# Multiphysics Severe Accident simulation (SIMMER code)

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IAEA National training course on Heavy Liquid Metal Cooled Fast Reactors: Benefits and Challenges

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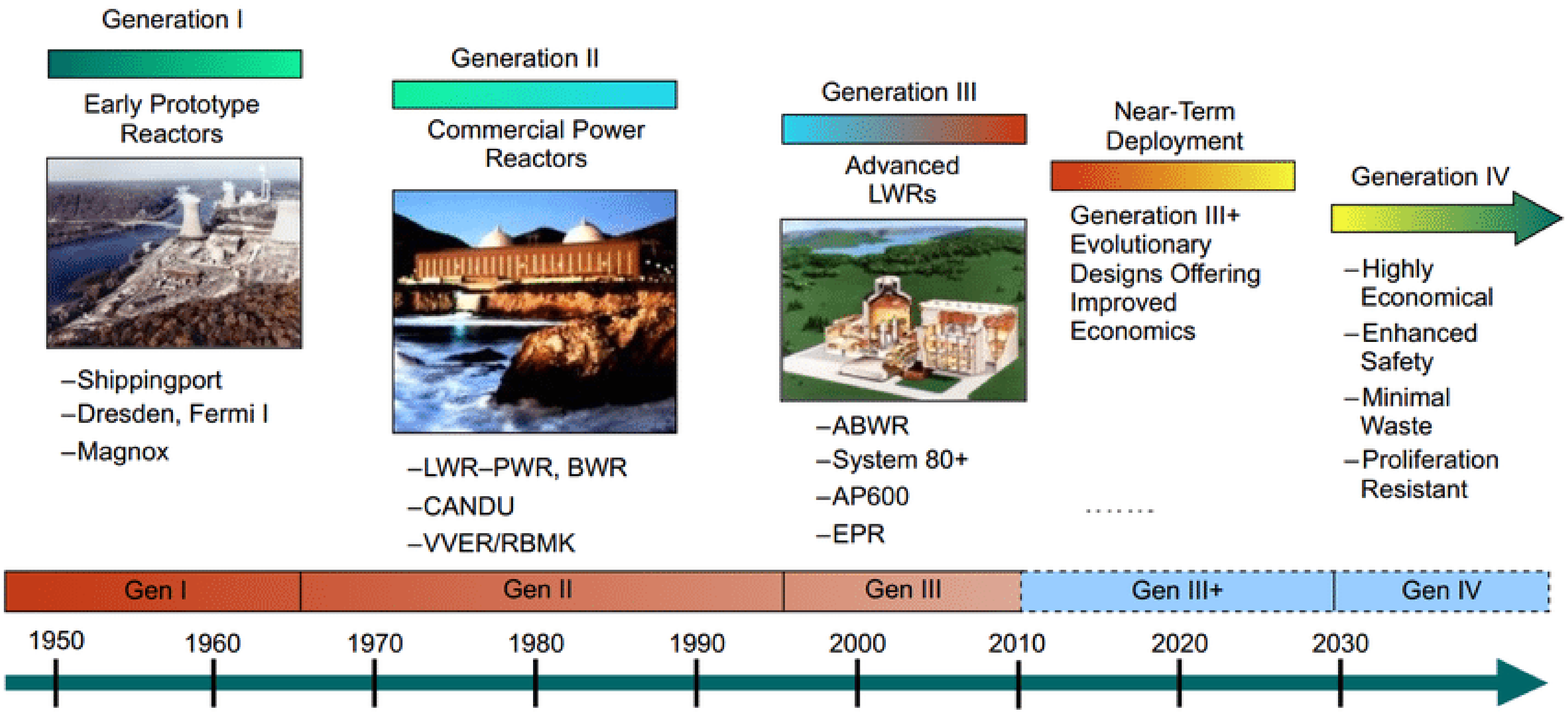
IAEA

# LMFR safety approach: background




DOI:10.13140/RG.2.2.26088.01281

# LMFR safety approach: background

### Sustainability 1

Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production.

### Sustainability 2

Generation IV nuclear energy systems will minimise and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.

### Economics 1

Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

### Economics 2

Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

# LMFR safety approach: background

| Safety & Reliability 1 | Safety & Reliability 2 | Safety & Reliability 3 | Proliferation Resistance & Physical Protection |
|---|---|---|---|
| Generation IV nuclear energy systems operations will excel in safety and reliability. | Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage. | Generation IV nuclear energy systems will eliminate the need for offsite emergency response. | Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism. |

# LMFR safety approach: background

**Fundamental Safety Function (Req. 4 SSR-2/1)**

1. **control of reactivity**
2. **removal of heat** from the reactor and from the fuel store
3. **confinement of radioactive material**, shielding against radiation and control of planned radioactive releases, as well as limitation of accidental radioactive releases

**LMFR – List of events**

- Reactivity and power distribution anomalies
- Increase in heat removal from primary system
- Decrease in heat removal by Secondary System
- Decrease in Primary Coolant System Flow Rate
- Decrease in Primary Coolant Inventory
- Challenges to reactor Building

**Challenges to:**

- Heat generation balance
- Heat removal balance
- Integrity of physical barriers against releases

# LMFR safety approach: background

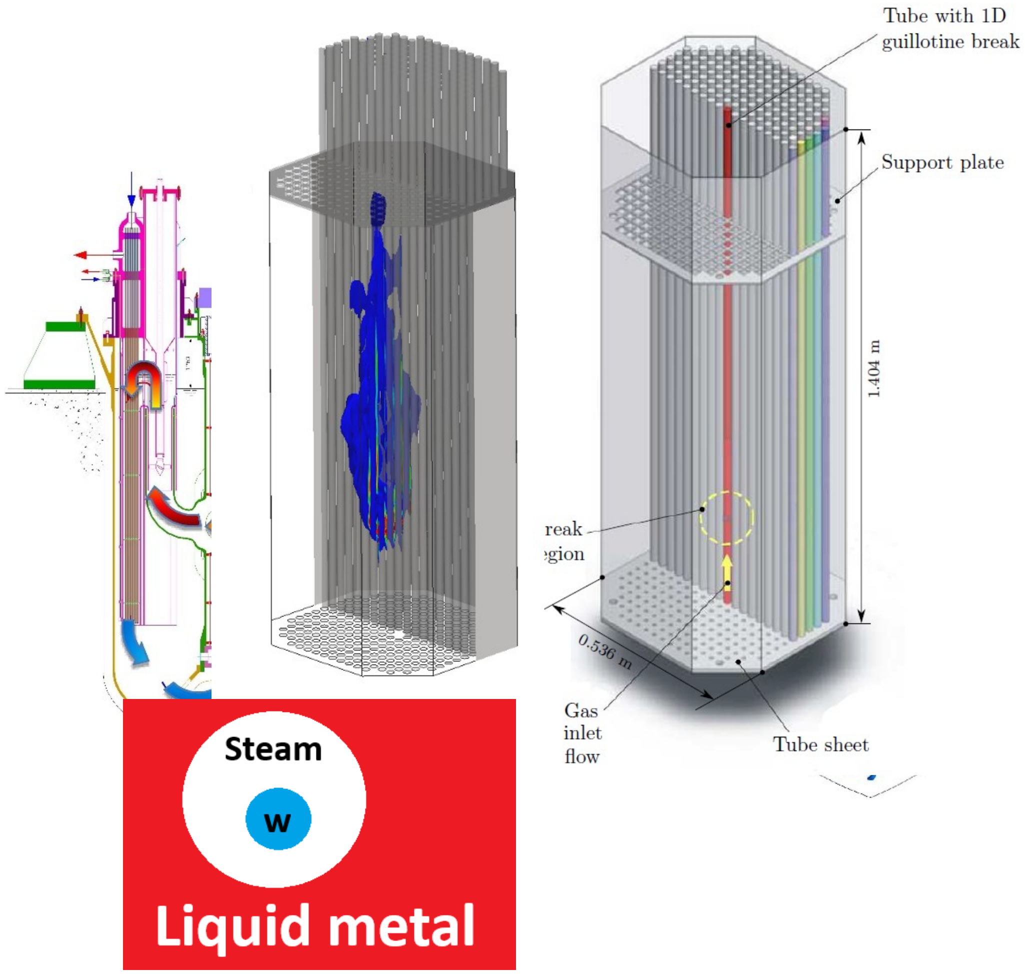
## Initiators for transient conditions (SFR)

- Protected
- Unprotected: *"Unprotected transients, also called anticipated transients without scram (ATWSs) are a group of design extension conditions (DECs) that can significantly challenge sodium cooled fast reactor (SFR) safety and are used to categorize the higher probability core disruptive accident (CDA) initiators. This category results from the observation that a small group of <u>low probability events combined with a reactor protection system (RPS) failure</u> (**no reactor scram**) would lead to coolant boiling and a **core melting scenario**."* (from "IAEA NUCLEAR ENERGY SERIES No. NR-T-1.16")

# LFR safety: possible initiators

## Steam Generator Tube Rupture (SGTR)

- Safety issues: water interaction with lead
  - formation and propagation of pressure waves due to dynamic interactions between the discharged jet flow and molten lead
  - formation and expansion of the mixing zone leading to pool sloshing
  - pre-mixture entering a coolant-coolant interactions (CCI) regime leading to a steam explosion
  - water evaporation results in Reactor Vessel pressurization
  - steam transport toward the reactor core with potential reactivity insertion




ALFRED reactor - https://doi.org/10.1016/j.nucengdes.2019.110359; SGTR - https://www.psi.ch/en/sacre/projects/steam-generator-tube-rupture-sgtr

# LFR safety: possible initiators

## Transient OverPower (TOP)

- A TOP event is an accidental situation where the reactor's power output increases above normal levels, often caused by a positive reactivity insertion
- Examples from ALFRED:
  - Inadvertent control rod assembly withdrawal
  - Control rod assembly drop
  - Changes in core geometry due to earthquake
  - Fuel assembly loaded in an incorrect position
  - Fuel assembly loaded with incorrect composition
  - SG tube rupture
  - Fuel rod damage

# LFR safety: possible initiators

## Loss of Flow (LOF)

- The primary coolant stops circulating within the reactor core, the normal removal of heat is then interrupted, potentially leading to fuel overheating and damage
- Design provisions to prevent or mitigate the outcomes
  - The low vapor pressure and high boiling point of lead allow the reactor to operate at atmospheric pressure, minimizing the risk of explosive steam formation. This, along with lead's high heat capacity and thermal expansion properties, enables passive removal of decay heat through natural circulation
  - High Boiling Point of Lead far exceeds normal operating conditions, making coolant boiling an unlikely failure mechanism
  - Natural circulation of the lead coolant can establish a partial flow, removing heat and mitigating the event

# LFR safety: possible initiators

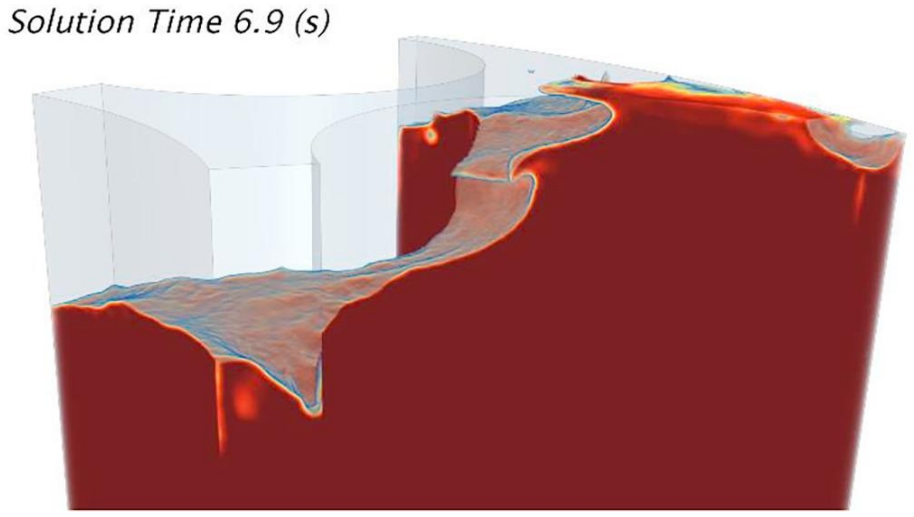
## Loss Of Heat Sink (LOHS)

- Scenario where the flow of coolant from the reactor to the final heat removal system is interrupted. This failure leads to an accumulation of heat within the reactor core, causing the lead coolant and fuel temperatures to increase

# LFR safety: possible initiators

## Sloshing

- Sloshing refers to the undesirable fluid motion of the high-density molten lead coolant during, e.g., seismic events. The high forces generated by sloshing and the inertia of the fluid can exceed the yield stress of the reactor vessel and internal structures, leading to plastic deformation or rupture. In addition, sloshing can entrain gas from the free surface into the molten lead, creating voids that can lead to changes in reactivity and deteriorating local heat transfer, both of which can lead to core damage



# LFR safety: possible initiators

## Channel blockages

- A channel blockage is an event where the flow of lead coolant through one or more fuel assemblies is obstructed, partially or totally, potentially causing fuel cladding failure, fuel assembly (FA) failure and core damage. These blockages can be caused by foreign objects or the accumulation of oxides and debris, and they are a significant safety challenge, requiring effective detection and mitigation strategies to prevent dangerous increase in local temperatures.

## Other safety considerations

**Core compaction following earthquakes**

- the rearrangement of fuel assemblies into a geometrically more compact configuration induced by earthquakes might lead to positive reactivity insertions

**Coolant freezing**

- the high melting point of the coolant can pose concerns related to the possibility of lead freezing/solidification: is this a safety issue or an investment protection issue?

**Structural erosion and corrosion**

- molten lead interacts with structural materials through corrosion at high-temperature and erosion

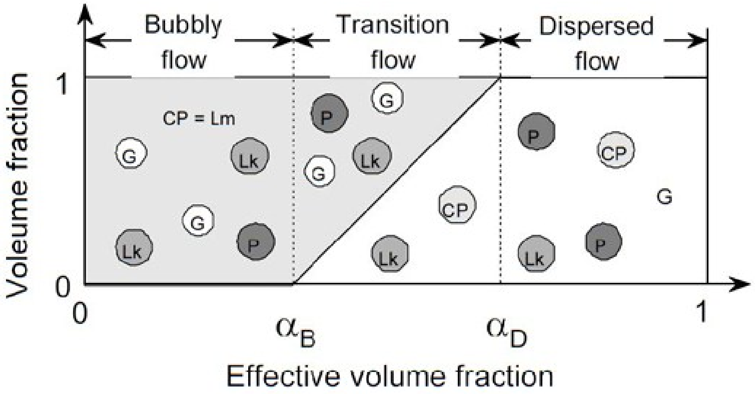
# Safety analysis: SIMMER code

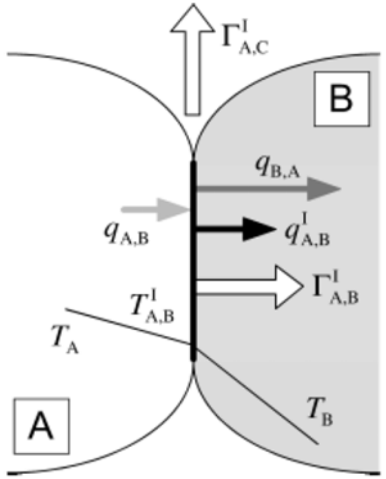
**SIMMER-III/IV are 2D and 3D fluid dynamics codes coupled with a structure model and a space-, time- and energy-dependent neutron dynamics model**

## Fluid Dynamics

- 8 velocity fields (7 for liquid, 1 for gas)
- Multi-phase, multi-component flow
- Phase transitions
- Flow regime (pool-channel)
- Interfacial area tracking
- Elaborate EOS (various fuels, coolants and gases)
- Heat and mass and momentum transfer

| | | EOS sub-materials | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| EOS materials | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | fuel* | MOX | $UO_2$ | C-100 | C-8416 | C-50 | C-22 | MSRE | MSBR |
| 2 | steel | 316SS | 316SS | | | | | | |
| 3 | coolant* | sodium | water | lead | LBE | LBE** | | | |
| 4 | control | $B_4C$ | $B_4C$ | | | | | | |
| 5 | fission gas | Xe | air | | | | | | |



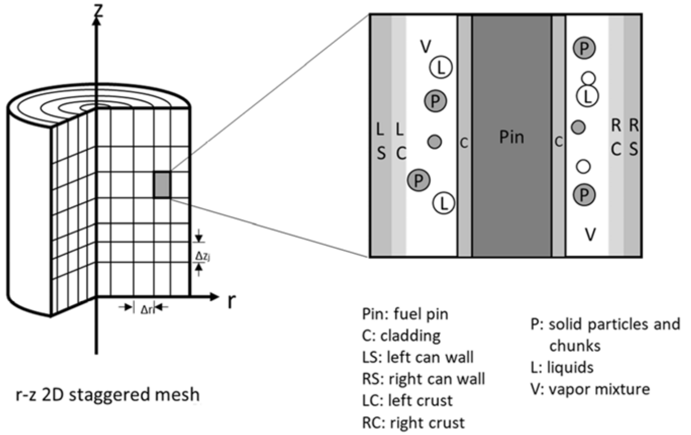



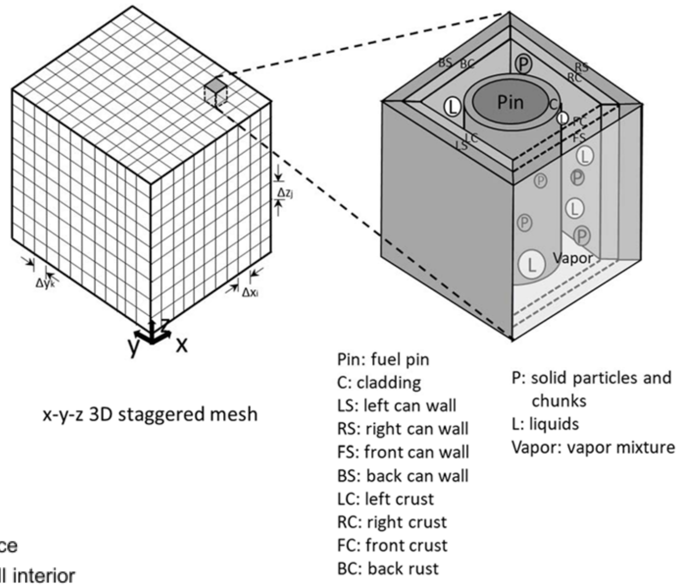

DOI:10.11484/jaea-research-2024-008

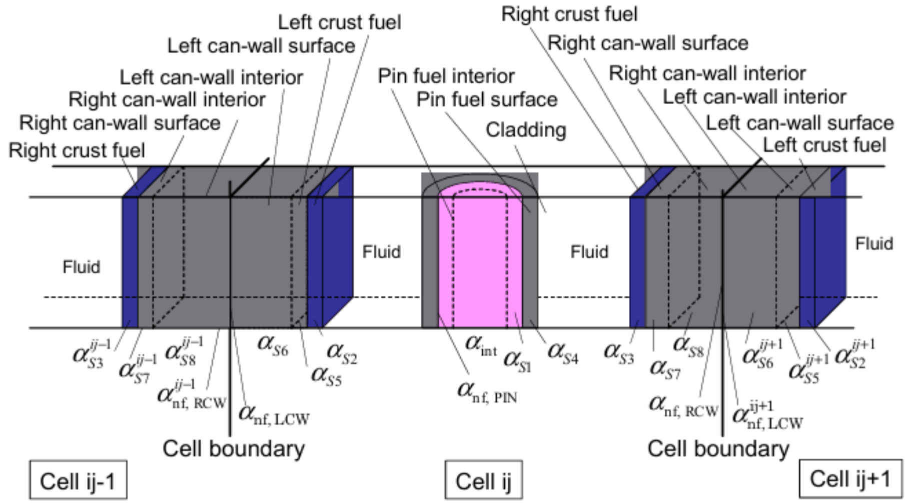
# Safety analysis: SIMMER code

## Structure model

- General structure model
- Pin models
- Advanced fuels
- Loop model (IHX & pumps)
- Axial + radial heat transfer
- Virtual structure model
- Structure disintegration
- Freezing on structures




*DOI:10.11484/jaea-research-2024-008*

# Safety analysis: SIMMER code

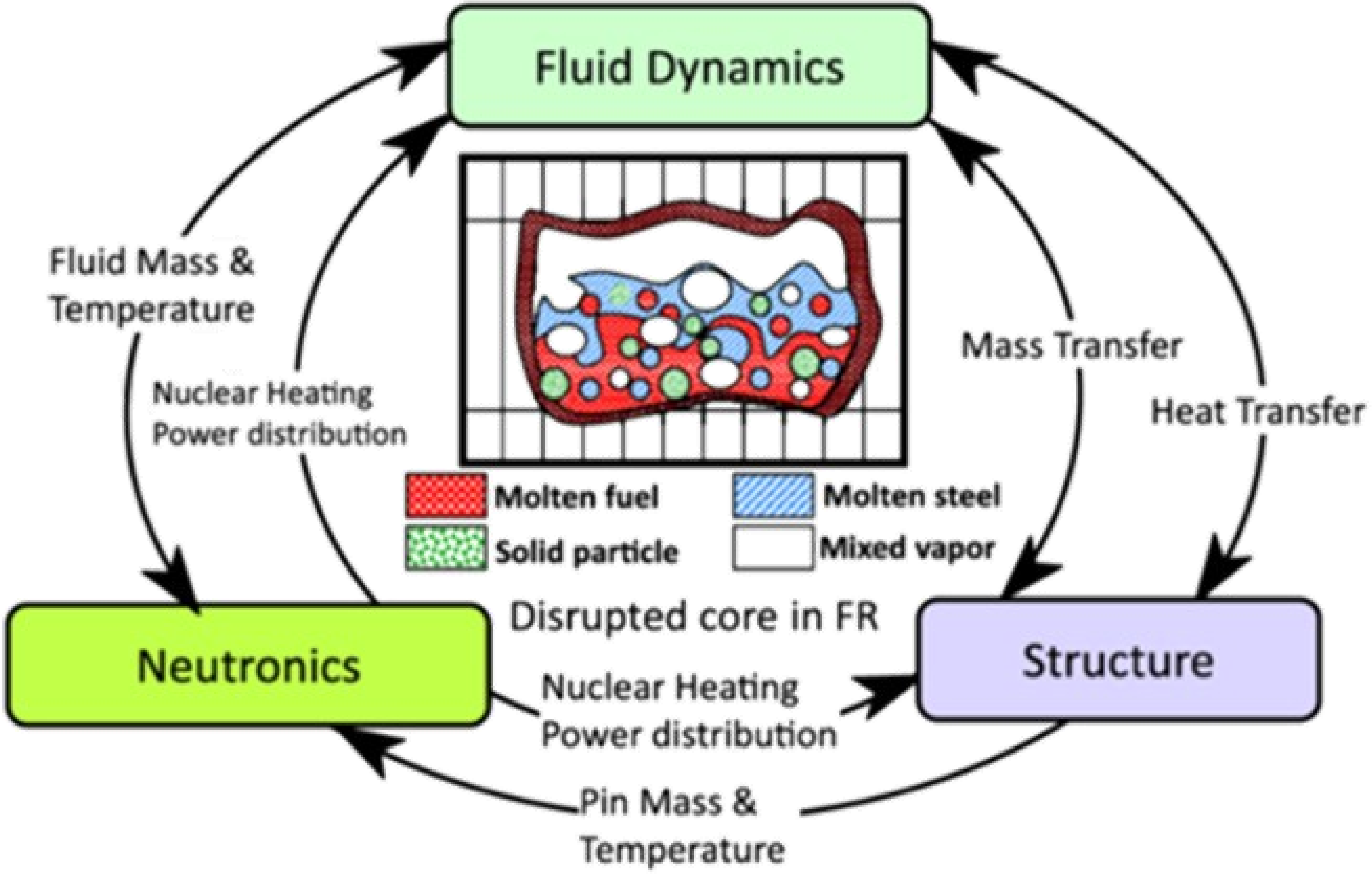
**Neutronics**

- Neutron transport theory
- Improved quasi-static method
- Cross-section generation
- Heterogeneity treatment
- Decay heating
- External neutron source
- Precursor movement

- An advanced neutron transport model based on the diffusion-synthesis acceleration method of TWODANT is coupled with SIMMER-III.
- The SIMMER-IV neutronics module with the THREEDANT model.
- Major improvements from the former SIMMER-II, in addition to the flux shape solution method: the neutron up-scattering capability for possible application to thermal neutron systems, and the treatment of an external neutron source for simulating sub-critical systems.
- Other neutronics-related models are: a simple decay heat model based on the SAS4A modeling, and the specified power history capability without neutronics calculation.

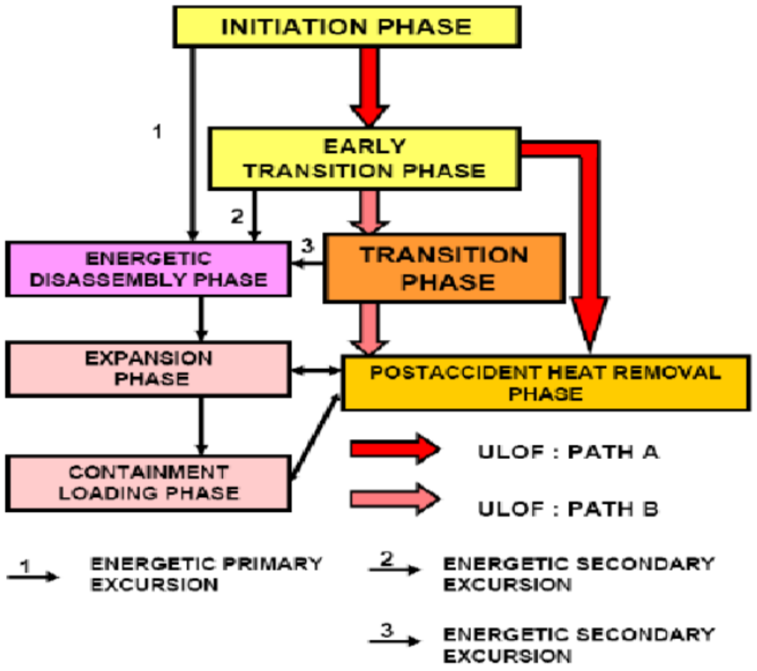
# Safety analysis: SIMMER code

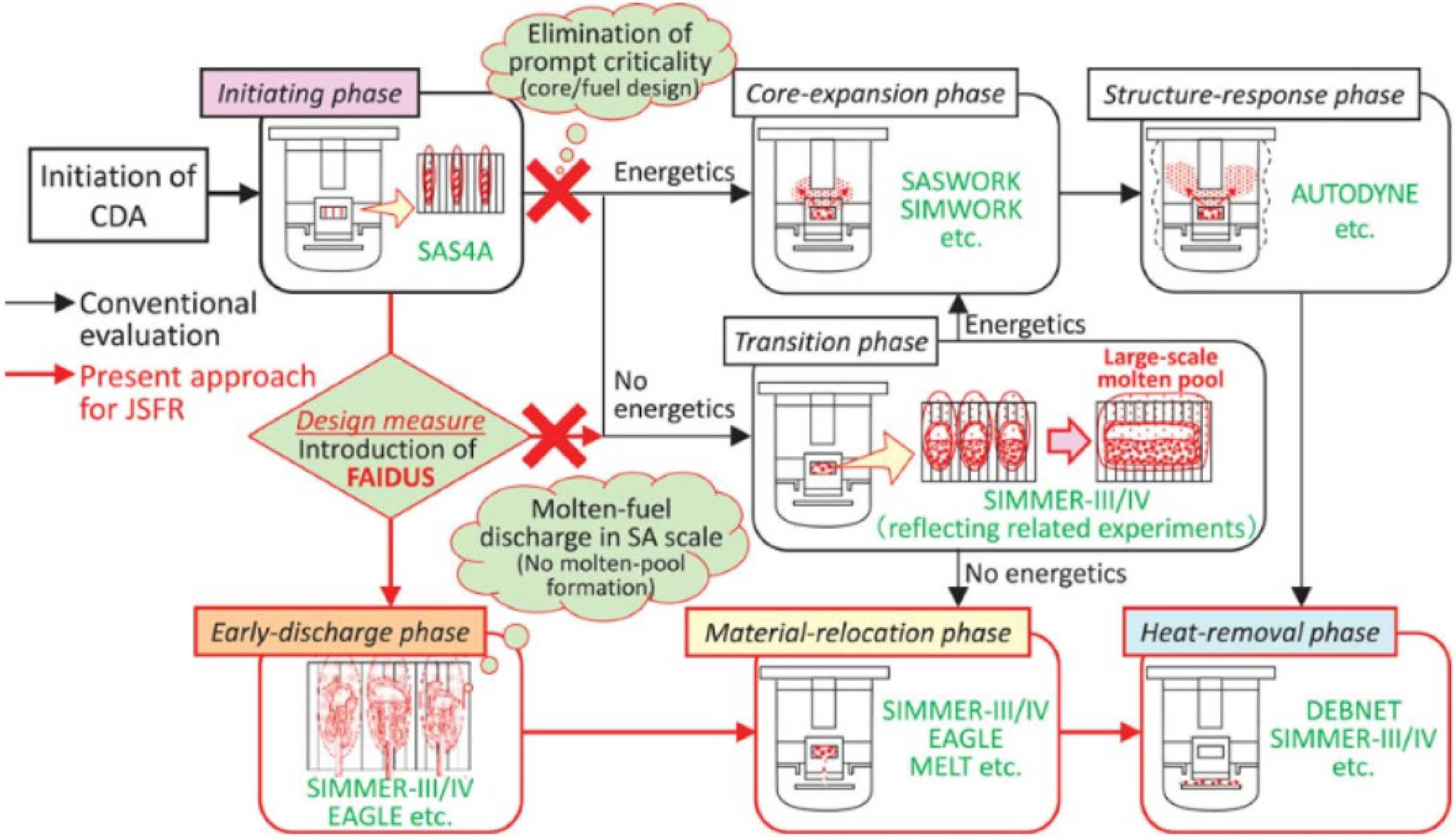
- Based on SIMMER-II
- Developed for CDA analysis of SFRs
- Multi-component, multi-phase, multi-velocity fields coupled neutronics/TH
- 2D and 3D version (SIMMER-III/-IV)
- Extensive validation for:
  - Basic phenomena modelling (Phase 1)
  - Integral experiments modelling (Phase 2)
- Renewed interest: SIMMER consortium in 2025, new SIMMER meeting in 2026




DOI:10.1016/j.net.2015.03.001

# SA progression and tools




doi:10.3390/su4061274 + http://dx.doi.org/10.1080/00223131.2013.877405

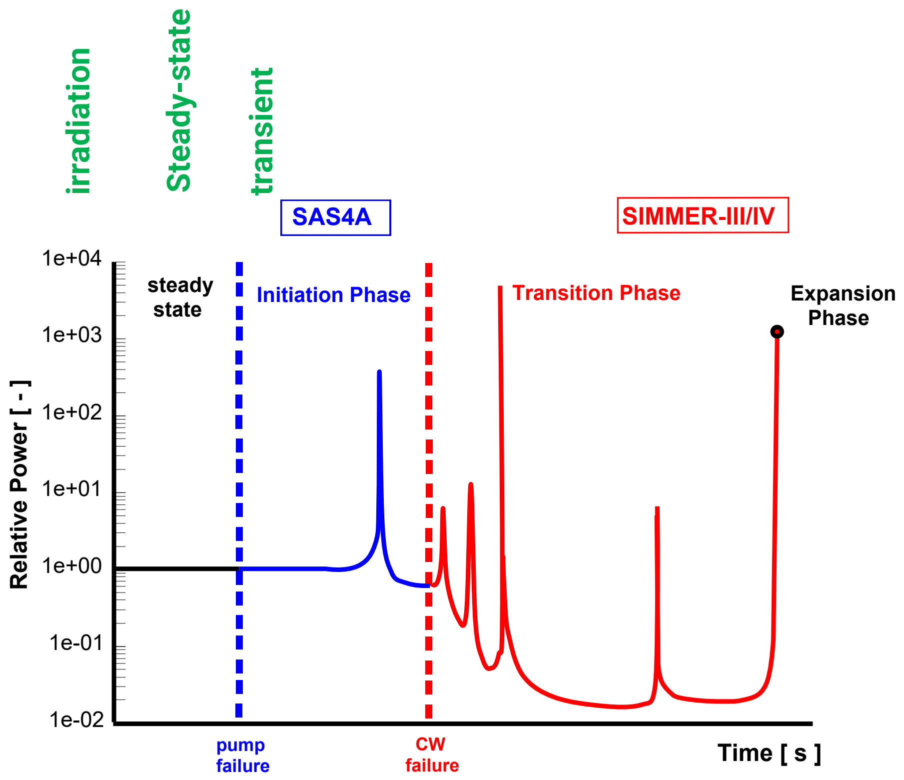
# SA initiating and progression

Modeling of **Initiation Phase (IP)** with **SAS-SFR**

- Multi 1D code
- Elaborate pin model
- Neutronics model: point kinetics

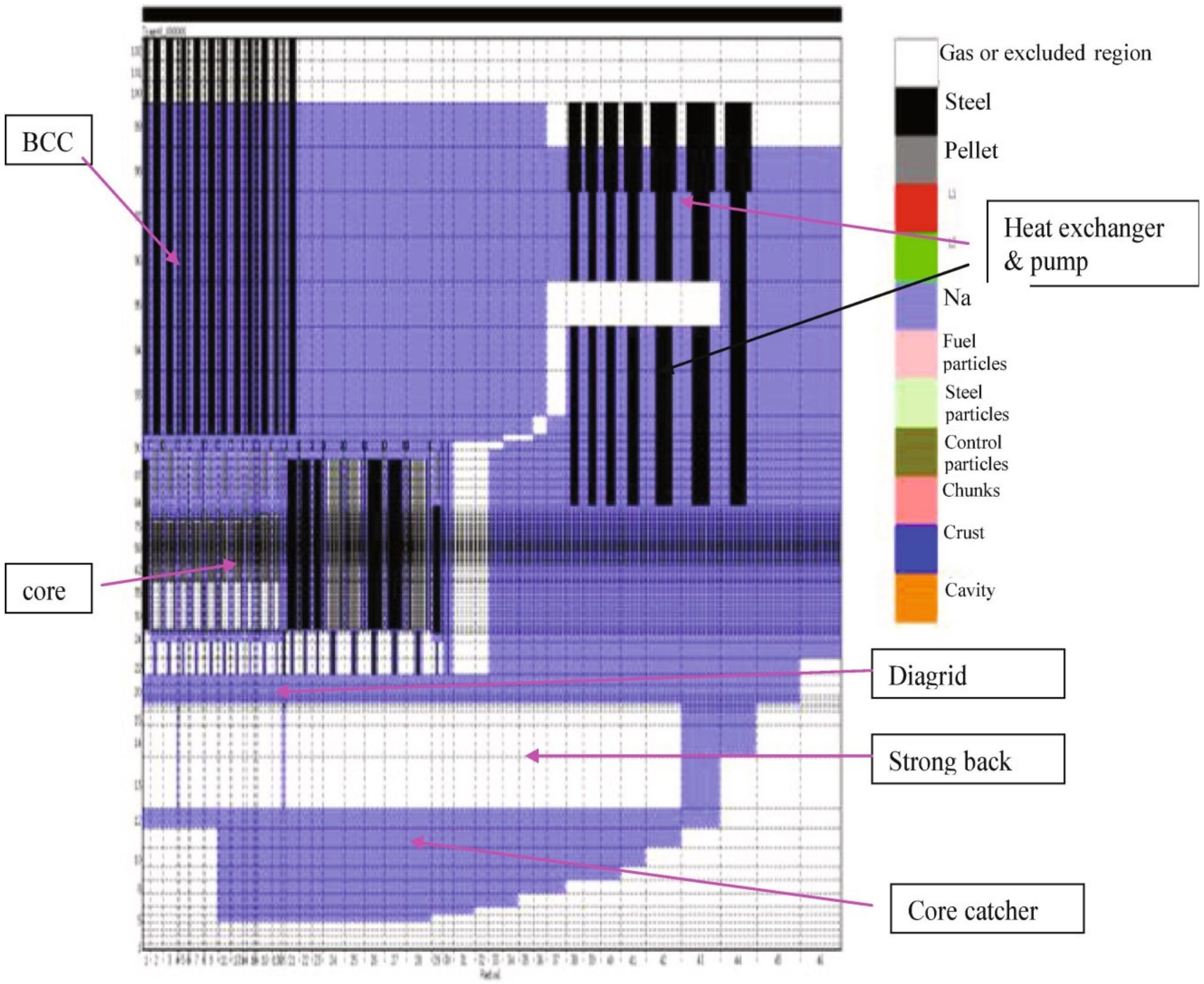
Modeling of **Transition Phase (TP)** with **SIMMER-III/IV**

- 2D/3D model
- General models for mat. movement & interaction
- Neutronics model: space-time kinetics



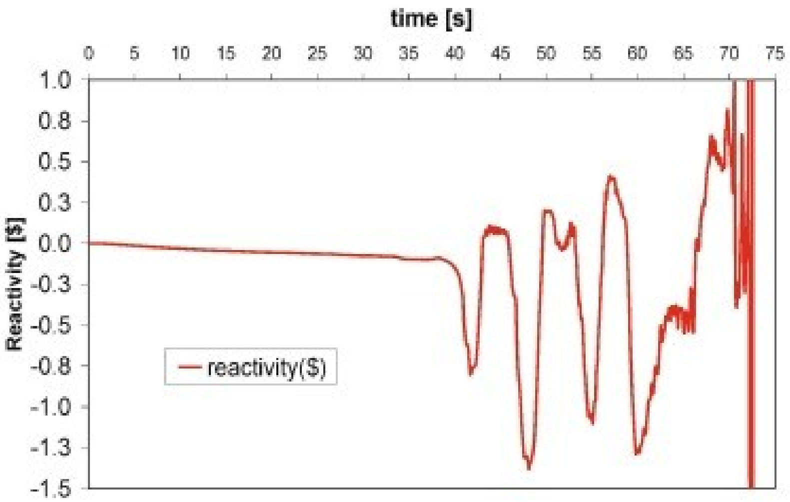
# SIMMER code calculation

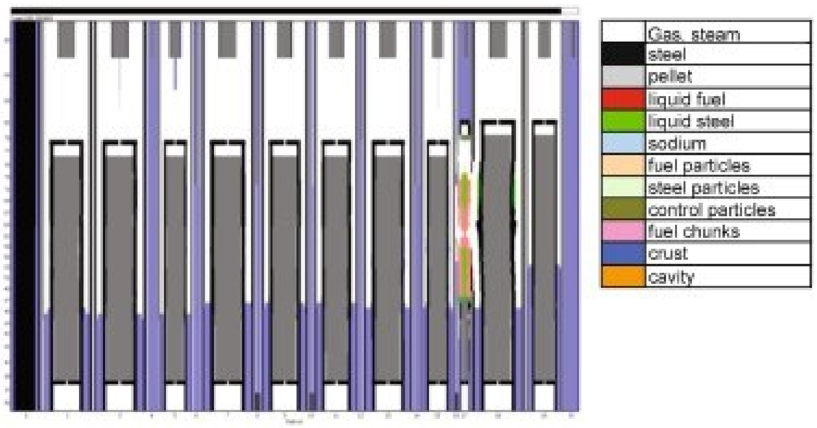
- Executable
- Input file
- Output files (TBD by the user)
- Restart files
- Postprocessor (reads selected variables from a specific output file) →

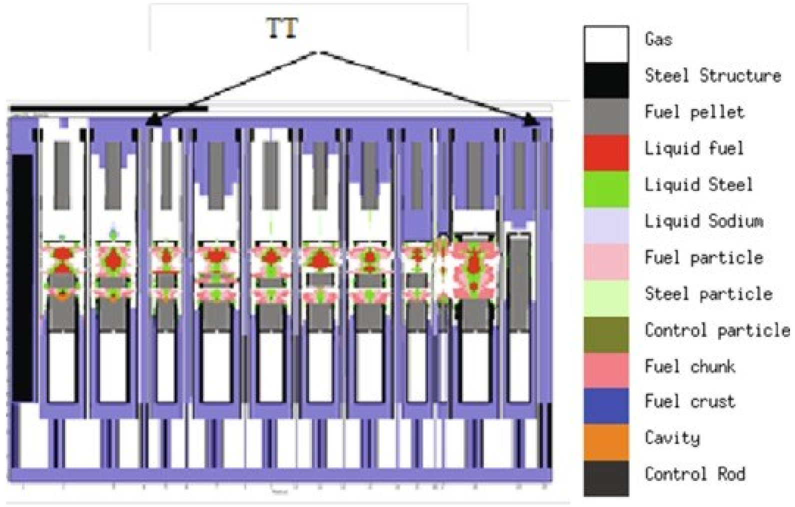



https://doi.org/10.1016/j.nucengdes.2020.111037

# SIMMER code calculation: SFR ULOF

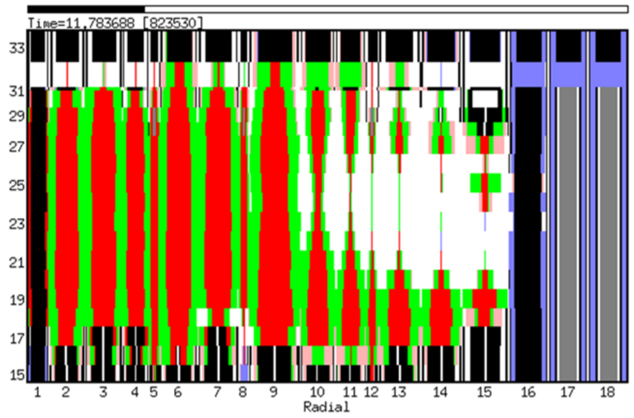


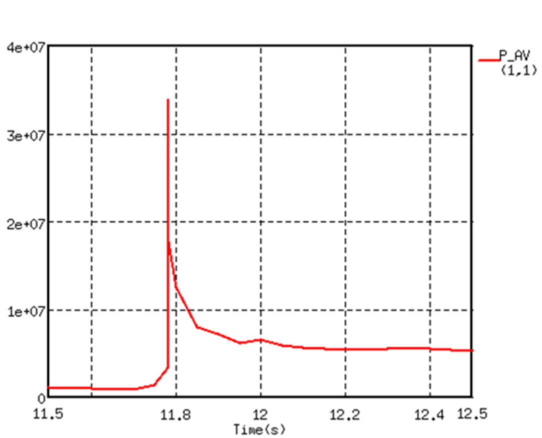




Initiation phase

Transition phase

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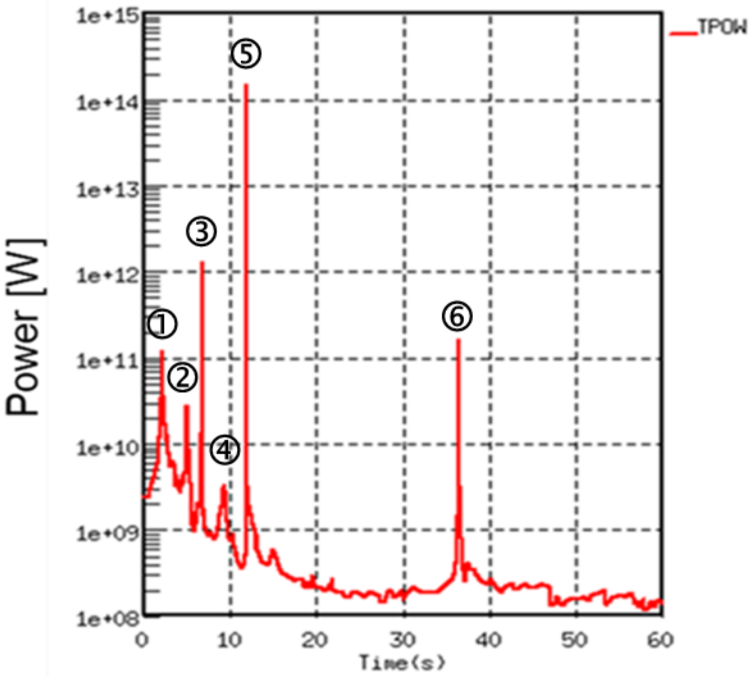
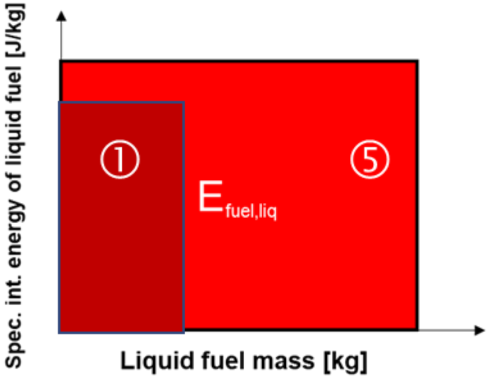
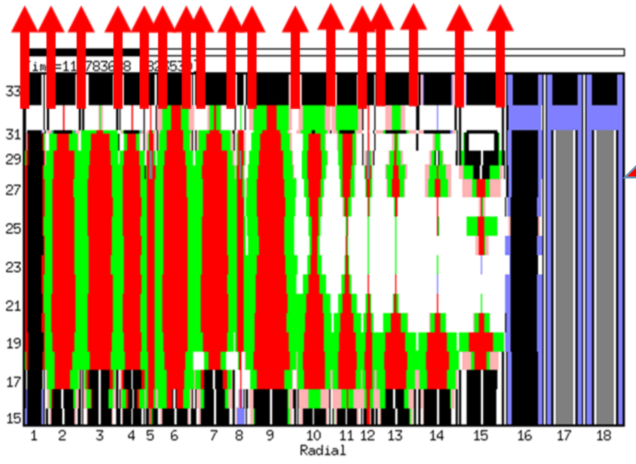
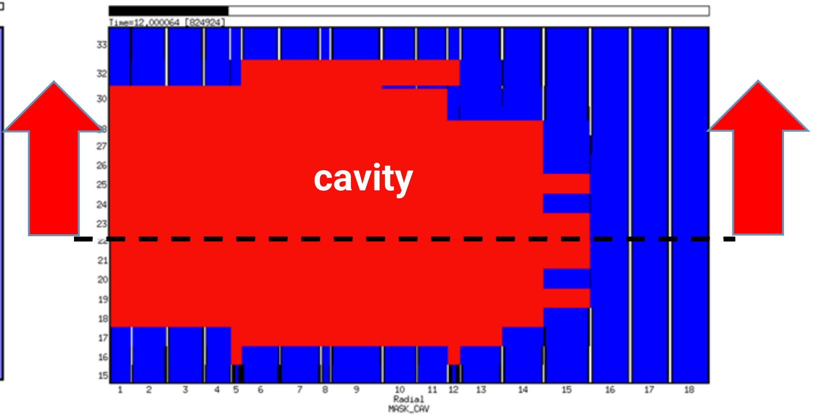
# Disassembly phase

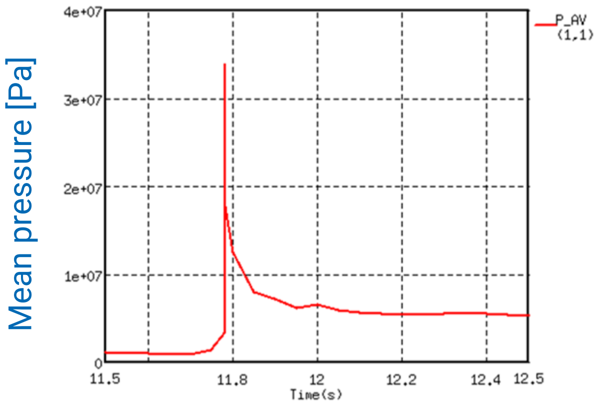


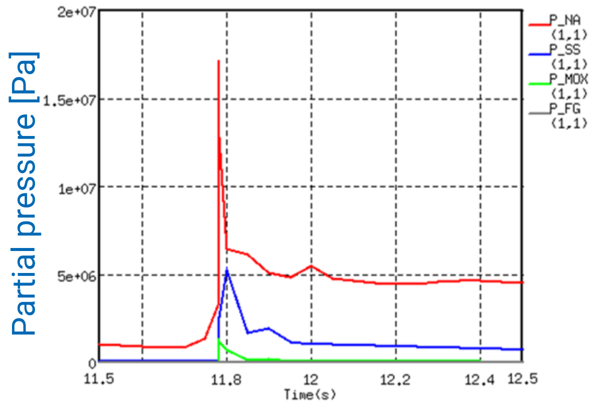

Judge by $M_{fuel,liq}$, $T_{fuel,liq}$, $p_{av}$, …



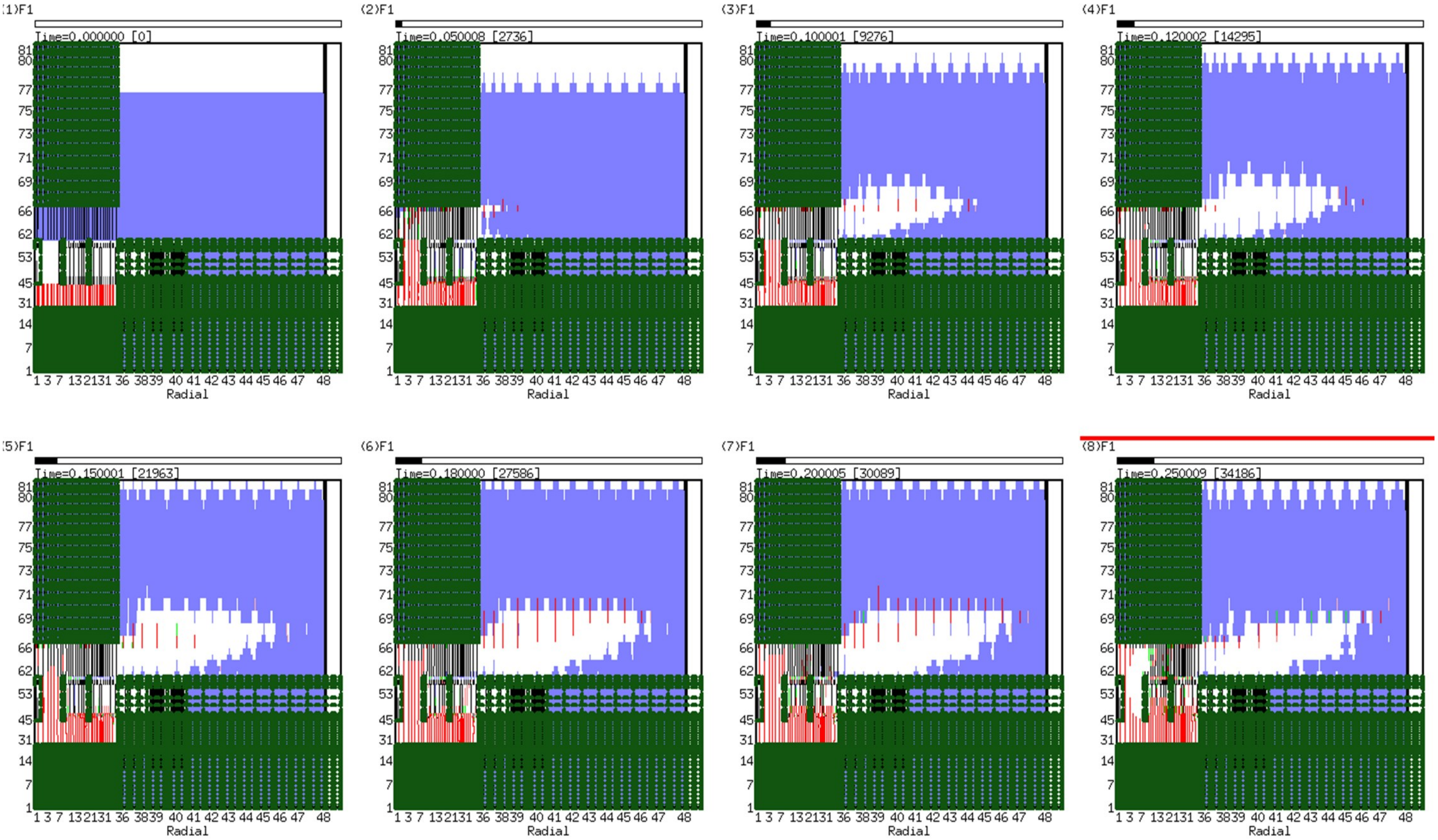



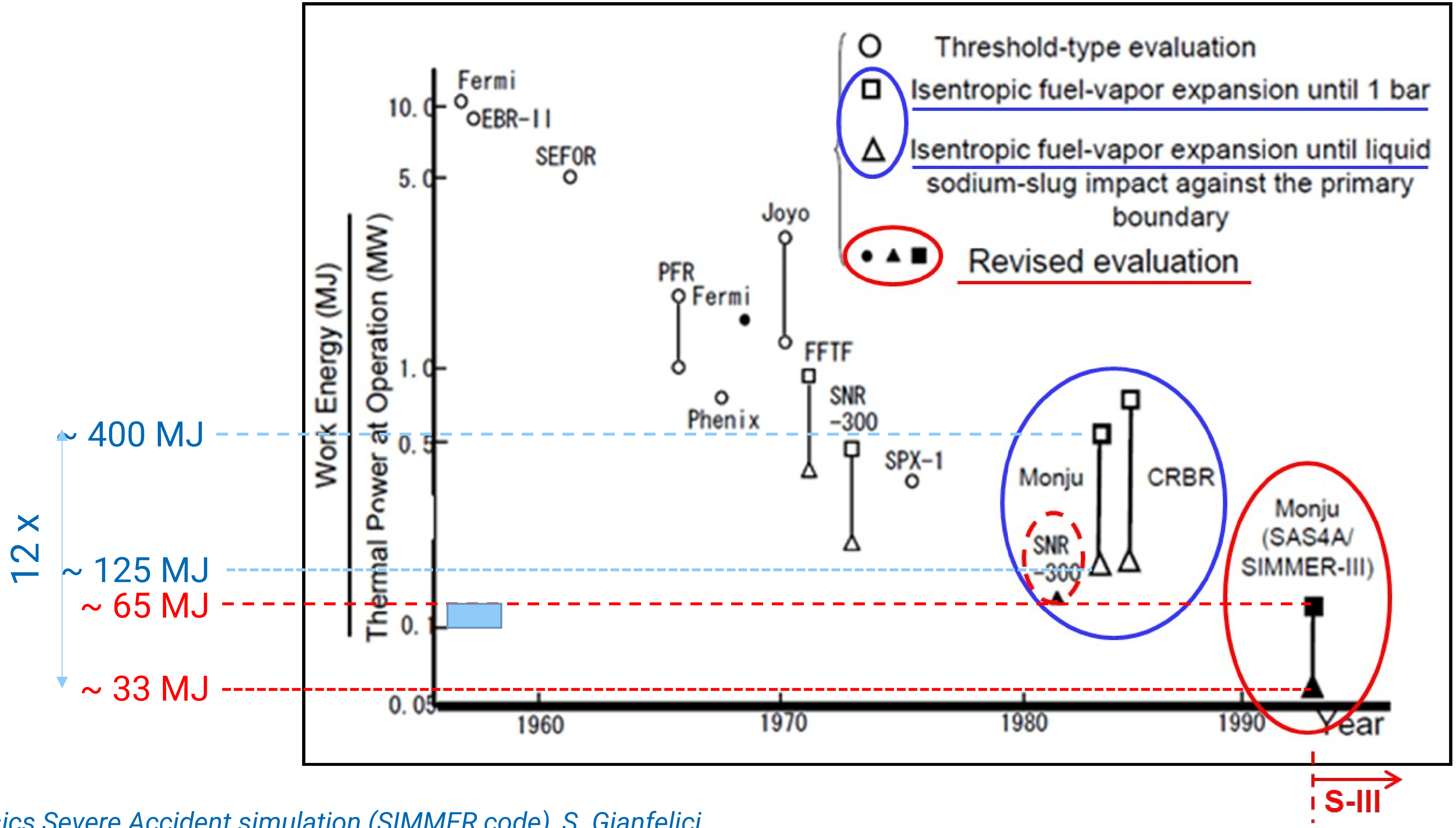



# Expansion phase



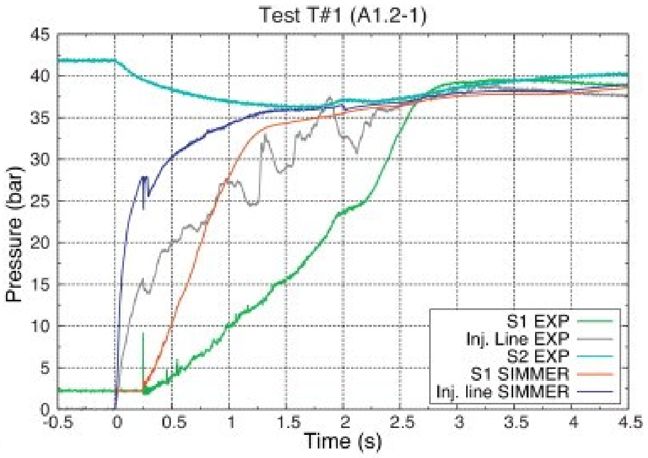

- **Example for SIMMER-III EP simulation** for a medium size SFR reactor.
- Upper core structure of inner core assumed to be partly thermally eroded (realized by removal of pins for six inner radial rings).
- Impact of sodium slug.

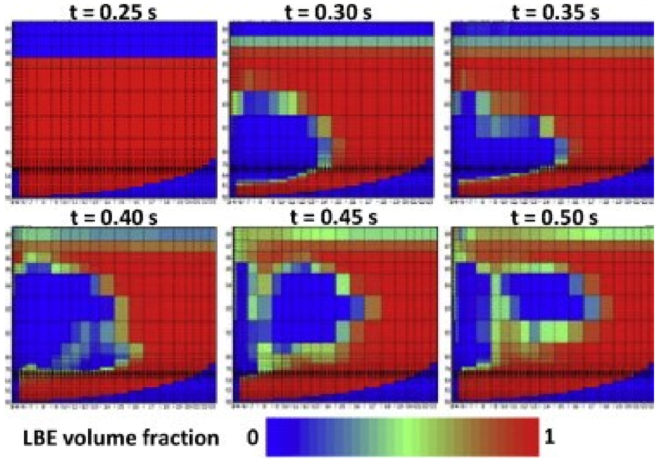
# Mechanical work assessment

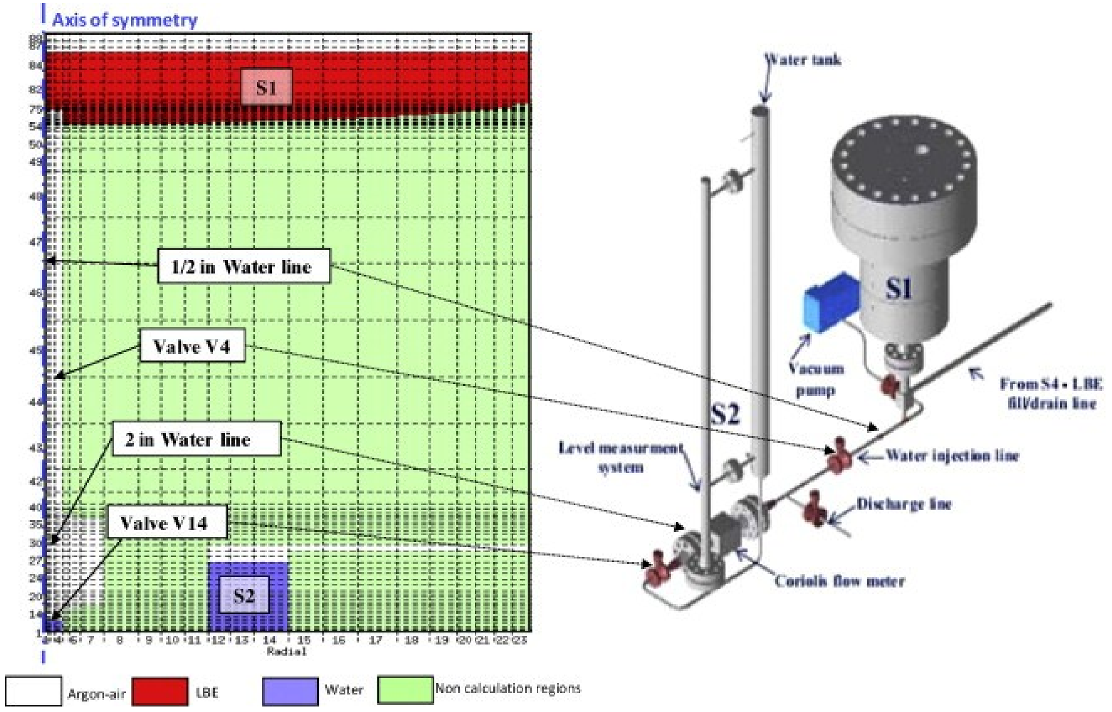


# SIMMER code calculation: SGTR

- "Coolant-Coolant interaction"
- Formation of large bubble with displacement of LM
- Cover gas compression, sloshing, pressurization
- In picture: S-III calculation of LIFUS5/mod2 THINS experiments

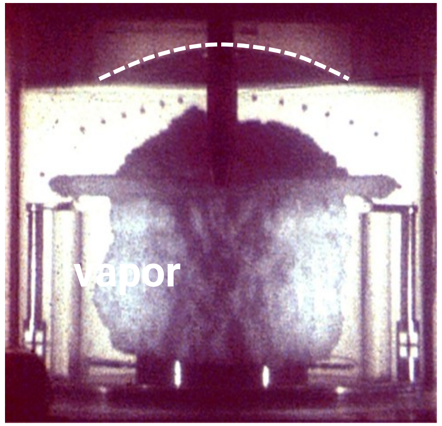


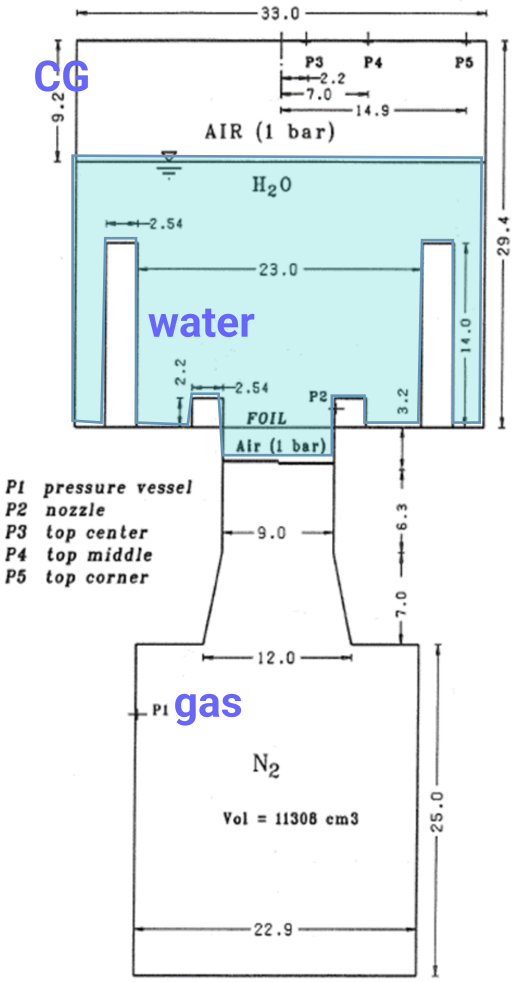




https://doi.org/10.1016/j.nucengdes.2014.11.016

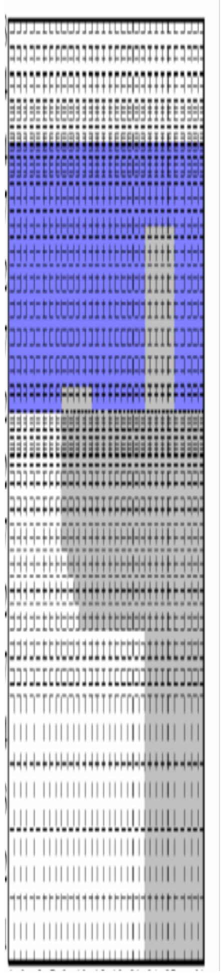
# „Schnelle Gas Injektion“ – Fast Gas Injection Experiment




Recorded expansion




Test facility



SIMMER model

**General Tests Conditions**

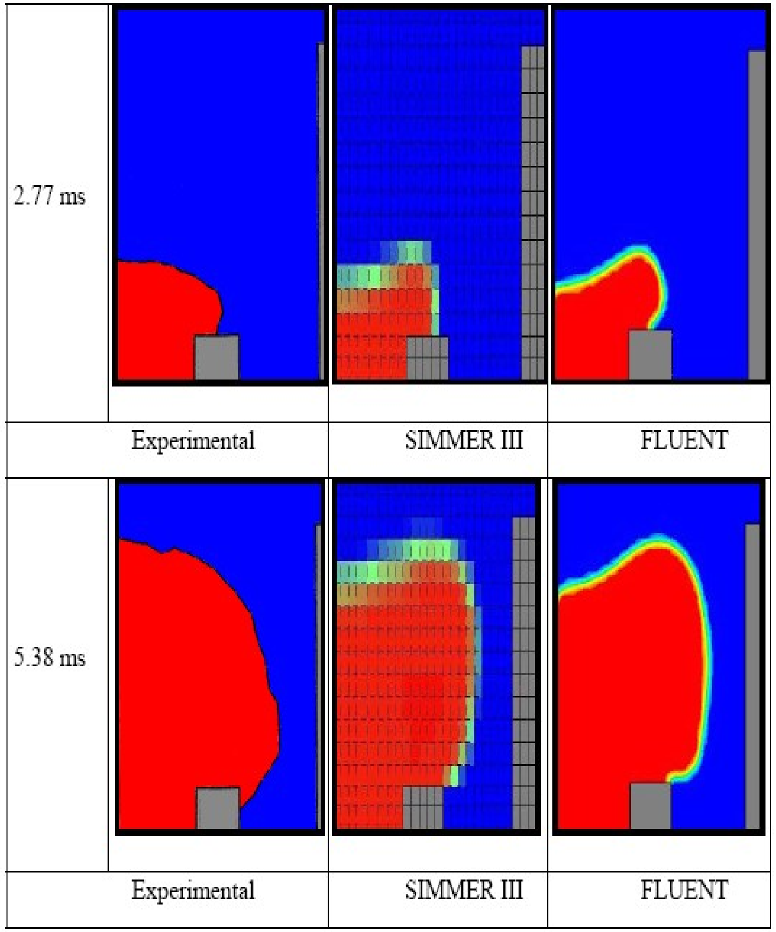
- Nitrogen Temperature: 293.15 K
- Water Temperature: 293.15 K
- Air Temperature: 293.15 K
- Air Pressure: 0.1 MPa

- 3 different nitrogen injection pressures: 0.3, 0.6 and 1.1 MPa
- 3 different geometrical configurations
- 2 different nozzle's diameter: 6 and 9 cm

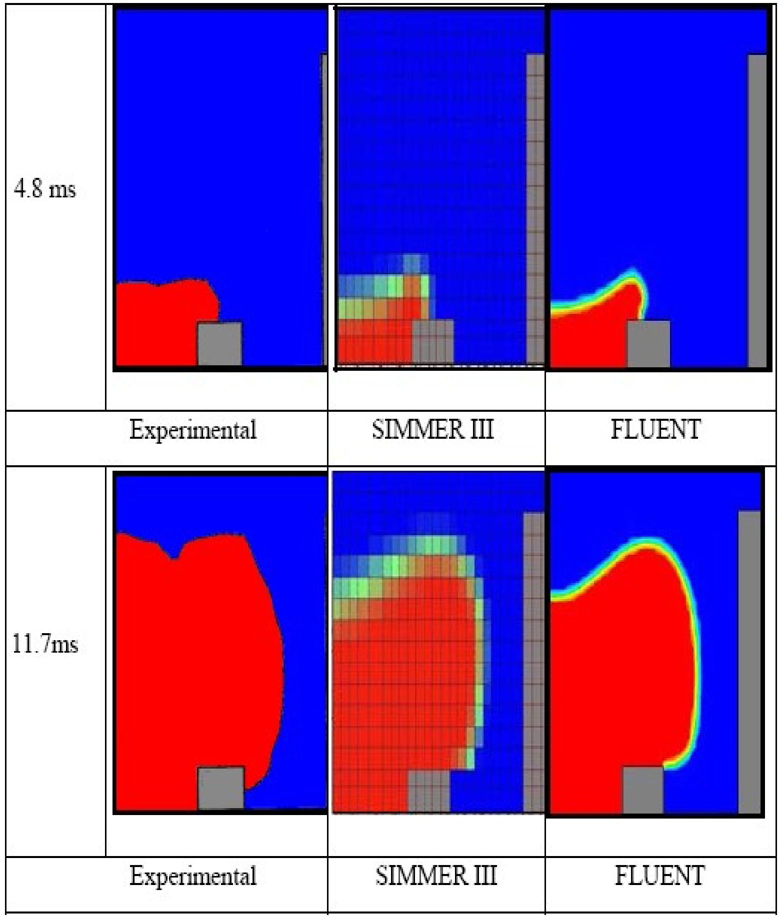
SGI also used for SIMMER V&V

# „Schnelle Gas Injektion“ – Fast Gas Injection Experiment

**Bubble shape and bubble volume**
(Comparison of experiment/simulation, code-to-code comparison)

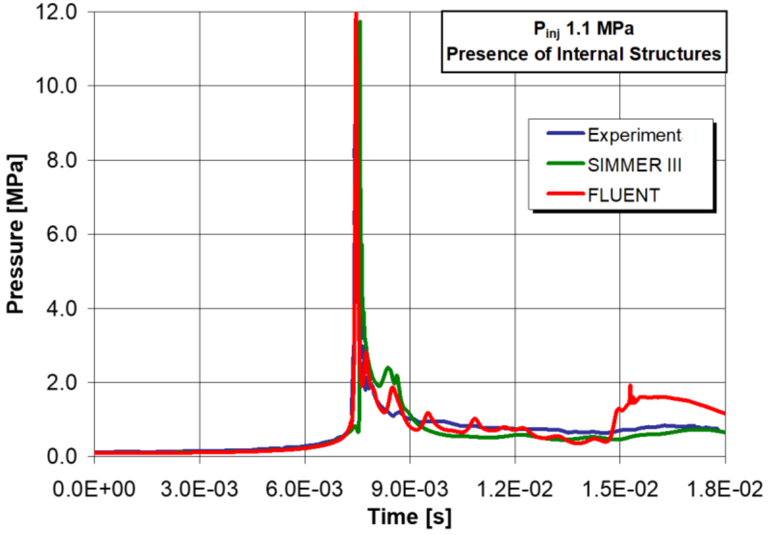



**SGI Test 91**

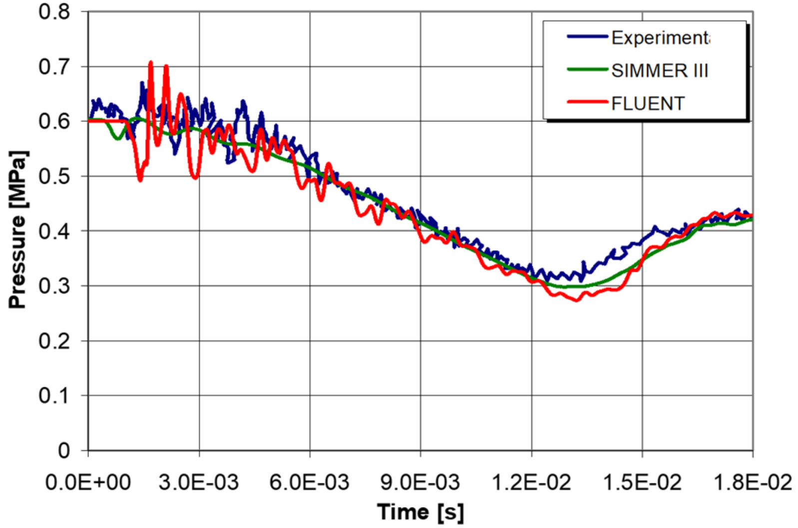



**SGI Test 96**

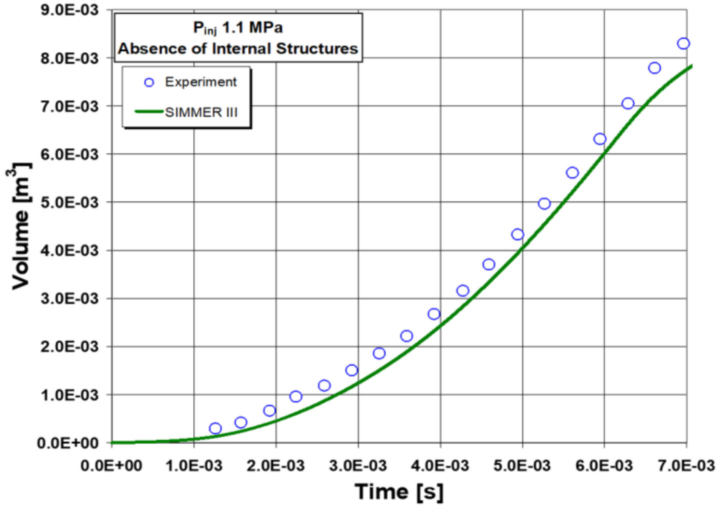
# „Schnelle Gas Injektion“ – Fast Gas Injection Experiment




Pressure in CG region

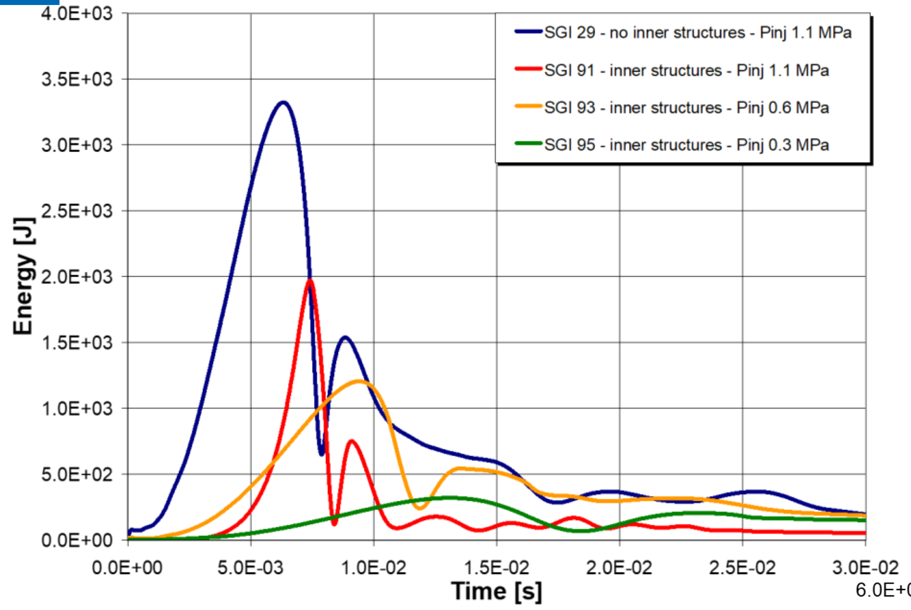



Pressure in water

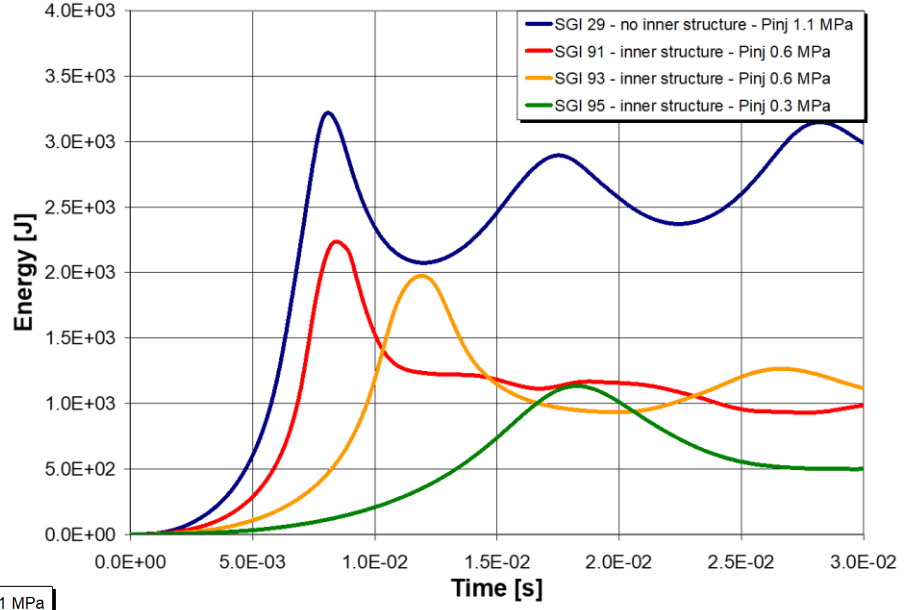



Bubble growth

# SGI Experiment – Mechanical Energy Evaluation

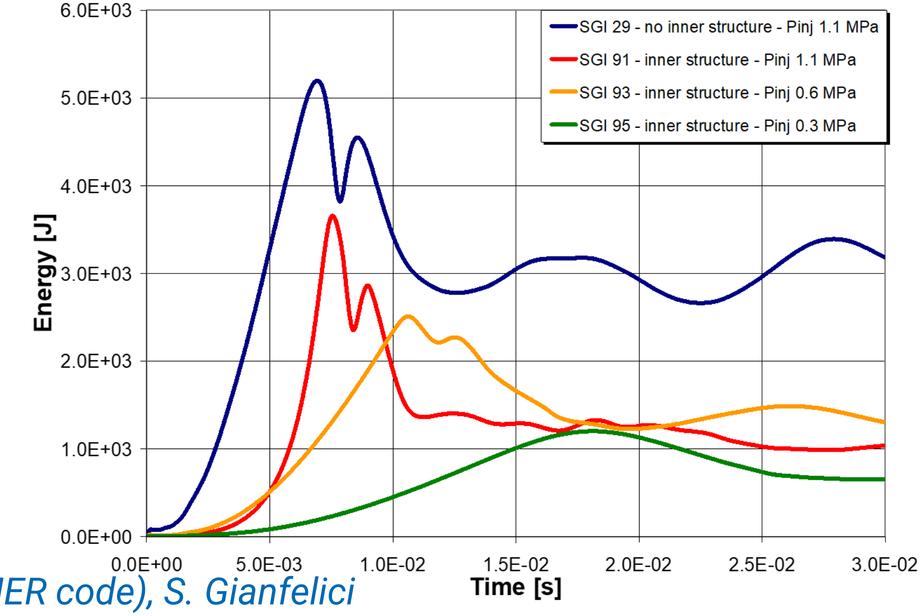



Kinetic energy




Compression work

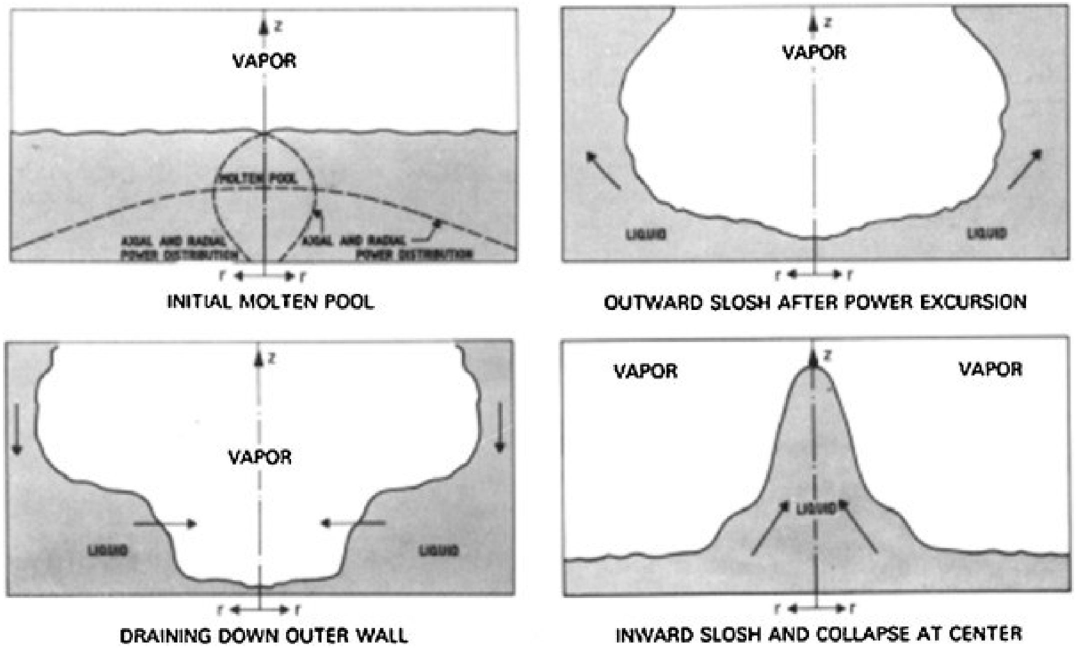
No evaluation of mechanical energy components available from experiment

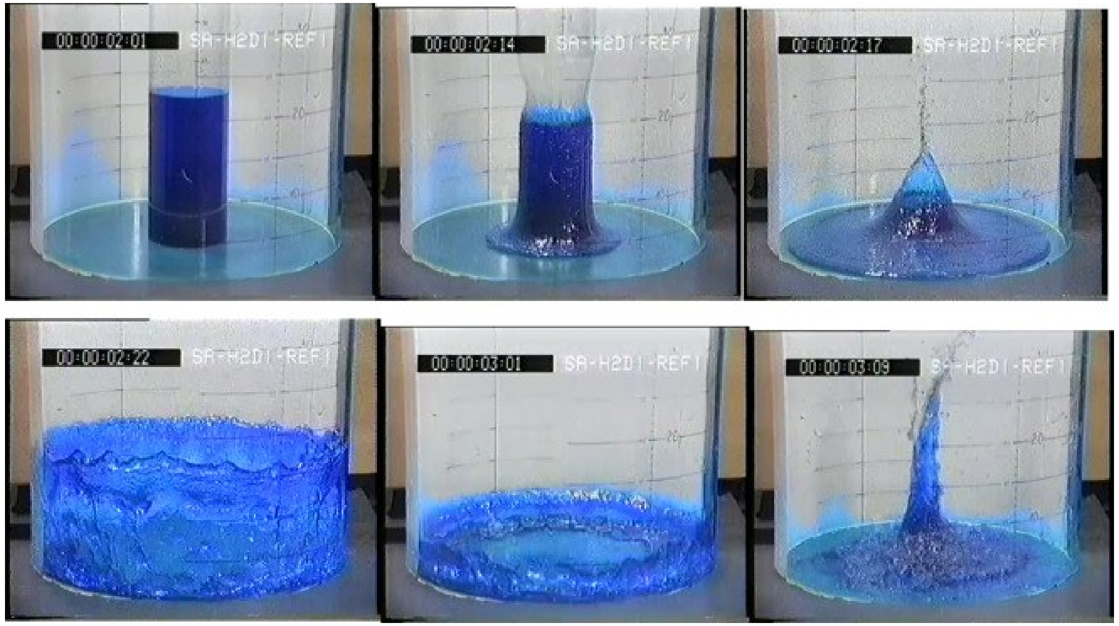



Mechanical Energy

# SIMMER code calculation: sloshing

- Term used as well for fuel/clad melt compaction
- Movement of LM caused by earthquakes or displacement
- Great inertia can cause loads on the surrounding structures

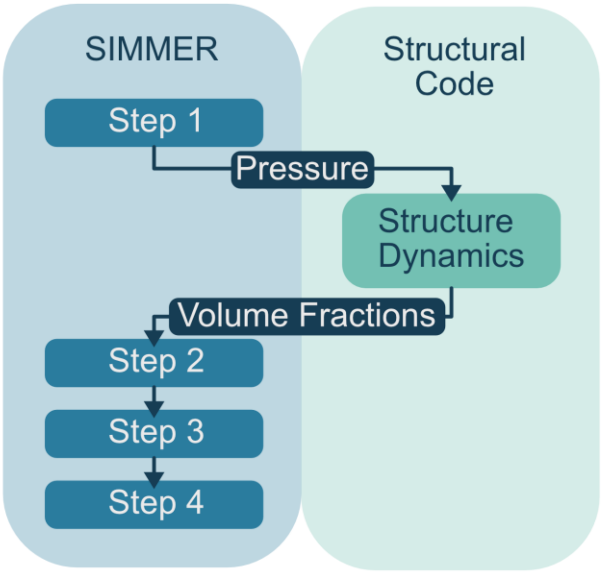


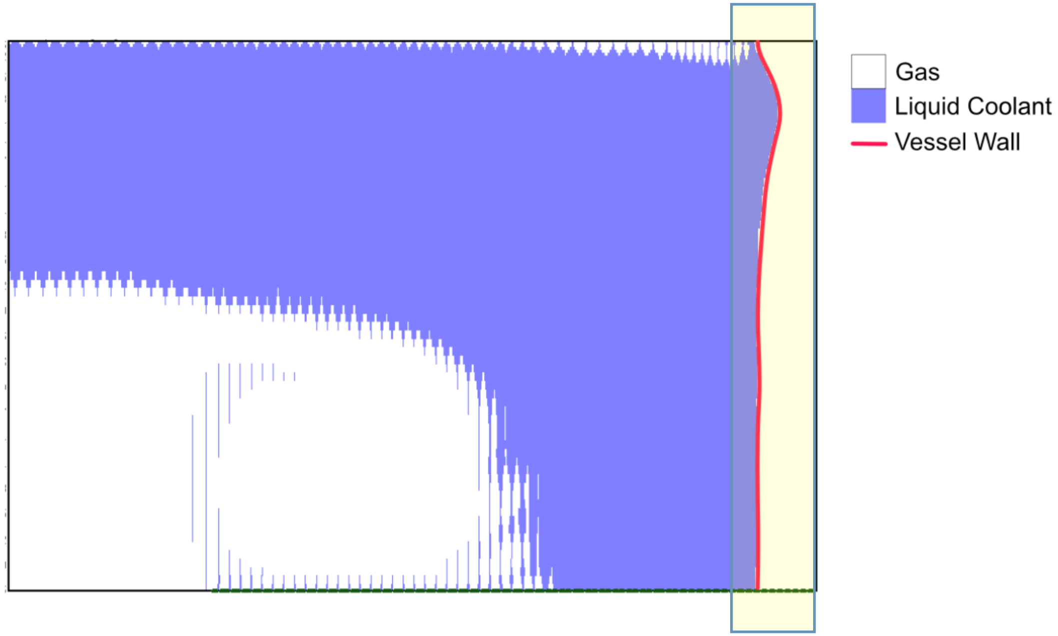

https://doi.org/10.1016/j.ijhydene.2016.01.152

# Structures feedback

**Couple SIMMER with a structural code for vessel** (limited to radial material deformation)

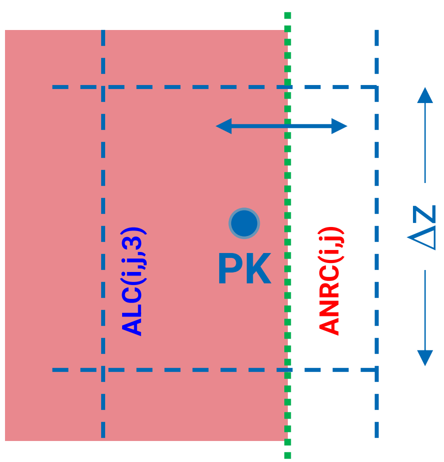



Coupling with C++ programs directly in SIMMER




Additional mesh row at wet side of wall. Non-flow volume of right can wall used for coupling of structure code.

Wall not explicitly modeled at S-III side




Non-flow volume of right CW made variable

Input to structure code: force at vessel segment

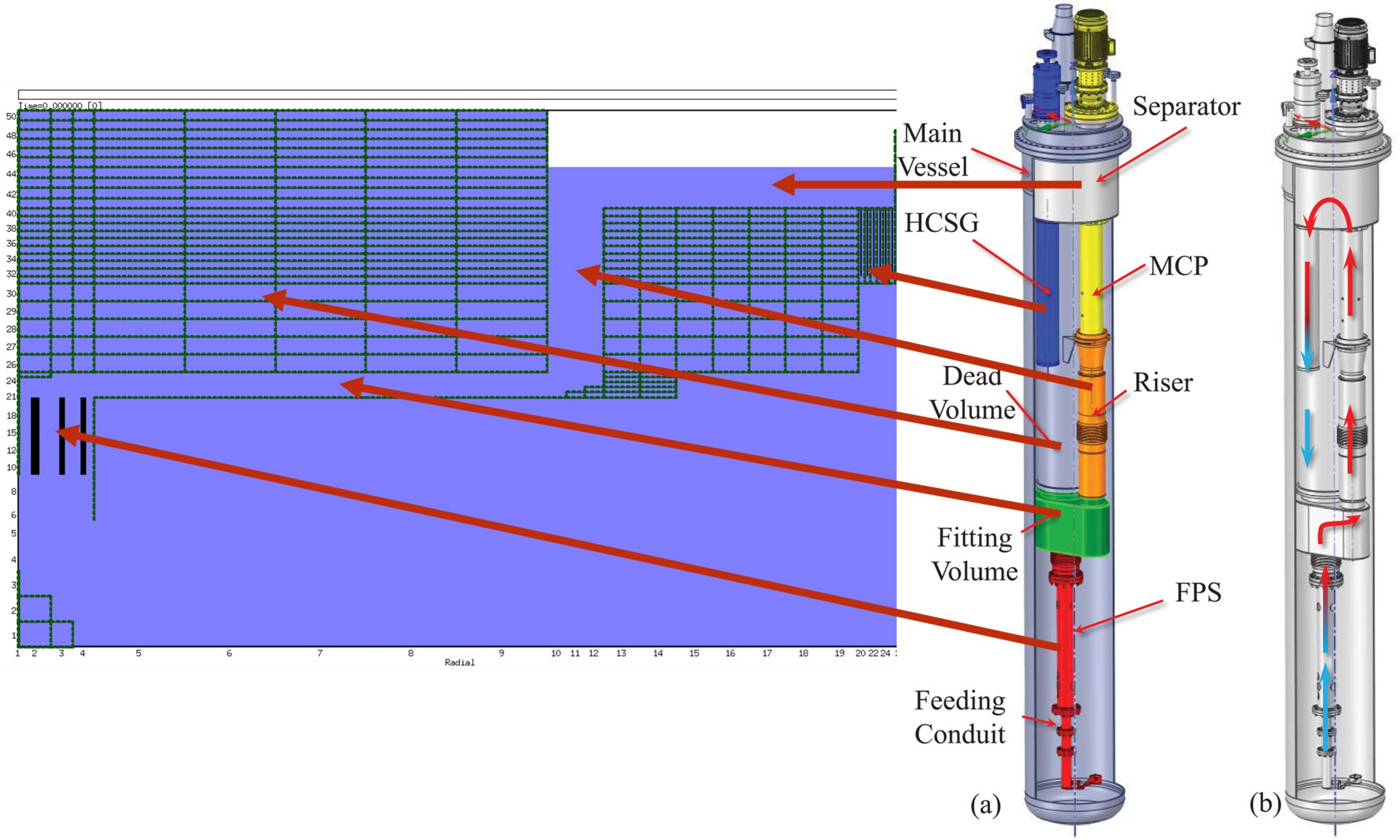
Output from structure code: wall displacement (ANRC)

Concept

"Numerical Simulation of Fluid-Structure Interaction during the Expansion Phase in Sodium Cooled Fast Reactors"
Max Hartig, (2019)

# SIMMER code calculation: ULOF/LOHS

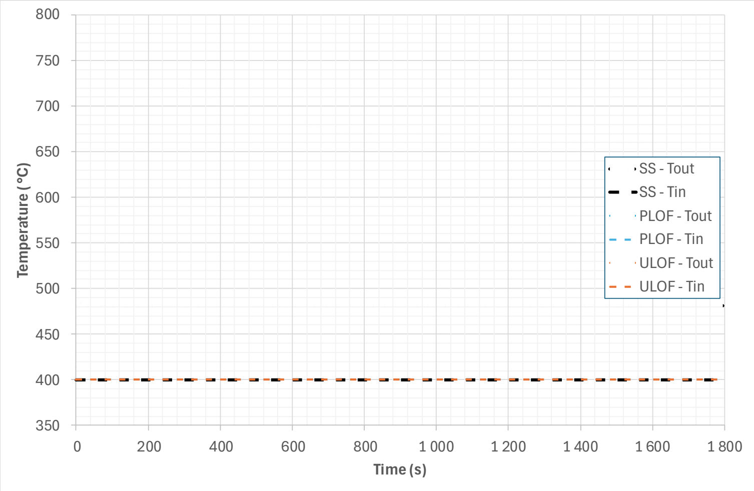
- Example: CIRCE-THETIS
- Loss of flow/loss of heat sink transients
- SIMMER model with power generation, pump, HXs
- LOHS simulated by virtual wall bypass

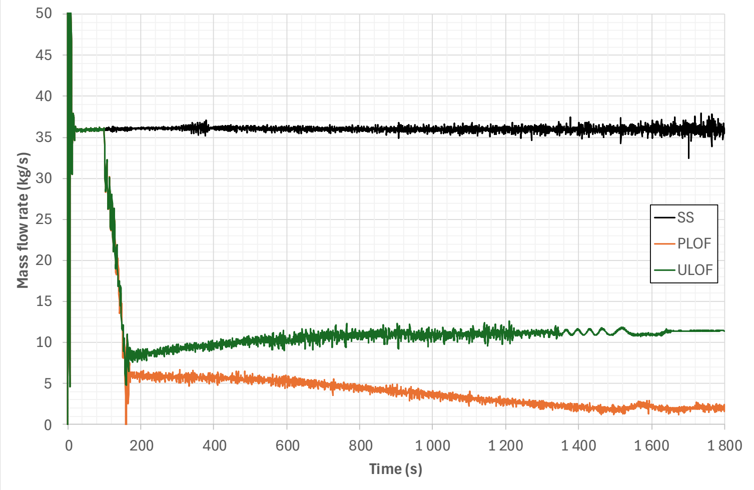



*Upcoming FR26 paper*

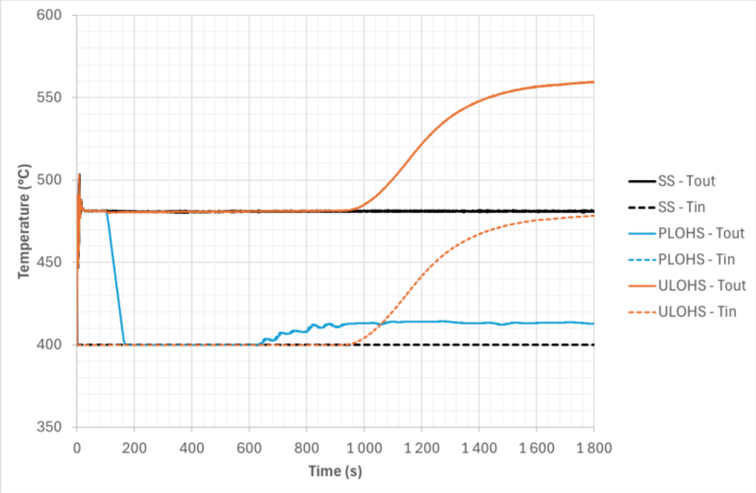
# SIMMER code calculation: ULOF/LOHS

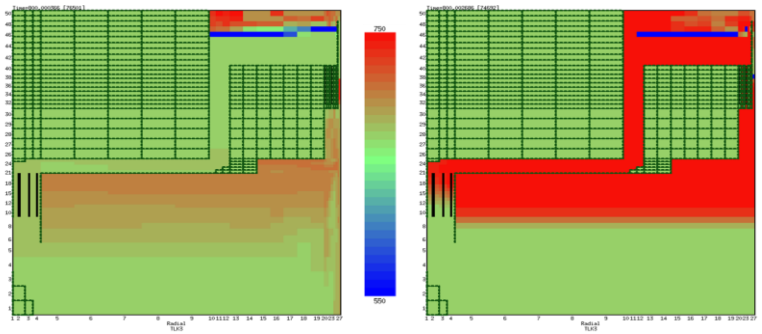
## PLOF/ULOF



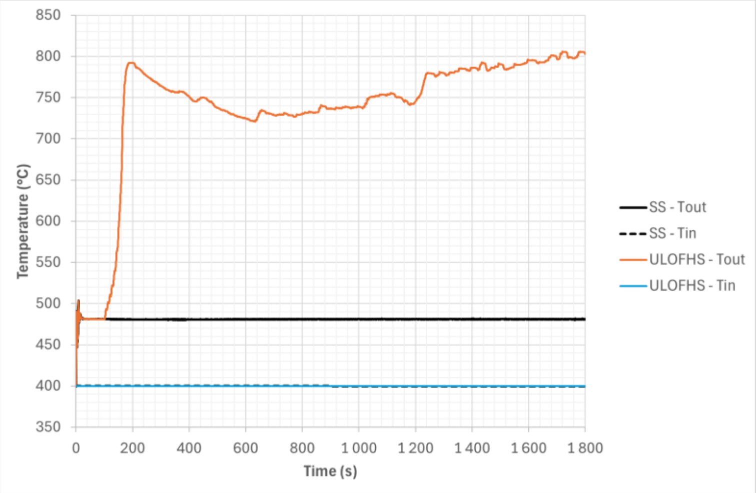




## PLOHS/ULOHS



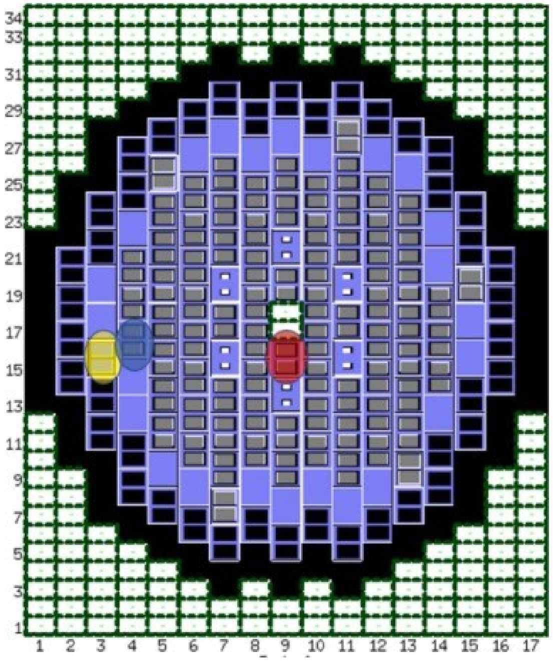
## ULOF+ULOHS

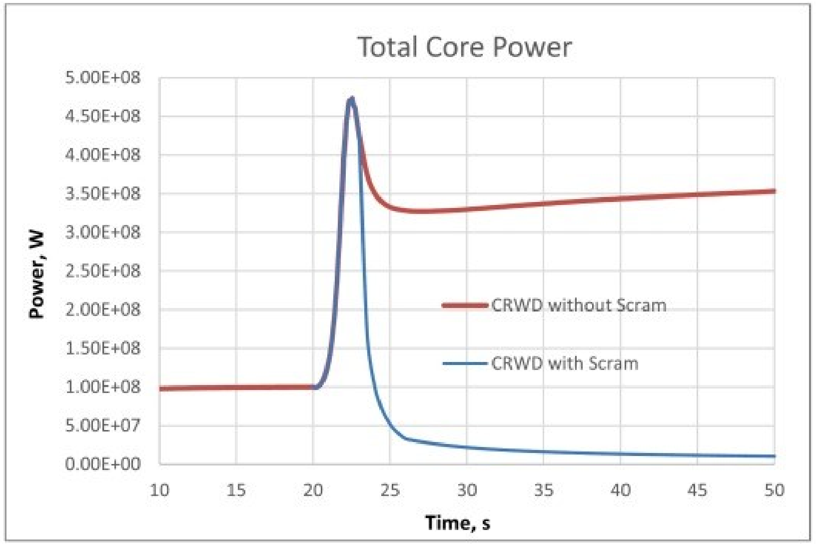


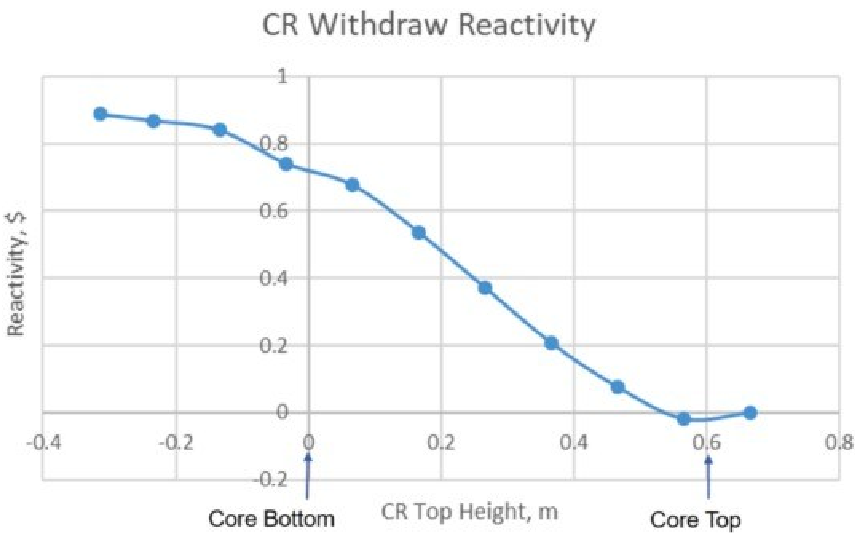

*Upcoming FR26 paper*

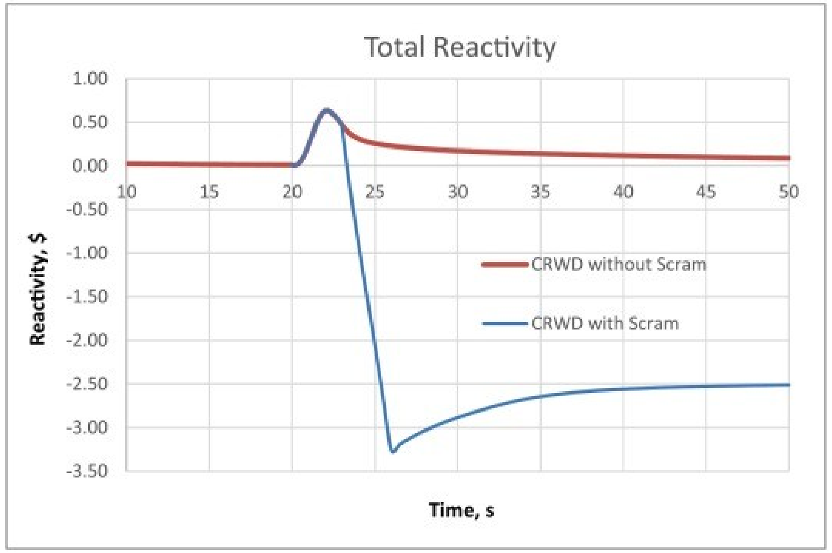
# SIMMER code calculation: TOP

- Example: control rod withdrawal in MYRRHA code
- CR fixed, but external reactivity can be provided
- Reactivity/power feedbacks evaluated





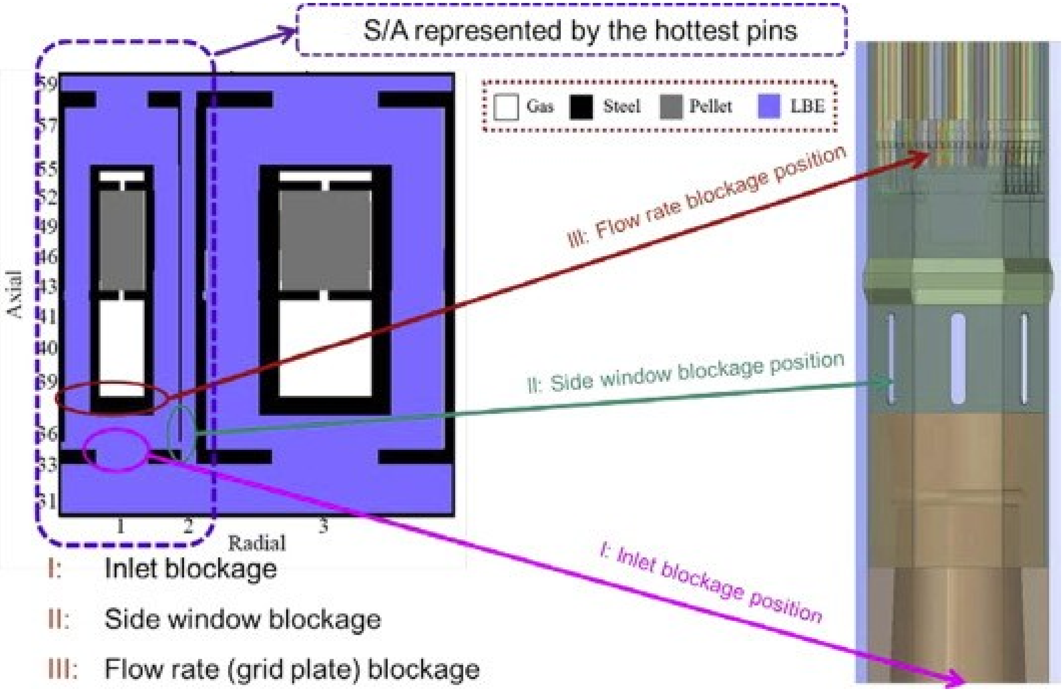



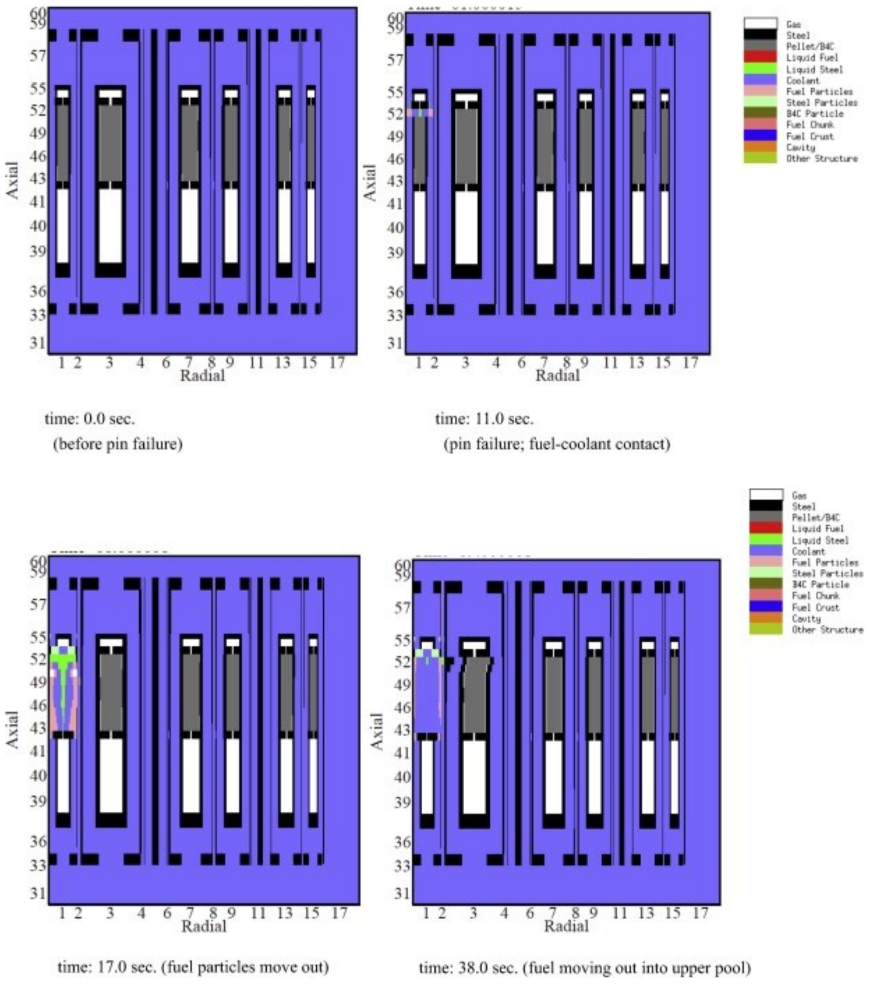




https://doi.org/10.1016/j.nucengdes.2025.114419

# SIMMER code calculation: channel blockages

- Partial or total blockage of a SA channel
- Possible pin and SA failure
- Potential propagation to the nearby SAs
- Fissile material relocation and reactivity swings




https://doi.org/10.1016/j.anucene.2015.01.002

# Conclusions

- Simulation of LMFR accidents requires a detailed modelling of a relevant number of physical phenomena at different time and size scales
- Even if originally developed mainly for SFR CDA/transition phase simulation, the flexibility of the SIMMER code allowed its extension to different scenarios and reactors (from LWR to MSR, even specific fusion application!)
- Neutronics <=> TH feedbacks affected by phase changes and material relocation is another strength of the SIMMER code
- Extension to LFR applications is being recovered and reassessed for new designs and specific needs
- However, every new application and model requires a validation process, which is still ongoing for LFRs

# References

Sources available @ https://jopss.jaea.go.jp/search/servlet/interSearch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- Multi-phase Flow Topology and Interfacial Areas Model: JAEA-Research 2024-010 (2024)
- Momentum Exchange Functions Model: JAEA-Research 2024-011 (2024)


# Thank you for your attention! …questions?

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