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# Behavior of fast reactor fuel during transient and accident conditions

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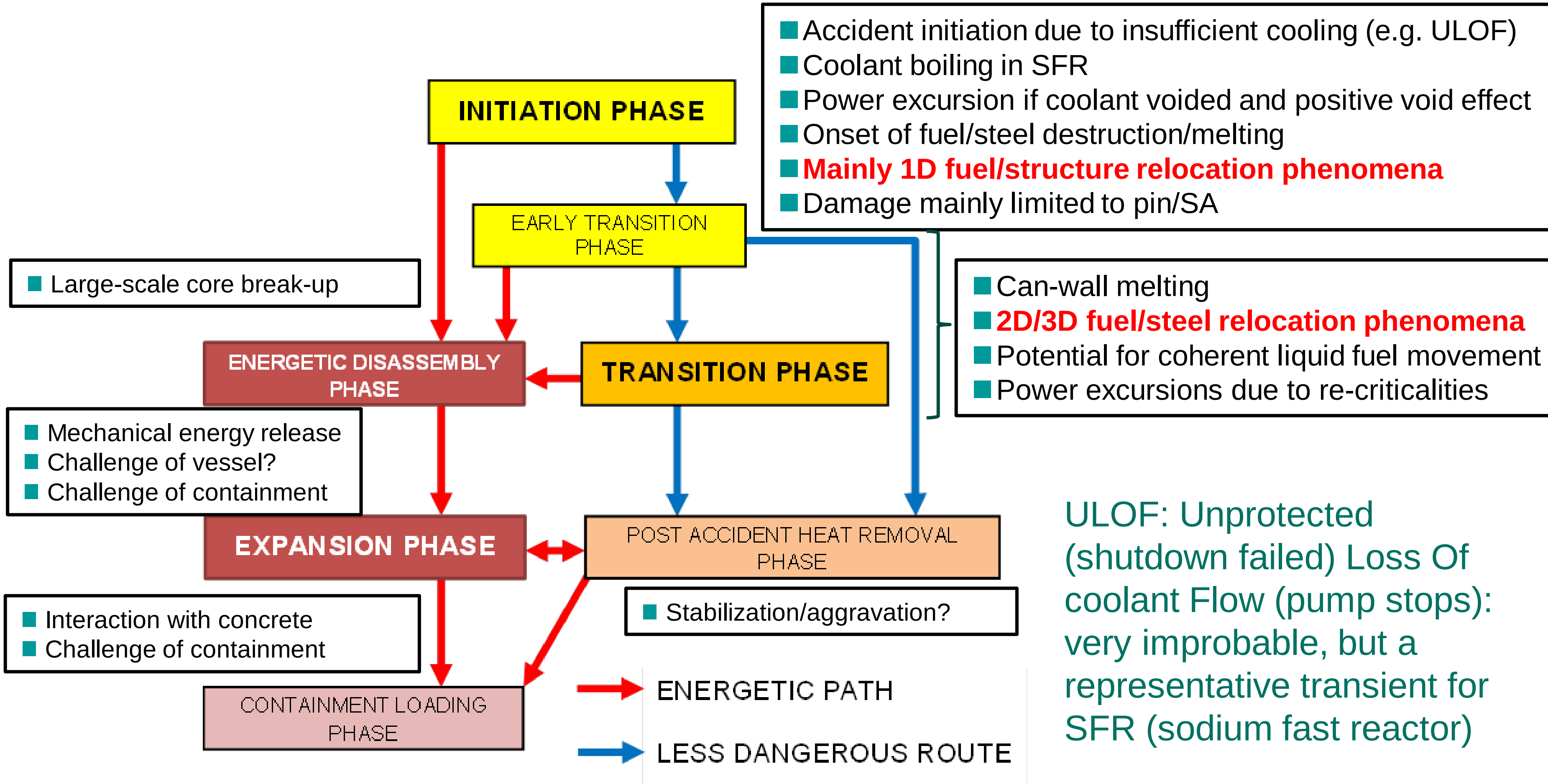
# Hypothetical accident progression in fast reactor with solid fuel (main attention: SFR with MOX/UOX)




ULOF: Unprotected (shutdown failed) Loss Of coolant Flow (pump stops): very improbable, but a representative transient for SFR (sodium fast reactor)

**To show that offsite emergency responses are not needed, one should evaluate possible mechanical energy release**

# Major Phenomena at steady-state, initiation Phase (IP)

- **Fuel Pin evolution under irradiation and thermal load at steady-state**
  - Pellet restructuring including evolution of the central hole, accumulation and release of fission gas/He, axial/radial expansion, gap conductance variation, gap closure, clad evolution, etc.
  - Assumed power history including fuel reloading/reshuffling scheme as boundary conditions for TH calculations for selected representative pins

- **Fuel pin evolution during IP (depending on scenario ULOF / UTOP/…)**
  - Power depending on reactivity (balance of neutrons/generated neutron)
  - Doppler (negative reactivity effect if fuel T increases), *coolant void effects (positive/negative depending on fuel, location, design),* expansion effects of core (negative), deformations (?), and Control Rod drive line (negative)
  - Cavity formation/grow and in-pin molten fuel relocation to axial periphery, in particular for annular pins (negative), the relocation may also delay clad failure
  - Fuel swelling and fission gas/He release
  - Coolant boiling (in SFR), clad/fuel melting/failure and propagation, Fuel-Coolant Interaction (FCI)
  - *Fuel/Clad relocation in the axial position and accumulation/freezing at axial periphery, axial power distribution following fuel relocation*
  - Blockage phenomena
  - Can-wall melting/failure

# SAS4A, SAS-SFR, SASSYS: examples of codes for initiation phase in SFR

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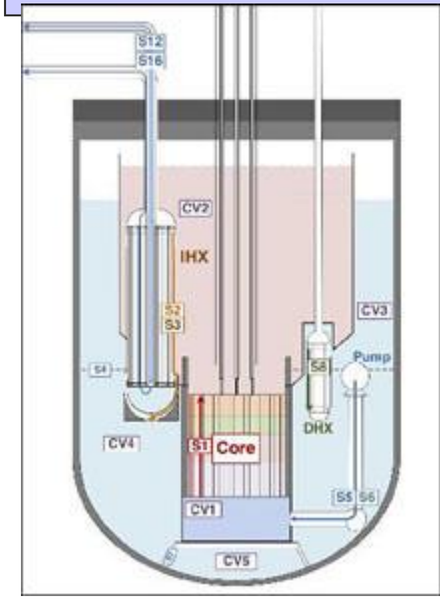
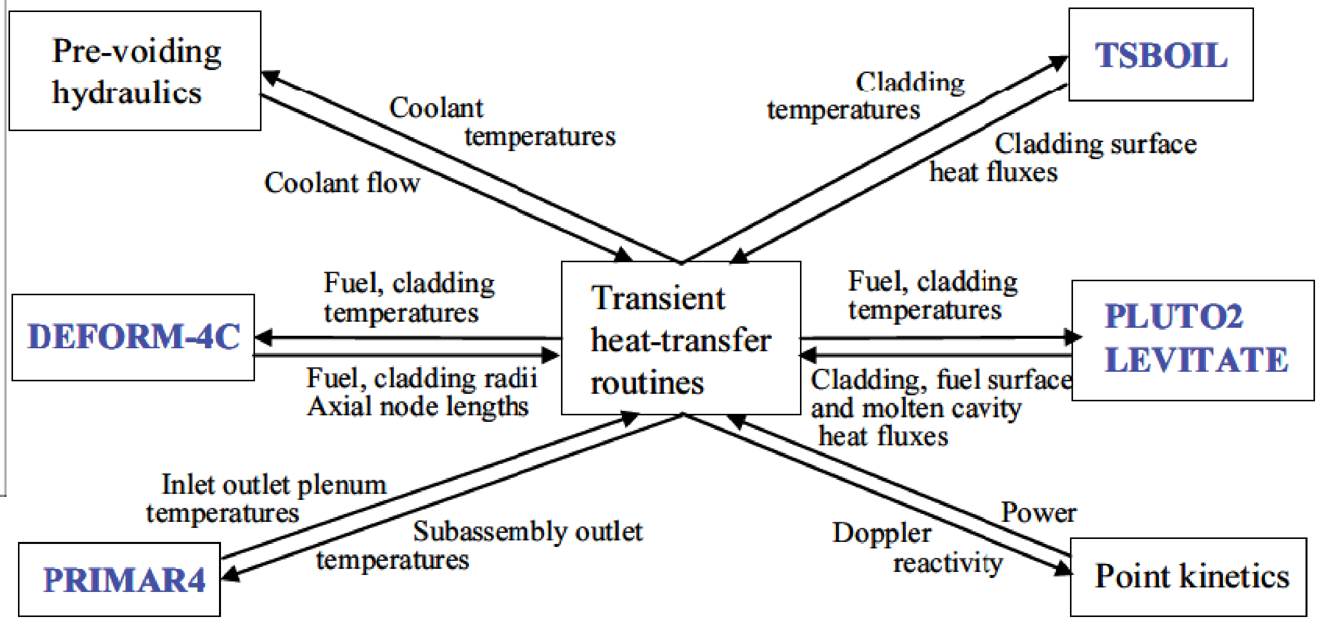
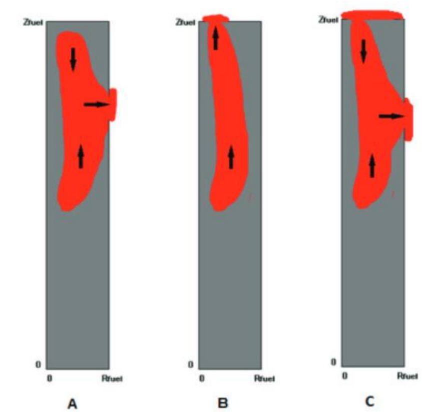



www.ne.anl.gov/codes/sas4a-sassys-1

- “Channels”: represent pins with pellets, gap, clad, coolant, associated structure (canwall…)
  Axial nodes of constant solid mass before fuel movement, Radial nodes for pellet etc.
- Several channels in the core are treated independently (except for inlet/outlet, reactivity), e.g. 1 channel per group of similar (burnup, power) subassemblies
- Material movement inside channel only, e.g.
  A) Cladding failure before in-pin motion (in particular for fast transients),
  B) In-pin motion before cladding failure (in particular for slow transients),
  C) Cladding failure after in-pin motion
  see Figure ->
  from: Tentner et al, LEVITATE-M Fuel relocation model…, Trans. ANS vol.117,2017



# SIMMER-III and SIMMER-IV Multi-physics Codes: initially main attention to late transient phases (transition, expansion, …)

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**SIMMER-III/IV are 2D (RZ) and 3D (XYZ, R-Theta-Z) 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

**$C^4P$ (KIT route)**
**560 Group Master Library**
**Basis: JEFF, JENDL, ENDF/B**
**Full Range Neutron Spectrum**

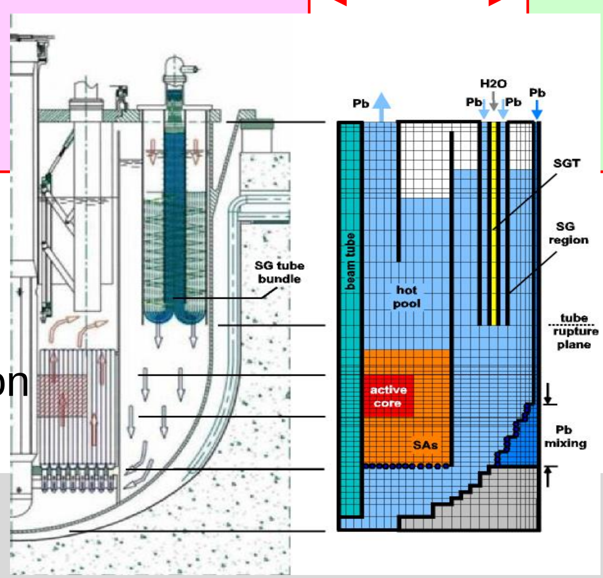
## Structure model

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

## Neutronics

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

SIMMER model example (SG Tube Rupture simulation in ADS)->




SIMMER:
- Slower than SAS4A, in particular in 3D
- Fuel irradiation/failure models: behind SAS4A
- But: applicable for late transient phases (after can-wall melting)
- Coupled route: SAS4A for the initiation phase, then SIMMER (coupling is not straightforward)

# Equation of State and Thermal-physical properties: SIMMER-III/IV materials

| *material number* (MNMAT) | *material type* (MNMATN) | *submaterial number* |
|---|---|---|
| 1 | Fuel | MOX, $UO_2$, $Al_2O_3$, Corium (4), Molten Salt (2) |
| 2 | Structure | SS 316 (steel boiling T close oxide fuel melting T) |
| 3 | Coolant | Na, $H_2O$, Pb, LBE (2), $He_2$ |
| 4 | Absorber | $B_4C$ |
| 5 | Gas (non condensable) | Xe, Air |

(default values; other selection: input block &XERG)

*(More EOS sets have been developped within the S-III community but not included in the code.)*

## Basic assumption: materials are immiscible

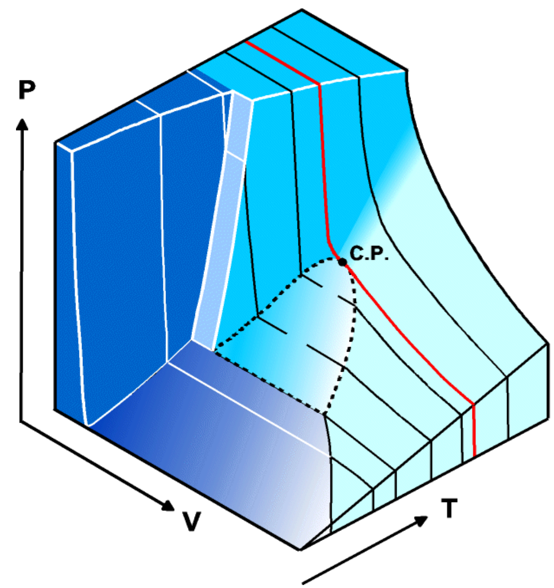
- no alloy formation featuring new properties
- no chemical reactions etc.

## Materials decribed over a wide temperature range

(from $T_\infty$ to supercritical conditions)

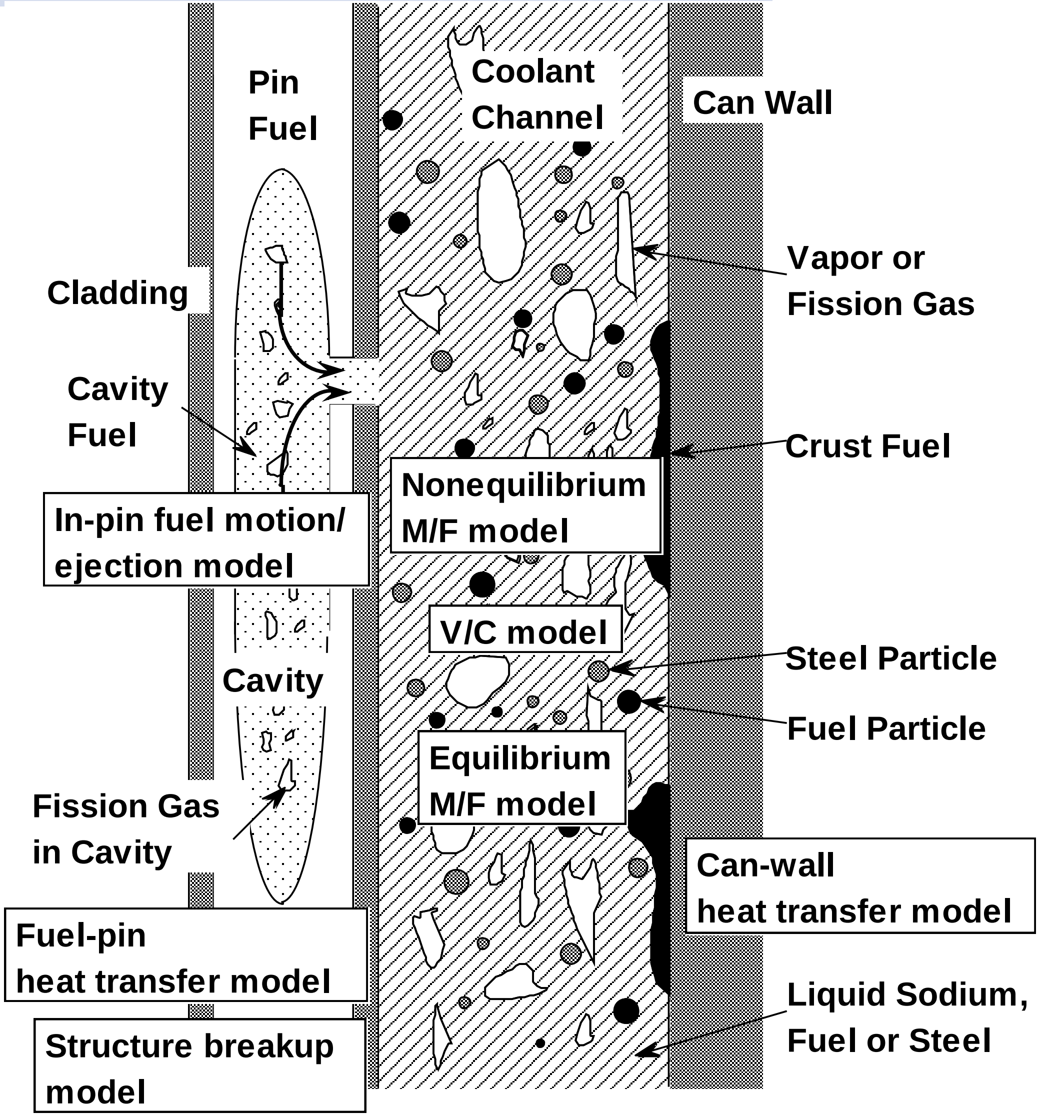
- Solid state (n.a. for coolant)
- Particles (n.a. for coolant)
- Liquid state (n.a. for absorber)
- Vapor state (n.a. for absorber)

Compressibility formulation for liquids and particles.

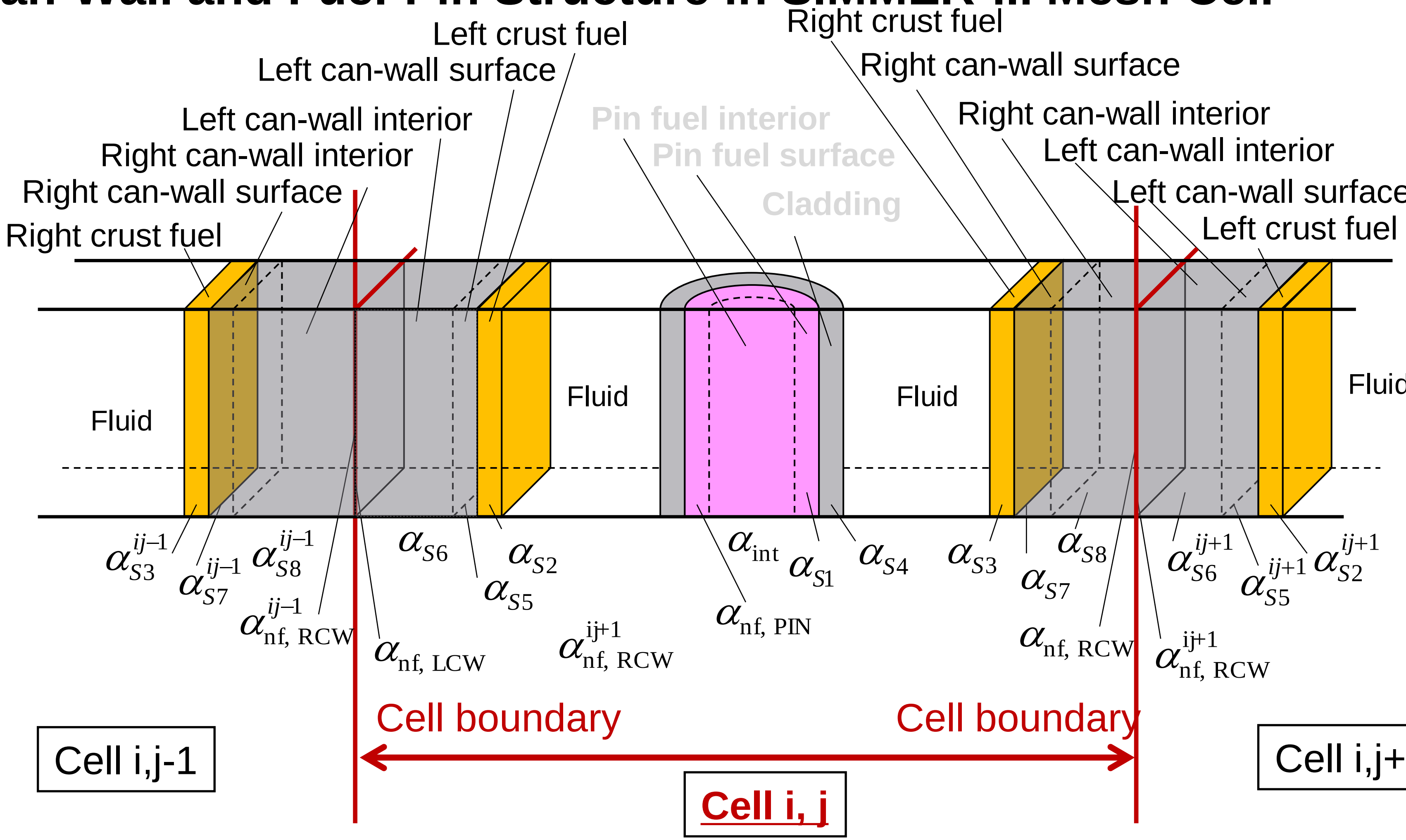


# Heat and mass transfer model in SIMMER-III/IV

- Non-equilibrium (interfaces) and equilibrium (in bulk): melting/ freezing (M/F) & vaporization /condensation (V/C) models
- Can-wall heat transfer model
- Structure breakup model
- Fuel-pin heat transfer model
- In-pin fuel motion/ejection model



# Can-Wall and Fuel-Pin Structure in SIMMER-III Mesh Cell



## SIMMER SPIN model

- **Simplified Fuel-Pin Model (SPIN)**
  - Developed as a **standard** model.
    - The accident progression behavior CDAs is often less sensitive to modeling details of fuel pins, especially for a Loss Of Flow accident.
  - The heat transfer inside the fuel-pin is calculated loosely coupled with a fluid-dynamics with large time steps (reactivity steps).
  - 2-node pin fuel representation (surface and interior).
  - Cladding is represented by 1-node.
  - Implicit heat-transfer calculations using internal energies.
  - Gap conductance (input constant or calculation) and fuel porosity.
  - Break-up based on a thermal criterion (melt fraction) or collapse due to no support.

# SIMMER DPIN model

Neither **SPIN** nor **DPIN** do calculation of Pin mechanics. NO fuel-cladding mechanical interaction (PCMI).

**But: DPIN model can calculate the mechanical pin failure due to cavity pressurization or internal pressure burst type failure.**

**DPIN can:**

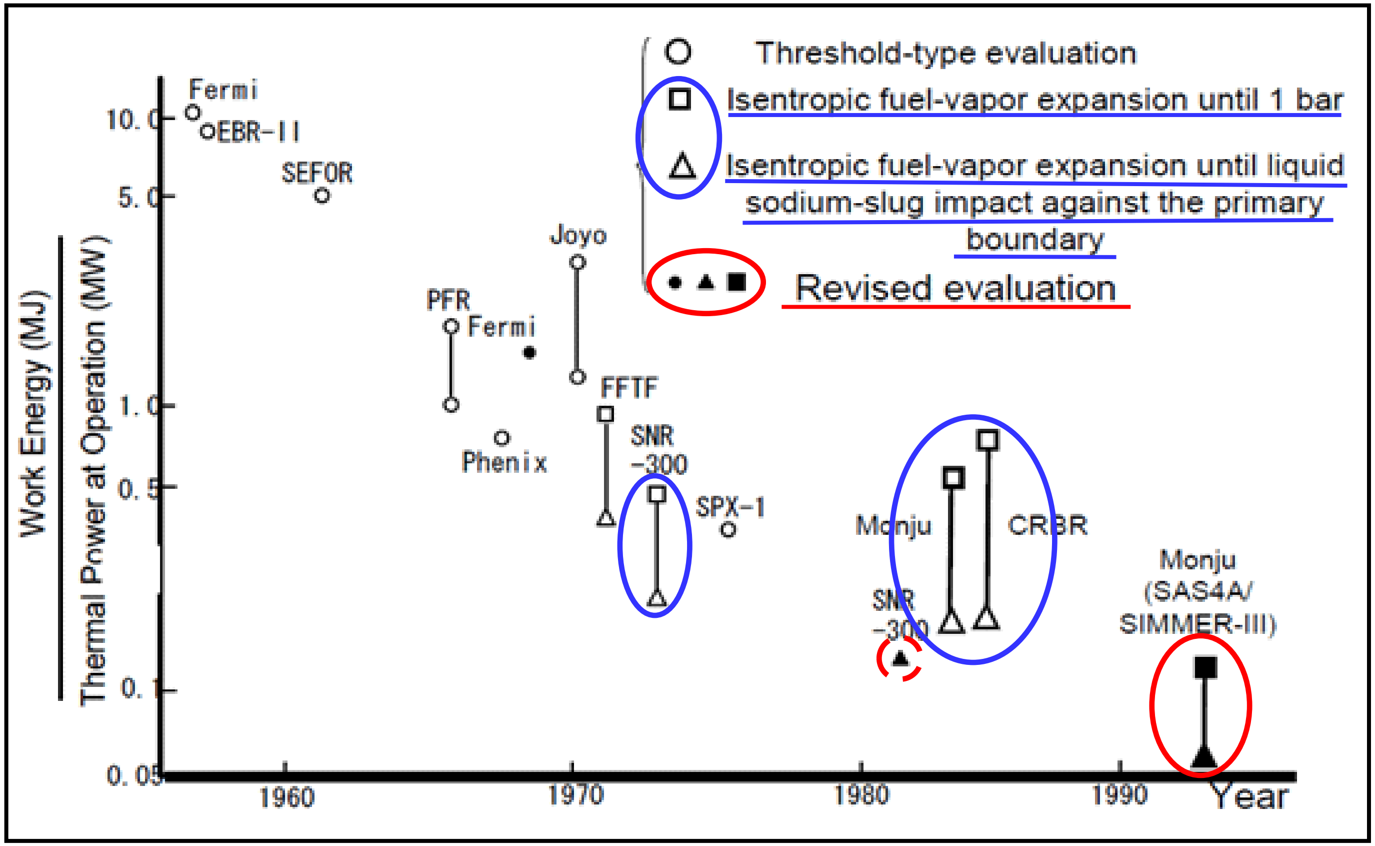
- Deal with the detailed (many radial nodes) pin model up to failure
- Cavity initialization at failure onset

**Description of detailed pin model after failure :**

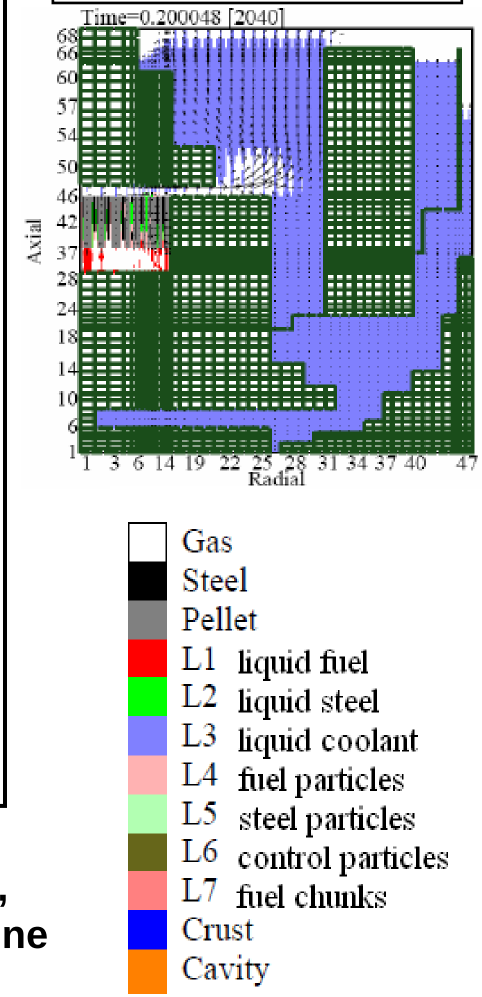
- Pin failure model based on thermal criterion or collapse due to losing support, including area melt fraction
- Description of fuel cavity: cavity initialization and extension
- Heat and mass exchange between cavity and solid fuel
- Fuel ejection
- In-pin fuel motion

## *Mechanical Work Assessment in SFR: much less conservative evaluations for mechanical energy release with advanced codes like SIMMER*

### Trend of evaluated work energy




**Fuel/Steel Discharge after Excursion and Acceleration of Sodium**




**R. Nakai, SFR Safety Principles & Safety Approaches for future SFR, IAEA-GIF Joint Workshop on Safety Aspects of SFR, Vienna, 23-25 June 2010.**

# Molten fuel temperature and thermal-to-mechanical conversion ratio

- Past SIMMER analyses for SNR-300, other systems: applying different assumptions and models (in-pin-fuel motion, clad failure, 2D approximations for control rods, particle viscosity models, etc.)

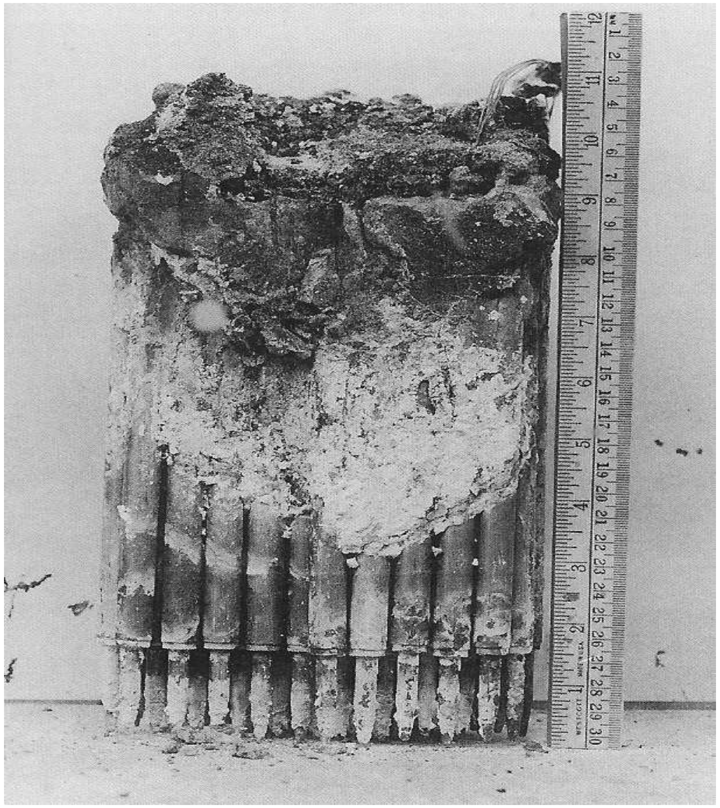
- Results evaluated for TP in a Risk-Oriented Study for SNR-300* → large range of fuel temperatures.

| Peak fuel temperature intervals [K] and probabilities in % | | | |
|---|---|---|---|
| < 4000 | 4000-5000 | 5000-6000 | 6000-8000 |
| 40 | 50 | 9 | 1 |

- Most probable range of values for the thermal-to-mechanical conversion ratio: 0.15% - 0.3%, **higher conversion ration values for higher fuel T**.
- **No significant mechanical work below 4000 K.**
- **Severe accident prevention and mitigation:**
  - **Low probability of core melting (favorable feedbacks including coolant void coefficient, passive safety systems): during IP**
  - **Controlled material relocation (early fuel discharge): during TP**

**Risikoorientierte Analyses zum SNR-300, Gesellschaft für Reaktorsicherheit, GRS-51 (1982)*

# Meltdown of EBR-I core due to a positive reactivity feedback



EBR-I core after meltdown (above): reactor stopped automatically after meltdown onset, small amount of gaseous FPs released, new core installed later

EBR-I: very small SFR with highly enriched U metal fuel operated in USA in 1950s and later

The fast acting positive reactivity component: due to inward heated fuel rod bowing

The slow large negative reactivity component: due to massive support plate at the top causing the fuel rods to bow outward

Different reactivity feedbacks at slow/fast transients

Transient analyses are needed for safety assessments

In EBR-II (larger than EBR-I), larger FFTF SFRs: no core damage after unprotected loss of flow: passive shutdown due to favorable feedbacks (+ special devices in FFTF)

# ULOF SIMULATION in ESFR Working Horse (WH)

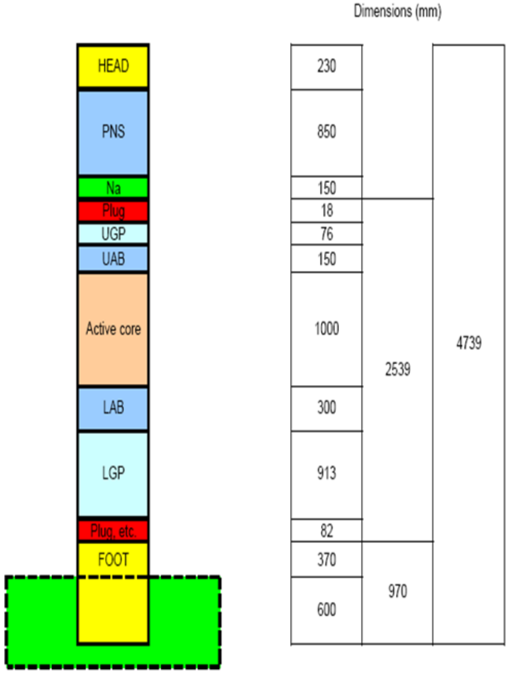
- WH (Working Horse) ESFR core, pool-type oxide fuel, power 3.6 GWth, poposed by CEA, studied in EU FP7 CP-ESFR project

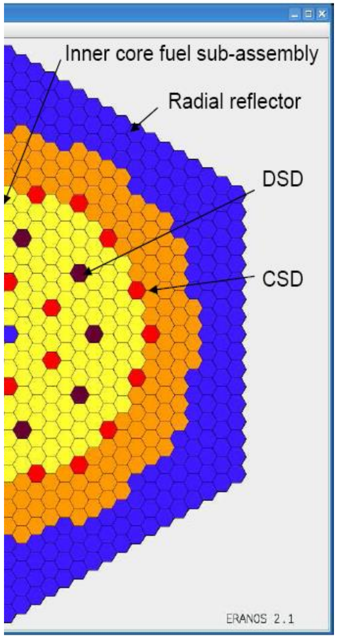
- ULOF simulations performed at KIT with two codes: SAS-SFR (IP) and SIMMER (later phases)

- SAS-SFR: assumption of no mass/heat
- transfer between the channels in the core: calculations till can-wall melting

- Void effect reduced, but remains positive
- Core breeding enhanced vs earlier EU large reactors: due to thicker pins: higher fuel volume fraction

- Better reactivity feedbacks, no fertile blankets needed for zero-breeding, reactivity loss with burn-up is low



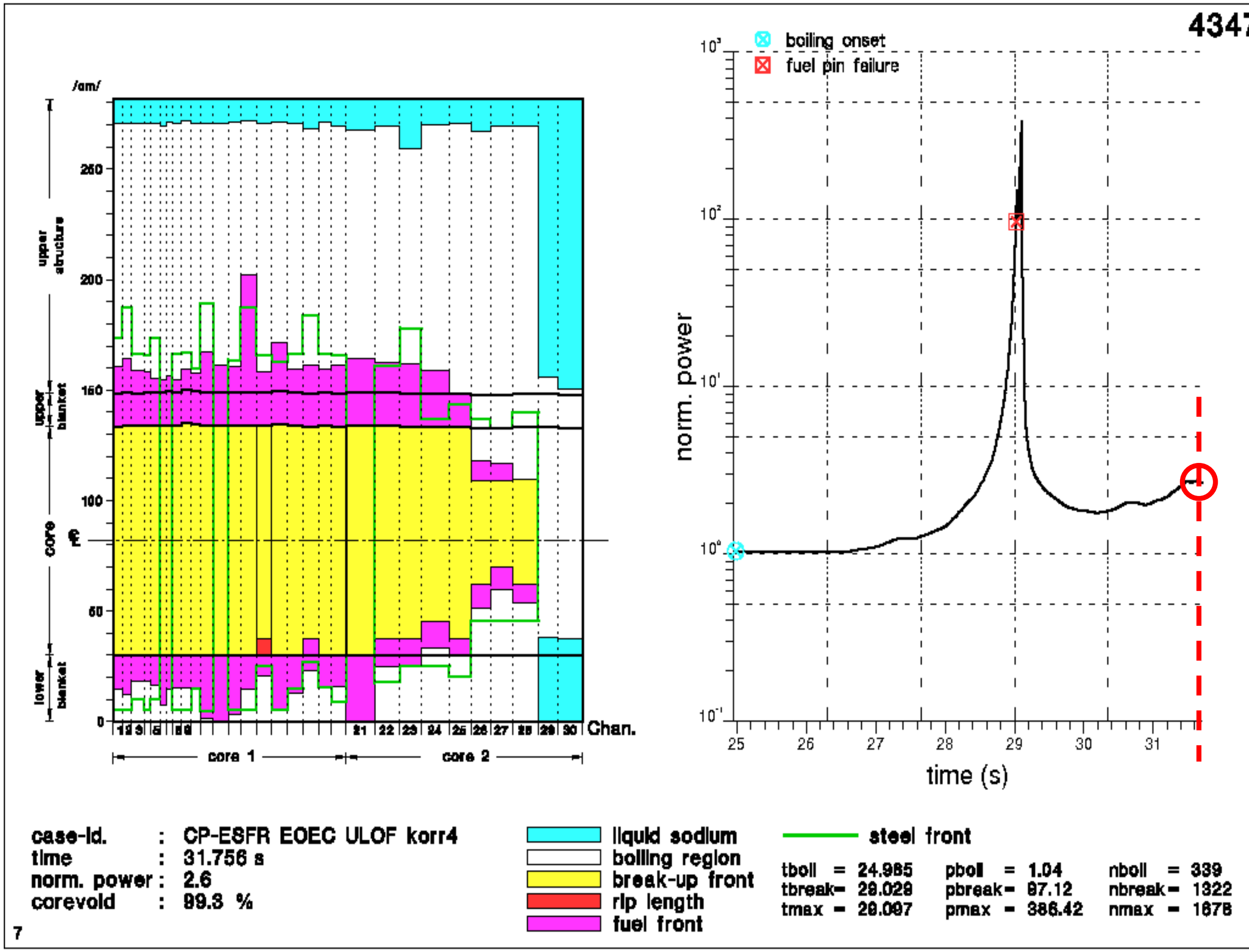
# ULOF in ESFR WH: Initiation Phase calculations with SAS-SFR

Coupling at t = 6.8 s after boiling onset (CW failure)

1st power excursion: ~ 350 – 400 x P0: due to quite positive void effect

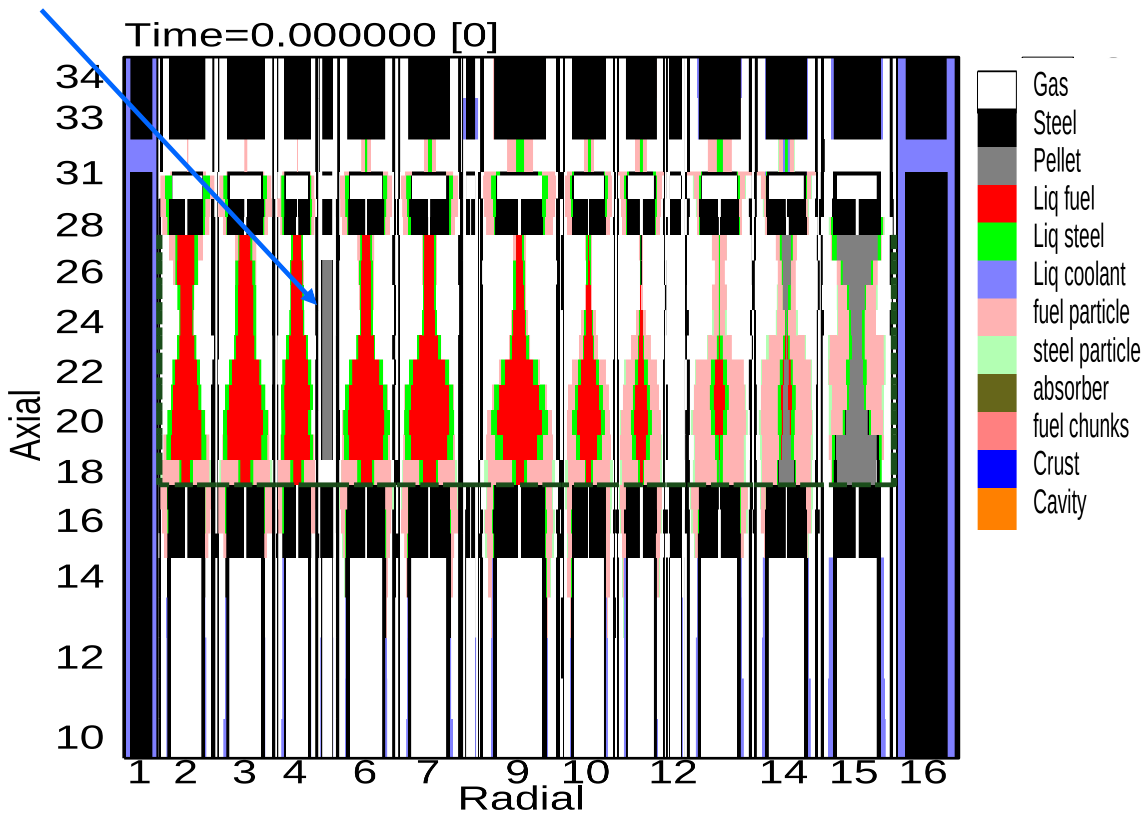
At the coupling point: power = 2.56 x P0, Reactivity: -0.27 $

SAS-SFR results hereafter by W. Pfrang et al., KIT



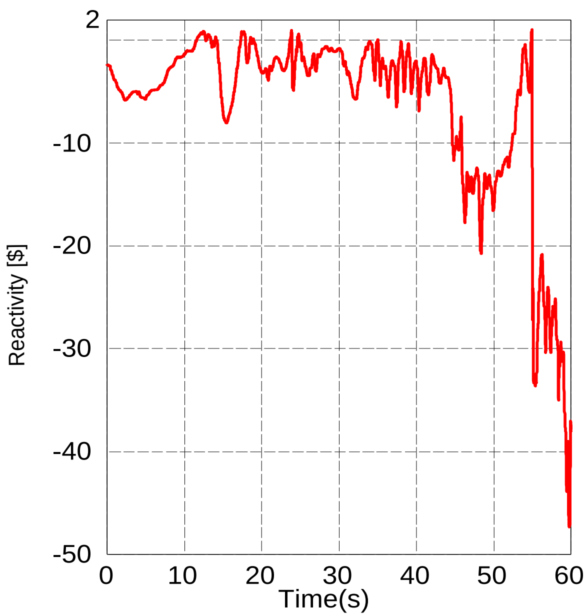
## ULOF in ESFR WH: start of transition phase

- At start of SIMMER simulations (t=0: coupling point), reactivity is -0.27$
- Study: Prompt introduction of CRs at t=0: absorber in radial mesh #5: -2$ extra reactivity
- Large part of fuel is molten or broken into chunks/particles at t=0
- Core axially plugged by frozen material outside fissile zone
- Calculations model: full vessel simulation, (only core region shown)

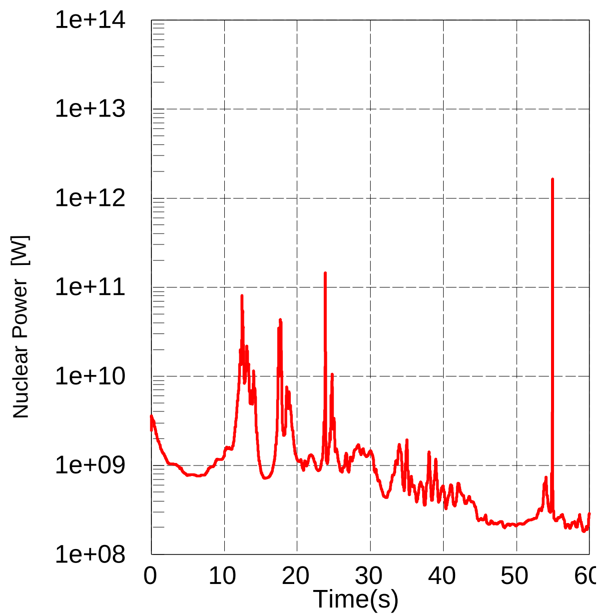



Material distribution at start of TP

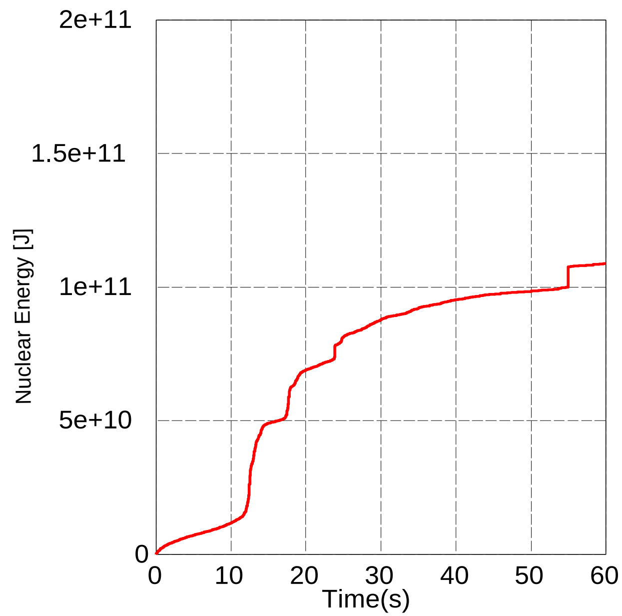
# ULOF in ESFR WH: Reactivity, power and nuclear energy in the closed pool




Reactivity




Power

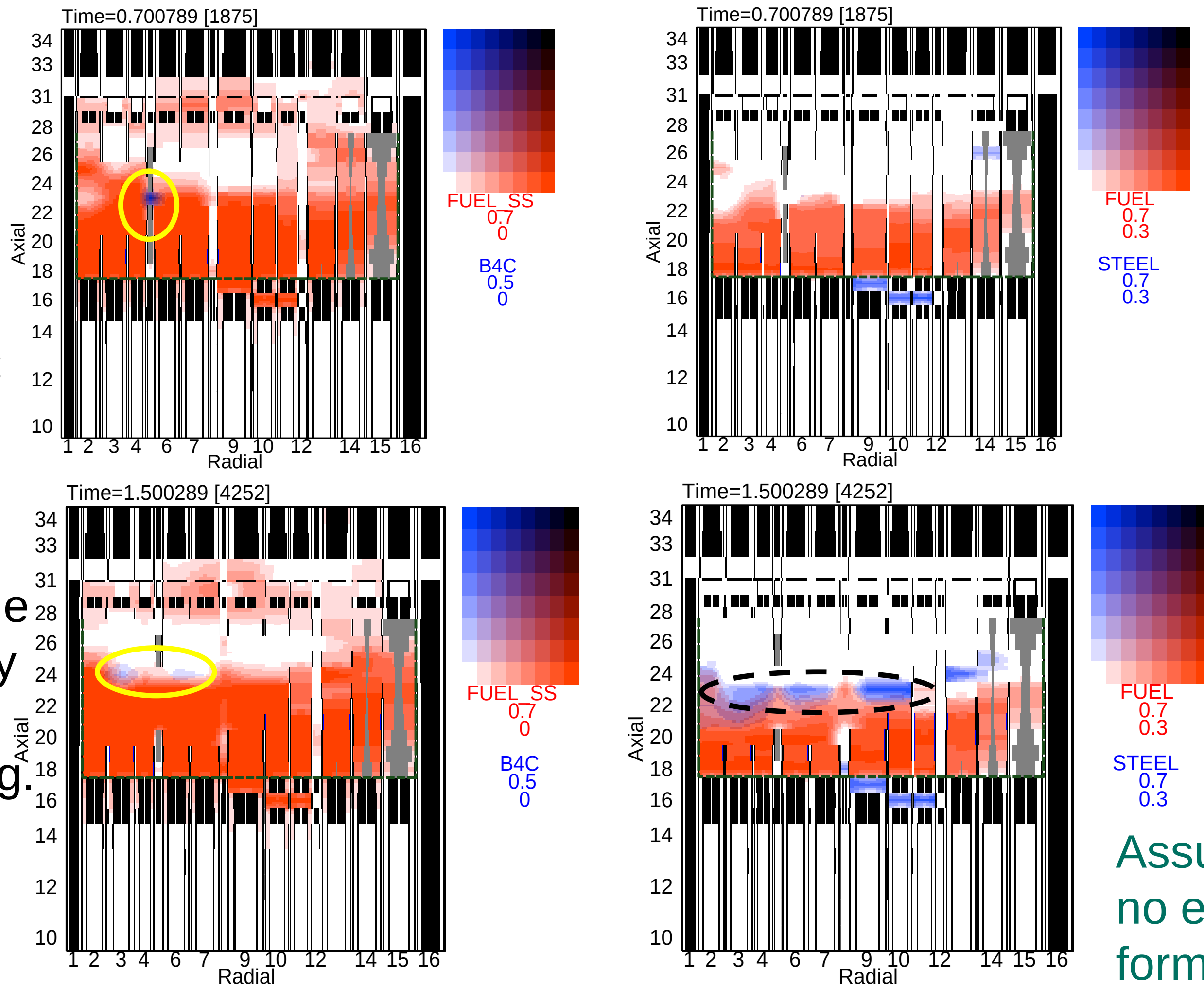



Nuclear energy

# ULOF in ESFR WH: B4C/Fuel and Steel/Fuel Redistribution in the closed pool

t = 0.7 s: CanWall still existing to a large extent. Structure around B4C pin fails, B4C particle release.

t = 1.5 s: B4C particles float at the top of pool; density driven fuel/steel separation ongoing.




B4C/Fuel

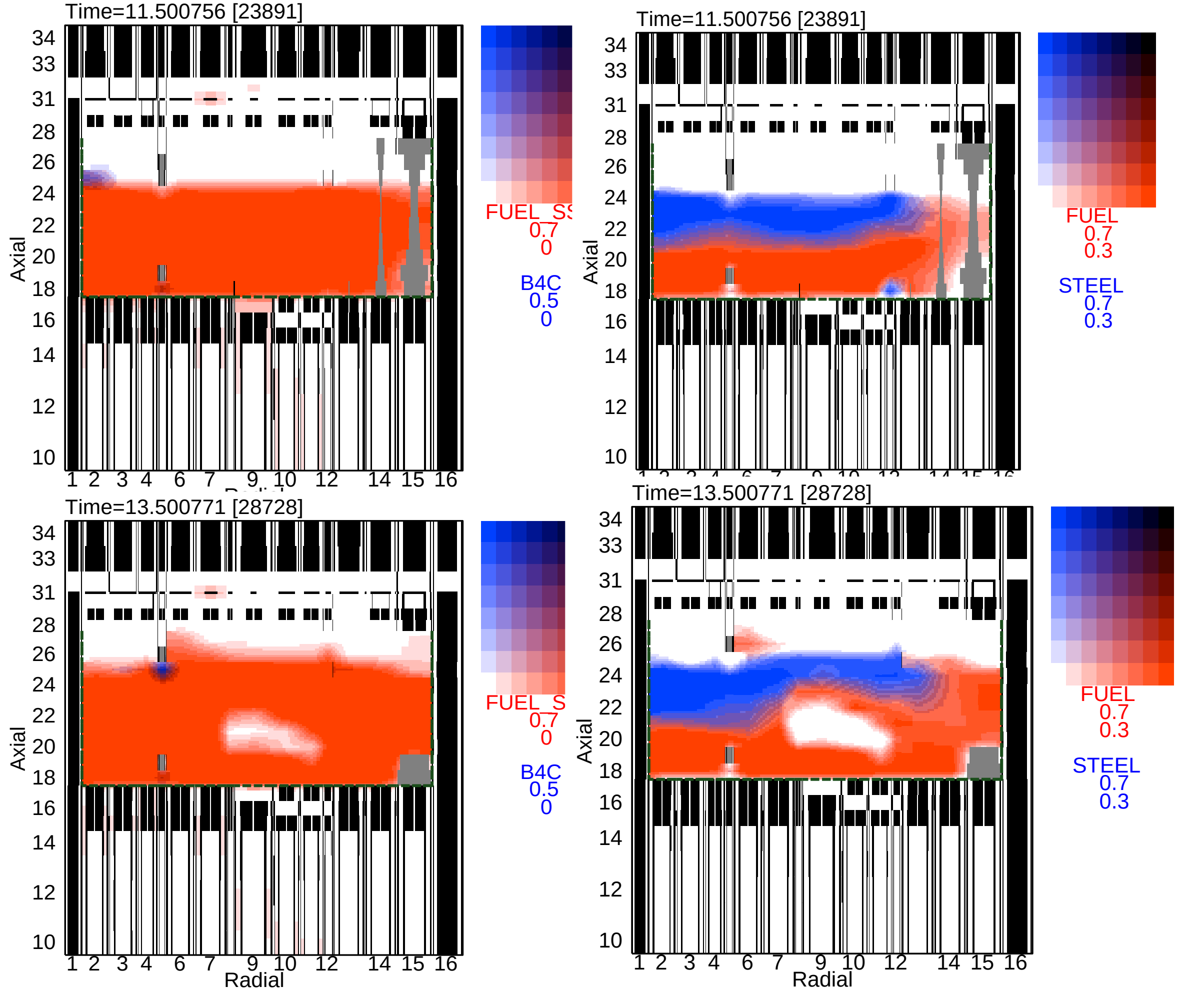
Steel/Fuel

Assumption: no eutectic formation as B4C-steel

# ESFR WH: B4C/Fuel and Steel/Fuel Redistribution in closed pool with CR

t = 11.5 s: re-criticality reached. Pronounced fuel/steel layering. Steel as reflector layer Absorber above fuel.

t = 13.5 s: vaporization of small amounts of liquid steel causes sloshing



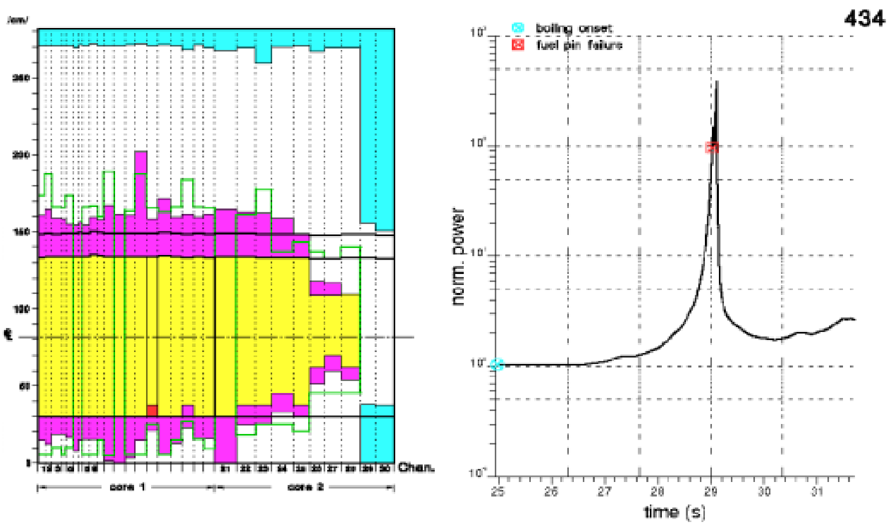

B4C/Fuel

Steel/Fuel

# Old and new (low void) SFR designs

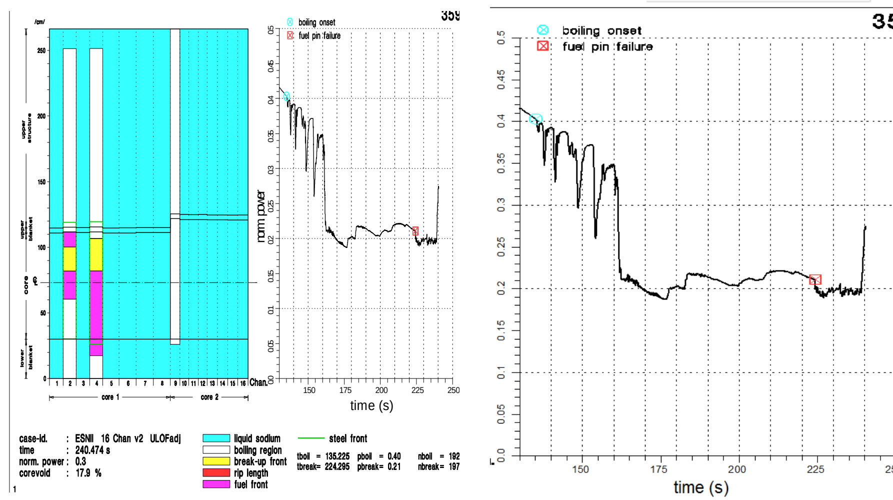
Comparison of ULOF power history until can-wall (CW) failure: *SAS based values*


**ESFR WH**




- IP dominated by large positive void worth
- Large power excursion ~400 x $P_0$
- Core largely destroyed

**ASTRID of ESNII+**




- IP influenced by **negative coolant** void feedback
- **Longer pump coast-down**
- No excursion - power steadily reduced, but oscillations due to Na plenum voiding/rewetting
- Much longer time till core melting
- Local damage: 2 channels; 3 channels voided

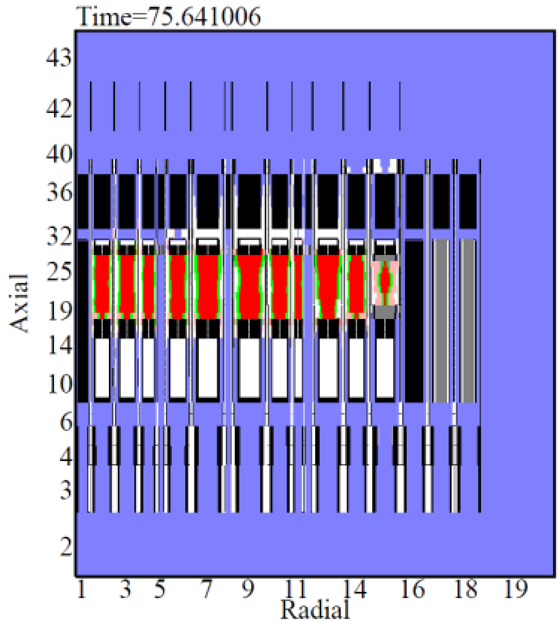
CW failure: end of SAS application range ➔ continued by SIMMER-III simulation

# SFR examples – situation at begin of Transition Phase (TP)

## Comparison of material distribution *

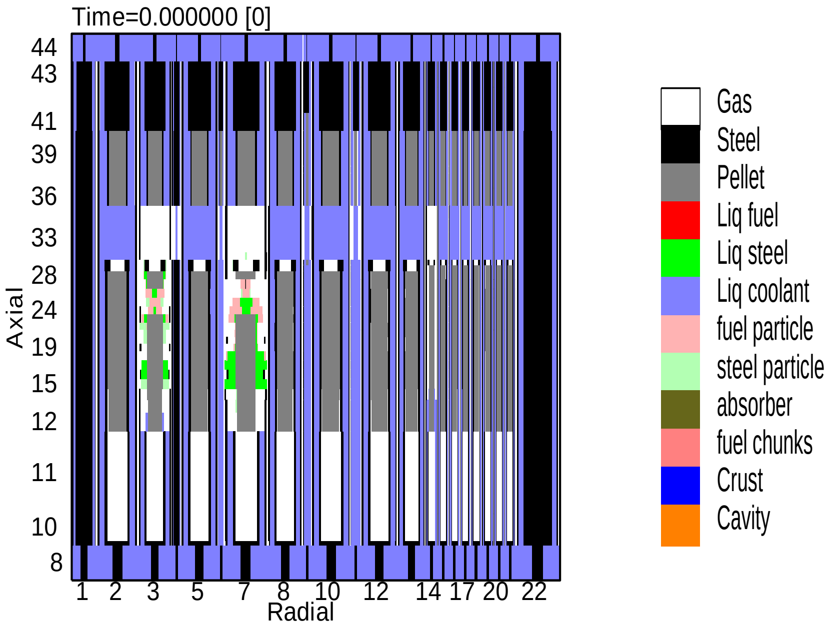
** SIMMER side – based on SAS IP results*

**ESFR WH**




- Major fraction of fuel in liquid state
- Core plugged at axial periphery (TH decoupled from Na plena)

**ASTRID of ESNII+**

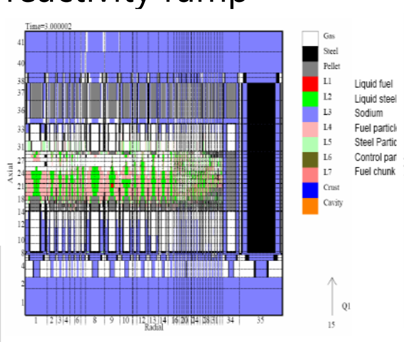


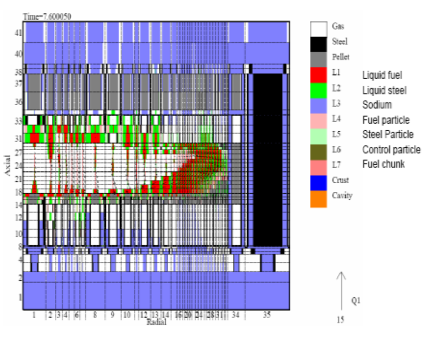

- Major fraction of fuel intact
- Some fraction as chunks (larger than particles, geometry restrictions for movement)
- Wetted core benefits from mixed convection

Low void cores: possibility of massive core melting canot be excluded

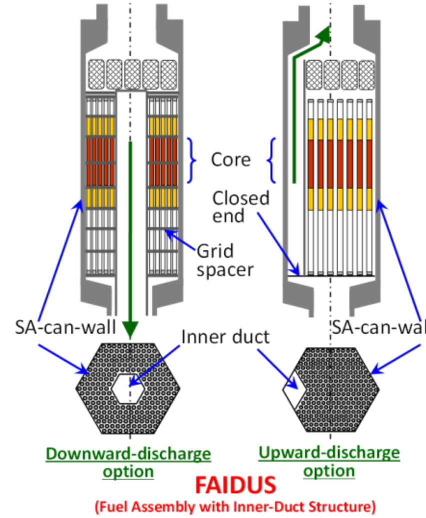
# Major Phenomena during transition phase

- Massive fuel/structure melting->creation of molten pool
- Decay heat: major heat source at subcritical conditions
- Stratification of fuel from other materials, sloshing movement leading to re-criticalities
- Eutectic formation (e.g. steel/B4C) – *no model*
- Power excursions due to re-criticalities, *higher thermal-to-mechanical energy conversion ratio with energy accumulation!*
- Discharge of core materials to axial periphery and reactivity reduction
  - For conventional designs in particular through CR follows
  - Special SA designs as FAIDUS in JSFR or
  - Discharge tubes in ESFR-SMART
- Blockages at axial periphery preventing fuel discharge
- Radial molten fuel motion: potentially with high reactivity ramp



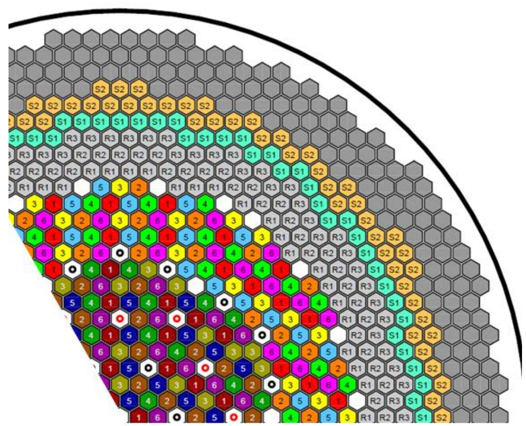



Enhancement of molten fuel discharge




JSFR: Relatively high void effect +FAIDUS

| | | |
|---|---|---|
| 1 2 3 4 5 6 | Outer fuel | 288 |
| 1 2 3 4 5 6 | Inner fuel | 216 |
| | CSD / DSD | 24 / 12 |
| R1 R2 R3 | 1st / 2nd /3rd reflector ring | 66 / 96 / 102 |
| S1 | Spent Inner / Outer fuel storage | 108 |
| S2 | Spent Inner / Outer fuel storage | 144 |
| | Corium discharge tubes | 31 |



ESFR-SMART: Near-Zero Void Effect, Discharge tubes

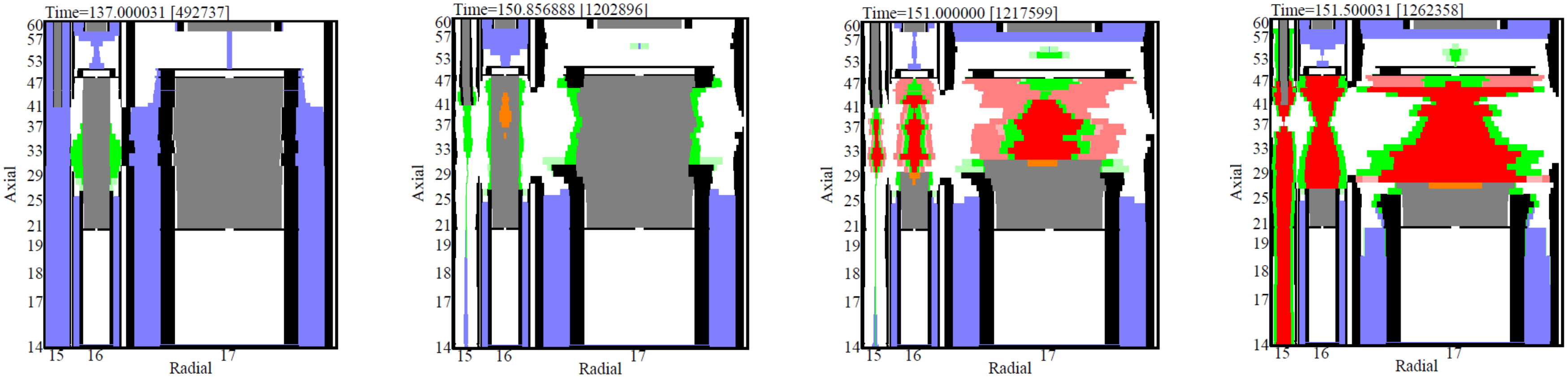
# SIMMER application to ESFR-SMART

Different core in ESFR-SMART for void effect reduction (ca. 5$ -> 0.5$ at EOEC): upper Na plenum, shorter axially and larger radially core, lower fertile blanket, see Figure ->


**Steel removal effect: strongly positive in FR designs with solid fuel**

**Early fuel discharge is important**

- Propagation molten fuel to Control Rod tubes: may help to prevent re-criticality

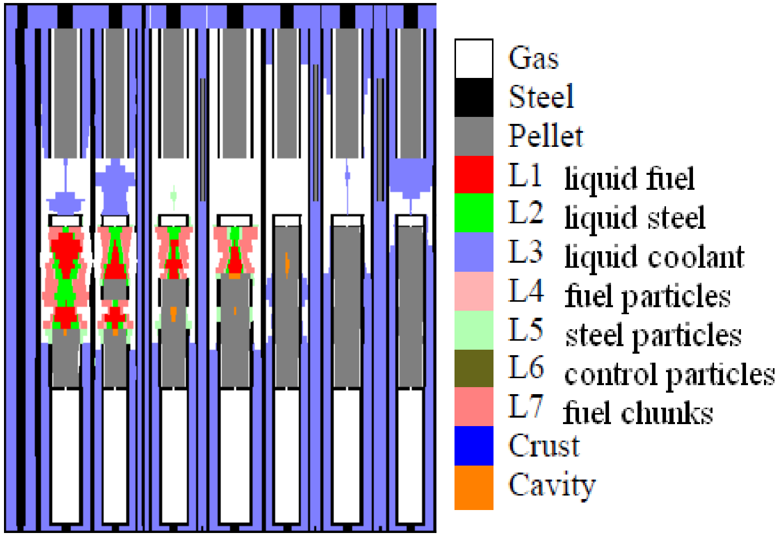


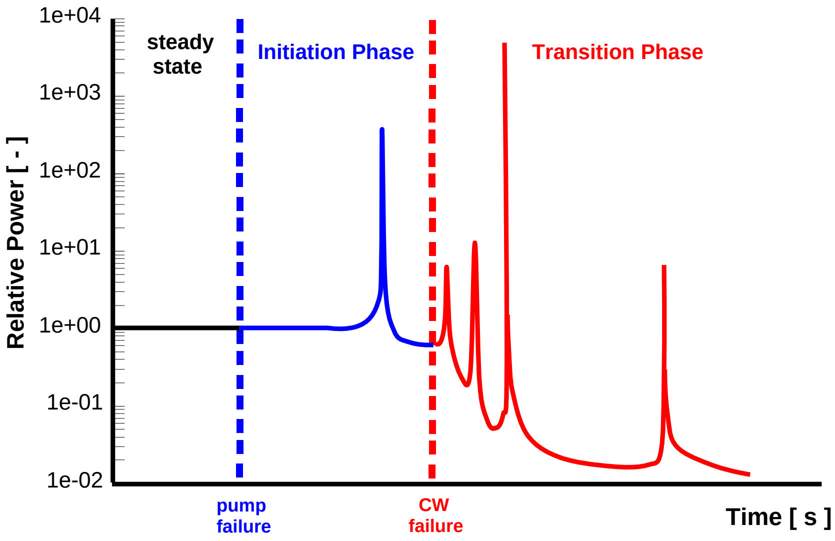

Sodium boiling → Clad failure → Fuel melting → Fuel propagation

| | | | | | |
|---|---|---|---|---|---|
| (white) | **gas** | (red) | **molten fuel** | (pink) | **fuel particles** |
| (black) | **cladding** | (green) | **molten steel** | (light green) | **steel particles** |
| (grey) | **pellet** | (blue) | **coolant** | (olive) | **control particles** |

# Severe accident simulations: new options

- Previously developed tools for steady-state and IP: not general enough to address new designs, e.g. possibility of two separate molten fuel cavities in ASTRID inner core.
- SA to SA heat transfer may influence transient progression in low-void cores
- The coupling point may have to be moved to an earlier time, e.g. steady-state
- Reduction/exclusion of coupling uncertainties, efforts on preparing inputs for different codes, but extension of SIMMER needed
- Coupled approach: available for SFR only

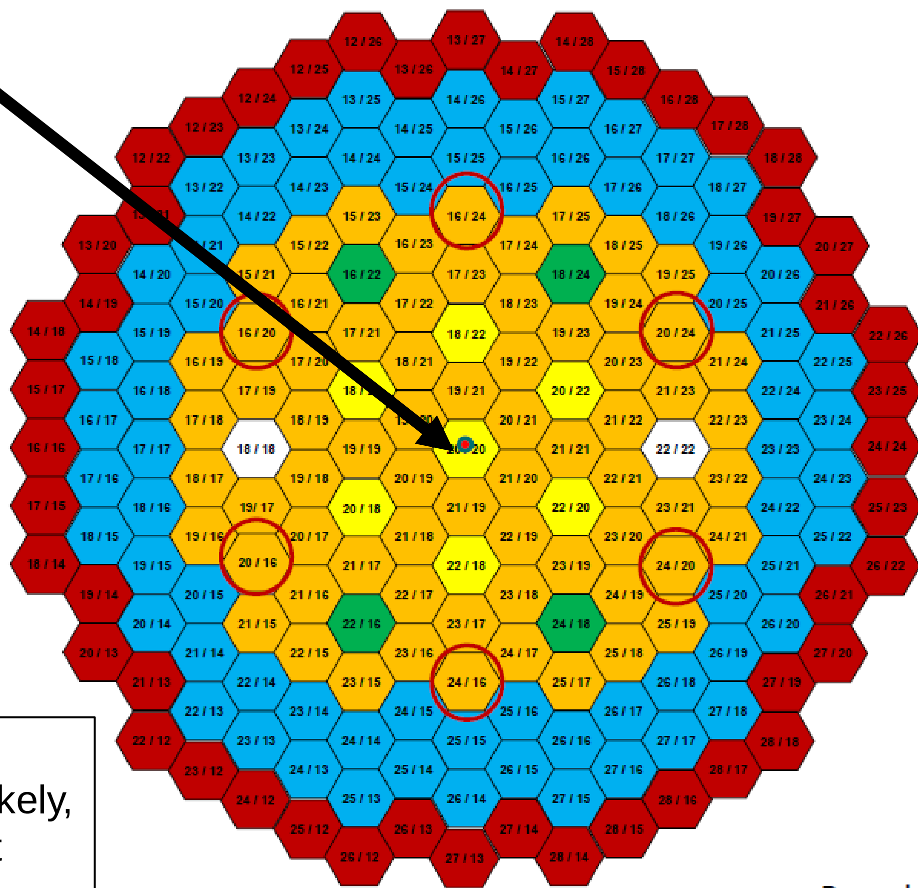


# SIMMER Simulations of MYRRHA starting from steady-state

Preliminary version of the critical core

The central IPS replaced by FA in the SIMMER simulation



- 68 FAs
- 7 (central) IPS
- 4 $B_4C$ (LBE)
- 2 $B_4C$ (He)
- 70 Dum

151 S/As

Homogeneous Zone: 50 / 50 % T91 / LBE VF, to model barrel, steel plates/inserts (inside it) and LBE (outside it)

Additional positions (besides the 7 central) available for $B_4C$ or IPS + 6 for radioisotope production

Barrel (inner) ∅ = 1422.63 mm

**HLM coolant:**

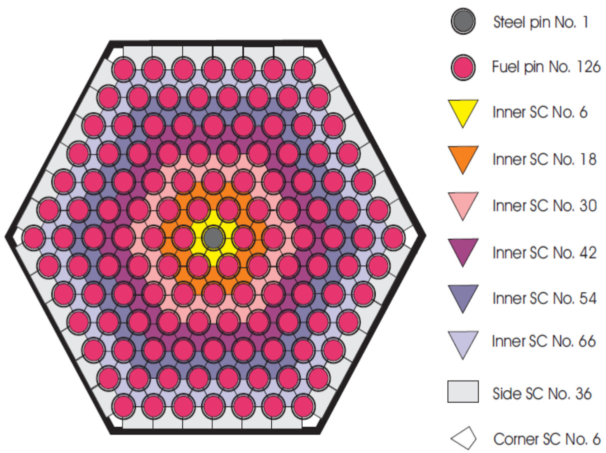
- Coolant voiding unlikely, except gas blow-out
- No (energetic) FCI

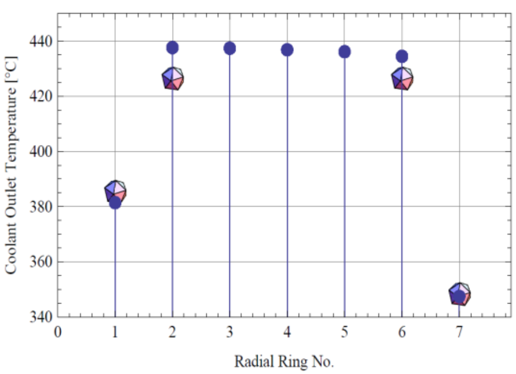
## EU-Project *MAXSIMA – Severe Accidents in MYRRHA Reactor*

(forerunner projects: XT-ADS, CDT, SEARCH)

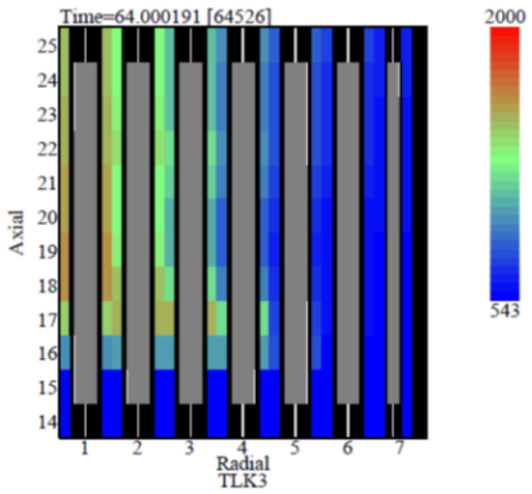
Study of transient behavior for **TIB** initiator

- Subchannel geometrical arrangement
- Momentum exchange model developed for the Cross Flow
- Results have been confirmed by a subchannel code

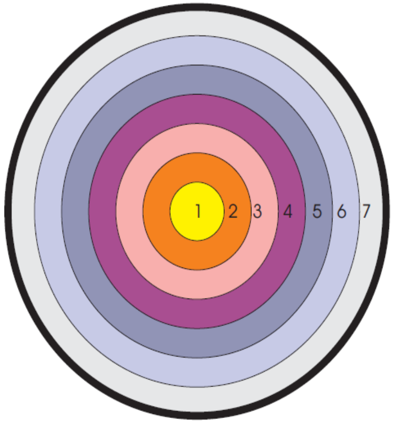



Steady State Case
Points : SIMMER
: Subchanflow

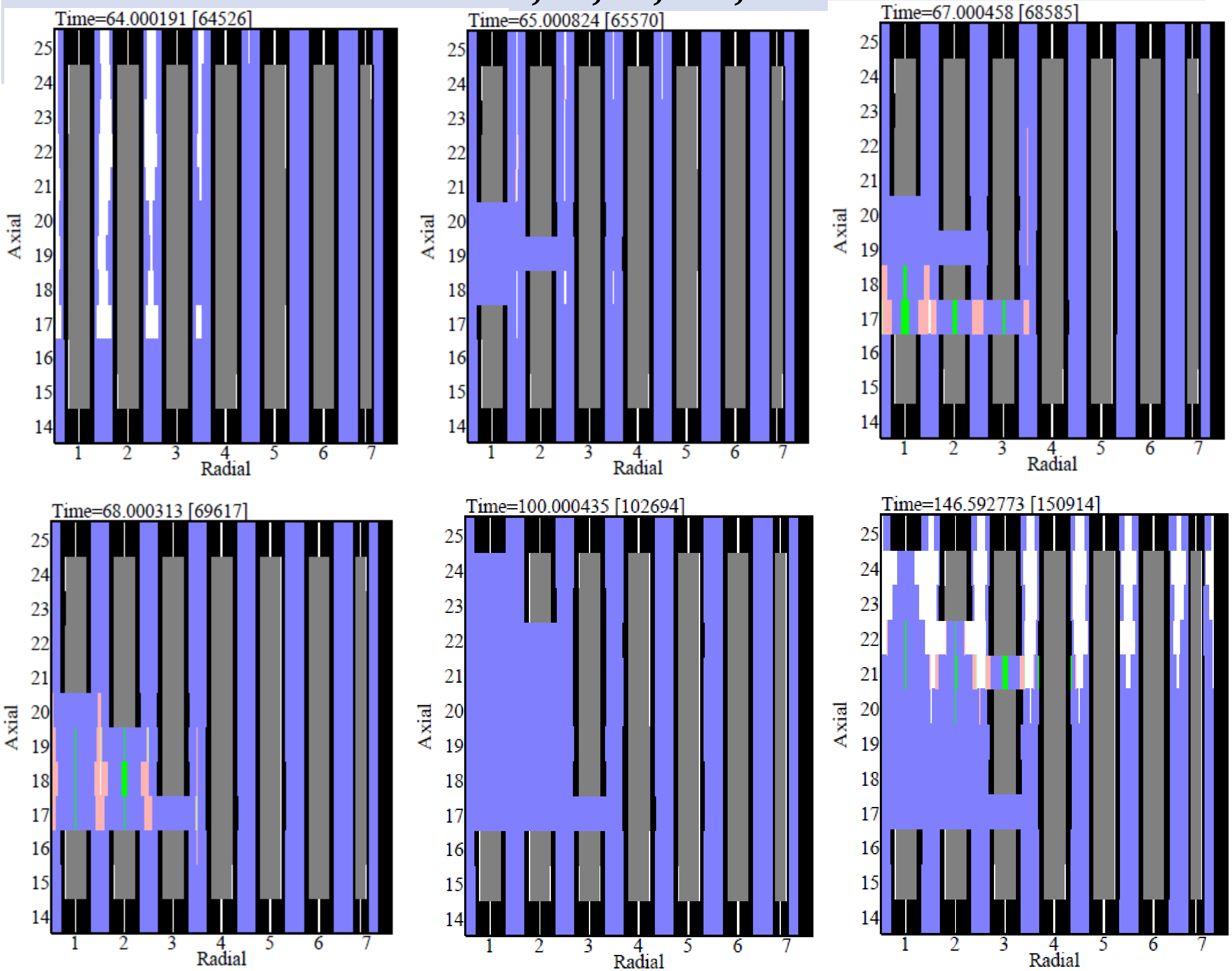


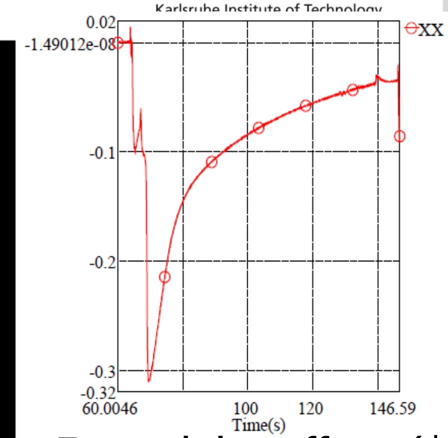

Coolant T before at pin failure



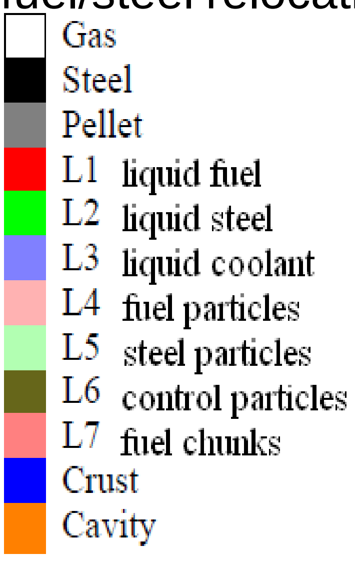
# Blockage in central FA: 5 pin rings, blocked area: 50%, starts at t=60, (others), pin failure/gas blow-out at 64 s: Material distributions at t=64, 67, 68, 100, 146

fuel swelling
jamming



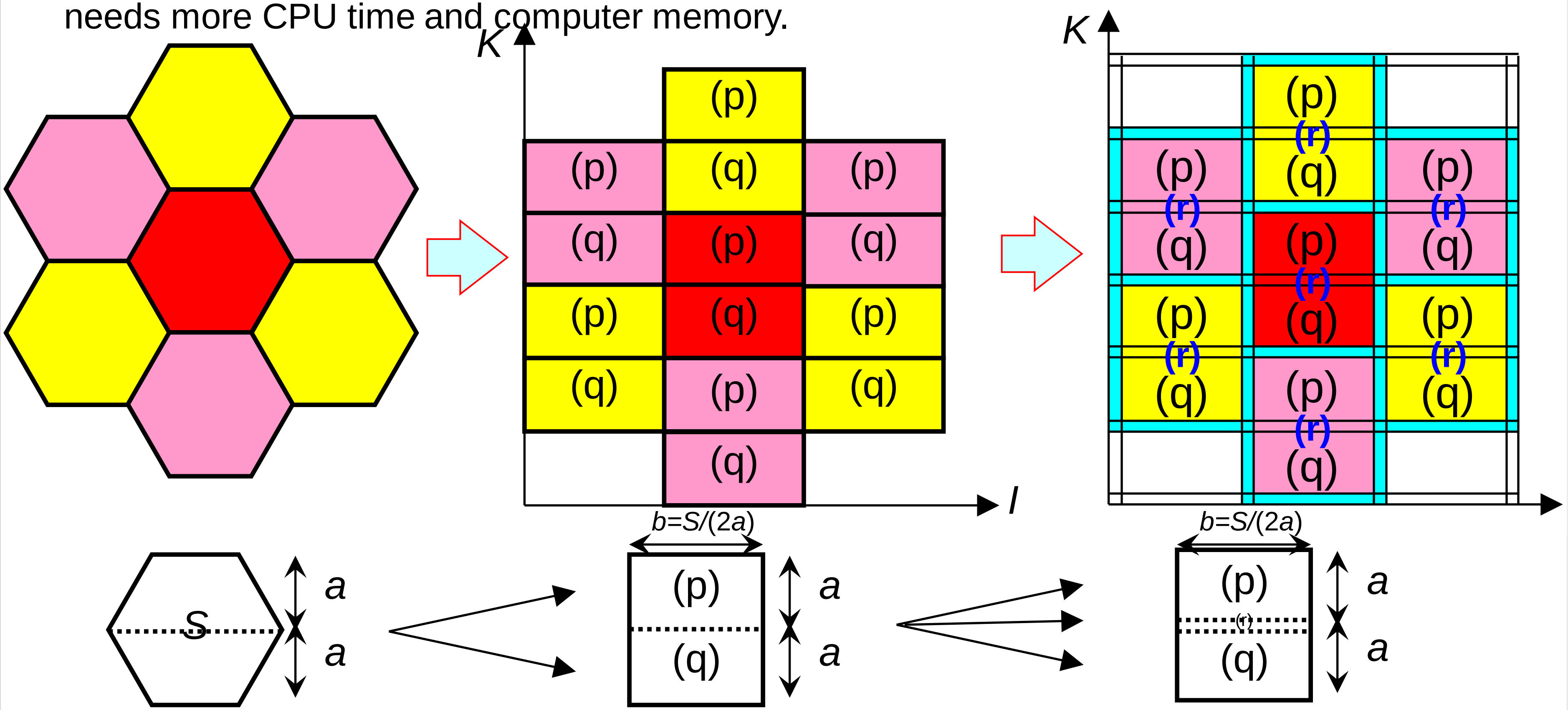




Reactivity effect ($)
Doppler effect,
fuel/steel relocation



# 3D Models: blockage studies in MYRRHA with intra-SA gaps

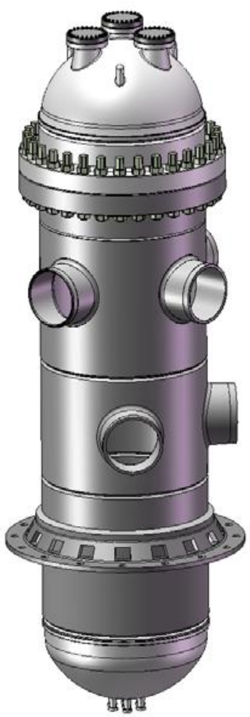
- The coolant flow through inter-wrapper gaps between subassemblies can retard or even prevent the can-wall failure and its propagation.
- Gaps were modeled with special meshes in a 2D case providing quite different results as compared with implicit option.
- The gaps are explicitly modeled also in 3D which takes account of 3-D heterogeneity and needs more CPU time and computer memory.




(p) with left, right and back CWs,
(q) with left, right and front CWs,
(r) with left and right CWs
(Others) filled with 100% coolant (hexcan gaps)

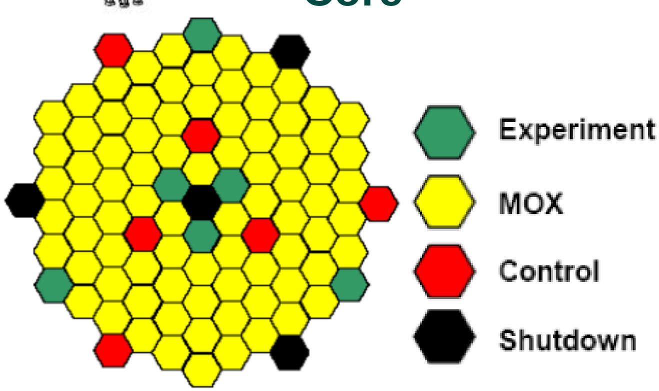
# ALLEGRO SIMMER-III Modeling

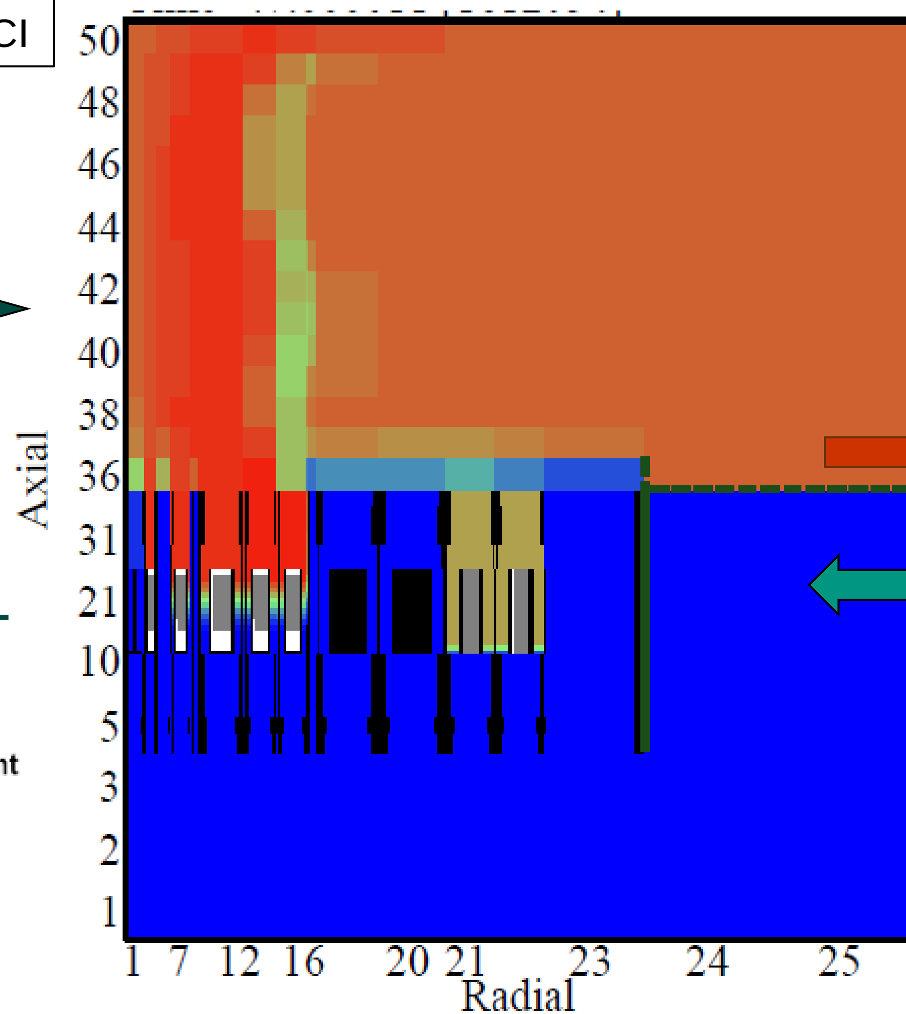
**Gas coolant:**
- No voiding / no FCI



**Pressurized Vessel**

**Core**

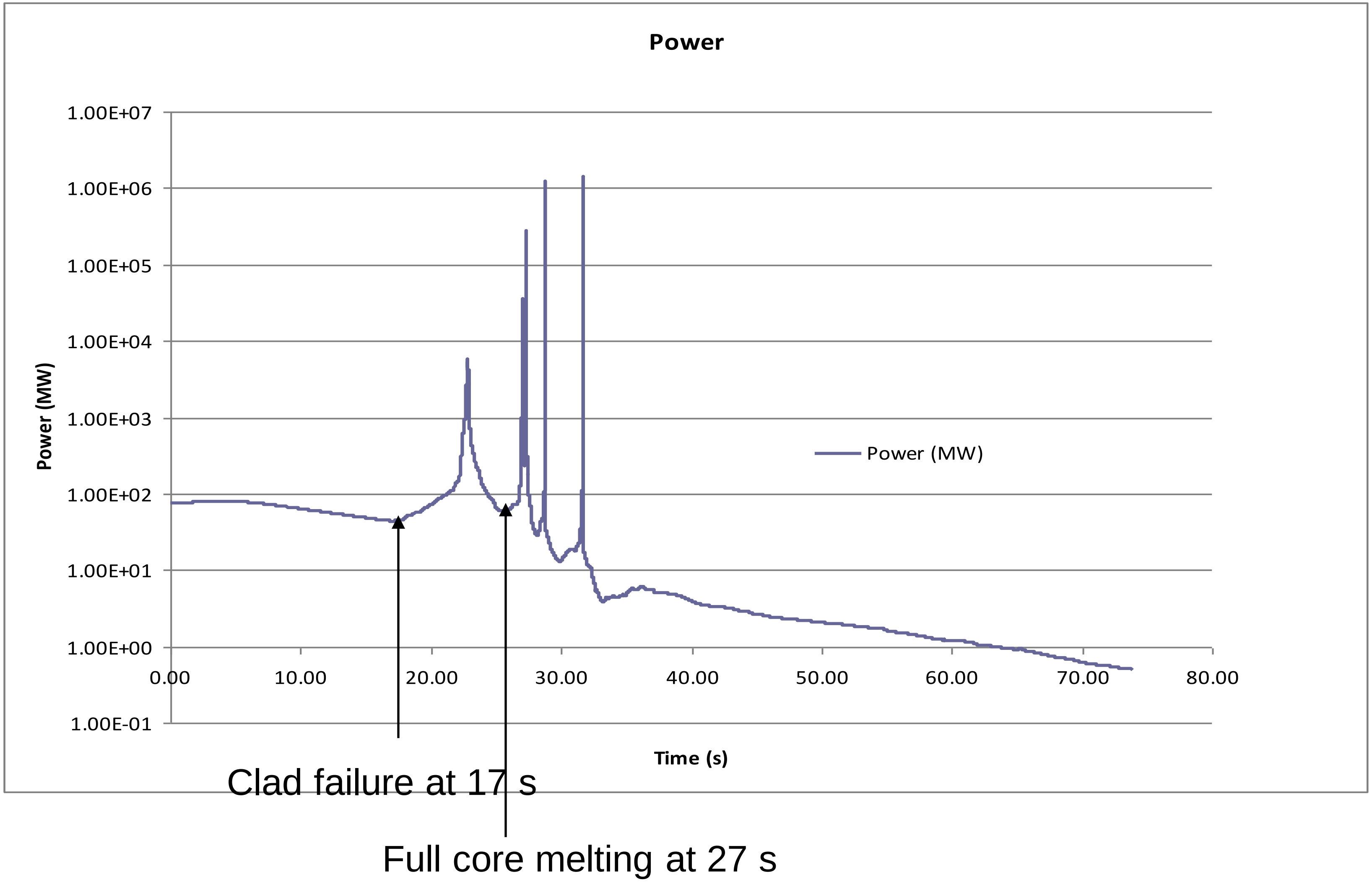


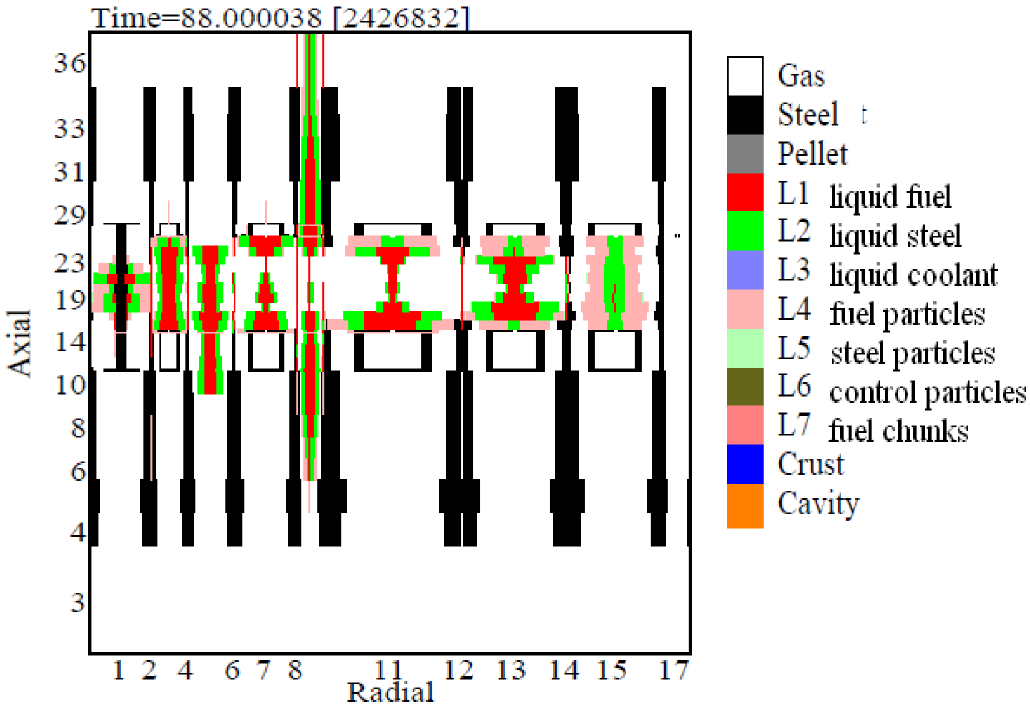

**Hot Outlet**

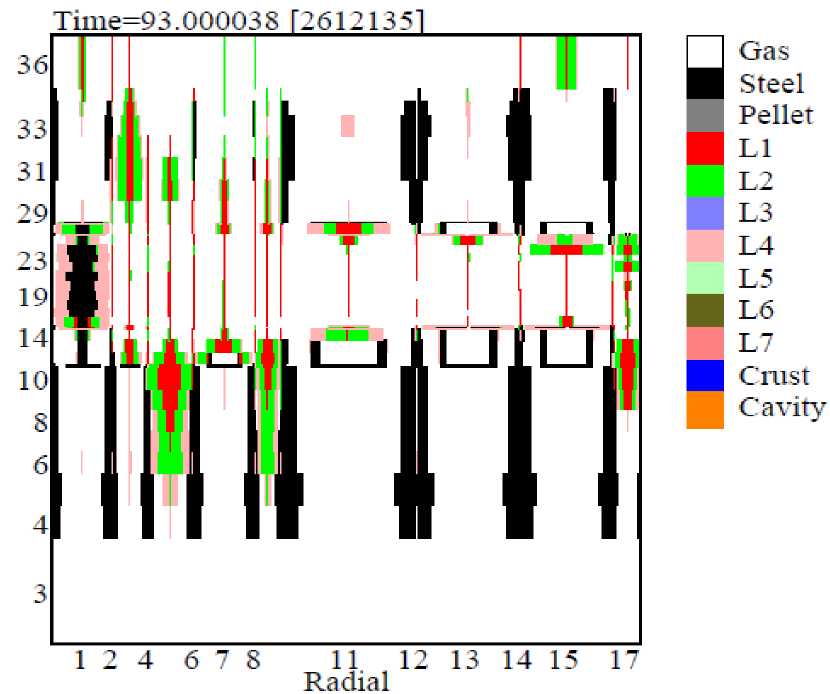
**Cold Inlet**

# ALLEGRO ULOCA Calculation Results: primary pump broken, same inlet and outlet pressures  5 sec after



# ALLEGRO ULOCA Calculation Results




t = 28 s: fuel melting and ejection after the first power peak

t = 33 s: fuel dispersed after the final power peak

# Concluding remarks

- Fast reactors with solid fuel: flexible options for Pu and MA management, but (unlike LWRs) far from most optimal reactivity configuration

- Hypothetical accidents should be analyzed even if their probability is extremely low (combination of events with low probability), one may learn about new phenomena (e.g. existence of a transition phase) from a complex code

- High uncertainties in modeling assumptions (in pin fuel motion experimentally observed in all slow transients with annular fuel, but also in other cases) and employed data => parametric studies

- Mechanical energy release to be assessed to prove the system integrity (source term issues not considered here)

- Reduction of the coolant void effect (geometry, fuel composition, sub-criticality), passive safety devices improve core behavior during initiation phase, may prevent core melting

- Core melting events to be analyzed, steel separation from fuel may provide positive reactivity feedback

- Conversion to mechanical energy higher for cores with higher T => early molten fuel discharge important for reducing mechanical energy release

- Codes for accident analyses aunder development: new reactor designs, experiments, models, and computers