Karlsruhe Institute of Technology

SIMMER Modeling of Accident Initiation Phase in Sodium Fast Reactors

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Technical Meeting on State-of-the-art Thermal Hydraulics of Fast Reactors

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❑ Introduction: SIMMER Code

SIMMER-III/IV: 2D (RZ)/3D (XYZ) fluid-dynamics codes coupled with structure model and a space-, time- and energy-dependent neutron dynamics model.

Primarily developed for analyses of already disrupted cores, now more efforts to start simulations from nominal conditions

isotxs/brkoxs data files:
Multigroup nuclear data libraries (11 to 72 groups) produced from libraries with more energy groups (KFKINR, C4P, ERANOS) or directly from evaluated files

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
- Loop model (IHX & pumps)

Structure model

- General structure model
- Pin model
- Advanced fuels
- 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

Code is developed and applied by JAEA (Japan), CEA (France), KIT (Germany), and their partners; KIT contributing in particular on neutronics.

SIMMER CODE HISTORY

- 1974-1986: SIMMER-II: NRC/LANL
  - 2D, 2-field, multi-component system code with spatial neutron kinetics (diffusion or transport)
- 1986-1988: AFDM: LANL, JNC (now JAEA), KfK (now KIT), CEA, …
  - 2D, 3-field fluid-dynamics prototype code
- 1988-1989: Initiation of SIMMER-III (LANL+JNC)
  - 2D Code design and framework
- 1992: Initiation of JNC-CEA-KfK cooperation
- 1993: Release of Version 1 (fluid system code)
- 1996: Release of Version 2 (coupled with spatial neutron kinetics)

- 2000: Completion of Phase 1 and 2 code assessment (validation)
  - Phase-I : Basic phenomena and processes (& verification)
  - Phase-II : Elaborate in-pile and out-of-pile tests
- **SIMMER application: significant impact on phenomenological understanding of severe accidents**
  - **Existence of a Transition Phase (sodium boiling will not automatically lead to core disassembly) – accident does not end with primary excursion**
  - **Re-criticality : unstable Fuel/Structure pools with dynamic sloshing motions**
  - **Strong reduction of mechanical work potential via momentum and heat exchange with upper structures**

❑ Introduction: Application to Accident Initiation Phase in SFRs

Thermal Hydraulic Simulation Approaches:

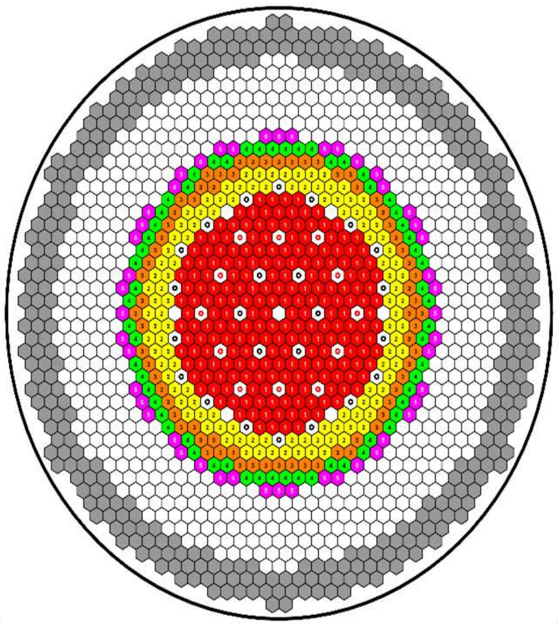
- Treatment of coolant in inter-subassembly gaps, for which special meshes in plane are allocated,
- Sub-channel-scale mesh modelling,
- Heat exchanger modelling with boundary conditions for the secondary circuit coolant, instead of a simpler approach for heat sink in the primary circuit
- Gas-Expansion Module (GEM) treatment.

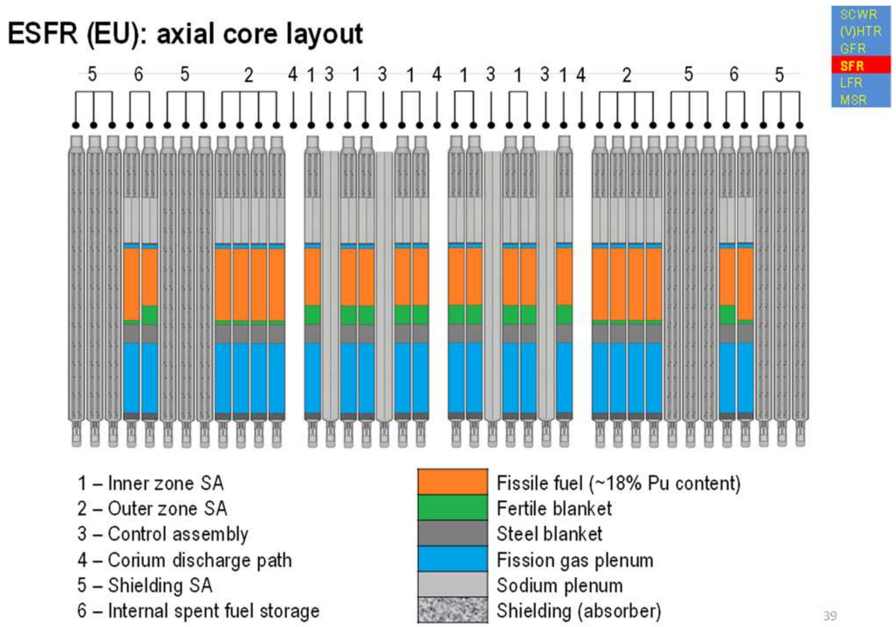
Neutronic Models Developed:

- Reactivity feedbacks due to thermal core expansion in axial and radial directions,
- Control rod driveline (CRDL) reactivity feedback model.

❑ Example: ESFR-SMART

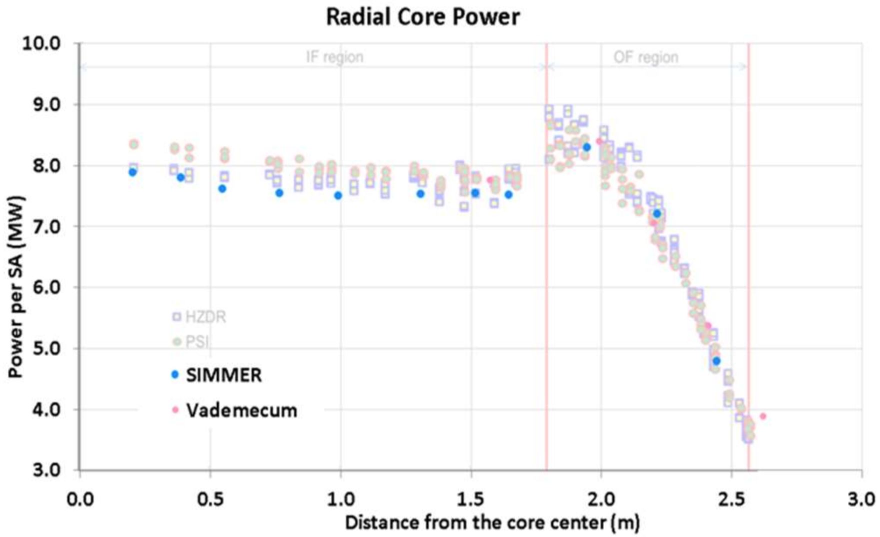
- ESFR-SMART Concept Design: P= 3600 MWth and Sodium Tin = 395 C and Tout = 545 C
- Fissile part is higher in the outer zone and the lower fertile part is shorter
- Hottest FAs are in innermost ring of the outer zone
- Boiling onset takes place there. The effective boiling void worth is negative.

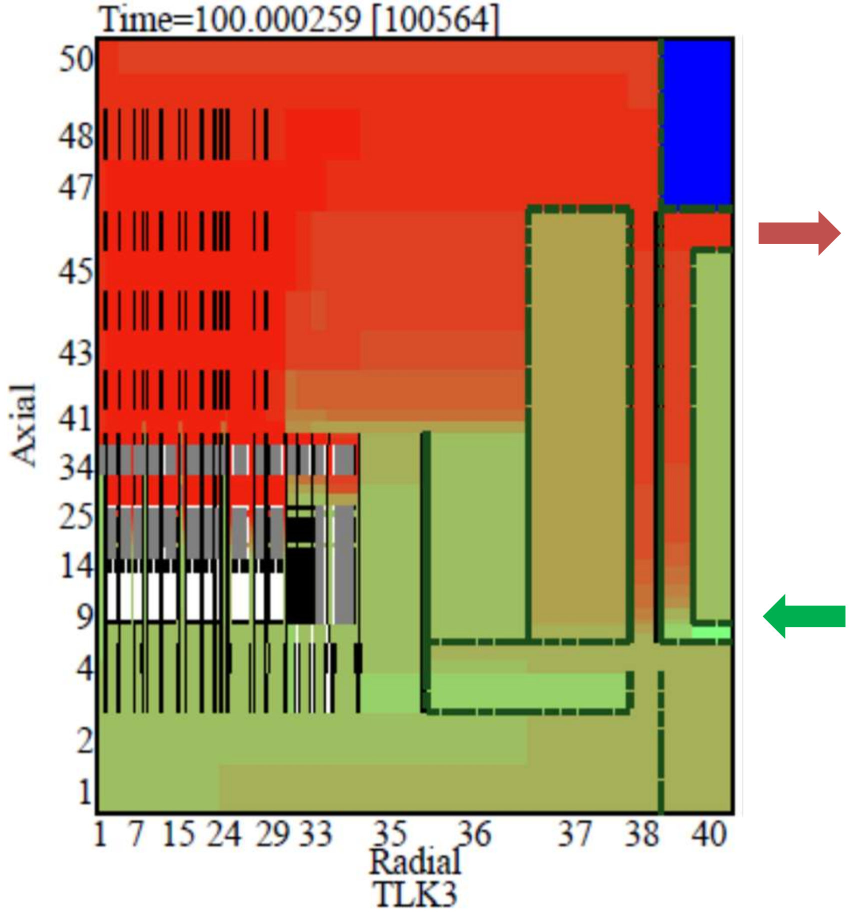




SIMMER ESFR-SMART Model

- Geometric and thermal hydraulic model, where cover gas is modelled
- Neutronic feedback: Doppler and coolant feedback are automatically taken into account.
- Thermal expansion models for the core, axial and radial, and CRDL are included.





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❑ Neutronic Feedback Coefficients

Parameter	Unit	SIMMER	Reference (Serpent calculations)
K_{eff}		1.00937	1.00471
Prompt Neutron Lifetime	[s]	4.25E-07	4.74E-07
Beta Effective	[pcm]	347	362
Doppler Constant Fissile 1500 K -> 1800 K Fertile 900 K -> 900 K	[pcm]	-808	-685
Core Void Worth without Voided Gaps at T_{cool} 763.2 K	[pcm]	1755	
Core Void Worth with Voided Gaps	[pcm]	1727	1542
Upper Gas Plenum + Plug Void Worth	[pcm]	**-41.3**	**-62**
Coolant Density Reactivity Coefficient	[pcm/K]	49/110.8= 0.442	48/110.8 = 0.433
Axial Thermal Expansion Coefficient	[pcm/K]	-0.0715	-0.083
Radial Thermal Expansion Coefficient	[pcm/K]	-0.711	-0.646
Control Rod Drivelines Expansion Coefficient	[pcm/cm]	-423/14.5	-423/14.5

SIMMER ESFR-SMART ULOF Results

ESFR-SMART CORE THERMAL HYDRALIC CONDITIONS

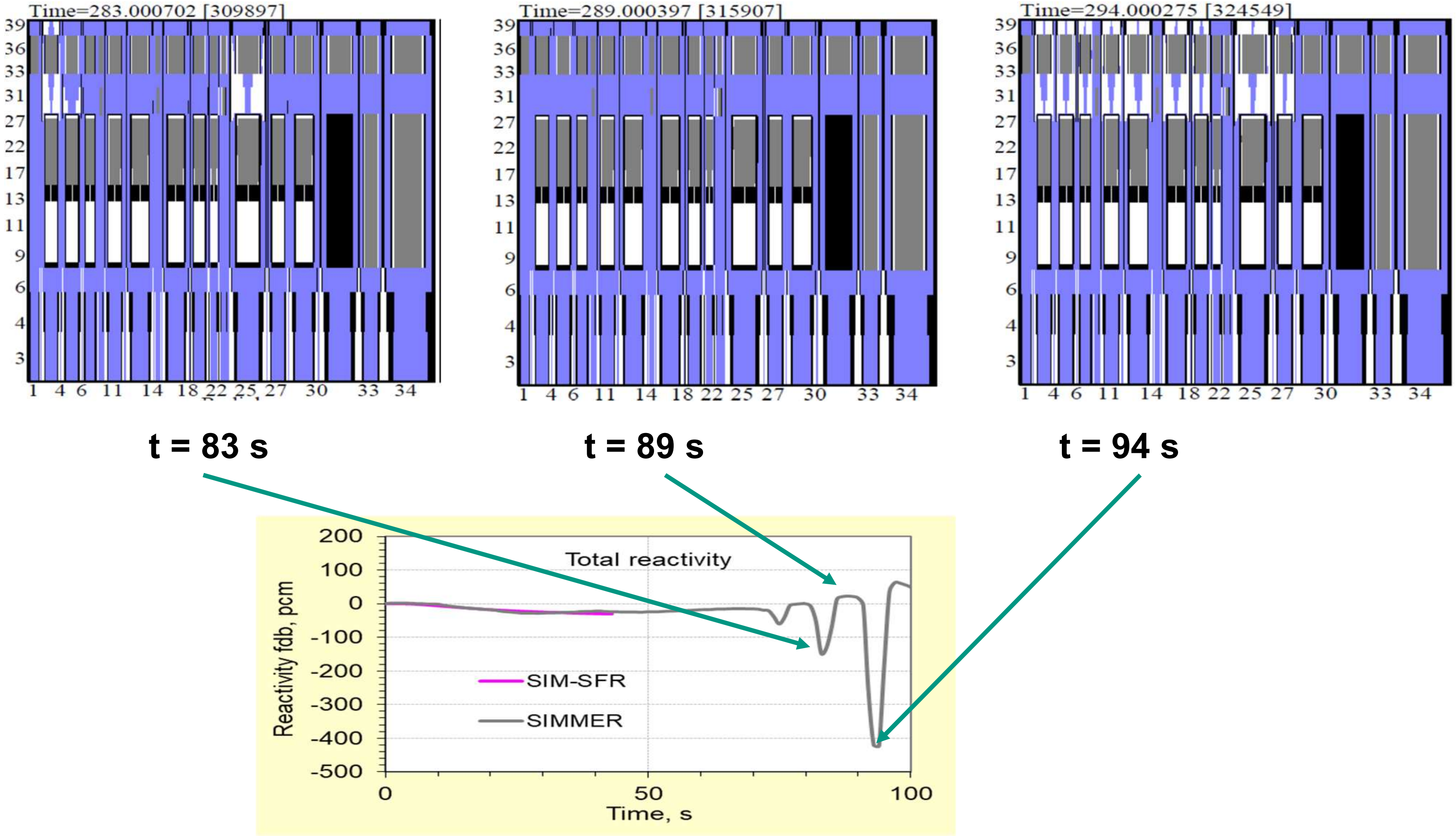
Case No.	Case Description	Boiling Onset	Power Excursion
1	Axial Fuel-Driven and CRDL	43 s	Yes at 117 s
2	Axial Clad-Driven and CRDL	69 s	No

The thermal expansion coefficient of CRDL is 1.82E-5.

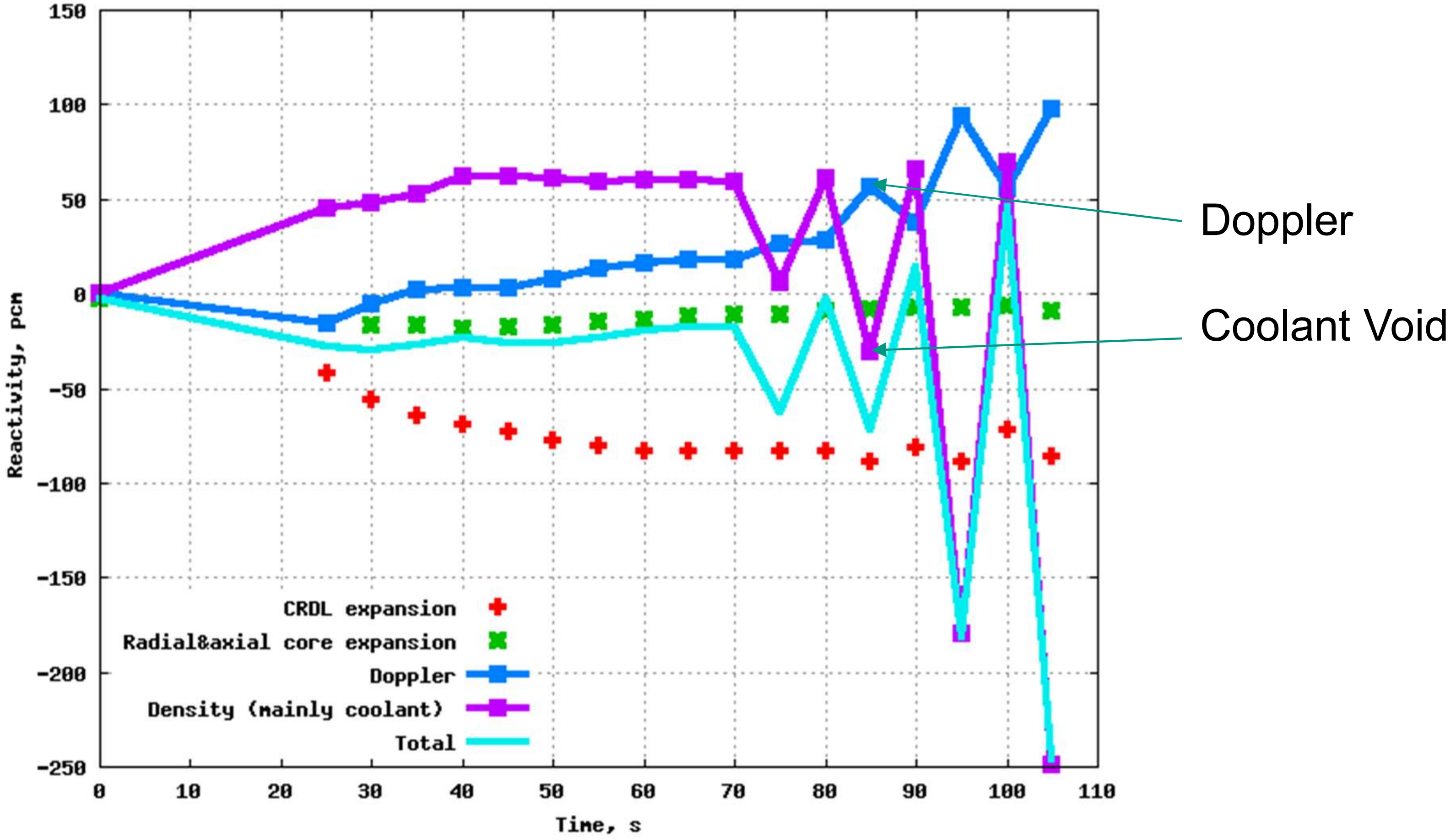
Let's first look at Case 2 results

❑ SIMMER ESFR-SMART ULOF Results

Case 2 Results: boiling void and reactivity



❑ SIMMER ESFR-SMART ULOF Results



The results show that the power oscillation is due to the negative effect void reactivity and the time delay of fission thermal power to the coolant. The fuel Doppler and coolant density reactivity feedbacks (fuel power and coolant power) are anti-phased.

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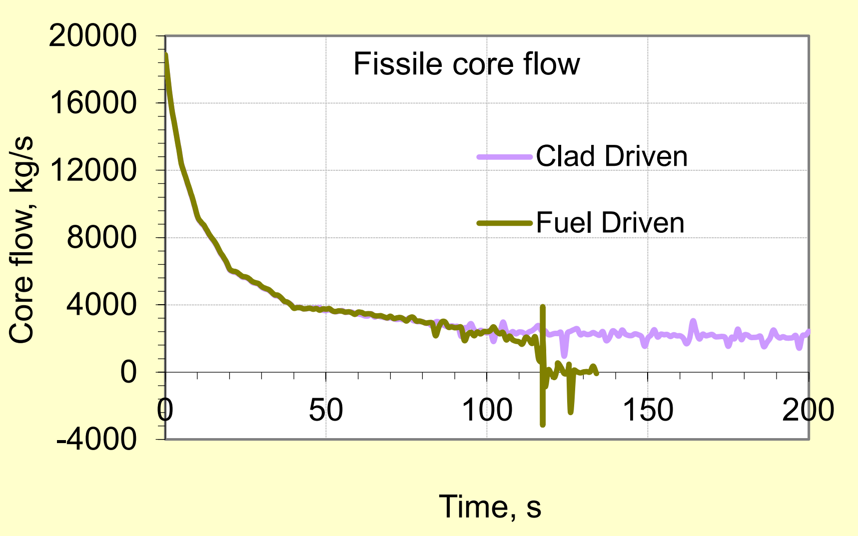
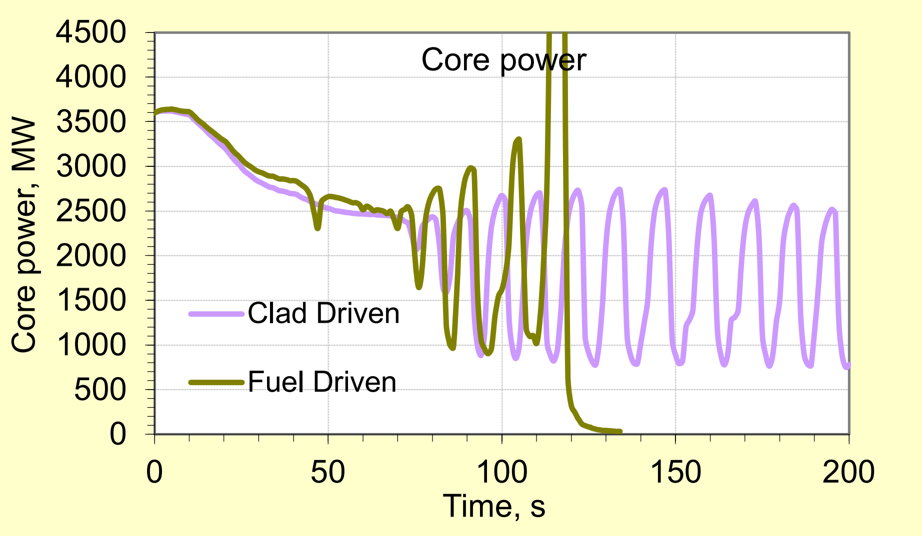
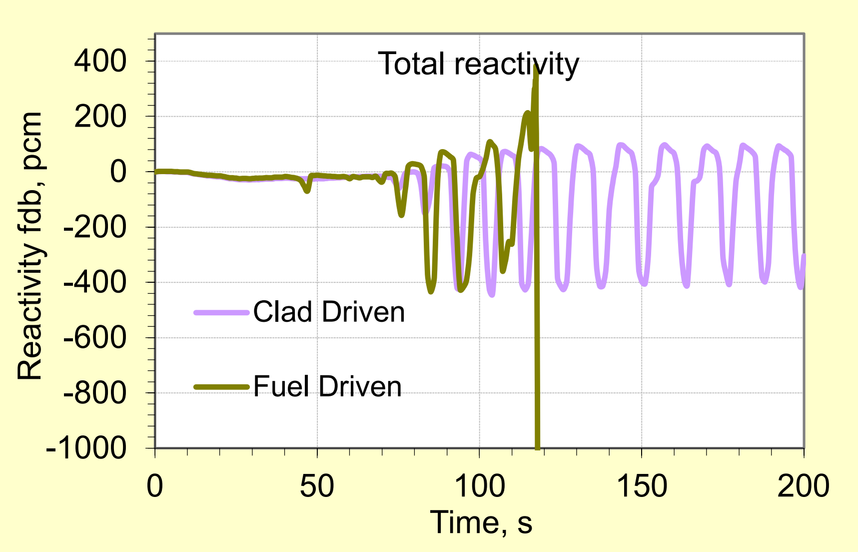
❑ ULOF Results with Power Excursion







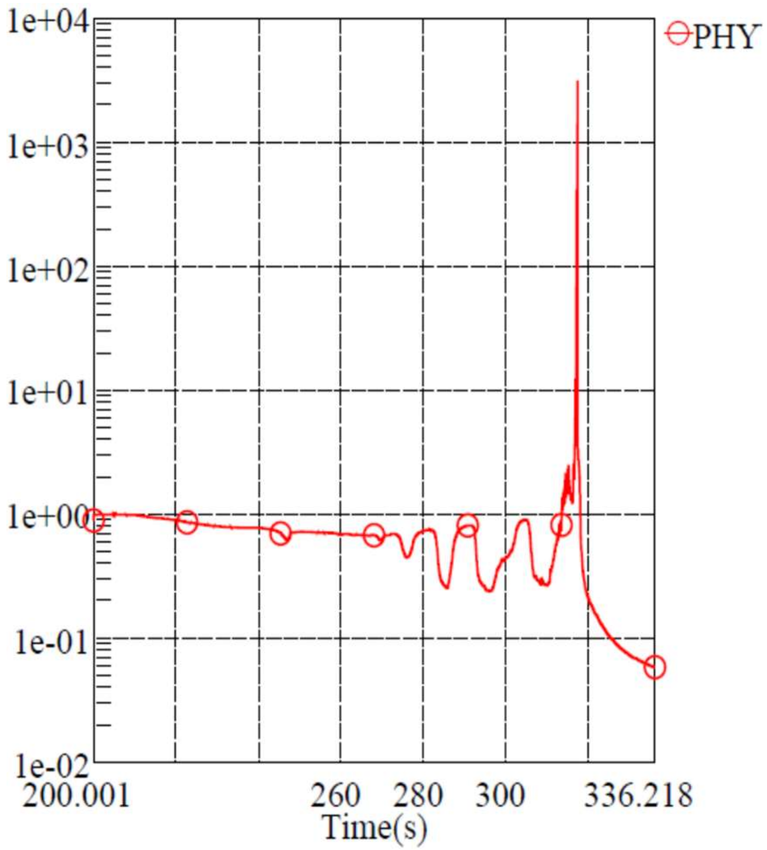
Case 1: Fuel driven ThmExp, boiling onset at 43 s

Power excursion at 117 s

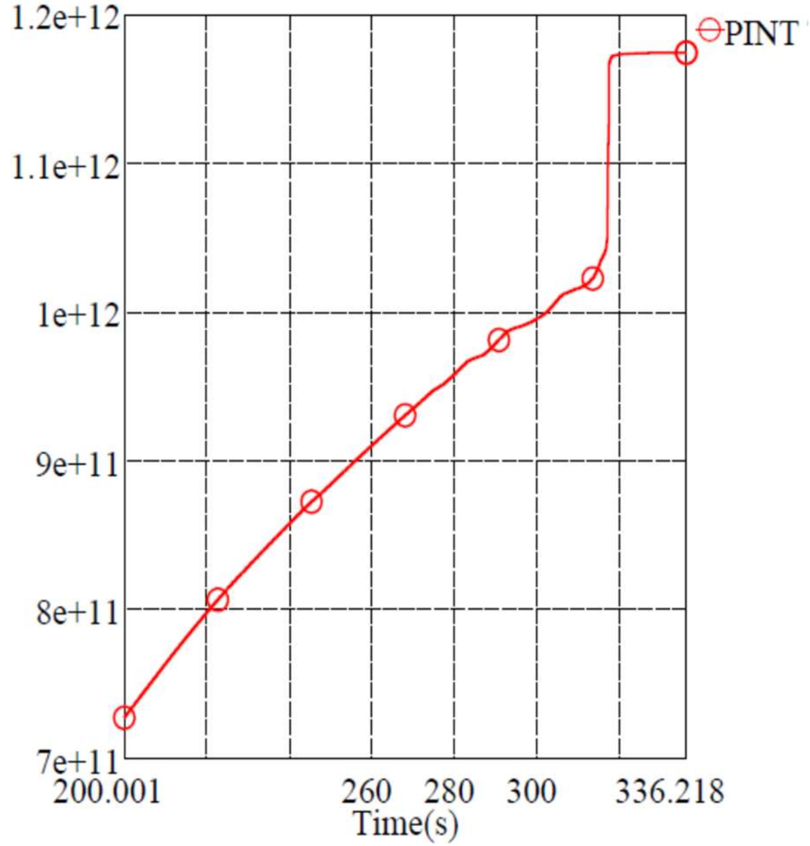
Case 2: Clad driven ThmExp, boiling onset at 69 s

No power excursion

❑ ULOF Results with Power Excursion



Normalized Power in Case 1



Thermal Energy Release, J

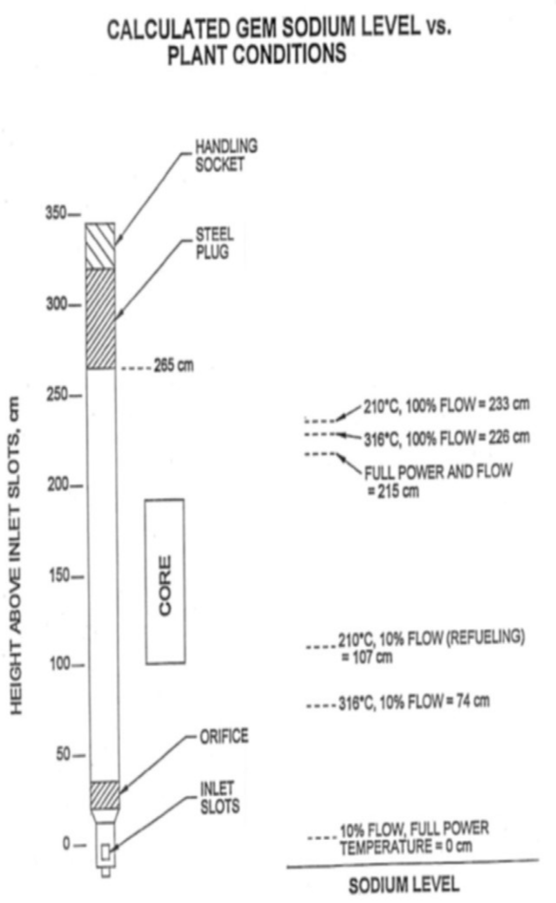
The power excursion generates about 100 GJ

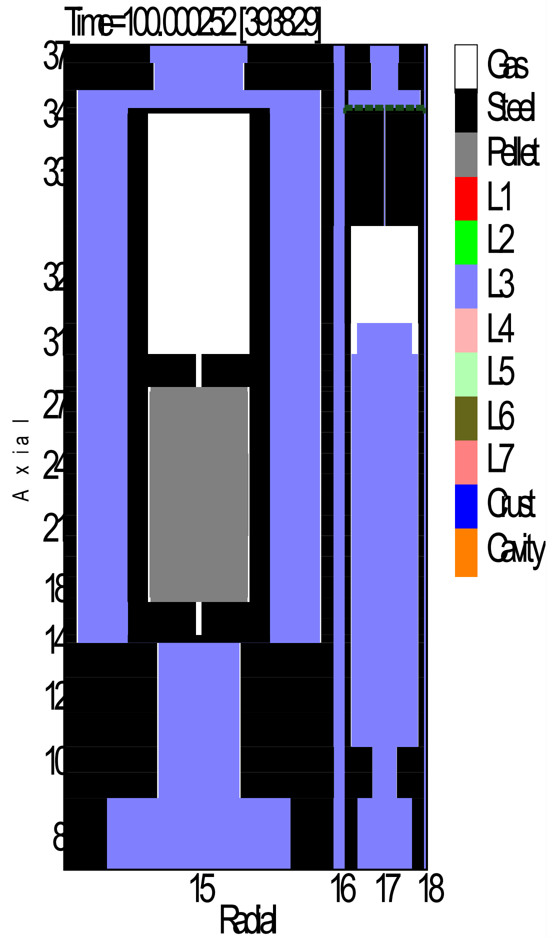
❑ Example: FFTF

- The Fast Flux Test Facility (FFTF) at the Hanford site in Washington was designed by the Westinghouse Electric Corporation for the U.S. Department of Energy (DOE). After reaching criticality in 1980, FFTF operated until 1992, providing DOE with the means to test fuels, materials, and other components in a high fast neutron flux environment.
- Gas Expansion Modules (GEM) were a new passive reactivity control device added to the periphery of the FFTF core during the LOFWOS tests. GEMs are hollow tubes sealed at the top and open on the bottom with Argon cover gas trapped inside. During normal operation, the pressure head of the primary pumps compresses the gas to a level above the top of the fuel column in the driver assemblies, filling the GEMs with sodium. Following a pump trip and a corresponding decrease in the sodium pressure, the trapped gas would expand and displace sodium, increasing the neutron leakage from the core and decreasing the core reactivity.
- The SIMMER simulations here are done under the IAEA benchmark, for which test results are available.

❑ SIMMER FFTF Model

- ➢ Overal geometric and thermal hydraulic model was made for FFTF, especially with GEM model.
- ➢ Neutronic feedback: Doppler and coolant feedback are automatically taken into account.
- ➢ Thermal expansion models for the core, axial and radial, and CRDL are neglected, which are roughly compensated in reality.





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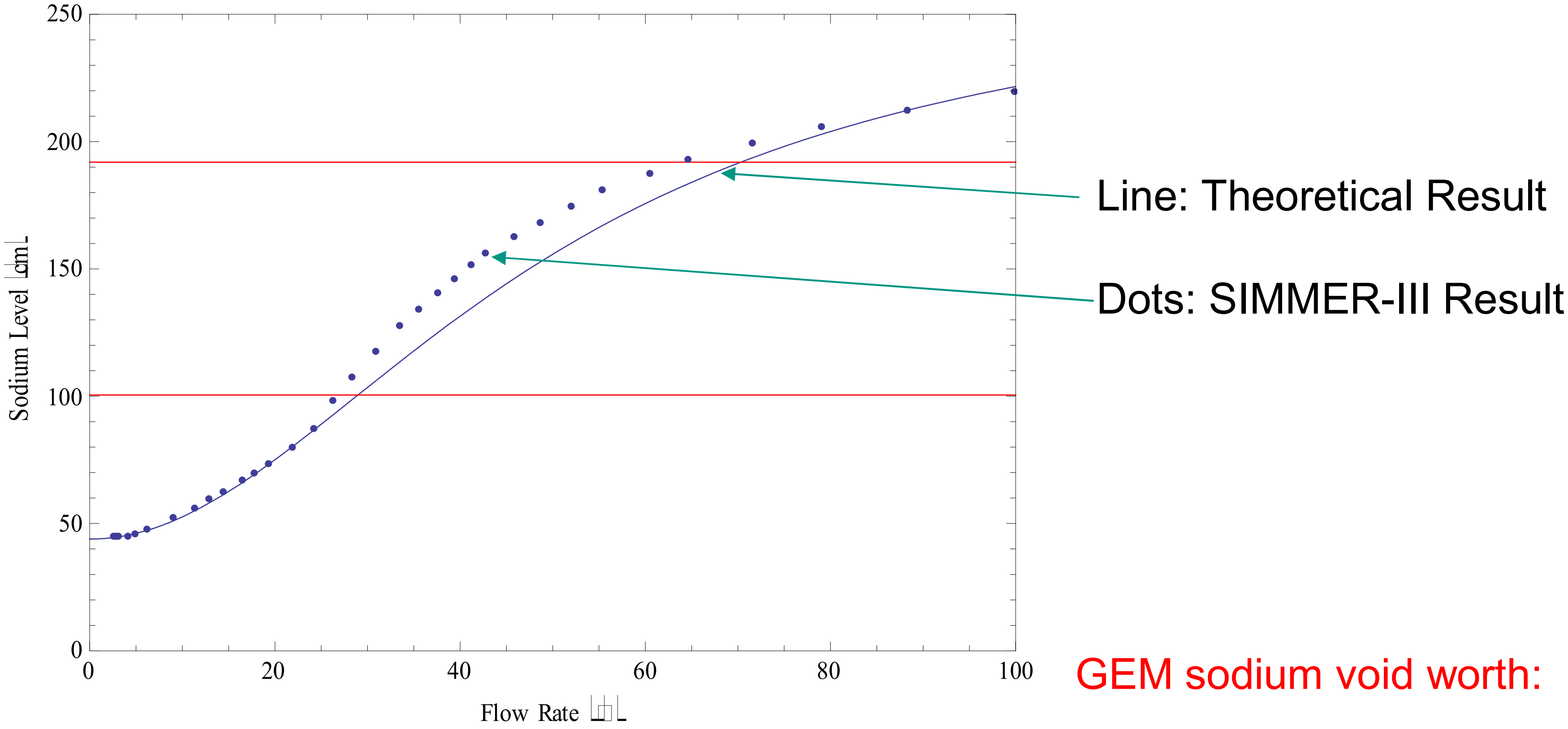
SIMMER FFTF LOFWOS Results



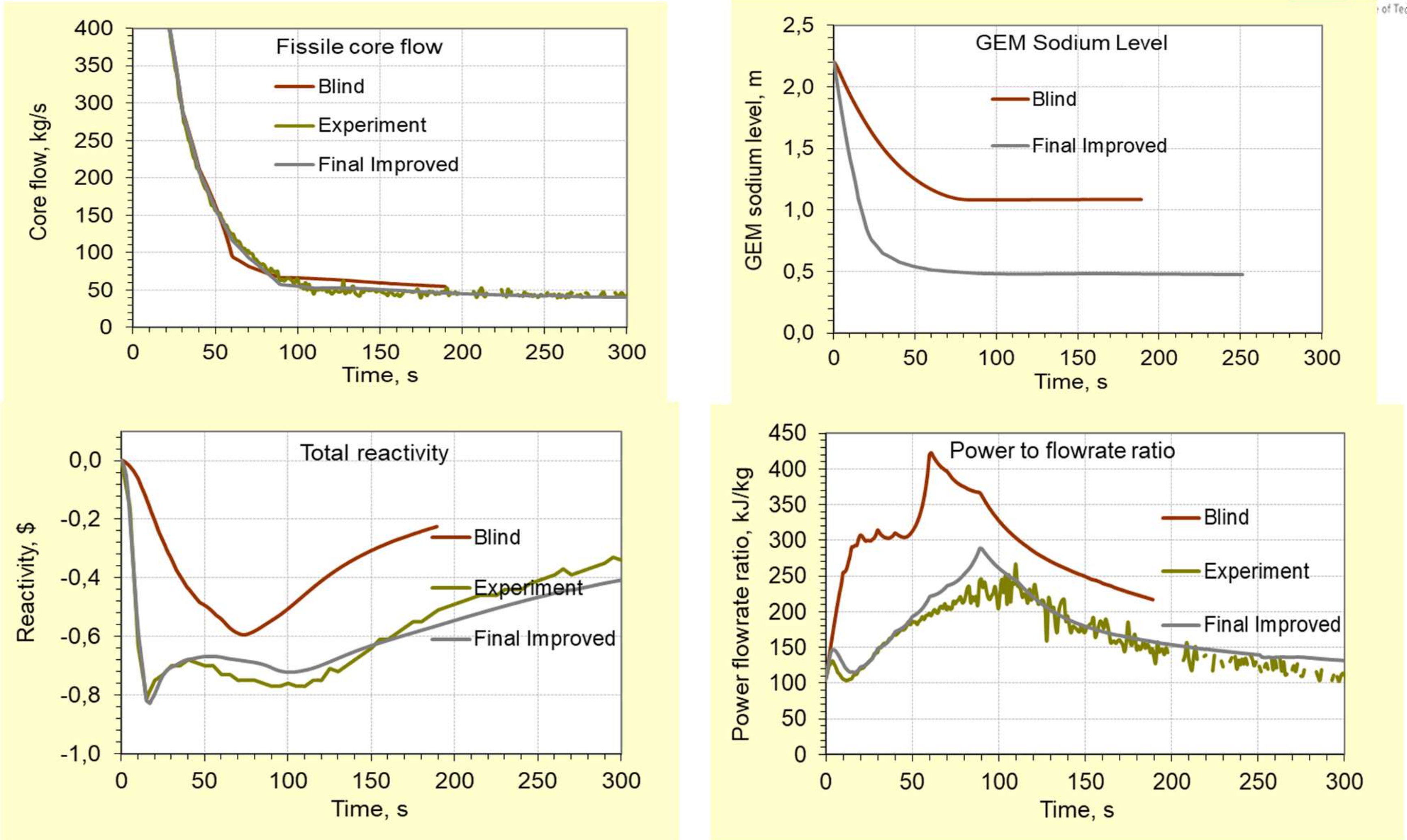
GEM sodium level vs relative flow rate

GEM sodium void worth:

KIT SIMMER: -448pcm

ANL-Reference: -442pcm

❑ ULOF Results with Power Excursion



The core flow rate is simulated well, even in the blind phase

The GEM soldium level simulation is improved significantly, so that the reactivity and the power are well agreed with experimental ones.

❑ Conclusions

- The thermal expansion model is included and the new CRDL model is developed and used for ESFR-SMART.
- 2 cases with fuel/clad driven axial thermal expansion models are calculated and presented.
- Sodium boiling oscillations with a period of about 10s are observed and explained, where the oscillation amplitude may increase or decrease with time. It is decisive for, whether the prompt criticality can be reached.
- Power excursions obtained in the first case (fuel-driven axial thermal expansion), with about 100 GJ thermal energy release.
- No power excursion in the last case (clad-driven axial thermal expansion) with strongest negative feedback.
- FFTF with GEM is simulated and presented. The results are well agreed with experimental ones.

Acknowledgement:

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IAEA-CRP on Benchmark Analysis of FFTF Loss Of Flow Without Scram Test (I32011) 2019-2022