Karlsruhe Institute of Technology

ON THE PURSUING OF SAFETY ENHANCEMENTS IN SODIUM FAST REACTORS

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Intro & Outline

	1960	1970	1980	1990	2000	2010	2022
FBR National Programs							
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International collaborations (e.g. CABRI ,…)							
EU funded Projects							

- Outcome of long lasting international collaboration in SFR safety (400+ years of reactor operation):
  - Improved core designs, structural components and passive safety systems.
  - Development of numerical simulation computer codes for design as well as licensing process.
- Assessment of enhanced SFR core designs under ULOF transient

SFR Safety Analysis

- Licensing: demonstration of safety functions under normal operation and accident conditions:
  - i) reactor shut-down maintaining safe condition
  - ii) adequate core heat removal after shut-down
  - iii) retention capabilities for radioactive and hazardous material to minimize its release to the environment.

- CP-ESFR project milestone: identification of initiating events in DBC that may challenge the safety functions.

- Category DBC4: initiating events not expected to occur during plant lifetime (freq.$<10^{-4}$ per reactor-year):
  - Unprotected Transients (shutdown system is assumed to fail)
    - Runaway of control rods: Unprotected Transient Over-Power
    - Loss of the active core cooling capability: Unprotected Loss of Flow
  - Break of LIPOSO (pipelines joining the primary pump with the core diagrid).

- ULOF importance:
  - Potential to progress into the coolant boiling phase (and eventually into partial or even total core destruction).
  - Detailed consideration of the particular effects of various specific design characteristics (e.g. upper sodium plenum, absorber layers, discharge tubes, etc.).

SFR reactor designs in EU projects

	CP-ESFR	ESNII+	ESFR-SMART
Time	2009-2012	2013-2017	2018-2022
Target	SFR	Gen-IV (SFR, LFR, GFR.)	SFR
Reactor power (MWth)	3600	1500	3600
Total number of SA	453	291	504
Number of pins per SA	271	217	271
Core inlet temp. (°C)	395	400	395
Core outlet temp. (°C)	545	550	545
Av. core structure temp. (°C)	470	475	470
Reactor performance	Minor Actinides transmutation	ASTRID	Improved CP-ESFR reactor
Safety measures	decrease sodium void worth	negative sodium void worth	corium discharge tubes passive SR (Curie-point triggered)

SFR reactor designs in EU projects

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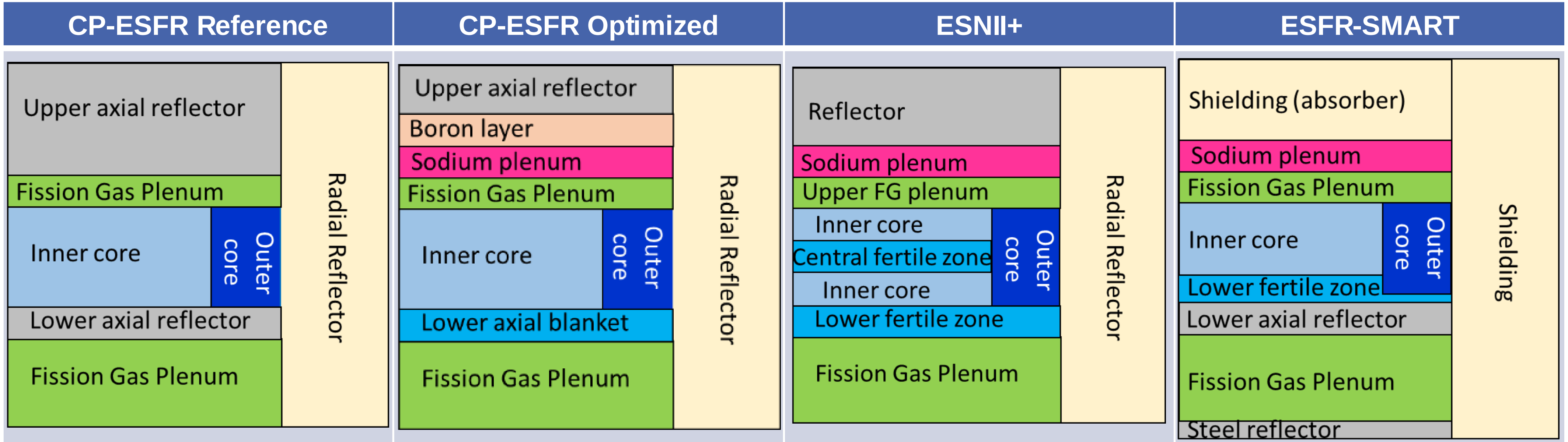


Sodium void (density) reactivity:

- Less neutron capture (positive effect)
- Neutron spectrum hardening (positive effect)
- Larger mean free path: neutron leakage increase (negative effect)

Measures:

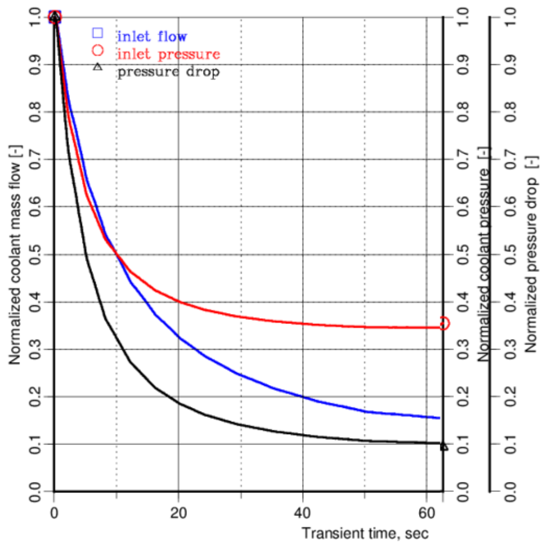
- a large sodium plenum at the top of the core (where neutron leakages are increased)
- axially heterogeneous fuel pins with a central fertile layer in IC (increasing neutron flux in the upper fissile layer)
- shortening of the fissile zone in the IC
- absorbing zone in upper shielding (reducing neutron reflection back to the fissile core during voiding)

ULOF transient

- Unintentional simultaneous coast-down of all primary pumps + failure of the reactor shut-down system.

- The primary mass flow rate:

$$\frac{\dot{m}(t)}{\dot{m}_0} = \frac{1}{1 + \frac{t}{\tau}}$$

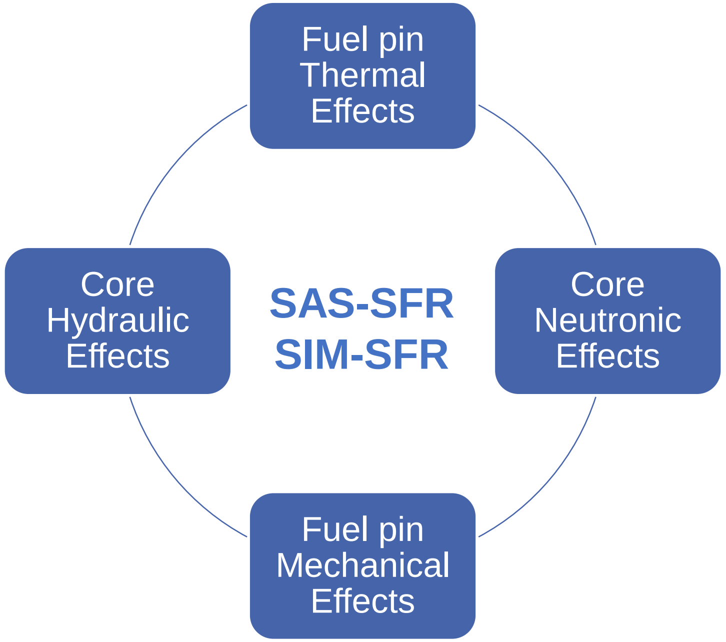


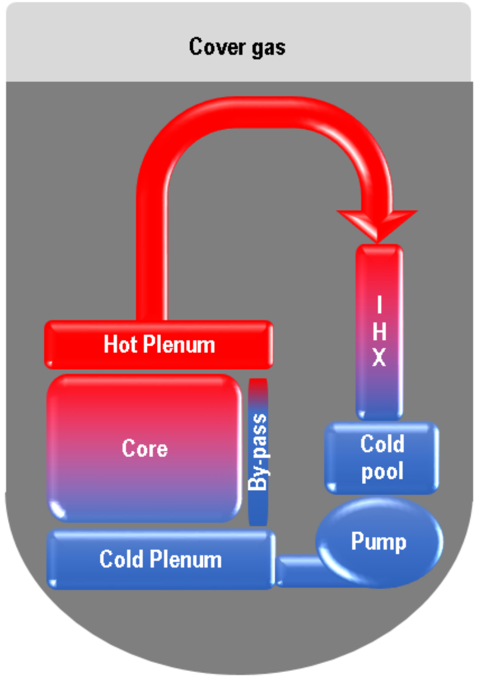
τ (halving time): 10 s, except for ESNII+ case which is 24 s.

- No pony motors or other devices maintaining coolant
- Evaluation at EOEC core conditions (except for the CP-ESFR Opt. at BOL)
- EOEC represents the worst-case scenario where the fuel/pin configuration is in degraded thermal and mechanical conditions and all control rods are essentially in the withdrawn position.
- Reactivity feedbacks: Doppler, fuel cladding, sodium reactivity, control rods driveline thermal expansion.

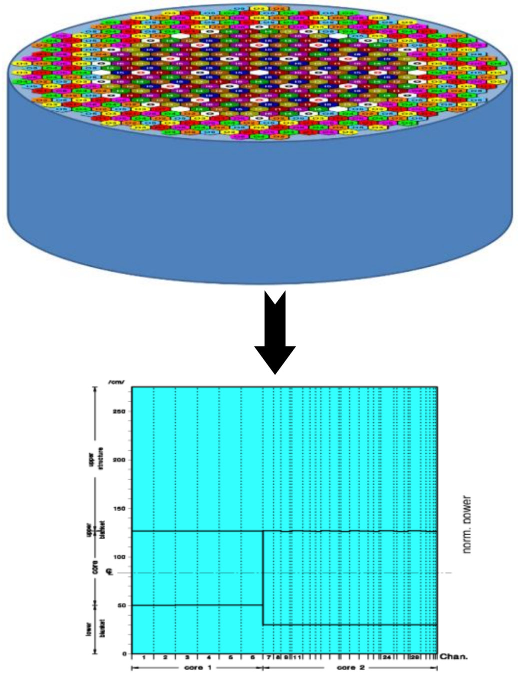
SIM-SFR and SAS-SFR codes

- SAS-SFR and SIM-SFR: reference codes in SFR safety evaluations
- Developed and supported by the Karlsruhe Institute of Technology.
- Validated against experimental data from large-scale experiments (i.e. CABRI, SCARABEE, KNS-37, TREAT, Phenix, SPX, etc.).





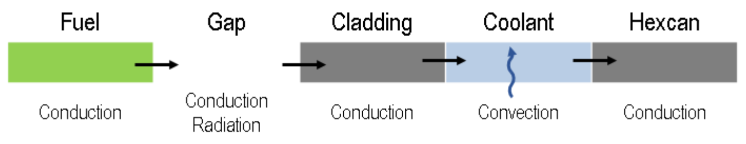
SFR core

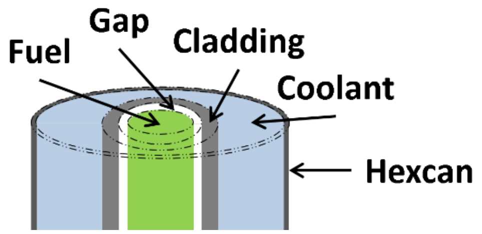


Code representation with SA channels

ULOF Code modelling

- Reactor representation:
  - SIM-SFR: core, the primary, secondary and tertiary cooling circuits, including IHX and SG
  - SAS-SFR: core and primary cooling circuits including IHX
- SA representation:
  - SIM-SFR: average power and a peak power fuel representation for each core zone
  - SAS-SFR: SA grouping based on similar TH conditions undergoing same irradiation (ESFR-SMART 34 SA groups)
- Reactivity feedbacks:
  - SIM-SFR: Doppler, fuel&cladding axial exp. , diagrid radial expansion, coolant expansion and CRDL axial exp.
  - SAS-SFR: Doppler, coolant density, fuel&cladding axial exp., fuel and clad relocation, diagrid radial exp., CRDL ax. exp.
- Gap model: special, high fidelity fuel pin mechanics models.
  - SIM-SFR: dynamic model (burn-up dependence of both fuel and cladding material)
  - SAS-SFR: URGAP model (gap size, fuel-clad contact pressure, gas content and composition and surface roughness)



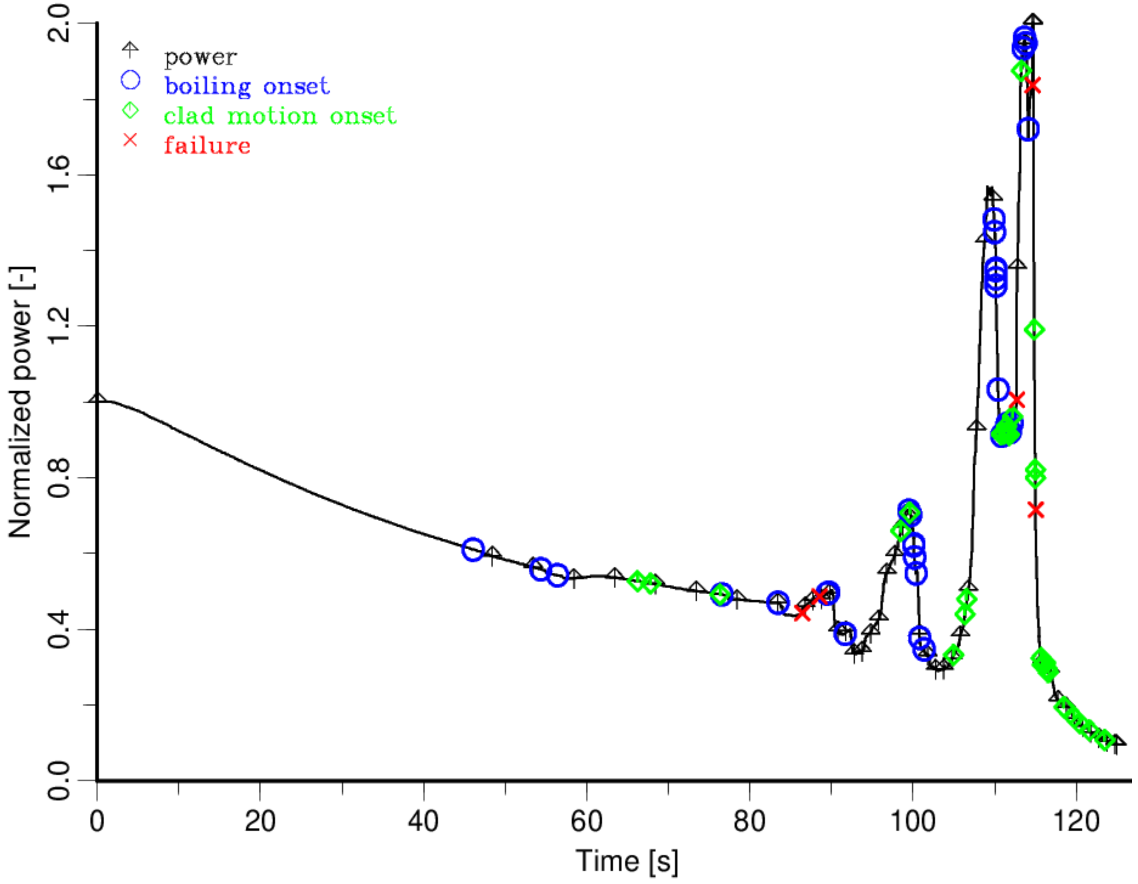


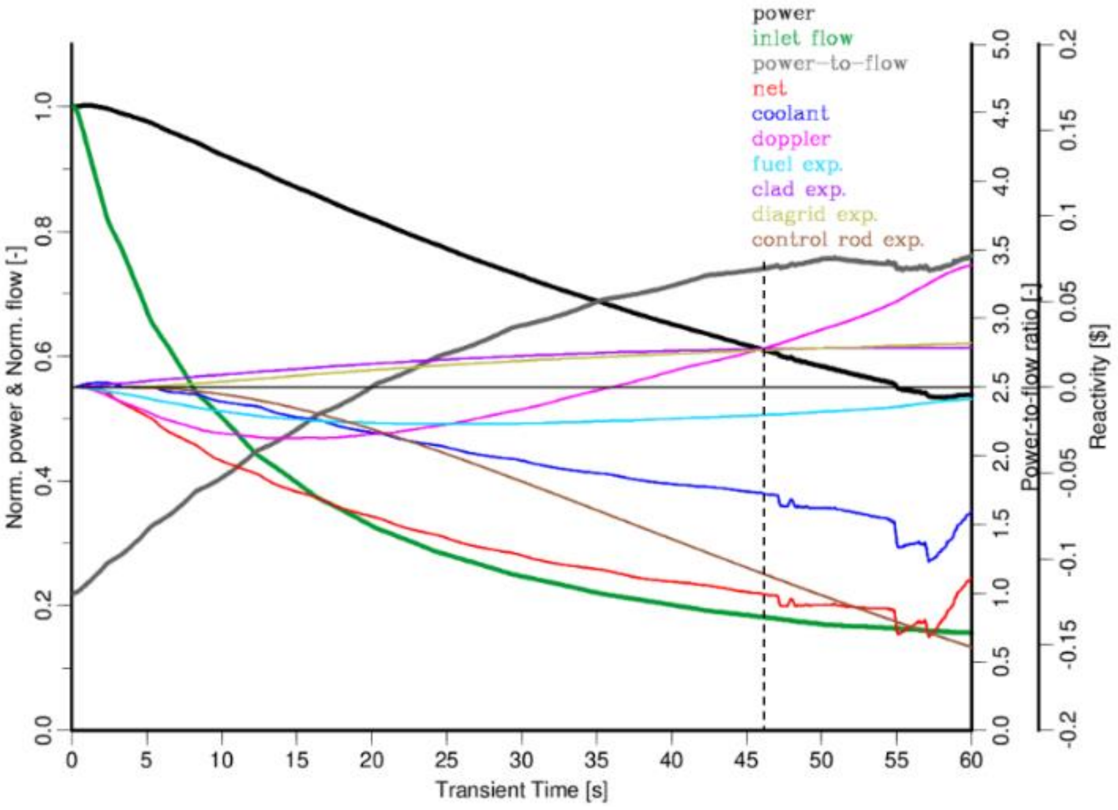
ULOF code results in CP-ESFR and ESNII+

- CP-ESFR:
  - The optimized core improved the safety response by reducing peak temperatures and enlarging grace times.
  - Not sufficient to avoid a power excursion once sodium boiling commenced.
- ESNII+:
  - Upper sodium plenum provided only a small delay in boiling onset (void effect dominated by the fissile core voiding) → sodium plenum does not play a decisive role in improving total void effect
  - Transient progression beyond pin and hexcan failure, driven by cladding failure and relocation from the fissile core zone.
  - Optimization of the core neutron physics alone was not sufficient to avoid a power excursion during the ULOF transient.
- This type of core geometrical modifications established a direction to progress for achieving higher safety levels and risk prevention of core meltdown accident.

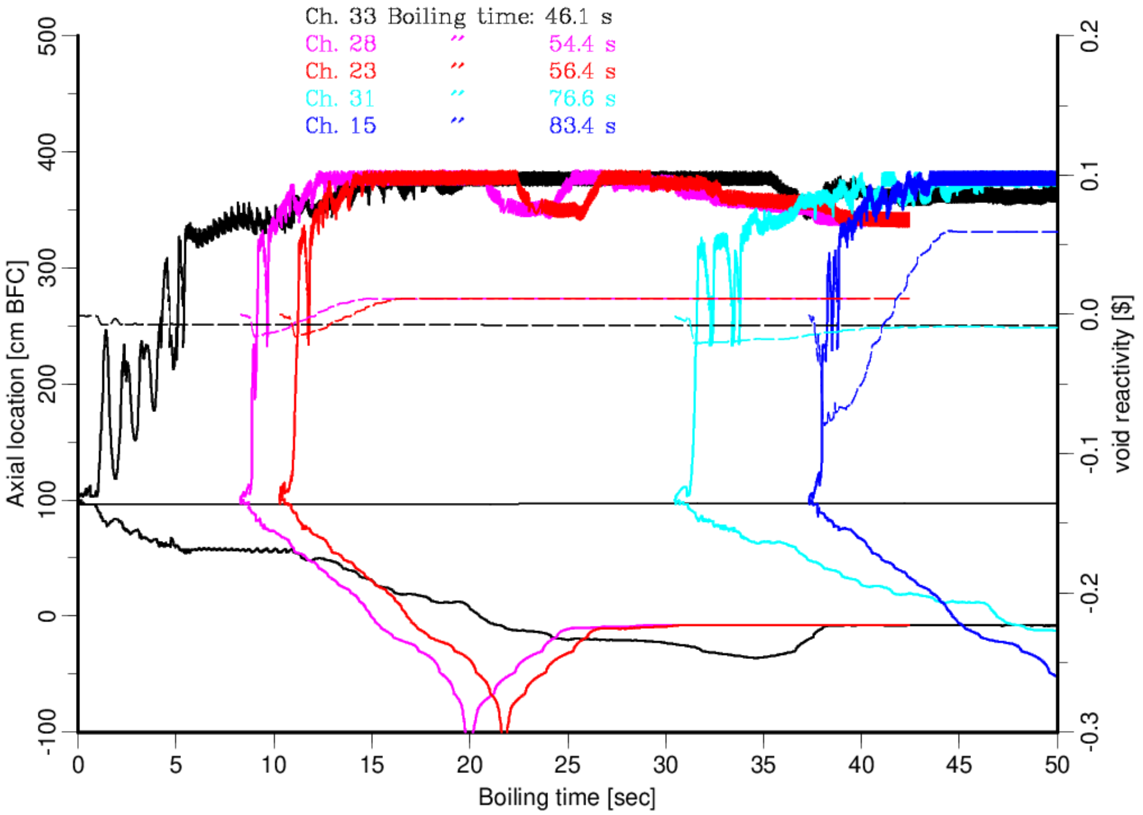
SAS-SFR results for ESFR-SMART ULOF

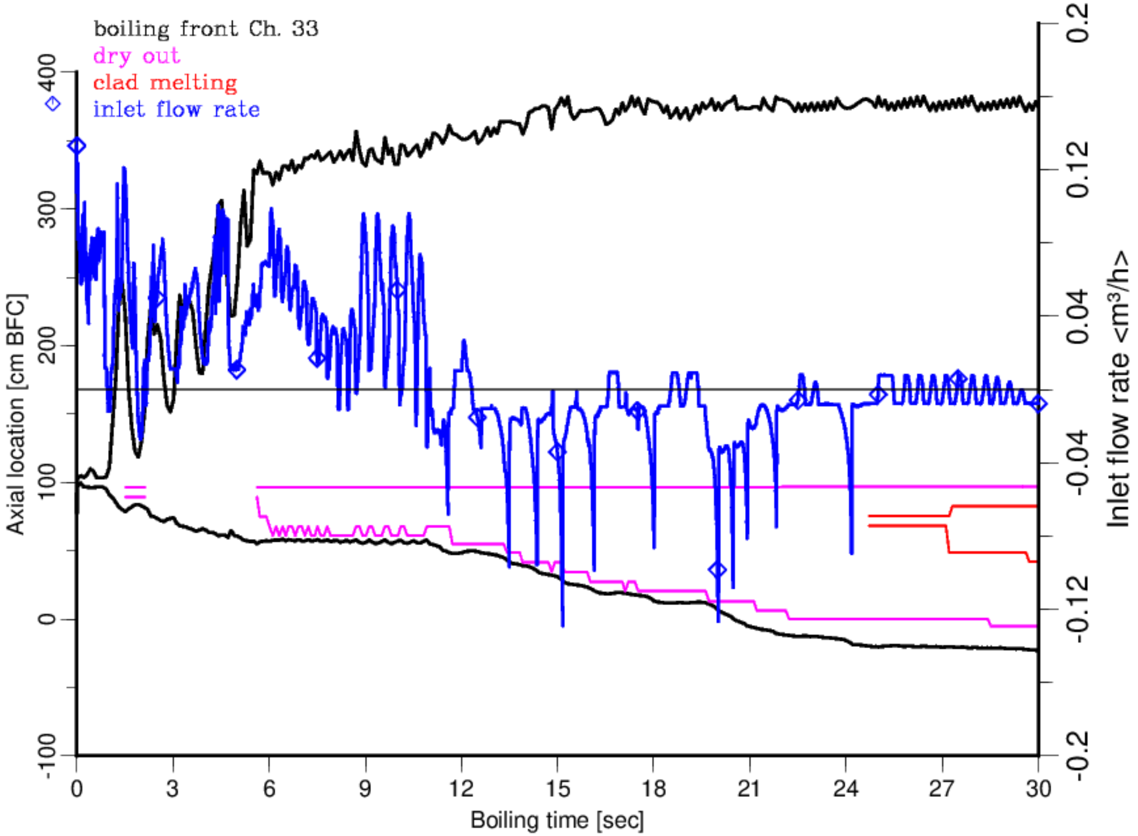
- Sodium boiling starts in ch. 33 (OC) at 46.1 s, nominal power is 0.61, net reactivity is -0.12 $.





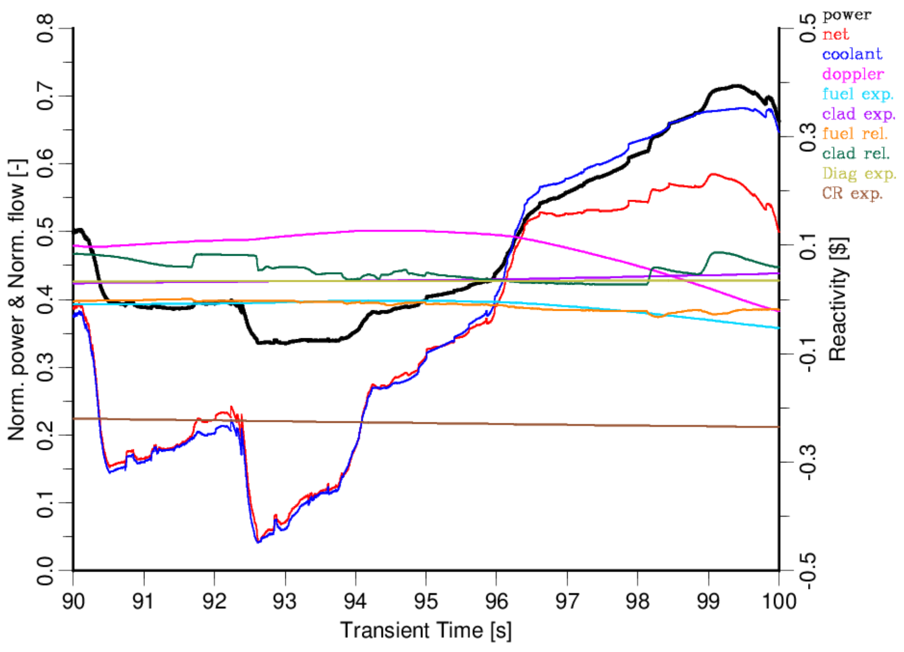
SAS-SFR results for ESFR-SMART ULOF

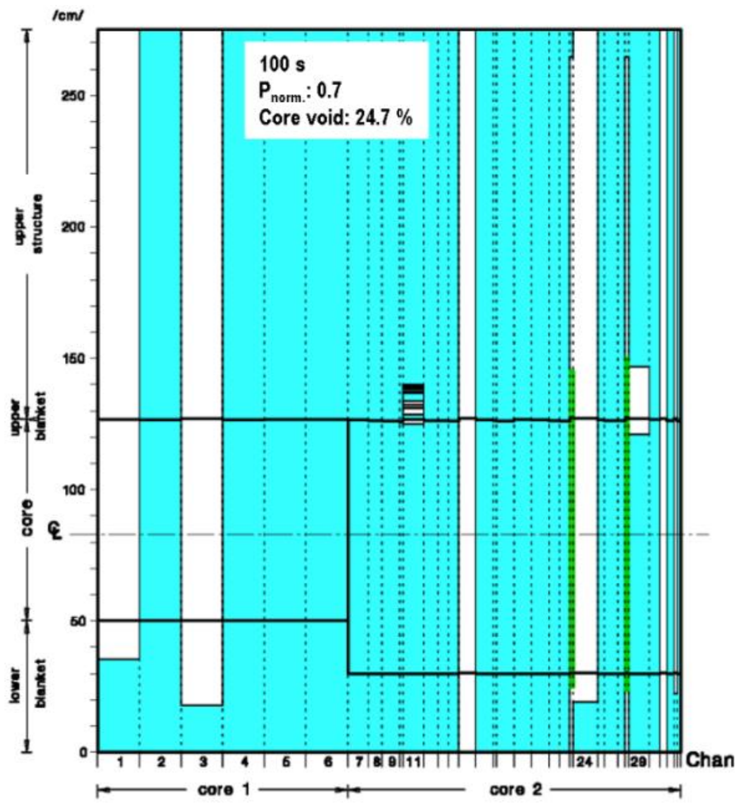


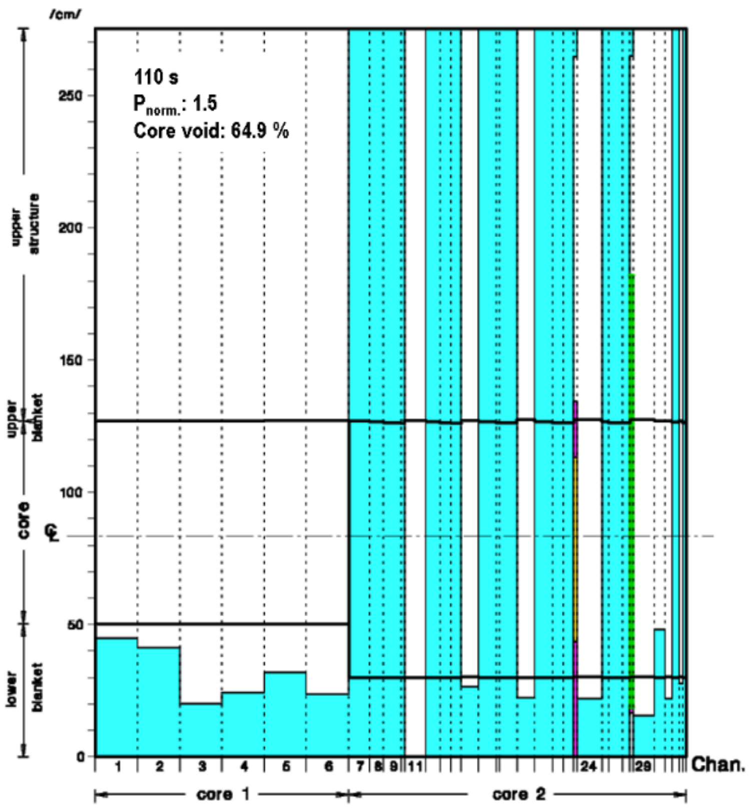


Fuel pin break-up failure mechanism: clad integrity compromised due to the high clad temperature and fuel pellet heat-up exceeds the melting limit and built-up cavity pressures.

ULOF transient period 90-100 s







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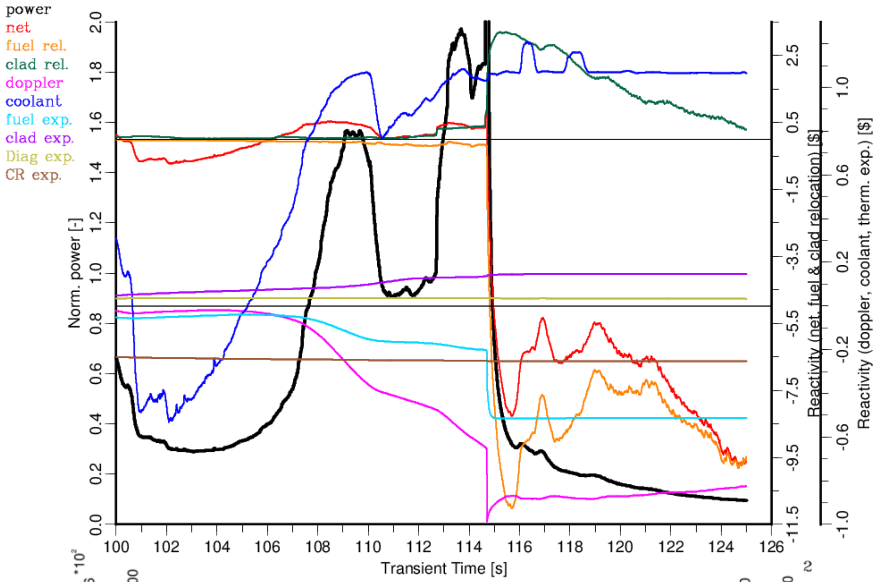
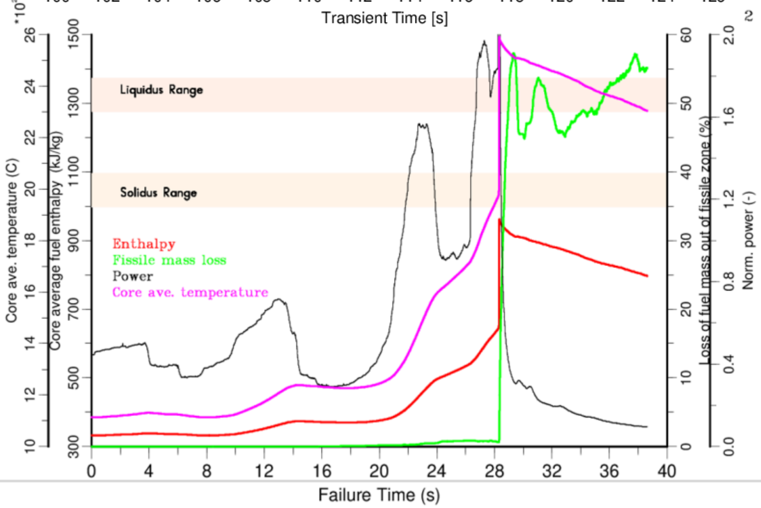
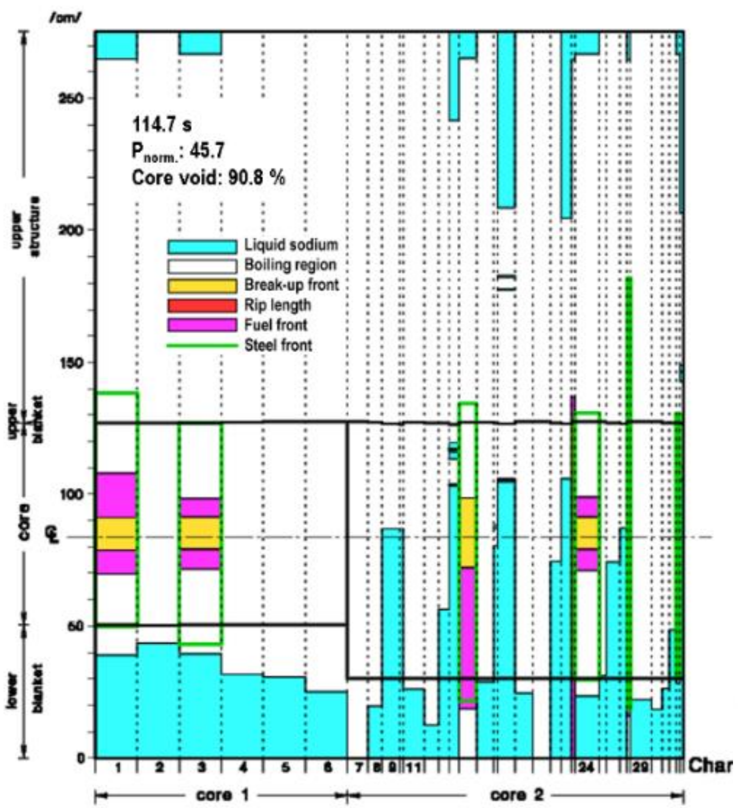
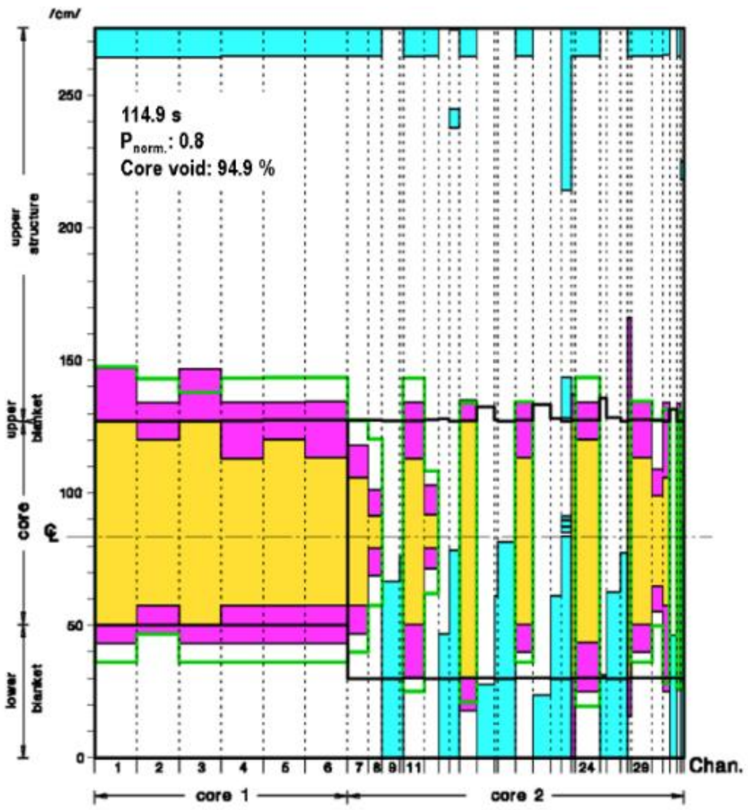


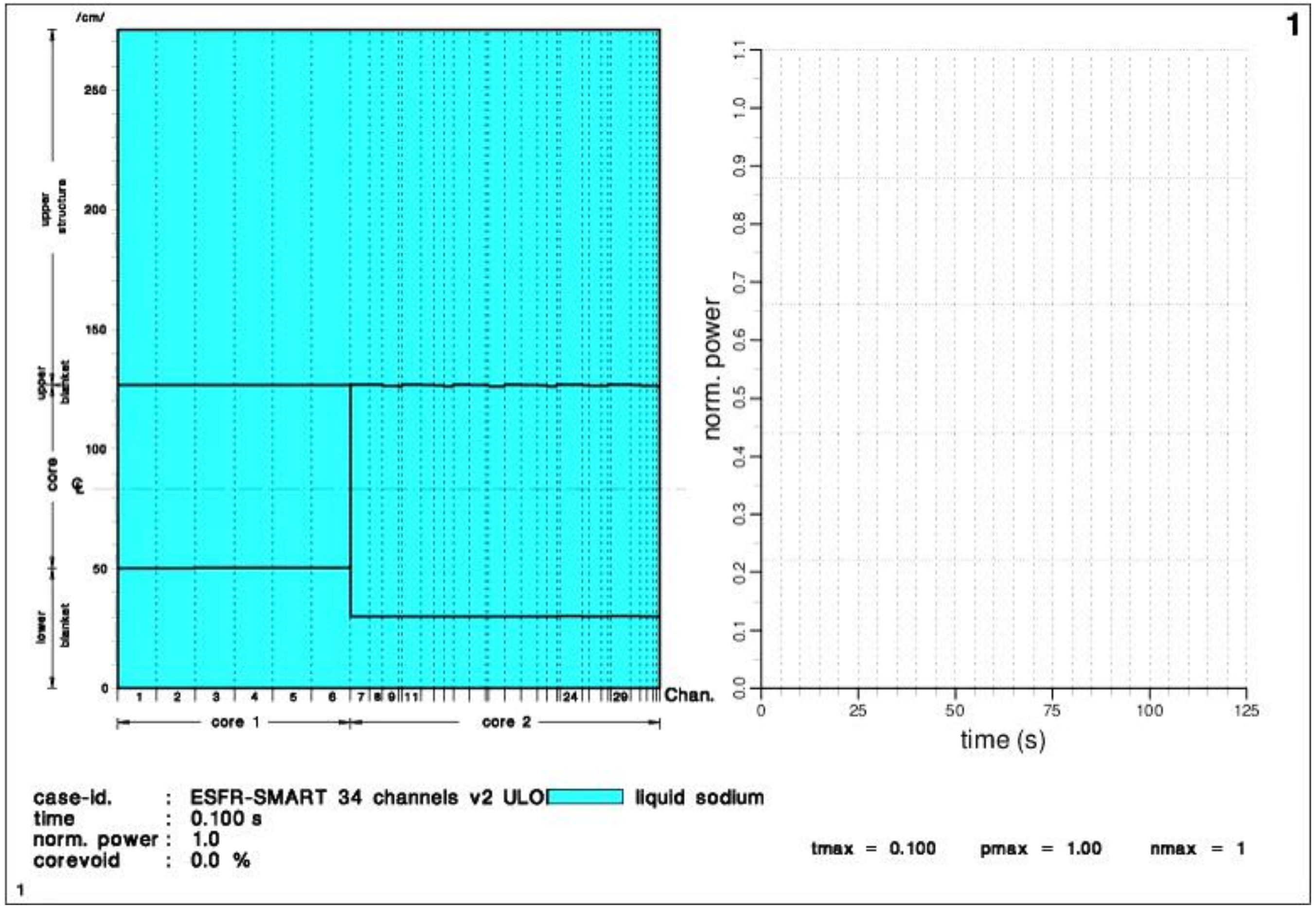


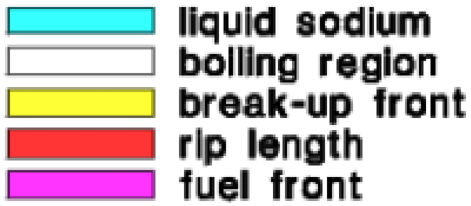




No hexcan damage: transient does not progress further and following accidental sequences (i.e. recriticality) are no longer expected.

SAS-SFR results for ESFR-SMART ULOF





Video

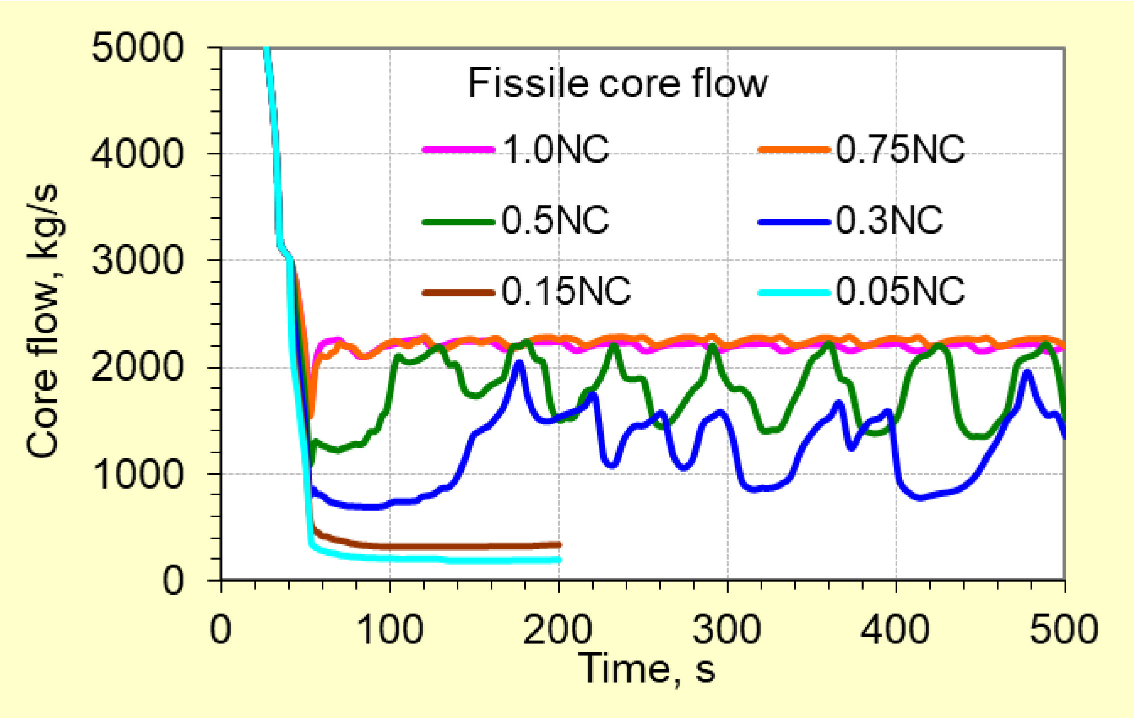
504 SAs with 271 pins per SA

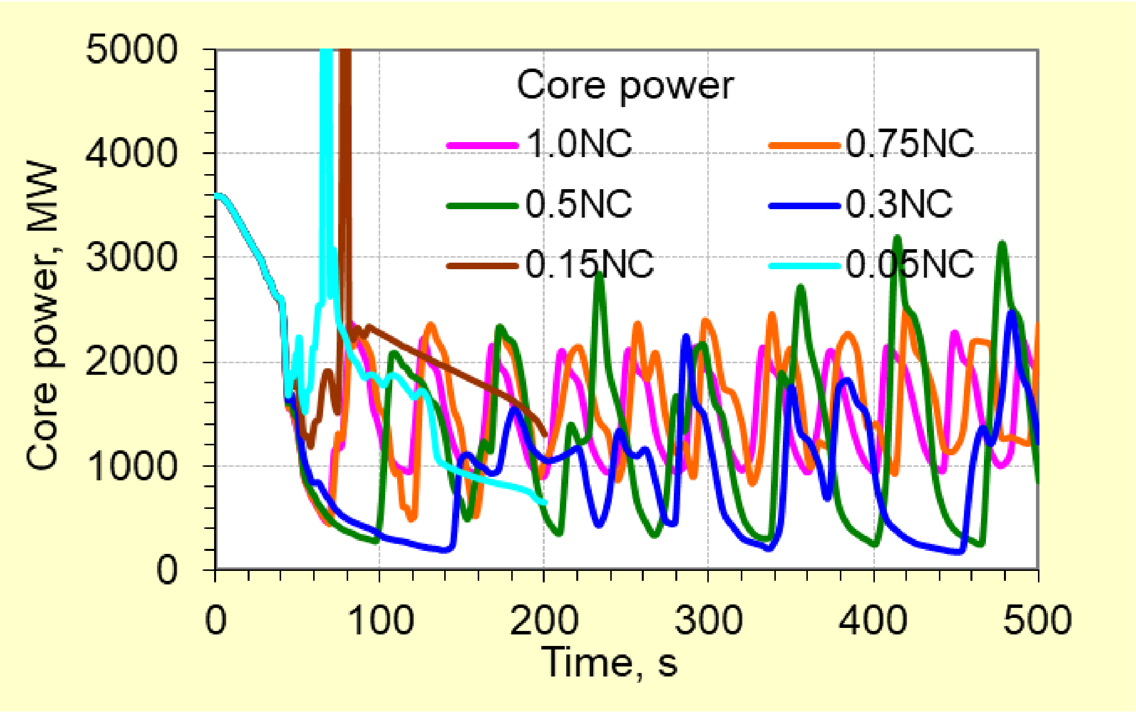
Computational running time

- 36 representative pins (6 ch. inner core, 30 ch. outer core)
- Fuel pin irradiation:
  - Real irradiation time: 1800 d
  - Computing time: 38 min. total → ~1 min. per SA
- ULOF transient:
  - Real transient time: 125 s
  - Computing time: ~17 h total → 0.5 h per SA

SIM-SFR results for ESFR-SMART ULOF

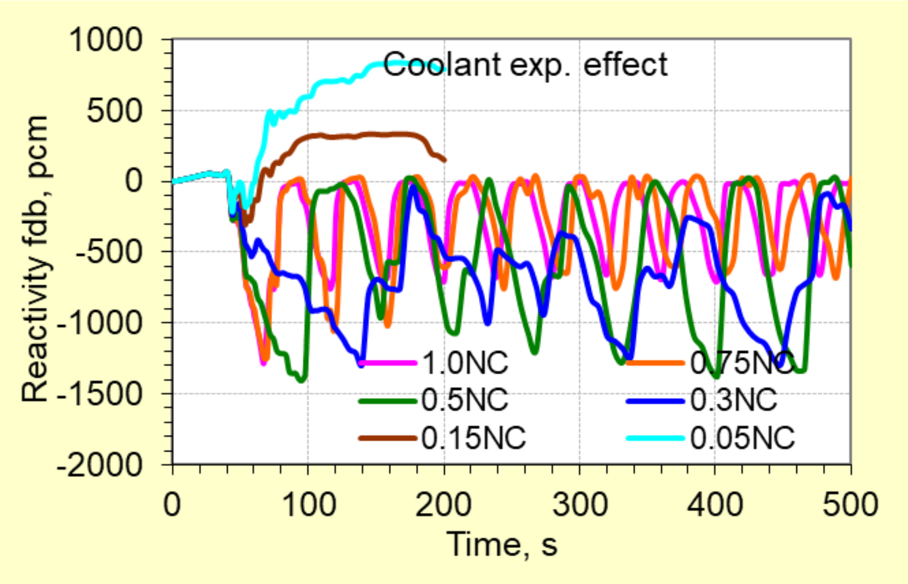
- During ULOF sodium flowrate decreases down to natural circulation flowrate and even below depending on sodium voiding.
- Boiling onset sequence (outlet fissile region): i) PP* OC, ii) Av.P** OC, iii) PP IC and iv) Av.P IC.
- Flow blockage due to boiling not known precisely: sensitivity study to investigate the natural circulation flow reduction.

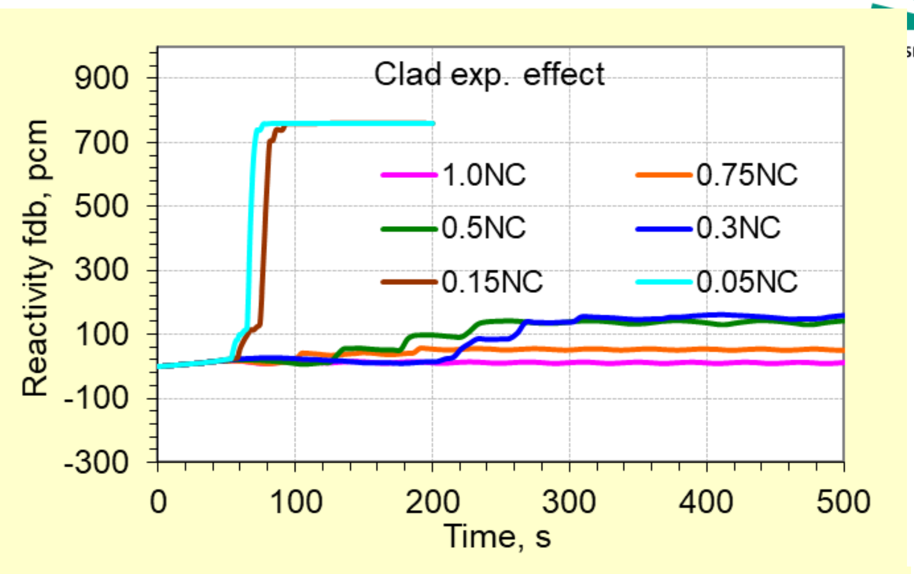


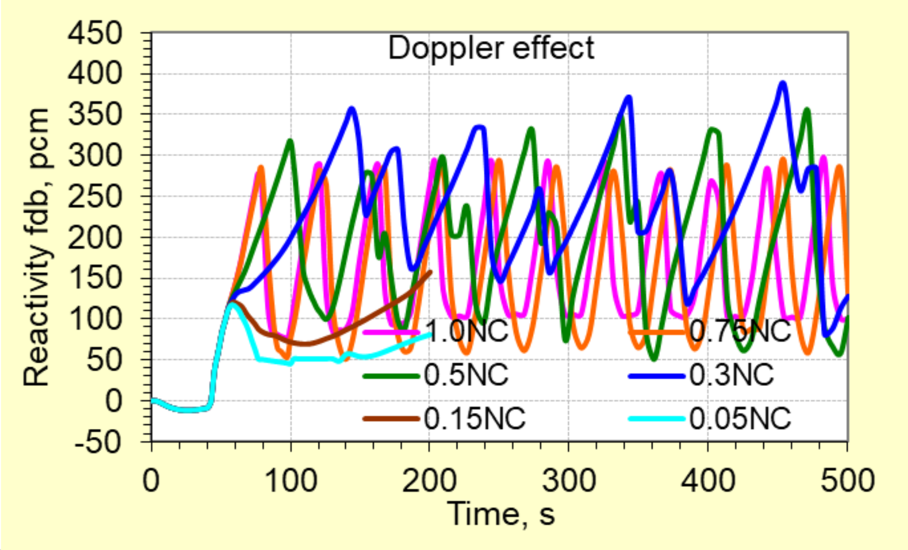


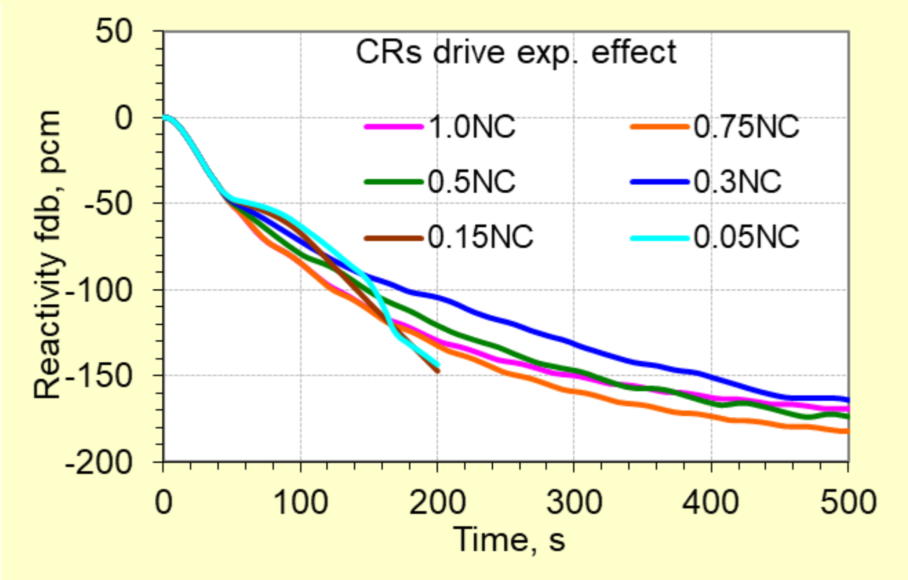
* Peak Power, ** Average Power, IC: Inner Core, OC: Outer Core

SIM-SFR results for ESFR-SMART ULOF









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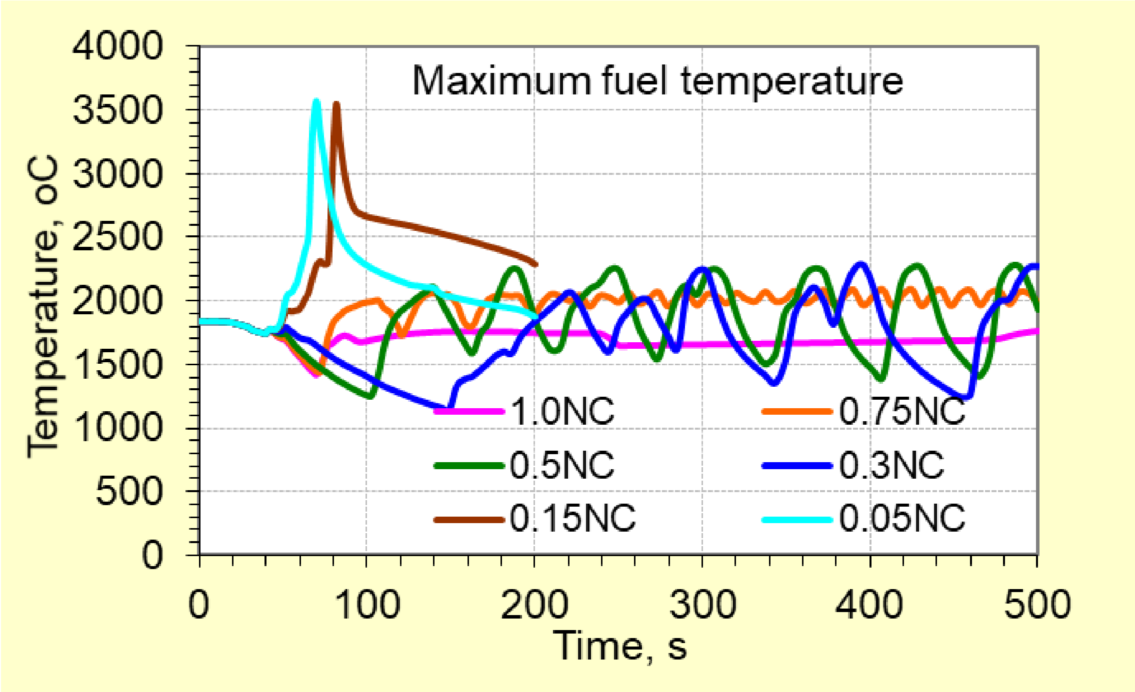

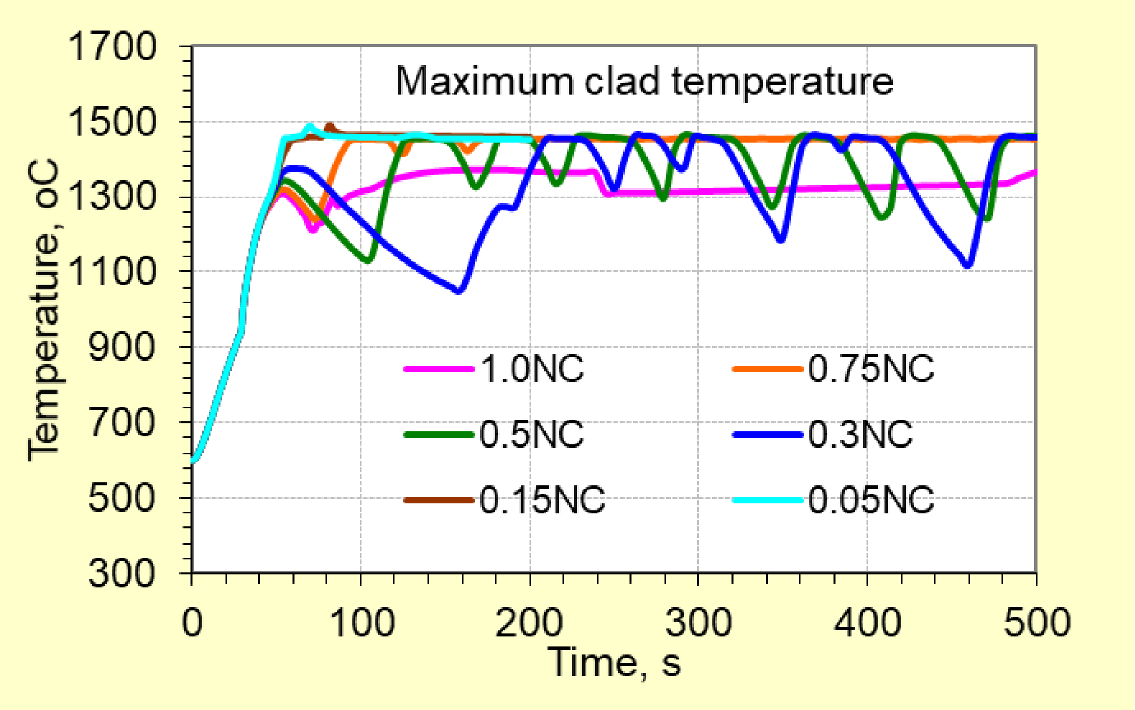

The 15% and 5% flow choking cases basically replicate the SAS-SFR ESFR ULOF results.

CONCLUSIONS

- Assessment of SFR performance + verification & validation of computational tools
- Measures considered to reduce the void reactivity effect in large SFR:
  - Sodium and boron layers (CP-ESFR Optimized core)
  - Central fertile layer in the inner core region (ESNII+ core)
  - Reducing inner core fissile fuel region (ESFR-SMART core).
  - Optimizations not sufficient to avoid a power excursions, though increase grace time, not melting/rupture of the SA hexcan.
- Future R&D:
  - Sodium two-phase flow: large scale code validation comparisons based on experimental data sets (KNS-37 test)
  - New two-phase flow experimental tests reflecting the current trends in core designs.
  - Large scale clad relocation prevention: core and SA-design measures or min. flow rate (active/passive means, pony motor)
  - Assessment of SMRs based on SFR technology, where high benefits are expected in terms of safety and flexibility.
  - New code strategies to find the right compromise between:
    1. computing capabilities (new programming languages, parallelization, etc.)
    2. phenomena description (neutronics, thermal-hydraulics, pin thermal-mechanics, corium relocation, etc.)
    3. details of reactor description (pin-by pin level, core level or up to whole plant level).
    - Advantages for the safety analysis of advanced systems (Machine Learning, Digital Twins) compared to current Fortran-based codes
    - Attractive research to future nuclear engineers/scientist → costly person-intense requiring support of public and private stakeholders.

Acknowledgement

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  - CP-ESFR project: 7th Framework Programme FP7-232658
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  - ESFR-SMART project: H2020 program 2014-2018 grant agreement 754501