REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

Title	# LOCA accidents
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Commission européenne

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Introduction

Loss Of Coolant Accident (LOCA):

“A potential accident in which a breach in a reactor’s pressure boundary causes the coolant water to rush out of the reactor faster than makeup water can be added back in. Without sufficient coolant, the reactor core could heat up and potentially melt the zirconium fuel cladding, causing a major release of radioactivity.”

US Nuclear Regulatory Commission
(https://www.nrc.gov/reading-rm/basic-ref/glossary/loss-of-coolant-accident-loca.html)

The accident evolution and phenomena involved depend on several aspects such as the size and position of the break, the reactor design and the related safety systems.

		Large break		Intermediate break	Small break
Break size	cm^2	>1000	400-1000	80-400	<80
	%	>25	10-25	2-10	<2
Occurrence probability		1e-4	3e-4	8e-4	3e-3

*Reference value for KWU PWR 1300 MWe

Emergency Core Cooling Sistems (ECCS)

To mitigate a LOCA progression, Emergency Core Cooling Sistems (ECCS) deliver borated water to the reactor core to provide core cooling, and sufficient negative reactivity for safe shutdown following DBA.

In a PWR, the ECCS consists mainly of:

- **High Pressure Safety Injection System (HPIS)** that injects borated water in the primary coolant system by pumps with high head and low flow rate.
- **Accumulators** (coolant tanks pre-charged with an inert gas; a check valve opens their discharge lines)
- **Low Pressure Safety Injection System (LPIS)** that uses low head and high flow rate pumps to inject borated water.

Safety criteria (example of 10 CFR 50.46)

The ECCS should fulfill safety criteria set by the regulatory authorities. For example, the 5 safety criteria stated in 10 CFR 50.46 (NRC Code of Federal Regulations, Title 10, Part 50.46) are:

1. Peak Cladding Temperature: it shall not exceed 1204°C (2200°F). The criteria should prevent significantly embrittlement of the cladding (caused by microstructural modification) that can fragment during the quenching phase of a LOCA.
2. Maximum Cladding Oxidation: the oxidation shall nowhere exceed 17% of the total cladding thickness before oxidation.
3. Maximum Hydrogen Generation: the hydrogen generated from the chemical reaction of cladding with water shall not exceed 1% of the amount that would be generated if all the cladding metal were to react.
4. Coolable Geometry: calculated changes in the geometry shall be such that the core remains amenable to cooling.
5. Long-Term Cooling: the core temperature shall be maintained at an acceptably low value and decay heat shall be removed for the extended period of time required by the long-lived radioactivity remaining in the core.

Large Break Loss Of Coolant Accident
LBLOCA

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

LBLOCA phases

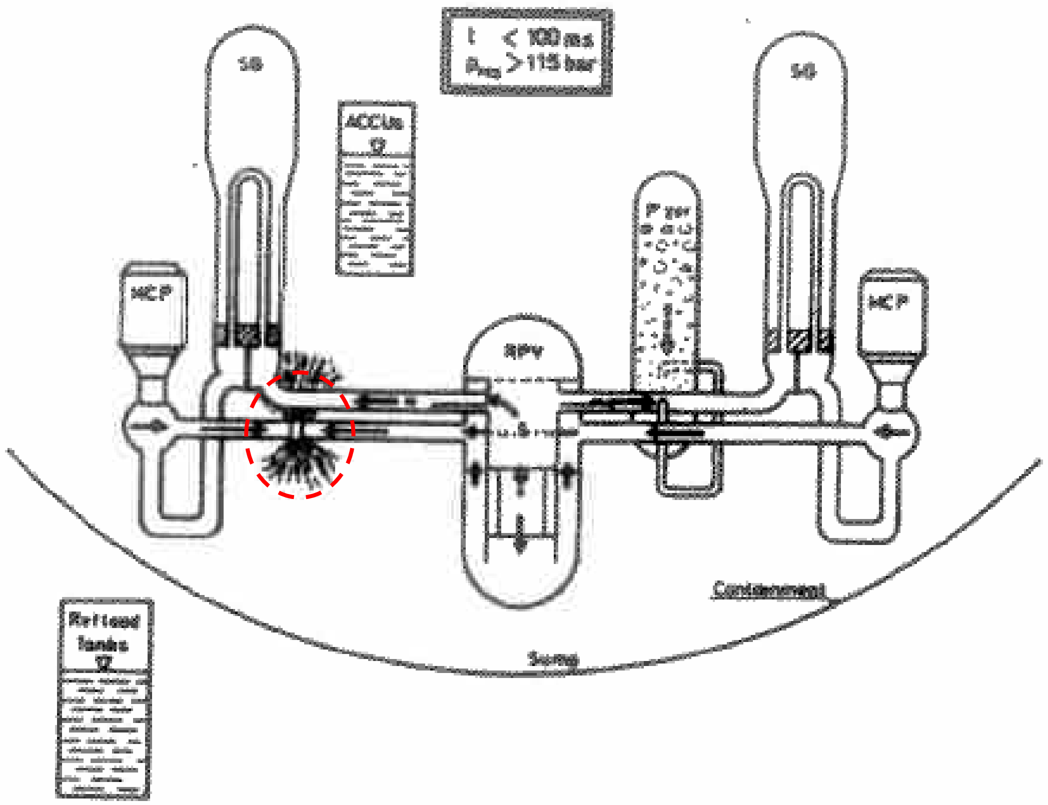
The LBLOCA generally studied is the double-ended break of the hot or cold leg. It is also called “guillotine break” or “200% break”.

The LBLOCA transient can be divided into three main phases where specific phenomena occur:

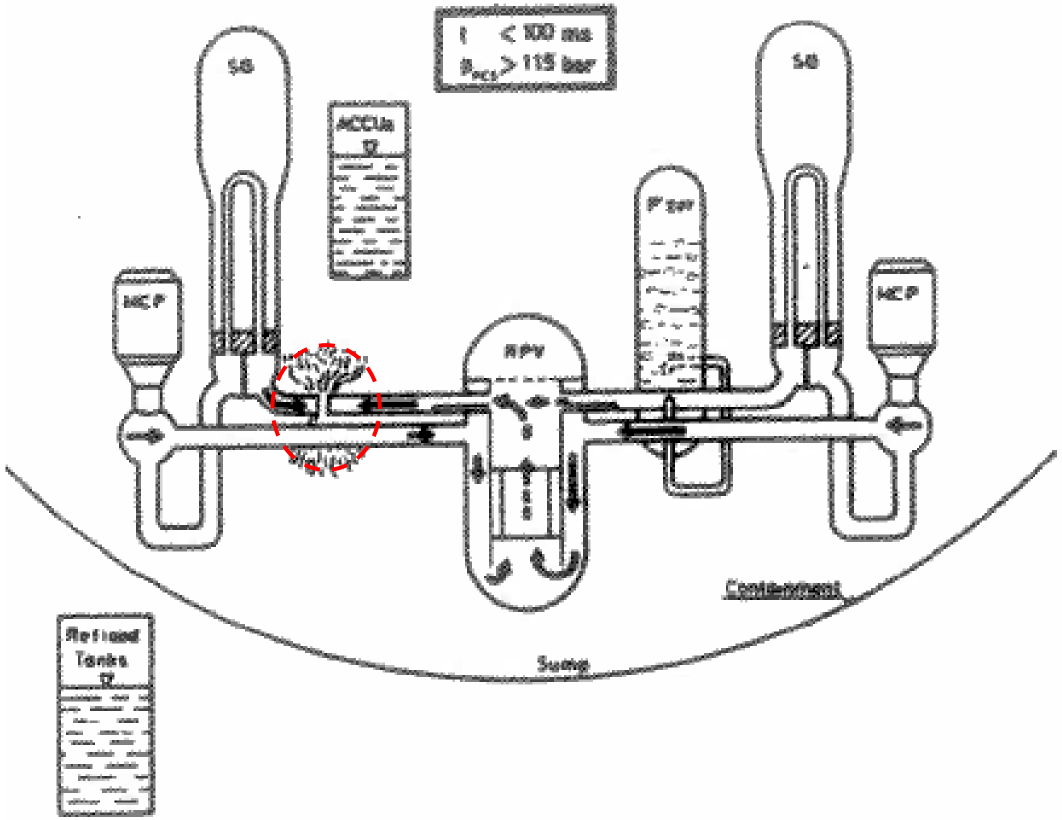
1. Blowdown (subcooled and saturated)
2. Refill
3. Reflood

After these phases the long term cooling of the reactor begins.

LBLOCA: Blowdown



Cold leg LBLOCA



Hot leg LBLOCA

LBLOCA: Blowdown (subcooled)

- At the pipe break:
  - the primary coolant is expelled from the rupture, and it remains initially subcooled (for ~100 ms);
  - the system experiences a rapid subcooled depressurization causing the flow in the reactor core to accelerate for an hot leg break or decelerate for a cold leg break.

- This phase is characterized by the formation of a depressurization wave propagating through the primary cooling system and the reactor pressure vessel, where it could cause a dynamic deformation of the core barrel.

- Such deformation could hinder the insertion of the control rods.

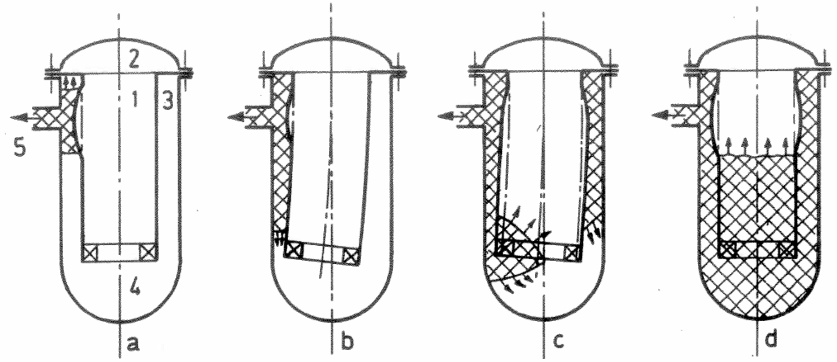


Fig. 22: Depressurization Wave and Resulting Deformation of the Core Barrel after a Large Cold Leg Break [2]
1 Core Barrel
2 RPV Head
3 Downcomer
4 Lower Plenum
5 Break Location close to Inlet Nozzle ; shadowed areas: zones of reduced pressure

LBLOCA: Blowdown (saturated)

- At around 100 ms, the local fluid saturation pressure is reached and the primary fluid boiling (flashing) starts.

- Then the depressurization continues at a considerably reduced rate since choking flow rate through the break decreases if steam is present upstream the break.

- The negative reactivity coefficient, together with decreasing fluid density and voiding in the core (moderator loss), causes the fission process to stop and the core power decline, within a few hundred milliseconds, to the fission product decay heat power.

- The reactor SCRAM, which is usually triggered by low pressurizer pressure (≤145 bar) and water level signal, and high containment pressure signal, occurs at about 0.4 s into the LOCA transient, and is in principle not required in case of Large Break LOCAs in LWRs.

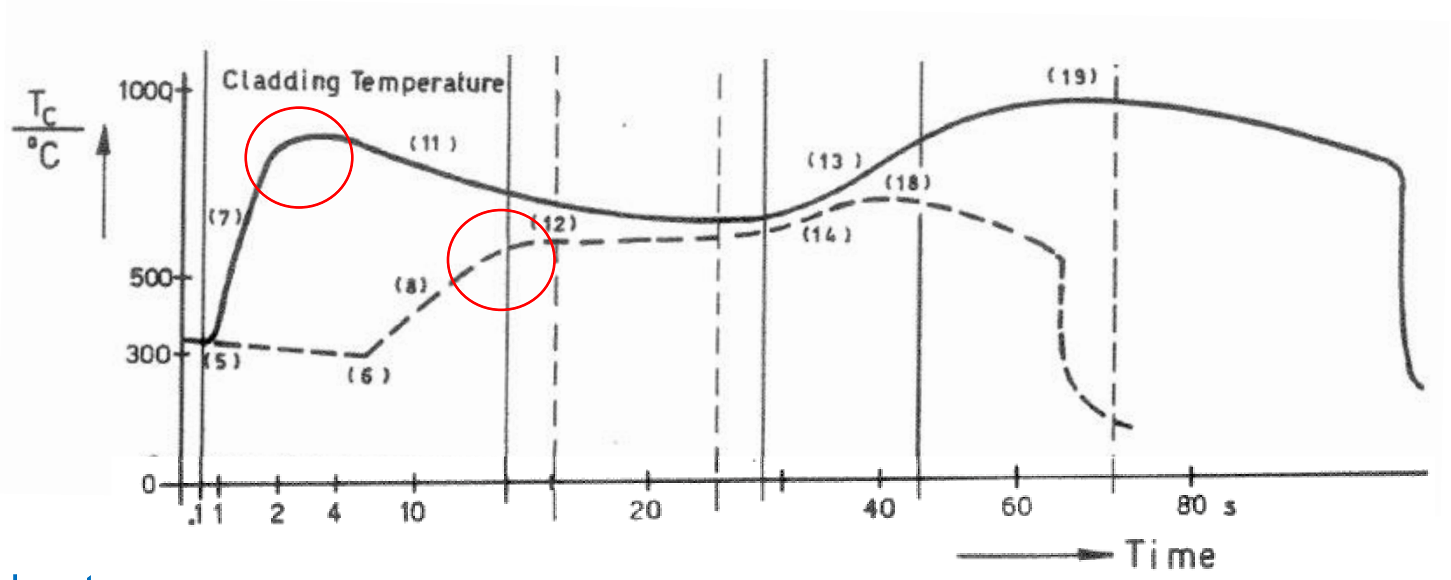
- The reduced coolant pressure and flow through the core, causes a drastic degradation of the cooling for the fuel rods: thermal crisys (DNB or dryout) occurs.

LBLOCA: Blowdown (saturated)

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Stored heat redistribution, first clad temperature peak:

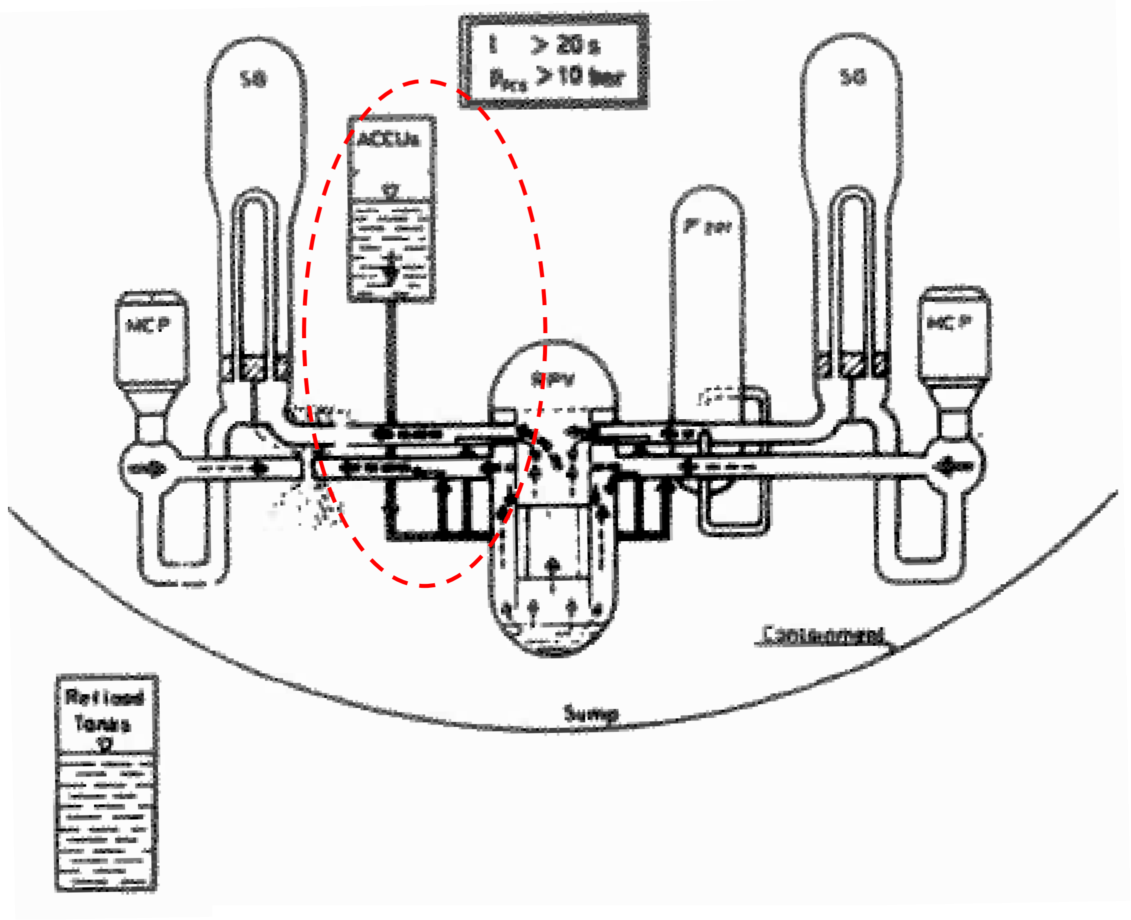
- Loss of heat removal → stored heat within the fuel redistributes and leads to an equalization of the internal temperature distribution → the cladding temperature starts rising sharply.
- According to conservative calculations, in the worst case the real maximum cladding temperature would barely exceed 900°C.



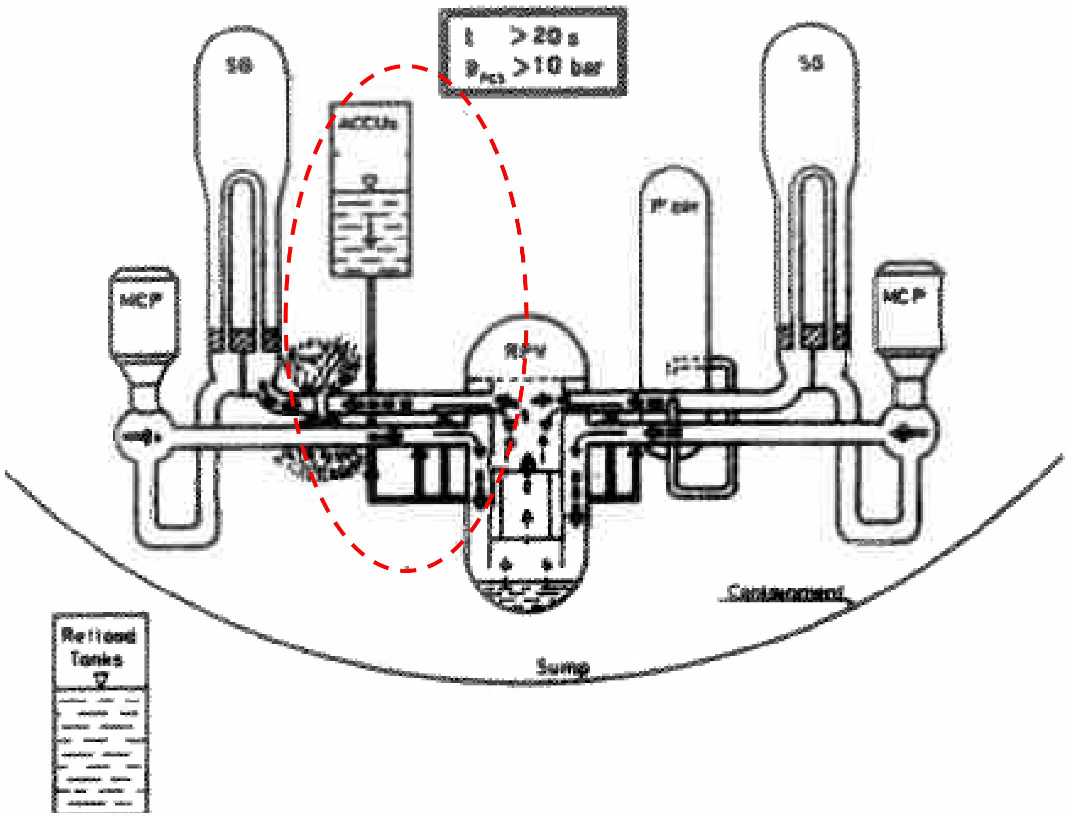
Additional heat sources:

- fission decay heat;
- heat generated by the chemical reaction between zircaloy and steam (hydrogen and zirconium dioxide are formed) for cladding temperatures >980°C

LBLOCA: ECCS activation (accumulators)



Cold leg LBLOCA



Hot leg LBLOCA

LBLOCA: ECCS activation (accumulators)

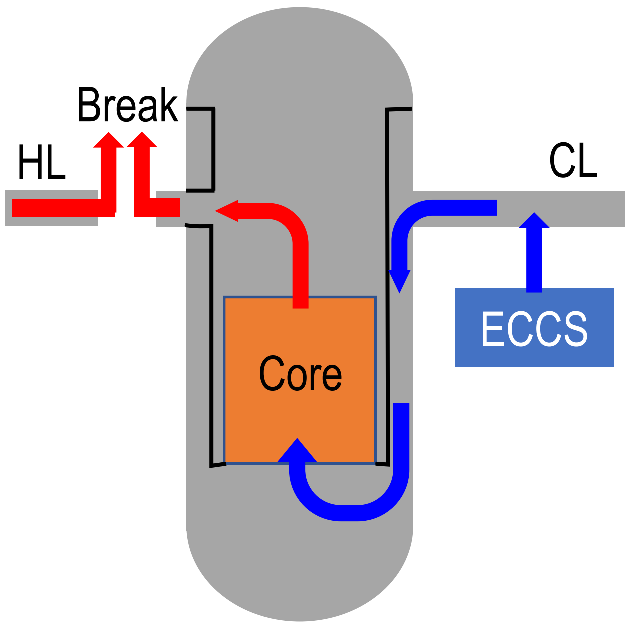
- When the primary system pressure decreases below the gas pressure in the dome of the ECCS accumulators, the relatively cold emergency coolant is discharged from the accumulators through automatically opening check valves.

- This occurs after 10-15 s, depending on both the system depressurization rate and the accumulator pressure (e.g. about 45 bar in Westinghouse plants, 27 bar in KWU plants).

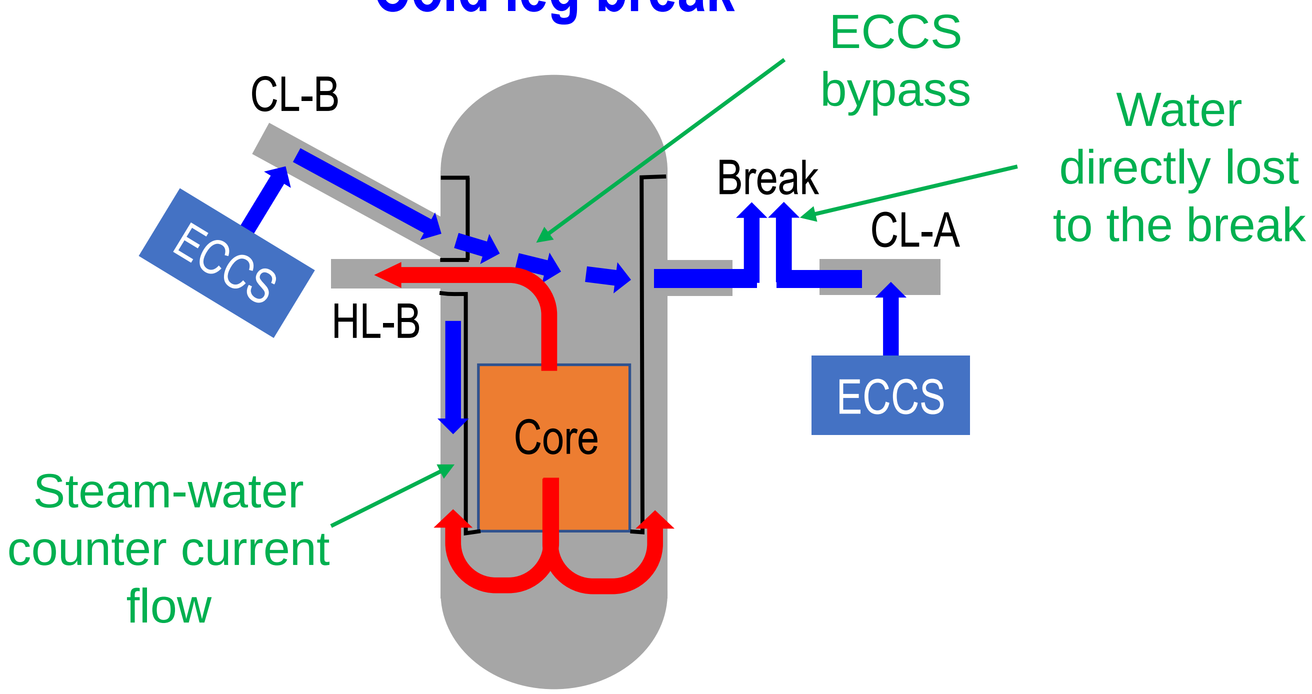
LBLOCA: ECCS bypass

The most severe LOCA is in general the cold leg break one since in this case the ECCS water bypasses the core.

Hot leg break



Cold leg break



LBLOCA: ECCS bypass

- Since at this time the system pressure is still high with respect to containment pressure, there is still a substantial mass flow rate through the break.

- In hot leg break LOCA with continuing upward flow through the core, the emergency coolant will penetrate the downcomer, refill the lower plenum and finally reflood the core.

- In cold leg break LOCA, lower plenum refilling is delayed essentially by :
  - Steam water counter-current flow in the downcomer annulus
  - Accumulator ECC bypass around the downcomer

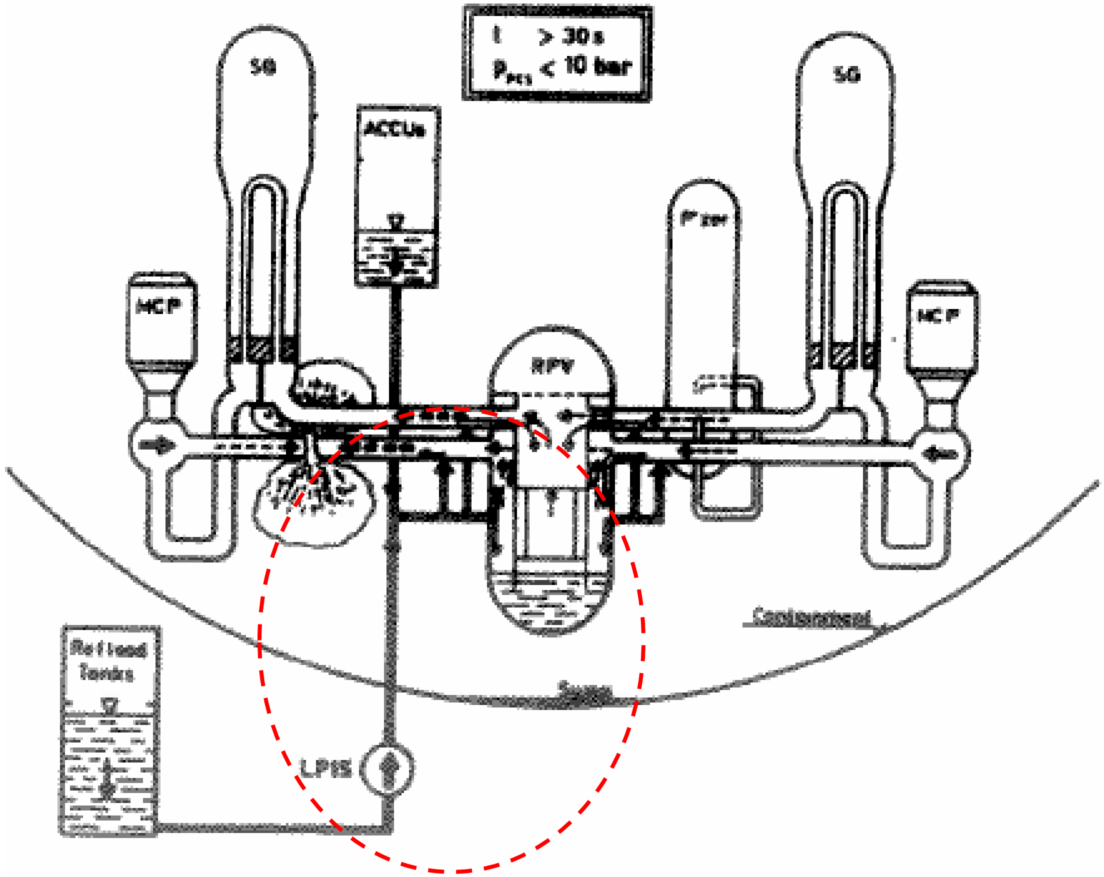
LBLOCA: ECCS LPIS activation

- After about 30 s, when the system pressure has dropped below about 10 bar, the Low Pressure Injection System (LPIS) starts operating.
- For a short period, emergency coolant is supplied from both the accumulators and the LPIS, until the accumulators have emptied.
- The LPIS continues to inject water for as long as is required, taking water from the RWST and, later on, from the containment sump.
- The HPIS is not needed in LBLOCA:
  - the pressure decreases so rapidly that both accumulators and LPIS are very quickly activated,
  - it would not make a significant contribution due to the low nominal mass flow rate.

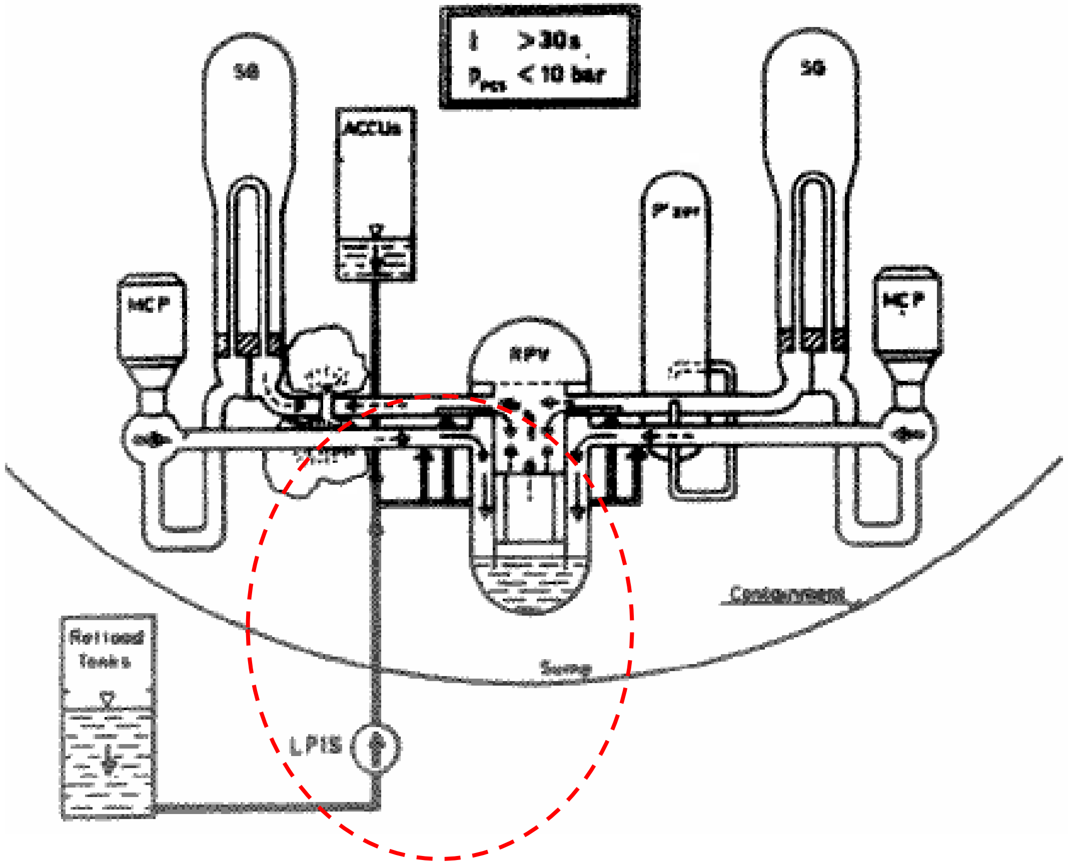
LBLOCA: End of blowdown

- The blowdown phase is usually considered to have terminated when the pressure equalization between primary system and containment (at about 2-4 bar) has been achieved and break mass flow has become negligible, which occurs in either break location at about 30-40 s into the LOCA transient.
- Under cold leg break conditions, it is only after steam flow from the intact loop cold legs has become negligible, that gravity forces begin to overcome the entrainment forces in the downcomer and emergency water starts to penetrate the downcomer and to refill the pressure vessel.

LBLOCA: Refill



Cold leg LBLOCA



Hot leg LBLOCA

LBLOCA: Refill

- The refill period starts when emergency coolant water reaches the pressure vessel lower plenum for the first time and causes the water level to start rising again; refill is terminated when the water level has reached the Bottom of Active Fuel (BAF).

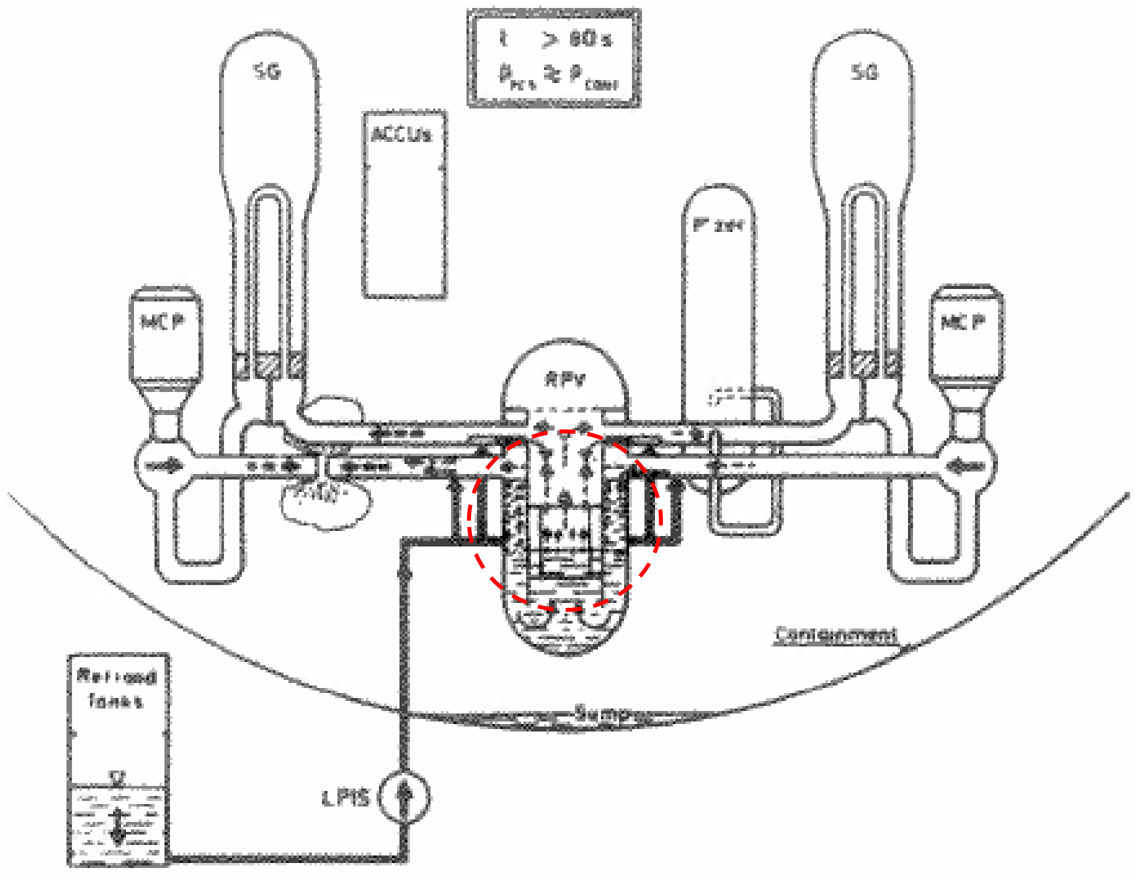
- As the lower plenum fills and the coolant reaches the bottom of the core, steam begins to be generated.

- During the whole period from before accumulator injection initiation, up to the end of refill, the reactor core is essentially uncovered and the fuel rods are uncooled except by thermal radiation and by the small natural convection current in the steam-filled core.

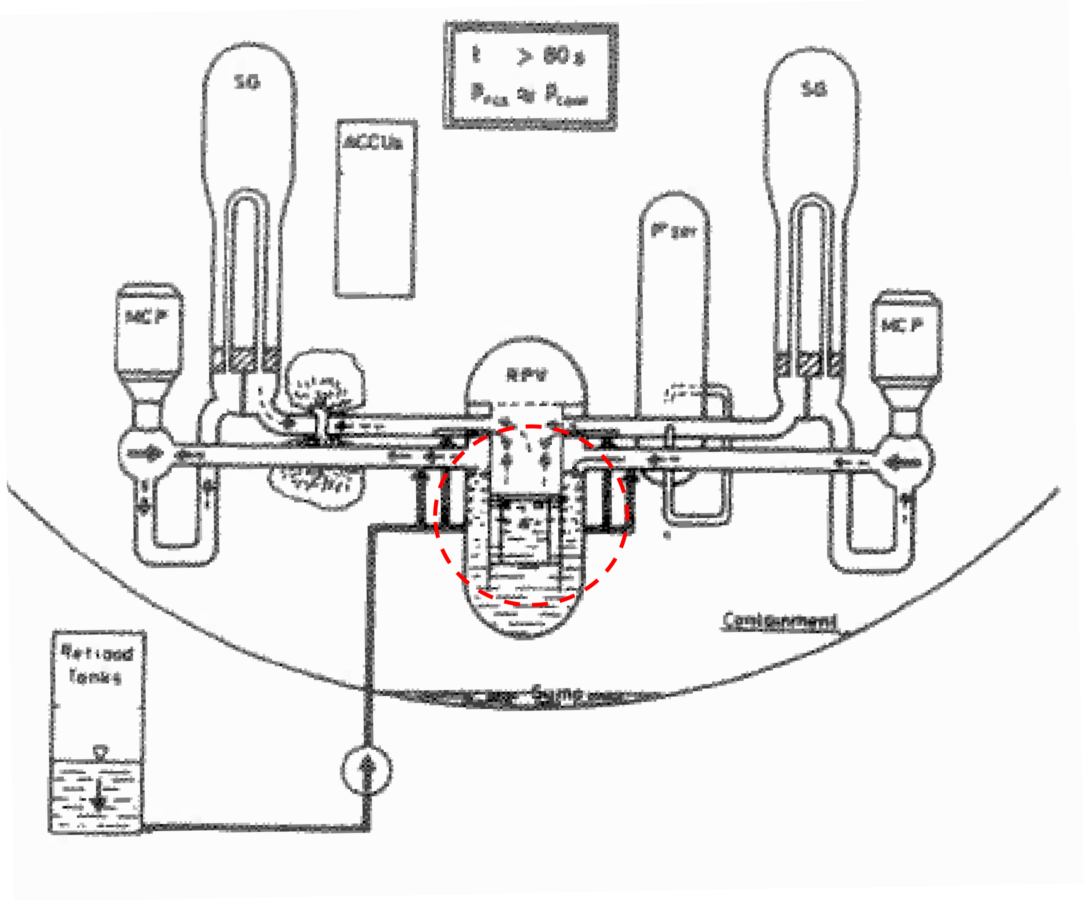
- Due to the decay heat release, the core temperatures rise adiabatically during this period at a rate of about 8-12°C/s for PWRs and about 5-7°C/s for BWRs.

- The refill period is the period with the poorest core cooling of the whole LOCA.

LBLOCA: Reflood



Cold leg LBLOCA

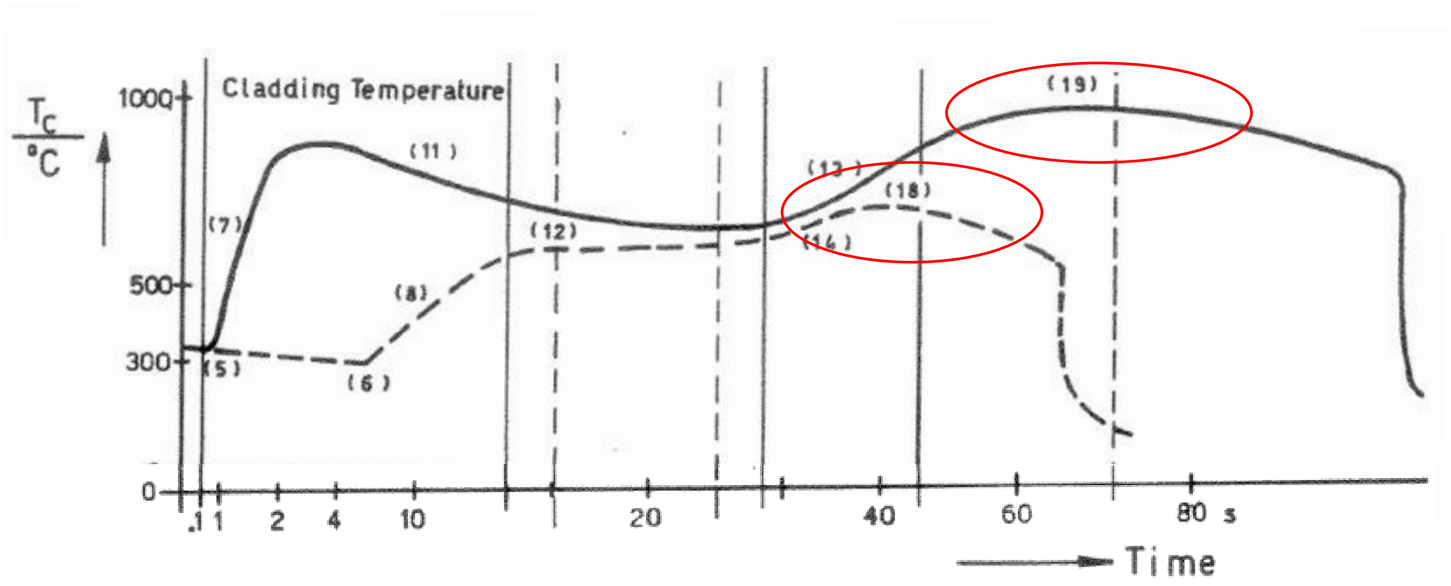


Hot leg LBLOCA

LBLOCA: Reflood

Second peak cladding temperature:

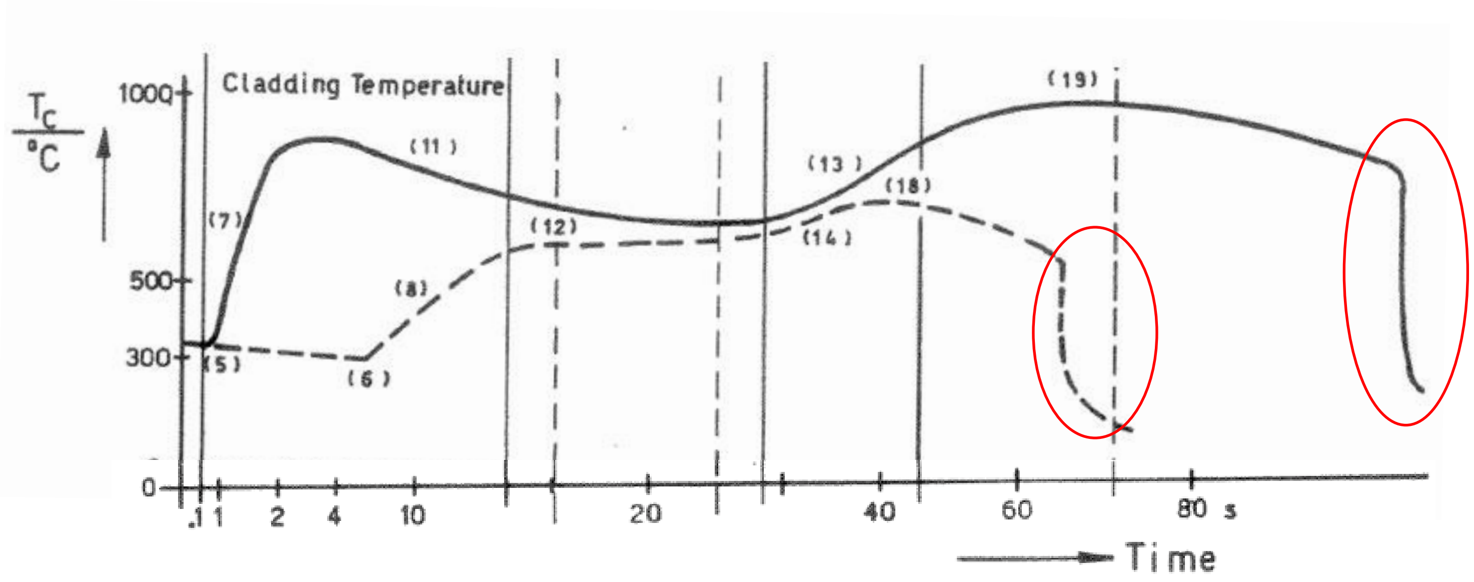
- The water that enters the core is heated up and starts boiling. At about 0.5 m above the BAF the boiling process causes a rapid flow of steam upwards through the core.
- This flow entrains a substantial amount of water droplets which provide an initial cooling of the hotter core regions.
- This cooling effect becomes increasingly effective, progressively reducing the rate of rise of cladding temperature and finally reversing the rise in temperature of the hot spot.



LBLOCA: Reflood

Core quenching:

- When the cladding temperature has sufficiently decreased (to about 350-550°C) the emergency coolant rewets the cladding surface and causes a sharp temperature drop (quenching).
- This quench front rises into the core from the bottom end (in case of cold injection only) or propagates from both ends into the core (in case of cold and hot leg or upper head injection).
- When the whole core has quenched and the water level has finally risen above the Top of Active Fuel (TAF), the reflooding period is considered to be terminated (1-2 minutes).



LBLOCA: Long term cooling

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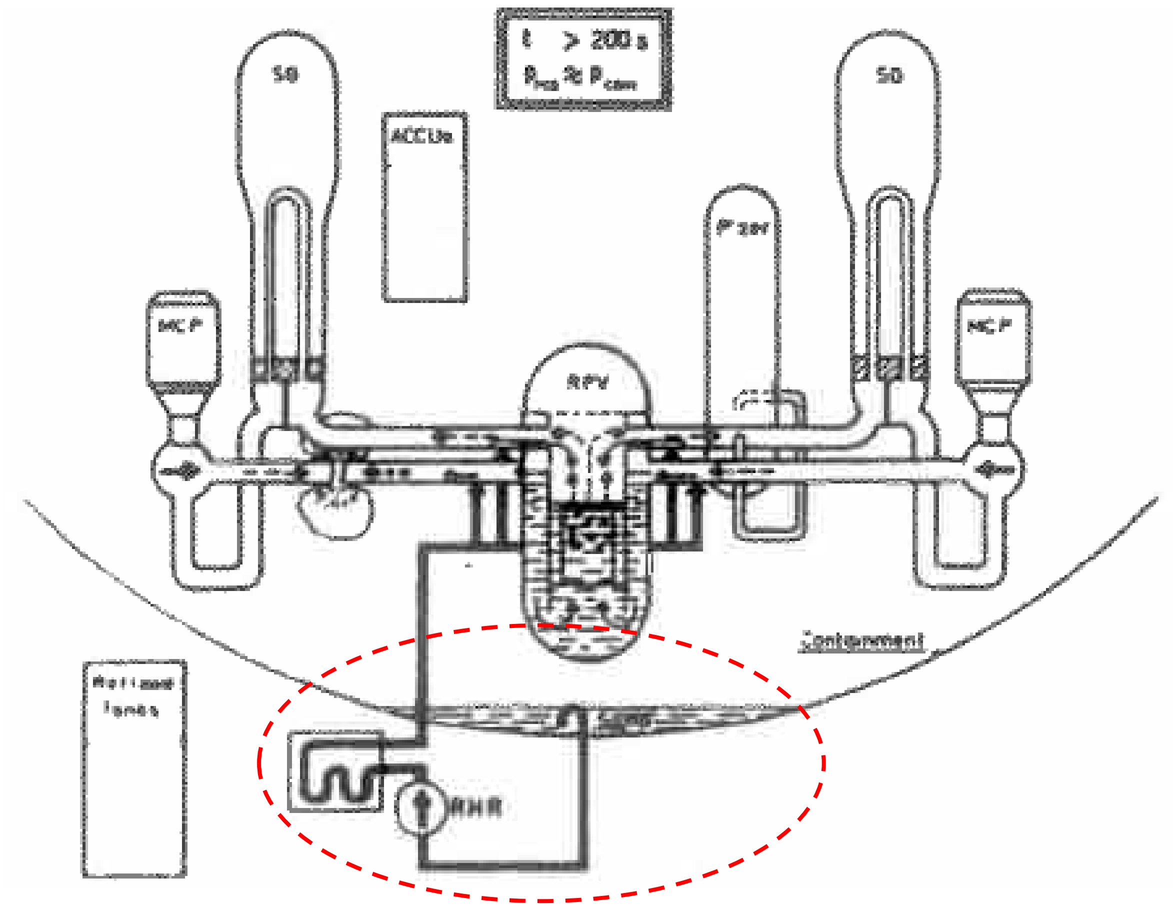
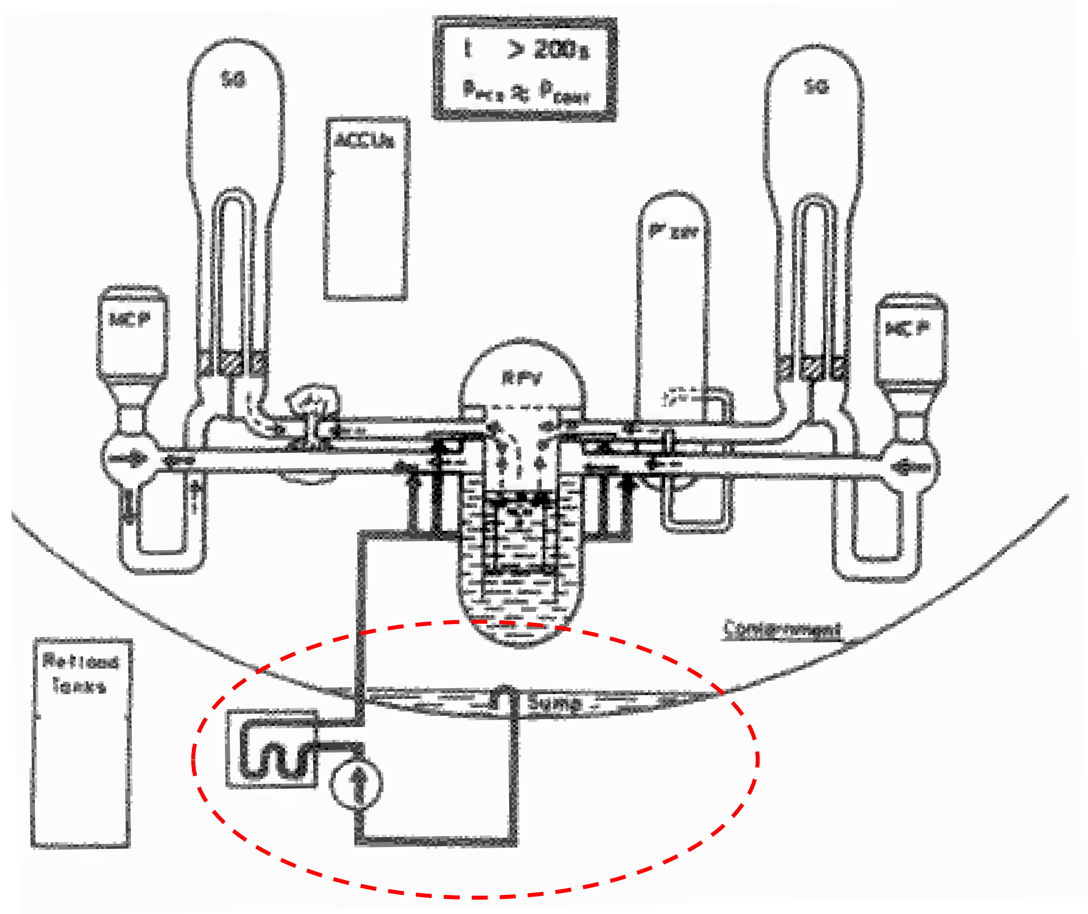


Cold leg LBLOCA



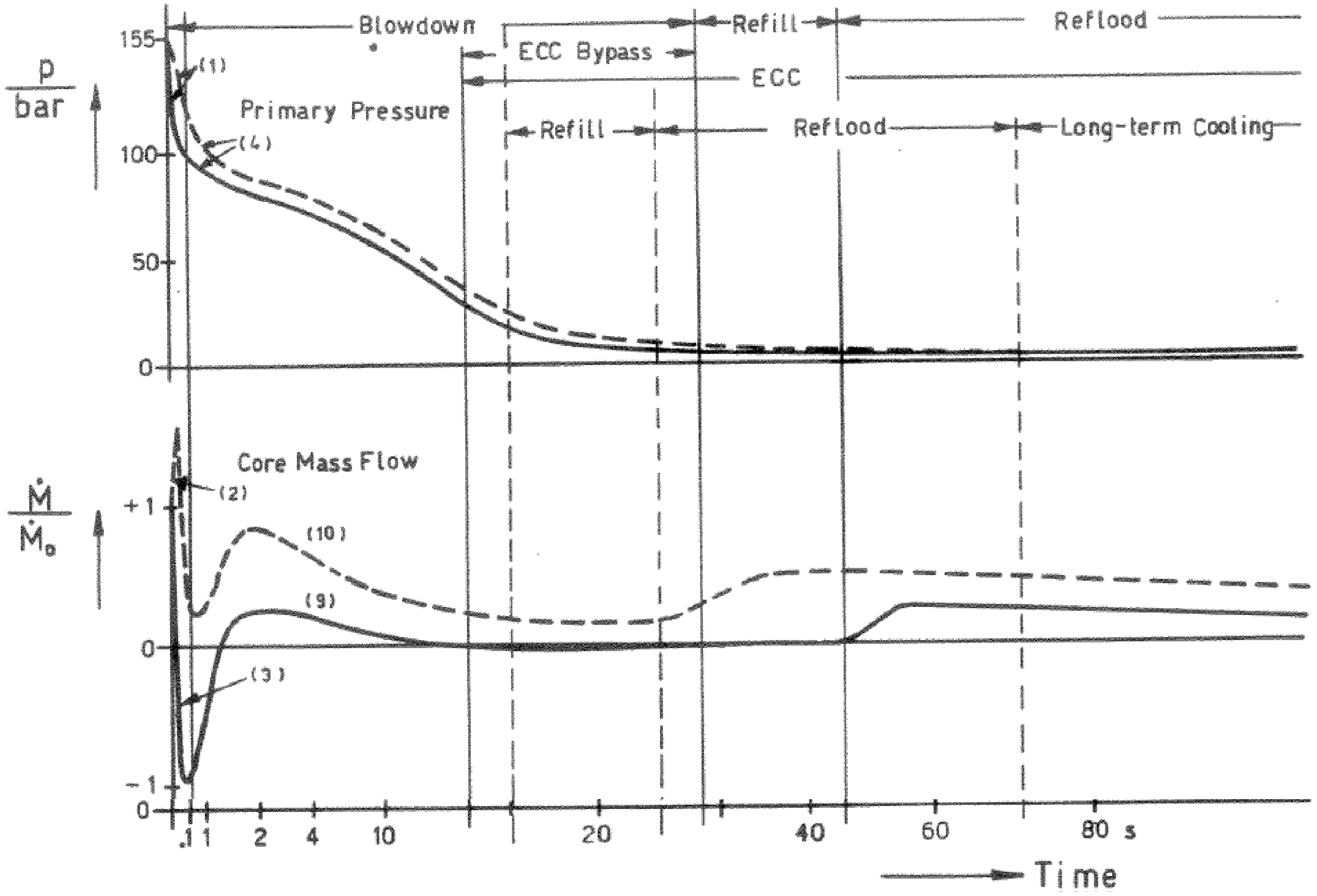
Hot leg LBLOCA

LBLOCA: Long term cooling

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- After the end of the reflood phase the “fast” part of the LOCA transient is terminated.
- However it is still necessary to continue to remove the decay heat power produced in the core.
- This is called “long-term cooling” and it is achieved by the Residual Heat Removal System (RHRS)
- Once the injection tanks are emptied, the sump circulation begins.

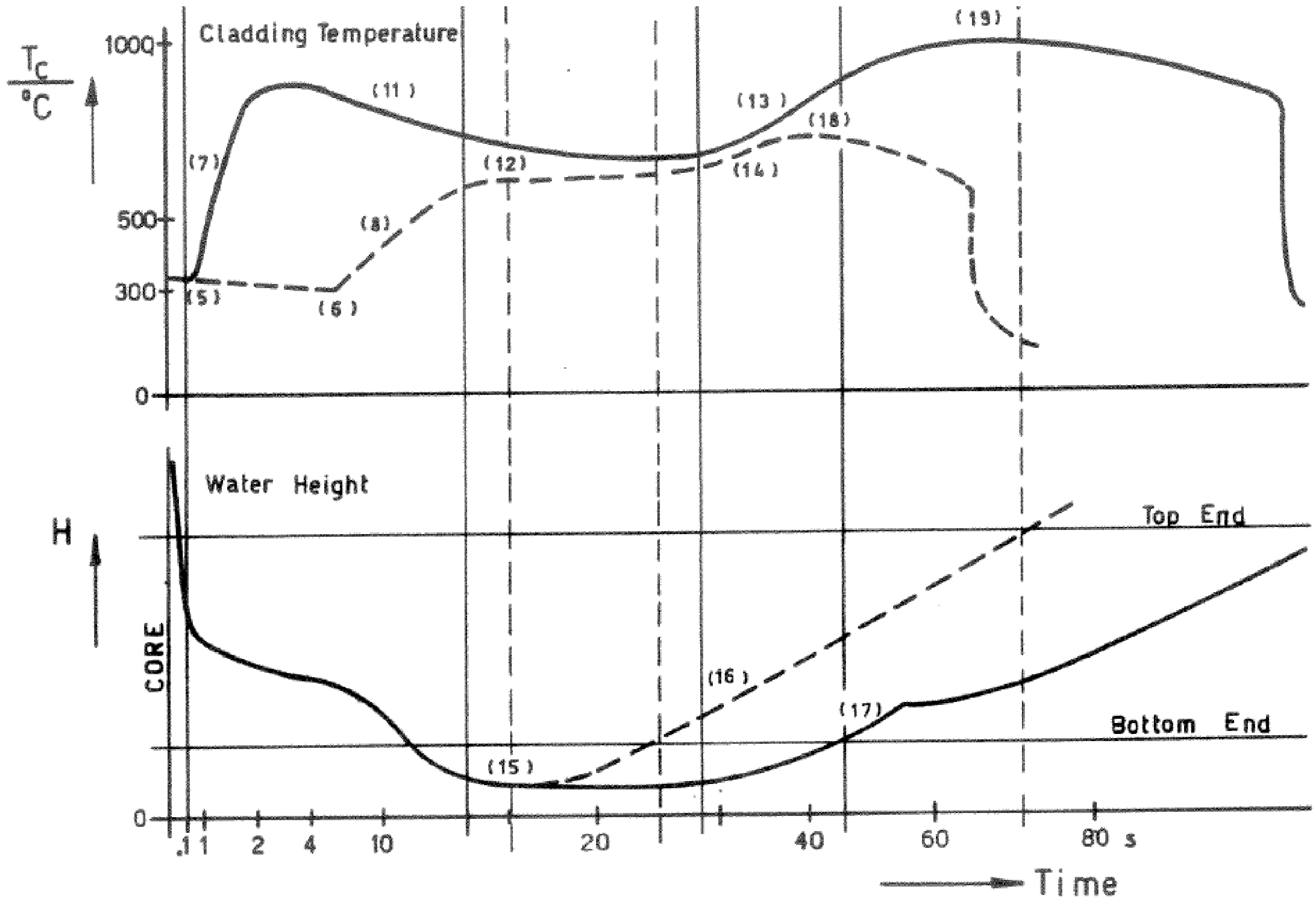
LBLOCA phases



CL break
HL break

LBLOCA phases

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS



CL break
HL break

LBLOCA from theory to practice…

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

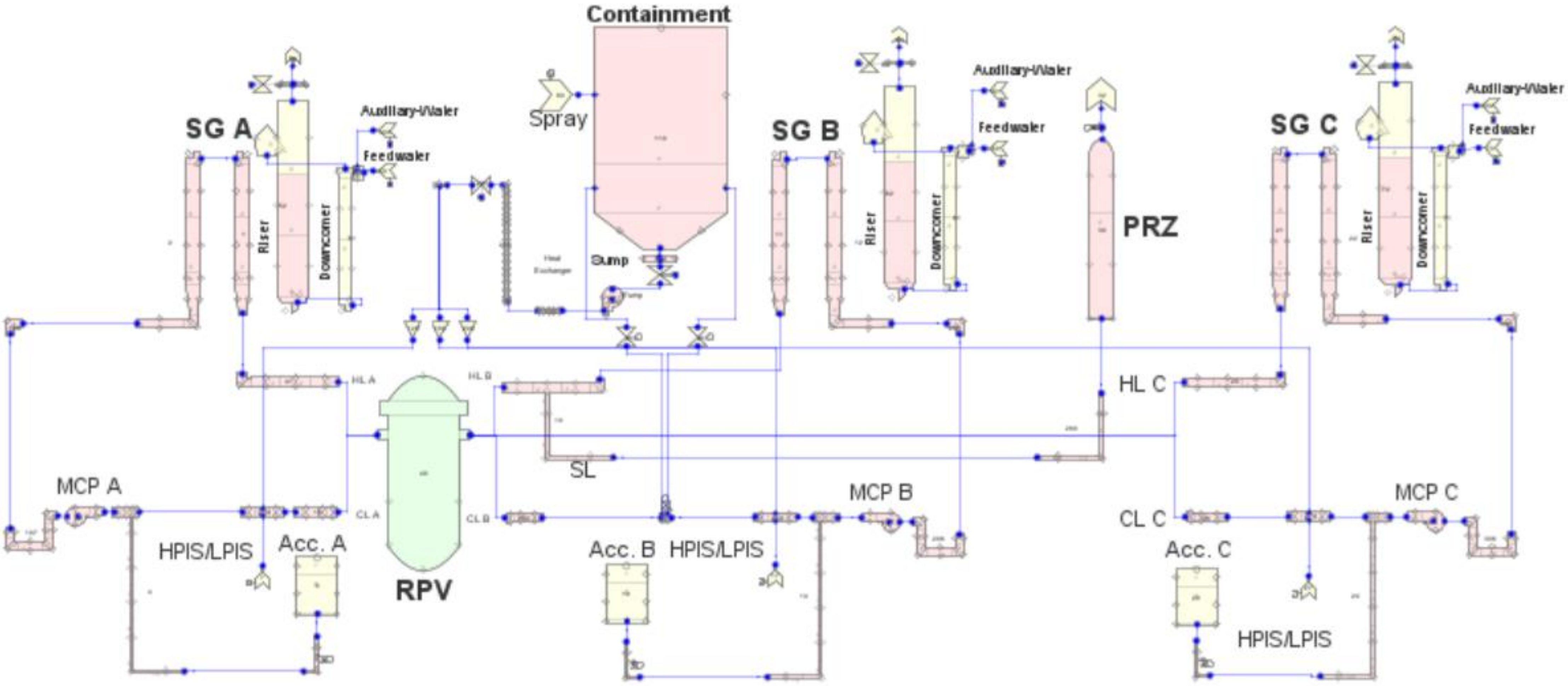
- Deterministic Safety Analysis (DSA) are performed to analytically characterize the phenomena taking place during an accident (e.g. DBA and BDBA). It gives the necessary information to judge if selected safety requirements are fulfilled by the selected NPP in transient conditions.

- LBLOCA transient may be simulated by thermal-hydraulic system codes.

- In the following slides it is shown an exemplificative calculation performed with the TRAC/RELAP Advanced Computational Engine (TRACE) code, developed by USNRC.

- A generic three loops western type PWR was considered and the double ended guillotine break of one cold leg was postulated.

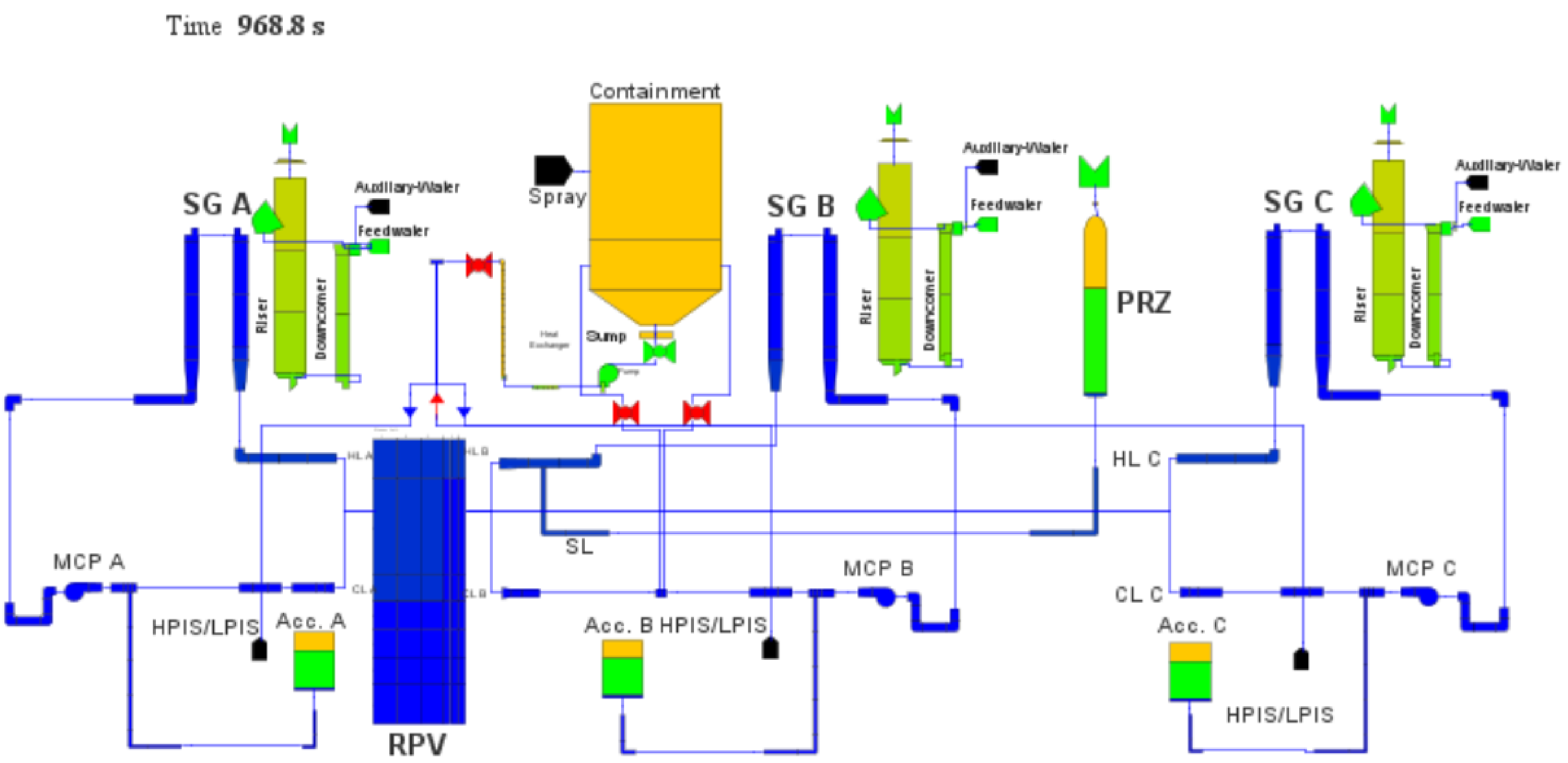
LBLOCA simulation, nodalization

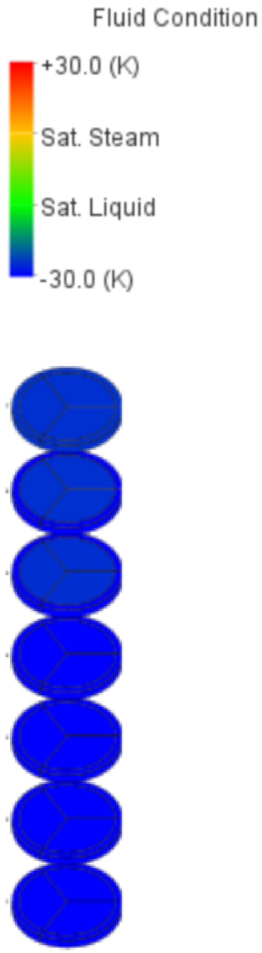


LBLOCA simulation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Steady state conditions

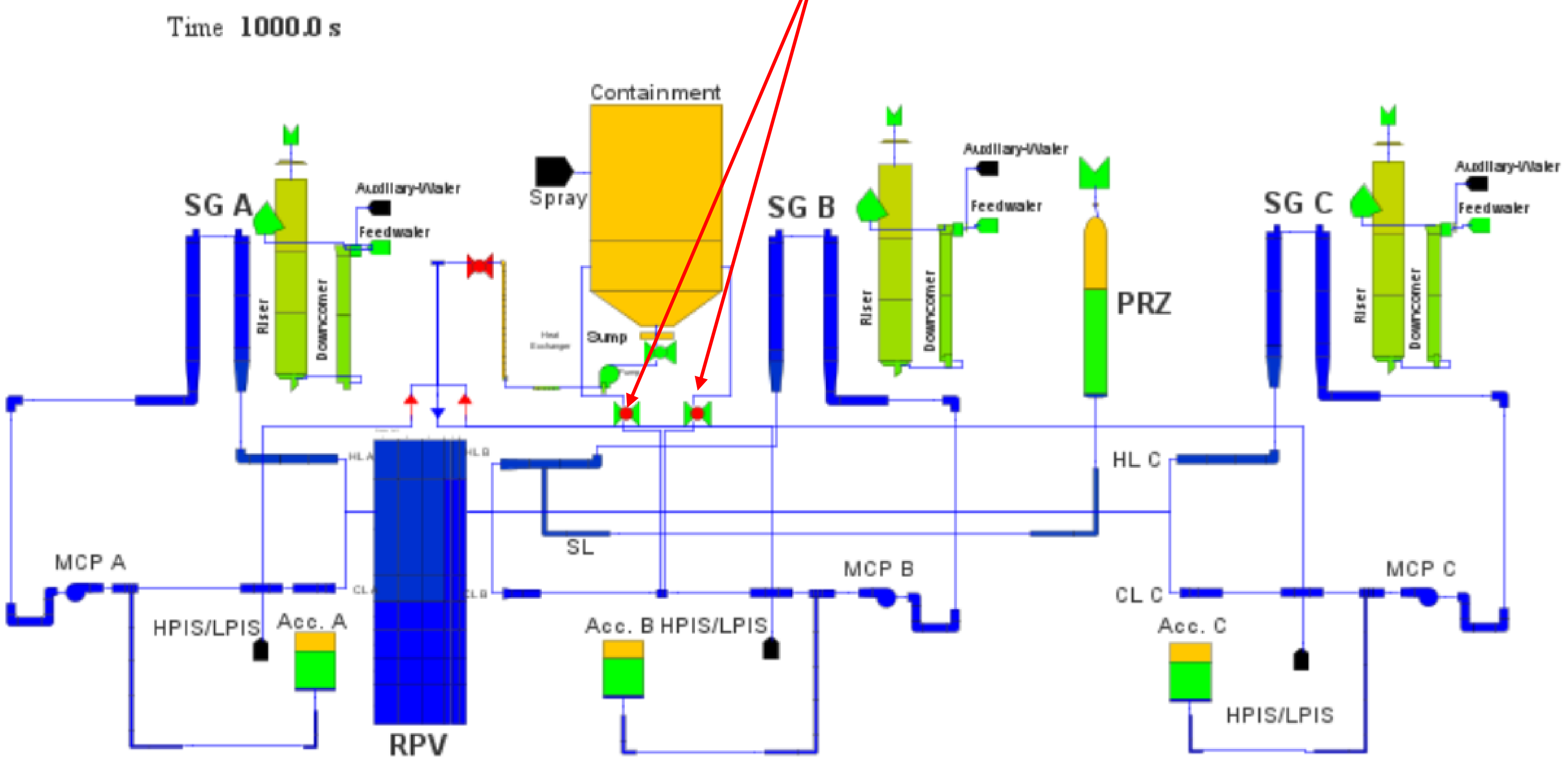


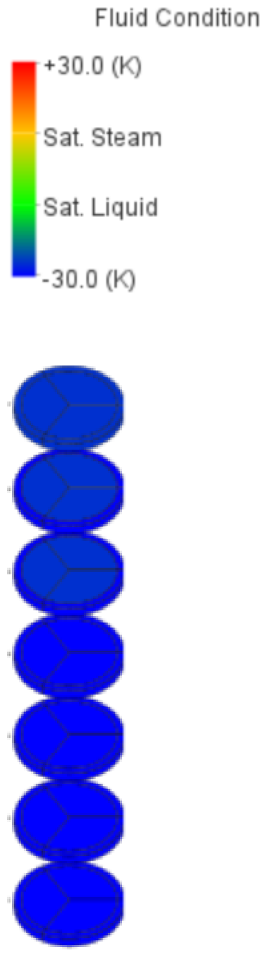


3D RPV

LBLOCA simulation

Opening of the break



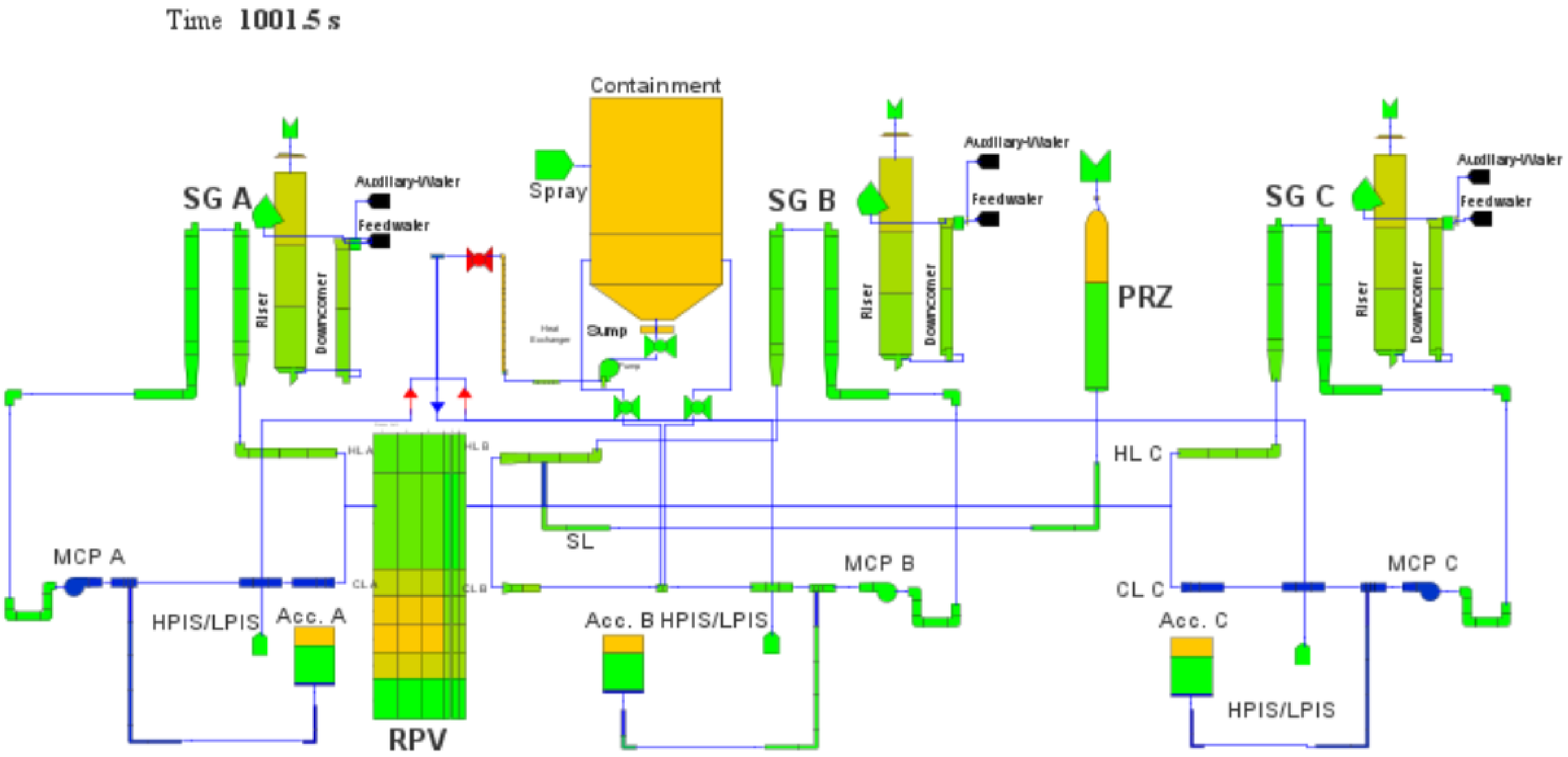


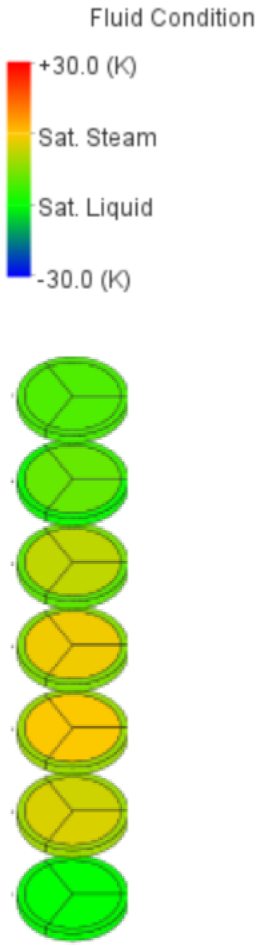
3D RPV

LBLOCA simulation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

Blowdown phase





3D RPV

LBLOCA simulation

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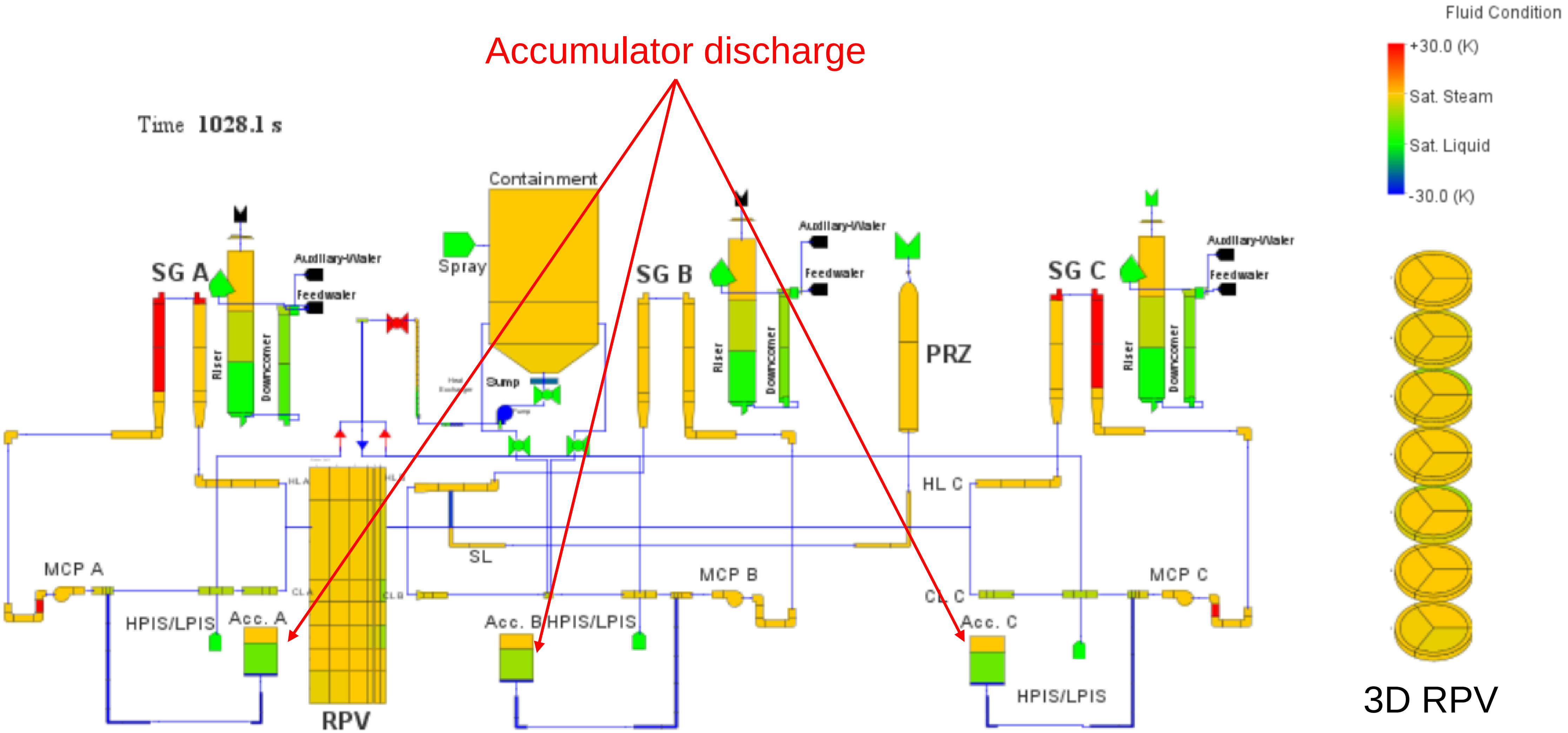
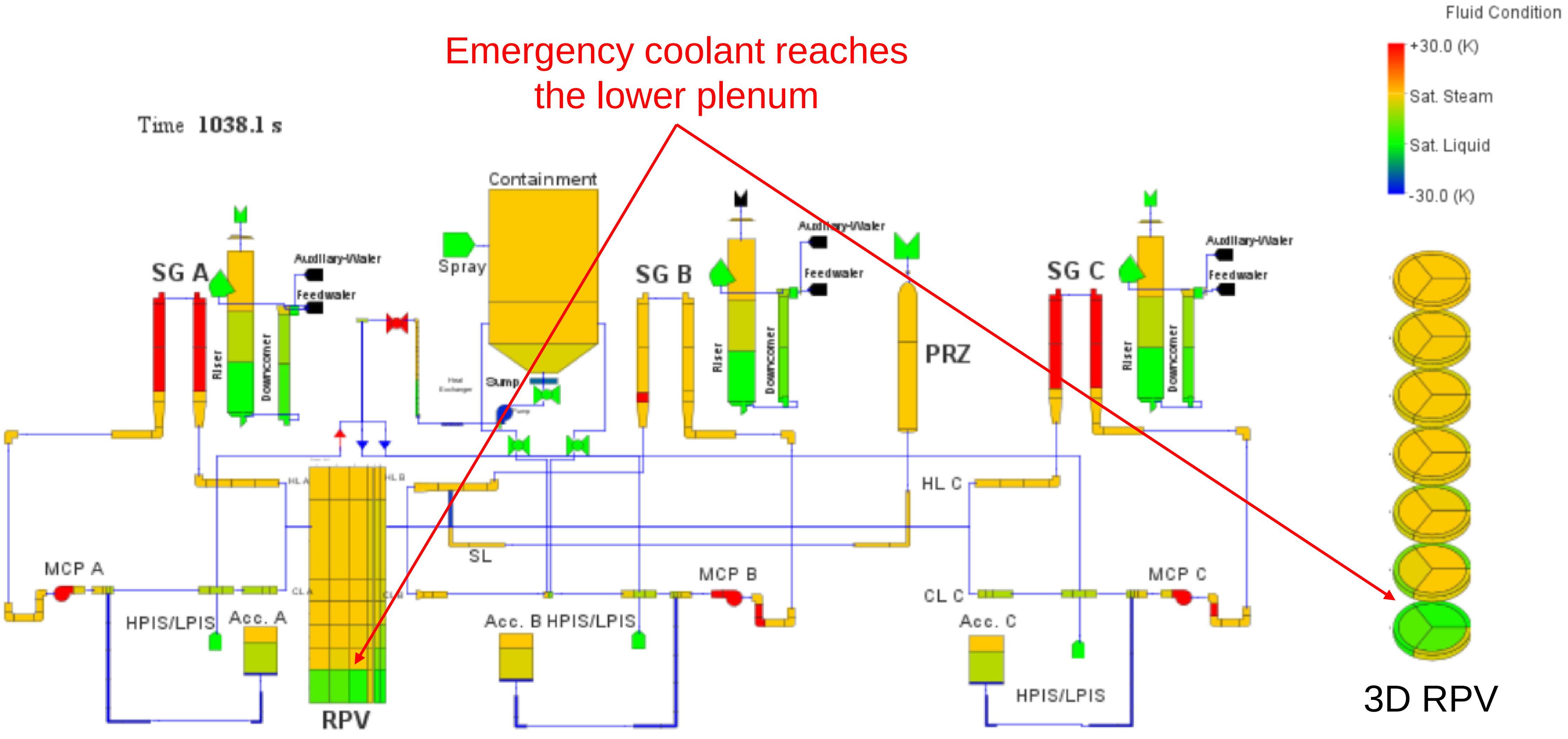


LBLOCA simulation



LBLOCA simulation

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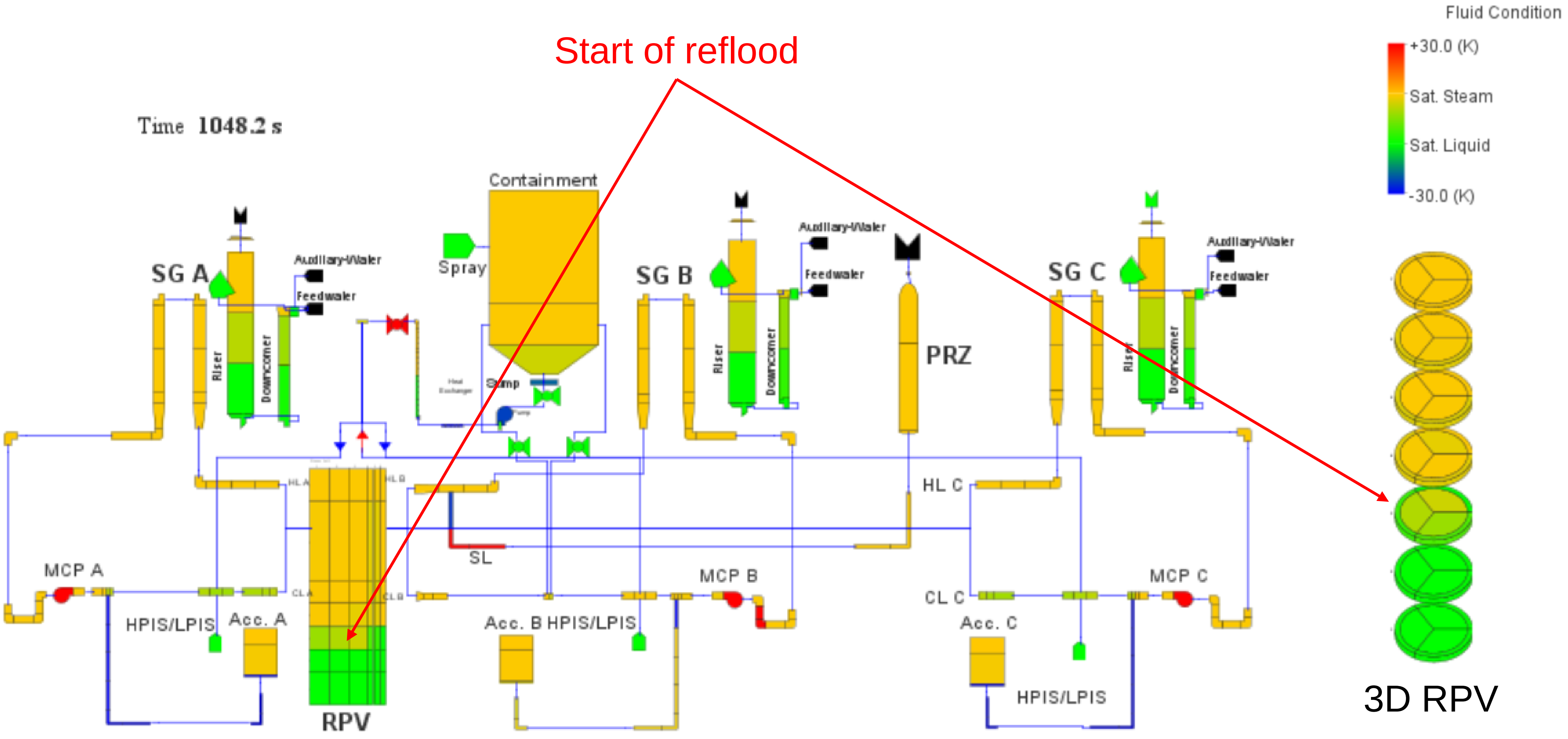

LBLOCA simulation

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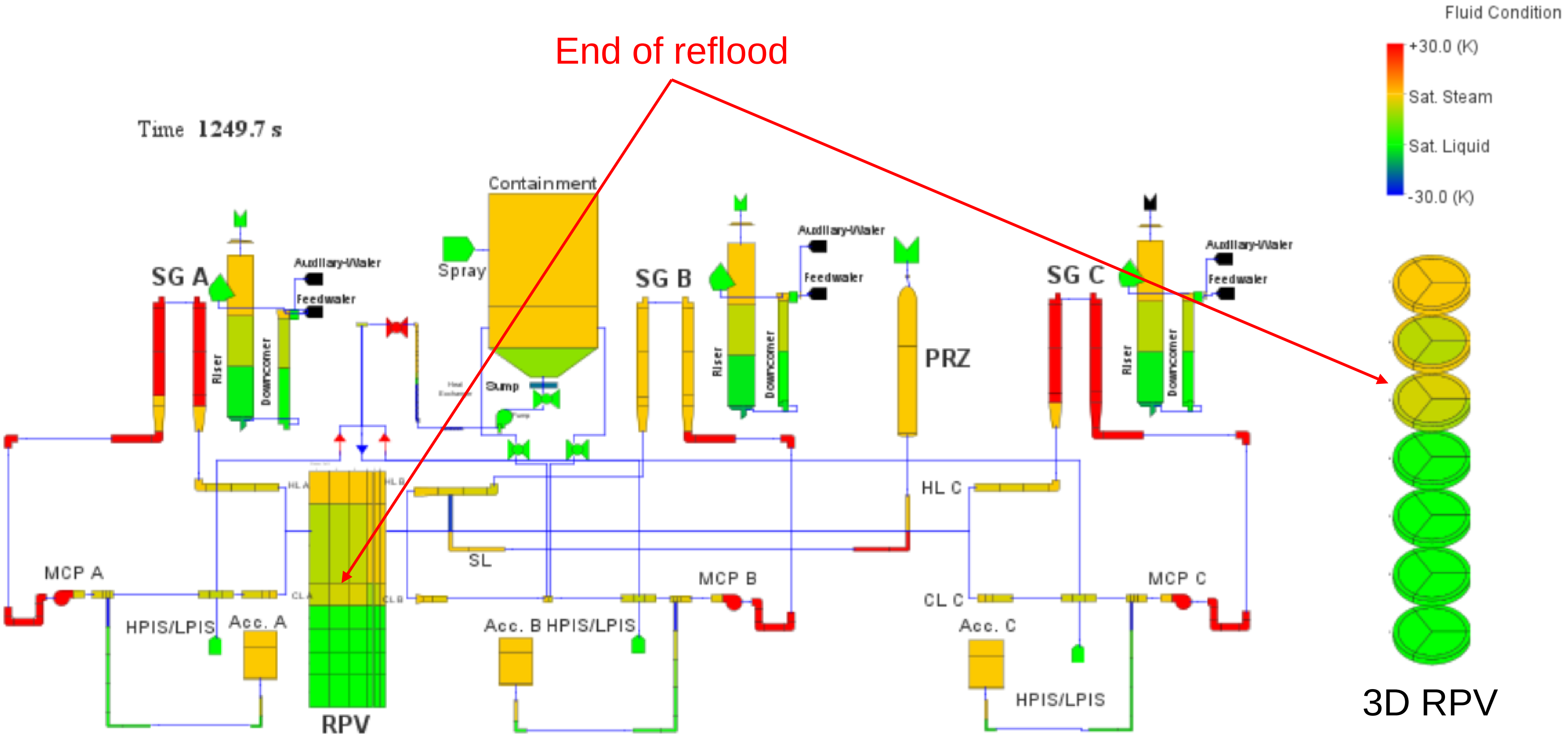
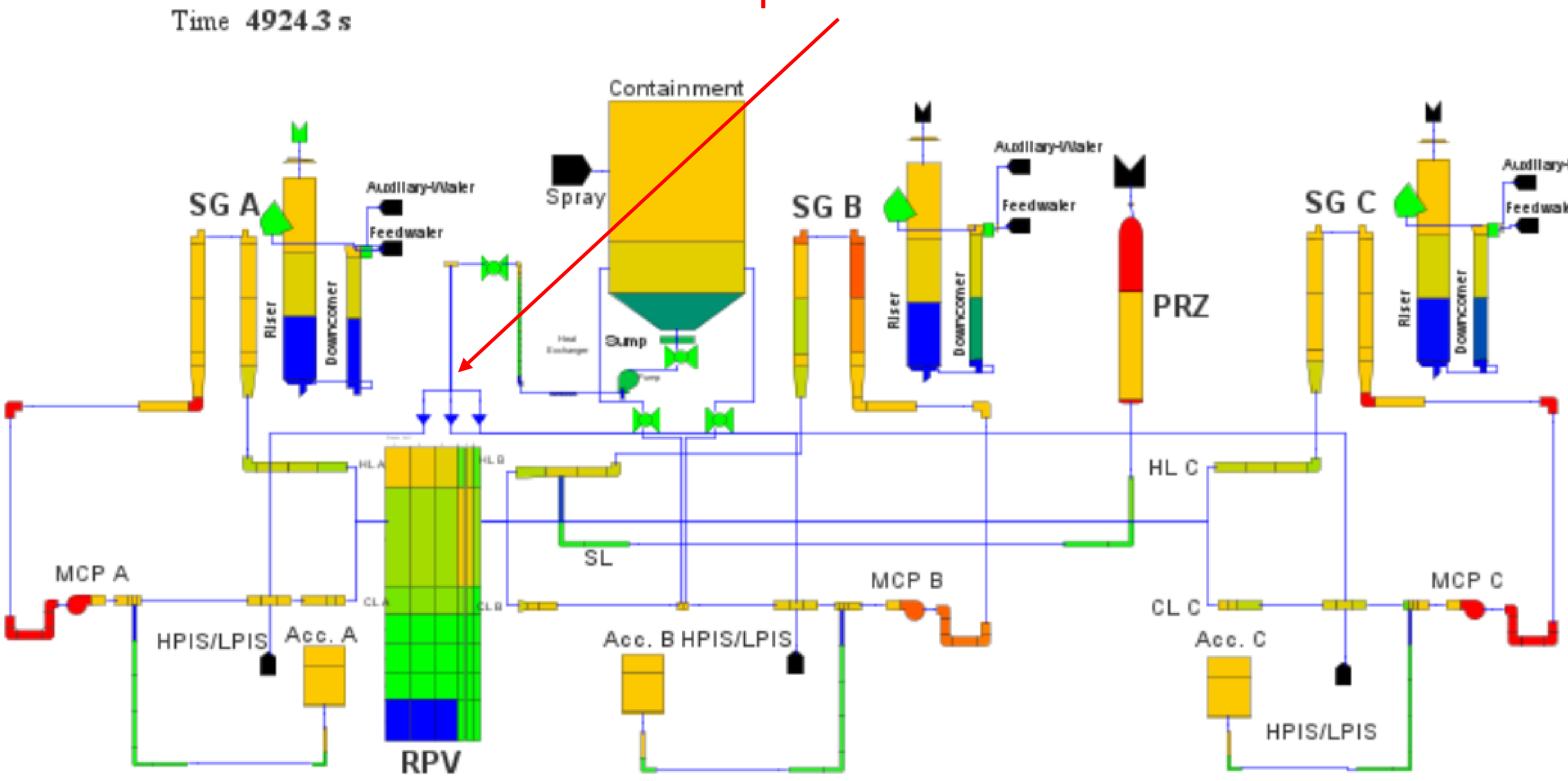
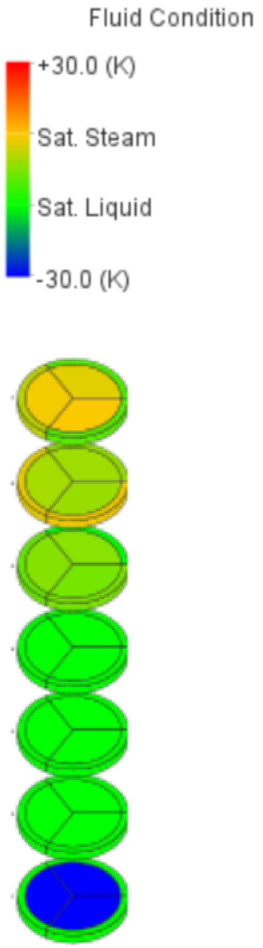


LBLOCA simulation

Long term cooling, start of sump circulation



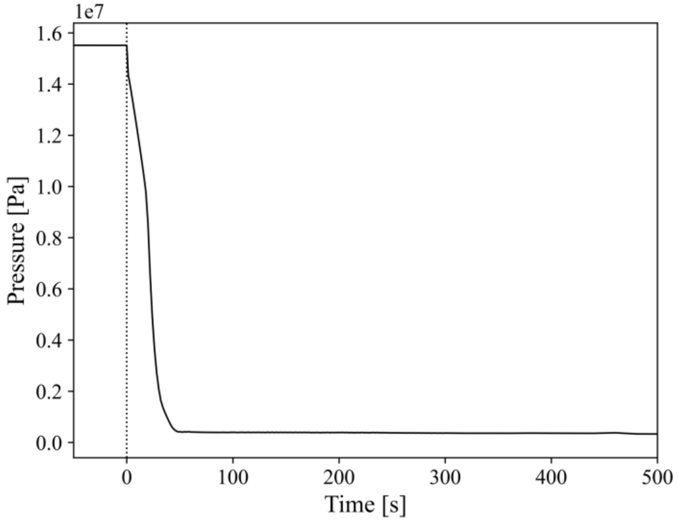


3D RPV

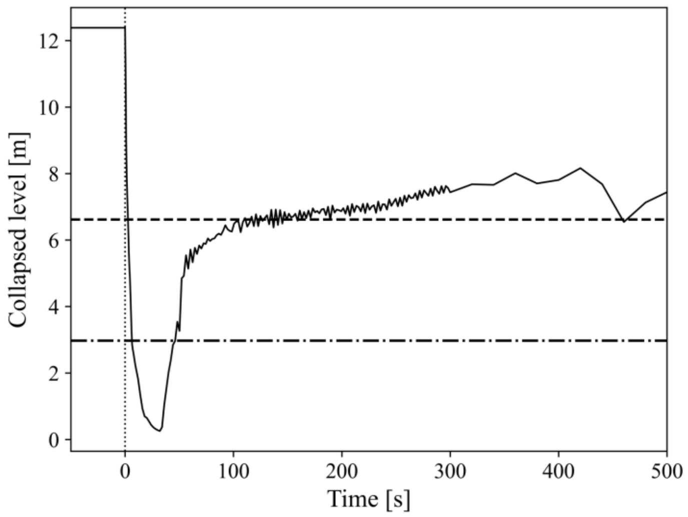
LBLOCA simulation

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

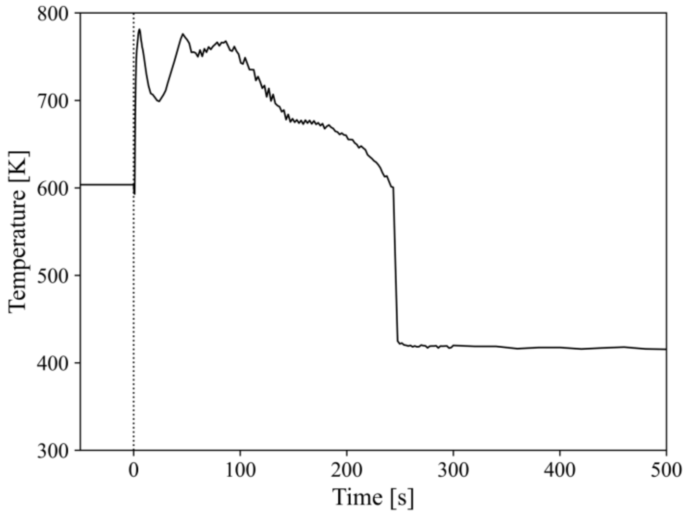
Primary pressure



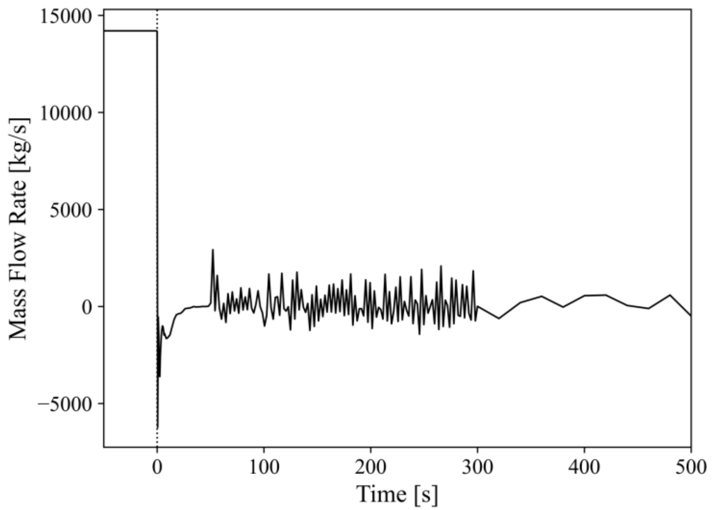
RPV level



Maximum cladding temperature



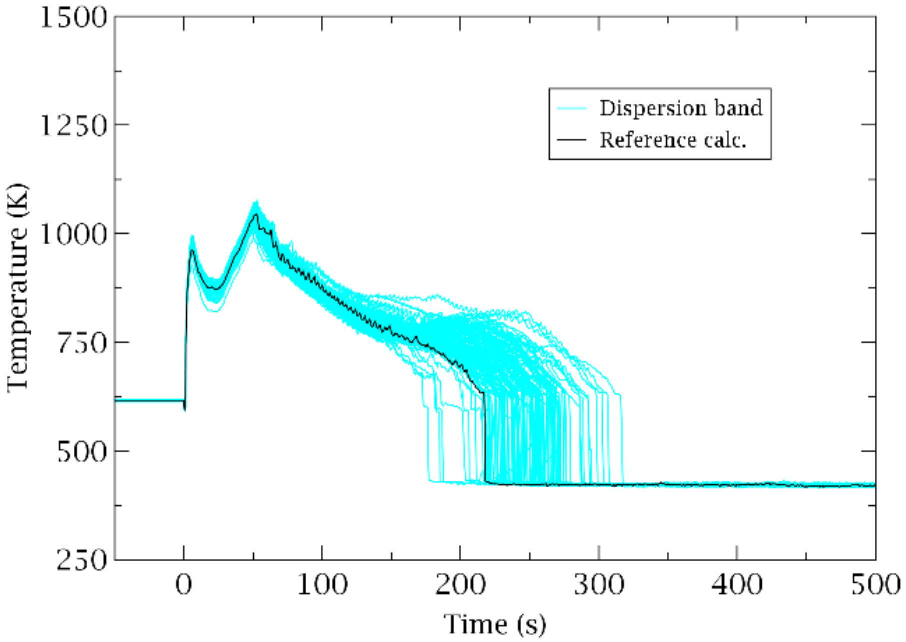
Core flow rate



LBLOCA simulation, uncertainty analysis

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

- At the beginning of the use of computational tools to perform deterministic safety analysis, a conservative approach was adopted.
- The improvement in the computational capabilities and in the knowledge of thermal-hydraulic phenomena during the ‘70 and ‘80 enabled the adoption of a more realistic approach known as Best-Estimate (BE).
- However, lacks are still present in the knowledge of physical phenomena, models, closure equations, etc.
- Therefore, it is not possible to consider the result of a BE calculation as the real value of a parameter and it is important to quantify the related uncertainty.
- This approach is called Best-Estimate Plus Uncertainty (BEPU).



Small Break Loss Of Coolant Accident SBLOCA

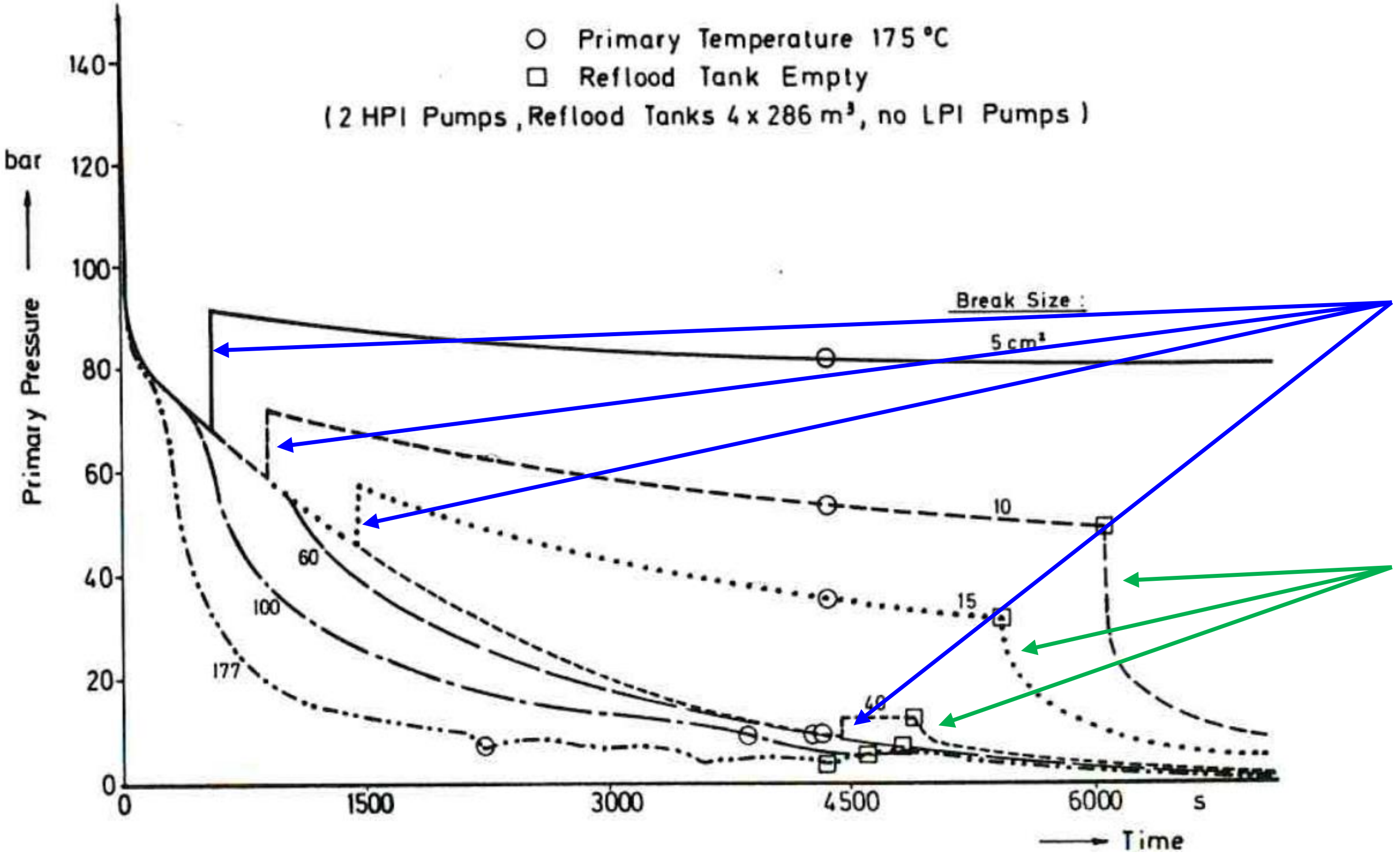
This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847656.

SBLOCA

- The LBLOCA was the accident considered mainly at the beginning for the design of the ECCS.
- After the Three Mile Island 2 accident, increased attention was devoted to SBLOCA.
- The SBLOCA transient is much slower than the LBLOCA and other thermal-hydraulic phenomena affect the accident progression (e.g. natural circulation between the reactor core and the steam generators).
- The HPIS is fundamental to mitigate the accident progression.

SBLOCA

- The accident progression is strongly influenced by the break size, location and orientation.
- The operation of the main heat removal system (or secondary cooling system) is needed to depressurize the primary cooling system to the LPIS activation pressure.
- After the pump shut-off, the primary coolant circulation is maintained by natural circulation.



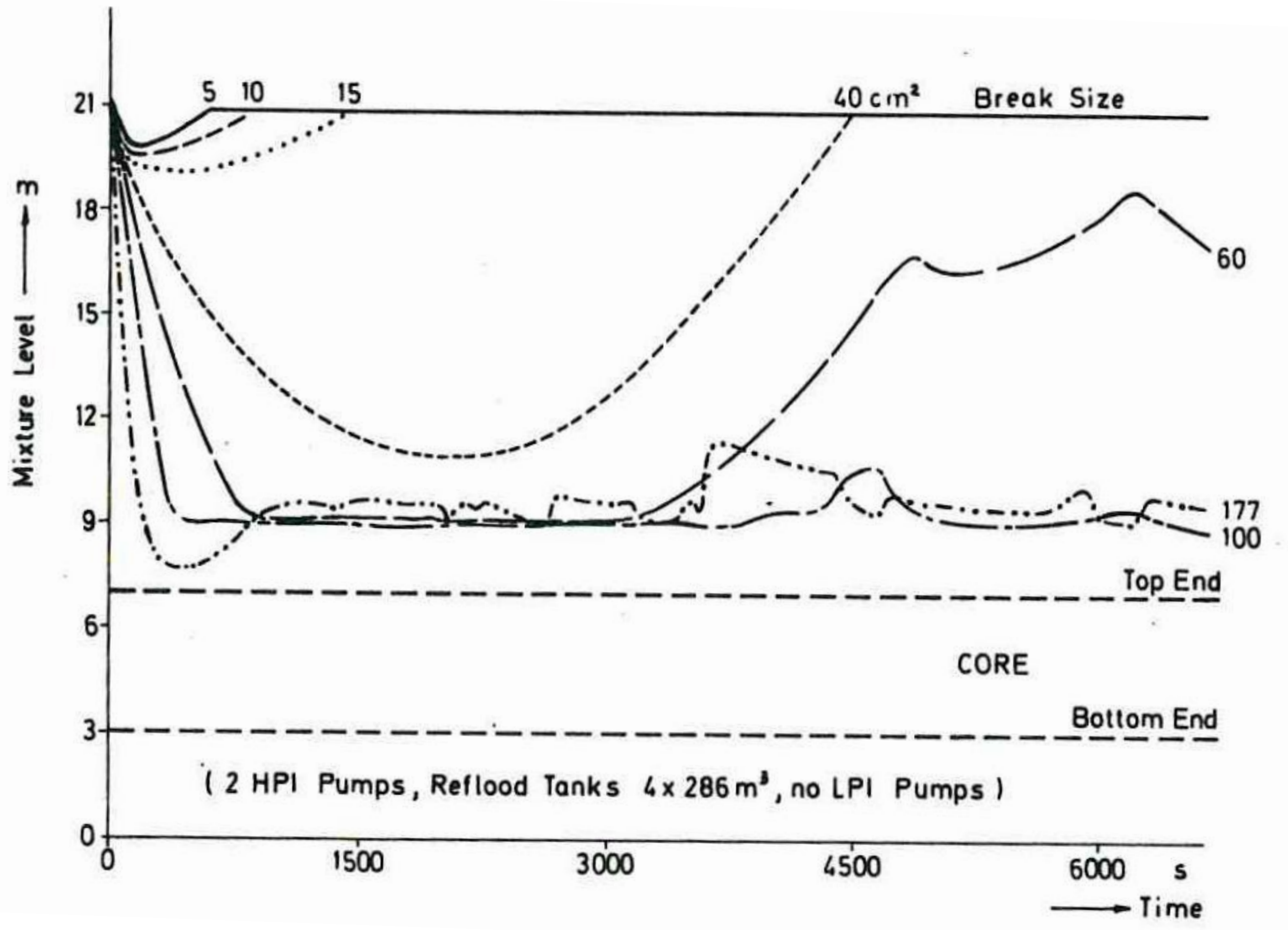
Break <1% → HPIS can refill the primary system and the pressure has a step increase determined by the HPIS pumps' head and delivery characteristic

Then the pressure reduces to the saturation value when the water storage tanks have emptied.

REDUCTION OF RADIOLOGICAL CONSEQUENCES OF DESIGN BASIS & DESIGN EXTENSION ACCIDENTS

SBLOCA

- Due to the ECCS intervention the core should be never uncovered



Reference

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Thank you!

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