ESFR-SMART
sodium fast reactor safety

WP:	WP3.1 “Dissemination, education and Training”
Task:	3-1-3 Workshops and Summer School
Speaker:	Michael Flad
Affiliation:	KIT
Event:	Workshop N°7 Sodium-Cooled Fast Reactor Severe Accidents
When:	2022 April 5th-8th
Where:	CEA Cadarache (France)

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754501.

Outlook

- Accident Phases
- Behavior of SFR during Secondary Phase
  - Conditions at end of Primary Phase
  - Pool formation and further development
  - Important driver for reactivity during Secondary Phase
  - Recriticalities and power excursions
  - Termination of Secondary Phase
  - Secondary Phase for an Innovative SFR
- Consequences from Secondary Phase

Accident Phases (1/2)

Why sub-divide an accident into different phases?

- Focus on dominant phenomena of the event
- Assessment of phases by specialized codes
- Uncertainties related to branching into different phases
- Former lack of codes capable of describing the whole sequence

Phases of a severe accident

- Initiation Phase (primary phase)
- Transition Phase (secondary phase)
- Expansion Phase (post disassembly expansion phase)
- Containment loading Phase
- Post-accident heat removal phase etc.

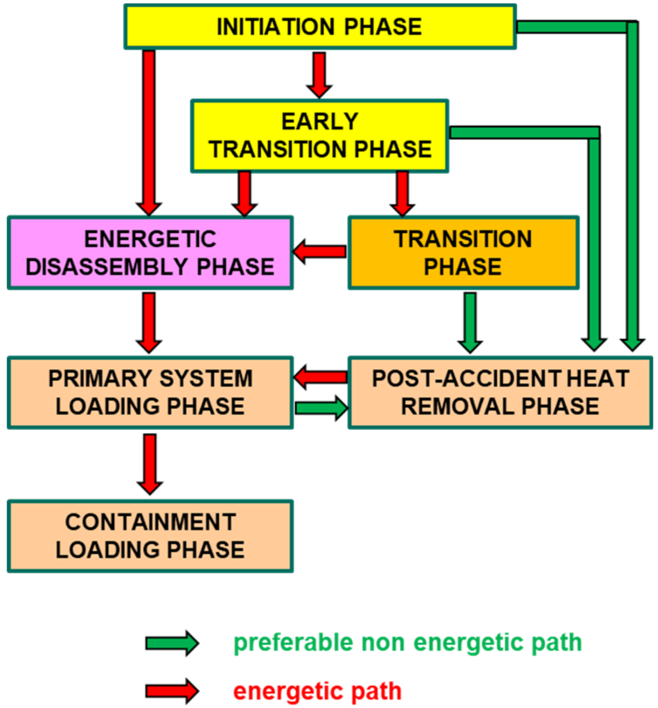


Fig. Phases of a severe accident

Accident Phase (2/2)

Initiation Phase (IP)

- Accident initiation until CW failure: *multi-1D code (SAS); point-kinetics*
- Potentially primary power excursion

Transition Phase (TP)

- Power profile according to fuel redistribution: *2D/3D code (S-III); space-time kinetics*
- Risk of large pool formation & fuel compaction: *multi-component, multi velocity fields*
- Risk of secondary power excursions with high energy release

Expansion Phase (EP)

- Final outcome of the energetic path leading to core dissassembly
- Conversion of thermal into mechanical energy: *multi-component, multi velocity; FCI*
- Potential challenge for PV (sodium slug/pressurization): *(input for) structure code*

Secondary Phase: Evaluation Tools

SIMMER-II
AFDM
SIMMER-III (2D)
SIMMER-IV (3D)
SIMMER-V (3D)

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

C^4P
1968/560 Group Master Library
Basis: JEFF, JENDL, ENDF/B
Full Range Neutron Spectrum

Structure model

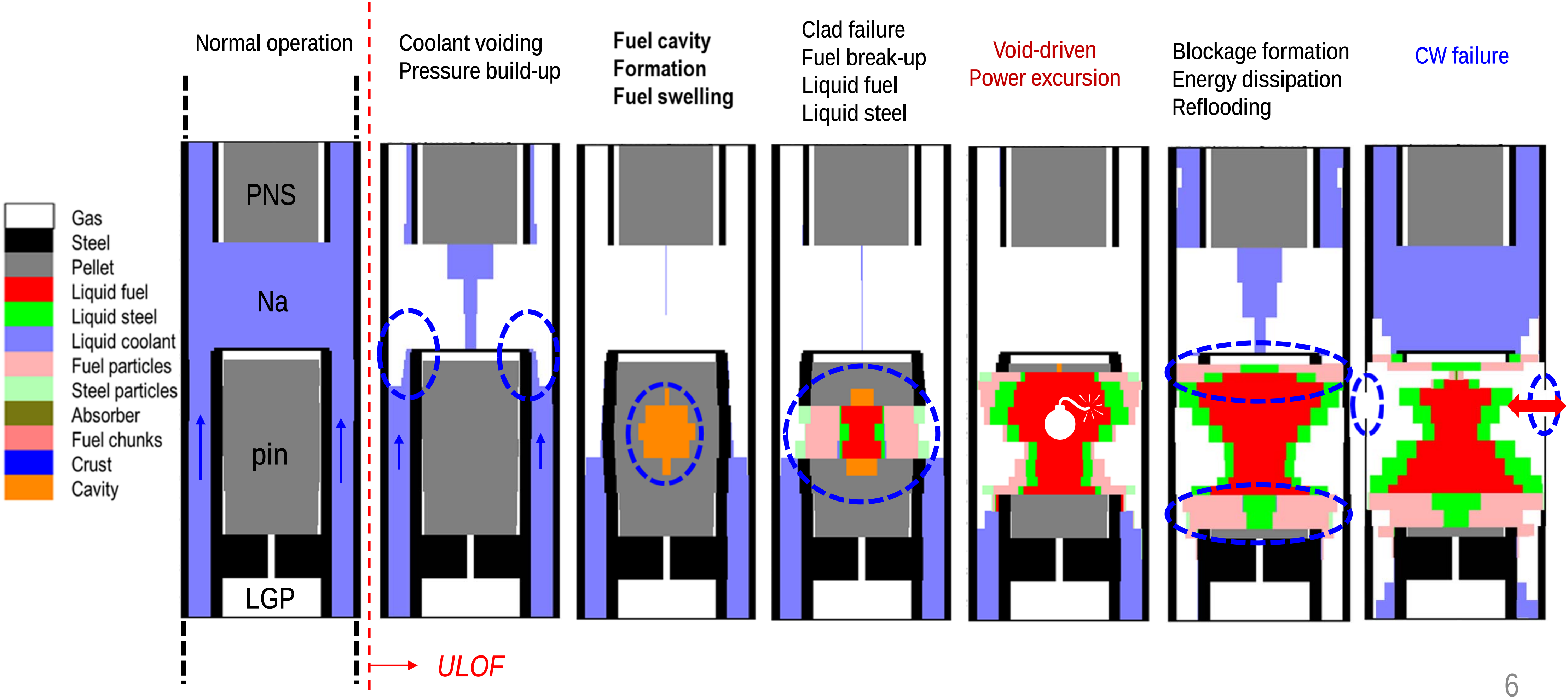
- General structure model
- Pin model (new fuels - development)
- Axial + radial heat transfer
- Virtual structure model
- Structure disintegration
- Freezing on structures

Neutronics

- Neutron transport theory
- Improved quasi-static method
- Cross-section generation
- heating
- External neutron source
- Transient source importance

No structure mechanics!

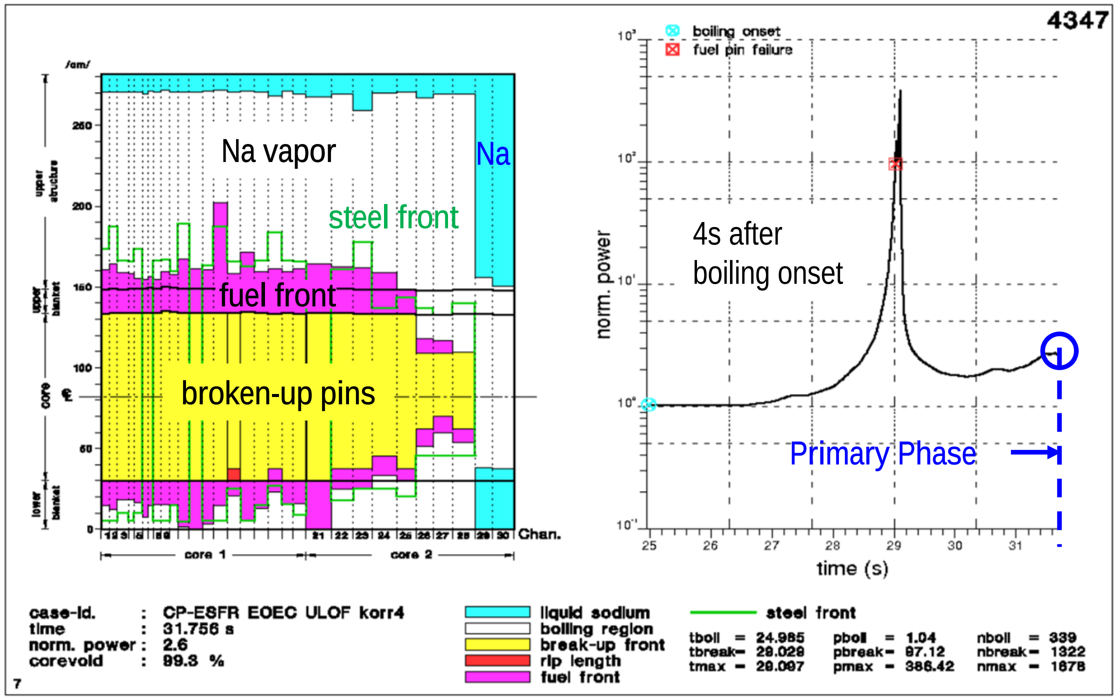
Primary Phase Phenomena



Primary Phase / Start of Secondary Phase

Core damage pattern

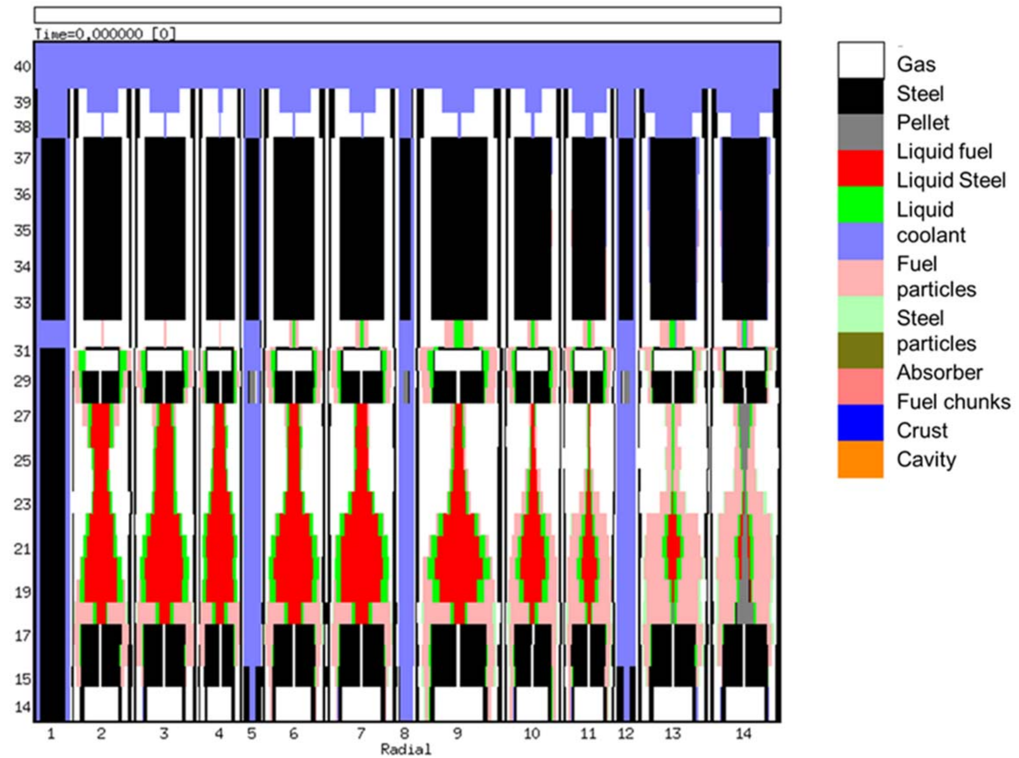
Primary power peak: ~ 400 P_0



SAS-SFR simulation (multi-1D)

data transfer

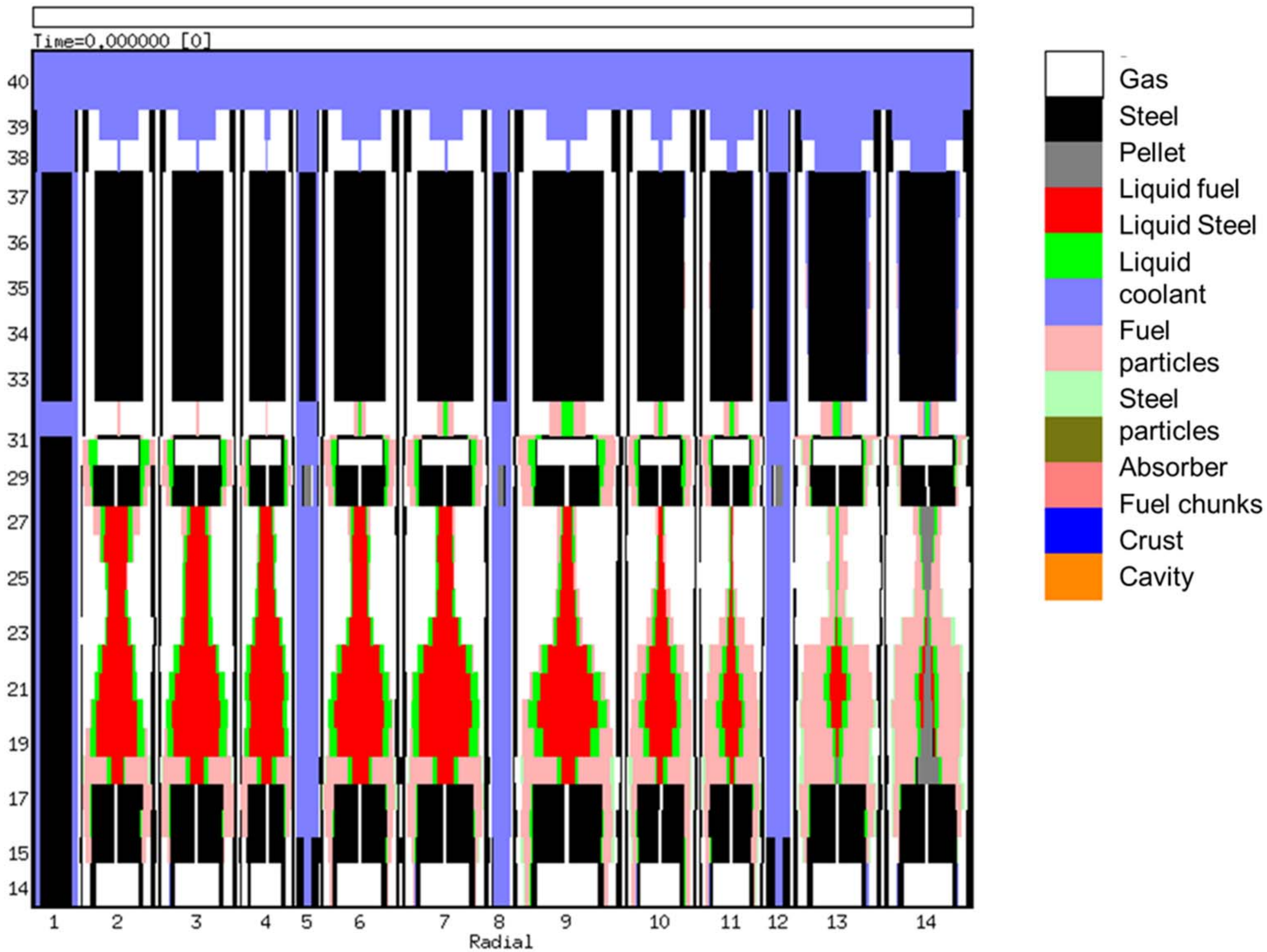
Secondary Phase

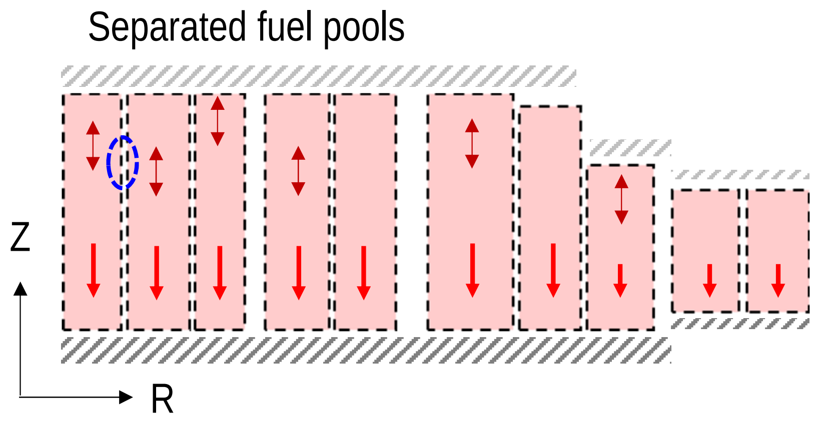


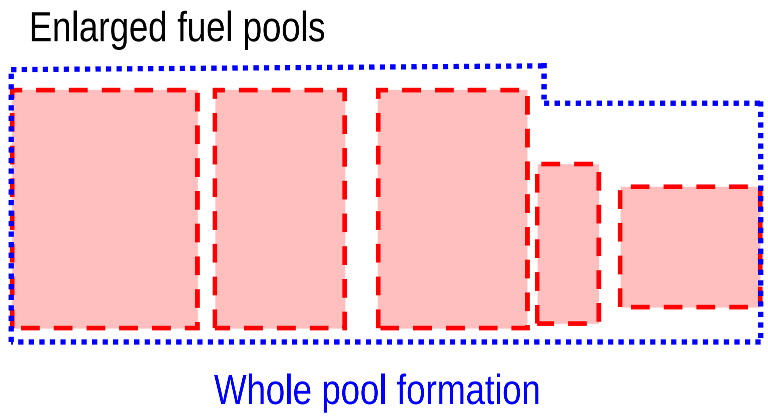
SIMMER-III (2D)

SIMMER-III starting conditions based on SAS-SFR

Secondary Phase Behavior / Pool Formation (1)

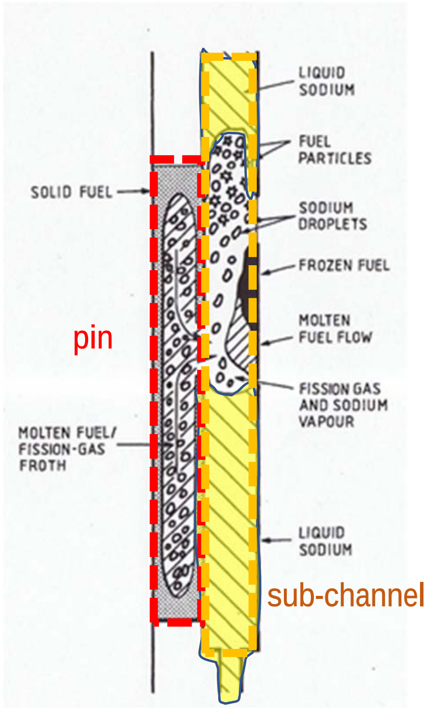




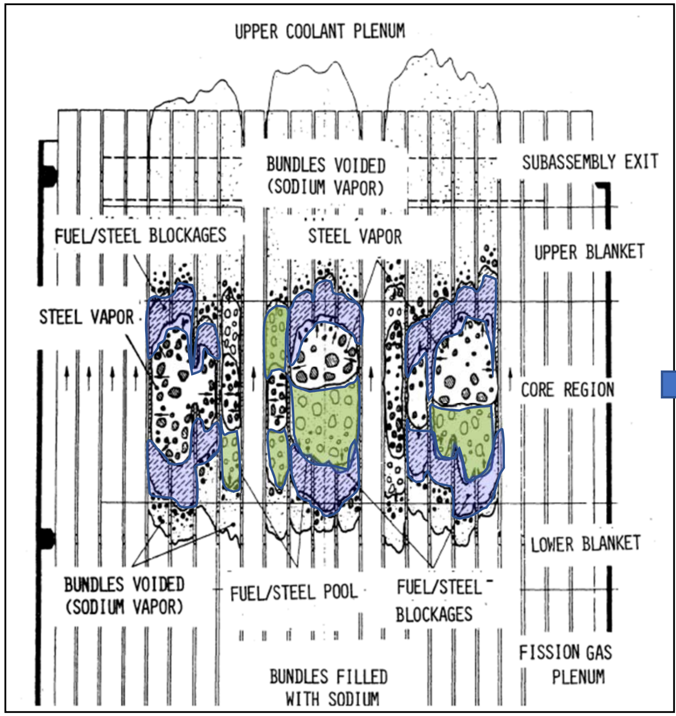


Secondary Phase Behavior / Pool Formation (2)

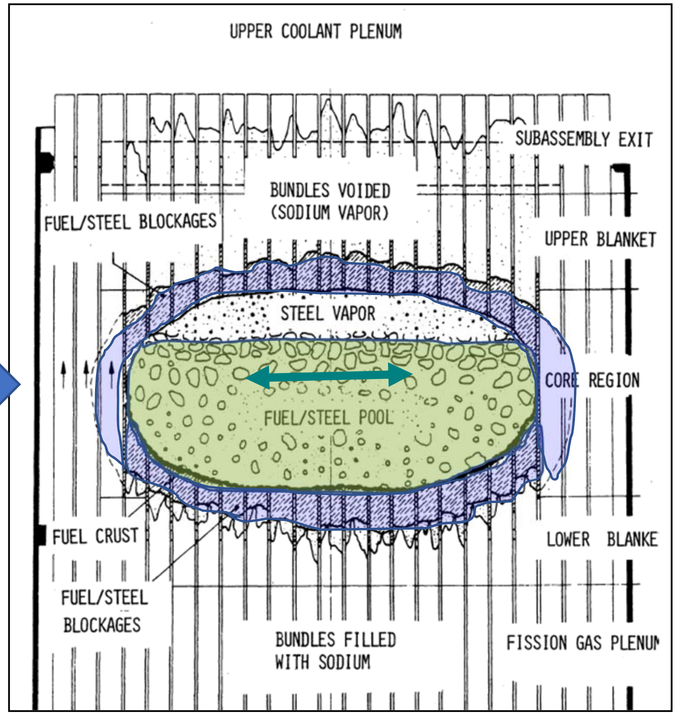
Primary Phase



Secondary Phase

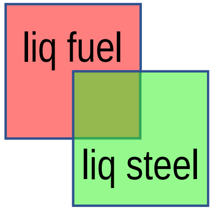


Individual pools

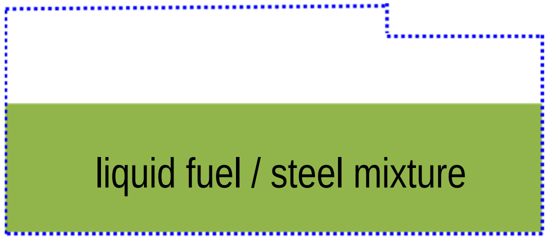


Whole fuel/steel pool

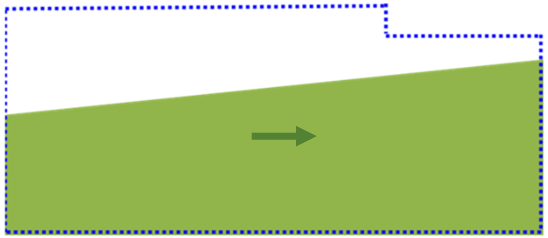
Secondary Phase Behavior / Sloshing (1/2)



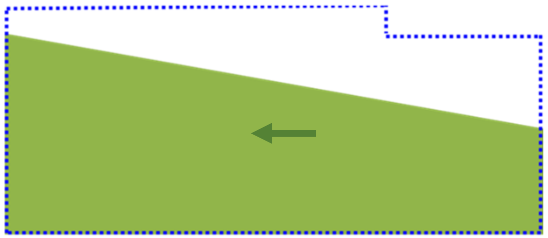
Whole pool formation



Risk of coherent fuel sloshing motion towards core center



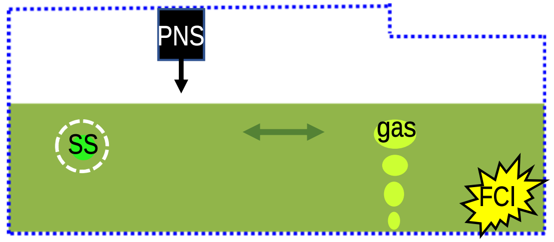
Outward sloshing $\rho \downarrow$



Inward sloshing $\rho \uparrow$

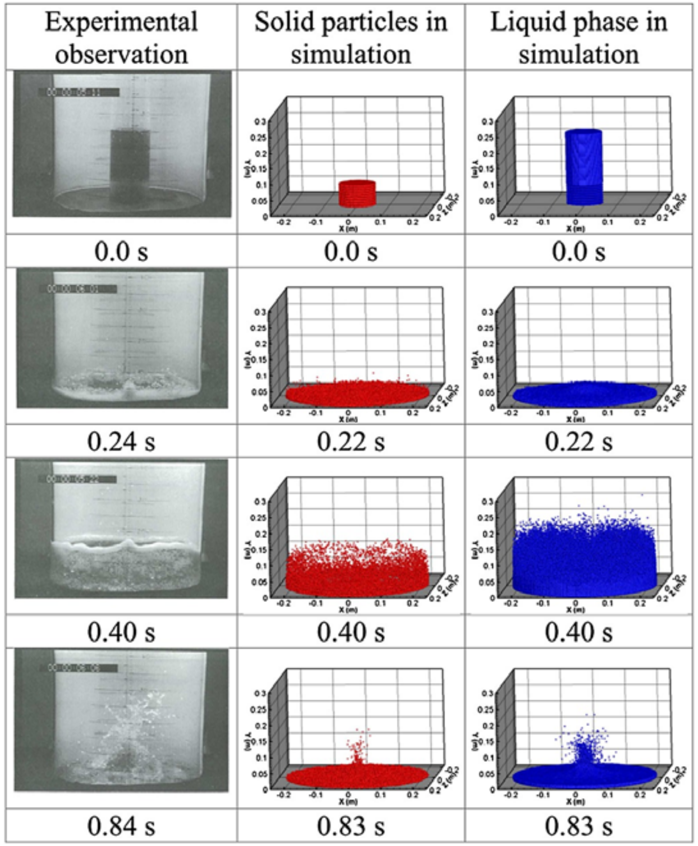
Mechanism for pool sloshing:

- Fuel/coolant interaction (FCI)
- Vapozation of liquid steel (rapid phase changes)
- Objects falling into pool
- Self-actuated pool sloshing
- FG release
- Core volume increase
- …



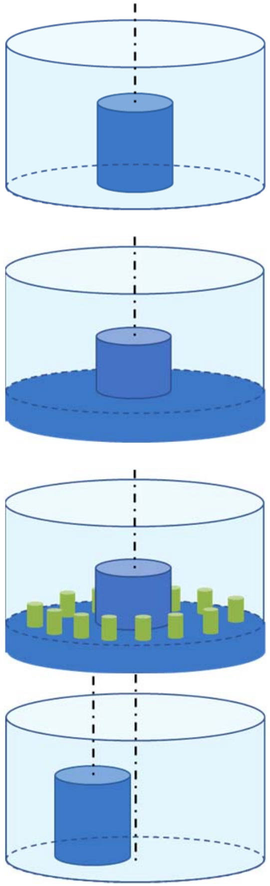
„*Fuel carries ist own worth*":
➔ space-time kinectic model required for Secondary Phase of accident

Secondary Phase Behavior / Sloshing (2/2)



Sloshing experiment (KIT) and numerical simulations

Experiments



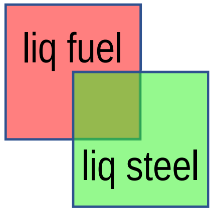
dry base — Splash at centerline most pronounced (despite precise alignment: many attempts required)

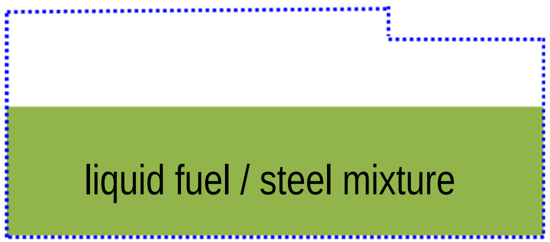
wet base — Pile-up effect large reduced

dam & obstacles
off-cetered
— All other configurations drastically reduce effect

3D simulation with largely reduced effect

Secondary Phase Behavior / Fuel/steel Redistribution



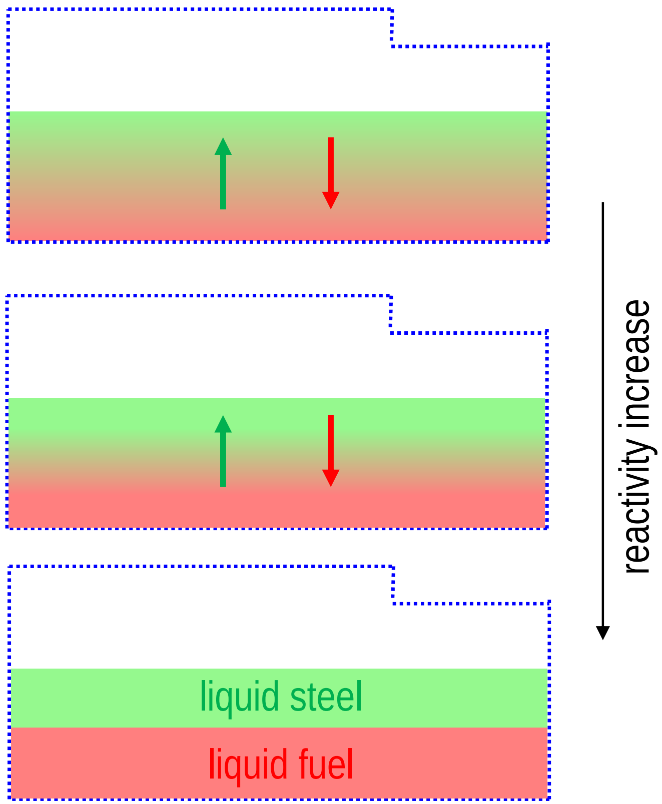


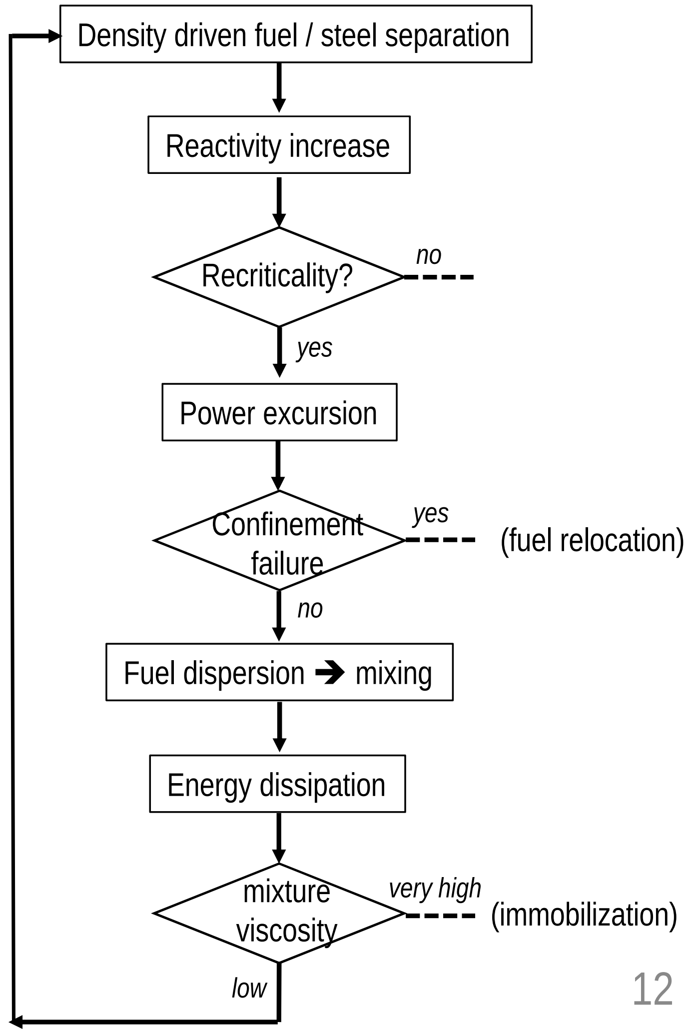
ρ liq. fuel: 8800 kg/m³ (3500 K)

ρ liq. steel: 6700 kg/m³ (2500 K)

Most common reason for cycles of recriticalities in simulations

Density driven separation of liquid phases





Secondary Phase Behavior / FCI

Fuel/coolant interactions (FCI) with rapid vaporization:

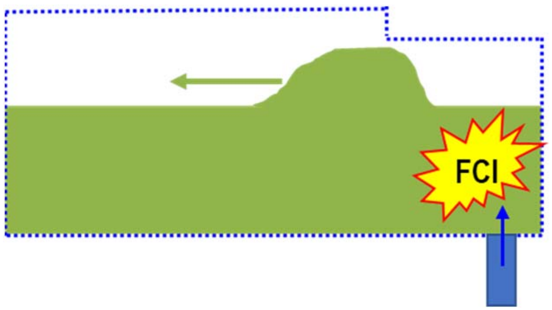
Risk of large amount of liquid melt accelerated towards core center

Typical reactivity ramp rates (according to simulation results):

fuel/steel redistribution	5 … 10 cent/s
radial fuel compaction (FCI)	0.5 … 1 … several $/s

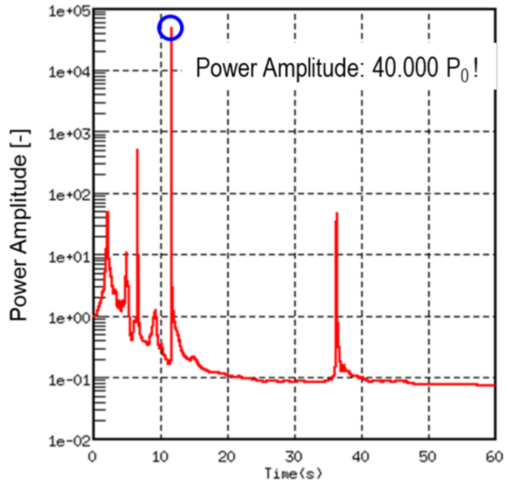
At unfavorable conditions: very high power amplitudes (2D effects)

At favorable conditions: enhancing fuel dispersal ➔terminate transient
Hard to rate generally …

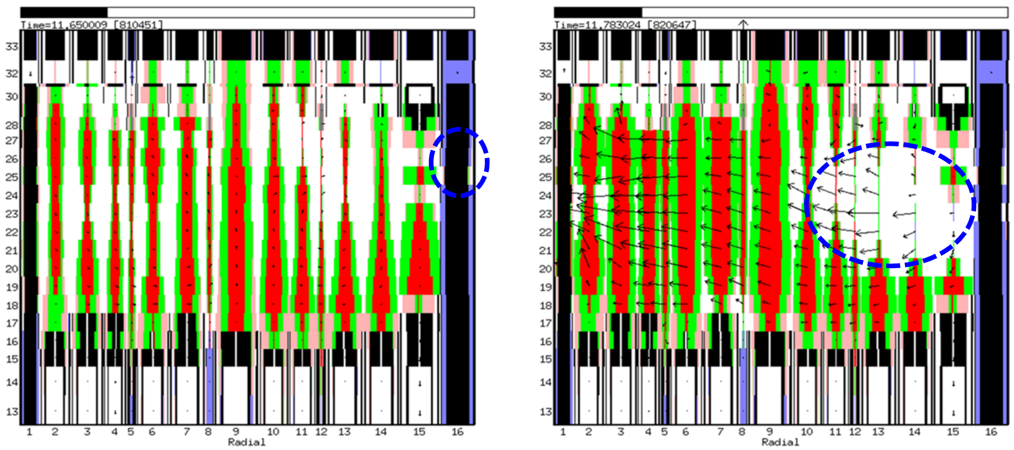


Example from CP-ESFR:

Largest peak cause by FCI

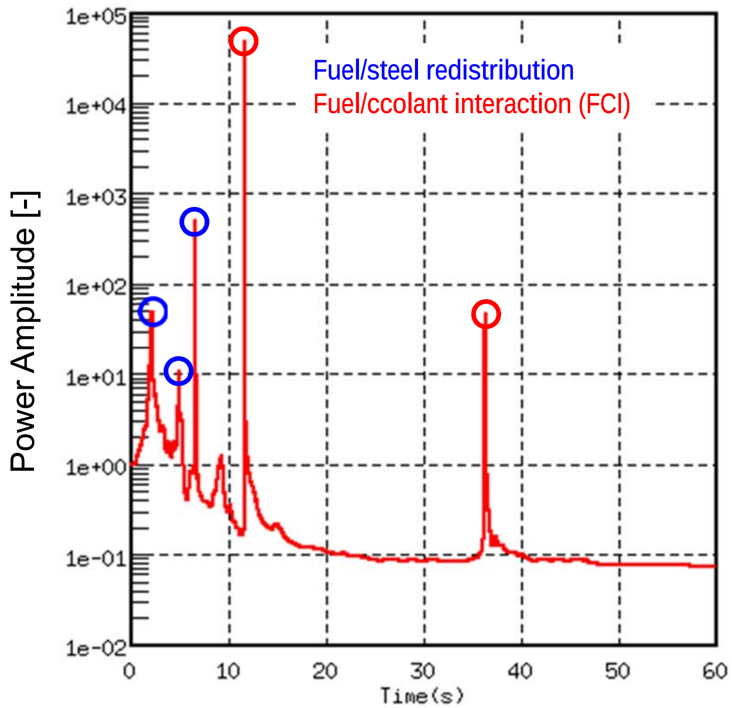


FCI after failure of CW of radial reflector: melt pushed towards center (vector unit: 30 m/s).

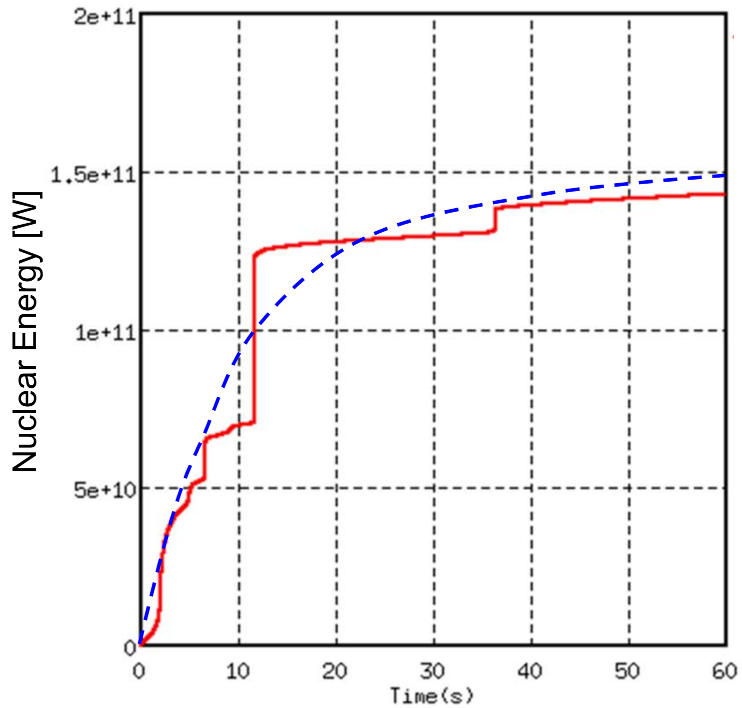


Secondary Phase: Termination (1/2)

Power history



Nuclear energy

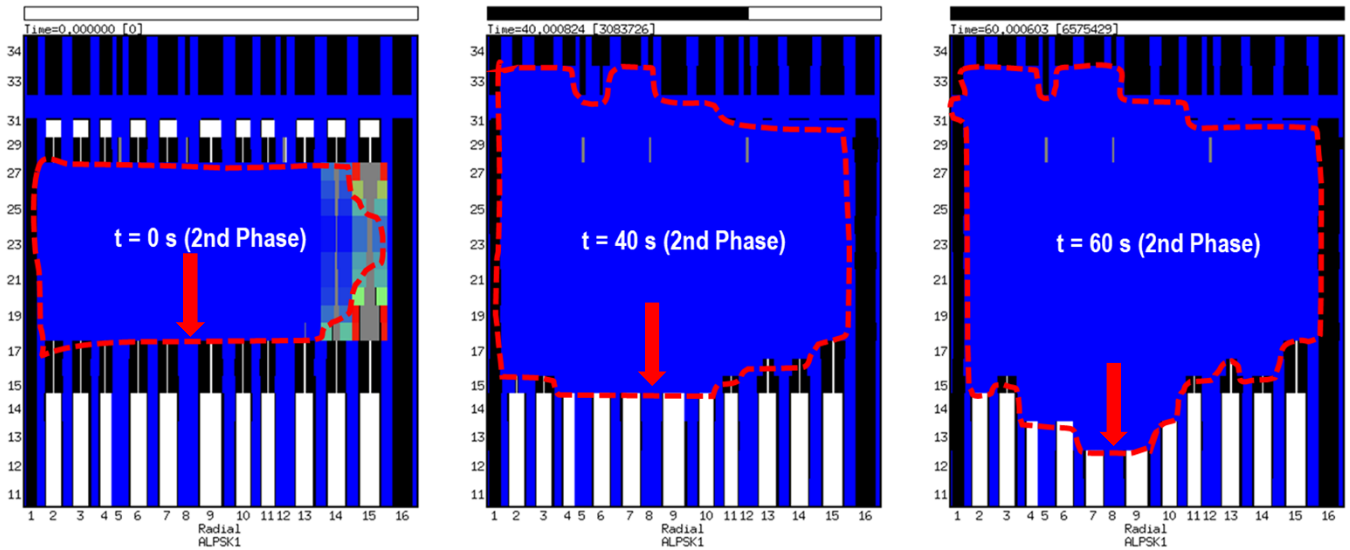


Upper limit for energetics

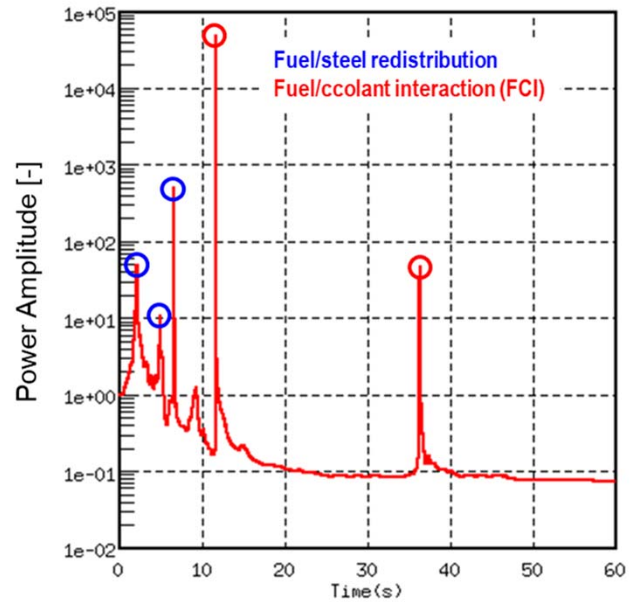
➔ asymptote caused by early fuel dispersal

Secondary Phase: Termination (2/2)

Thermal erosion of core



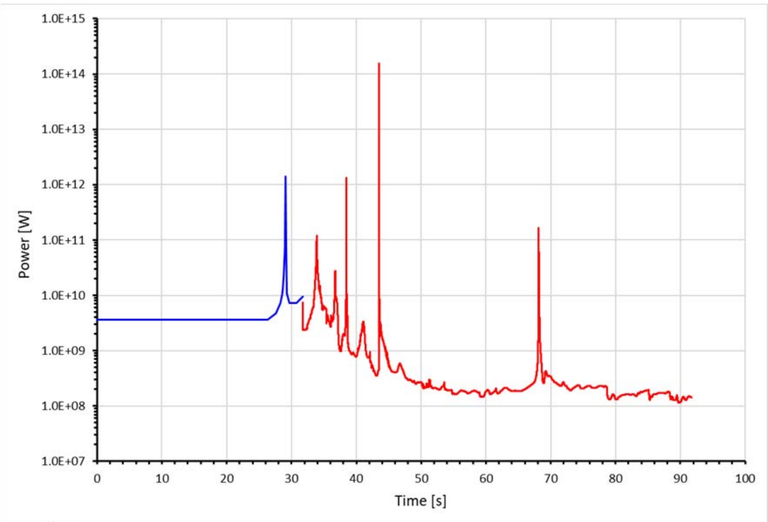
The poorly cooled core slowly settles down: plugs are melted to form again deeper down. Once the LAB and LGP etc. are destroyed, the core inventory is relocated to the CC.

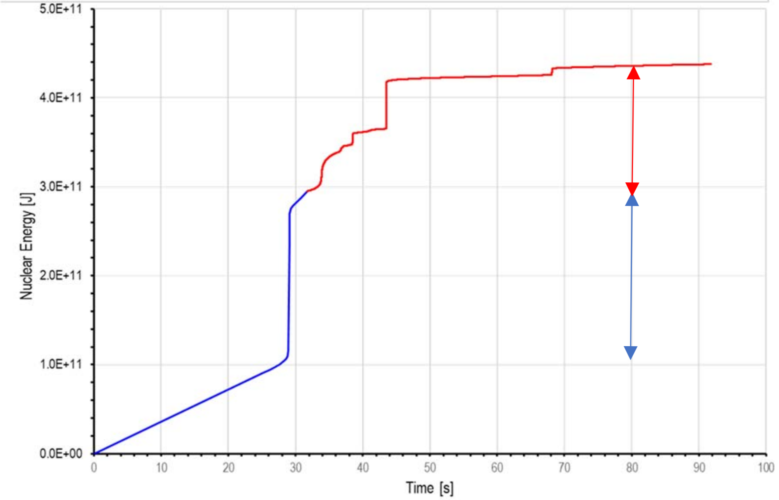


In SIMMER, a structure mechanics model does not exist. Material failure can only be caused by thermal failure, not by load.

It is upon the user to decide whether a power peak would lead to EP or not.

Secondary Phase Behavior: Conventional SFR





„Conventional Reactor“: CP-ESFR

Power: 3.6 GW

SVRE: ~+5 $

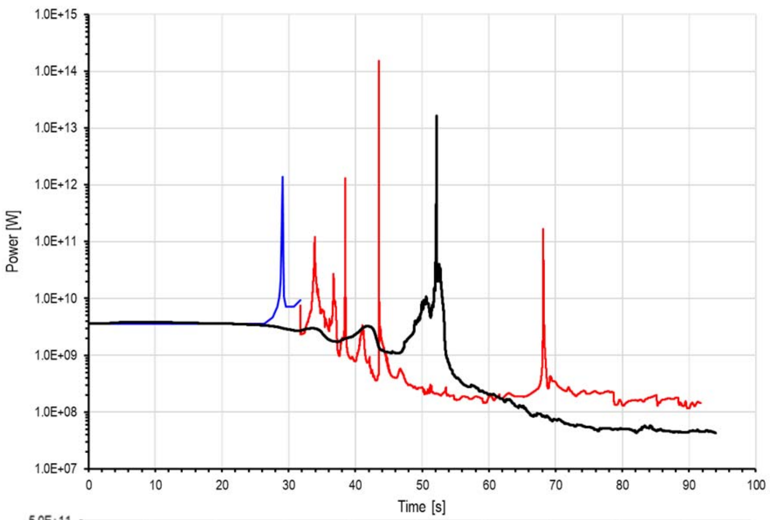
Primary Phase:

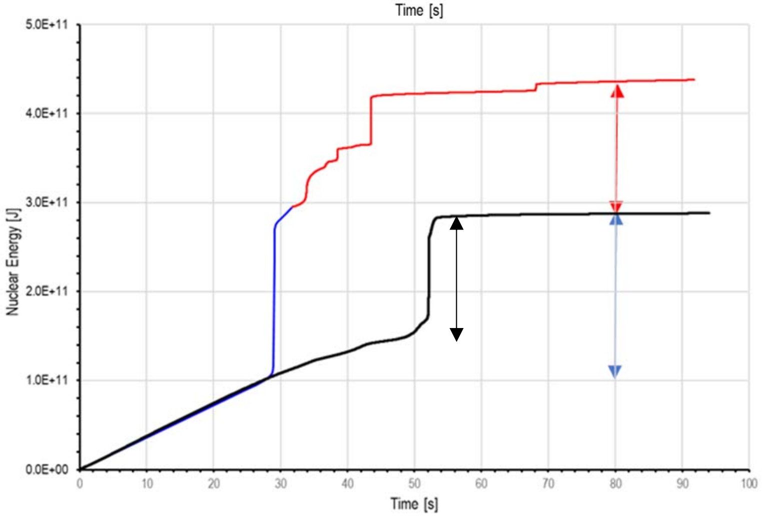
- 25 s till boiling onset
- 29 s till primary excursion
- 32 s till CW failure
- Pmax ~ 400 P_0
- ΔE ~ 195 GJ

Secondary Phase:

- Cycles of recriticalities
- simulation stopped after 60 s
- Pmax ~ 40.000 P_0
- Tfuel ~ 4300 K
- ΔE ~ 143 GJ

Secondary Phase: Conventional SFR vs Innovative SFR





„Conventional Reactor“: CP-ESFR

Power: 3.6 GW

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25 s till boiling onset

29 s till primary excursion

32 s till CW failure

Pmax ~ 400 P_0

ΔE ~ 195 GJ

Secondary Phase:

Cycles of recriticalities

Tfuel ~ 4300 K

Pmax ~ 40.000 P_0

ΔE ~ 143 GJ

simulation stopped after 60 s

„Innovative Reactor“: ESFR-SMART

Power: 3.6 GW

SVRE: ~ 0 $

Primary Phase:

32 s till boiling onset

51 s till primary excursion

52 s till CW failure

Pmax ~ 3900 P_0

ΔE ~ 116 GJ

Secondary Phase: almost non-existent

no cycles of recriticalities

Tfuel ~ 3500 K

Pmax ---

ΔE ~ 0.02 GJ

subcritical after 54 s

104 s caclulated

Secondary Phase Behavior: Innovative SFR

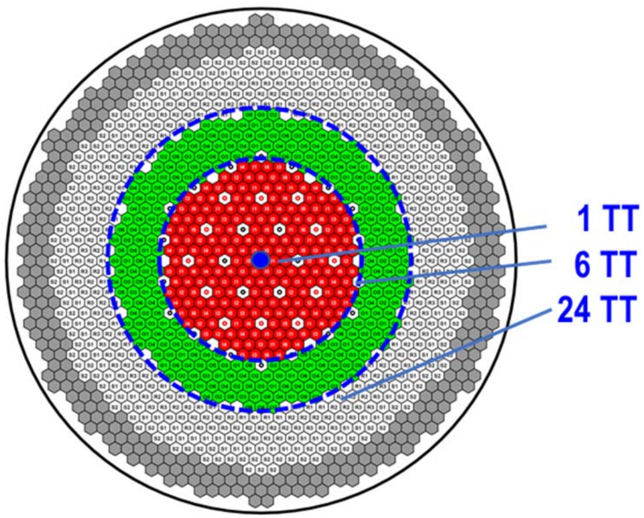
Most important design features of ESFR-SMART:

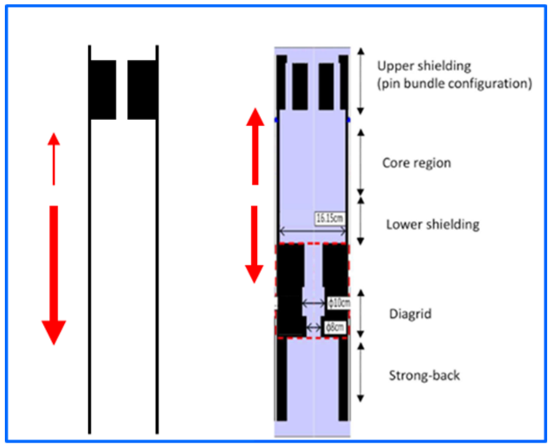
- *Core with inverted bowl-shape design*
- *Large sodium plenum*
- *PNS with neutron aborbing layer*
- *Largely reduced sodium void reactivity feedback*

- Transfer tubes TT for controlled material relocation
- Passive safety rods

➔ Focus of SIMMER-III Secondary Phase Analyses:

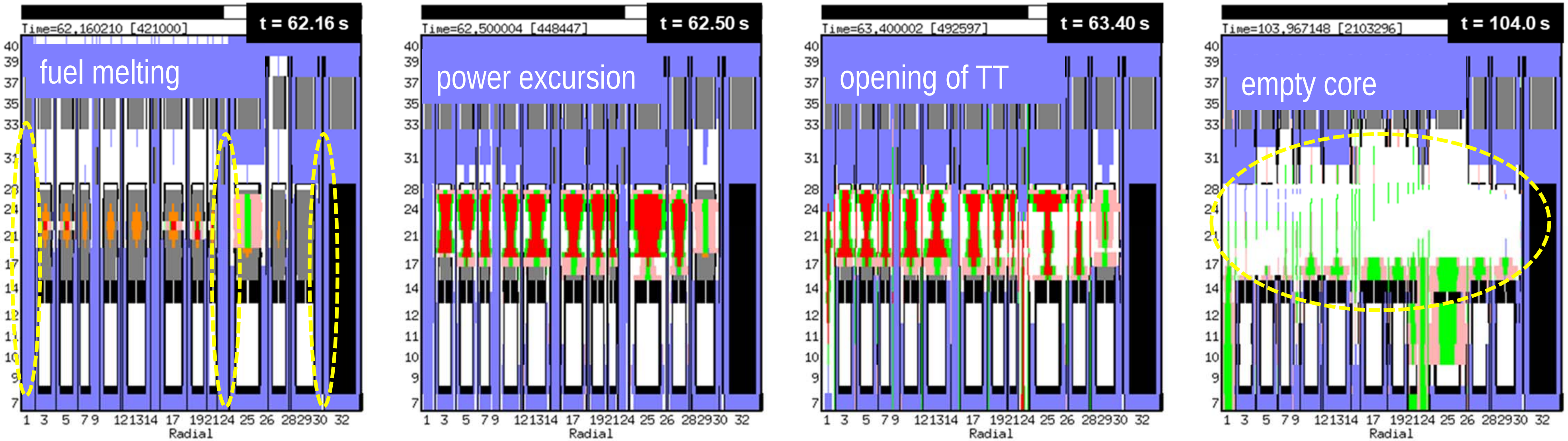
Testing of measures to mitigate severe accidents

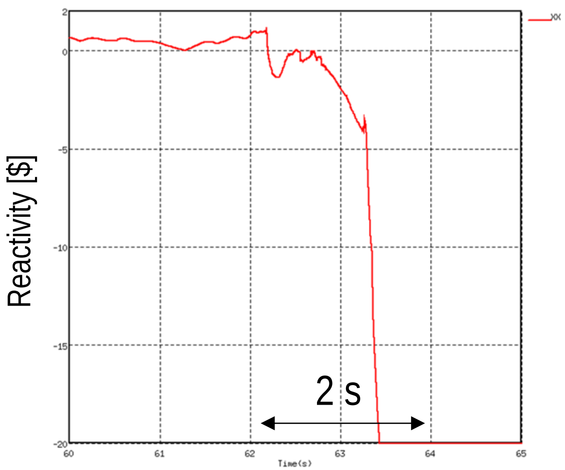




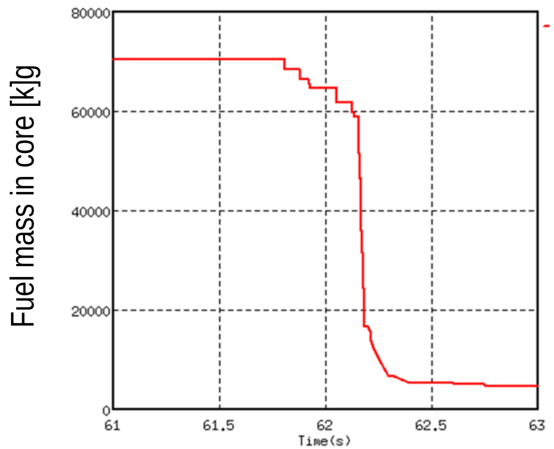
Transfer Tube: simplified layout (left) used in simulations

Secondary Phase: Innovative SFR / Transfer Tubes (1/2)





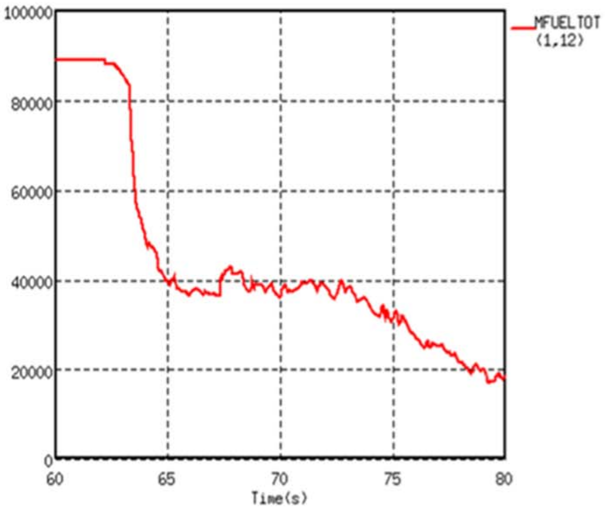
Discharge through 7 TT (out of 31) leads to deep subcriticality in less than 2 s.

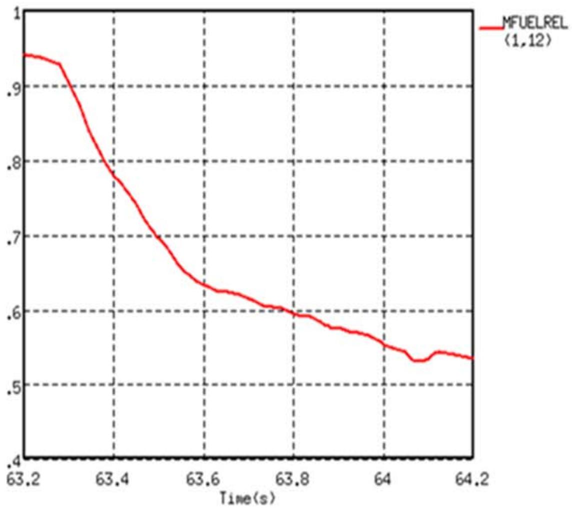


Secondary Phase: Innovative SFR / Transfer Tubes (2/2)

Transfer tubes with high fuel relocation potential **practically eliminate Secondary Phase.**

Due to the radial powerprofile, the 6 inner ones open firstly, quickly followed by the central one (t ~ 51.5 s after ULOF onset).
The outer 24 open at ~ 70 s, but cannot contribute to the fuel relocation (core already empty).





The *massive corium mass flow rate* (xx t/s @ ~ 3500 K) requires special focus on the core catcher against thermal in terms of *resistance against erosion and sufficient retention capabilities* (no clusters of hot melt arriving at the vessel).

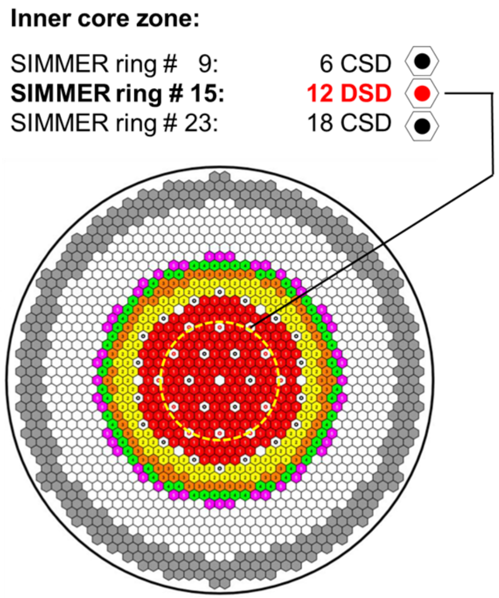
Secondary Phase: Innovative SFR / Passive Safety Rods

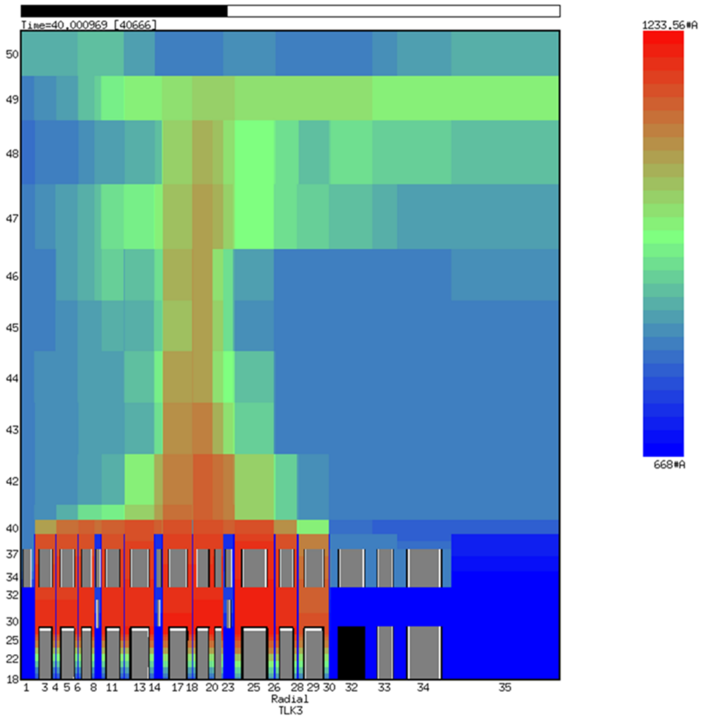
Study of Safety rods insertion at SA conditions

Curie-point release of safety rods:

- Trigger event is reached ~ at boiling onset
- 1 DSD rod is suffient to bring the core into a sub-critical state

Inserting absorber material under fuel pool conditions bears the risk that B4C becomes mobile after clad failure and floats atop of the pool because of ist low density.





Δt_{ULOF} = 30 s

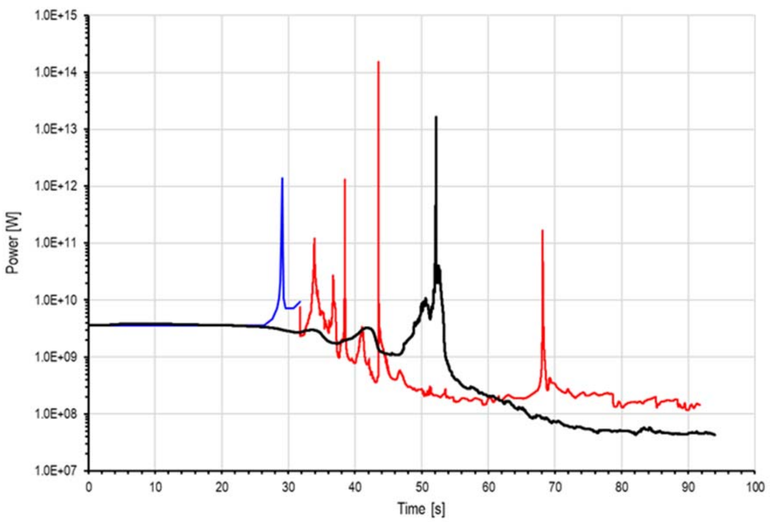
Secondary Phase: Consequences (1/6)

Important question: What does a high nuclear energy release mean for further accident phases?

➔ Conversion of internal energy into mechanical energy ➔ Expansion Phase (EP)

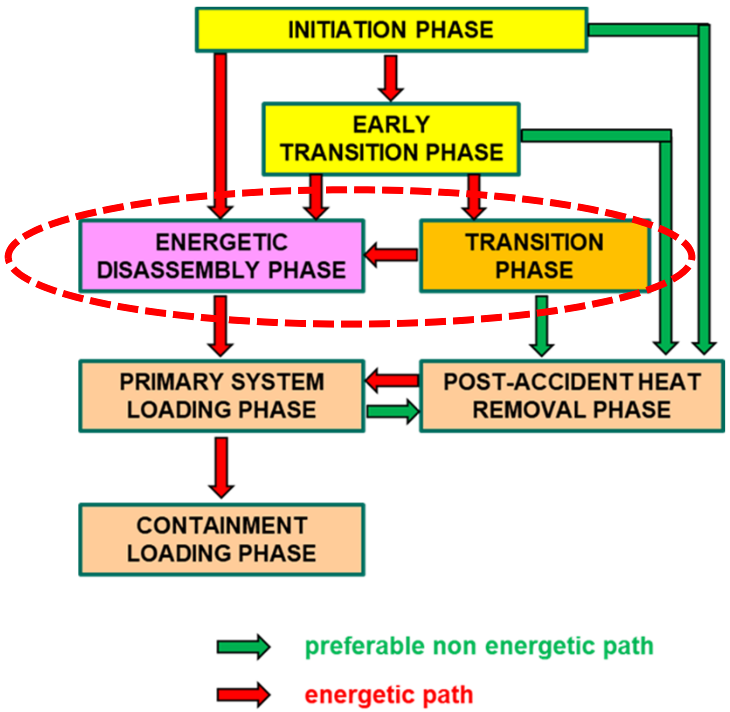
For a large power reactor, a mechanistic approach is required.

SIMMER has a suitable FD framework for this tasks, but lacks a structure mechanics module (deformation or rupture of vessel and internal structures due to forces).



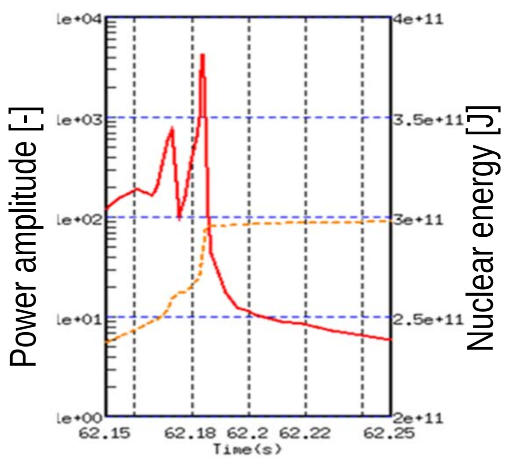
At which power peak and at which moment in time the EP would be entered, SIMMER cannot predict.

An automatic branching into another accident phase is only reasonable, if each accident phase is througly understood.

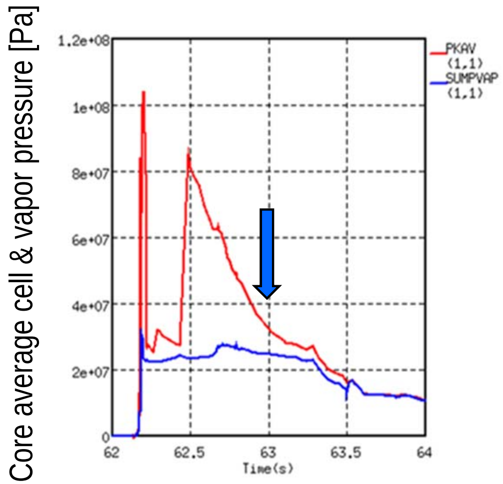


Secondary Phase: Consequences (2/6)

Choice for entering EP more simple for ESFR-SMART: one excursion only.

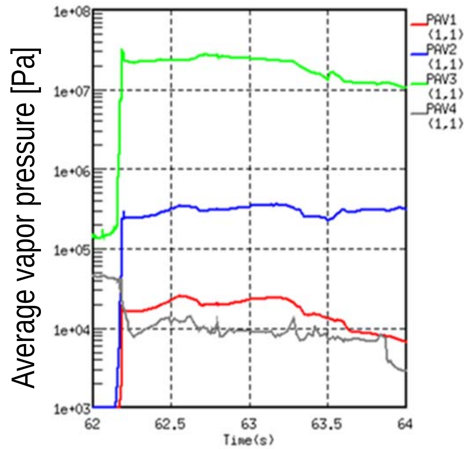


Excursion with double hump.



First peak too short for material relocation of structure failure.

Core pressure: 20 … 30 MPa for chosen value

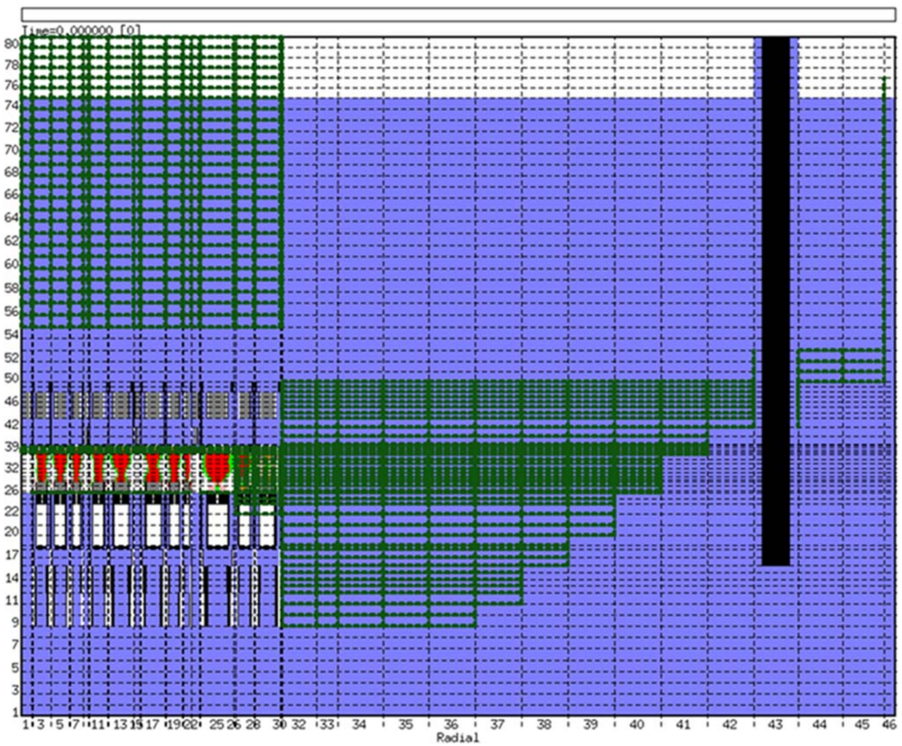


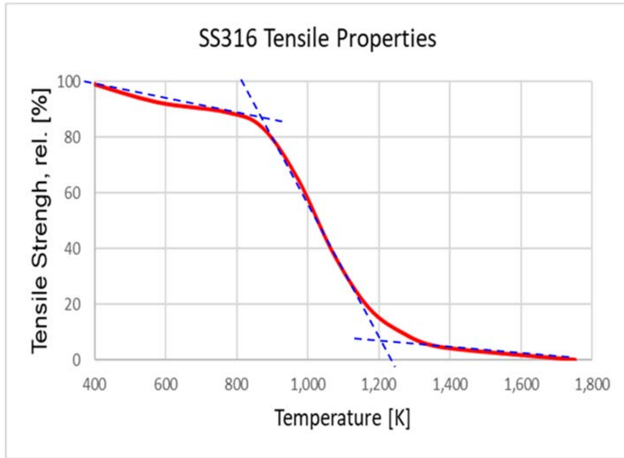
Vapor pressure dominated by Na vapor, plus steel; fuel vapor and FG uninportant.

Tfuel, liq = 3500 K
Tsteel, liq = 3200 K
Mfuel, liq = 45 to
Msteel, liq = 22 to

Secondary Phase: Consequences (3/6)

SIMMER-III EP model: full vessel domain. No neutronics (fast transient, subcritical), mesh refinement in hot Na pool and CG region.





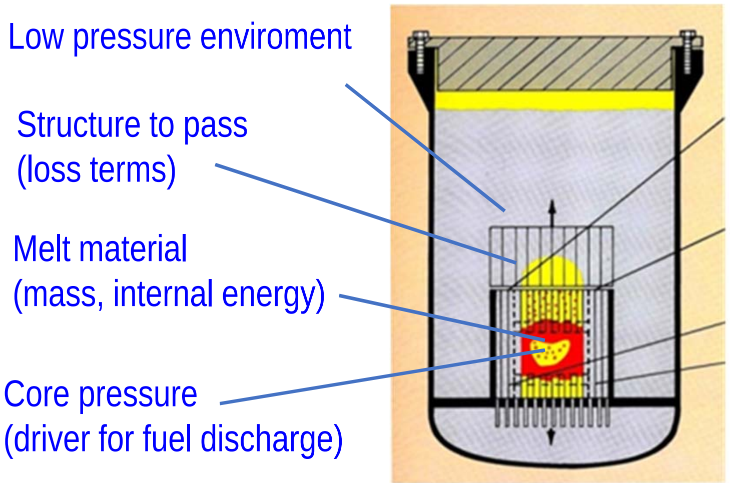
Rough idea from data of short-time elevated SS316:

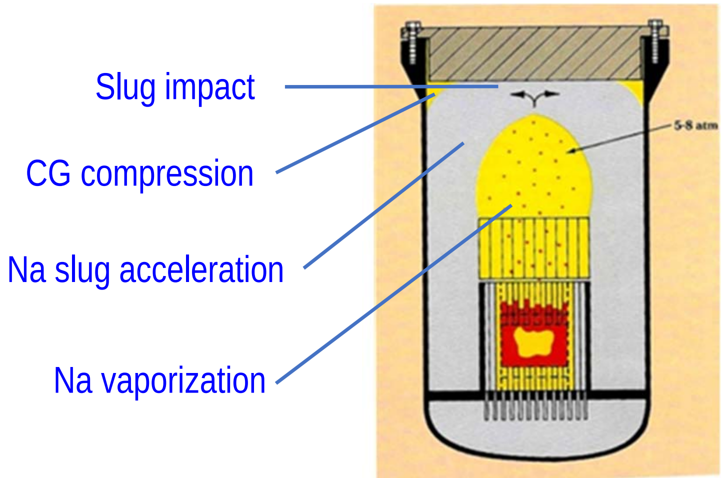
Upper core structure at T > 1200 K is expected to fail under given pressure loads.
The endangered material is then manually removed in a parametric case.

Secondary Phase: Consequences (4/6)

Mechanistic approach:

- Time- and space-dependent solution
- Loss terms considered (mass, momentum, energy)
- Exchance of thermal energy between hot melt and sodium
- Sodium vaporization and pressure build-up
- Acceleration of sodium slug upwards, eventually with impact
- Coolant redirection etc.

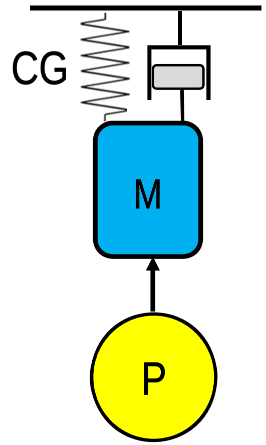




Evaluation of transient mechanical energy components from basic FD quantities:

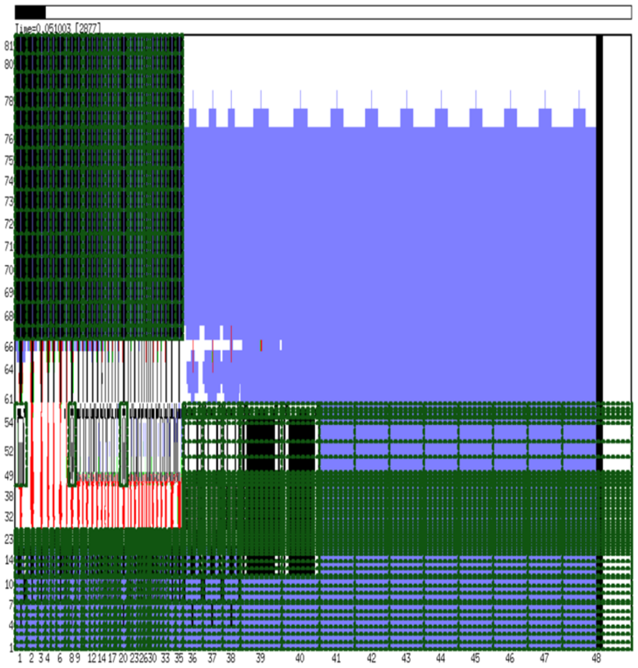
$$E_{mech}(t) = E_{pot}(t) + E_{kin}(t) + pdV(t) + \ldots$$

E_{def}, E_{rupt}, … n.a.

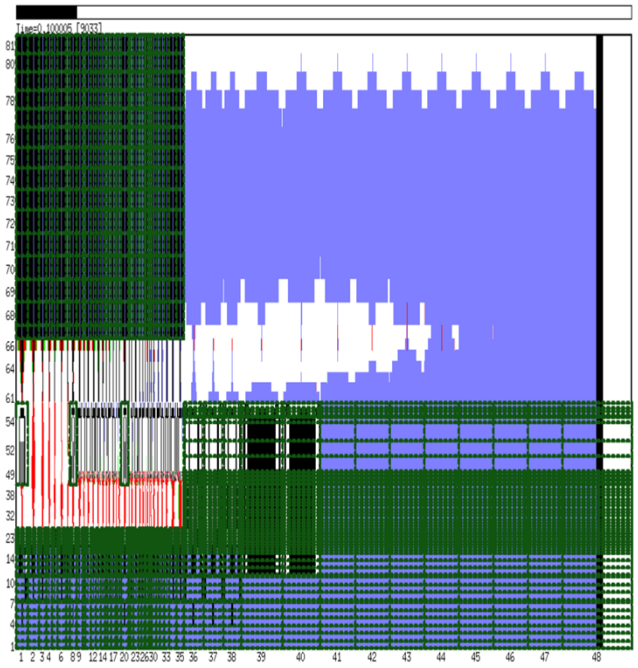


Secondary Phase: Consequences (5/6)

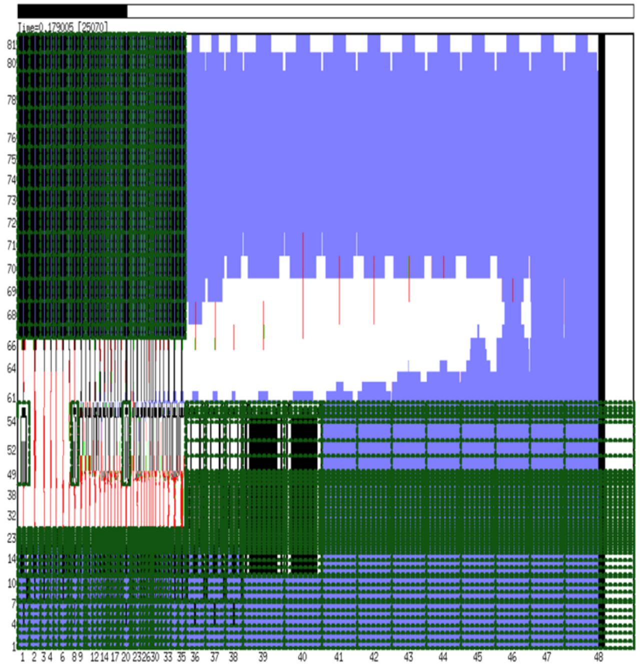
Example for SIMMER EP simulation (not ESFR-SAMRT)



Melt ejected into hot pool
Melt partly vaporises
Na bubble formation



Expanding Na bubble
Displaced sodium (level rises)



Sodium slug impact

Secondary Phase: Consequences (6/6)

The SIMMER Code is not specialized for EP applications, like e.g. EUROPLEXUS.

As the primary & secondary phases are evaluated with SIMMER, it is suggestive to use available quantities of

- Melt mass and internal energy
- Core pressure
- Conditions of flow paths through the UCS
- etc.

to assess the mechanical work potential.

The missing structure mechanics module, however, implies infintely rigid structures.
For internal structures, parametric variations (manually removed material) seems to be a valid approach.

Based on own experience, the condition of the UCS (available flow path) largely affects the melt discharge rate, which in turn, affects the outcome of the mechanical energy.

Thank you!