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ESFR-SMART
sodium fast reactor safety

ULOF primary phase: neutronics behavior

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

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Sodium Fast Reactor (SFR) Reactivity Potential

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- In SFRs and other FRs, **fuel enrichment is higher** than in LWRs: due to different cross-sections in relevant energy regions, higher neutron leakage

- Separation of fuel from structure and coolant, further fuel compaction may lead to **overcriticality** -> SFR operates not in most reactive configuration, unlike LWRs. **Coupled neutronics and TH calculations** are needed for severe accident simulations.

- Under hypothetical accident conditions, major reactivity variations are expected after massive core melting and material relocation: during **transition phase (TP) or secondary phase**. Main reasons for overcriticality: fuel compaction, reduced neutron absorption by steel after fuel/steel separation.

- Important reactivity variations may occur on the way from nominal conditions to core melting: during **the initiation phase (IP) or primary phase**. Recent reactor designs as ESFR-SMART aim to eliminate massive core melting, therefore IP simulations are of particular interest.

- On the other hand, we want to study consequences of hypothetical core melting even if IP simulations do not predict it. Therefore we consider different simulation options for IP, including **pessimistic** ones.

Reactivity, power, decay heat

- Reactivity is a “weighted” **balance of neutrons** (-leakage, -absorption, + generation, etc.) **per generated neutron**. “Weighted” means that e.g. neutrons in the core center are taken with a higher weight than those at core periphery.
- Reactivity is often measured in $: units of beta-eff (a typical $ value in SFR: 0.00350)
- Amplitude of power - due to neutron fission and capture reactions - depends mainly on reactivity, but also on history (due to delayed neutrons)
- If the reactivity in dollars is well below 1$, the amplitude after a prompt (e.g. within 1ms) reactivity variation varies as ~ 1/(1-reactivity[$]).
- Example: amplitude doubles after adding reactivity of 0.5$ at critical conditions, then it grows slowly (scale of seconds) due to build-up of delayed neutron precursors
- The **total power** is the sum of the power due to **fission and capture** reactions and of the **decay heat** (e.g. 6% or 7% at nominal), if we neglect gamma & kerma.
- After a prompt 0.5$ reactivity introduction, the total power varies in a short time by less than factor of 2, e.g. by a factor of 1.94 or 1.93.

Beta-eff and coolant void effect

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- Beta-eff is the effective (or weighted) delayed neutron fraction. It differs from beta, delayed neutron fraction: **delayed neutrons are more thermal** than prompt fission ones.
- The physical meaning of beta-eff is the contribution of delayed neutrons to the reactivity
- In LWRs with UOX, beta-eff is greater than beta: because thermal neutrons are more effective, that makes also the coolant void/density effect negative.
- In SFRs with MOX, beta-eff is smaller than beta because fast neutrons are more effective, this also makes **coolant void effect in an infinitely large MOX core positive**.
- Due to neutron leakage enhancement, e.g. by size reduction, one can achieve a negative void effect in SFR with MOX. This is difficult to achieve in LWRs with only MOX because the leakage in LWRs is much smaller than in SFRs.
- Beta for MOX is smaller than beta for UOX. Due to this and the above reasons, beta-eff in SFRs with MOX is about half of that in LWRs with UOX.
- Beta-eff in SFR is greatly contributed by U-238 due to higher U-238 fission contribution and high U-238 beta. Therefore ADS options for U-free fuels are considered.

SFR Accidents, ULOF

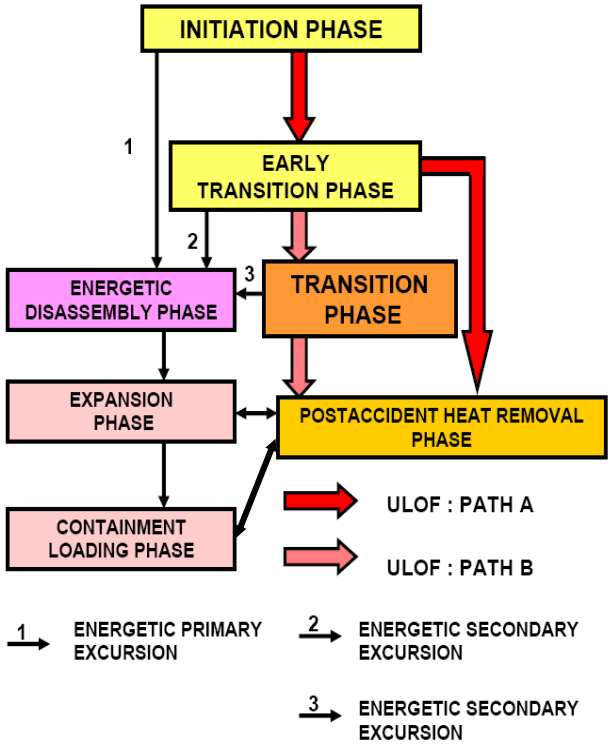
Accidents

- Classic unprotected accidents, assuming no active, delayed 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 the 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!)

Fuel pin at steady-state and initiation Phase

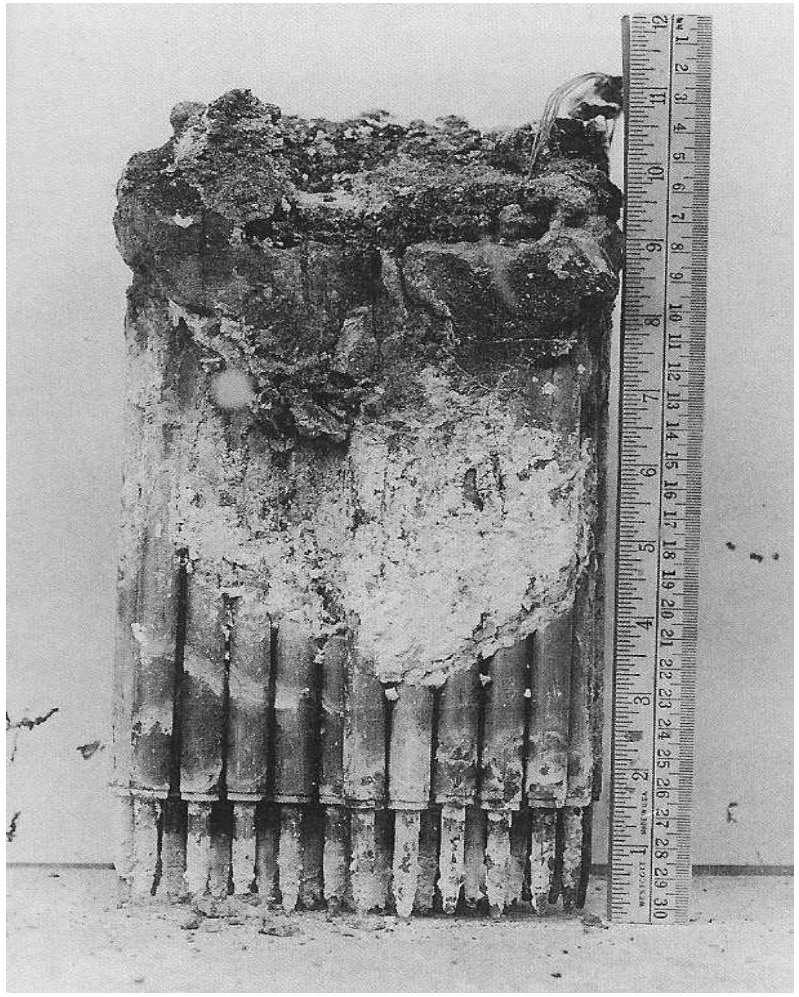
- **Fuel Pin evolution under irradiation and thermal load at steady-state**
  - Assumed power history including fuel reloading/reshuffling scheme provides as basis for fuel simulations before the transient:
    - Variation of the isotopic composition
    - Pellet restructuring including evolution of the central hole,
    - Accumulation and release of fission gas/He,
    - Axial/radial pellet expansion,
    - Gap conductance variation, gap closure, clad evolution, etc.

- **Fuel pin evolution during IP (depending on scenario ULOF / UTOP/…)**
  - Power depends on reactivity that varies due to Doppler and other reactivity effects
  - Cavity formation/grow and in-pin molten fuel relocation to axial periphery, in particular for annular pins (negative reactivity effect)
  - The relocation may also delay clad failure
  - Fuel swelling and fission gas/He release
  - Coolant boiling, clad/fuel melting/failure and propagation,
  - Fuel-Coolant Interaction (FCI)
  - Fuel/Clad relocation axially and accumulation/freezing at axial periphery, power distribution being affected by fuel relocation
  - Blockage phenomena
  - Can-wall melting/failure

Reactivity effects during IP

- Fuel heating, i.e. Doppler effect (-) or cooling (+)
  - Doppler effect is initially positive at ULOF
- Sodium density variations, core voiding after coolant boiling (+ or -)
  - Void effect is positive at the core center, negative at the periphery
- He/Fission gas release from a broken pin into coolant (+ or -)
  - Also leads to local void
- Radial and axial fuel and structure expansion, subassembly bowing (-)
  - Radial effect depends on core mecahnics, cylidrical or more complex
  - Axial effect depends on whether the fuel is sticked to clad or not, that depends on fuel bun-up
- Control Rod (CR) Driveline Expansion (-)
  - Depends on CR location, can be enhanced as a passive measure
- Destruction of the initial pin geometry reduces heterogeneity effects (mainly fuel/clad), may effectively increase neutron absorption by structure (-)
  - Heterrogeneity effects larger for modern designs with thick pins
- Molten steel and molten fuel relocation (++, --, depending on direction)

Reactivity effects: meltdown of EBR-I core due to a positive reactivity feedback



EBR-I: a very small core with highly enriched U, operated in USA

A fast-acting positive reactivity component: due to inward fuel rod bowing when the rods are heated up

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

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

Computation of reactivity effects and transient reactor power (1)

- Point-kinetics (PK):
  - Distributions of power and reactivity coefficients are computed in advance by reference neutronics codes, deterministic or Monte-Carlo
  - Reactivity coefficients are computed for particular effects: Doppler, fuel density, etc. can be normalized, e.g. per kg.
  - The related reactivity effects are assumed to be linear (double effects for double variations of values, e.g. of fuel density) and independent (one can sum-up contributions from Doppler, fuel density etc.). Power shape assumed to be constant.
  - Improved approaches by considering different Doppler coefficients for voided and non-voided configurations, by following fuel relocation with respect to power profile.
  - Very fast power calculations during the transient: no cross-section generation, no neutron flux calculations
  - Quite complex and time-consuming models (3D, fine spatial/angle/energy mesh) can be used for computation of the distributions
  - Usually accurate near nominal conditions, limited to IP

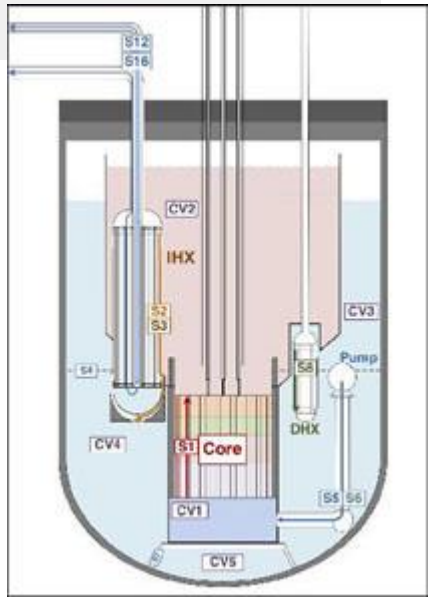
Computation of reactivity effects and transient reactor power (2)

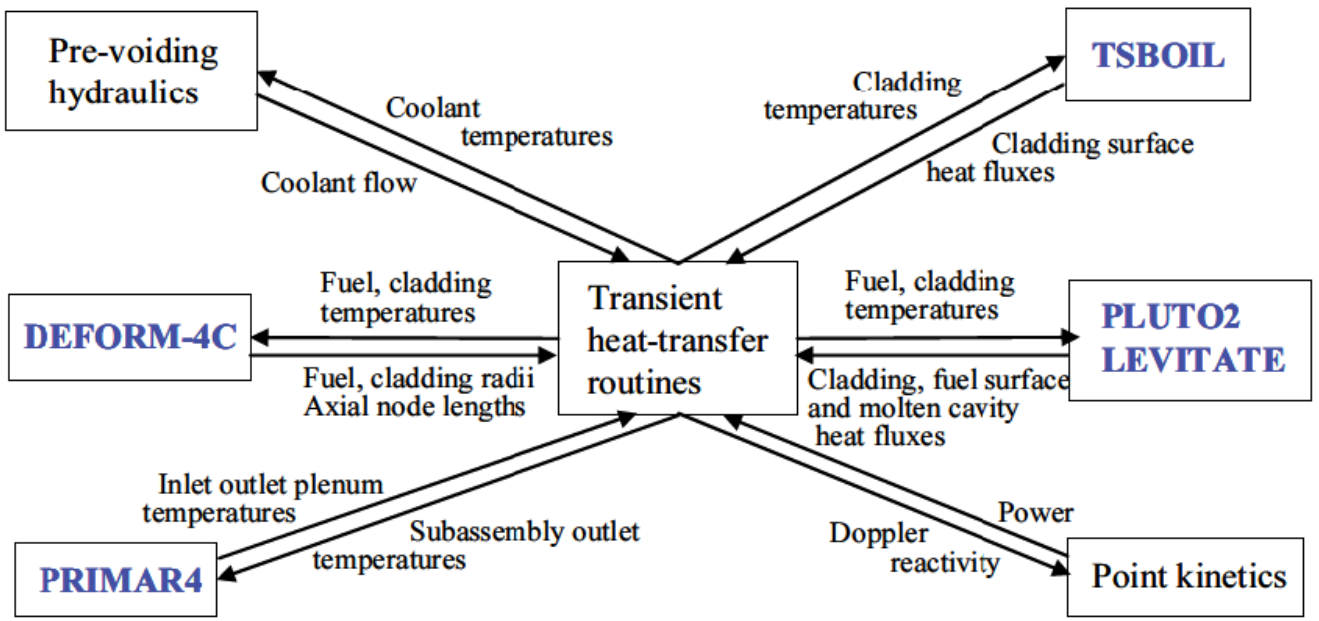
- Spatial kinetics (SK):
  - Neutron flux shape is recomputed many times during the transient for calculating power and reactivity. The generation cross-section (nu*sigmaf) is normalized by k-eff computed at steady-state. The initial k-eff is formally not important, but an indicator.
  - Transient reactivity is computed by neutron balance, its components (Doppler, etc.) are not neccesarily computed, but this can be done by doing extra calculations
  - No assumption on linear superposition of different reactivity effects,
  - Cross-section preparation (SIMMER makes for that self-shielding calculations) is done more frequently for computing the reactivity; flux shape calculations are performed less frequently: to save time
  - Application of complex (3D, fine mesh) neutronics models may take a lot of time, simple 2D coarse-mesh (e.g. 1 radial mesh per HEX ring) models often preferred
  - Coarse mesh models may overestimate amplitude of reactivity variations e.g. due to coherent voiding/condensation, also for PK, but fine mesh is faster for PK
  - Spatial kinetics models are applicable for IP and TP

Computation of reactivity effects and transient reactor power (3)

- Combination of spatial kinetics (SK) and point-kinetics (PK) approaches:
  - SK models usually allow use of an „external reactivity“ (PK allows too), that can be used to modify the computed reactivity
  - Example: starting with approximate density and temperature distributions, achieving a steady-state with a constant power, introducing an external reactivity to continue from the achieved steady-state that in the following is treated as critical
  - SK introduces external reactivity as modification of the generation cross-section (nu*sigmaf). This is similar to k-eff approach in static neutronics,
  - The reactivity effects that are not taken into account in SK (currently in the SIMMER code: thermal expansion of core and control rod driveline, CRDL) can be taken into account as „external reactivity“ contributions.

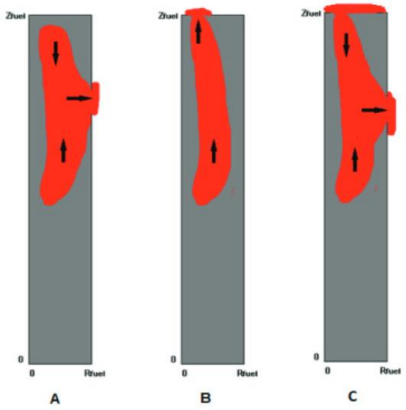
SAS4A/SAS-SFR/SASSYS: example of codes for initiation phase in SFR using point-kinetics





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

- "Channels": pins with pellets, gap, clad, coolant, associated canwall
  Axial nodes of constant solid mass , several radial nodes in a pellet.
- Several channels in core treated independently (except for inlet/outlet, reactivity; e.g. 1 channel per group of similar (burnup, power) SAs
- Material movement inside channels 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



Core thermal expansion effects: SAS approach

Lagrangian mesh is employed for SAS4A channels, usually representing one or more SAs

Point-kinetics scheme employs fuel and other reactivity worth curves along Z computed in advance for each channel, normalized per kg of fuel, steel etc.

Axial expansion: introduction of fuel into lower fuel worth regions above the core leads to a negative reactivity variation

Radial expansion: parametric, vs. variations in core radius

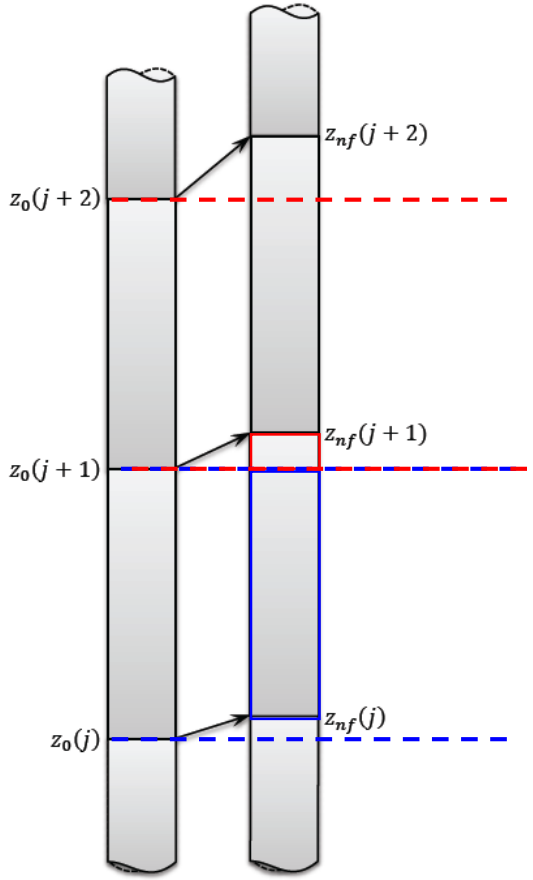


Figure 4.5-1. Original and Expanded Fuel Axial Meshes

SIMMER-III & SIMMER-IV: examples of codes using spatial kinetics

SIMMER-III/IV are 2D/3D fluid dynamics codes coupled with structure and spatial kinetics models

JAEA
CEA
KIT
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

Nuclear data at KIT: 11-group and 560-group XS libraries, C4P for generation of problem oriented libraries from 560-groups (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

SIMMER:

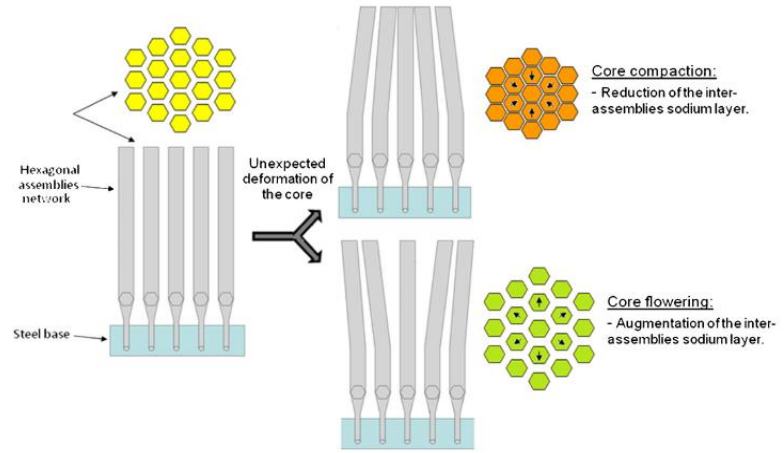
- Slower than SAS4A, in particular in 3D
- Fuel irradiation/failure models: from external codes or simplified approach on gap conductance etc.
- Applicable to TP, coupled route mainly used in the past: SAS4A for IP phase, then SIMMER (coupling is not straightforward)

Core thermal expansion: SIMMER approach

Assumptions

→ Radial expansion: driven by steel expansion (grid plate, constraint plate), cylindrical or more complex shape

→ Axial expansion: driven either by fuel or steel clad depending on burn-up state

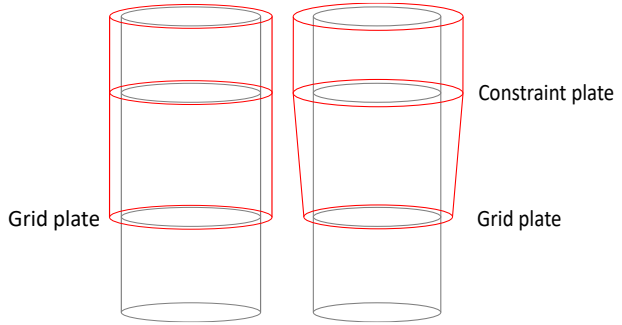


Boundary conditions

→ **Advantage of spatial kinetics: power profile varies with time (neutronics)**

→ **Eulerian mesh**

→ **Time-efficient**: avoid extra neutron transport calculations if possible



In reality:
Mesh expansion
>> non regular mesh

→

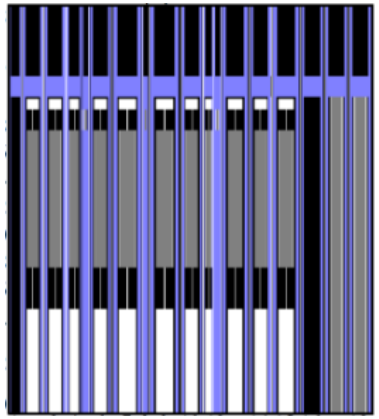
Constraint: SIMMER environment

Dimensions are kept while effect is taken into account via density modifications (cross section)

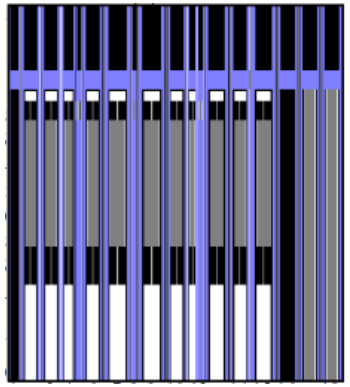
Thermal expansion in SIMMER: based on the equivalence principal

- ***"Increasing all linear dimensions of <u>any</u> given reactor by a certain factor while simultaneously reducing all material densities by that same factor will result in <u>exactly</u> zero change to reactivity and flux distributions"***

Homogeneous uniform isotropic expansion of a ESFR-WH core by factor of 1.02



$k_{eff} = 1.004174$



$k_{eff} = 1.004174$

Equivalent core with initial dimensions and reduced density by factor of 1.02**2 for all materials/nodes

S.B. Shikhov, Perturbation theory formulas for the effect of the dimensions on the critical mass in a fast reactor --- Journal of Atomic Energy, volume 6 Number 2, 1959, p. 90-94.

M. Reed et al., The "Virtual Density" Principle of Neutronics and Its Application to Geometric Perturbation Theory, ANS Transactions, 2012, p.977-980.

Thermal expansion in SIMMER: equivalence approach and the procedure

- Equivalence principal: modified dimensions in radial and axial directions to modified dimensions only in axial direction, also material densities are modified
- This can be used also for considering SA bowing effects, but needs a special mechanics model
- Then one may proceed with axial expansion ring-wise (2D) or node-wise (3D, not yet implemented in a production code version
- For axial expansion we consider: (1) equivalences between density and dimension variations (the coefficients are computed by SIMMER at nominal), (2) XS remapping approaches
- Density remapping does not work well because of self-shielding effects: small amount of fuel in a “non-fuel” node is more efficient that the same amount of fuel in a “fuel” node.
    - This effect to consider also for molten fuel relocation into large non-fuel nodes
- The computed effect is added to the external reactivity

Additional considerations:

- expansion influences all material densities, except coolant
- the expansion effect in the core is negative, but in the sodium plenum it is slightly positive
- the effect does not vary with time after pin failure.
- axial expansion effect is zero in a radially infinite lattice of subassemblies -> the effect is small in a radially large reactor

ESFR-SMART features and transient behavior

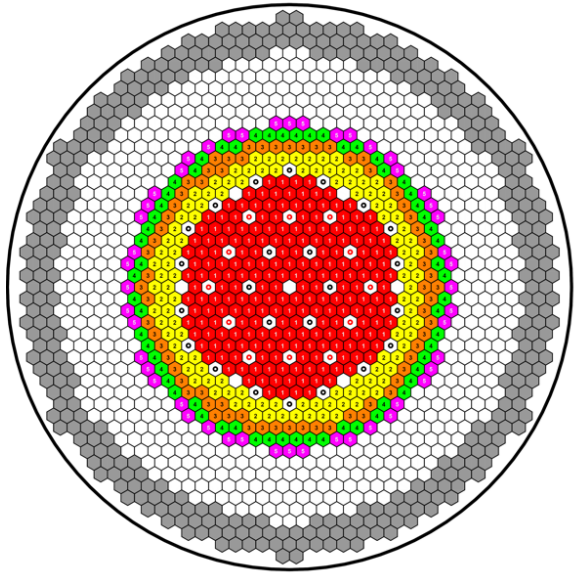
- ESFR-SMART developed on the basis of ESFR-WH. Thick pins (pellet radius 0.4715), high fuel volume fraction, small Na fraction, low void, relatively low enrichment (higher than in ESFR-WH), strong Doppler, small reactivity loss vs. burnup, tight environment for fuel relocation within SAs if special paths are not available

- Flattened core (compared to ESFR-WH): low void effect, higher enrichment and reactivity loss per cycle vs. ESFR-WH

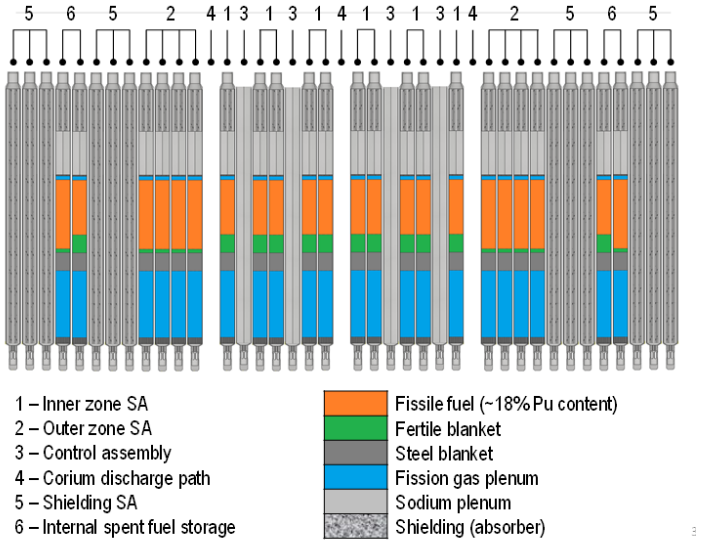
- Corium discharge tubes or transfer tubes (TT): to enhance fuel discharge, also reduce sodium void

- Sodium plenum: low void effect, also additional volume for potential melt relocation

- Unique enrichment and shorter inner core (radial inner fertile blanket as compared to the axial one in ASTRID): may reduce amount of fissile in the inner core after full core melting



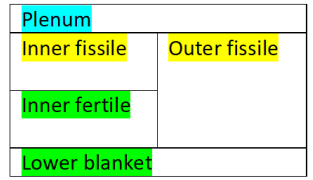
ESFR (EU): axial core layout

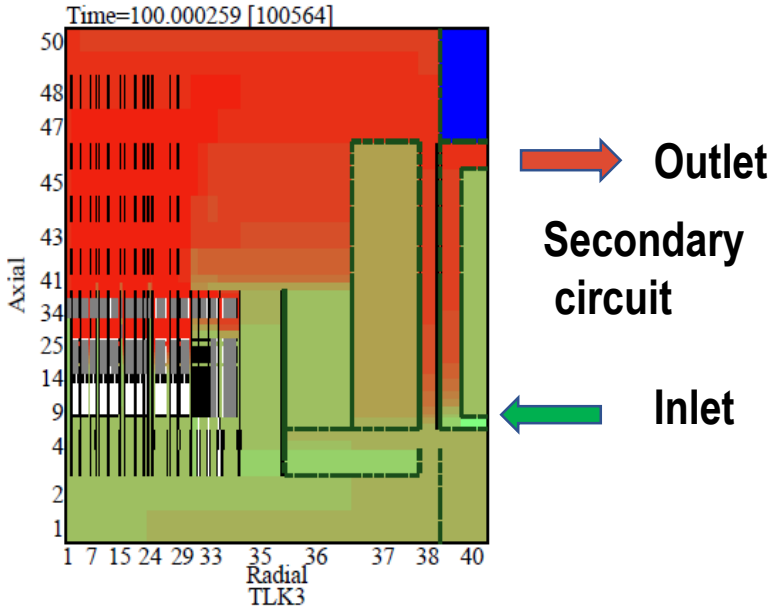


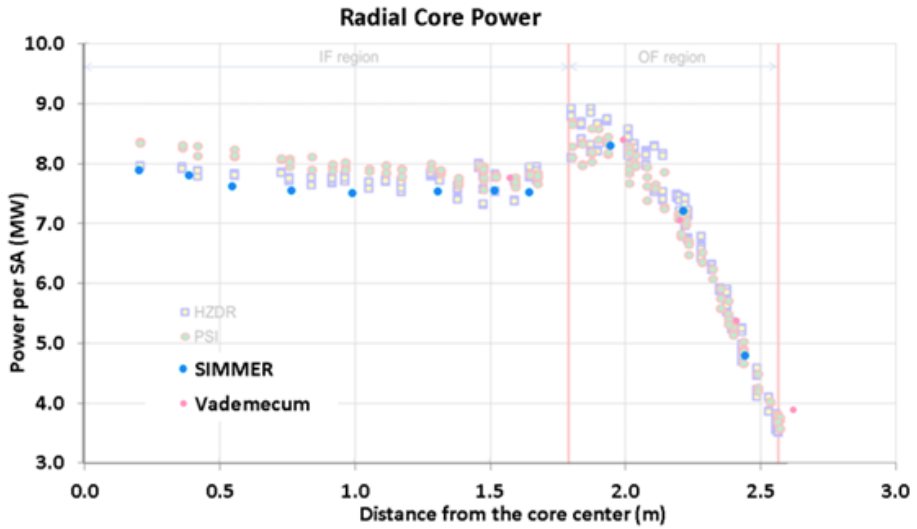
ESFR-SMART ULOF calculations: with SIMMER only (all following slides)

- 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



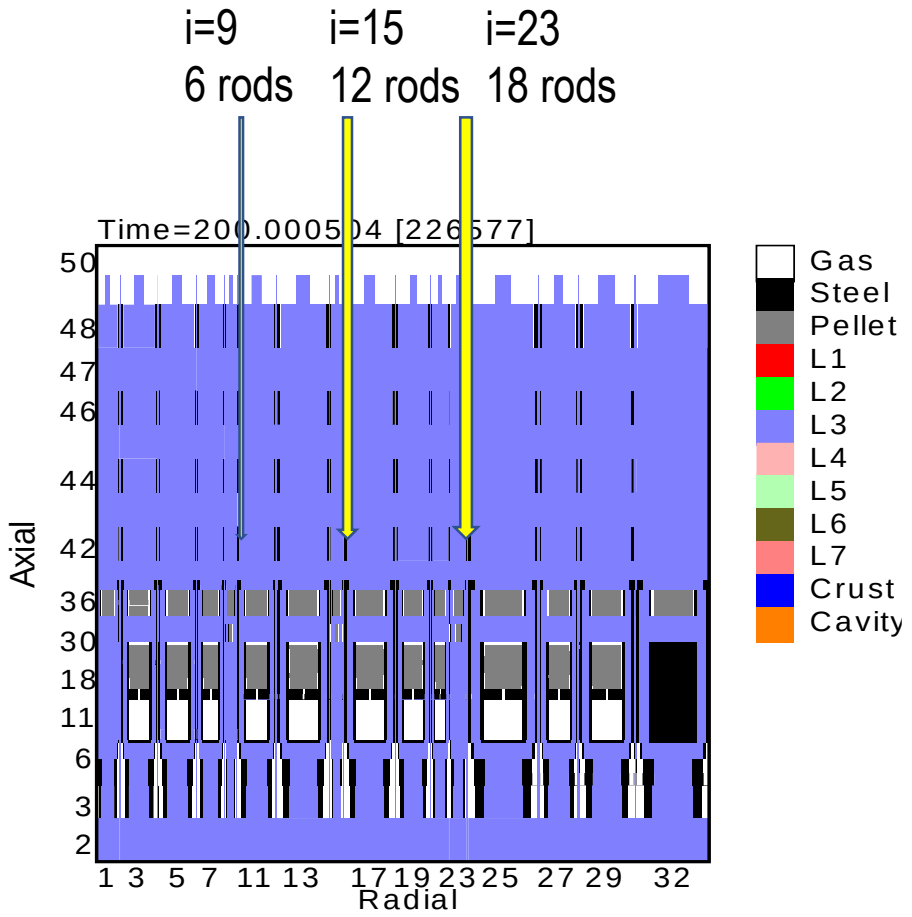




Thermal Expansion Model and New CRDL Model

- 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



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

ULOF non-conservative simulation

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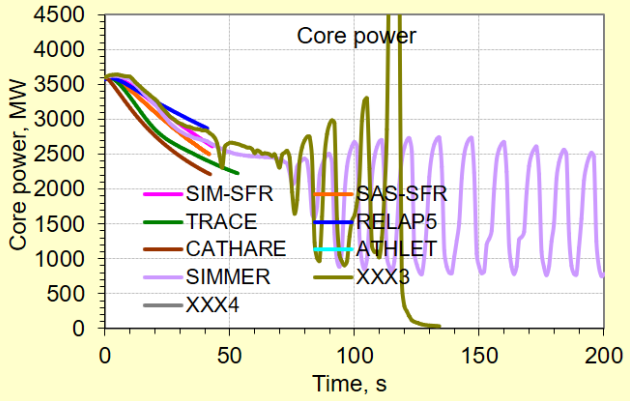
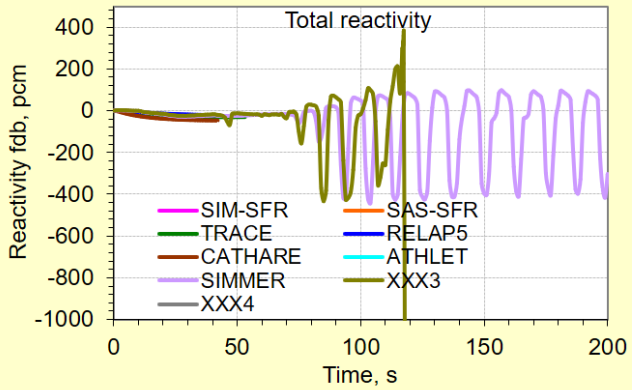
- CRDL uses only the first steel thermal expansion coefficient BSTEEL1.
- The radial thermal expansion option used is „cylindrical“, meaning it is driven by the bottom inlet temperature, changes very slightly in transient.
- Originally BSTEEL1 = 1.528E-5, fuel and clad driven axial thermal expansions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

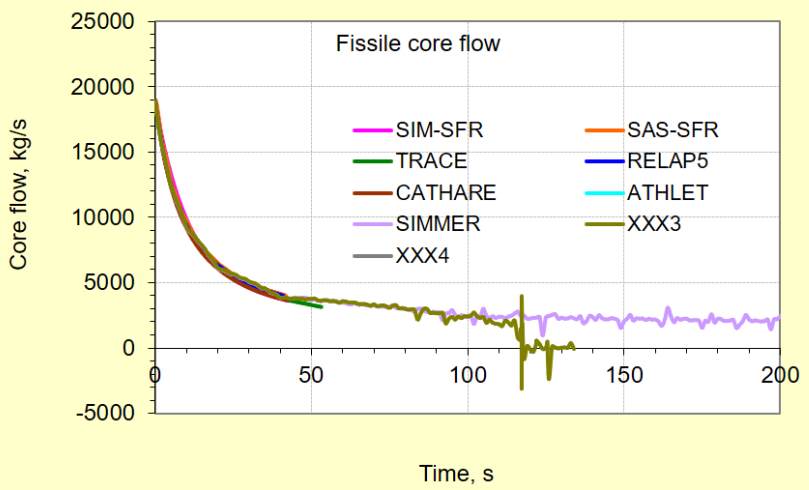
Case No.	Case	Address	Power Excursion
1	BSTEEL 1.53 CRDL with Fuel-Driven	3-ULOF200s-CN-Repeat	Yes at 102 s
2	BSTEEL 1.53 CRDL with Clad-Driven	2-ULOF200s-CN-CladDriven	Yes at 129 s
3	BSTEEL 1.82 CRDL with Fuel –Driven	5-ULOF200s-CN-BSTEEL1.82	Yes at 117 s
4	BSTEEL 1.82 CRDL with Clad-Driven	4-ULOF200s-CN-BSTEEL1.82-CladDriven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



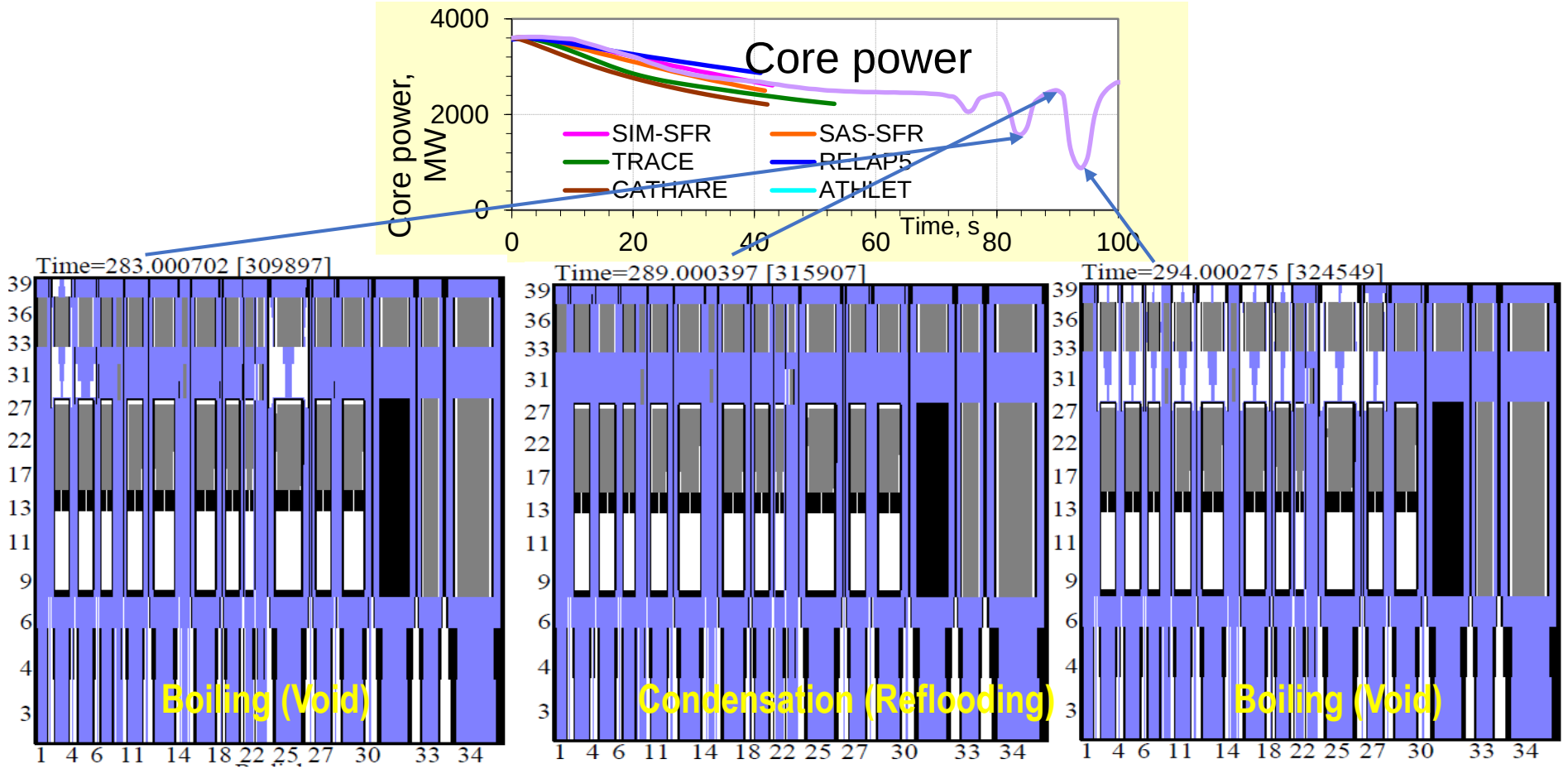




Case 3: Fuel driven ThermExp, boiling onset at 43 s
Power excursion at 117 s

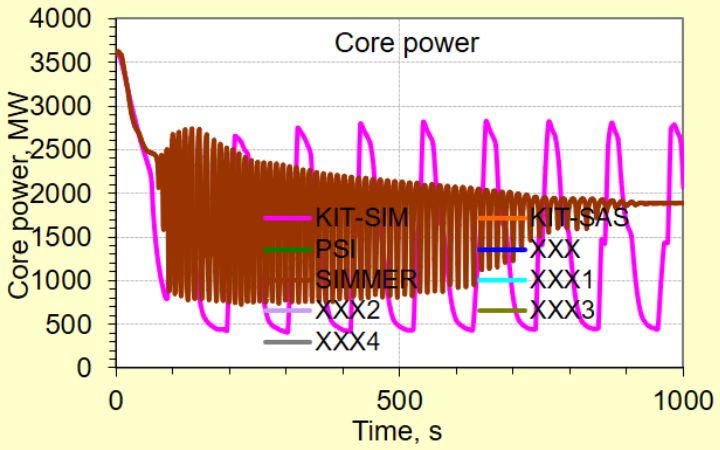
Case 4: Clad driven ThermExp, boiling onset at 69 s
No power excursion

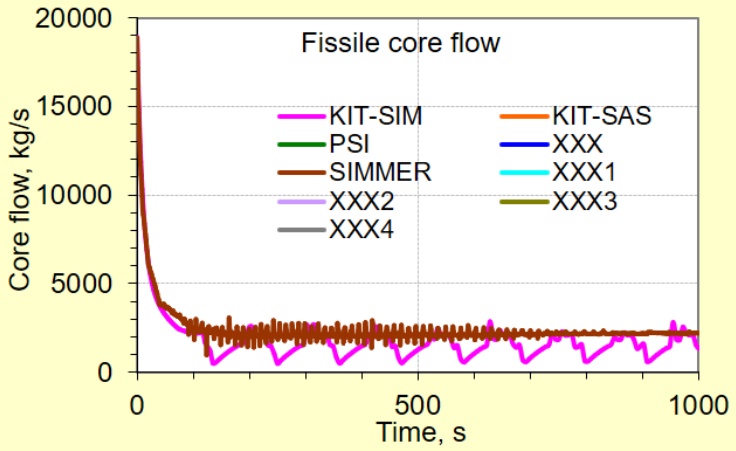
Case No. 4 with boiling oscillation: reactivity lower after plenum void (in white), higher after re-flooding by sodium (in blue)

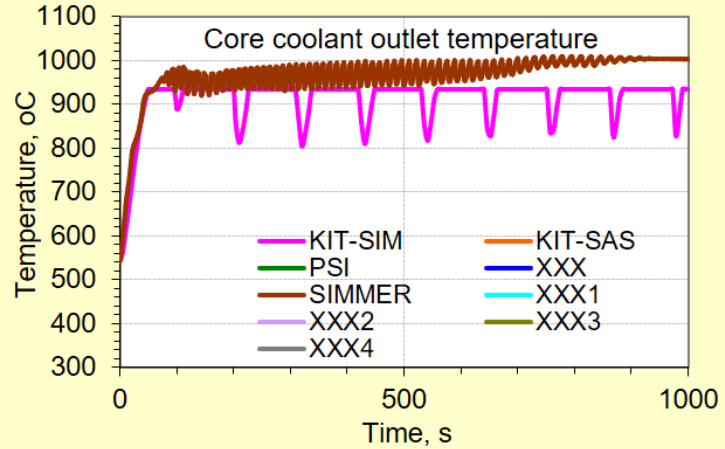


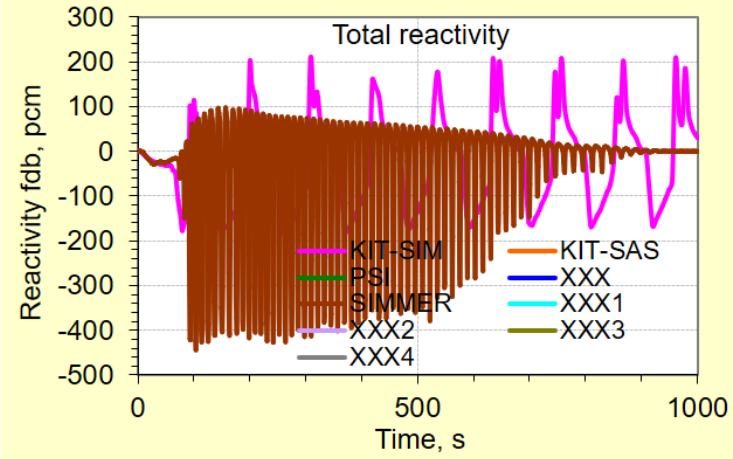
Comment: by comparing 2D and 3D SIMMER results for ASTRID (paper for FR22, together with EdF), we see a lower amplitude in 3D

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)

Conclusive remarks

- Severe accident simulations in SFR: coupled neutrinics and TH codes are needed
- Advanced neutronics are developed since long time, to be improved further
- ULOF IP simulations are important for safety assessment, also offer a basis for TP studies
- IP is driven by sodium void, other feedbacks; a low sodium void effect helps in general
- 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 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 can be avoided.

Thank you!