Karlsruhe Institute of Technology

ULOF initiation phase analyses

A. Rineiski, X.N. Chen, M. Flad

ESFR-SMART
sodium fast reactor safety

ESFR-SMART Spring School, March 2021, online

Institute for Neutron Physics and Reactor Technology (INR)

Sodium Fast Reactor (SFR): Reactivity Potential, Accidents, ULOF

Reactivity Potential

- In SFR, fuel is not in most reactive configuration, reactivity insertion possible after e.g.
  - Sodium void by boiling, He/Fission gas release into coolant (reactivity effect: + or -, depends on location and design)
  - Molten material motion including steel/fuel separation by different densities (++)
  - Core melting scenario's and molten core behaviour should be studied

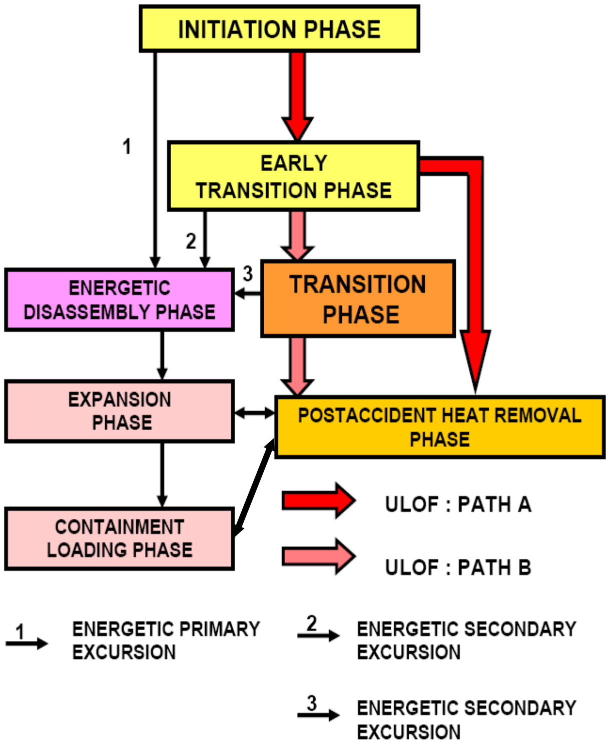
Accident simulation

- Classic unprotected accidents, assuming no/delayed active/pasive shutdown systems
  - Unprotected Loss of coolant Flow (ULOF): pump out of operation
  - Unprotected Transient Overpower (UTOP): reactivity introduction by Control Rod (CR)
  - Unprotected Loss of Heat Sink (ULOHS): to the secondary circuit
  - Total Instantaneous coolant flow Blockage (TIB): in one or more subassemblies (SAs)

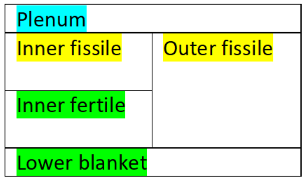
Why ULOF is important?

- ULOF is a global transient: affects the whole core
- May lead to sodium voiding and core melting
- Covers major important phenomena occurring in case of core disruption
- Often shows the highest energetics potential

Severe accident transient phases in SFR



- **INITIATION PHASE (IP) :** 'Ouverture', but does not give the complete picture and especially not the potential on thermal and mechanical loads. IP ends when transition to massive core melting starts
- **TRANSITION PHASE (TP)** determines outcomes of transient: multiple event channels, increase of reactivity range scale …
- **Control of IP:** by design measures on reactivity effects such as coolant void, Doppler, thermal expansion, …
- **Control of TP:** design measures cannot make fuel/steel separation and fuel movement effects small, so we need measures that facilitate early molten fuel discharge from the core and make it subcritical, thus avoiding multiple re-criticalities (the major challenge!)
- **Design measures may influence IP and TP**
  - Differently: small sodium volume fraction may reduce the void effect (+IP), but hinder fuel discharge: (-TP)
  - In the same direction: transfer tubes and sodium plenum reduce void effect (+IP) and facilitate fuel discharge (+TP)
  - In the same direction: reduction of inner core height at core bottom and unique enrichment help to reduce void effect (+IP) and inner core fissile inventory after melting (+TP)



System evolution at steady-state and IP

- Steady-state: variation of fuel isotopic composition
- Steady-state: pin evolution under irradiation
  - Pellet restructuring/evolution of central hole, gap conductance variation, gap closure, clad evolution, etc.
  - Fuel swelling, accumulation/release of fission gas/He (also IP)
  - axial/radial expansion (also IP)
- Particular phenomena to simulate during IP
  - Coolant boiling, clad/fuel melting/failure and propagation,
  - Fuel-Coolant Interaction
  - Fuel/Clad relocation axially, accumulation/freezing at axial periphery, affects axial power
  - Blockage phenomena
  - Can-wall melting/failure
- Reactivity effects during IP
  - Doppler effect: negative/positive if fuel T increases/decreases, after ULOF the power and fuel T may initially decrease
  - Coolant density/void effects: positive/negative depending on location and design
  - Core thermal expansion: driven by fuel thermal expansion (non-irradiated fuel) then the effect is similar to Doppler (+ or -), or by clad expansion (irradiated fuel), negative effect
  - CR drive line expansion: negative
  - Cavity formation growth, in-pin molten fuel relocation to axial periphery, in particular for annular pins: negative
  - Fuel/steel mixing after melting introduces a not-very small reactivity for thick pins

Simulation code : SIMMER-III & SIMMER-IV

Karlsruhe Institute of Technology

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.

Focus on transition phase, but applicable to a larger scope

JAEA
KIT
CEA
ENEA
UNIPI
SCK.CEN
EdF
Other partners

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

C4P: Generation of SIMMER XS libraries with f-factors
Basis: 560-Group Master Library
JEFF, JENDL, ENDF/B
Full Range Neutron Spectrum

Structure model

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

Neutronics

- Cross-section generation: 11-72-group libraries
- Neutron transport for flux shape (Sn): 4 to 72 groups
- IQS: flux amplitude computed more often than shape
- Fuel composition: fissile + fertile vectors, enrichment
- Heterogeneity treatment: Water-Cooled Systems
- Decay heat model: Decay Heat Precursors
- Movable neutron precursors: Molten Salt Reactors
- External neutron source: Accelerator Driven Systems

Simulation Routes with SAS and SIMMER (1)

Karlsruhe Institute of Technology

Simulation Routes:

Thermalhydraulics + Neutronics Design

SAS-4A (SAS-SFR) SIMMER

SAME (SIMMER interface)

SIMMER SIMMER

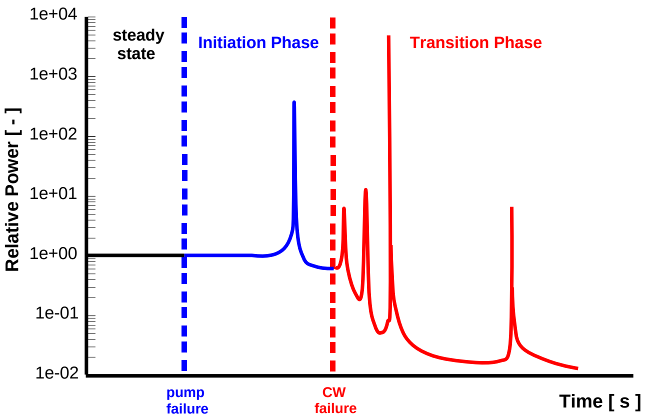
STRUCTURE, FLUID-DYNAMICS,
THERMAL-HYDRAULICS &
CONTAINMENT CODES

- **Design Codes :** Subchannel analysis, core mechanics, neutronics, burn-up ...
- **SAS4A (SAS-SFR):** focus on initiation phase, multiple 1D TH „channels“ in the core, point kinetics, detailed pin mechanics, applicable till can-walls melt and radial movement is possible
- **SIMMER:** Initial focus on transition phase, 2D/3D TH coupled with 2D/3D neutronics, more time-consuming; core phenomena, in-vessel phenomena, out of vessel phenomena, applicable till post accident heat removal phase (PAHR)
- **Structural, Fluid-dynamics, Thermal-hydraulics, Containment Codes :** PAHR, structural loadings, containment behavior, radioactivity release

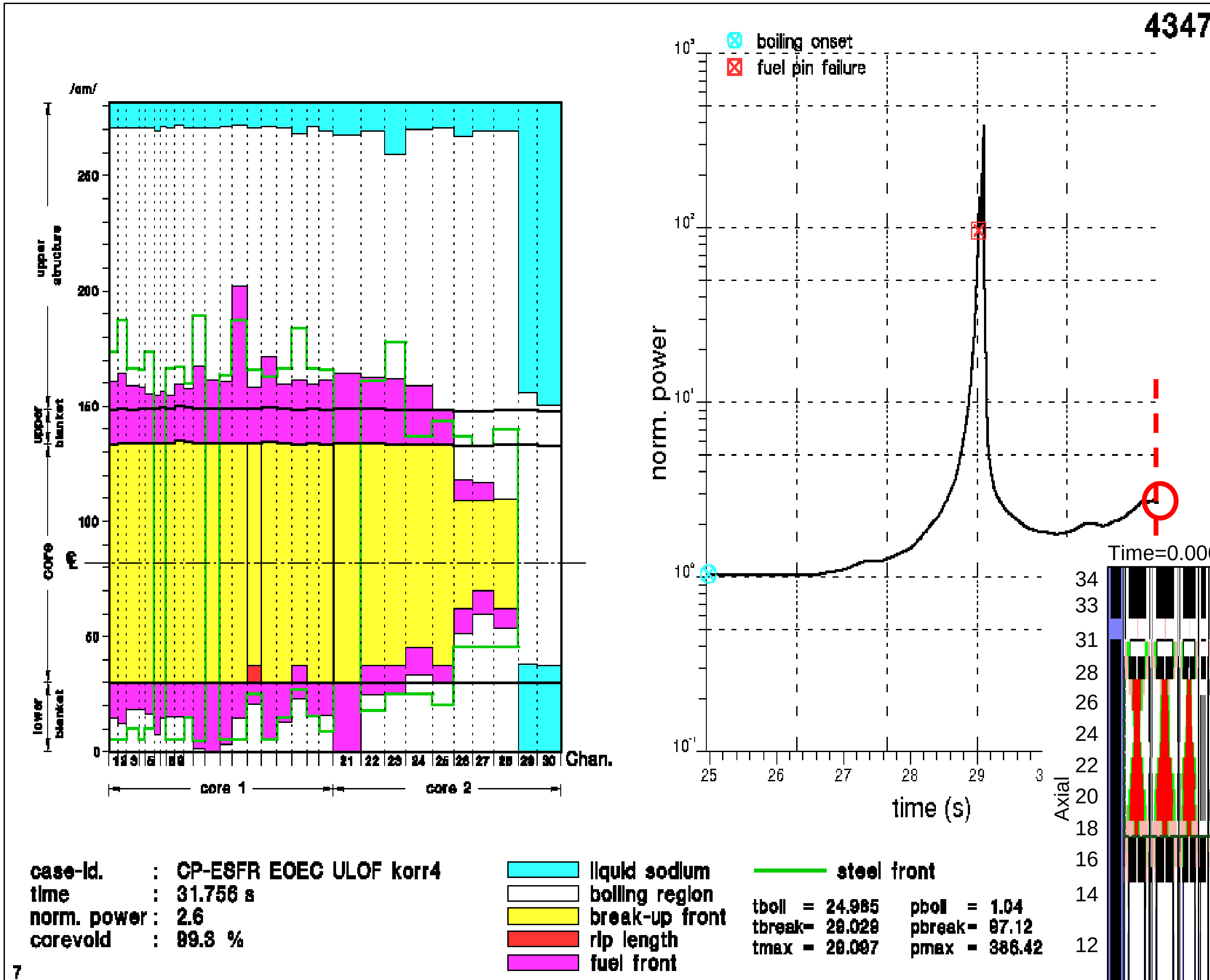
Simulation Routes with SAS and SIMMER (2)

- **SAS + SIMMER route:**
- **Steady-State:** SAS simulates core under irradiation, SIMMER is employed to compute values that SAS4A doesn‘t provide (regions not considered in SAS), to validate SIMMER model
  - External neutronics codes: to provide data for SAS (power, reactivity coefficients)
- **IP:** SAS performs transient calculations, SIMMER may have to be employed too
- **SAME :** Data transfer from SAS4A to SIMMER and combining with SIMMER computed values
- **TP :** SIMMER calculations
- Advantage: SAS is focused on IP with dedicated models for in-pin fuel motion, sodium boiling

- **SIMMER route:**
- **Steady-State:** Get Steady-State starting from initially imbalanced (from input) temperature, pressure, flow, neutronics conditions;
  - External neutronics codes: to provide a validation basis for SIMMER
  - External fuel codes (also SAS) to get fuel properties after irradiation
- **IP and TP:** SIMMER calculations
- Advantage: reduction of uncertaities related to coupling of quite different tools

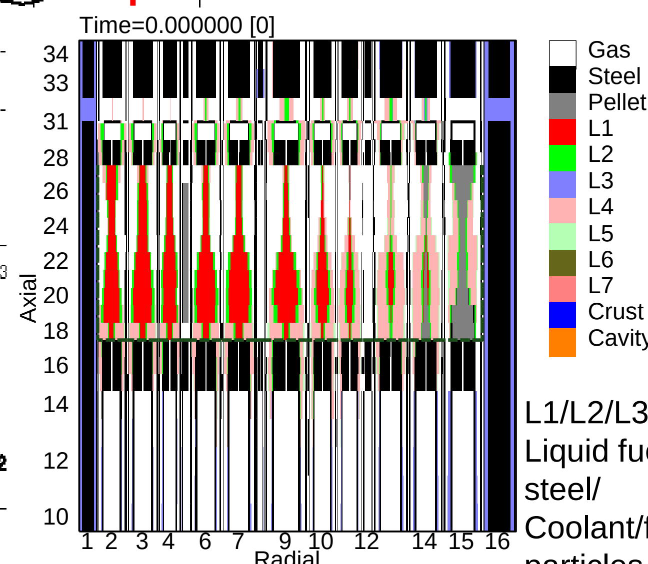


ULOF in ESFR-WH (positive void effect): IP calculations with SAS-SFR



- Coupling at t = 6.8 s after boiling onset (canwall failure)
- 1st power excursion: ~ 350 – 400 x P0
- Reactivity at coupling: -0.27 $
- SAS-SFR results (left) by W. Pfrang et al., KIT

SIMMER model after coupling (below)

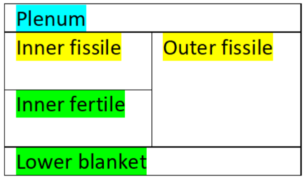


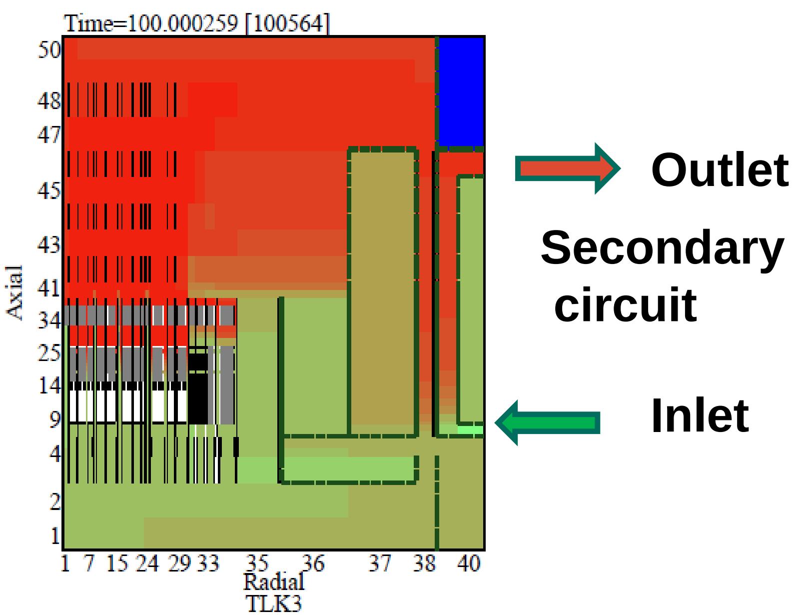
L1/L2/L3/L4 Liquid fuel/ steel/ Coolant/fuel particles

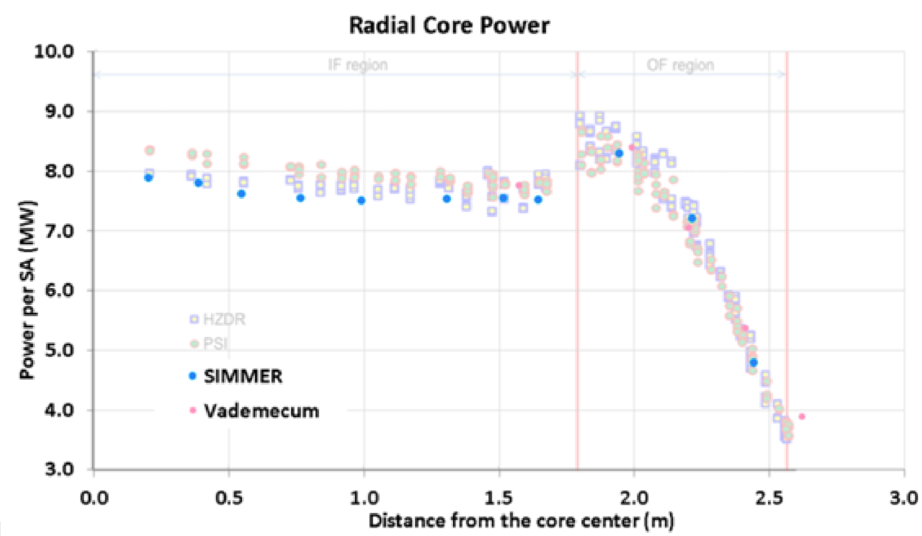
ESFR-SMART ULOF calculations: with SIMMER only (all following slides)

- Full vessel domain simulation, 2D RZ model
- Radial meshes for fuel SAs, CRs, Transfer Tubes, gaps between SAs
- Pump model;
- IHX model and secondary circuit model

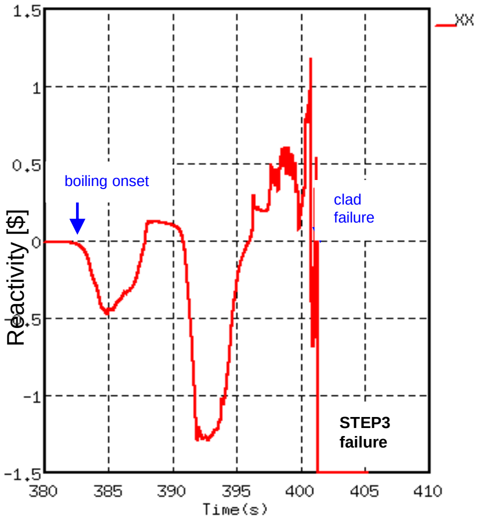
- SIMMER fissile/fertile compositions: first as averaged EOEC core/blanket isotopic compositions
- Some fissile material from the last radial core ring exchanged with fertile material from the blanket: to improve the radial power profile

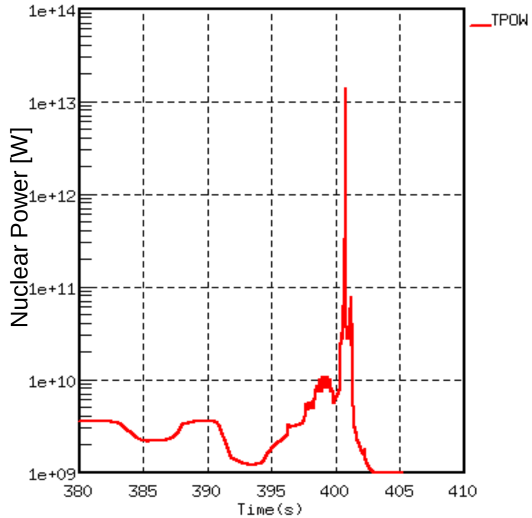


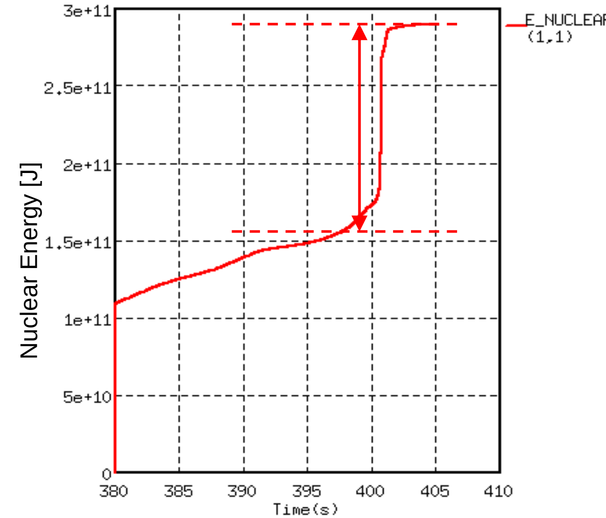


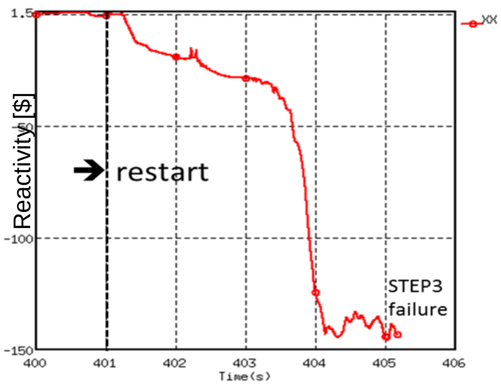


ULOF conservative simulation (without core and CRDL expansion feedbacks)









Results of KIT simulation:

	t (s)	Δt (s)
Start of ULOF	**350.0**	**0.0**
Boiling onset	**382.4**	**32.4**
Clad failure	400.2	50.2
Liquid fuel	400.7	50.7
Power peak	**400.8**	**50.8**
CW failure	401.1	51.1
TT CW failure	**401.5**	**51.5**
Calculation terminated	405.2	55.2

ESFR-SMART

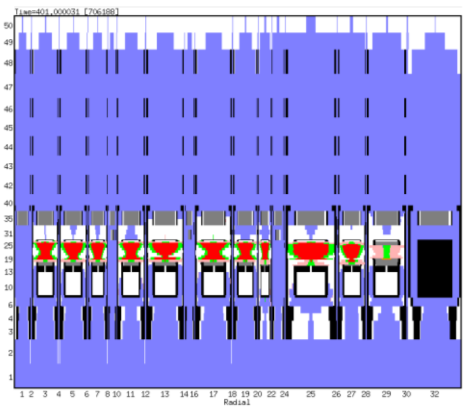
t peak, prim	50.8 s
ρ Max	1.18 $
P max	1.4e13 W / ~ 3,900 x P0
ΔE nuc	1.16e11 J

CP-ESFR (WH)

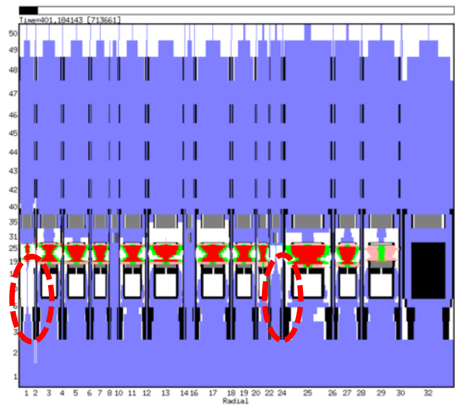
t peak, prim	29.1 s
P prim	~ 370 P0
P sec	1.5e14 W / ~ 42,000 x P0
ΔE nuc	1.4e11 J (TP)

ULOF conservative simulation

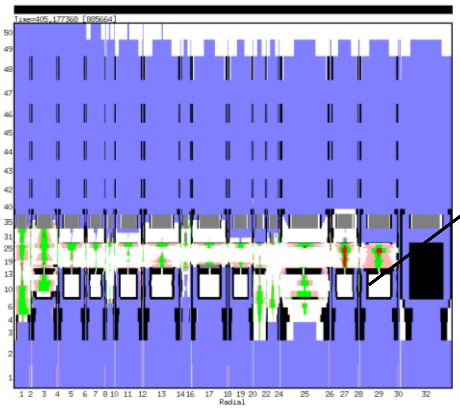
Pool situation before opening of TT



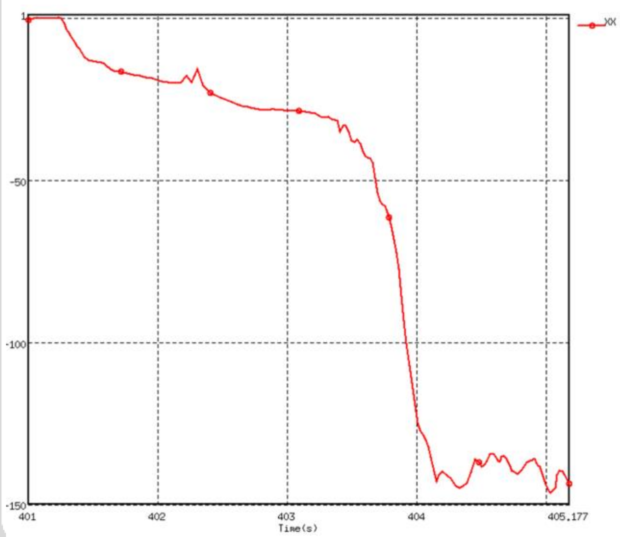
Discharge through central & inner TT



Huge amount of fuel relocated



Outermost fuel SA ring: delayed melting. Thus, 24 outer TTs do not discharge fuel by this time.



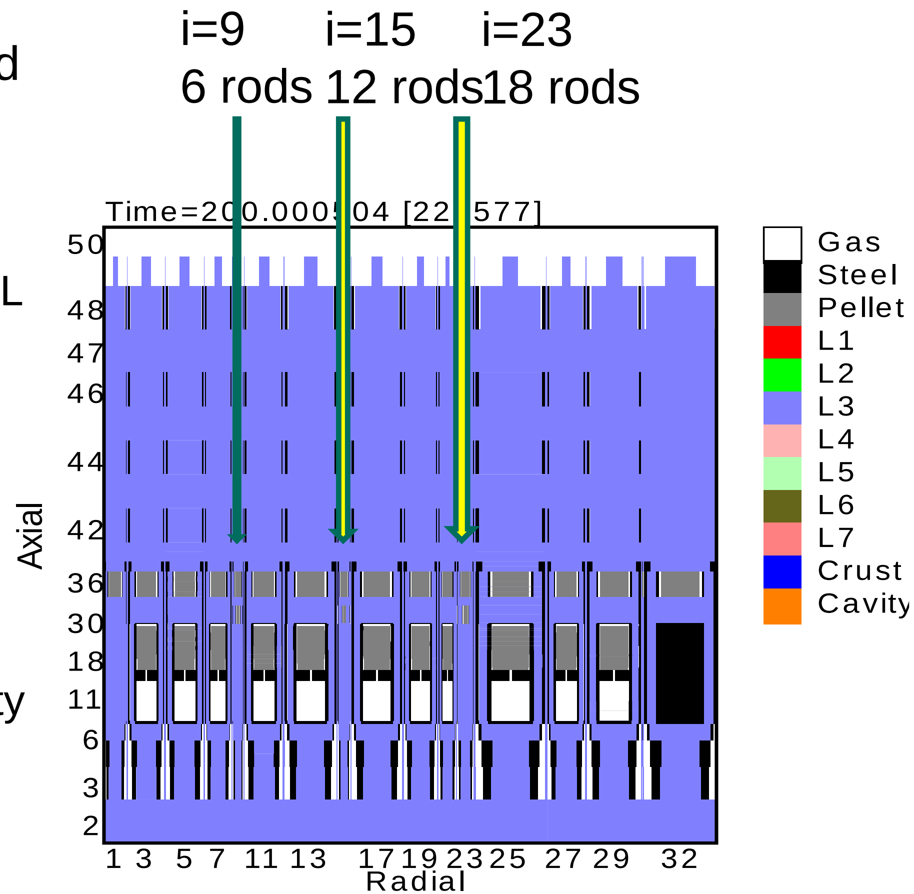
Reactivity history

➔ **Suitable basis to study molten core behavior:**

- Fuel/steel data of molten pool for simulation of flow through TT
- Corium characteristic for Core Catcher loading

Thermal Expansion Model and New CRDL Model

- Use a previously developed thermal expansion model for SIMMER (axial and radial expansion)
- Use a new CRDL model for SIMMER
  - Average CRDL introduction: from CRDL middle point temperature
  - Temperature middle point j= 42
  - CR driveline length: 7.045 m
  - DCRDL (displacement)/RCRDL (reactivity) table
  - DCRDL=0.,0.05,0.145, ! CR Bottom displacements, m
  - RCRDL=0.,-131D-5,-423D-5, ! reactivity values for the bottom displacements, absolute values



Karlsruhe Institute of Technology

Neutronic Feedback Coefficients

Parameter	Unit	SIMMER	WP1.3 Serpent
Keff		1.009373	1.00471
Neutron Gen Time	[s]	4.3E-07	4.7E-07
Beta-Effective	[pcm]	347	362
Doppler Constant: Fissile 1500 K -> 1800 K, Fertile 900 K -> 900 K	[pcm]	-808	-685
Core Void Worth with voided gaps	[pcm]	1727	1542
Upper Gas Plenum + Plug Void Worth	[pcm]	-41.3	-62
Coolant Feedback Coefficient	[pcm/K]	49/110.8= 0.442	48/110.8 = 0.433
Axial Thermal Expansion	[pcm/K]	-0.072	-0.083
Radial Thermal Expansion	[pcm/K]	-0.711	-0.646
Steel Thermal Expansion Coef. for CRDL	[1/K]	1.82 E-5	1.82 E-5
Control Rod Driveline	[pcm/cm]	-423/14.5	-423/14.5

Karlsruhe Institute of Technology

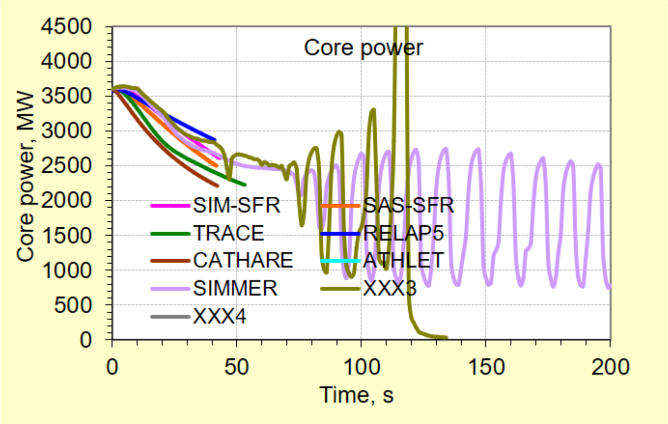
ULOF Simulations

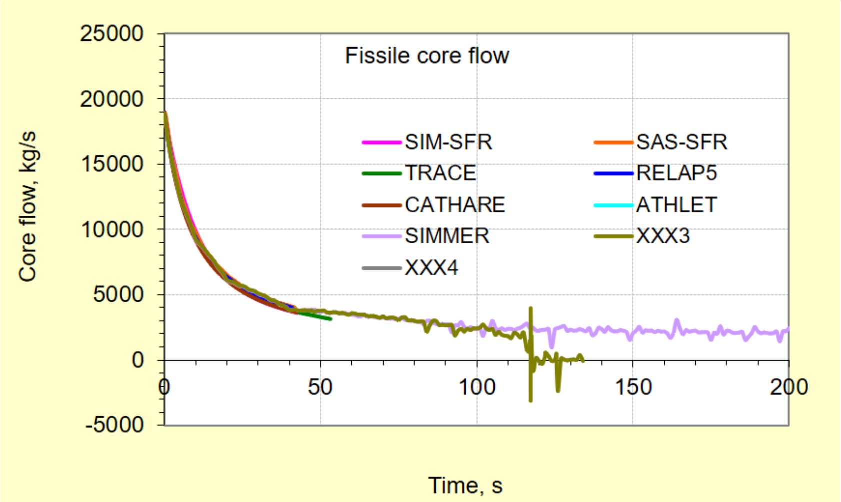
- CRDL uses only the first steel thermal expansion coefficient BSTEEL1.
- The radial thermal expansion option used is „cylindrical“, meaning it is driven by the bottom inlet temperature, changes very slightly in transient.
- Originally BSTEEL1 = 1.528E-5, fuel and clad driven axial thermal expansions
- Afterwards BSTEEL1 = 1.820E-5, as well fuel and clad driven axial expansions

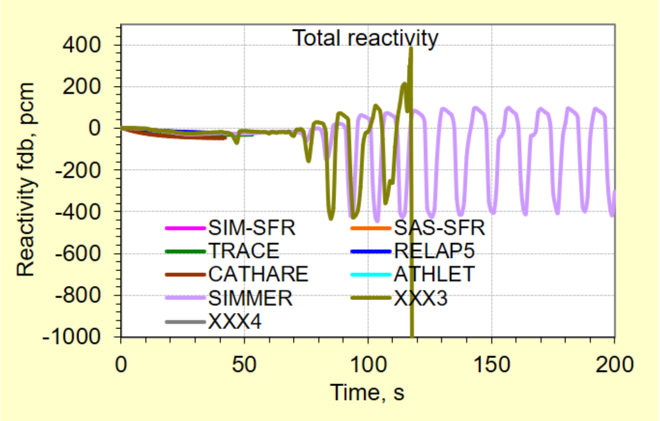
Case No.	Case	Address	Power Excursion
1	**BSTEEL 1.53 CRDL with Fuel-Driven**	3-ULOF200s-CN-Repeat	Yes at 102 s
2	**BSTEEL 1.53 CRDL with Clad-Driven**	2-ULOF200s-CN-CladDriven	Yes at 129 s
3	**BSTEEL 1.82 CRDL with Fuel –Driven**	5-ULOF200s-CN-BSTEEL1.82	Yes at 117 s
4	**BSTEEL 1.82 CRDL with Clad-Driven**	4-ULOF200s-CN-BSTEEL1.82-CladDriven	No within 400s

ULOF non-conservative simulation with fuel-driven and clad-driven thermal expansion models

Case 3 Fuel Driven vs Case 4 Clad Driven





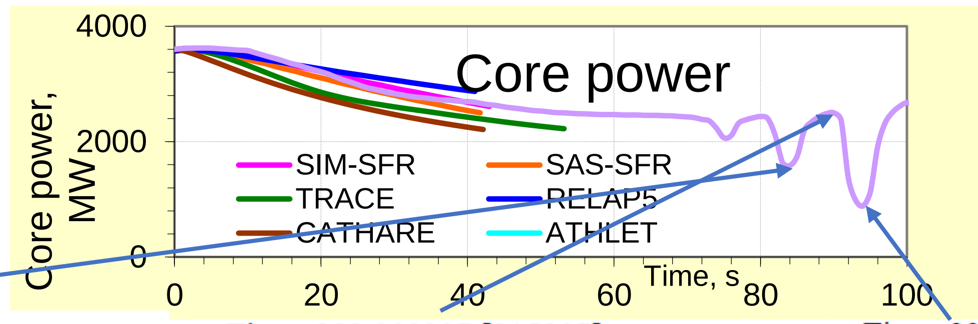


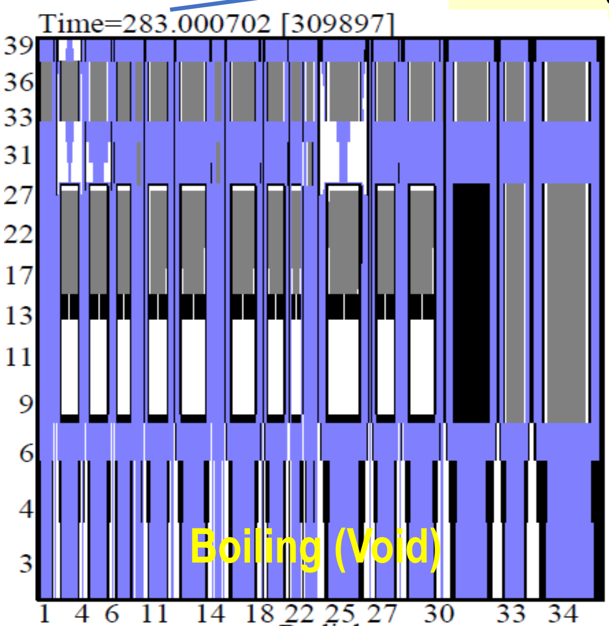
Case 3: Fuel driven ThermExp, boiling onset at 43 s
Power excursion at 117 s

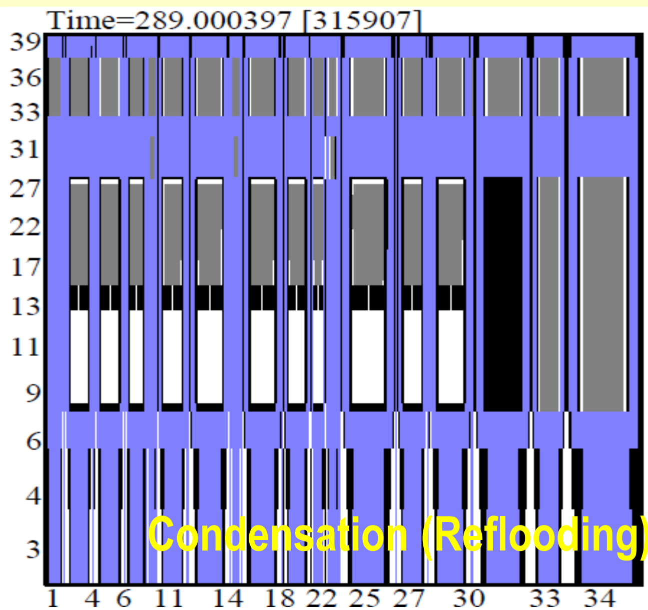
Case 4: Clad driven ThermExp, boiling onset at 69 s
No power excursion

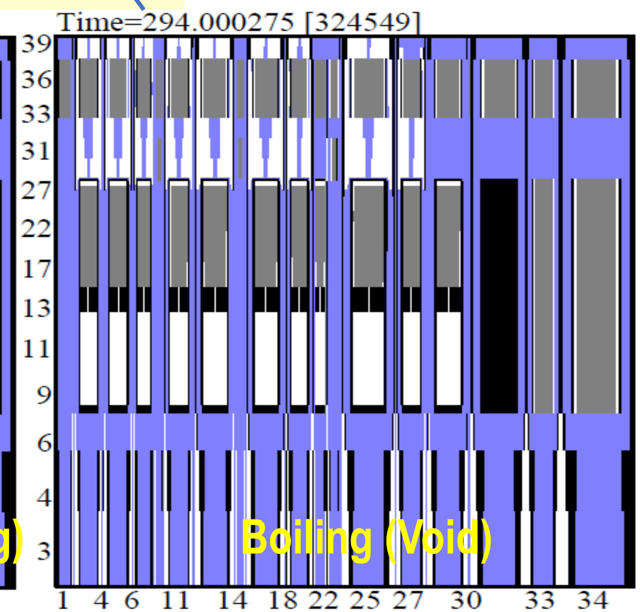
ULOF non-conservative simulation: boiling oscillation and reactivity effects

Case No. 4 with boiling oscillation: reactivity lower after plenum void (in white), higher after re-flooding by sodium (in blue)



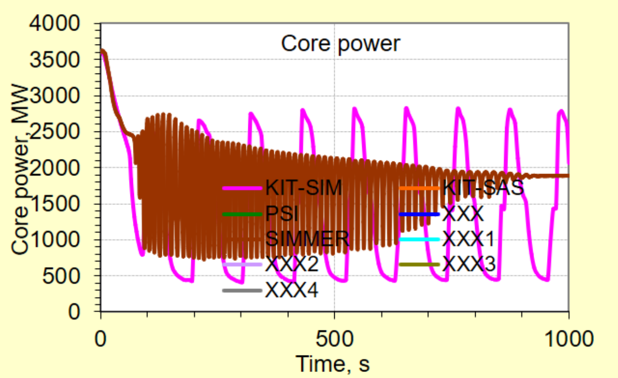


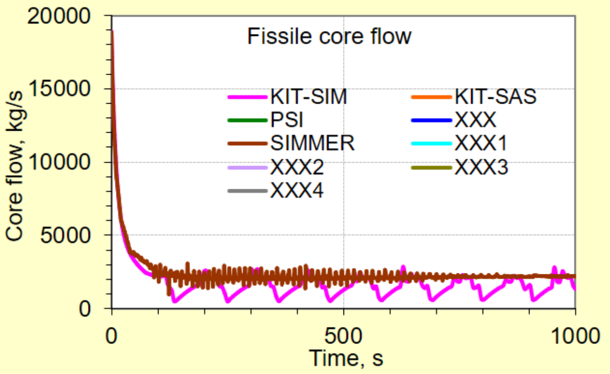


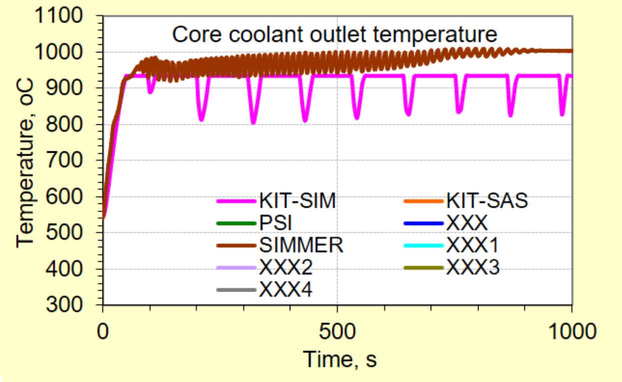


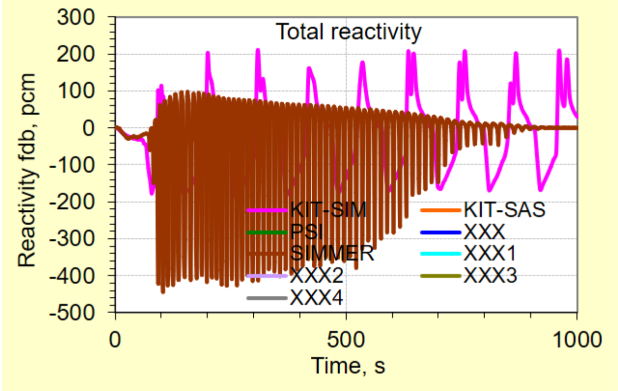
Karlsruhe Institute of Technology

Case 4 Long Time Calculation









- The boiling oscillation decays and finally disappears
- Why? Answer: Finally no boiling. Again Why?
- Due to sodium boiling the pressure at the cover gas increases from 1 bar to 2.7 bar.
- 1 bar => boiling temperature 883°C (1156 K)
- 3.2 bar=> boiling temperature 1027°C (1300 K)

ULOF IP simulations: conclusive remarks

- ULOF IP simulations are important for safety assessment, also offer a basis for TP studies
- IP is driven by sodium void, other feedbacks; a small sodium void effect may help
- TP is driven by molten fuel/steel separation and fuel relocation; early fuel discharge may help
- Earlier studies for ESFR cores with definitely positive void effect always predicted strong power excursions shortly after ULOF start
- In the ESFR-SMART core with a near-zero void effect, IP simulations provide different results depending on assumptions
- Conservative simulations, without core and CRDL thermal expansion feedbacks, predict ESFR-SMART core melting, offer a basis for molten core analyses
- Non-conservative simulations preliminary confirm that core melting after ULOF may be avoided.
- Conservative simulations preliminary confirm that new safety measures (transfer tubes, sodium plenum) are effective for facilitating early molten fuel discharge
- Next KIT presentation by M. Flad et al. continues on ULOF transient studies for post-IP phases.