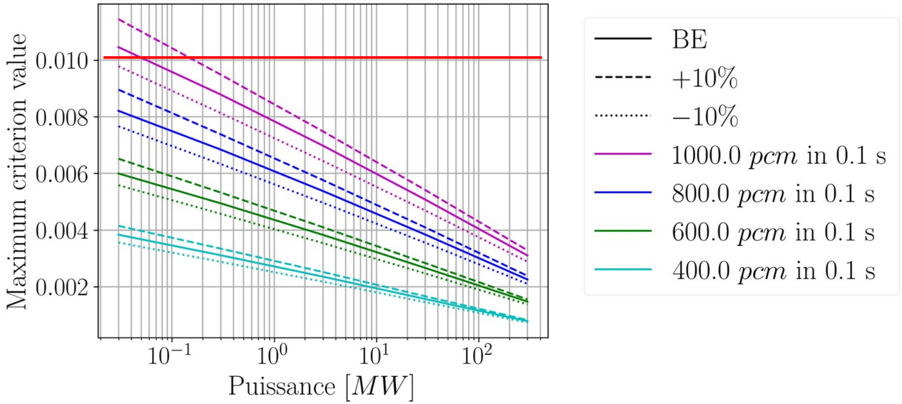


← Step reactivity

- All the maximums of criterion calculated are above 0.01
- Increase the dilatability increase the max value

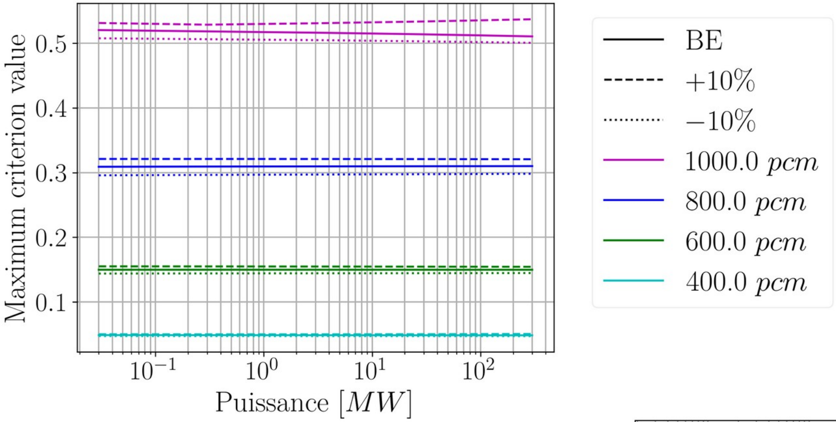
Ramp reactivity →

- Low power, higher value
- Only for more than 1000 pcm in 0.1 s at low power



Results of reactivity insertion, dilatability sensitivity

- Calculation in the chloride version of the MSFR reactor

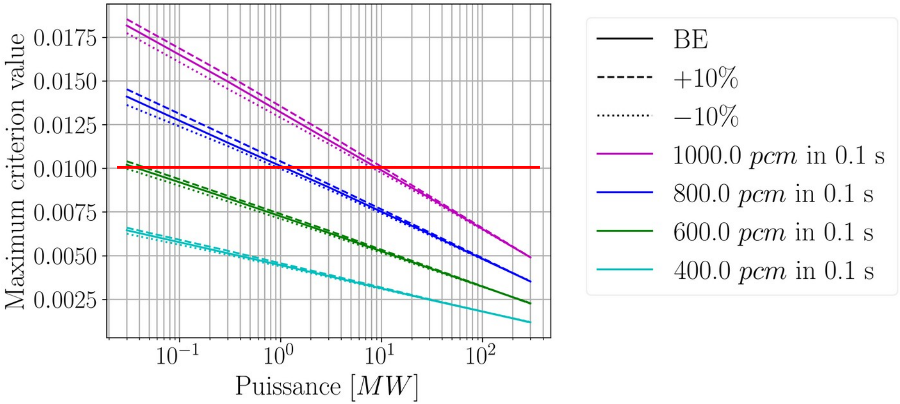


← Step reactivity

- All the maximums of criterion calculated are above 0.01
- Increase the dilatability increase the max value

Ramp reactivity →

- Low power, higher value
- Only for more than 600 pcm in 0.1 s at low power



Discussion

- The calculations show that:
  - Steps: the maximal value does not depend on the core power of the core
  - Ramps: The lower the core's power, the higher is the maximum value of the criterion
  - At low power, it's easier to have a compressible phase during a ramp reactivity transient
- Differences between the Fluoride and the Chloride:
  - For the same power, the maximal value of the criterion is higher in the Chloride than in the Fluoride version
  - In both cases, the speed of sound is set at 1500 m/s
  - The dilatabilities are:
    - $-280 \cdot 10^{-6}$ K^{-1} for the chloride
    - $-210 \cdot 10^{-6}$ K^{-1} for the fluoride
  - The differences in the criterion probably come from these differences

Chaining of calculation tools

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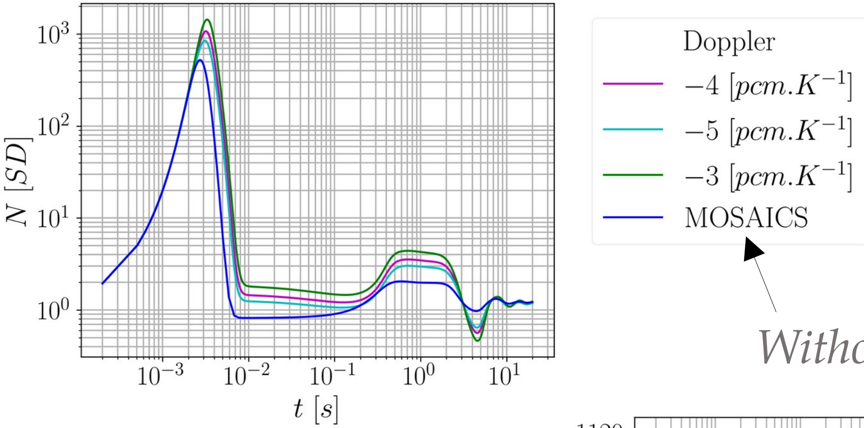
Objective

- Reactivity transient with and without compressible phase
  - Comparisons and estimation on how important is the compressible calculation
    - What is the impact of the compressible transient in term of safety
    - Is the transient really different with the compressible phase than without?
  - Study the impact of the criterion and the impact of the trigger value
- Variation of the core's properties:
  - Variation of the Doppler effect value to quantify its impact on the neutronic power and the temperature increase
- Study the impact of dilatability on reactivity transient:
  - What is the impact of the dilatability on the transient?
  - How the reactor parameters impact the behavior of the transient

Results : Doppler variation

- Fluoride MSFR, at 3 GW power, 400 pcm step reactivity



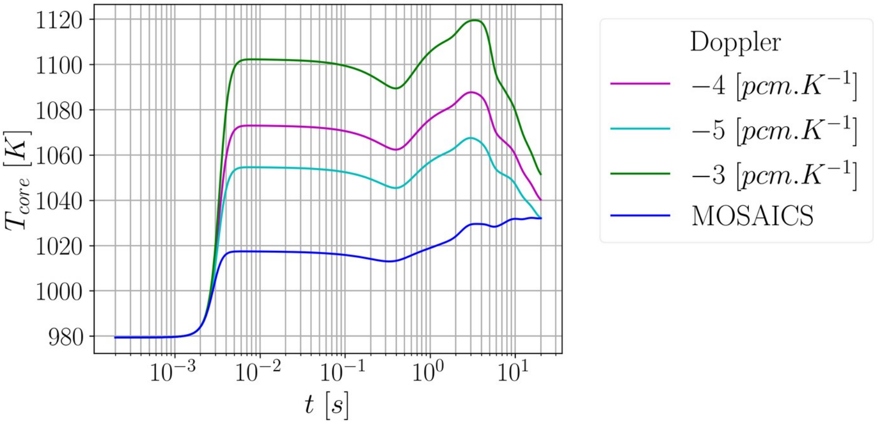
← Normalized power

- The lower the Doppler effect, the higher the neutronic power is calculated

Without compressible phase

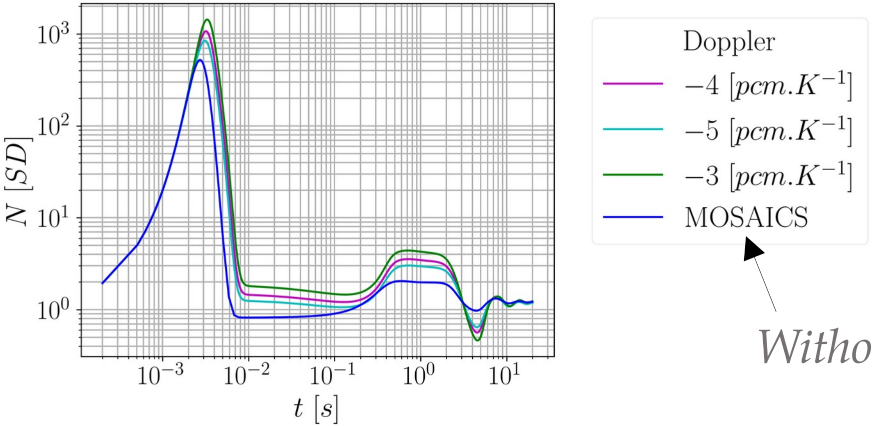
Mean temperature →

- The Doppler effect strongly impacts the mean temperature
- The compressible phase also



Results : Doppler variation

- Fluoride MSFR, at 3 GW power, 400 pcm step reactivity



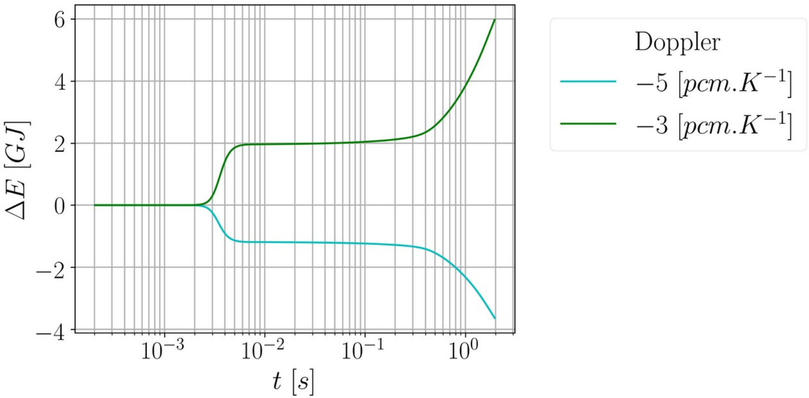
← Normalized power

- The lower the Doppler effect, the higher the neutronic power is calculated

Without compressible phase

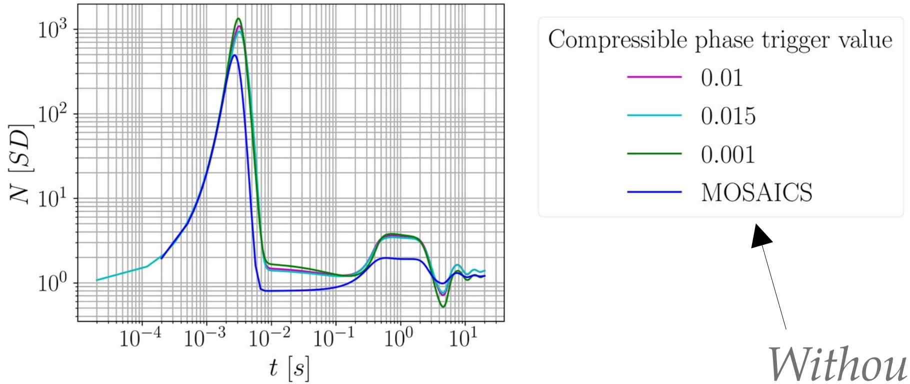
Energy difference with BE

- A variation of 1 pcm/K on the Doppler effect induce around 1 and 2 GJ of differences in the neutronic energy deposit



Results : Criterion variation

- Fluoride MSFR, at 3 GW power, 400 pcm step reactivity



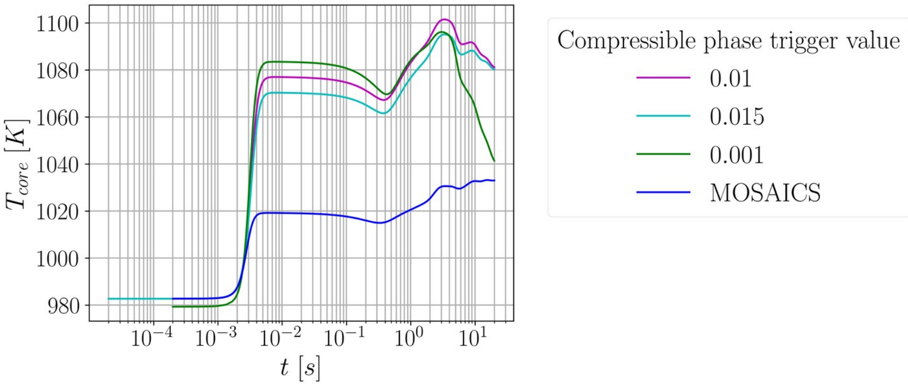
← Normalized power

- When the trigger value decreases, the maximum calculated power increases

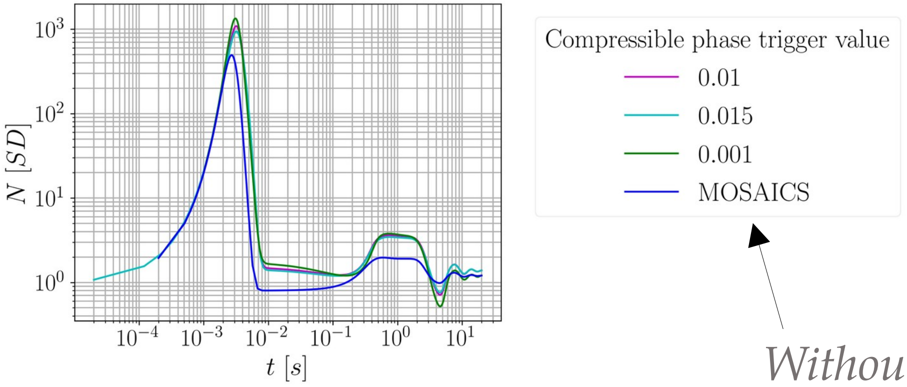
Without compressible phase

Mean temperature →

- Same than the normalized power



- Fluoride MSFR, at 3 GW power, 400 pcm step reactivity



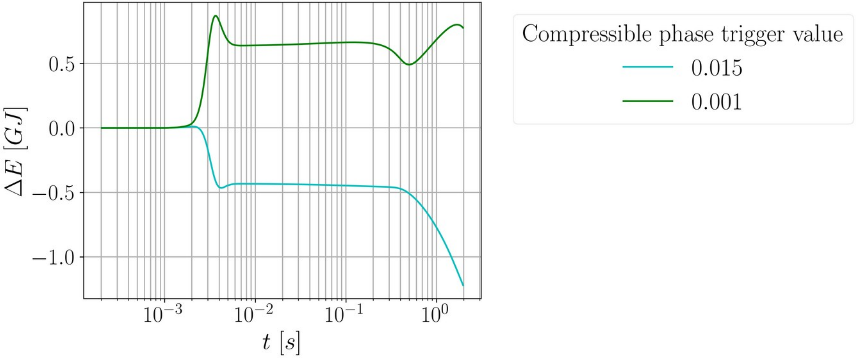
← Normalized power

- When the trigger value decreases, the maximum calculated power increases

Without compressible phase

Energy difference with BE

- When the trigger is higher, 0.5 GJ are missed in the compressible phase and if the trigger is lower, less energy is deposed in the salt.



Discussion

- Reactivity transient with and without compressible phase
  - As expected, the neutronic power and the temperature increases are higher during the compressible phase than on a full incompressible calculation.
- Variation of the core's properties:
  - When the Doppler effect decrease, maximum neutronic power and temperature increases are larger

Conclusions and Perspectives

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Conclusion and perspectives

- The work on chaining MOSAICS and COCCINELLE is on a good way, some work still have to be done:
  - Chaining for ramp reactivity insertion has not been performed
  - Some questions about the vaporization are still studied
- Characterization of criterion:
  - The behavior of the core is different under ramp and step reactivity transients
  - The lower the power of the core, the more probable a reactivity transient will lead to a compressible phase
    - Step reactivity is not realistic
  - Compressible transient is not always important to model
- Transients with both of the calculation tools:
  - The compressibility is important for the presented calculation
  - The value of the trigger is important but the impact is not as strong as the Doppler effect for example

Thank you for listening

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Bibliographie

Back-up

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Differences between chloride and fluoride salt

- Neutronic feedback :

Feed-back	U/Pu - Cl	Th/U - F
Doppler [$pcm.K^{-1}$]	-0,6	-4,0
Density [$pcm.m^3.kg^{-1}$]	8,6	4,0

- Thermodynamic properties:
  - These values are estimations and can vary a lot with experiment & concept

Properties	U/Pu - Cl	Th/U - F
Density [$kg.m^{-3}$]	2771.7	4122.2
Heat capacity(Cp) [$J.K^{-1}.kg^{-1}$]	630.7	1602.3
Volume core [m^3]	30	9
Volume heat capacity [$MJ.K^{-1}.m^{-3}$]	1.7	17.0
Thermal intertia [$MJ.K^{-1}$]	52.4	59.4

Compressible transition criterion

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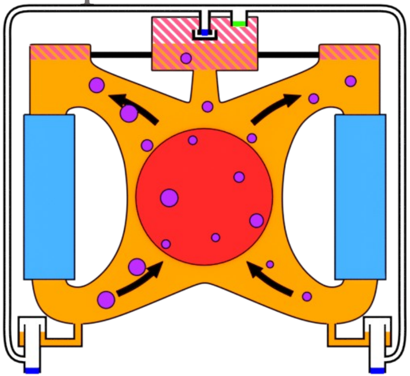
Compressible criterion

- Thanks to physicals considerations, the compressible transition criterion have been modified.
- The criterion is calculated into 2 steps:
  - Estimation of a pressure increase
  - Calculation of the criterion

$$\frac{\delta P}{\varrho c^2} \ll 1$$

    - P : Pressure
    - ϱ : Mean density
    - c : Speed of sound ~ 1500 m/s
  - This is a Mach number: $v = \frac{\delta P}{\rho c}$
  - The flow become compressible when $\frac{\delta P}{\varrho c^2} \ll 1$ is not verified:
    - $\frac{\delta P}{\varrho c^2} > 0.01$

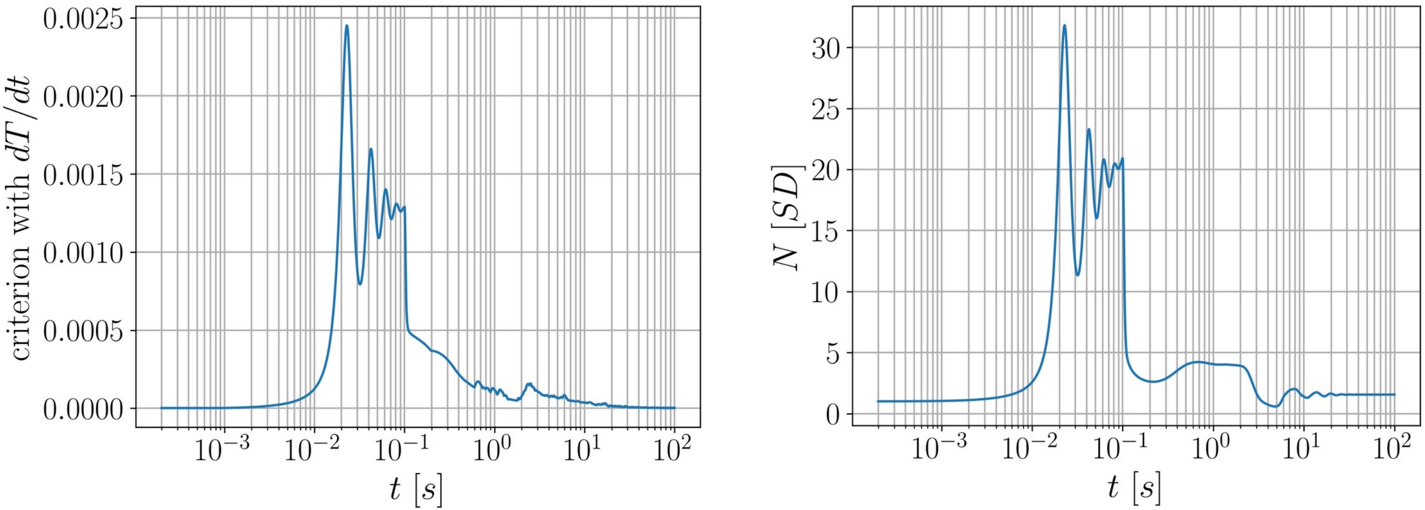


- The way to estimate δP changed

Compressible criterion

- The modified criterion is calculated with the following pressure estimation:
  - $\delta P = \frac{\alpha}{\beta} \frac{dT}{dt} t_c$
    - $\frac{dT}{dt}$: Maximum temperature variation
    - α : Dilatability
    - β : Compressibility
    - t_c : Caracteristic time
  - Come from evolution of pressure rise at fixed volume
- Here, t_c is the characteristic time of the physical phenomena.
  - $t_c = \frac{L_{core}}{c_{sound}}$
- The temperature derivative for the calculation is the highest temperature derivative calculate in the whole core.

Results (1000 pcm in 0.1 s in the reference MSFR)



- Now the evolution of the criterion follow the evolution of the power :
  - Seems more physical
- In this calculation, the criterion is not crossed