Karlsruhe Institute of Technology

ESFR-SMART
sodium fast reactor safety

WP:	**WP3.1 “Dissemination, education and Training”**
Task:	3-1-3 Workshops and Summer School
Lecture : Speaker:	***UTOP sequences descriptions*** *Sara Perez-Martin*
Affiliation:	*Karlsruhe Institute of Technology*
Event:	Workshop N°7 Sodium-Cooled Fast Reactor Severe Accidents
When:	2022 April 5th-8th
Where:	Pertuis (France)

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 754501.

Power vs. Flow

- Power
  - Active devices: control rod activation
  - Passive forces: reactivity feedbacks
    - Doppler, diagrid expansion, CRs ✓
    - Sodium boiling in core ✗
- Failure of active devices: Unprotected Transients
  - Unprotected Power Ramps
  - Unprotected Transient Over Power

- Flow
  - Active devices: mechanical pumps, pony motors, MHD pumps
  - Passive forces: natural circulation ✓
- Failure of active devices: Unprotected Transients
  - Unprotected Loss Of Flow
  - Unprotected Loss Of Heat Sink

Importance of the time scale

- Power generation and deposition:

  - Long time scale:
    - steady-state manner (days, months): power operation irradiation where coolant flow is adapted to power

  - Middle time scale:
    - Ramps (minutes): coolant flow can barely adapt to the power

  - Short time scale:
    - Ramps (seconds), short pulses (ms): coolant flow cannot follow at all the power

UTOP

- The causes can be
  - Inadvertent control rod withdrawal: malfunctioning of the CR holding system
  - Bubble passage through the core: bubbles flowing in the primary circuit (cavitation in the pumps)

Causes	Prevention	Detection	Consequences
Inadvertent control rod withdrawal	Active systems, frequent maintenance	…	Power ramps (slow/rapid)
Bubble passage through the core	…	Core monitoring (flowmeters, neutron detection)	Fast power peaks

Consequences of UTOP

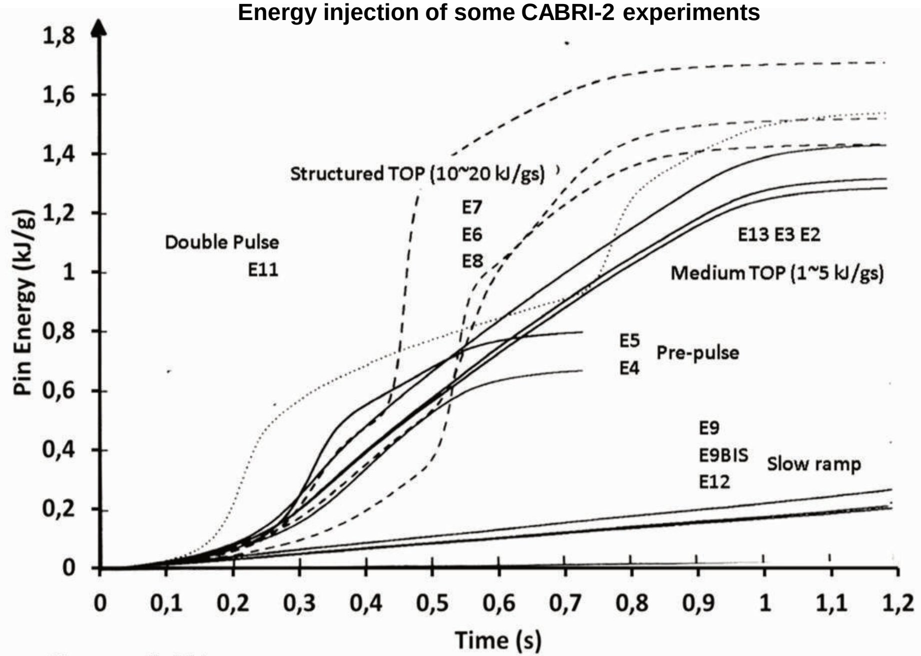
- It depends on the type of UTOP:
  - Slow or fast power ramps
  - Fast power peaks

- The phenomena occurring under TOP conditions were studied in the CABRI programs where the lessons learnt are:
  - Physical phenomena taking place
  - The role of **pin design** (smeared density, cladding material)
  - The role of **pin state** (burn-up level, FG content)

- All these aspects allow us to prevent and mitigate the consequences of UTOP.
- Prevention by fuel pin design (passive system)

Experimental Power Transients

- CABRI power transients were characterized by the thermal energy release rate:
  - Slow power transients (1 to 3 % PN/s)
  - Energetically benign transients (Δt_h = 200 – 500 ms)
  - Structured transients (Δt_h = 20 – 50 ms)
  - Fast and energetic transients (Δt_h = 20 – 50 ms)


Energy injection of some CABRI-2 experiments

- Cooling
  - Nominal cooling conditions
  - Deteriorated cooling conditions (boiling onset and beyond)
  - Highly deteriorated cooling conditions (up to and beyond clad relocation)

- The **fuel enthalpy at failure** characterizes not only the fuel state but also its mobility.
- It provides the initial conditions for the subsequent fuel relocation.

The role of fuel enthalpy

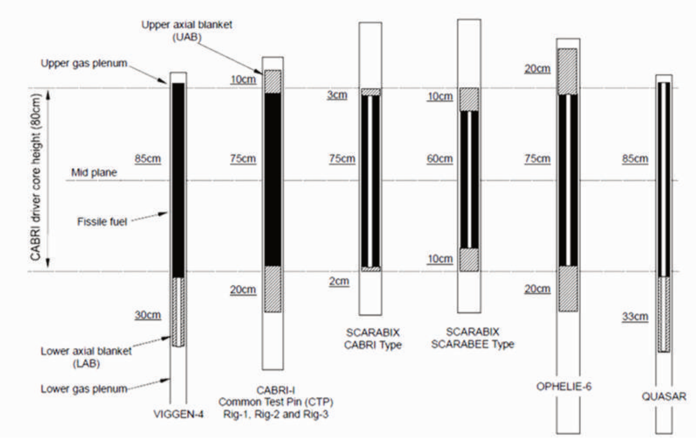
- High fuel enthalpy at failure (~1.3-1.6 kJ/g)
  - 70-100 % of the fuel at the peak power position is molten.
  - The failure due to cavity pressurization
  - Liquid fuel is superheated and highly mobile

- Medium fuel enthalpy at failure (~1.1 -1.3 kJ/g)
  - About 30 - 70 % of the fuel at the peak power position is molten.
  - When clad temperatures are <~1100 - 1200°C, the failure is due to superposition of pellet-clad mechanical interaction (PCMI) and cavity pressurization.

- Small fuel enthalpies at failure (~ 0.9 -1.1 kJ/g)
  - Less than ~30 % of the fuel at the peak power position is molten.
  - The failure is due to solid fuel-clad mechanical interaction.

Slow power ramps

This type of power tests were studied in CABRI programs using different irradiated industrial pins designs.



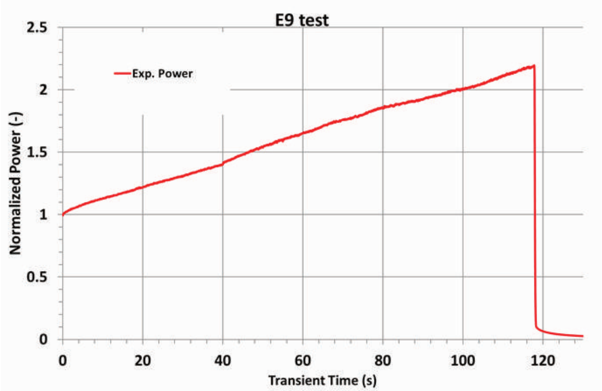
	Rig-1/2/3	Ophelie-6	Scarabix	Viggen-4	Quasar
Eff. upper FG plenum length (m)	0.094	0.183	0.357	0.075	0.065
Upper axial blanket (m)	0.10	0.2	0.03	-	-
Pellets	solid	solid	solid	-	-
Fissile pellet stack height (m)	0.750	0.750	0.750	0.850	0.835
pellets	solid	hollow	hollow	solid	hollow
chamfers	no	no	yes	no	no
smear density(%)	**86.98**	**82.94**	**81.3**	**88.1**	**79.77**
peak burn-up (%)	**1**	**4.8**	**6.4**	**11.8**	**12.1**
Pellet	solid	solid	solid	hollow	hollow
Lower ax. Blanket (m)	0.2	0.2	0.02	0.30	0.33
Lower FG plenum length (m)	0.246	0.682	0.213	0.497	0.492
as fabr. pellet porosity (%)	7.5/7.0	4.5	4.0	4.5	4.5
as fabr. O/M ratio	1.98	1.974	1.982	1.969	1.962
Clad material	316 - CW	316 - CW	15–15 Ti	15–15 Ti	15–15 Ti

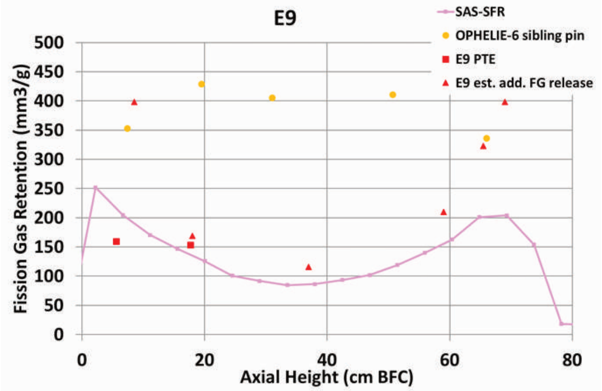
- Major role of fission gases during the transient:
  - At high temperature level significant **fission gas-related phenomena** such as grain boundary separation, fuel swelling, and gas release to free volumes observed → having an big impact on fuel thermal state and on molten **fuel cavity pressurization** → an important parameter for both fuel pin failure and in-pin fuel relocation.
  - The power level leading to these gas-related phenomena depends on the **gas retention** (radial profile) being a function of the **linear power level during burnup.**
- High margin-to-failure considering their EOL condition especially for low-smear density fuel.

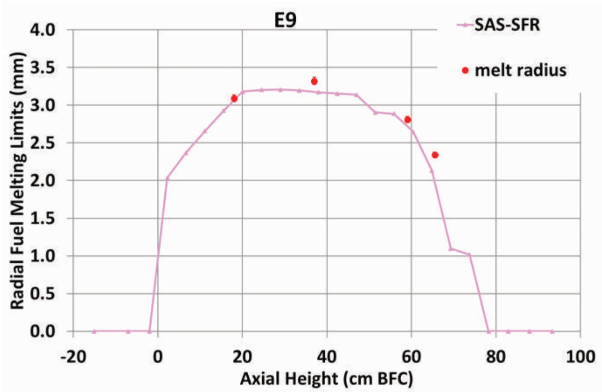
Fuel pin behavior under the slow power ramp transients in the CABRI-2 experiments. J. Charpenel, F. Lemoine et al. Nuclear Technology Vol. 130 252-271 2000

Slow power ramps

- In hollow pellets with medium burnup and low smear density, large fuel swelling leads to fuel thermal conductivity degradation affecting the melting power. But no clad deformation and consequently **no failure** were observed (E9 and E9bis) → high margin to failure due to low smear density and the reduction of the cavity pressure (in-pin fuel relocation)



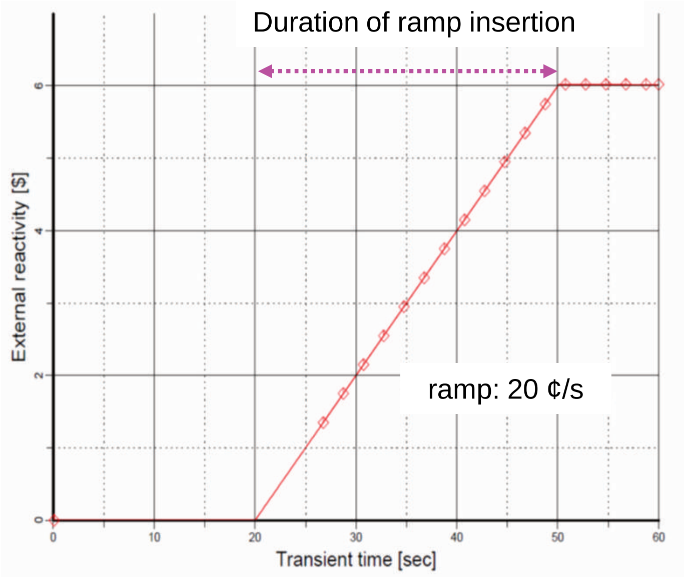




- With the solid pellet design (Viggen4 pins) and high burnup level of 12 at.%, the solid fuel swelling due to fission gases retained in the outer fuel zone, with high grain fragmentation, resulted in **clad deformation and failure** .The pin failure led to fuel ejection, with a mass molten fuel fraction of ~10%, which initiated FCI

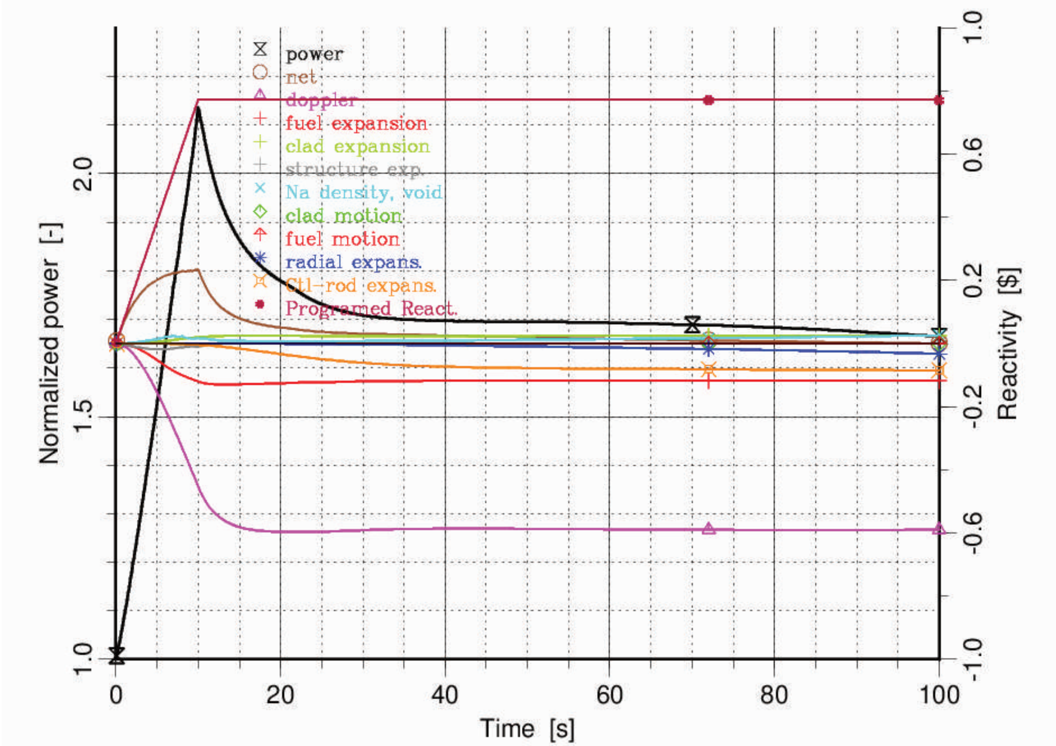
UTOP in Reactors

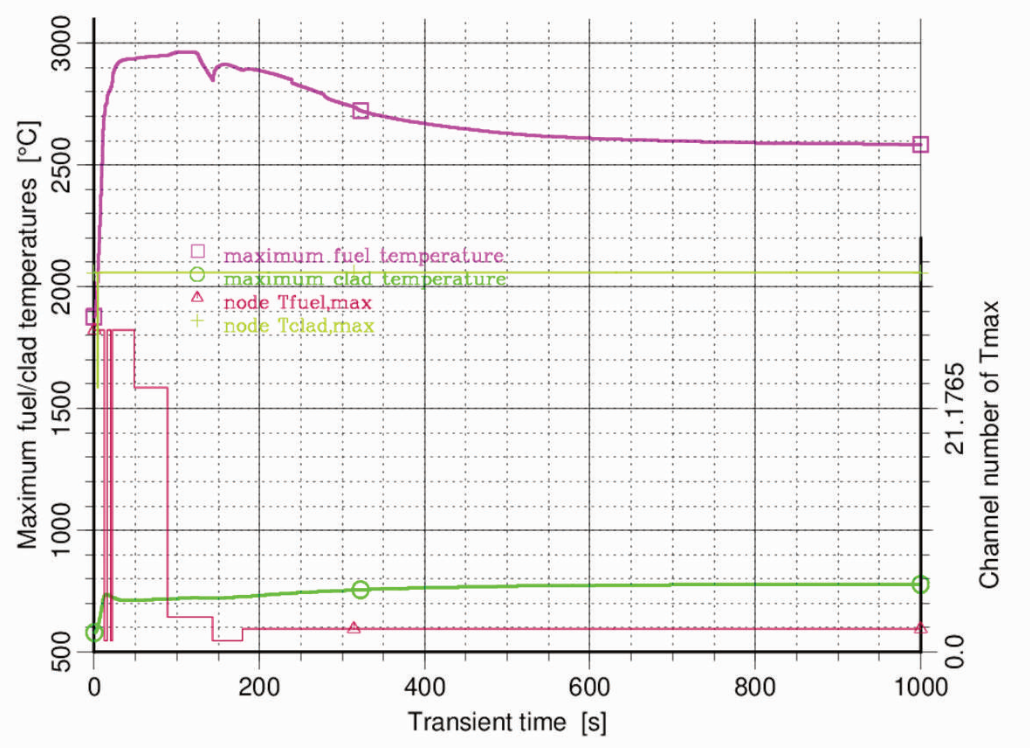
- Boundary conditions:
  - The insertion of reactivity simulated according to $\rho_{ext}(t) = r_{\$/s}(t - t_{onset})$
  - Pump head of the primary pumps is kept unchanged.
  - Heat sink: heat rejection capabilities maintained unchanged
- In-pin pre-failure fuel relocation is effective because the fuel central hole extends up/down to FG plena
- The in-pin fuel relocation occurs even under small pressure differences between melt cavity and FG plena
- Reactivity insertion vs. Doppler effect
- Fuel thermal state and available volume to host FG release
- Effects on clad plastic straining (material type, load rate and dpa dependent)
- Mechanical clad failure
- At failure, sodium in the channel is liquid sodium → FCI high pressures



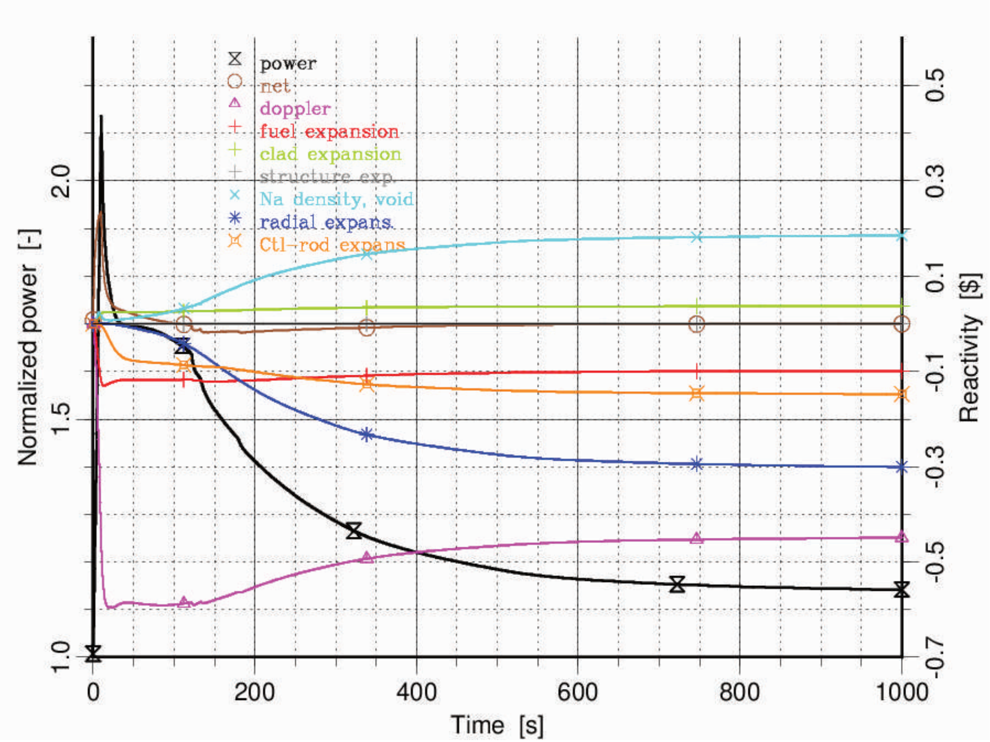
UTOP in ESFR-SMART reactor

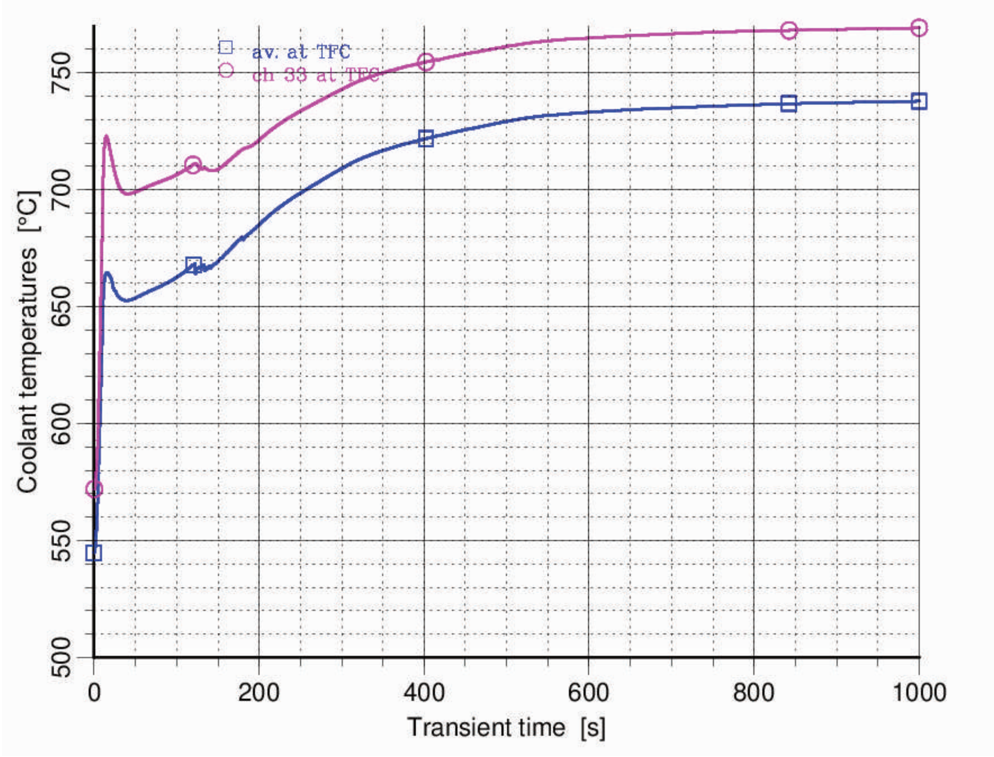
- Insertion of 280 pcm positive reactivity (<1 $) by moving the CSD bank initially inserted by 2 steps as a whole out of the core at constant speed in 10 s, assuming CSD bank withdrawal speed of 1 cm/s, starting at time t = 0 s.
- All pumps in normal operation (primary, secondary and tertiary cooling circuits). No reactor trip.



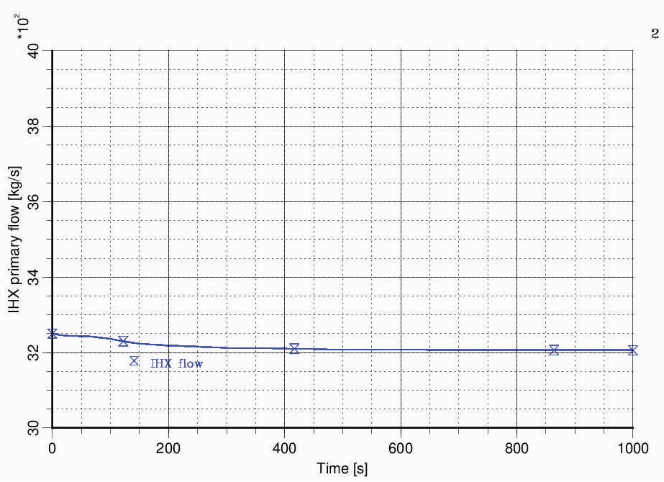


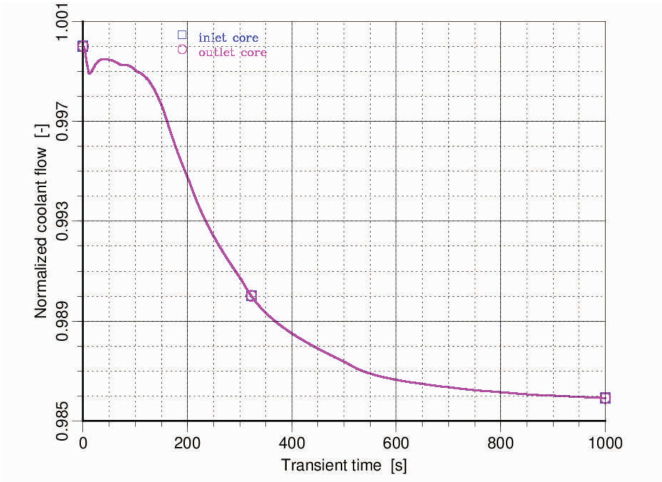
UTOP in ESFR-SMART reactor

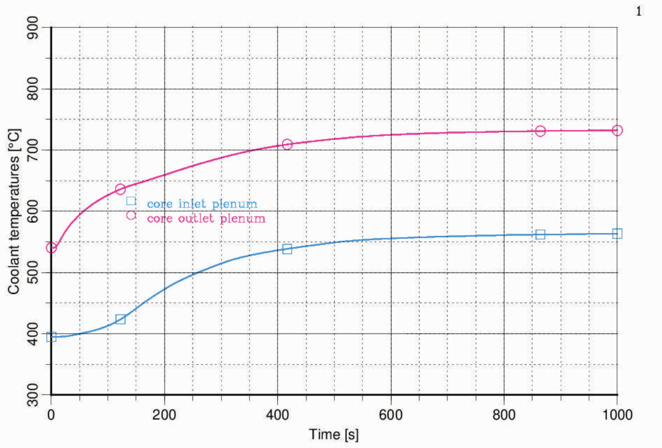


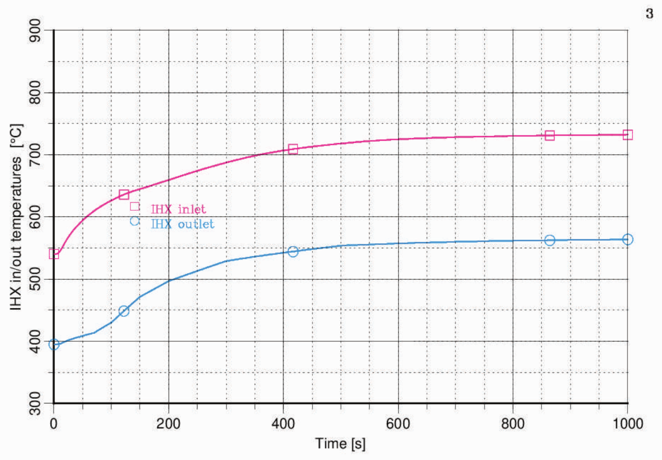


UTOP in ESFR-SMART reactor





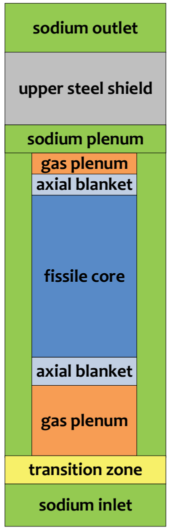


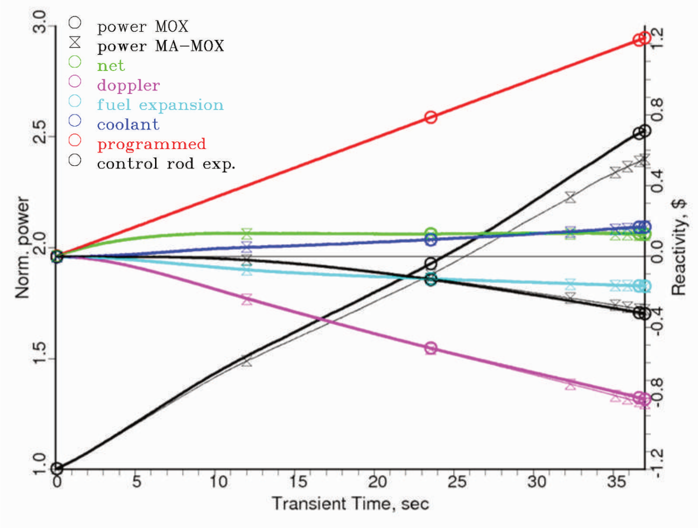


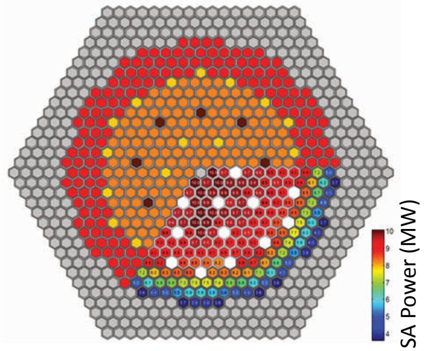
UTOP in CP-ESFR reactor

- Reference Oxide core of the CP-ESFR project
- Two cases were calculated:
  - MOX fuel core: MOX case
  - MOX fuel with MA: MA-MOX case
- Nominal operating conditions at EOEC and unprotected runaway of grouped control rods.
- Control rods are initially inserted 25 cm into the core and then they are withdrawn so that a reactivity of 33 c/s is inserted during 45 s leading to a total insertion of 1.5 $.

Total reactor power (MWth)	3600
Core inlet/outlet temperature (ºC)	395 / 545
Core fuel	(U,Pu)O_2 (~15% Pu) (U,Pu,MA)O_2 (5% MA)
Height of the core (m)	1.00
Number of pins per SA	271
Number of fuel SA	453

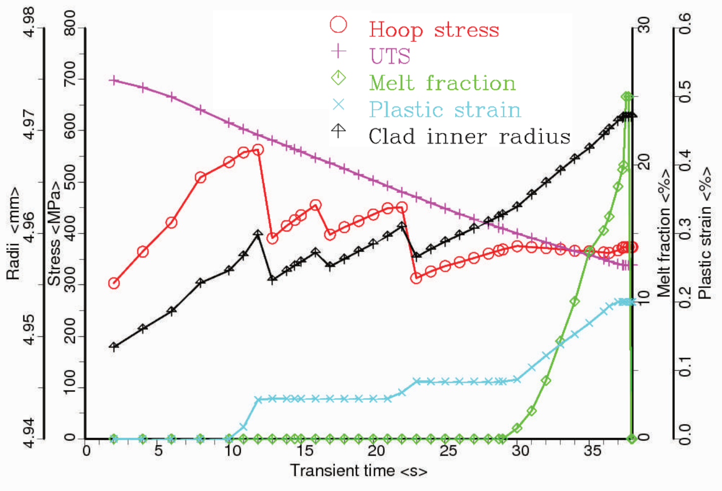




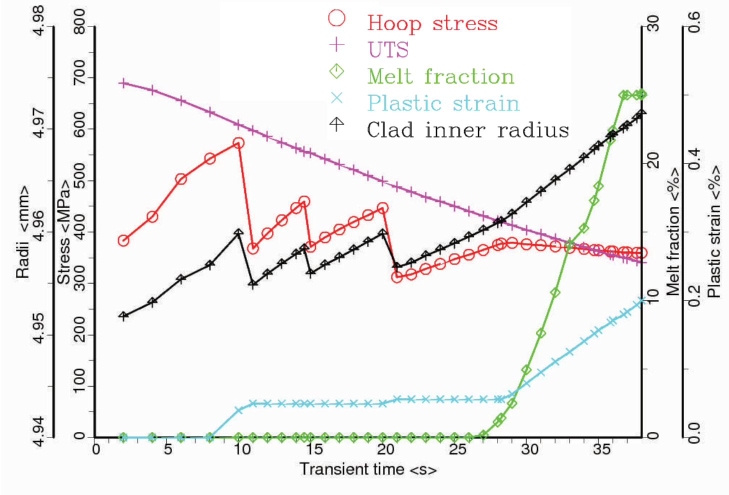


UTOP in CP-ESFR reactor

- Cladding is exposed to inner pressure caused by FGR and to additional stress from FCMI.
- Pin failure is achieved when the clad hoop stress (red line) reaches the ultimate tensile stress (pink line) and the clad strain meets the failure strain.
- Fuel melting fraction causes the last increase of load to the clad.
- The failure phenomenon is the mechanical clad failure due to the molten fuel cavity pressure.



MOX case

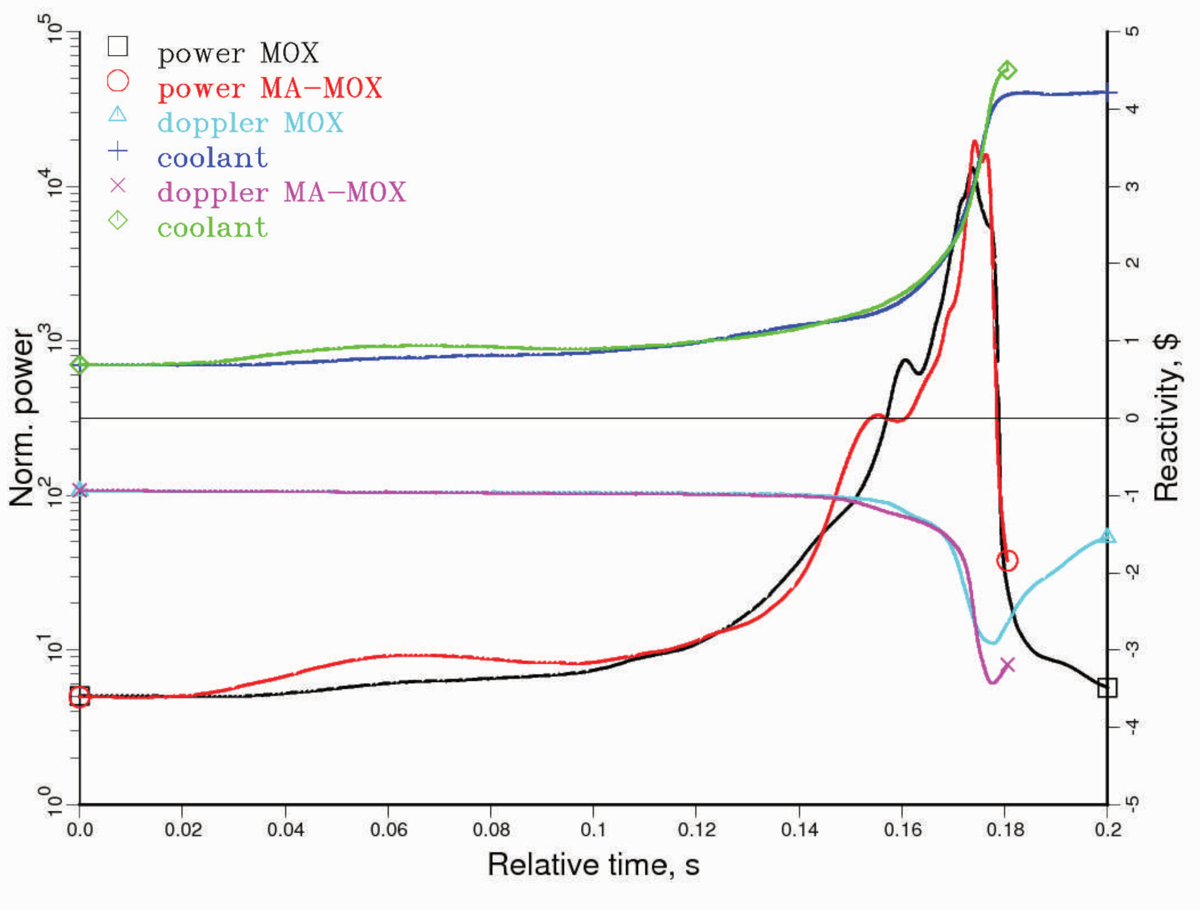


MA-MOX case

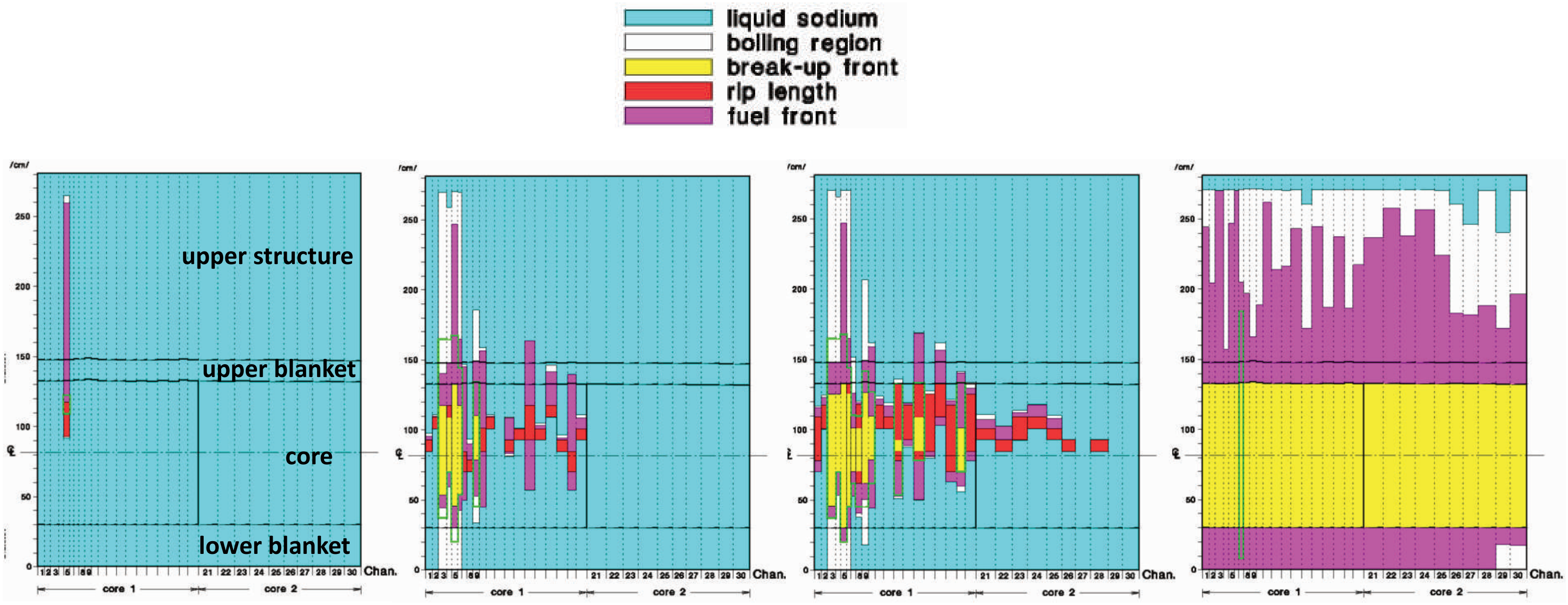
UTOP in CP-ESFR reactor

- The reactivity feedback due to sodium heat up is the same and the Doppler effect is 37 c larger for MA-MOX than for MOX fueled core due to the higher fuel temperature.

	First Pin Failure		Power Peak	
	MOX case	MA-MOX case	MOX case	MA-MOX case
Transient time (s)	37.38	37.99	40.38	39.37
Failure time (s)	0	0	2.99	1.38
Net reactivity ($)	0.13	0.12	1.00	1.00
Norm. power (-)	2.5	2.4	13159	19608



UTOP in CP-ESFR reactor



+ 0.4 s

+ 2.98 s

+ 2.99 s

+ 3.03 s

Conclusions

- Understanding the physical phenomena taking place during the initial phases of the UTOP
- Fuel pin design can be effective to prevent pin failure under UTOP (smeared density)
- Fuel enthalpy at the time of failure has a big role on the progression of the UTOP
- For the middle term, similarities are found between ULOF, UTOP and USAF