Design and safety studies of the MSFR draining system

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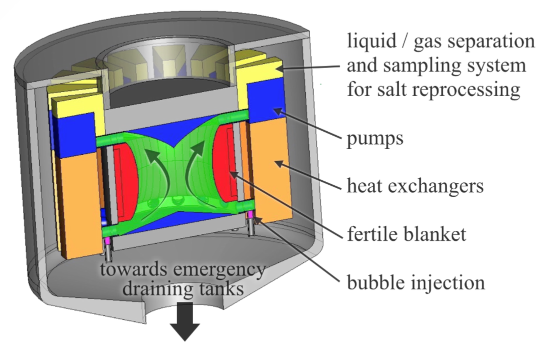
1 MSFR safety



- MSFR: Molten Salt Fast Reactor
  - Liquid circulating fuel in the form of a molten salt
  - Fast neutron spectrum
  - Breeder reactor
  - Thorium fuel cycle
- Safety analysis on-going within SAMOFAR WP1

- A few results of the MSFR safety analysis:
  - Postulated Initiating Events leading to accidental conditions
  - Lack of information on system design or procedures
  - The phenomena and accidental transient to be studied
  - Components/systems playing a major role for safety

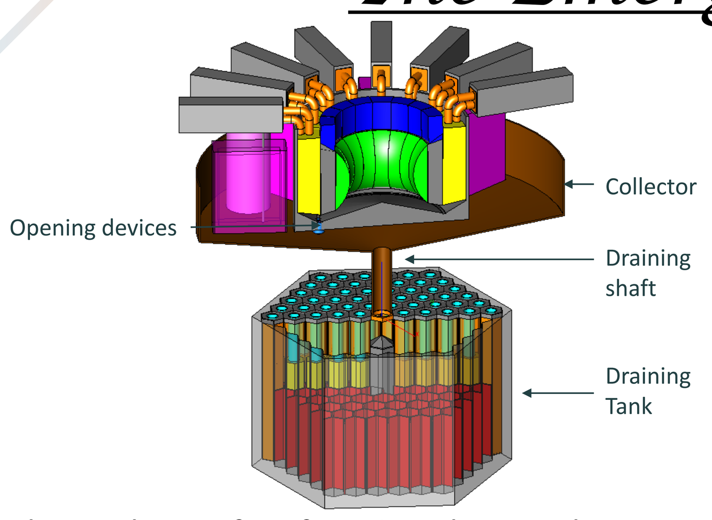
See the poster of Anna-Chiara Uggenti and Brian-May Sorby for the safety analysis application

Those systems have to be designed and studied in order to asses their ability to achieve the required safety functions

The Emergency Draining System is one of the systems identified as important for safety:

- It is useful in numerous accidental sequences
- Its triggering prevents the damage to the core structural materials (e.g. due to high temperatures)

2 The Emergency Draining System



- In case of severe anomaly, draining of the fuel into the Emergency Draining Tank (EDT) located under the core
- EDS sub-systems
  - Opening devices at the bottom of the core
    - Active systems
    - Passive systems activated by an excessive fuel temperature
  - Transfer system (collector + draining shaft)
  - Emergency Draining Tank

Redundant and reliable systems

- The nuclear safety functions have to be ensured in the EDS:
  - The system must be subcritical
  - The system must be able to evacuate the residual power over a long time period (preferably passively as the state of the reactor is already degraded
  - The system must be leak-proof

To design the EDS to ensure the safety functions → Design studies

- Over-accidents associated to EDS
  - LOHS - Loss Of Heat Sink
  - LOLF - Loss Of Liquid Fuel
  - DBA – Draining Blockage Accidents

To study accidental situations in order to incorporate sufficient safety margins → Safety studies

3 Draining plug

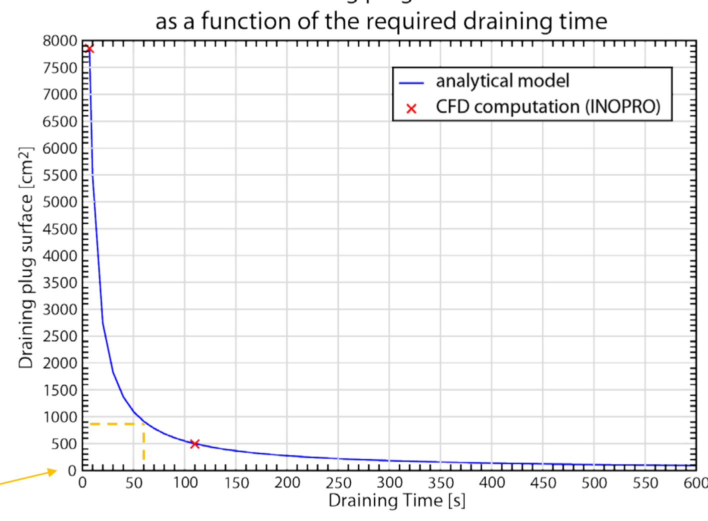
The fuel evacuation from the core to the EDS must be fast enough to prevent structural damages to the core due to high temperatures → Sizing of the openings through the collector to allow a fast draining

- Analytical model based on Torricelly law
- Fuel circuit assimilated to a cylindrical tank of height 2,2m and 18m^3 volume

$$S_2 = \Pi . r_1^{\,2} . \sqrt[2]{\frac{2.h}{g}} . \frac{1}{T} \quad \text{with} \quad r_1 = \sqrt{\frac{18}{h.\Pi}}$$

- h: core height =2,2 m
- g: gravity
- T: draining Time
- r_i:radius (i=1 core, i=2 plug)
- s_i: section (i=1 core, i=2 plug)

Draining plug surface as a function of the required draining time



- **Example: Draining time = 60s**
  - Corresponding fuel temperature elevation : 40°C < ΔT < 180°C
  - draining surface = 915.3 cm² ⇔1 plug of 17.1 cm radius or 16 plugs of 4.3 cm

Residual power

Residual power and delayed fission in core (for ULOHS)

4 Criticality studies

Objectives of the studies:

Ensure that the chosen design is sub-critical
- Configuration is not fixed yet

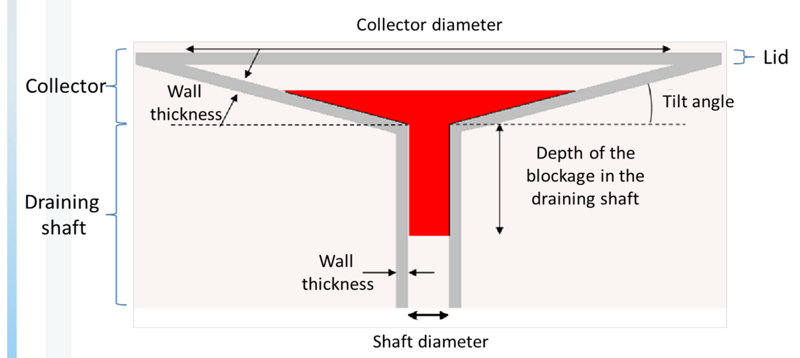
→ Find constraints on the geometry
- Do parametric studies

- Use of the Monte Carlo code **SERPENT2**
- Limiting criteria: **k_{eff} < 0.95**
  - Criteria used for normal conditions in fuel building and for radioactive package waste

5 Criticality study in the transfer system

- Studied case: Accidental case where a blockage prevents the fuel from flowing by and accumulation of fuel in the collector and in the draining shaft

Internship of Carole Seuvre



Transfer system geometry
- Shaft
  - Radius between 15 an 50 cm
  - Height between 1 and 2 meters
- Collector
  - Radius of 6 m imposed by the size of the structure located above

Simulation parameters
- Fuel volume equal to fuel circuit volume (18 m3)
- 30 cm wall thickness (conservative value)
- Lid added at the top of the collector to simulate the reflection by the structures above

- For a blockage between collector and draining shaft, previous studies have shown that the tilt angle should be less than 17° to respect the safety criteria
- Objective: determine if more constraining conditions can be found when the fuel is distributed between the collector and the shaft
- Configurations studied:
  - Shaft radius between 30 cm and 50 cm
  - Tilt angle 10°, 15°, 20°
- Variable parameters: depth of the plug in the shaft
  - Blockage at a given depth
  - Slow flow of the fuel

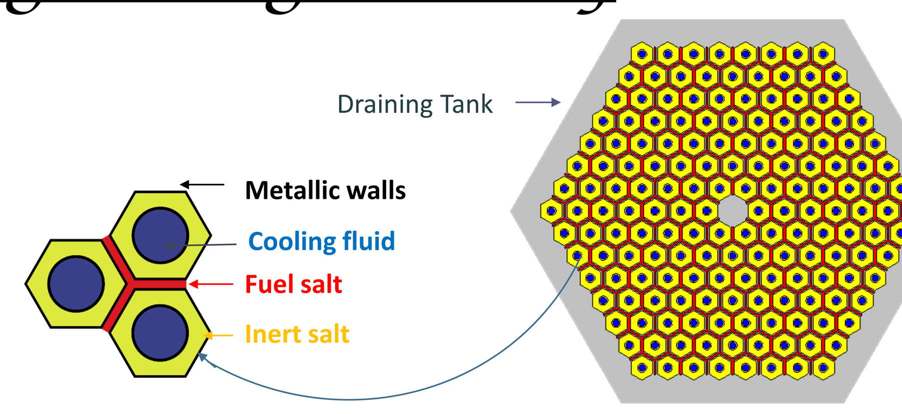
Shaft radius \ tilt angle		10°	15°	20°
30 cm	$k_{eff,max}$	0.90534	0.94298	0.96727
	Depth of the blockage	70 cm	50 cm	50 cm
	Δρ	+767 pcm	+439 pcm	+270 pcm
50 cm	$k_{eff,max}$	0.91894	0.94792	0.96925
	Depth of the blockage	130 cm	80 cm	70 cm
	Δρ	+3287 pcm	+1670 pcm	+984 pcm

- **Δρ:** increases with the shaft radius and decrease with the collector tilt angle

No reactivity increase above k_{eff} = 0.95 for tilt **angle lower than 15°**

6 Draining tank geometry

- Hexagonal tank
- Contains hexagonal cooling rods
  - Cooling fluid
  - inert salt
  - Metallic walls
- Fuel salt stored between cooling rods
- Central metallic hexagon to dispatch the salt
- Number of rows = number of cooling rods in one radius of the tank



What is the role of the inert salt?

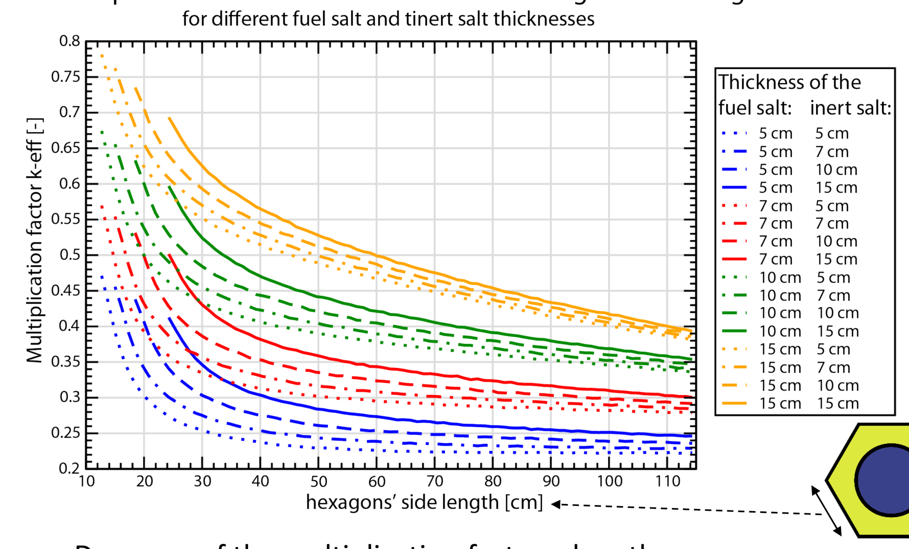
- Fusible material: store heat as latent fusion heat
- Reduce the power to be evacuated by the cooling system
- Increase the system's thermal inertia: maintain the fuel at liquid state as long as possible

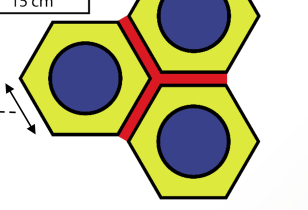
7 Criticality study in the draining tank

Objectives: ensure that the foreseen configurations for the EDT are subcritical => study of the multiplication factor as a function of the cooling rods side length for several geometries

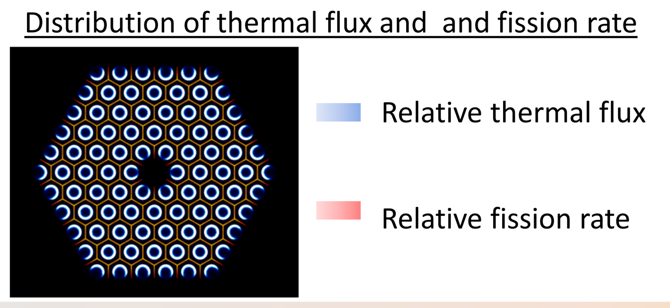
- Fixed parameter
  - Wall thickness: 3 cm
  - Number of rows: 5
- Configuration studied
  - Fuel salt layer thicknesses (5cm, 7cm, 10 cm, 15 cm)
  - Inert salt layer thickness (5cm , 7cm, 10 cm , 15 cm)
- Variable parameter
  - Hexagon side length

Multiplication factor as a function of the hexagons' side length for different fuel salt and tinert salt thicknesses





Distribution of thermal flux and and fission rate

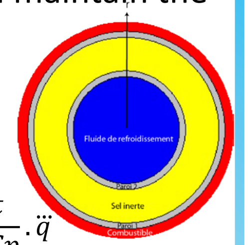


- Decrease of the multiplication factor when the size of the hexagons increases or when the amount of inert salt increases
- Increase of the criticality with the fuel salt layer thickness
- All configurations ensure sub-criticality with a sufficient margin even the most constraining ones (15 cm fuel salt)

The sizing is limited by the thermic and not the neutronics

8 Thermal studies in the draining tank

Objective: Design a system able to evacuate residual heat on a long period of time and maintain the fuel at liquid state as long as possible



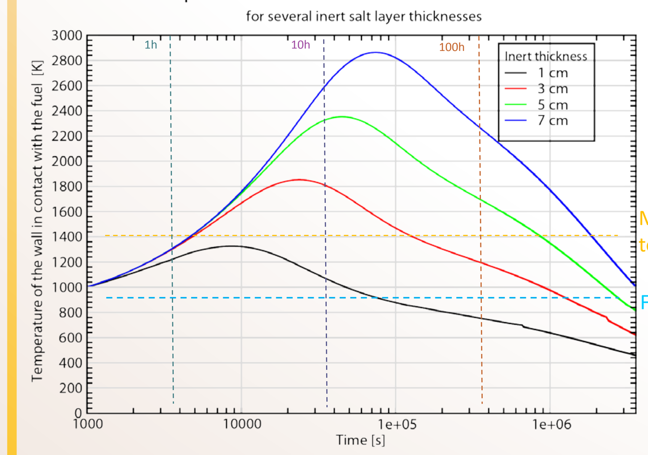
Model:

- Thermal conduction in 1D cylindrical geometry ⟹ Very conservative hypothesis

$$T_i^{N+1} = \frac{\Delta t.k}{\rho.Cp}.\left(\frac{1}{\Delta r^2} + \frac{1}{2.r.\Delta r}\right).T_{i+1}^N + \left(1 - \frac{2.k.\Delta t}{\rho.Cp.\Delta r^2}\right).T_i^N + \frac{\Delta t.k}{\rho.Cp}.\left(\frac{1}{\Delta r^2} - \frac{1}{2.r.\Delta r}\right).T_{i+1}^N + \frac{\Delta t}{\rho.Cp}.\ddot{q}$$

- Explicit Euler numerical scheme
- Inclusion of inert salt melting and freezing

Temperature of the wall in contact with the fuel for several inert salt layer thicknesses

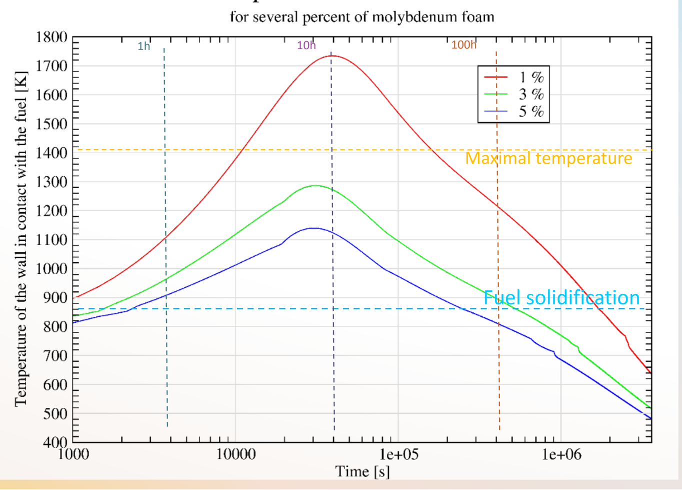


Only solution under maximal limit temperature is the one 1 cm inert salt; the fuel remains liquid only 1day 8h.

→ Take into account natural convection in fuel and inert salts

→ Improve the conduction in the inert salt layer

Evolution of the temperature of the wall in contact with the fuel for several percent of molybdenum foam



- Insertion of metallic foam in the inert salt simulated as an homogeneous mixture of metal and salt
- Advantage: with only 3% of Molybdenum the fuel stays below the limit temperature and solidifies after 6 days 5h.
- Drawback: Eliminate the possibility to have natural convection in the inert salt

9 Conclusions and perspectives

Opening devices
- The size of the opening device can be selected depending on the limit fuel temperature elevation
- Better estimation of the temperature elevation during draining to be performed (WP4)

Transfer system
- Sub-criticality with sufficient safety margin ensured for tilt angle of the collector lower than 15°
- Draining time through the transfer system and corresponding temperature elevation to be studied (EDF)

Emergency draining tank:
- The foreseen configuration of the EDT are largely subcritical
- The design of the EDT is more constrained by thermics than by neutronics
- Detailed studies to be performed with Fluent/Simmer to take into account the natural convection of the salt (CNRS/KIT)