ESFR-SMART
sodium fast reactor safety

WP:	WP1.3 “Measures to prevent sodium boiling”
Title:	Passive reactor shutdown system (section 3-3)
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Where:	Video Conference (Cambridge, UK)

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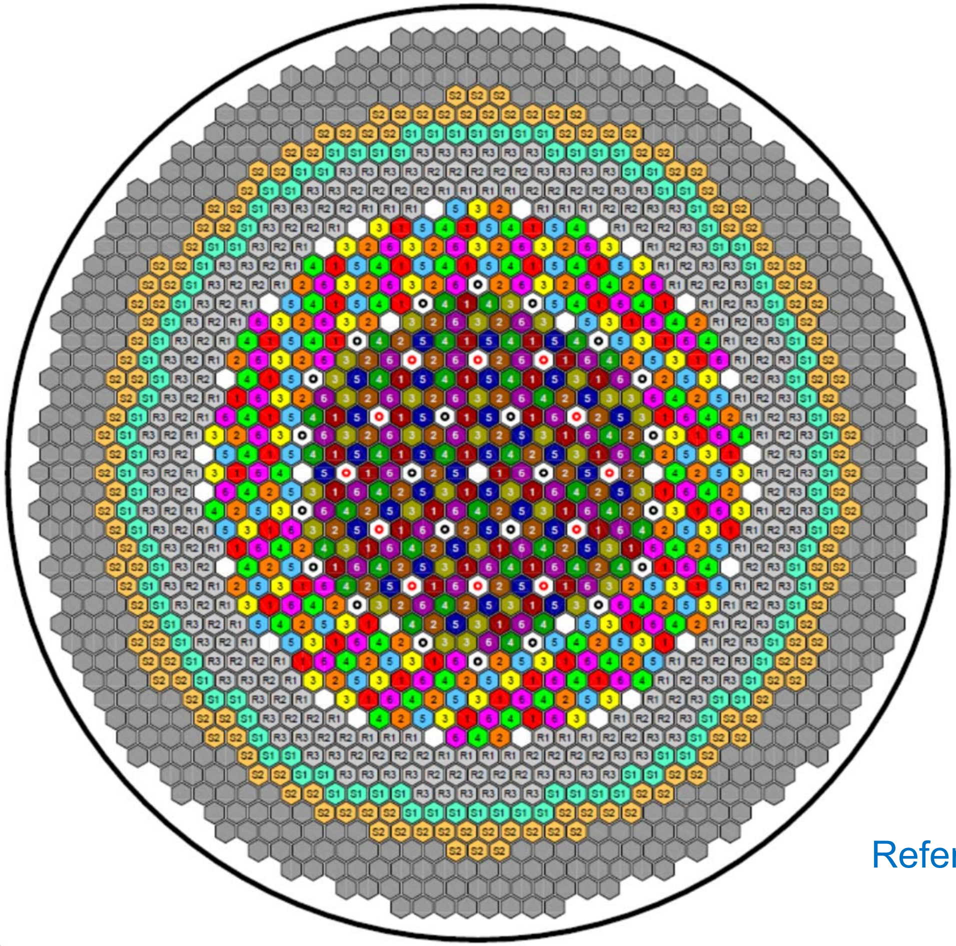
Radial layout for the ESFR-SMART core



1 2 3 4 5 6	Inner fuel	6 batches×36 = 216
1 2 3 4 5 6	Outer fuel	6 batches×48 = 288
	CSD / DSD	24 / 12
R1 R2 R3	1st / 2nd /3rd reflector ring	66 / 96 / 102
S1	Spent Inner / Outer fuel storage	3 batches×36 = 108
S2	Spent Inner / Outer fuel storage	3 batches×48 = 144
	Corium discharge tubes	31

Reference: Project deliverable D1.1.3

Reactor shutdown system rods (1/2)

Karlsruhe Institute of Technology

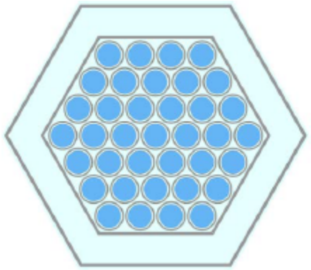
- ESFR has two groups of the absorber rods for reactor shutdown:

1. Control and Shutdown Devices/Rods (CSD) and
2. Diversified Shutdown Devices/Rods (DSD).

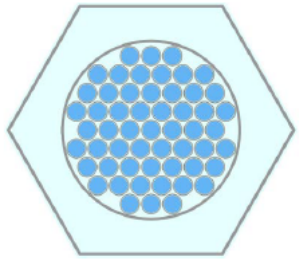
- Both types of absorber rods mentioned above consist of two enrichment zones: natural B_4C (lower part of 45 cm length) and 90% enriched B_4C (upper part of 40 cm length for CSD and 50 cm length for DSD).
- The total height of the absorber subassemblies is 409 cm.
- 24 CSD absorber SAs are located in the inner zone (6 SA) and at the periphery of the outer zone (18 SA).
- All 12 DSD absorber SA are located in the inner core zone.

Reactor shutdown system rods (2/2)

CSD			
Number of pins	37	**Rad. expn. coeff.**	**Nominal dim.**
Pin pitch (cm)	2.4300		
		Nominal T, °C	**ACE file T, K**
Pellet material	B4C Nat B4C Enriched	627	900
Gap material	He	470	900
Cladding material	EM10	470	900
Internal wrapper material	EM10	470	900
	Cold dim.	**Rad. expn. coeff.**	**Nominal dim.**
Pellet radius (cm)	0.9150	*1.0029*	0.91764
Clad inner radius (cm)	1.0415	*1.0054*	1.04716
Clad outer radius (cm)	1.1412	*1.0054*	1.14741
Internal wrapper inner flat-to-flat/2 (cm)	7.6000	*1.0054*	7.64129
Internal wrapper outer flat-to-flat/2 (cm)	7.8000	*1.0054*	7.84238



DSD			
Number of pins	55	**Rad. expn. coeff.**	**Nominal dim.**
Pin pitch (cm)	1.7420		
		Nominal T, °C	**ACE file T, K**
Pellet material	B4C Nat or B4C Enriched	627	900
Gap material	He	470	900
Cladding material	EM10	470	900
Internal wrapper material	EM10	470	900
	Cold dim.	**Rad. expan. coeff.**	**Nominal dim.**
Pellet radius (cm)	0.7000	*1.0029*	0.70202
Clad inner radius (cm)	0.7665	*1.0054*	0.77066
Clad outer radius (cm)	0.8189	*1.0054*	0.82339
Internal wrapper inner flat-to-flat/2 (cm)	7.2000	*1.0054*	7.23912
Internal wrapper outer flat-to-flat/2 (cm)	7.4000	*1.0054*	7.44020



Radial layout: CSD

Radial layout: DSD

Reference: Project deliverable D1.1.2

Passive reactor shutdown system (1/2)

- All 12 DSD rods belong to a passive reactor shutdown system.
- Two options of passive actuations are considered:

1. a Curie Point Electromagnetic (CPEM) lock option and
2. hydraulically (HYDR) suspended option.

- In both cases, the DSD rods have to provide redundant (to normal reactor shutdown system using CSD rods) safety shutdown capability to bring ESFR to shutdown power level conditions at the hot standby temperature from any operation condition assuming that the most effective absorber SA is stuck, i.e. not inserted.
- Thus, DSD rods are inserting the total of –1329 pcm of negative reactivity.

Passive reactor shutdown system (2/2)

- Regarding the CPEM option, the temperature of 650°C at the fissile core outlet is taken as an activation signal.
- After reaching the activation signal, CPEM rods are inserted into the core with a delay of 2 s, having full insertion time of 1 s.
-
- Regarding HYDR option, the reduction of the core flowrate to 45% of the nominal value is taken as an activation signal.
- After reaching the activation signal, HYDR rods are inserted into the core immediately without any delay, having full insertion time of 3 s.

Passive reactor shutdown system rods (1/3)

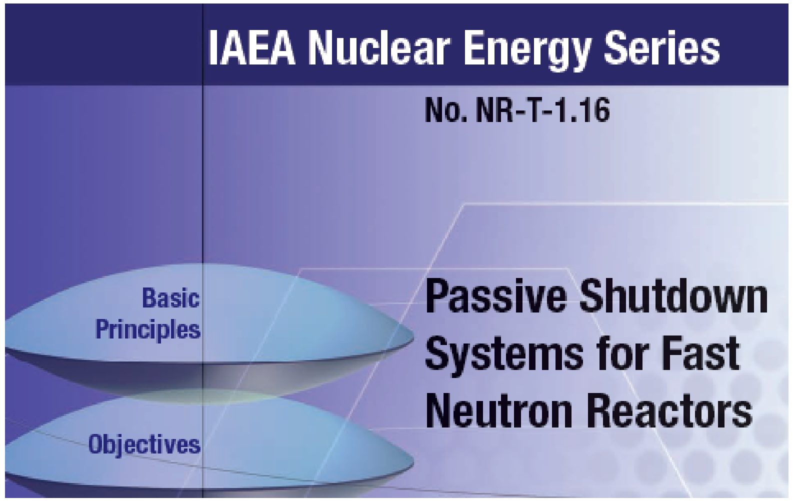
- For the currently analyzed ESFR reactor, there exist no real design of CPEM or HYDR rods.

- However, these two types of passive reactor shutdown system rods were intensively tested for sodium cooled fast reactors in the past by the Russians and the Japanese, and currently by the Japanese and the French.

IAEA-TECDOC-920

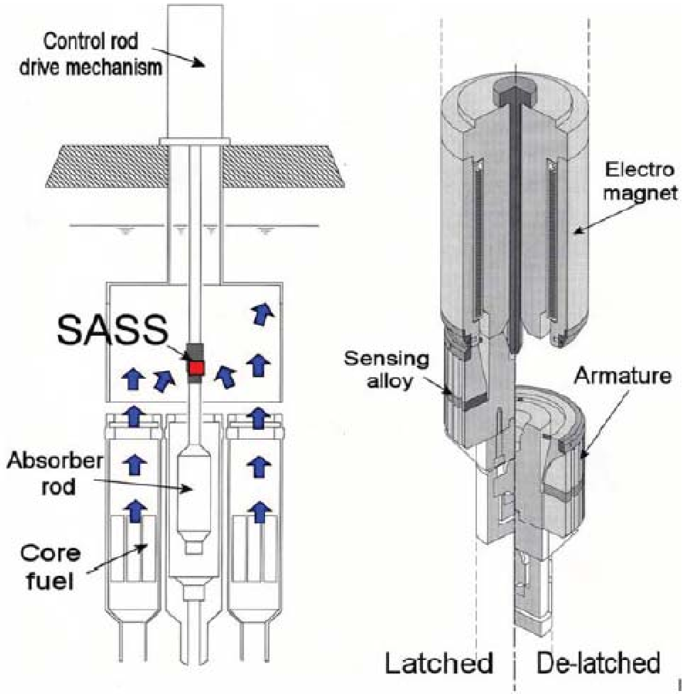
Technical feasibility and reliability of passive safety systems for nuclear power plants

Proceedings of an Advisory Group meeting held in Jülich, Germany, 21–24 November 1994

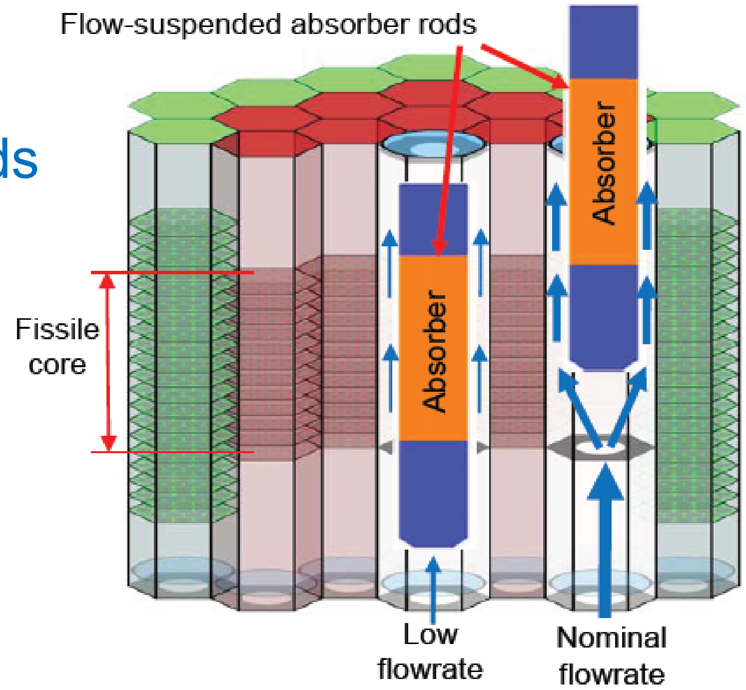


Passive reactor shutdown system rods (2/3)

CPEM rods principle



HYDR rods principle



Reference: IAEA Nuclear Energy Series No. NR-T-1.16, 2020. Passive Shutdown Systems for Fast Neutron Reactors, IAEA Nuclear Energy Series, Vienna, Austria, 124 pages.

Passive reactor shutdown system rods (3/3)

- It was demonstrated that these two kinds of passive reactor shutdown system rods were performing according to their design expectations.

- Thus, they can be used in real fast reactors during their normal operation, as well as accidental conditions.

Proceedings of ICONE-27
27th International Conference on Nuclear Engineering
May 19-24, 2019, Ibaraki, Japan

ICONE27-1265

HOLDING FORCE TESTS OF CURIE POINT ELECTRO-MAGNET IN HOT GAS FOR PASSIVE SHUTDOWN SYSTEM

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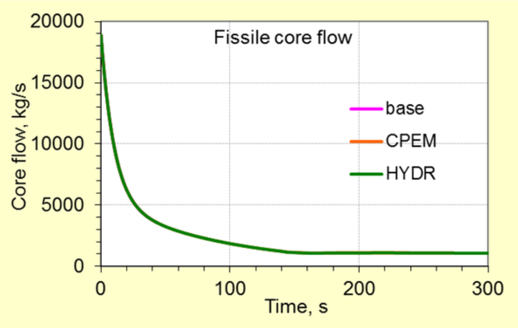
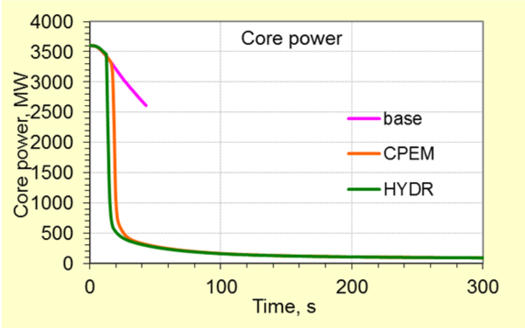
Passive reactor shutdown syst. performance (1/9)

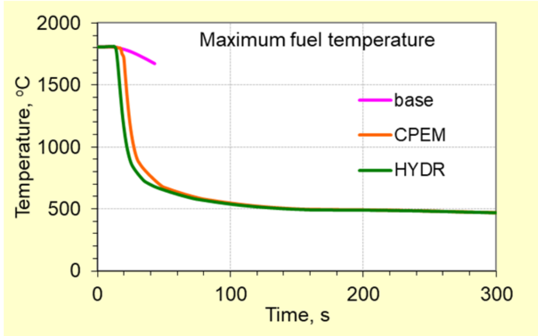
- The scenario for ULOF transient is as follows:

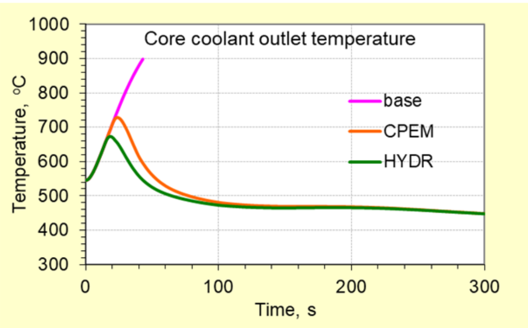
1. trip of primary pumps at time t=0 s;
2. due to common cause failure no pony motors are active during the transient, meaning that natural circulation of sodium takes place in the primary cooling circuit;
3. there is no reactor trip due to common cause failure of CSD rods;
4. forced circulation of the coolants continues in the secondary and tertiary cooling circuits of the reactor.

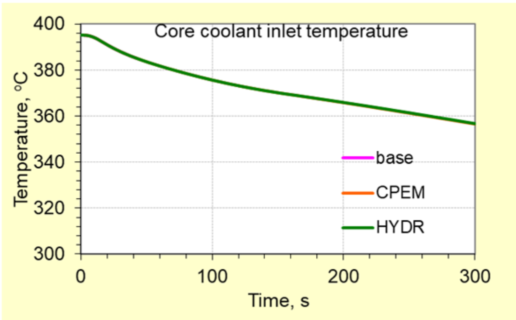
Passive reactor shutdown syst. performance (2/9)

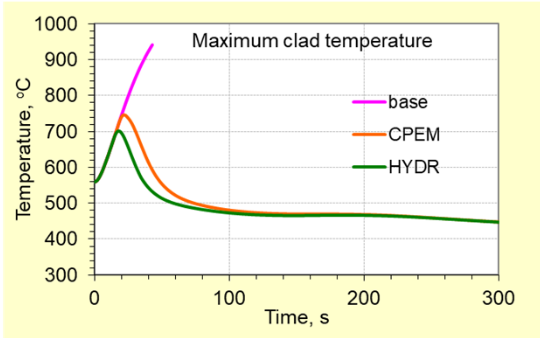










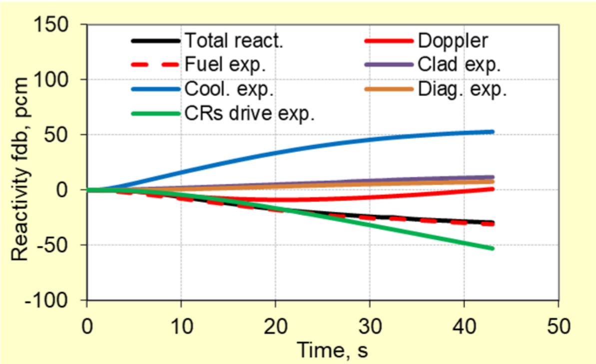


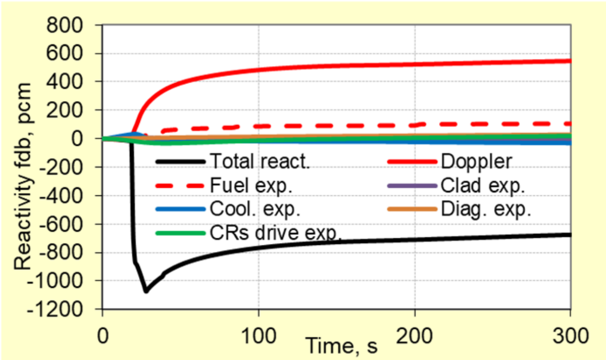
PSS: There is no more sodium boiling at the outlet of the core for the peak-power channel and peak-power pin clad failure is not predicted anymore.

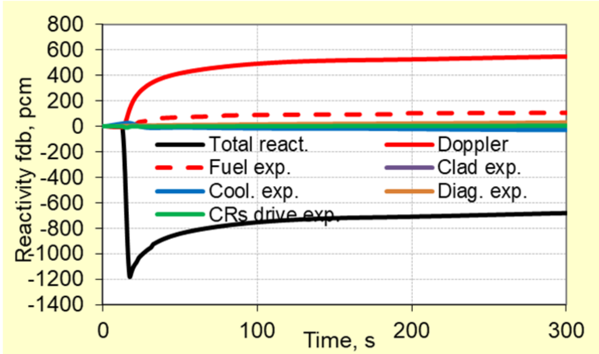
In the HYDR case, reactor shutdown takes place somewhat earlier, in comparison with the CPEM case.

Base case: Sodium at the outlet of the core for the peak power channel starts boiling at *t*~43 s into the transient. Peak-power pin clad failure is predicted at *t*~60 s into the transient.

Passive reactor shutdown syst. performance (3/9)







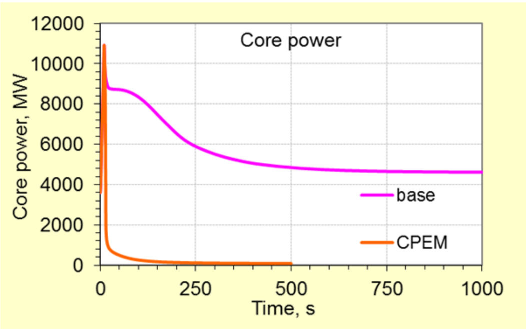
Conclusion: Both PSS options are capable to shutdown ESFR in a timely manner, in order to avoid the negative consequences of the base ULOF transient.

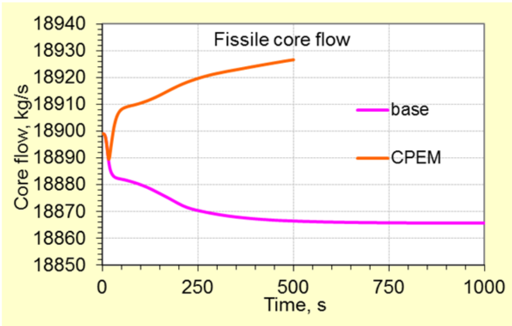
Passive reactor shutdown syst. performance (4/9)

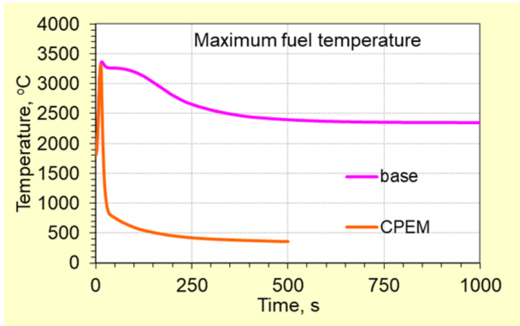
- The scenario for UTOP transient is as follows:

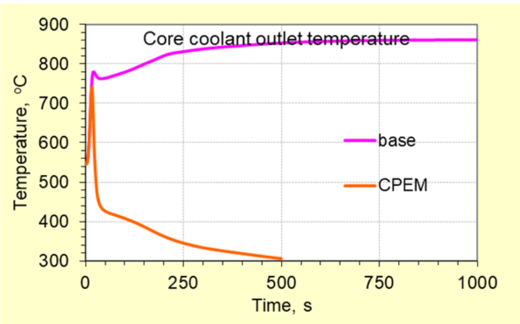
1. starting at time t=0 s, insertion of 400 pcm (slightly more than 1$) of positive reactivity with a constant speed within 10 s;
2. there is no reactor trip due to common cause failure of CSD rods;
3. forced circulation of the coolant continues in the primary, secondary and tertiary cooling circuits of the reactor.

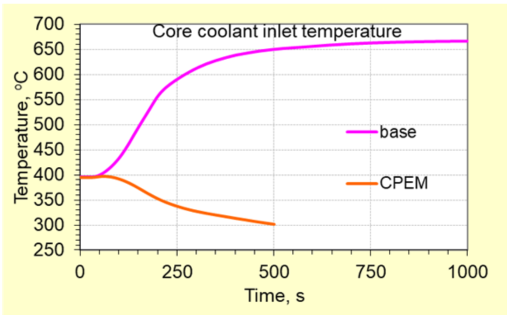
Passive reactor shutdown syst. performance (5/9)

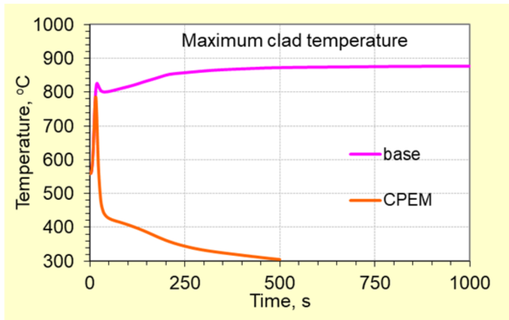








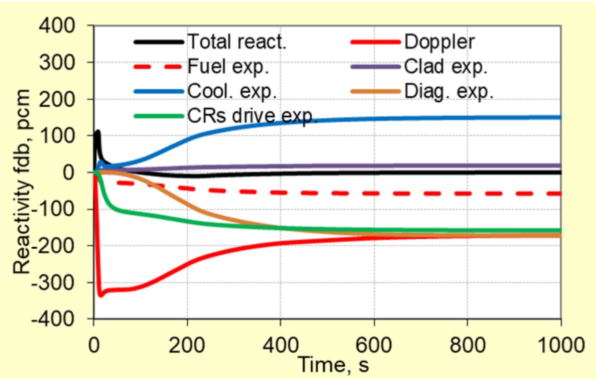


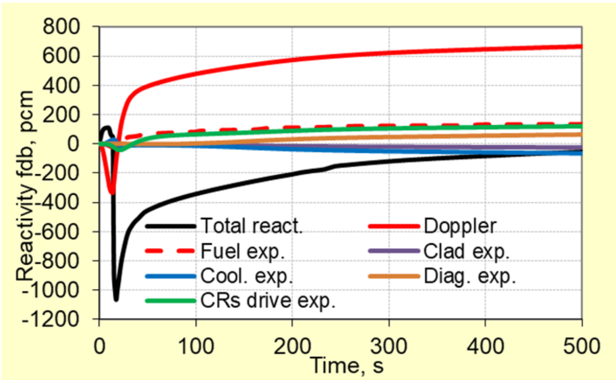


Base case: The reactor power increases up to a factor of 3.03 of the nom. power. Despite of the increased temperatures, no sodium boiling is being observed in the reactor core and clad of the peak power pin is not failing.

PSS: In about 3 s after the 400 pcm of positive reactivity insertion, activation of the DSD rods shutdown the reactor and all core and primary cooling circuit temperatures decrease.
No local fuel melting takes place in the reactor core.

Passive reactor shutdown syst. performance (6/9)





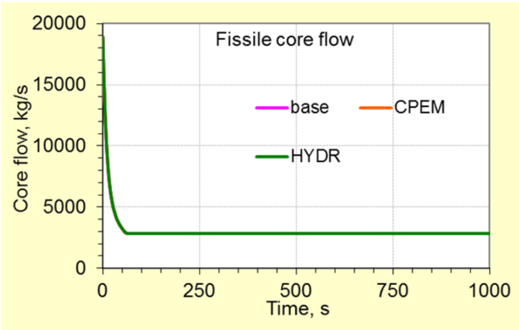
Conclusion: DSD rods (CPEM option in this case) are capable to shutdown ESFR in a timely manner, in order to avoid the negative consequences of the base UTOP transient.

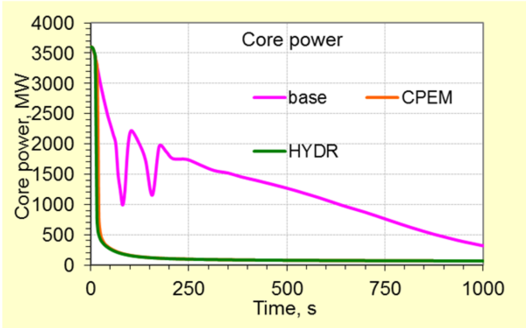
Passive reactor shutdown syst. performance (7/9)

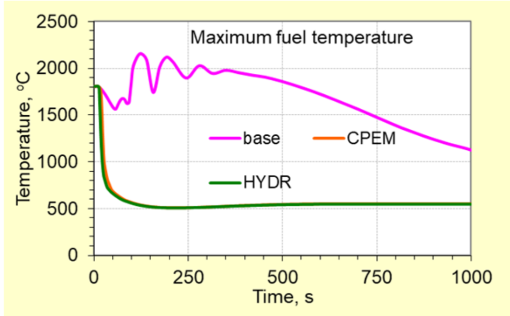
- The scenario for ULOOP transient is as follows:

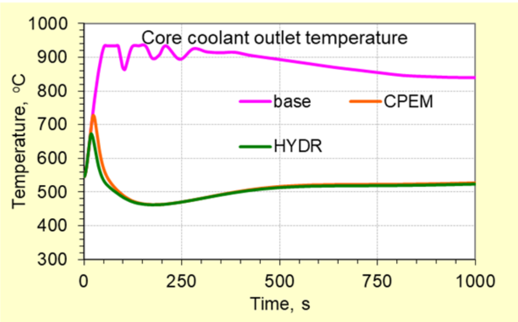
1. primary pumps trip at time t=0 s; pony motors, supplied by diesel generators, maintain minimum primary coolant flowrate at the level of 15% of the nominal flow;
2. secondary pumps trip at time t=0 s; natural circulation is established in the secondary cooling circuit;
3. tertiary pumps trip at time t=0 s; no diesel generators are usually foreseen to secure feedwater flowrate;
4. there is no reactor trip due to common cause failure of CSD rods.

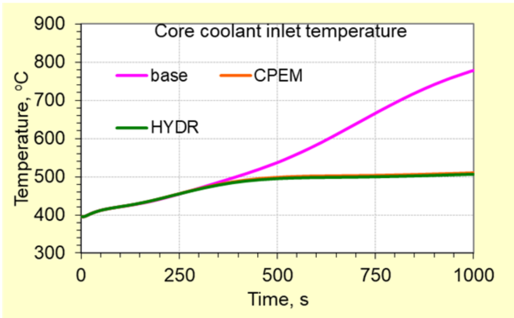
Passive reactor shutdown syst. performance (8/9)

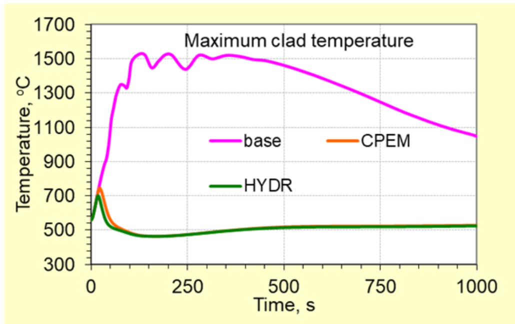








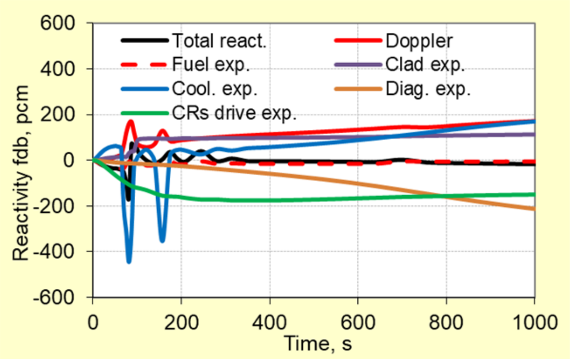


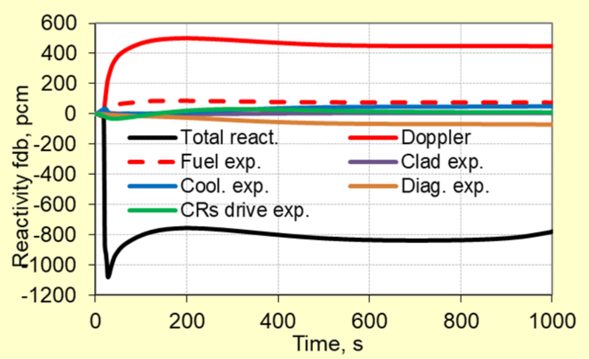


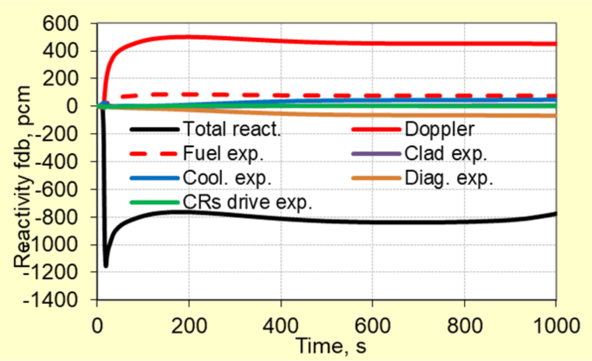
PSS: There is no more sodium boiling at the outlet of the core and the peak-power pin clad failure is not predicted anymore.
In the HYDR case, reactor shutdown takes place somewhat earlier, in comparison with the CPEM case.

Base case: Sodium at the outlet of the average-power channel starts boiling at t~52 s. The peak-power pin clad failure is predicted at t~63 s. However, despite of the increasing temp. in the reactor core, no localized fuel melting is expected.

Passive reactor shutdown syst. performance (9/9)







Conclusion: Both options are capable to shutdown ESFR in a timely manner, in order to avoid the negative consequences of the base ULOOP transient.

During the simulation of ULOOP transient, it was assumed that emergency diesel generators do not support feedwater supply to the SGs. It means that the final heat sink in base ULOOP scenario case does not exist. If there exists no final heat sink and there is no decay heat removal from the core, primary cooling circuit temperatures sooner or later will start growing, thus leading to the sodium boiling and loss of the core integrity. This is more dangerous for base ULOOP scenario, but is also important even for the case when DSD rods are actuated and the reactor is shutdown.

Conclusions

- Simulation of the above mentioned unprotected transients have demonstrated that DSD rods are capable to shutdown ESFR in a timely manner, in order to avoid the negative consequences of the ULOF, UTOP and ULOOP (in the simulated timeframe) transients.

- Despite of the fact, that the above analysis show that passive reactor shutdown system rods (CPEM and HYDR rods) can protect ESFR reactor from the analyzed unprotected transients by safely shutting it down, it is very important that real CPEM and HYDR rods designs are tested and validated in the future in the test facilities or test reactors, thus allowing their implementation in the operating sodium fast reactors worldwide, in this way enhancing their safe operation.