LFR safety approach and main ELFR safety analysis results

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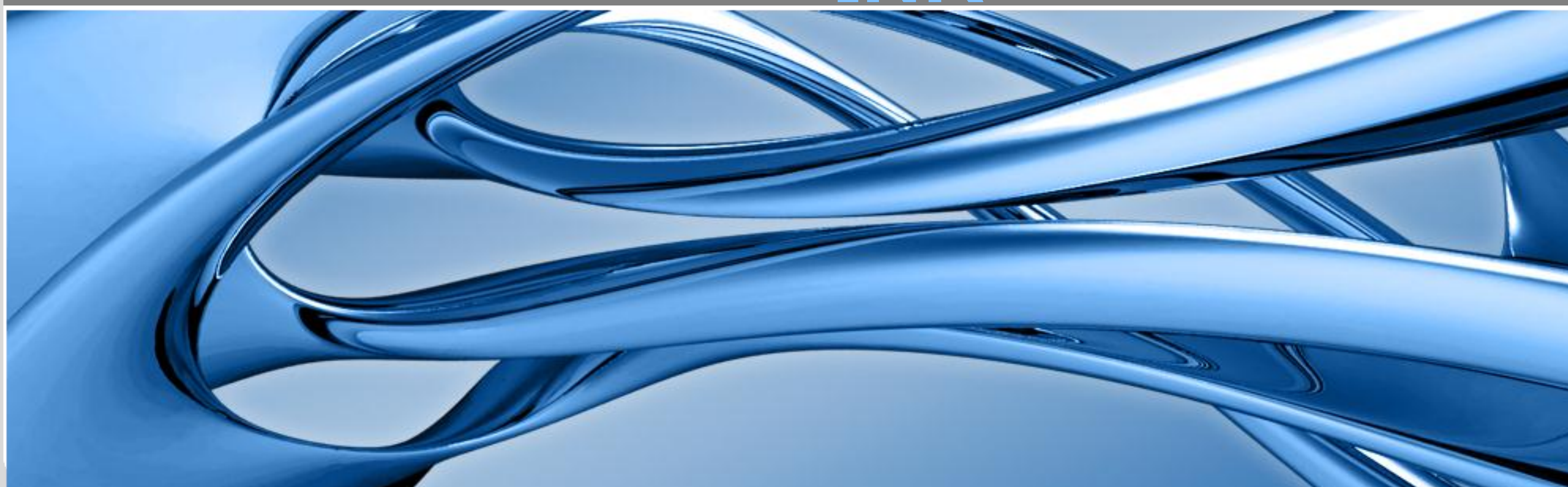
E. Bubelis, M. Schikorr, M. Frogheri, L. Mansani, G. Bandini, L. Burgazzi, K. Mikityuk, Y. Zhang, R. Lo Frano, N. Forgione

Presented by E. Bubelis

Karlsruhe Institute of Technology

Institute for Neutron Physics and Reactor Technology

SEVENTH FRAMEWORK PROGRAMME



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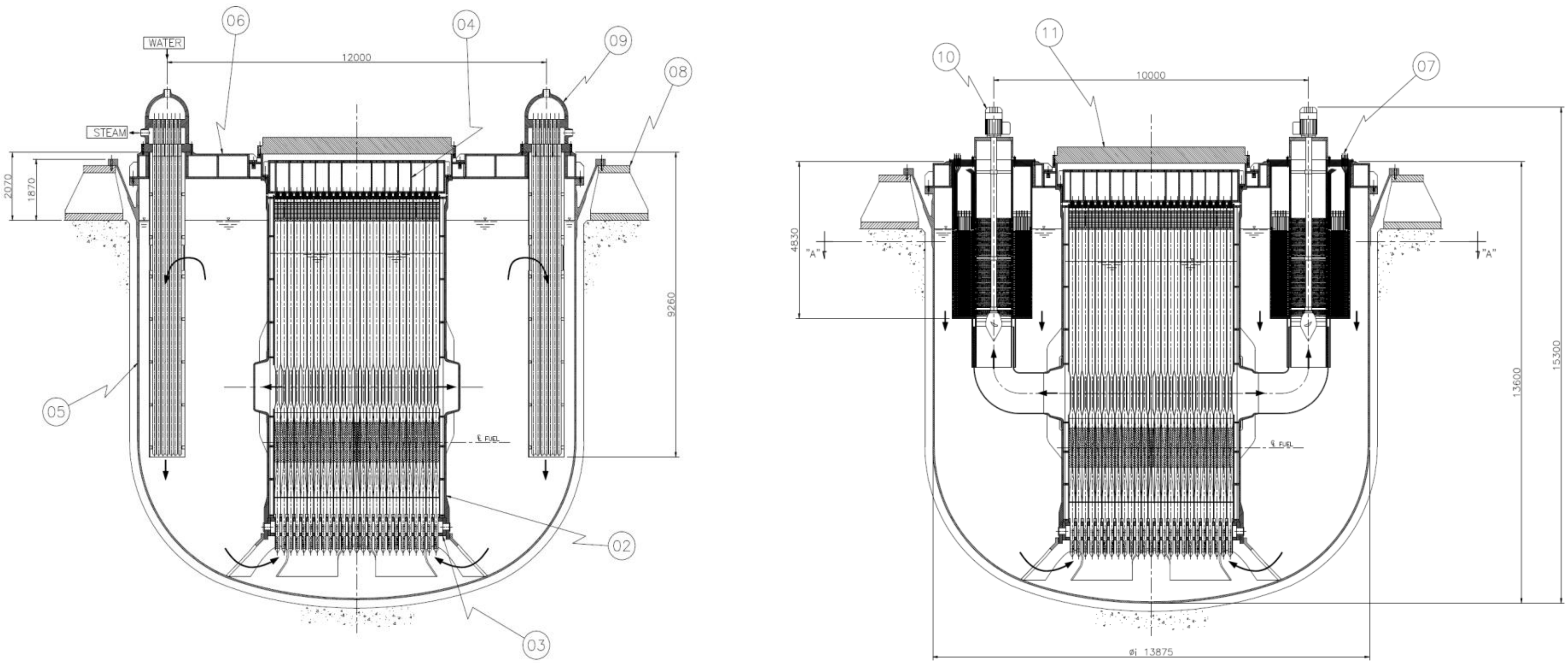
Object of the study: ELFR



Reactor block vertical sections: 01) Fuel assembly ;02) Inner vessel; 03) Core lower grid; 04) Core upper grid; 05) Reactor vessel ; 06) Reactor cover; 07) Steam Generator; 08) Vessel support; 09) DHR dip cooler; 10) Primary pump; 11) Reactor FAs cover

LFR Safety Approach

- A global safety approach for the LFR reference plant has been assessed and the safety analyses methodology has been developed.
- LFR follows the general guidelines of the Generation IV safety concept recommendations. Thus, improved safety and higher reliability are recognized as an essential priority.
- The fundamental safety objectives and the Defence-in-Depth (DiD) approach, as described by IAEA Safety Guides, have been preserved.
- The recommendations of the Risk and Safety Working Group (RSWG) of GEN-IV IF has been taken into account:
    - safety is to be “built-in” in the fundamental design rather than “added on”;
    - full implementation of the Defence-in-Depth principles in a manner that is demonstrably exhaustive, progressive, tolerant, forgiving and well-balanced;
    - “risk-informed” approach - deterministic approach complemented with a probabilistic one;
    - adoption of an integrated methodology that can be used to evaluate and document the safety of Gen IV nuclear systems - ISAM. In particular the OPT tool is the fundamental methodology used throughout the design process.

DBC & DEC transients analyzed for ELFR

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T-1 : PLOF, DHR-1 or DHR-2 available, reactor trip

T-2 : ULOF, SCS in forced convection

T-3 : ULOHS, PPs active, DHR-1 or DHR-2 available

T-4 : UTOP, study max possible reactivity insertion w/o core melting

T-5 : ULOF+ULOHS, DHR-1 or DHR-2 available

T-6 : OVC, FW temp drop from 335 ^{o}C to 200 ^{o}C in 1 sec, reactor trip

T-7 : SLB, reactor trip

T-8 : SA blockage, determine max acceptable SA flow reduction factor

T-9 : SGTR (limited scope, low priority, based on experiments)

Protected transients: T-1, 6, 7 – PLOF, OVC, SLB

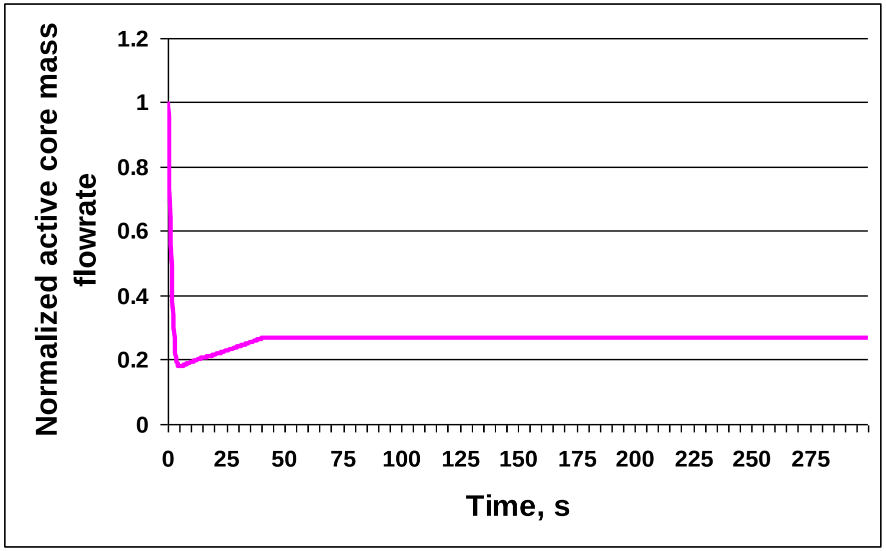
The automatic reactor shutdown activated by different scram signals is able to rapidly bring the ELFR plant to safe plant conditions.

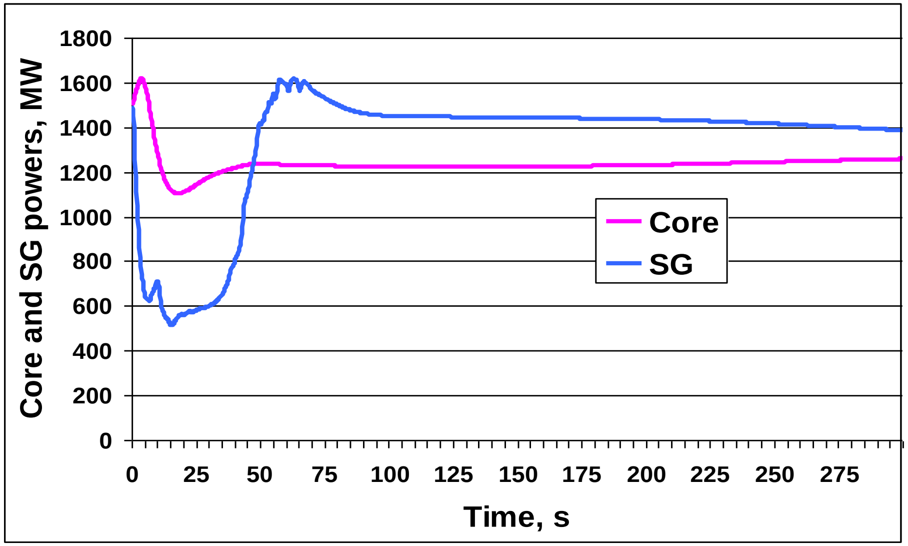
The consequent isolation of the secondary circuits and start up of decay heat removal system is able to maintain the plant in safe conditions in the medium and long term.

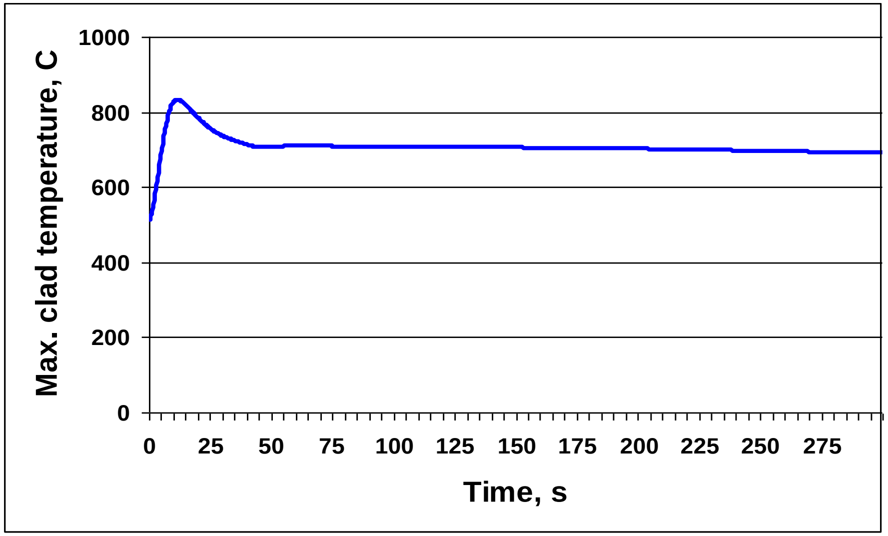
In all transients, the potential of Pb-freezing in the coldest points of the primary system is reached after several hours into the transient, assuring sufficient grace time for manual, corrective operator action.

T-2 : ULOF, SCS in forced convection

PSI TRACE results



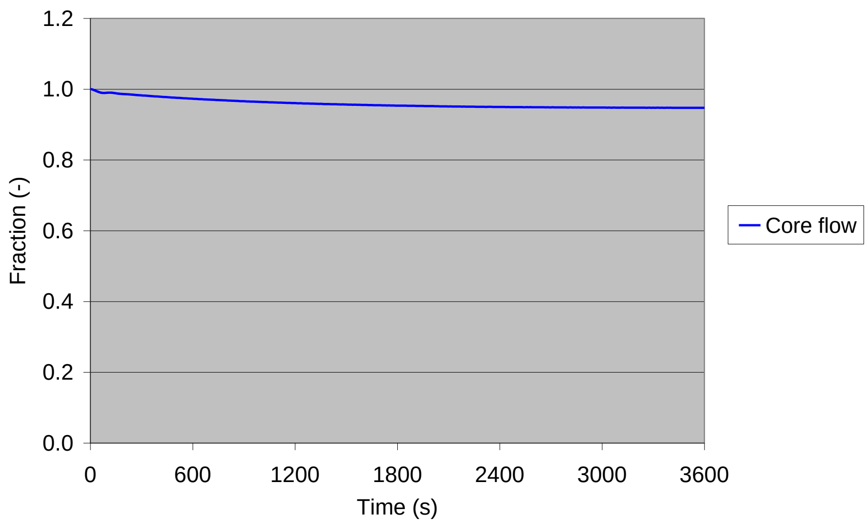


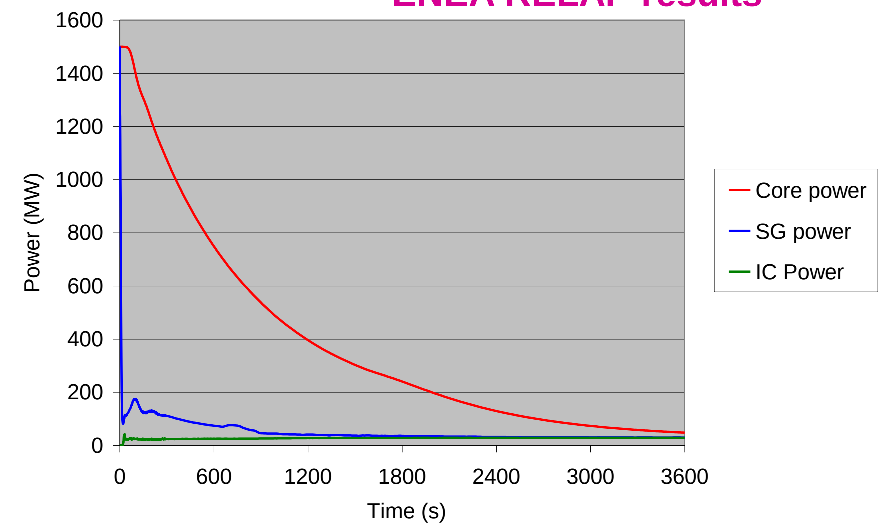


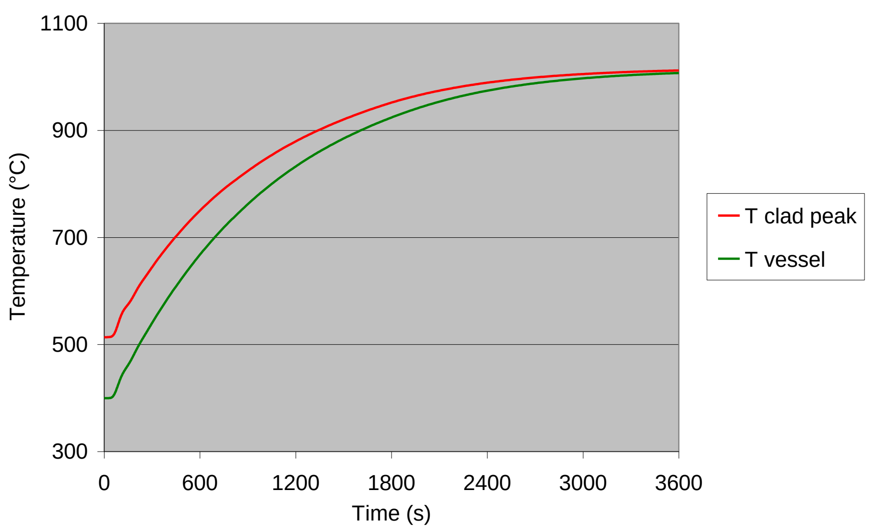
Due to the enhanced natural convection capability in the primary circuit, in case of ULOF the maximum temperatures reached in the primary system are low enough to assure the integrity of the clad and the vessel in the short term, providing sufficient grace time for corrective operator action.

T-3 : ULOHS, PPs active, DHR-1 or DHR-2 available

ENEA RELAP results





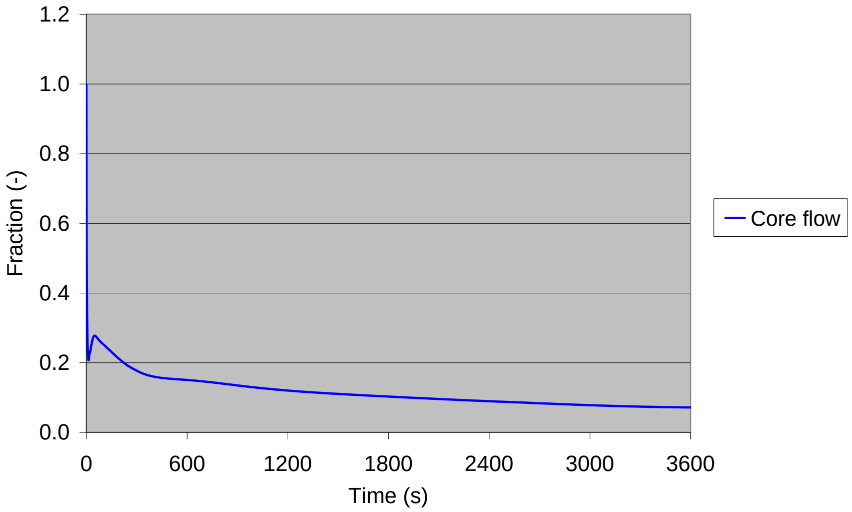


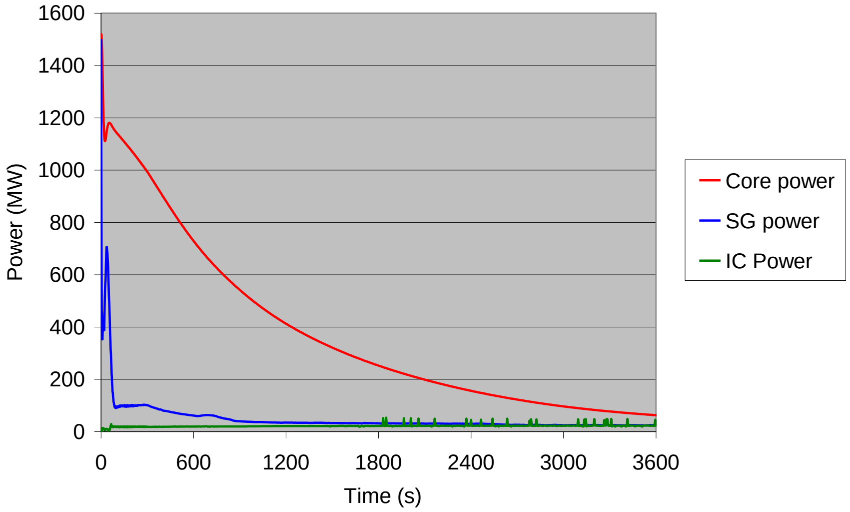
The main potential safety issue is the maximum reactor vessel wall temperature that might exceed 700 °C within ~12 min.

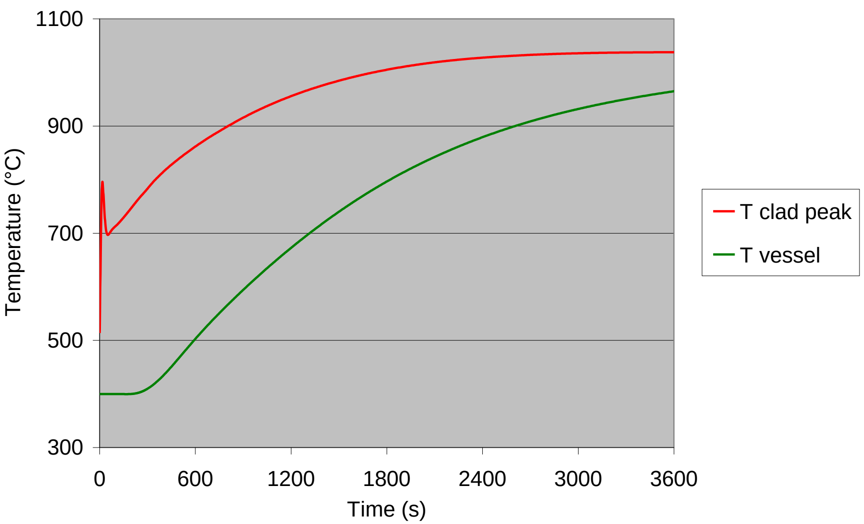
The integrity of the clad and the vessel seems not guaranteed in the medium/long term, because of the high temperatures reached in the primary system.

T-5 : ULOF+ULOHS, DHR-1 or DHR-2 available

ENEA RELAP results





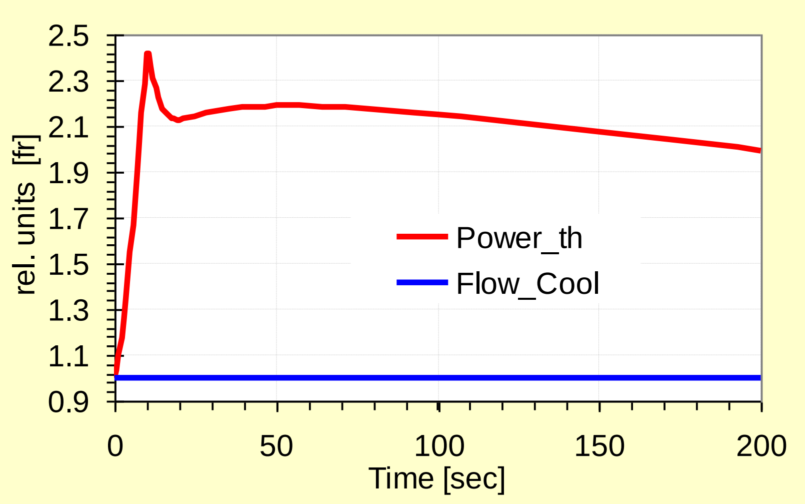


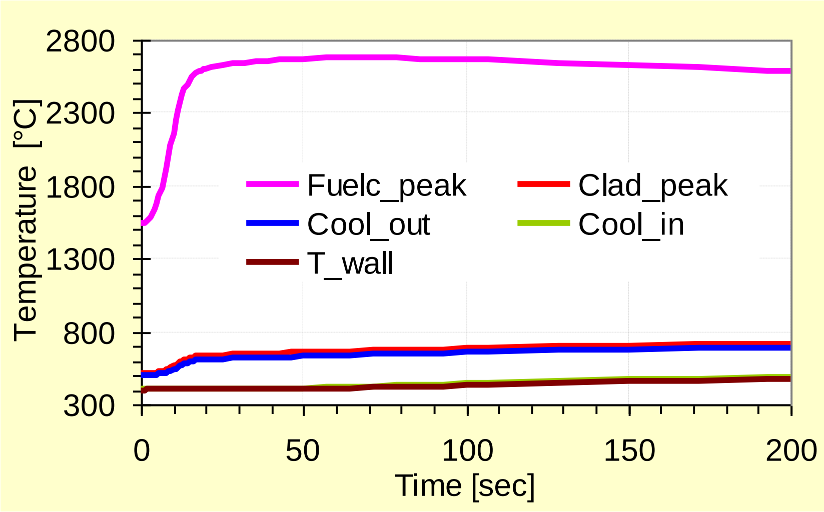
The main potential safety issue is the maximum reactor vessel wall temperature that might exceed 700 °C within ~22 min.

The integrity of the clad and the vessel seems not guaranteed in the medium/long term, because of the high temperatures reached in the primary system.

T-4 : UTOP, study max possible reactivity insertion w/o core melting

KIT SIM-LFR results





Case: 260 pcm in 10 sec

For <u>reactivity insertion of 200 pcm in 10 sec</u> time interval at EOC conditions, peak power fuel pin cladding survives and fuel melting is not observed, even in the center of the peak power fuel pins (pellets).

For <u>reactivity insertion of 260 pcm in 10 sec</u> time interval at EOC conditions, peak power fuel pin cladding survives, however fuel melting should be expected in the center of the peak power fuel pins (pellets).

T-8 : SA blockage, determine max acceptable SA flow reduction factor

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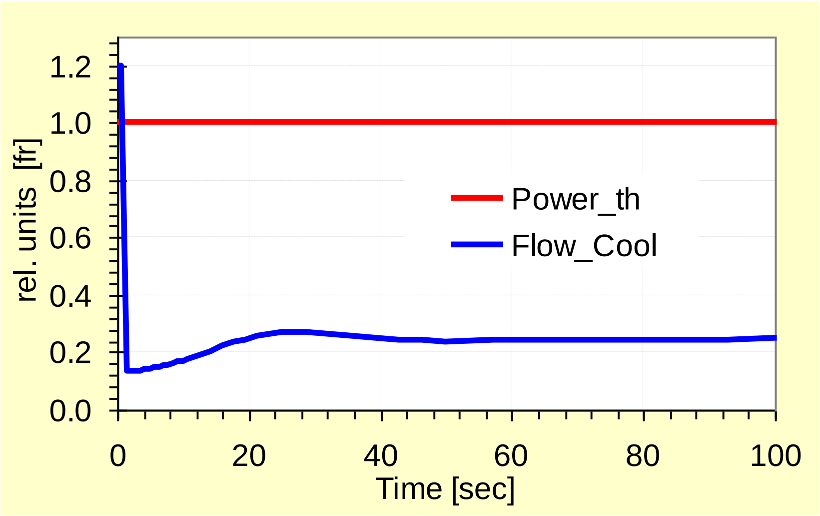
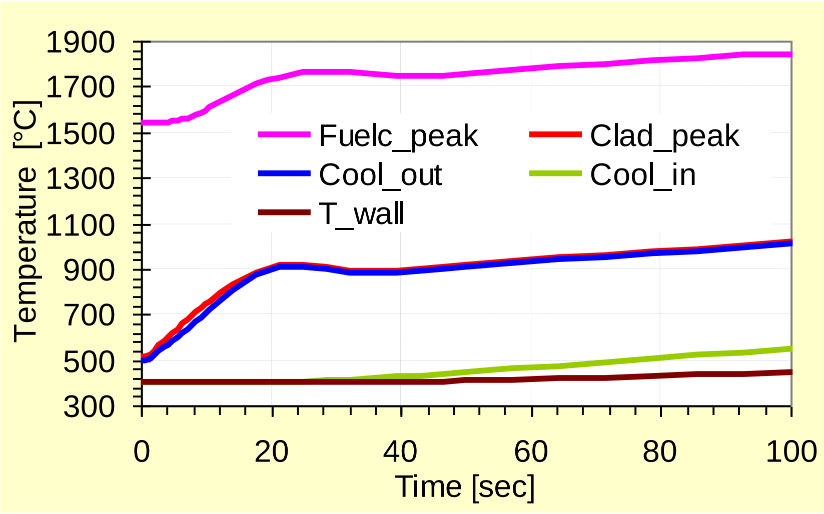
KIT SIM-LFR results





Extreme case: Flow in hottest SA blocked 97.5%; w/o radial heat transfer; EOC

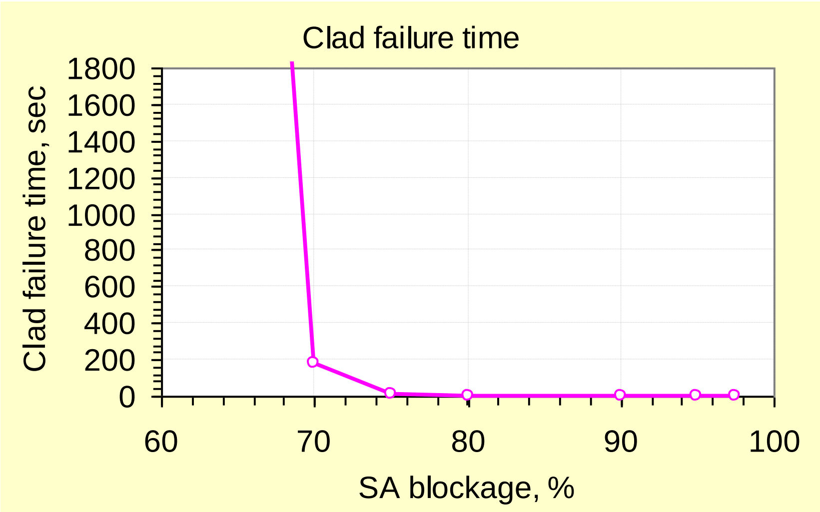
As a result of the SA blockage, the flow rate will initially decrease to ~ 14 % nominal, gradually recovering to about 24% flow rate at ~50 sec into the transient due to changing SA pressure conditions.

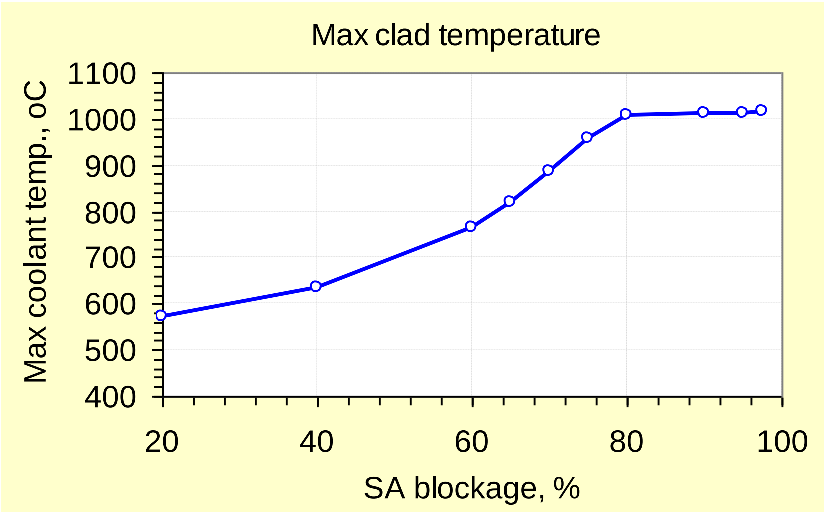
The power remains at 100% nominal throughout the transient.

Peak pin will fail ~93 sec into the transient as the cladding temperature will reach 1015 °C, having a peak pin fission gas pressure of ~41 bar.

T-8 : SA blockage, determine max acceptable SA flow reduction factor

KIT SIM-LFR results





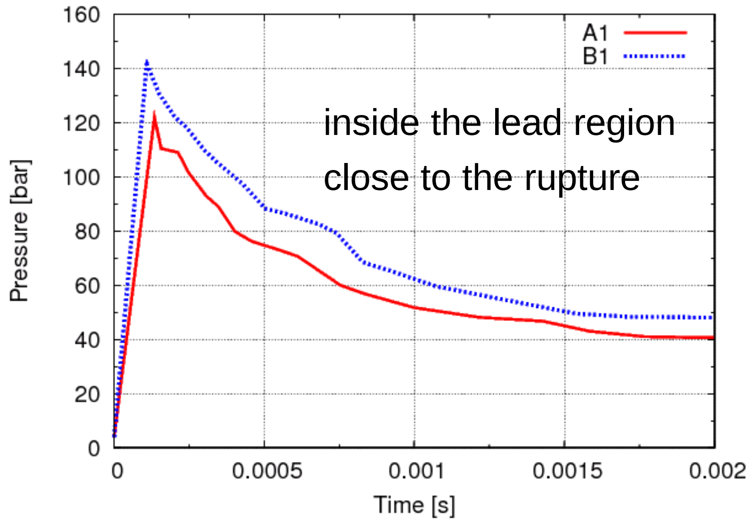
Case: Flow in hottest SA blocked 20 – 97.5 %; w/o radial heat transfer

Blockage	Clad failure time*	Max. cool. SA outlet temp.	Max clad temp (peak pin)	Max fuel temp (peak pin)
%	sec	°C	°C	°C
20	1.70E+11	556	571	1564
40	7.60E+08	621	636	1614
60	1.10E+05	753	766	1698
65	5.90E+03	806	818	1723
70	1.80E+02	876	887	1765
75	7	948	958	1810
80	-	999	1008	1837
90	-	1004	1013	1841
95	-	1005	1014	1842
97.5	-	1006	1015	1843
	* - max fission gas pressure ~41 bar			

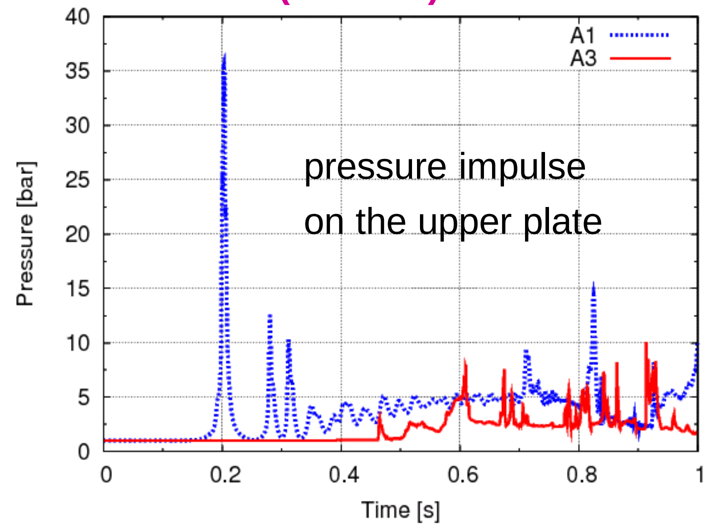
For flow blockages of < 75%, no pin failures nor fuel melting is expected, even under unprotected conditions.

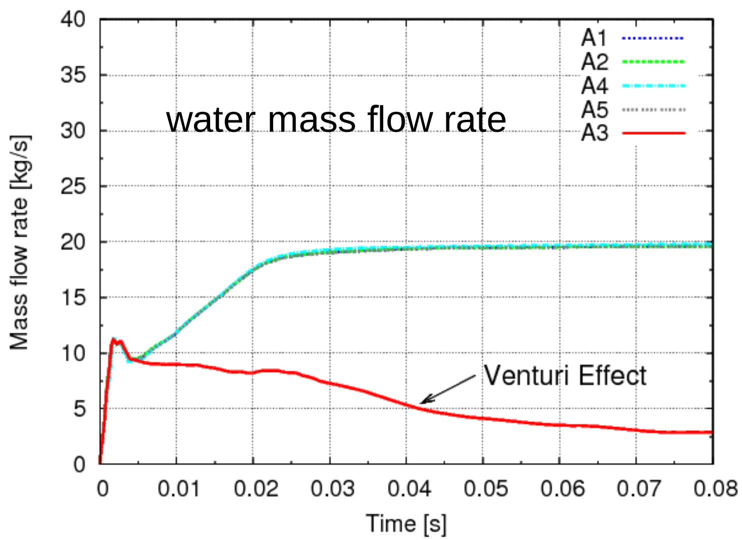
For flow blockages of > 75%, peak power pins clad failure has to be expected, but fuel melting is not expected even for a flow blockage of 97.5%.

T-9 : SGTR (limited scope, low priority, based on experiments)



UNIPI (CIRTEN) SIMMER results





Without any eng. safeguards or limiting mechanisms, the pressures induced by LWI, in case of instantaneous water vaporization, could be severe enough to lead to structural damage for the SG itself, while it poses no likely threat for the integrity of the in-vessel structures.

Vapour bubbles, generated during the LWI, have difficulty in reaching the core inlet section, as confirmed by the KALLA experimental data.

Conclusions

Unprotected transients (ULOF; ULOHS and ULOF + ULOHS):

Due to the enhanced natural convection capability in the primary circuit, in case of ULOF the maximum temperatures reached in the primary system are low enough to assure the integrity of the clad and the vessel in the short term, thus providing sufficient grace time for corrective operator action.

The main potential safety issue is the maximum reactor vessel wall temperature that might exceed 700 °C within ~12 min.

The integrity of the clad and the vessel seems not guaranteed in the medium/long term, because of the high temperatures reached in the primary system.

An optimization of the neutronic core design, in order to reduce the positive coolant expansion reactivity feedback could provide additional grace time.

Conclusions (continued)

Reactivity insertion:

These transients envelope positive reactivity insertions of the Design Basis events such as fuel handling errors, control rods withdrawal or seismic core compaction.

For reactivity insertion of 200 pcm in 10 sec time interval at EOC conditions, peak power fuel pin cladding survives and fuel melting is not observed, even in the center of the peak power fuel pins (pellets).

For reactivity insertion of 260 pcm in 10 sec time interval at EOC conditions, peak power fuel pin cladding survives, however fuel melting should be expected in the center of the peak power fuel pins (pellets).

Conclusions (continued)

FA flow blockage:

For flow blockages of < 75%, no pin failures nor fuel melting is expected, even under unprotected conditions.

For flow blockages of > 75%, peak power pins clad failure shall be expected, but fuel melting is not expected even for a flow blockage of 97.5%.

However there is time (several hundreds seconds) to detect the flow blockage occurrence, by means of temperature measuring devices installed at each FA outlet.

Conclusions (continued)

SGTR accident:

Several limiting mechanisms and potentially important effects have been analyzed and suggest that:

(i) the initial pressure shock wave poses no likely threat to in-vessel structures, except to few adjacent heat-exchange tubes;

(ii) the sloshing-related fluid motion is well bounded in a domain beyond the heat exchanger; and yet

(iii) the steam/water entrainment is expected to be comparatively limited due to the very large difference of density between steam and lead.

The potential gradual pressurization of the vessel after SGTR due to inflow of the steam is limited by rupture disks to relief the resulting over-pressure.

Moreover, a Venturi nozzle placed inside each spiral tube, mitigate the severity of SGTR interaction and reduce the potential effects on the entire reactor system.

A dedicated scaled facility should be foreseen to experimentally analyze in depth the SGTR phenomena further as part of the future R&D activities.

Conclusions (continued)

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General:

The safety analysis performed for the lead-cooled ELFR design demonstrated the robust nature of this plant design, ascribable to the inherently large thermal inertia of the lead-cooled primary system and optimization of safety relevant control, safety systems and components.

Acknowledgements

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