OPTIMIZATION OF SAFETY PARAMETERS AND ACCIDENT MITIGATION MEASURES FOR INNOVATIVE FAST REACTOR CONCEPTS

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Safety analysis

Among the GEN-IV systems, the sodium cooled fast reactors (SFRs) have collected the largest experience in Europe. A key issue for the success of SFRs is the promise of a higher and improved safety level.

Traditionally the analysis of the evolution of severe Hypothetical Core Disruptive Accidents (HCDAs) is broken down into different phases. In the current paper, we mainly deal with the initiating phase and the transition phase of an accident as the unprotected loss of flow (ULOF accident).

The key phenomenon of the initiating phase is the start of boiling and its development.
Traditionally researches were oriented to the sodium void worth reduction in order to control the energetic potential of the accident.

The key phenomena of the transition phase are the progression of core melting and the occurrence of recriticalities by fuel compaction.
Controlled Material Relocation (CMR) measures have been studied in order to enable a sufficient and timely fuel discharge (beyond the natural removal path usually not sufficient to prevent recriticalities) that influence and 'brake' the recriticality path.

Safety analysis

Starting from the former experience obtained, several preventive and mitigative measures dealing with the two phases have been applied to an industrial size (3600 MWth) advanced SFR under developement in Europe within the FP7-EURATOM CP-ESFR project.

For the initiating phase, the adoption of a large Na plenum and of an absorber layer above the core, has been introduced in the ESFR model for reducing the Beginning of Life (BOL) positive void worth.

For the transition phase, the adoption of 19 empty pins (filled by He) per subassembly has been considered in order to improve the CMR and therefore to reduce recriticalities.

Computational tools adopted

Neutronic Analyses:

Neutronic analyses have been performed by means of deterministic ERANOS code systems, adopting JEFF3.1 data library.

The effective cross-sections have been calculated by means of the ECCO cell code assuming actual geometries and fine-group energy structure (1968 groups).

The neutron flux has been calculated using the ERANOS transport theory module TGV/VARIANT. The 1968 energy groups effective XS have been collapsed to 33 groups XS for the flux calculation.

Transient Analyses:

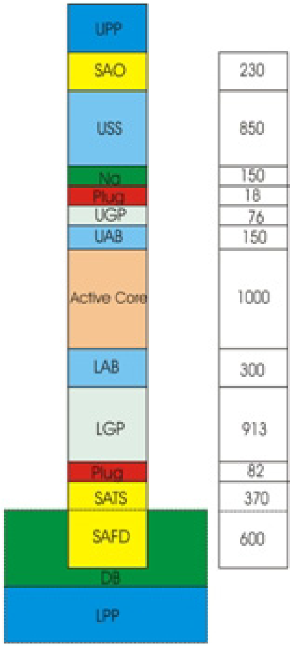
The transient analyses have been performed by the SIMMER-III multi-physics code systems.

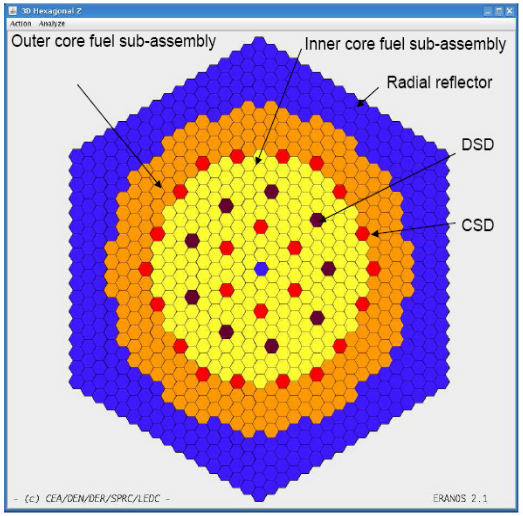
The SIMMER–III (2D) and SIMMER–IV (3D) multi-physics code systems are used as reference codes for severe accident simulation in SFRs.

ESFR REFERENCE model

The reference ESFR oxide core proposed within the CP-ESFR project is composed by 453 MOX fuel SAs subdivided in two zones (Pu content: 14.5%wt. in the inner core and 16.9%wt in the outer core) in order to reach at EOL a flat radial power profile.

The core active height is 100 cm and the equivalent core diameter is ca. 5 m.
Just above the core are placed the upper axial blanket (steel), the upper gas plenum, plugs, the Na plenum of 15 cm height and the upper steel structure. Below are placed the lower axial blanket (steel), the lower gas plenum, plugs and SAs feets.





ESFR-OXIDE REFERENCE CORE	
Reactor Power (MWth)	**3600**
Core Inlet Temperature (°C)	**395**
Core Outlet Temperature (°C)	**545**
Ave. Core Structure Temperature (°C)	**470**
Ave. Fuel Temperature (°C)	**1227**
Inner Fuel S/As	**225**
Outer Fuel S/As	**228**
Control and Shutdown Device (CSD)	**24**
Diverse Shutdown Device (DSD)	**9**
Targeted Fuel residence time (efpd)	**2050**

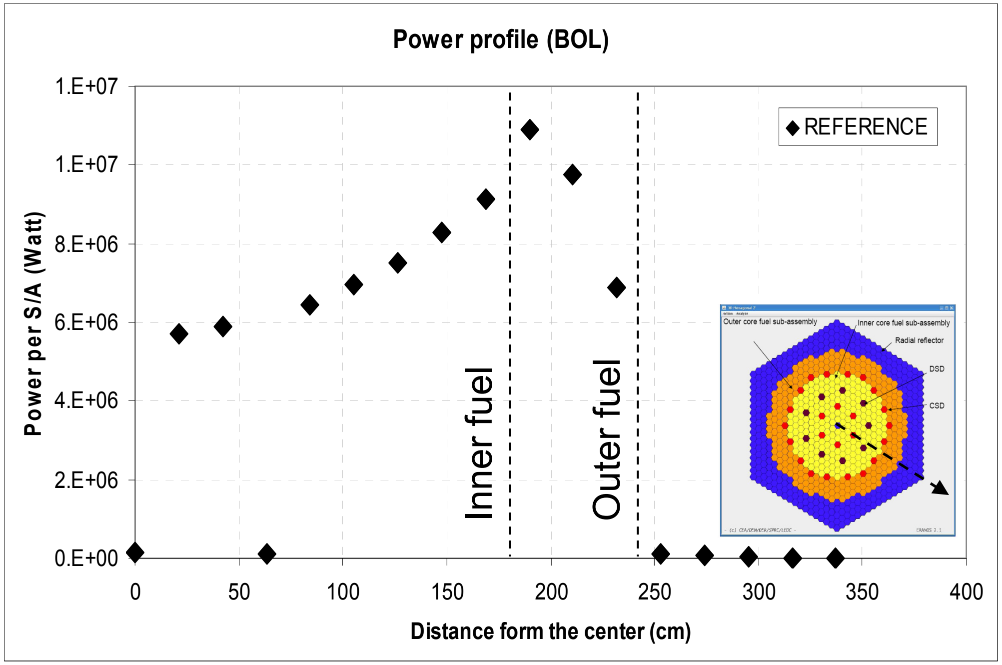
ESFR REFERENCE model

The **ESFR REFERENCE** core shows positive sodium void reactivity effect (SVRE) at BOL. The extended SVRE (when core and above structures are voided after sodium boiling onset) is positive too.

	ESFR REF
VOID EFFECT AT BOL	**pcm**
SVRE	**1402**
SVRE (Inner Fuel)	**856**
SVRE (Outer Fuel)	**612**
Extended SVRE	**1014**
Keff (BOL)	**1.00974**

DOPPLER CONSTANT	**Kd**
Inner Fuel	**-531**
Outer Fuel	**-503**
Inner + Outer Fuel	**-1062**

Radial power profile at BOL



Optimizations oriented to initiating phase of the accident

According to the literature, the major ways for reducing the positive Na-void worth are:

1) Increasing of the neutron leakage;

2) Softening the neutron spectrum.

Several measures have been tested within the CP-ESFR project. The most effective are here studied:

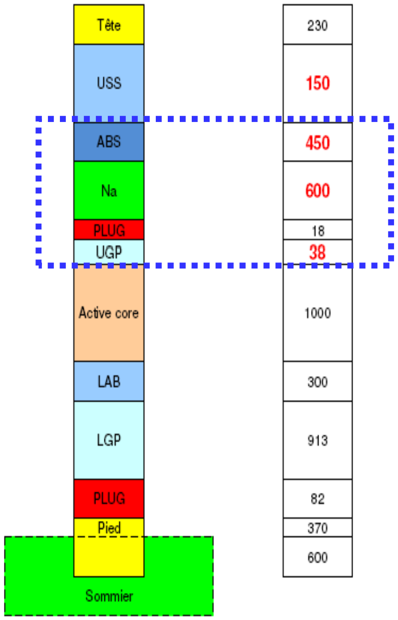
Studied measures for reducing the BOL void worth		Impact on		
Increasing neutron leakages	Softening the neutron spectrum	Extended SVRE	SVRE	SIMMER studies concerning Initiating and Transition phases
		pcm		
Na plenum + Absorber layer		~(- 900)		Analyzed
Low Fertile Blanket			~(-100)	Analyzed
Internal fertile layer			~(-200)	Not Analyzed
Changing H/D ratio			~(-200)	Not Analyzed
	Empty pins per SA		~(-180)	Analyzed
	Pins of diluents per SA		~(-180)	Not Analyzed

Optimizations oriented to initiating phase of the accident

In order to achieve a strong SVRE reduction, a very efficient way is to modify the region above the core adopting a higher Na plenum (60 cm).

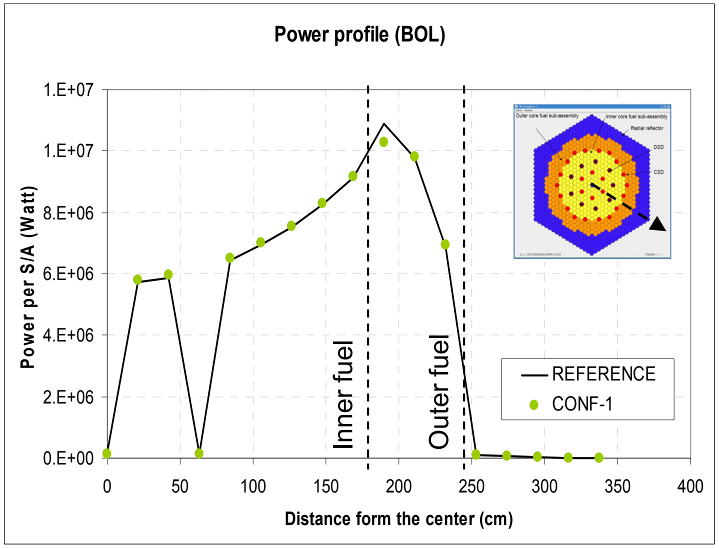
To increase the leakage term, Na plenum is shifted close to the core removing the UAB and halving the UGP height (this shifting gives a contribution of about 100 pcm).

An absorber layer (natural boron carbide) is placed above Na plenum for further reducing the reflection down to the core.



CONF-1

	REF	CONF-1
	pcm	
SVRE	1402	1380
SVRE (Inner Fuel)	856	844
SVRE (Outer Fuel)	612	598
Extended SVRE	1014	0
Keff	1.00974	1.00974

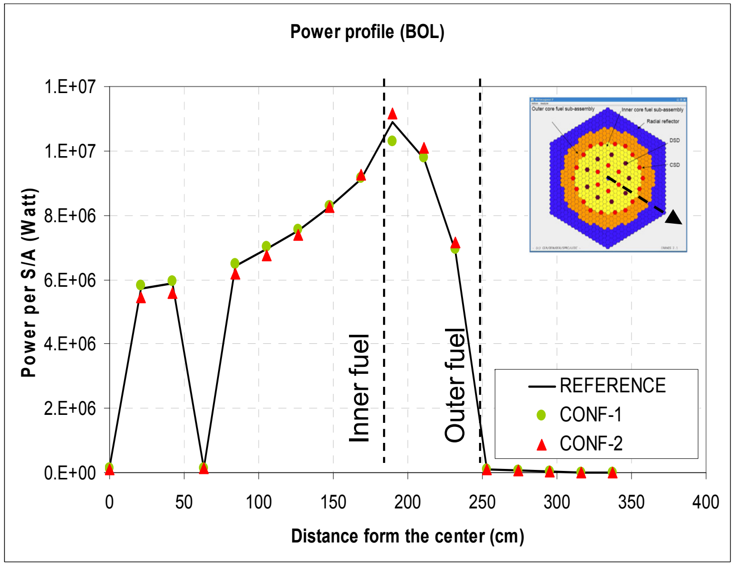


The enrichment has been increased homogenously (+0.36%wt. respect REF) in order to maintain the same BOL criticality level as REF

Optimizations oriented to initiating phase of the accident

The addition of a lower fertile blanket (depleted U oxide) below the inner and outer fuel zones (CONF-2) helps on reducing the core SVRE of about 120 pcm and to obtain a negative extended SVRE (-243 pcm at BOL).

	REF	CONF-2
	pcm	
SVRE	**1402**	**1270**
SVRE (Inner Fuel)	**856**	**754**
SVRE (Outer Fuel)	**612**	**570**
Extended SVRE	**1014**	**-243**
Keff	**1.00974**	**1.00985**



CONF-2

The enrichment has been increased homogenously (+1.9%wt. respect REF) in order to maintain the same BOL criticality level as REF

Optimizations oriented to initiating phase of the accident

Concerning CONF-2:

1) A smaller height for the absorber layer can be considered. The adoption of 15 cm height instead of the 45 cm does not change the figures obtained.
2) Better effects on SVRE reduction should be achieved by using an absorber material (e.g. B4C) in the lower blanket. However, it implies to adopt an higher Pu content in order to maintain the same BOL criticality level than REF.

In order to further improve the model, the adoption of several diluents (e.g. B4C, BeO, ZrH2) as well as the adoption of 19 empty pins grouped ring-wise in the centre of the subassembly has been analyzed.

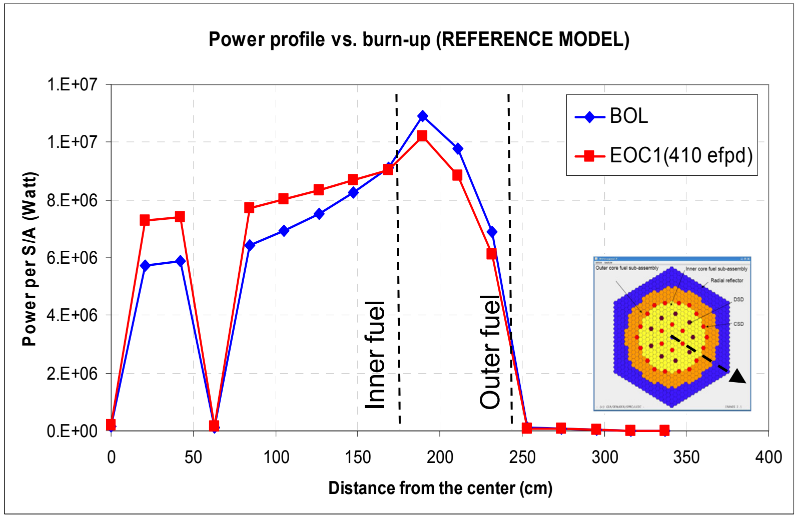
These measures, can also be useful for improving the CMR and then for mitigate the later accident phases.

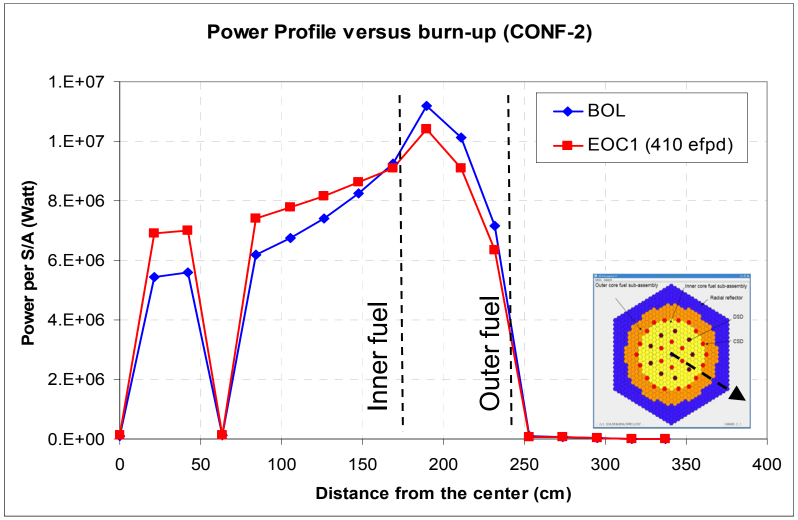
It has been evaluated that for diluents the average SVRE reduction is about 14pcm/pin.

ESFR optimized configuration

The extended SVRE for CONF-2 remain close to 0 pcm also after 410 efpd (1 cycle). The Doppler constant does not change drammatically.

	REF		CONF-2	
	BOL	EOC1	BOL	EOC1
	VOID EFFECT (pcm)			
SVRE	+1402	+1588	+1270	+1457
Extended SVRE	+1014	+1241	-243	+33
	K_D			
Inner + Outer Fuel	-1062	-907	-987	-852



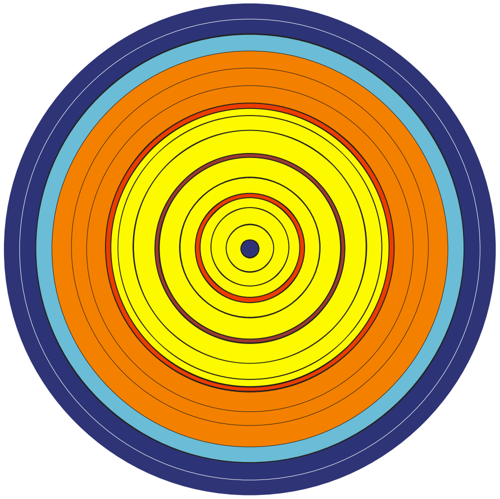


Initiating phase: SIMMER analysis

In order to confirm that the proposed core modifications influence the core behavior under transient conditions in the expected direction, analyses of an Unprotected Loss of Flow (ULOF) transient for the ESFR reference and for CONF-2 have been performed at KIT by means of the SIMMER-III code (2D calculations).

The SIMMER model

The oxide core has been transformed in a ring-wise core (8 rings represent the inner fuel and 3 the outer fuel)



For the axial model adopted in SIMMER

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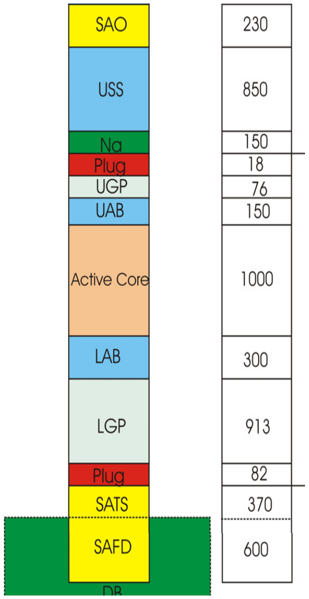
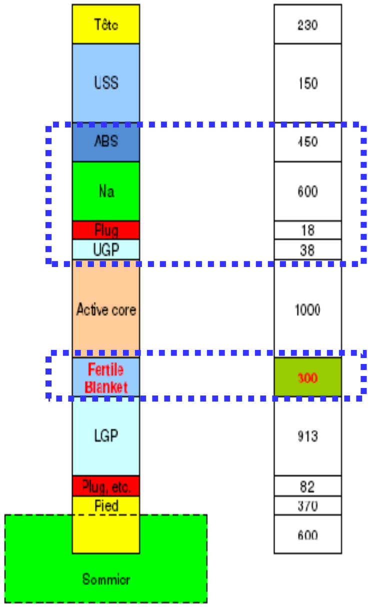


CONF-2



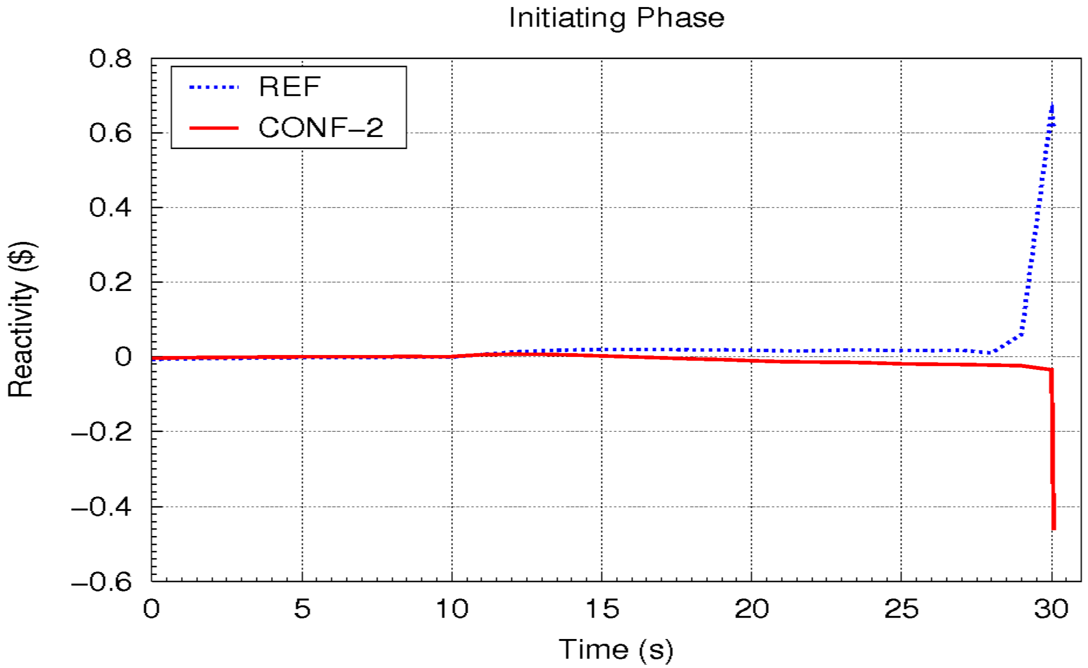
Initiating phase: SIMMER analysis

The net reactivity variation computed by SIMMER during the initiating phase of the transient for the two configurations confirms the ERANOS results.

For CONF-2, the reactivity drops down when Na starts to boil (ca. 11 s after ULOF, 30s needs to reach the steady-state) as expected by the negative SVRE and Doppler effects evaluated by ERANOS.

For the REF configuration, the reactivity goes up during the initiation phase as expected by the positive void effect evaluated.

However, for CONF-2 the net reactivity oscillates when the boiling spreads radially but it remains well below 1$



(in the SIMMER simulation axial and radial expansion reactivity effects were neglected).

Transition phase analysis: measures for CMR

An important focus of the SFR safety research is on the mitigation or even elimination of specific severe accident routes leading to core disruption and recriticalities.

To get a control on recriticalities and energetics, ideas have been developed to install dedicated means in a core close to the ESFR design that enhance and guarantee a sufficient and timely fuel discharge - a **controlled material relocation (CMR).**

A ULOF accident was assumed for the analysis (Case A-1 without CMR measure)

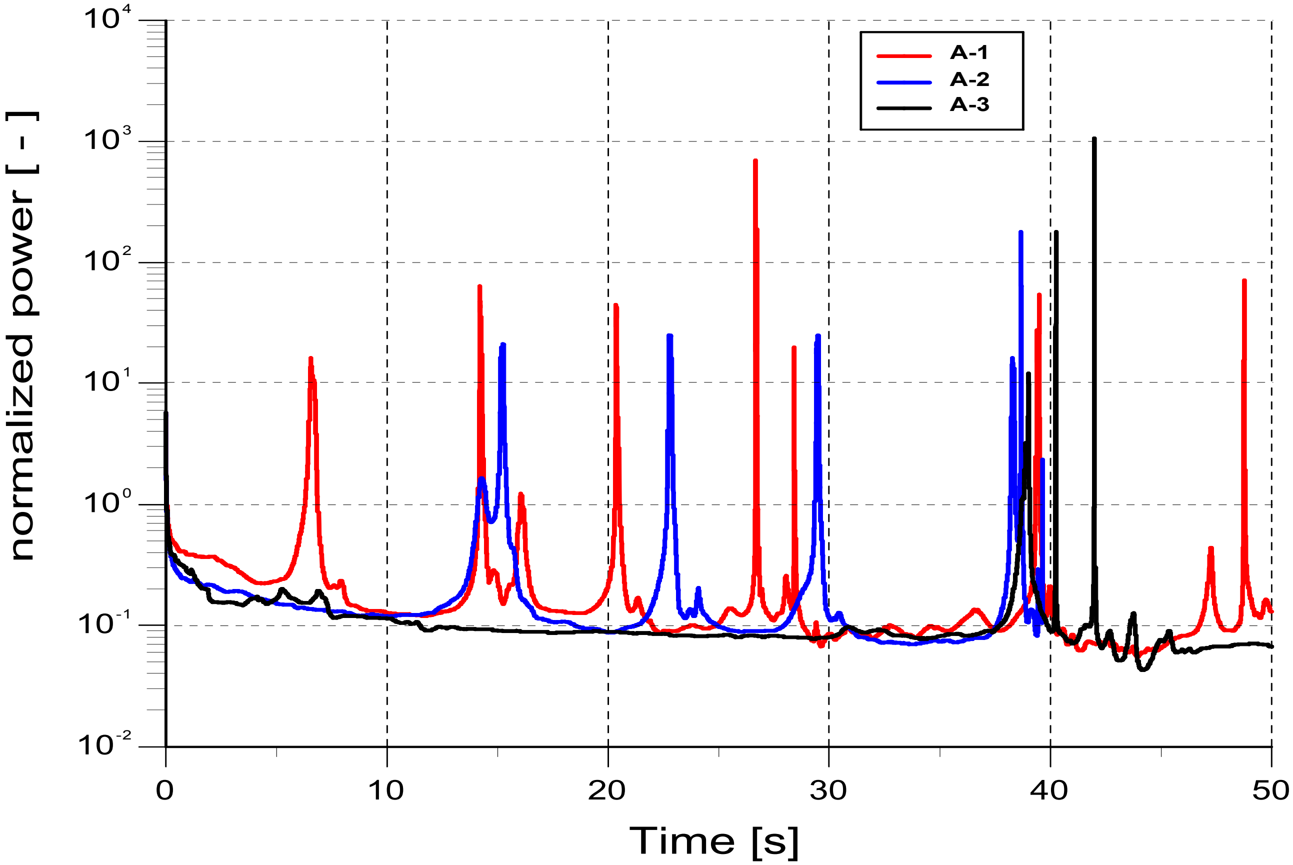
Within each subassembly 19 empty pins (filled by He) are inserted grouped ring-wise in the subassembly centre (Case A-2).

In an additional step, fuel release through control rod guide tubes (CRGTs) has been allowed (Case A-3).

Transition phase analysis: measures for CMR

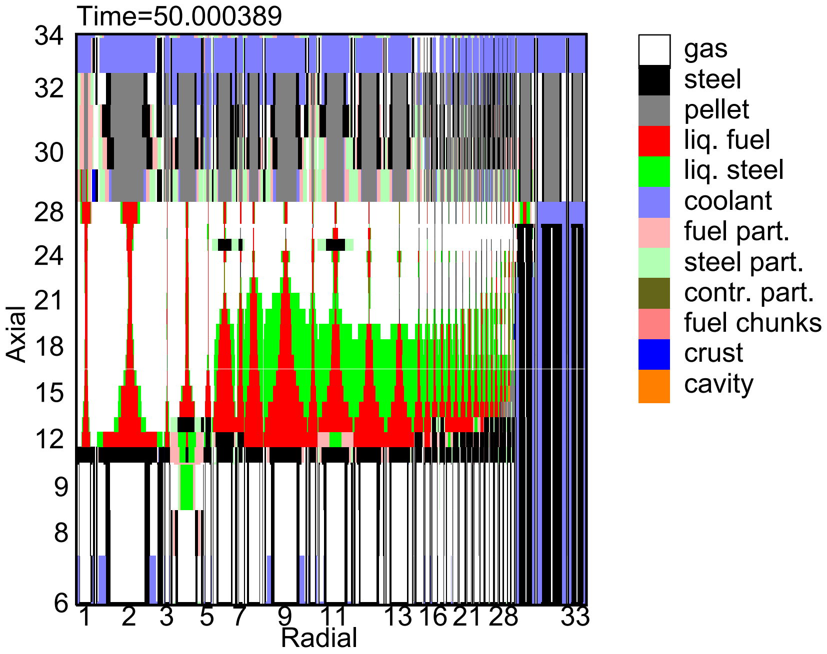
It can be recognized that in the cases with CMR measures recriticalities still take place.

However, the amplitude of power peaks and their frequency is reduced compared to case without any CMR measures.

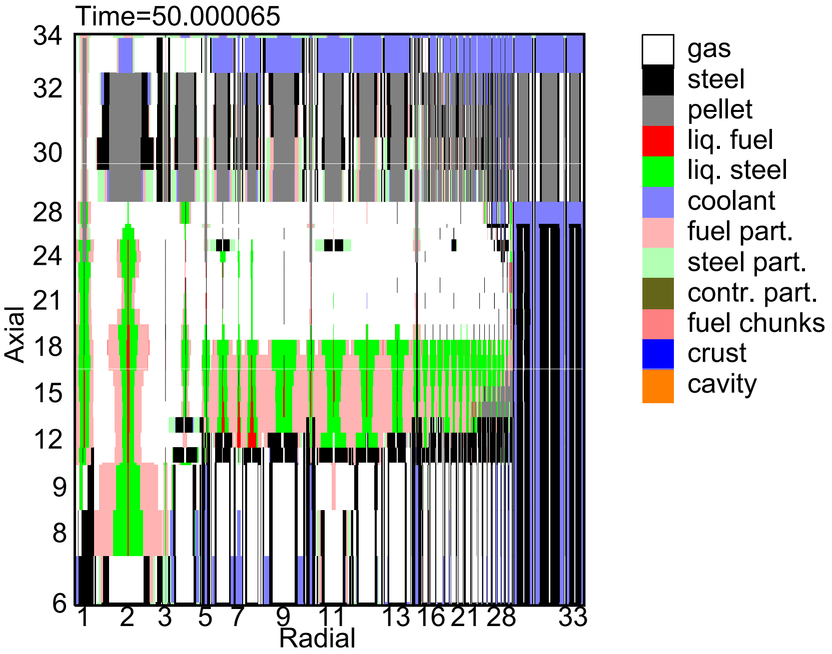


Transition phase analysis: measures for CMR

Here are represented the material distribution at the end of the simulation for A-1 and A-3 cases showing an increased release of fuel with the CMR measures.



A-1



A-3

Conclusions

For the **initiating phase** of the transient:

- The adoption of a higher Na plenum shifted closed to the core, as well as an absorber layer above help on reducing the positive void worth of the ESFR core. The extended SVRE drops down to zero.

- Adding a lower fertile blanket (depleted U oxide) helps on reaching at BOL negative extended SVRE (-240 pcm). This measure helps on reducing the core SVRE by ~200 pcm too.

- CONF-2 could further be optimized addind other measures (as empty pins) important also for the late phases of the transient. Studies are on-going also on introducing and burning MAs in the systems.

Conclusions

For the **transition phase** of the transient:

- The adoption of 19 empty pins per subassembly and fuel discharge via CRGTs have been considered in order to improve the CMR.

- The full elimination of recriticalities cannot be achieved with the analyzed CMR approach.

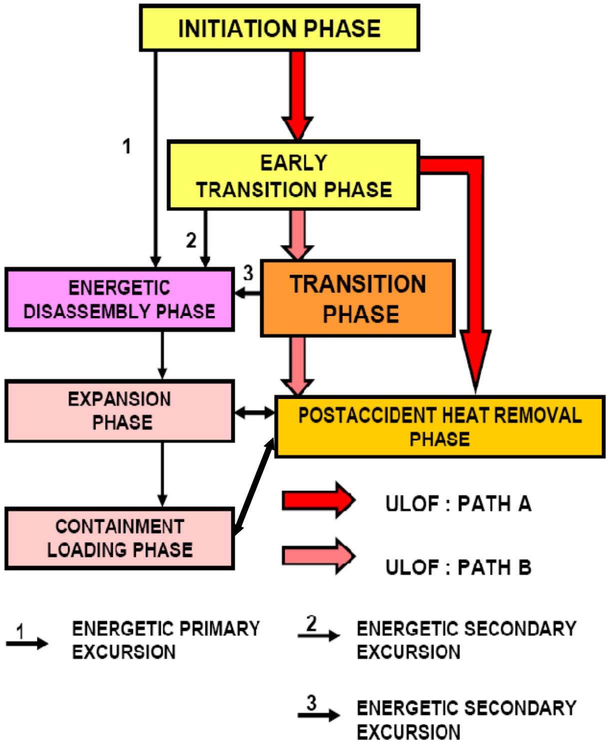
- The investigations show that without a too large change in the subassembly structure and taking into account the CRGTs the recriticality potential and its energetics can be substantially diminished.

Thank you for your attention!

Topics

- Introduction: Safety studies
- Computational tools adopted
- ESFR reference model description
- Optimizations oriented to initiating phase of the accident
- ESFR optimized configuration
- Initiating phase: SIMMER analysis
- Transition phase analysis: measures for CMR
- Conclusions

Safety analysis: HCDA development

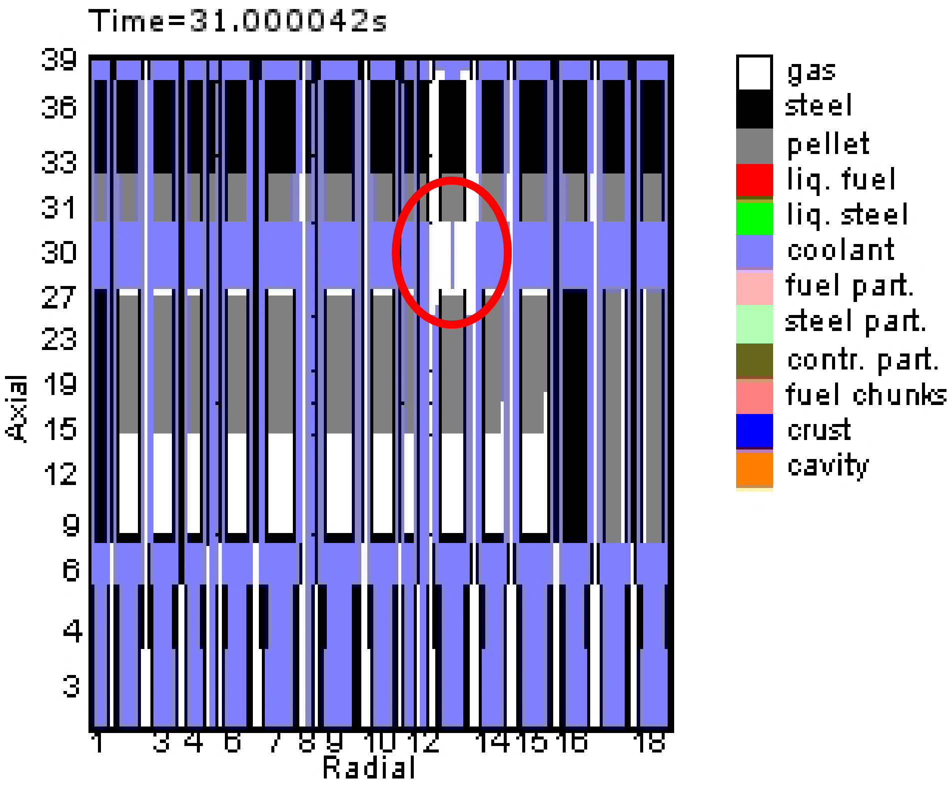


- **Initiation phase :** 'Ouverture', but does not give the complete picture and **especially not** the potential thermal and mechanical loads
- **TRANSITION PHASE** determines outcome of transient
- Traditionally : Control of initiation phase via void worth and Doppler
- Transition phase less accessible for control
- Opening of multiple event channels, increase of reactivity range scale, non-linearity, ….
- **Important new approach :** Obtain controllability of transition phase via CMR (controlled material relocation)

Initiating phase: SIMMER analysis

The material distribution computed by SIMMER when Na starts to boil is represented below.

It confirms that the sodium vapor is initially generated in the Na plenum above the core.

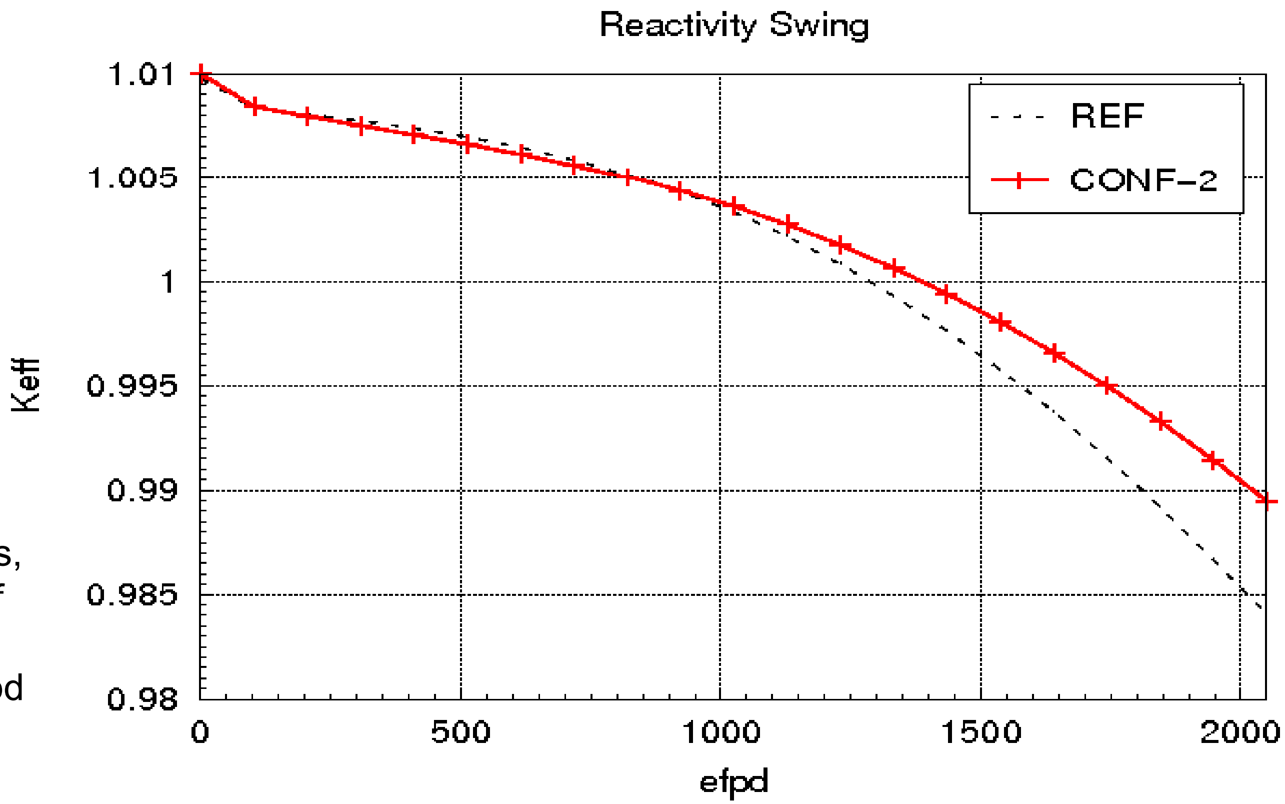


CONF-2

ESFR optimized configuration

CONF-2 has been selected for further studies.

For the burnup point of view, it shows a less pronounced reactivity swing respect to the reference configuration.



For both configurations, an average burnup of 100 GWd/tHM is reached after 2050 efpd