The SAMOSAFER project

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Context – Objectives (1/3)

♦ During SAMOFAR project, a **safety approach dedicated to liquid circulating fuel** fast reactors has been **developed** and **applicated**, based on ISAM tools

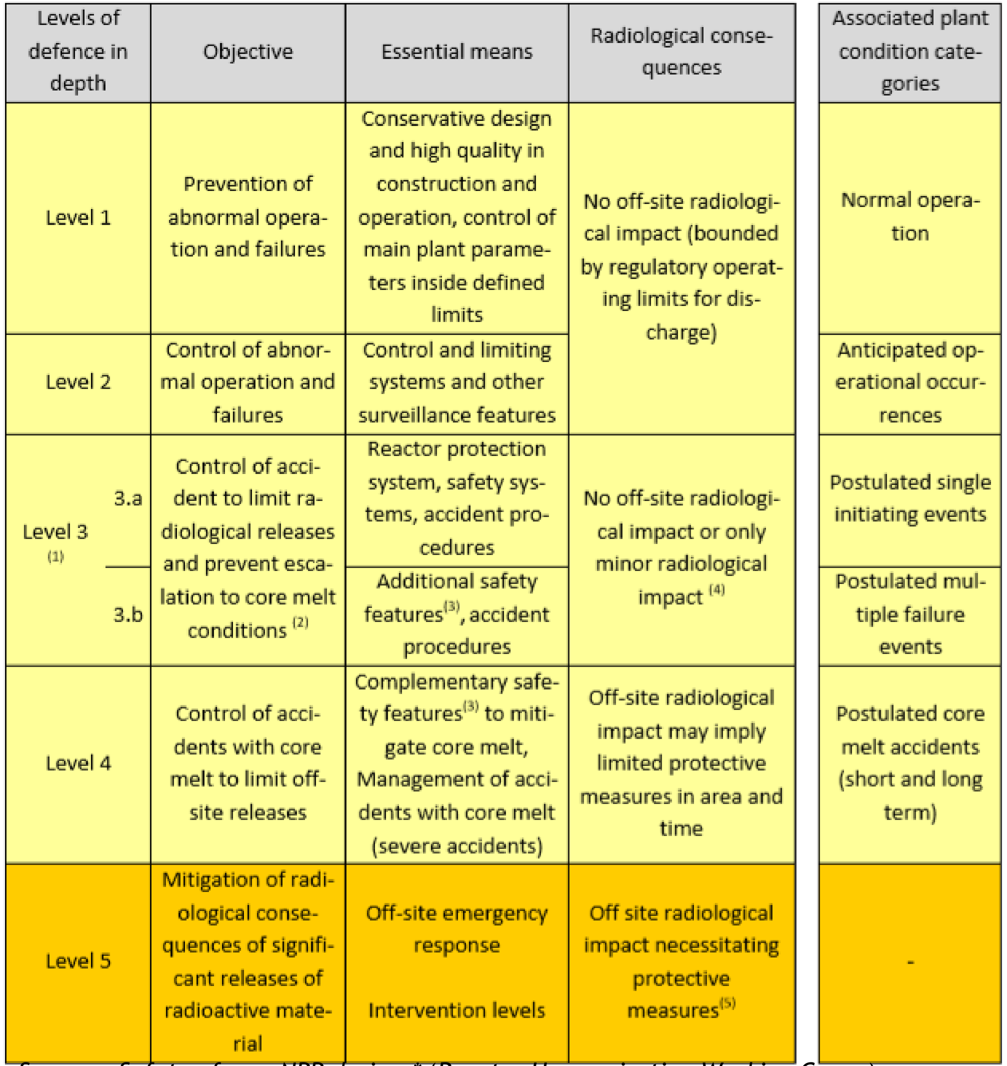
♦ The application of the methodology led – among other recommendations – to:

- draw up a **list of Postulated Initiating Events** (PIE) for MSR;
- propose a **first containment barrier analysis**;
- propose a **first application of Line of Defense** (LoD) **method**.

♦ The notion of Severe Accident – which was not needed so far – appears in the debate as soon as the **sufficiency of the safety provisions** is examined, in particular :

- one of the reasons leading to implement three containment barriers on PWR is the risk of simultaneous failure of several containment barriers, notably resulting from the **Severe Accident**
- the LoD method – which consists in implementing sufficient and independent provisions between the normal operation of the reactor and an unacceptable situation – usually takes the **Severe Accident** as reference situation to be prevented and mitigated

Context – Objectives (2/3)



Levels of defence in depth		Objective	Essential means	Radiological consequences	Associated plant condition categories
Level 1		Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation, control of main plant parameters inside defined limits	No off-site radiological impact (bounded by regulatory operating limits for discharge)	Normal operation
Level 2		Control of abnormal operation and failures	Control and limiting systems and other surveillance features		Anticipated operational occurrences
Level 3 (1)	3.a	Control of accident to limit radiological releases and prevent escalation to core melt conditions (2)	Reactor protection system, safety systems, accident procedures	No off-site radiological impact or only minor radiological impact (4)	Postulated single initiating events
	3.b		Additional safety features(3), accident procedures		Postulated multiple failure events
Level 4		Control of accidents with core melt to limit off-site releases	Complementary safety features(3) to mitigate core melt, Management of accidents with core melt (severe accidents)	Off-site radiological impact may imply limited protective measures in area and time	Postulated core melt accidents (short and long term)
Level 5		Mitigation of radiological consequences of significant releases of radioactive material	Off-site emergency response Intervention levels	Off site radiological impact necessitating protective measures(5)	-

Source : *Safety of new NPP designs** (Reactor Harmonisation Working Group)

♦ **The notion of Severe Accident directly impacts the definition of levels of DID**.

- level 3a and 3b features must prevent core melting;
- level 4's definition deals with core melt accident.

♦ Nevertheless, these levels of DID as defined by WENRA reflect some PWR specificities, that **cannot be directly applied to MSR, due to the liquid state of the salt**

♦ Thus, in order to define the safety objectives and to build the safety demonstration itself, the safety approach, based on a deterministic approach (implementation of DiD), including the **notion of Severe Accident**, **should be questioned**, and if necessary **adapted, to MSR concept**

Context – Objectives (3/3)

♦ The objective of this deliverable is to examine **how to implement the DiD principles on MSR in a meaningful way**, including a thinking on the **relevance of Severe Accident notion for MSR**

♦ Examination of the notion of Severe Accident, and **proposition to define a generalized notion** (Severe Plant Condition), applicable to MSR

♦ According to this definition and the issues raised during the analysis, proposition to **implement DiD principles for a MSR**, considering its specificities

SAM SAFER

« Severe Plant Condition » definition & Defense in Depth for a MSR

framatome

Methodology

♦ For PWR (and more generally for reactors with fuel assemblies), Severe Accident corresponds to the generalized core melting. This phenomenological definition is not directly transposable to all technologies of reactors → **Objective to define a generical notion, applicable to all concepts**

♦ Proposition to call this notion “**Severe Plant Condition**” (proposition of denomination mentioned in the RSWG)

♦ The guiding principle for the building of the SPC is the identification of the characteristics of the Severe Accident as generalized core melting, since the SPC definition should embrace its signification and implications on the safety approach

♦ **1st Step**: To list the characteristics of the generalized core melting for reactors with fuel assemblies

♦ **2nd Step**: For each characteristic, assess the relevance to include it in the SPC definition, according to the following criteria :

- Importance
- Application to all GEN IV concepts
- Independence from design

1st Step – Characteristics of generalized core melting (1/2)

♦ The Severe Accident as generalized core melting on PWR (and more generally reactors with fuel assemblies) is characterized by *(preliminary list, that could be completed)*:

- Fuel **phase change**
  - physical properties change
  - fuel geometry reconfiguration
  - systems ensuring the mitigation might be specific to the new fuel nature
  - significant uncertainties during the transition phase
- Fuel **relocation**
  - safety systems used to mitigate the accident might not be usable in the new location
  - retention of fuel in its new location becomes an issue
  - reduction of the number of containment barriers between the fuel and the environment
  - significant uncertainties

1st Step – Characteristics of generalized core melting (2/2)

- ♦ The Severe Accident as generalized core melting on PWR (and more generally reactors with fuel assemblies) is characterized by *(preliminary list, that could be completed)*:
  - ○ Risk of possible **reconfiguration in a more reactive geometrical configuration**
  - ○ **Important source term** involved
  - ○ Source term **dispersible** (liquid, gaseous)
  - ○ Important **energy release** (thermal or mechanical)
  - ○ **Confinement barriers** potential challenge:
    - ❖ Loss of the 1st barrier (loss of fuel cladding integrity due to temperature increase)
    - ❖ Challenge of the 2nd barrier (due to pressure increase in the primary circuit)
    - ❖ Challenge of the 3rd barrier (due to the pressurization of the containment, the corium-concrete interaction, the hydrogen risk)

- ♦ Remark: beyond these characteristics describing generic considerations about the phenomena involved during a Severe Accident, it is relevant to notice that some of them entail
  - ○ **Uncertainties** on the phenomenology of the accident
  - ○ A **paradigm shift**, leading to a different behaviour of the fuel, mainly due to fuel relocation

2nd Step – SPC definition

♦ A Severe Plant Condition (SPC) is defined as a situation including:

- A **high quantity of radiological elements** involved
- A **dispersable** source term, including both that:
  - The source term physical condition is either liquid or gaseous (including aerosols)
  - The equipment ensuring its retention in normal operating mode lose their leak tightness
- A **vector** (energy), enabling the transportation of the radiological elements
- A **risk of simultaneous failure of containment barriers** induced by the accident**, until potential alteration of the last containment barrier**

♦ *Remarks:*

- In practice, for a MSR, a relocation of the salt near the last containment barrier, with the residual heat challenging its integrity would correspond to a SPC
- *It is important to recall that this proposition remains only a definition, the objective remaining to design an appropriate safety archiecture to prevent releases to the environment, considering a wide spectrum of possible configurations for the nuclear plant*

Defense in Depth main guidelines to apply for a MSR

♦ Main DiD guidelines:

- **To implement a high level of prevention opposite to situations subject to lead to large radiological releases**
- **To integrate determinism**: if some phenomena can physically occur, and that we are able to implement provisions to ensure its management, therefore the deterministic approach imposes to do so (regardless its occurrence frequency)

Nota : it would be necessary to limit this reasoning with the notion of **residual risk**

- To ensure a sufficient level of **independance** between the provisions operating at different levels of DiD (**diversity** is a relevant way to provide independance)
- **To prevent the situations with high level of uncertainties**. Actually, if a situation presents a high level of uncertainties, ensuring its management would rely on hypothesis with uncertainties; thus it is preferable in that case to improve the prevention

Possible fuel salt relocation, a MSR specificity for DiD implementation

♦ **Close link between the levels of Defense in Depth and the location of the fuel salt**

- The possibility of **salt transfers:**
  - Leads to a change in the features ensuring safety functions
  - Includes uncertainties both for the transition phase and the final state.
  - Requires a certain homogeneity of the safety provisions repartition, for all safety functions and initiating events.
    For example, if strong and multiple provisions are implemented to cool the fuel circuit, there should not exist conditions requiring the transfer of the salt, leading to a bypass of these provisions (except if sufficient provisions are dedicated to these situations, but it represents a cost)
- **Independence**
  - Fuel salt relocation provides opportunities to implement independent features, including diversity (less constraints to implement different technological solutions)
- **The prevention of situations with high uncertainties might entails**:
  - To keep the salt in the fuel circuit as far as possible
  - To prevent the SPC as far as possible

Safety outcomes from other WPs

Safety outcomes from other WPs

♦ Since the proposed definition of Severe Accident is a methodological characterisation and does not correspond to a precise sequence, the link with other studies performed in SAMOSAFER is not obvious so far

♦ The end of the project was dedicated to provide a structured panorama of MSR safety, by centralizing the safety related activities performed in other WP & tasks

♦ Main outcomes

- **Improvement of the knowledge of Reactivity control function**
- **Progress in Accident management strategy** (in particular for Decay Heat Removal) and identification of remaining issues
    - **Freeze valve (detection, activation)**
    - **Reversibility of draining**
- **Containment main remaining issues**
    - **Failure modes of containment**
        - Temperature loadings (high radiation)
        - Corrosion, irradiation
    - **Bypass analysis**
    - **Gazeous FPs containment**

Thank you for your attention

SAMOSAFER

WP1
Risk identification of the FTU

SAMOSAFER Final meeting

S. Dulla and A.C. Uggenti

November 28th, 2023

Avignon, France

Objectives of the task

- **Risk identification** at the fuel treatment unit level (to complement the risk identification performed at the reactor level during SAMOFAR project) through a **functional analysis**
    - Elaboration of a list of **Postulated Initiating Event** for the FTU
    - Identification and prioritization of bounding cases for **future safety analyses**
    - Feedback on FTU design in a **safety-driven** approach

- MILESTONE MS2 (originally due M12, postponed to M17-end of Feb21): List of Postulated initiating Events on the FTU – Technical Note ✓
- DELIVERABLE D1.3 (originally due M36, postponed to M40-end of Feb23): Risk identification on the FTU - Report ✓

Topics covered during the activity

- Description of the fuel treatment unit
  - …
  - The fluorination
  - …
- Methodology for functional analysis
  - The Plant Breakdown Structure
  - The Functional Breakdown Structure
  - The FFMEA table
  - Identification and discussion of PIEs

Methodologies

- Starting hypotheses
- Outcome of the functional analysis
  - Reference events (PIE)
  - PIE description
    - Loss of Fuel Salt containment …
    - Loss of cooling …
    - …
- Open points and recommendations

Application & Results

Topics covered during the activity

- Description of the fuel treatment unit
  - …
  - The fluorination
  - …
- Methodology for functional analysis
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Methodologies

- Starting hypotheses
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    - Loss of cooling …
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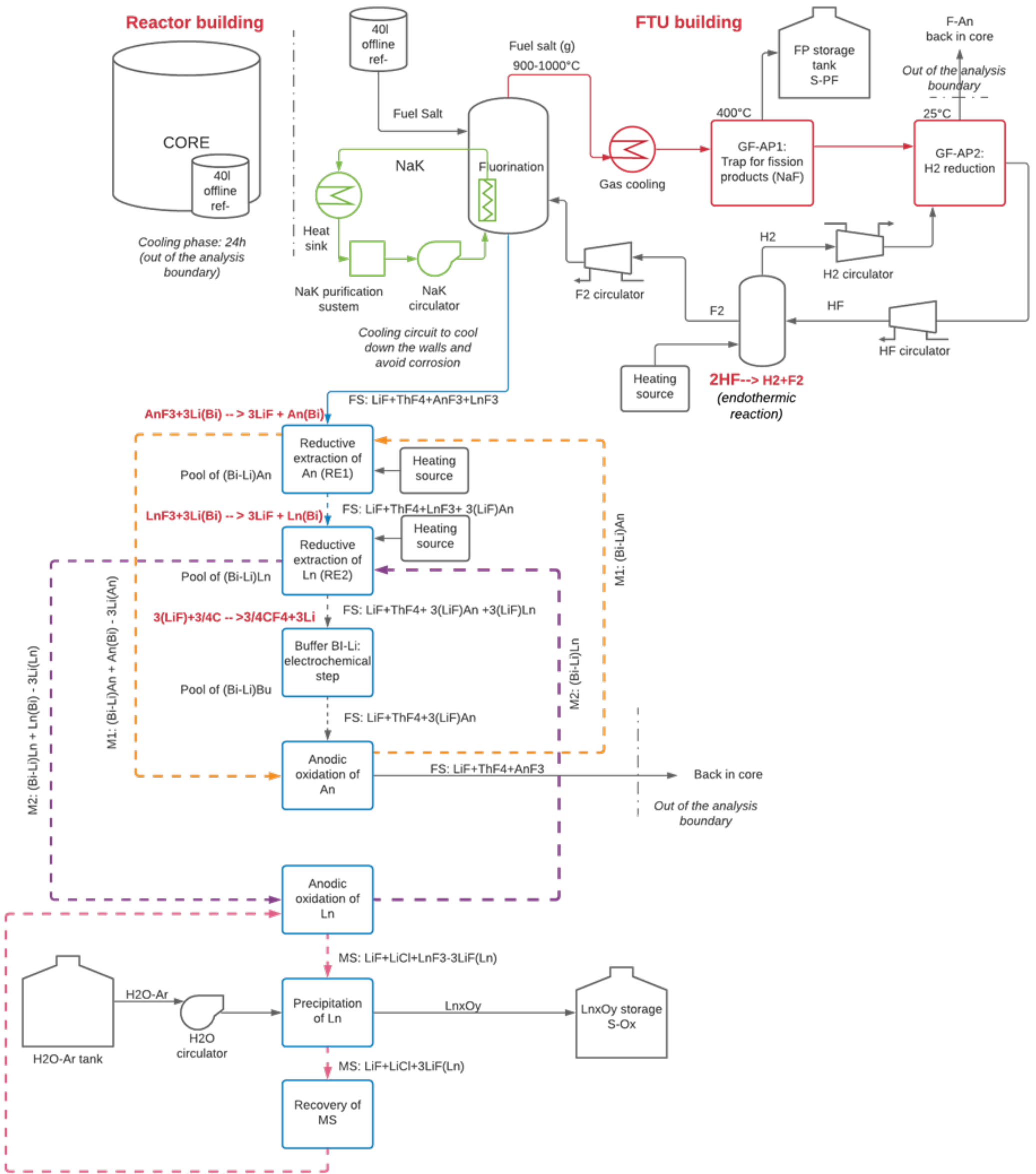
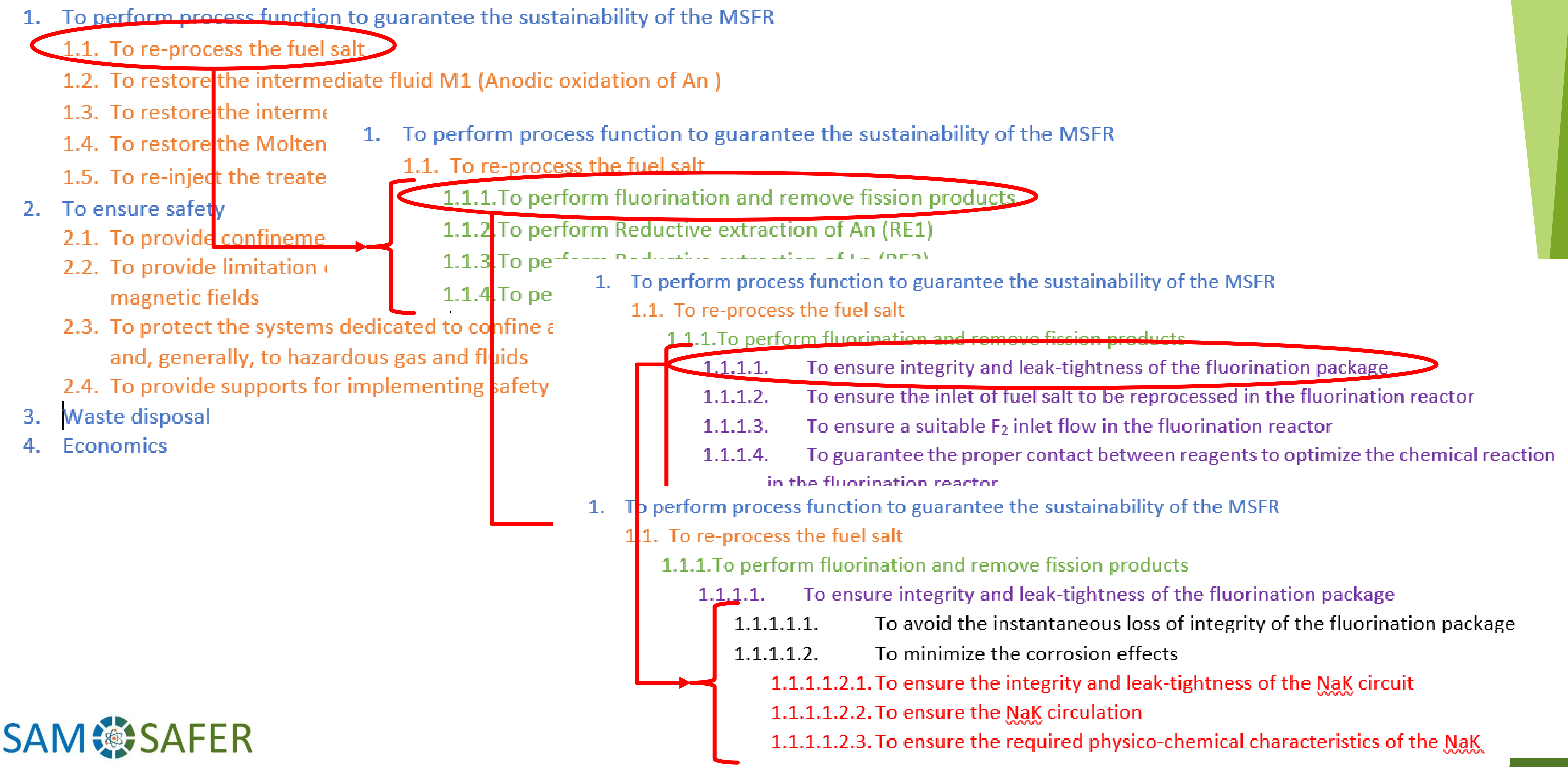
Application & Results

Plant Breakdown Structure



1. Fluorination systems
    1.1. Fuorination reactor
    1.2. NaK circuit
        1.2.1. Heat Exchanger
        1.2.2. NaK Circulator
        1.2.3. NaK purification System
        1.2.4. Heat sink
        1.2.5. Pipes&instrumentation
    1.3. Gaseous FP extraction
        1.3.1. Gas cooler
        1.3.2. GF-AP1 - FP trap package
        1.3.3. FP storage tank
        1.3.4. GF – AP2 - H_2 reduction package
        1.3.5. HF circulator
        1.3.6. F_2 circulator
        1.3.7. H_2 circulator
        1.3.8. H_2-F_2 reactor
        1.3.9. H_2-F_2 reactor heating source
2. Reductive Extraction of An (RE1 system)
    2.1. RE1 package
    2.2. RE1 package heating source
    2.3. Pipes and instrumentation
3. Reductive Extraction of Ln (RE2 system)
    3.1. RE2 package
    3.2. RE2 package heating source
    3.3. Pipes and instrumentation
    3.4. [… … …]

Functional Breakdown Structure



1. To perform process function to guarantee the sustainability of the MSFR
    1.1. To re-process the fuel salt
    1.2. To restore the intermediate fluid M1 (Anodic oxidation of An)
    1.3. To restore the interme
    1.4. To restore the Molten
    1.5. To re-inject the treate
2. To ensure safety
    2.1. To provide confineme
    2.2. To provide limitation (magnetic fields
    2.3. To protect the systems dedicated to confine a and, generally, to hazardous gas and fluids
    2.4. To provide supports for implementing safety
3. Waste disposal
4. Economics

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1. To perform process function to guarantee the sustainability of the MSFR
    1.1. To re-process the fuel salt
        1.1.1. To perform fluorination and remove fission products
        1.1.2. To perform Reductive extraction of An (RE1)
        1.1.3. To pe
        1.1.4. To pe

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1. To perform process function to guarantee the sustainability of the MSFR
    1.1. To re-process the fuel salt
        1.1.1. To perform fluorination and remove fission products
            1.1.1.1. To ensure integrity and leak-tightness of the fluorination package
            1.1.1.2. To ensure the inlet of fuel salt to be reprocessed in the fluorination reactor
            1.1.1.3. To ensure a suitable F_2 inlet flow in the fluorination reactor
            1.1.1.4. To guarantee the proper contact between reagents to optimize the chemical reaction in the fluorination reactor

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1. To perform process function to guarantee the sustainability of the MSFR
    1.1. To re-process the fuel salt
        1.1.1. To perform fluorination and remove fission products
            1.1.1.1. To ensure integrity and leak-tightness of the fluorination package
                1.1.1.1.1. To avoid the instantaneous loss of integrity of the fluorination package
                1.1.1.1.2. To minimize the corrosion effects
                    1.1.1.1.2.1. To ensure the integrity and leak-tightness of the NaK circuit
                    1.1.1.1.2.2. To ensure the NaK circulation
                    1.1.1.1.2.3. To ensure the required physico-chemical characteristics of the NaK

Compilation of the FFMEA table - dimension

Item	Process function	LOSS OF THE FUNCTION	PBS element	Op. Mode	Failure Type	Physical Cause of the loss of the function [optional]	Consequence	Detection Prevention Mitigation	Recommendations/Open points in the design	NOTE
1	1. To perform process function to guarantee the sustainability of the MSFR									
2	1.1. To re-process the fuel salt									
3	1.1.1.To perform fluorination and remove fission products									
4	1.1.1.1. To ensure integrity and leak-tightness of the fluorination package									
5	1.1.1.1.1. To avoid the instantaneous loss of integrity of the fluorination package	Loss of integrity of fluorination package	Fluorination package	N-OP	Loss of containment	Small leakage in the bottom part of the fluorination package (liquid)	Loss of liquid fuel salt. Damage of equipment (To be specified) Best case: the fuel salt freezes fixing the leak (only if the leakage is small enough) Worst case: the pressure inside the reactor is able to empty the liquid head of the fluorination reactor Intermediate case: pool of fuel salt below the fluorination package, loss of efficiency of the fluorination reactor. Contamination of the FTU building.	Control the amount of the fuel salt exiting from the fluorination package (buffer tank). Radioactivity detection triggering immediate shutdown of the FTU	In the next phases of the design, investigate the Shutdown conditions (e.g. Is the fluorination package kept in pressure? Does the fuel salt remain in the fluorination reactor?). The FTU emergency shutdown procedure has to be defined. The operational time of the fluorination package is not defined yet: once it will be defined, a different operational regime can be evaluated: for example the daily use of the fluorination can be substituted with a weekly or monthly use, for economical reasons. The current analysis focuses on the time the equipment is working	HP: for this analysis, the fluorination is supposed to work 1 hour per day.

One line for each function, from higher to lower levels

Compilation of the FFMEA table – failure type

Item	Process function	LOSS OF THE FUNCTION	PBS element	Op. Mode	Failure Type	Physical Cause of the loss of the function [optional]	Consequence	Detection Prevention Mitigation	Recommendations/Open points in the design	NOTE
1	1. To perform process function to guarantee the sustainability of the MSFR									
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Possible different scenarios for the same failure type, e.g. small vs large leakage

Compilation of the FFMEA table – consequences

Identification of possible consequences based on expert judgement

Item	Process function	LOSS OF THE FUNCTION	PBS element	Op. Mode	Failure Type	Physical Cause of the loss of the function [optional]	Consequence	Detection Prevention Mitigation	Recommendations/Open points in the design	NOTE
1	1. To perform process function to guarantee the sustainability of the MSFR									
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Compilation of the FFMEA table – detection, prevention and mitigation

Item	Process function	LOSS OF THE FUNCTION	PBS element	Op. Mode	Failure Type	Physical Cause of the loss of the function [optional]	Consequence	Detection Prevention Mitigation	Recommendations/Open points in the design	NOTE
1	1. To perform process function to guarantee the sustainability of the MSFR									
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Useful suggestions for the design development, based on the previous step

Compilation of the FFMEA table – recommendations

Item	Process function	LOSS OF THE FUNCTION	PBS element	Op. Mode	Failure Type	Physical Cause of the loss of the function [optional]	Consequence	Detection Prevention Mitigation	Recommendations/Open points in the design	NOTE
1	1. To perform process function to guarantee the sustainability of the MSFR									
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Synthesis of the emerged safety-oriented comments on the open points of the design

Reference events (PIE) + description

- **Loss of Fuel Salt containment** – includes different PIEs

- ***Leakage in the bottom part of the fluorination package*** (liquid release)
- Possible consequences (free evolution)
  - Loss of liquid fuel salt
  - Loss of F_2 gas
  - Pressure decrease in the fluorinator
  - Possible fire and toxic release
  - Damage to the equipment constituting the fluorinator
- Detection/prevention/mitigation
  - Control the amount of the fuel salt exiting from the fluorination package (buffer tank)
  - Radioactivity detection triggering immediate shutdown of the FTU
  - F_2 detection in the FTU building

- ***Leakage in the upper part of the fluorination package*** (gas release)
- Possible consequences (free evolution)
  - Loss of gaseous fuel salt and gaseous fission products
  - Pressure decrease
  - Contamination of the FTU building
  - The depressurization implies plausible enhancing of the chemical reaction in the fluorination reactor
  - Loss of F_2 gas (unreacted)
  - Possible fire
  - Toxic release
  - Damage of equipment
- Detection/prevention/mitigation
  - Radioactivity detection triggering immediate shutdown of the FTU and stopping the inlet of F_2
  - F_2 and H_2 detection in the FTU building

Open points and recommendations - I

- List of the design open points and recommendations raised from the FTU safety analysis

- Examples of **design open points**:
  - The normal shutdown conditions of the FTU have to be investigated
  - The FTU emergency shutdown and starting procedure has to be defined
    - …
  - In case of loss of NaK forced flowrate, the possibility to have a natural circulation of the NaK shall be investigated
    - …
  - In the step of reductive extraction of An (RE1) the re-criticality scenario practical elimination has to be demonstrated
    - …

Open points and recommendations – II

- List of the design open points and recommendations raised from the FTU safety analysis

- Examples of **recommendations**:

Nuclear safety principles

  - In the next phases of the design, evaluate to insert **redundant and diversified** shutdown valve on the F_2 inlet line powered by an emergency power and double-shell containment building around the fluorination package with radioactive detection between the 2 walls

Alternative technical solutions

  - …
  - **Other cooling fluids** can be evaluated in substitution of the NaK
  - In case of loss of NaK and subsequent fire, the **solutions already found for the SFR or other industrial sectors** using this fluid could be considered

Cross-fertilization

- ***NOTE***: most of the open points/recommendations focus on the fluorination step, as it is currently the one with a more advanced level of detail in terms of mode of operation and identification of components

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SAMOSAFER

Task 1.2 : reactivity insertions

T. Lemeute (CEA/CNRS), F. Bertrand (CEA)

Final project meeting
Avignon, France
November 28th 2023

Outline

- Background and aim of the task
- Initiating a reactivity insertion
- Overview of the modelling of reactivity insertion
- Illustration of the MSFR behaviour (Fluoride and Chloride version)
- Prospects

Background and aim of the task (1/2)

- Fast neutron reactors are more sensitive to reactivity insertions

  → $\frac{dP}{dt} \sim \left(\frac{r-\beta}{\Lambda}\right) P$

  → lower delayed neutron fraction than thermal spectrum reactors

  → shorter prompt neutron lifetime

  → larger power density

- Core kinetics is faster and for a same reactivity insertion the power increases much more

- The core is not in its most reactive configuration under operation for SFR but almost does for a MSR (the core is already very compact). However there is a potential for reactivity insertions, among other, if the salt outside from the core takes part of the chain reaction

- The expected MSFR behavior is robust because of good negative reactivity feedback for a fast reactor, but…

Reactivity insertions among other PIEs (1/2)

- What is the cause of an incident/accident ?
  - Increase of the ration of the generated power (P)/extracted power Q)in the core region → temperature increase in coolant and then possibly core materials

    -in nominal operating conditions : P/Q = 1 with

    $$Q = \dot{m}\, C_p (T_{out} - T_{in})$$

  - Accident families :
    - P ↗ → reactivity insertion (TOP)
    - Q ↘ → decrease of cooling

      → m ↘ overall or local, partial or toltal loss of flow (LOF)

      → T_{in} ↗ loss of heat think (LOHS)
- At this stage: no specific PIEs or reactor is yet considered !!

Reactivity insertions among other PIEs (2/2)

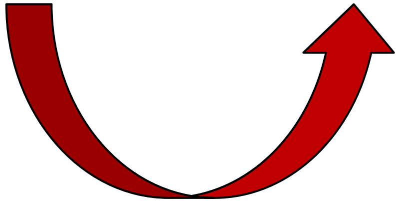
Reactivity increase can be due to (CEA SAMOSAFER analysis)

Physical effects:

- Temperature decrease (Doppler effect)
- Density increase
- Increase in volume concentration of fissile materials
    - -salt precipitation
    - -salt solidification
    - -salt condensation
    - -void fraction decrease
    - -refueling faults

-Neutron leak reduction

-Moderator insertion



Translation in events related to system and components

Illustration: over-cooling transients (MS1.2 of SAMOSAFER Project)

-an increase of the intermediate flow rate;

-an inadvertent starting of some of the DHR loops.

-an excessive loading from the electrical network;

-a depressurization of the PCS;

-a flow rate increase in the PCS or feed-water flow rate increase.

-uncoupling of the generator;

-loss of off-site power.

Reactivity feedback for chloride and fluoride concepts

- Neutronic feedback :

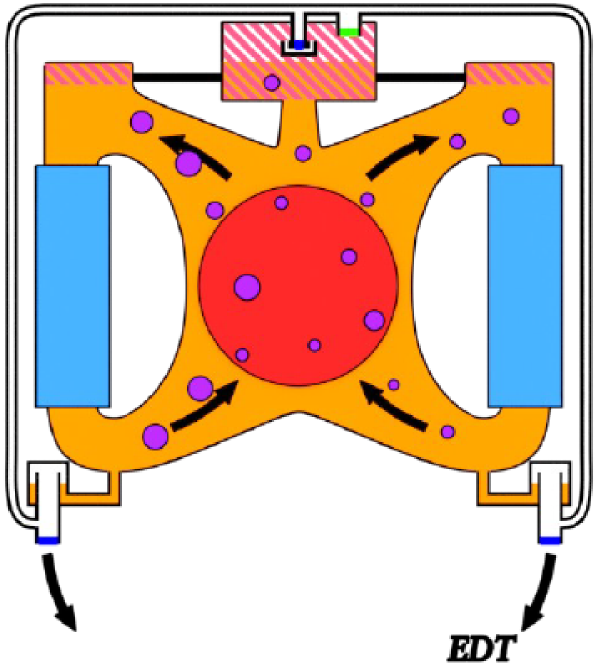
Feed-back	U/Pu - Cl	Th/U - F
Doppler [pcm.K^{-1}]	-0,6	-4,0
Density [pcm.m^3.kg^{-1}]	8,6	4,0

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

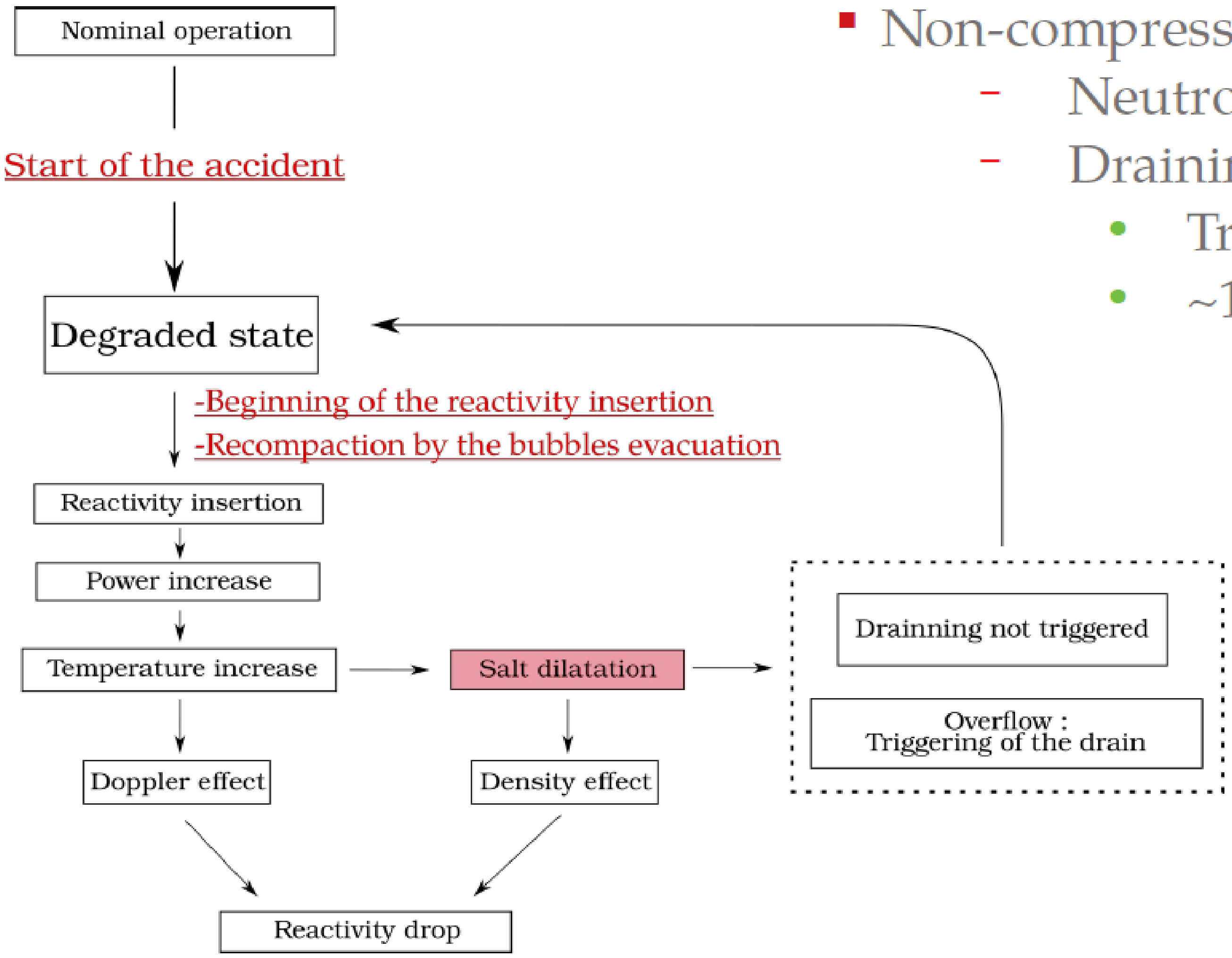
Properties	U/Pu - Cl	Th/U - F
Density [kg.m^{-3}]	2771.7	4122.2
Heat capacity(Cp) [J.K^{-1}.kg^{-1}]	630.7	1602.3
Volume core [m^3]	30	9
Volume heat capacity [MJ.K^{-1}.m^{-3}]	1.7	17.0
Thermal intertia [MJ.K^{-1}]	52.4	59.4

Studied concept regarding postulated reactivity insertions

- 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



About phenomenology and modelling (1/4)



Nominal operation

Start of the accident

Degraded state

-Beginning of the reactivity insertion

-Recompaction by the bubbles evacuation

Reactivity insertion

Power increase

Temperature increase

Salt dilatation

Doppler effect

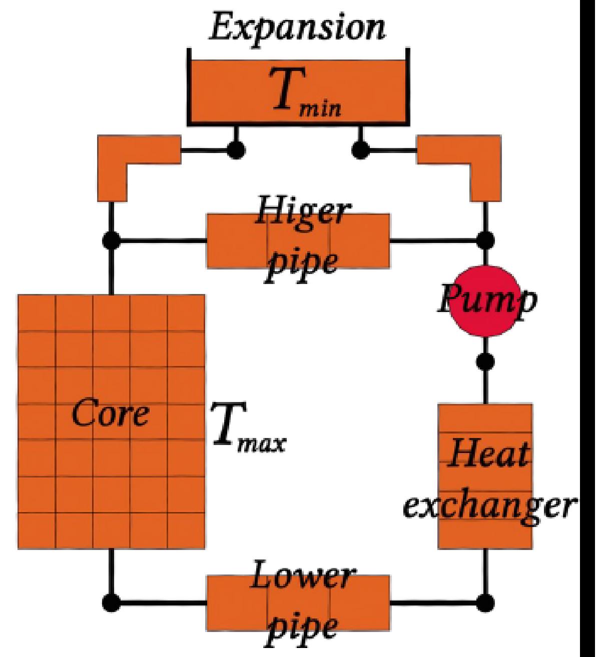
Density effect

Reactivity drop

Drainning not triggered

Overflow : Triggering of the drain

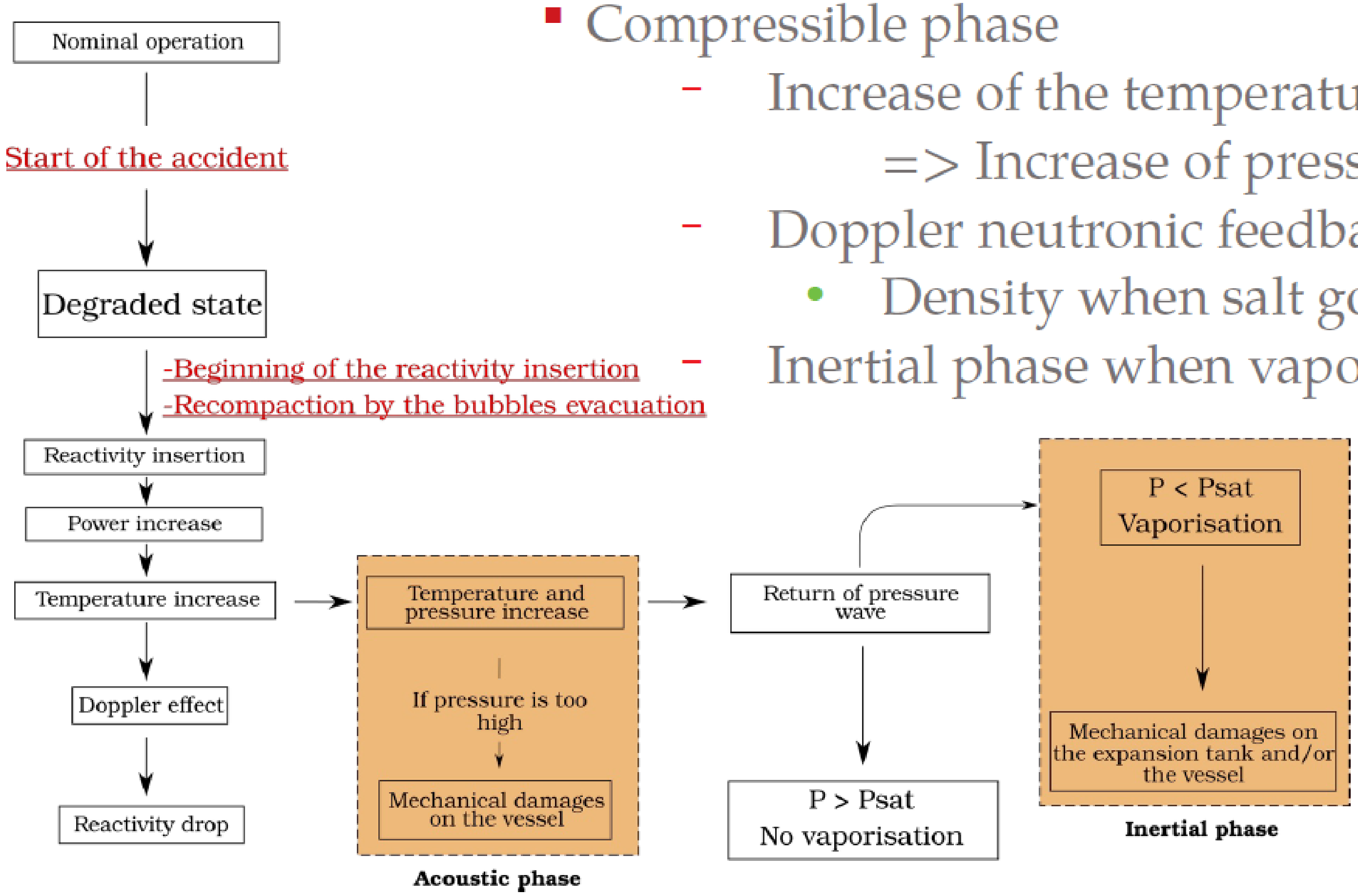
- Non-compressible phase
  - Neutrons precursors transport
  - Draining
    - Triggering by overflow
    - ~100 s



About phenomenology and modelling (2/4)

- 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



Nominal operation

Start of the accident

Degraded state

-Beginning of the reactivity insertion

-Recompaction by the bubbles evacuation

Reactivity insertion

Power increase

Temperature increase

Doppler effect

Reactivity drop

Temperature and pressure increase

If pressure is too high

Mechanical damages on the vessel

Acoustic phase

Return of pressure wave

P > Psat

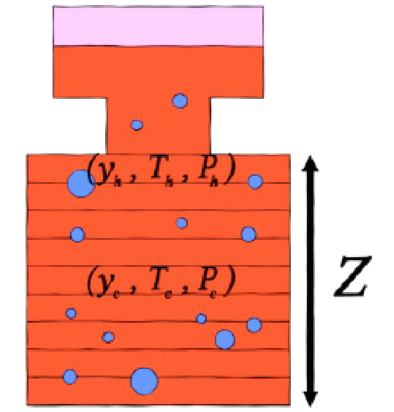
No vaporisation

P < Psat

Vaporisation

Mechanical damages on the expansion tank and/or the vessel

Inertial phase



🟧 *Fuel salt*

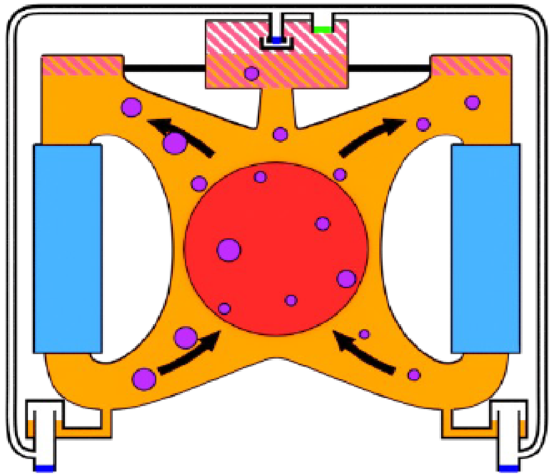
🟥 *Vaporized fuel salt*

🟪 *Gas in the expansion tank*

🟦 *Reprocessing gas*

About phenomenology and modelling (3/4)

- 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:

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

Criterion

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

Trigger value

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

SAM SAFER

About phenomenology and modelling (4/4)

- Possible storage of thermal energy in the reactor vessel ?

→ After the swelling of the salt free level in case of volatile species formation when the salt is heated

→ Investigation of reactivity oscillation around the prompt-criticality

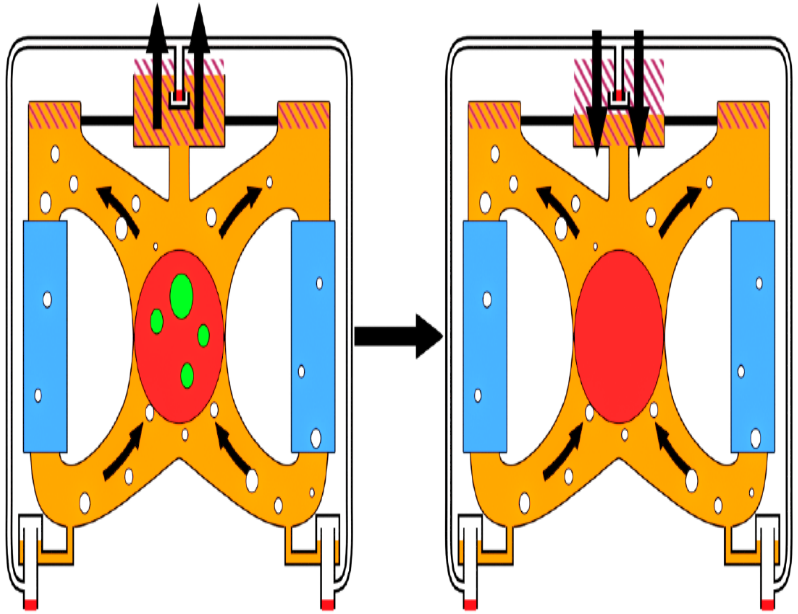
→ Reactivity increases when the free level goes down (compaction)

→ Reactivity decrease when the free level goes up

→ It is necessary to simulate this process its damping

→ Consequences on structures (thermal and mechanical) → E_{meca} , $T_{structures}$?

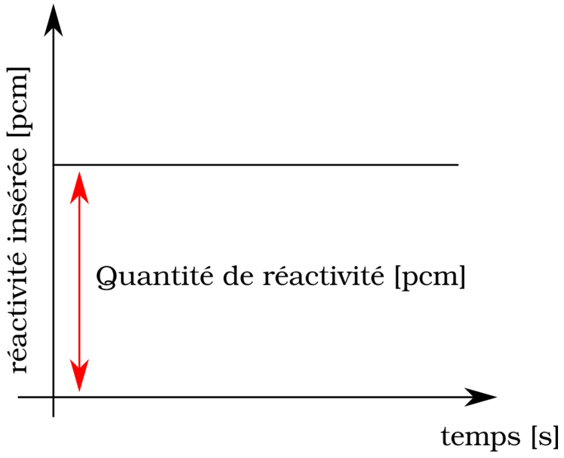
→ Impact of safety valve opening, of draining, of relief devices and what are the threshold that should not be exceeded.



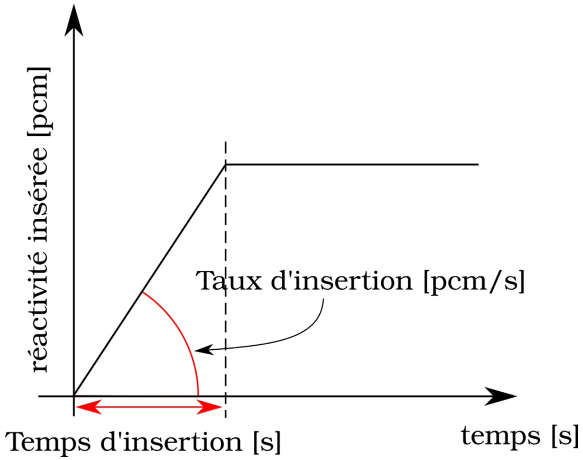
Thèse T. Lemeute

Hypothetical reactivity insertions (decoupled approach)

- Step :



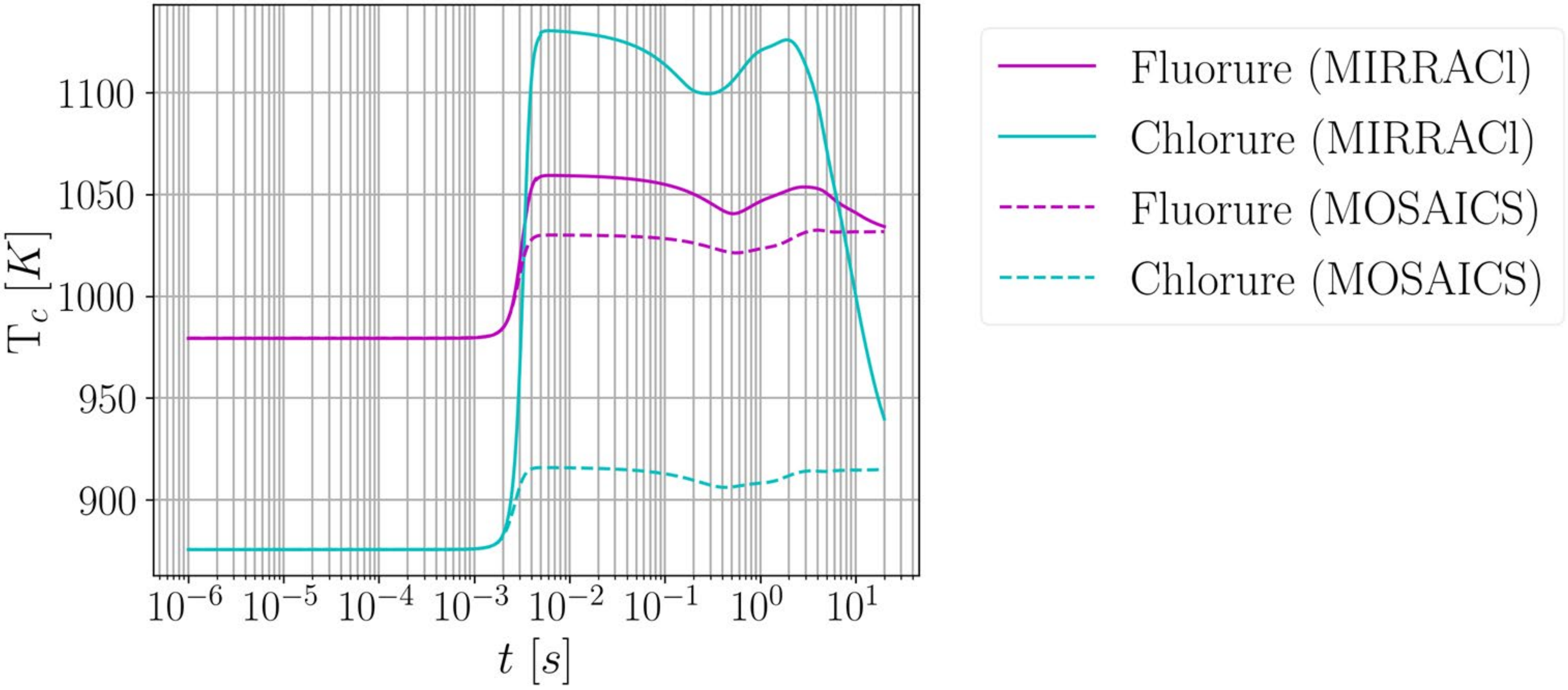
- Ramps :



- Assessment of Ma_{eq} :
  - MOSAICS : maximum value of Ma_{eq}
    - Defines the need to shift towards a compressible flow model or not
- Assessment of the compressible flow:
  - MIRRACl (MOSAICS/COCCINELLE): sensitivity studies

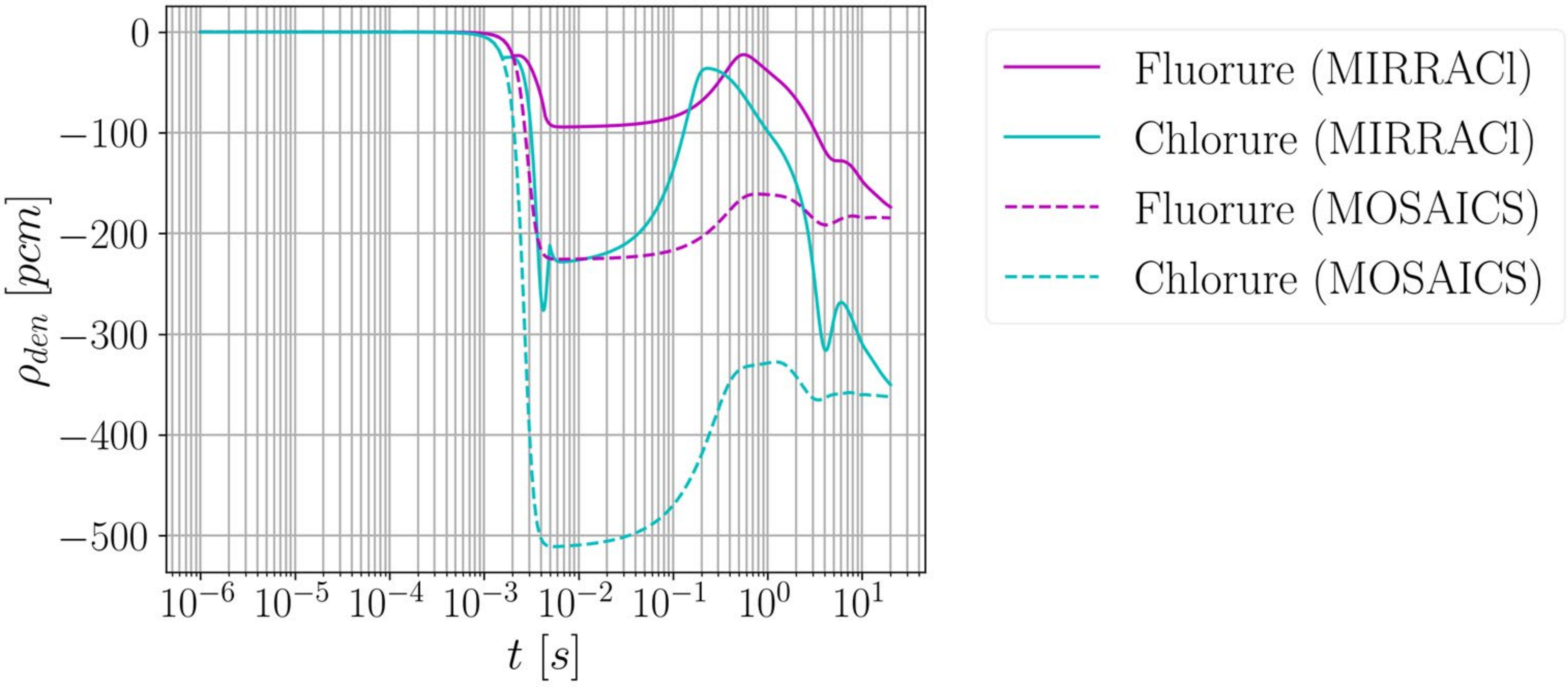
COMPRESSIBILITY EFFECTS

- Insertion of a 400 pcm step
- Difference between chloride and fluoride
  - Average temperature of the salt in the critical zone



COMPRESSIBILITY AND MAGNITUDE OF REACTIVITY FEEDBACK EFFECTS

- 400 pcm inserted as a step
- Differences between chloride and fluoride
  - Density reactivity feed-back



EFFECT OF DOPPLER FEEDBACK

- 400 pcm inserted
  - Doppler reactivity feed-back

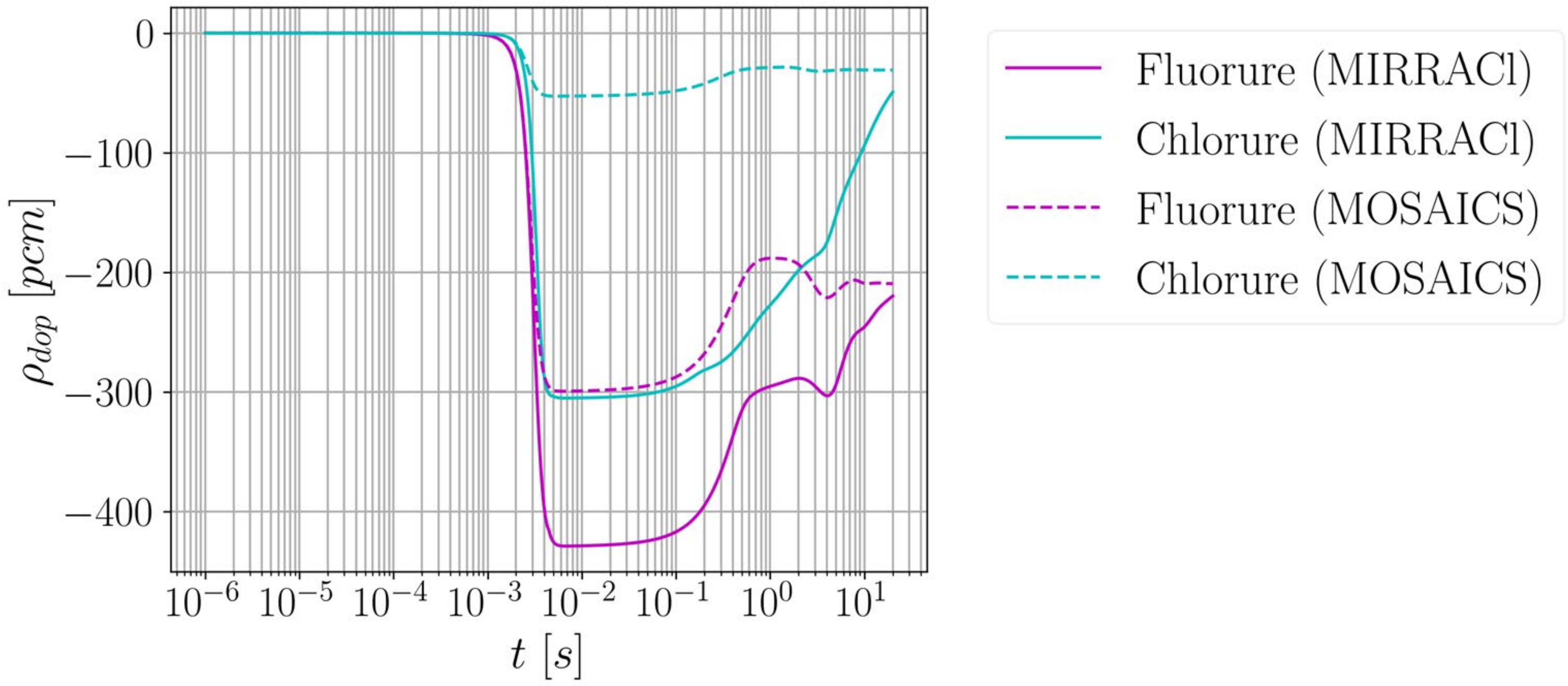
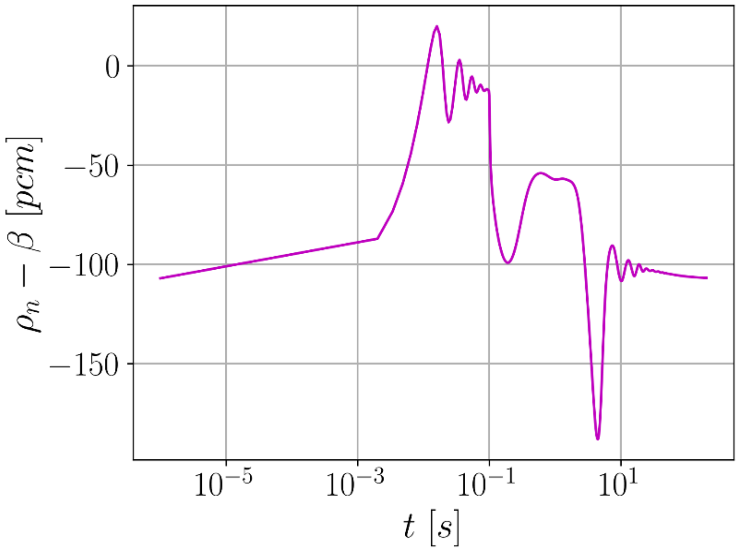
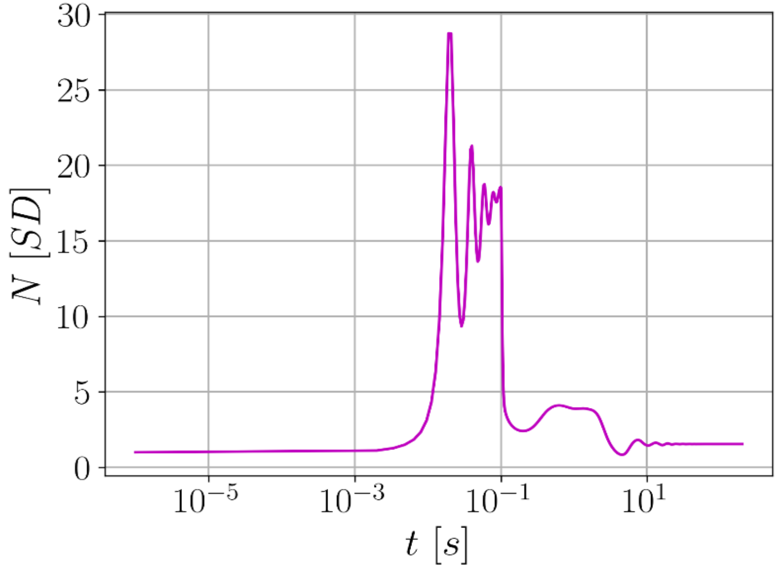
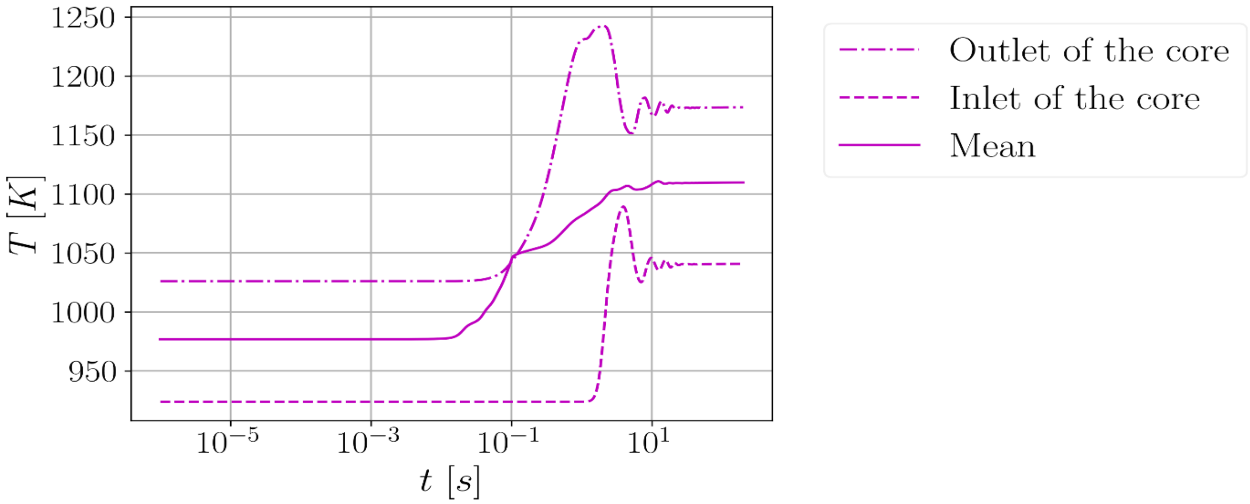


ILLUSTRATION OF REACTIVITY INSERTION RAMP

- 1000 pcm in 0.1 s







Conclusions and prospects

- Consideration of compressibility :
  - Dicrease of density stabilazing effect
    - Power increases more → T is higher → higher Doppler reactivity feed-back
  - Larger power increase
    - Larger temperature excursion
- Differences chloride fluoride :
  - Different neutron physic parameters → different transients
- Prospects (PhD Anna Maître: collaboration CNRS/CEA)
  - A single tool will encompass incompressible and compressible models → pressure/accoustic waves at the system scale and no shift on a Mach number criterion
  - Refinement of TH (Two-phase) and neutron physics models (variable flux shape) and more robust validation of models
  - Concept of the French burner will studied (chloride salt loop reactor)