Negative power reactivity coefficient in EPR™

Influence on primary system break (LOCA) and steam line break (SLB) accidents

A.PANICHI / J.GALARIN

EDF/DIPNN/SEPTEN – 16/11/2017

Summary

1. EPR presentation
2. Subcriticality function
3. Focus on Small Break LOCA (SB LOCA)
4. Focus on Main Steam Line Break faults (MSLB)

Abbreviations

CL	Cold leg
HL	Hot leg
RCS	Reactor Cooling System
MHSI	Medium Head Safety Injection
LHSI	Low Head Safety Injection
EBS	Emergency Boration System
RHR	Residual Heat Removal
CHRS	Containment Heat Removal System
ACCU	Accumulator
EFWS	Emergency Feed Water System
MFWS	Main Feed Water System
PZR	Pressurizer
ATWS	Anticipated transient without reactor trip
IRWST	In-containment Refueling Water Storage Tank
FPCS	Fuel Pool Cooling System
PCD	Partial Cool Down
LOCA	Loss Of Coolant Accident
(M)SLB	(Main) Steam Line Break
SG	Steam Generator
MSSV	Main Steam Safety Valve
MSRT	Main Steam Relief Train
RCCA	Rod Control Cluster Assembly
LOOP	Loss of Offsite Power
MCP	Main Coolant Pump
EDG	Emergency Diesel Generator

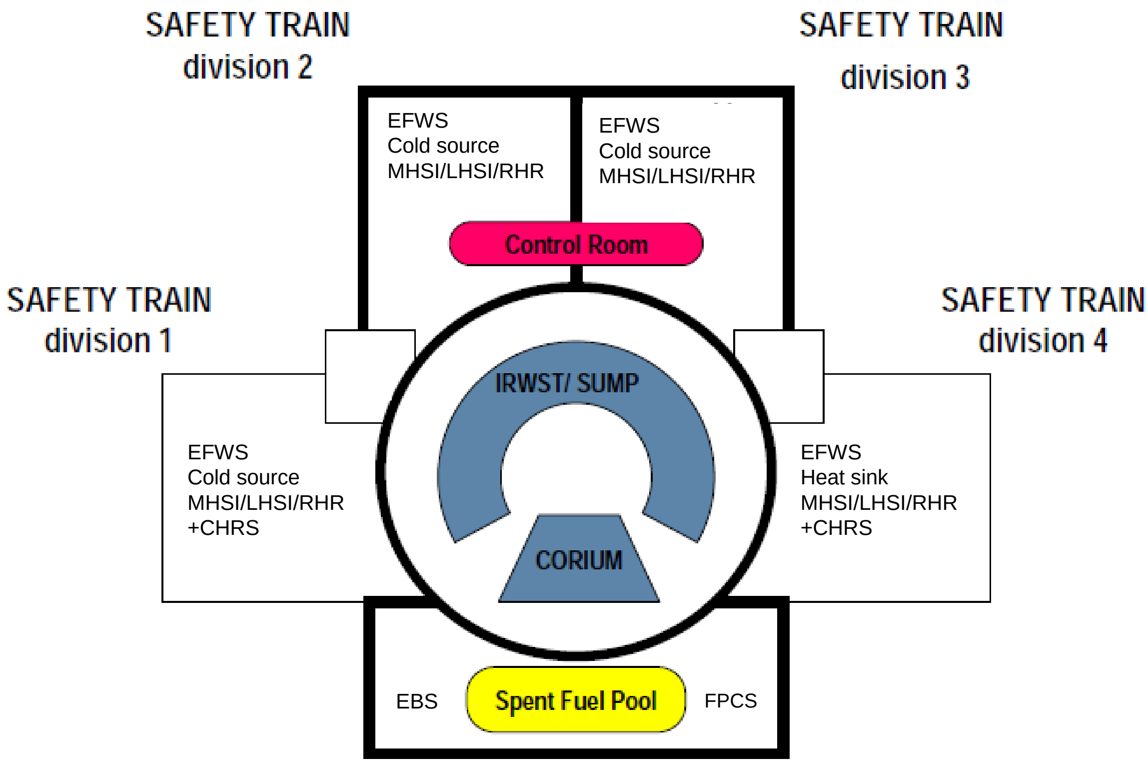
EPR™ main features

1. Competitiveness

- High power : 4300 / 4500MWth
- Expected life span : 60 years

2. Operational flexibility

- Manoeuvrability (charge tracking)
- Preventive maintenance into the containment building in normal operating conditions



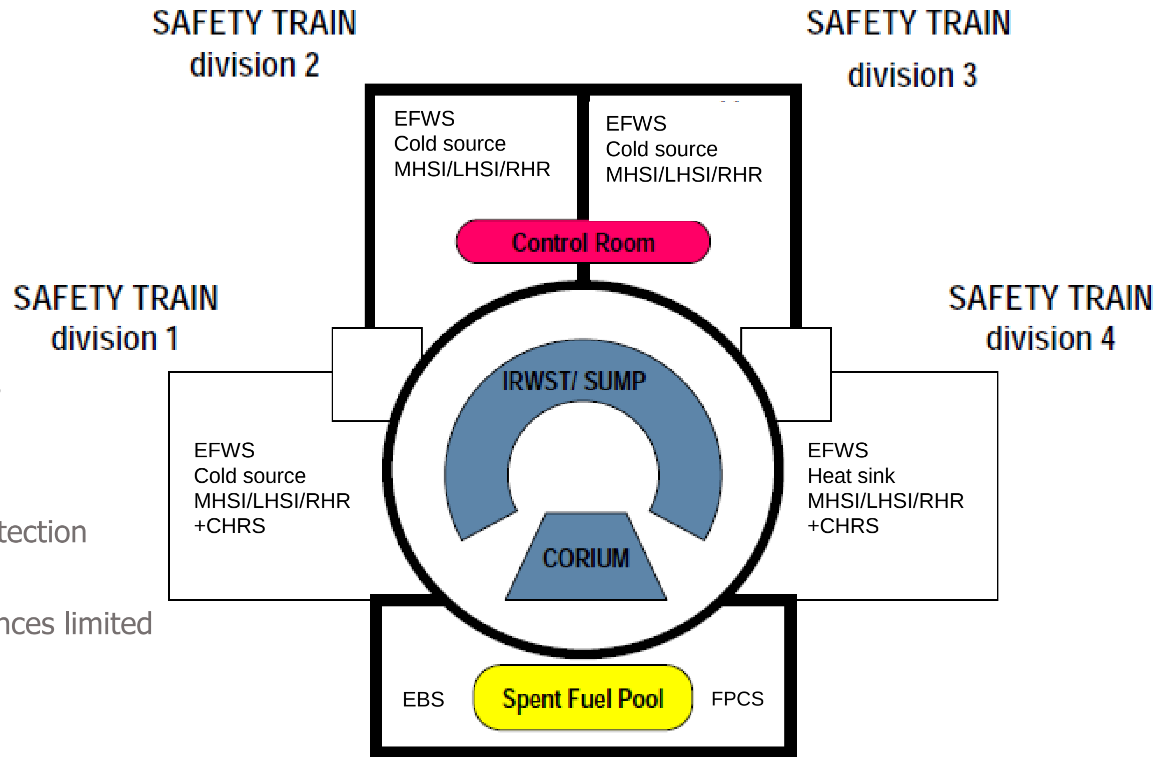
EPR™ main features

SAFETY

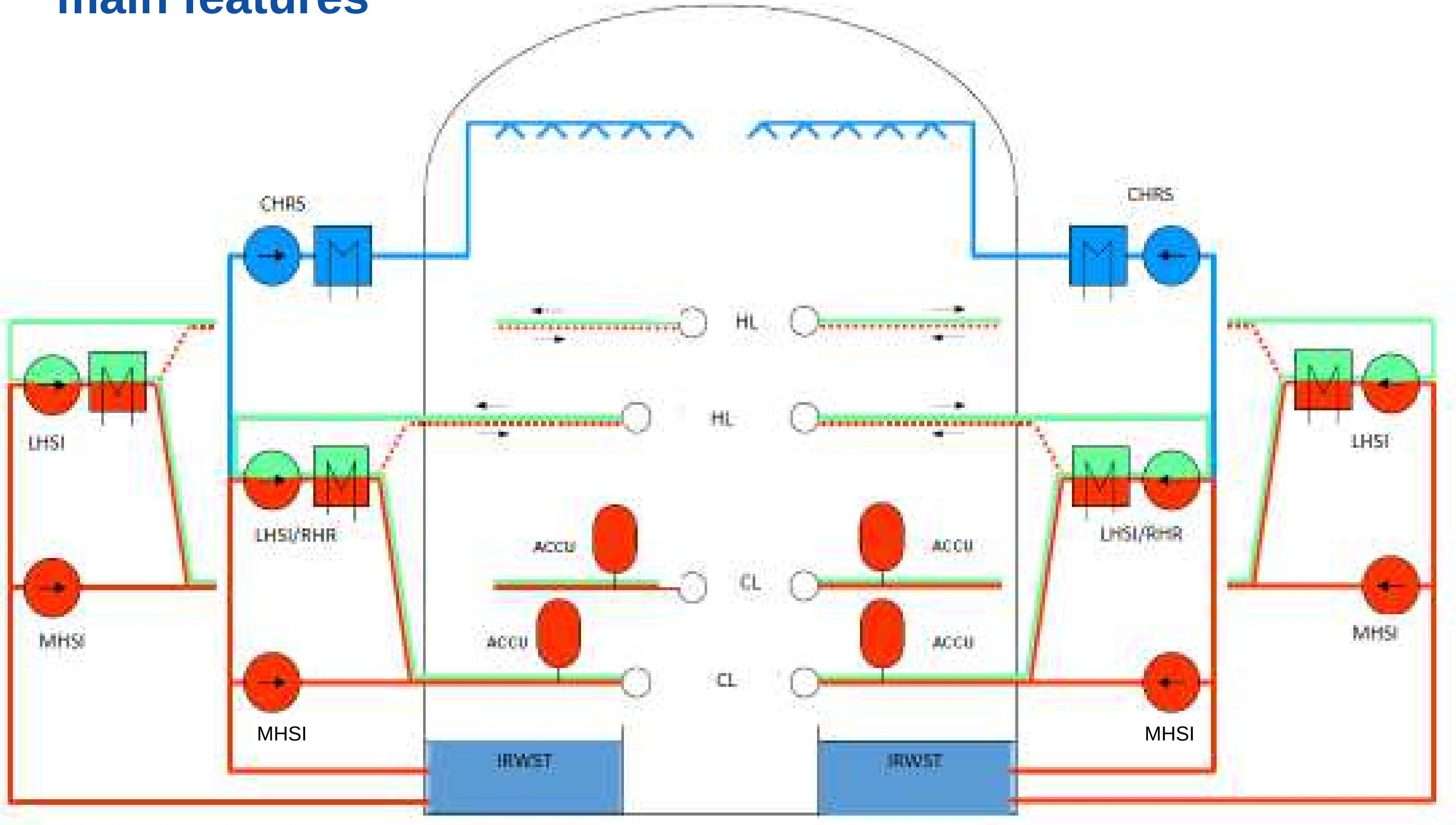
- Physical and electrical separation

(trains separated into divisions)

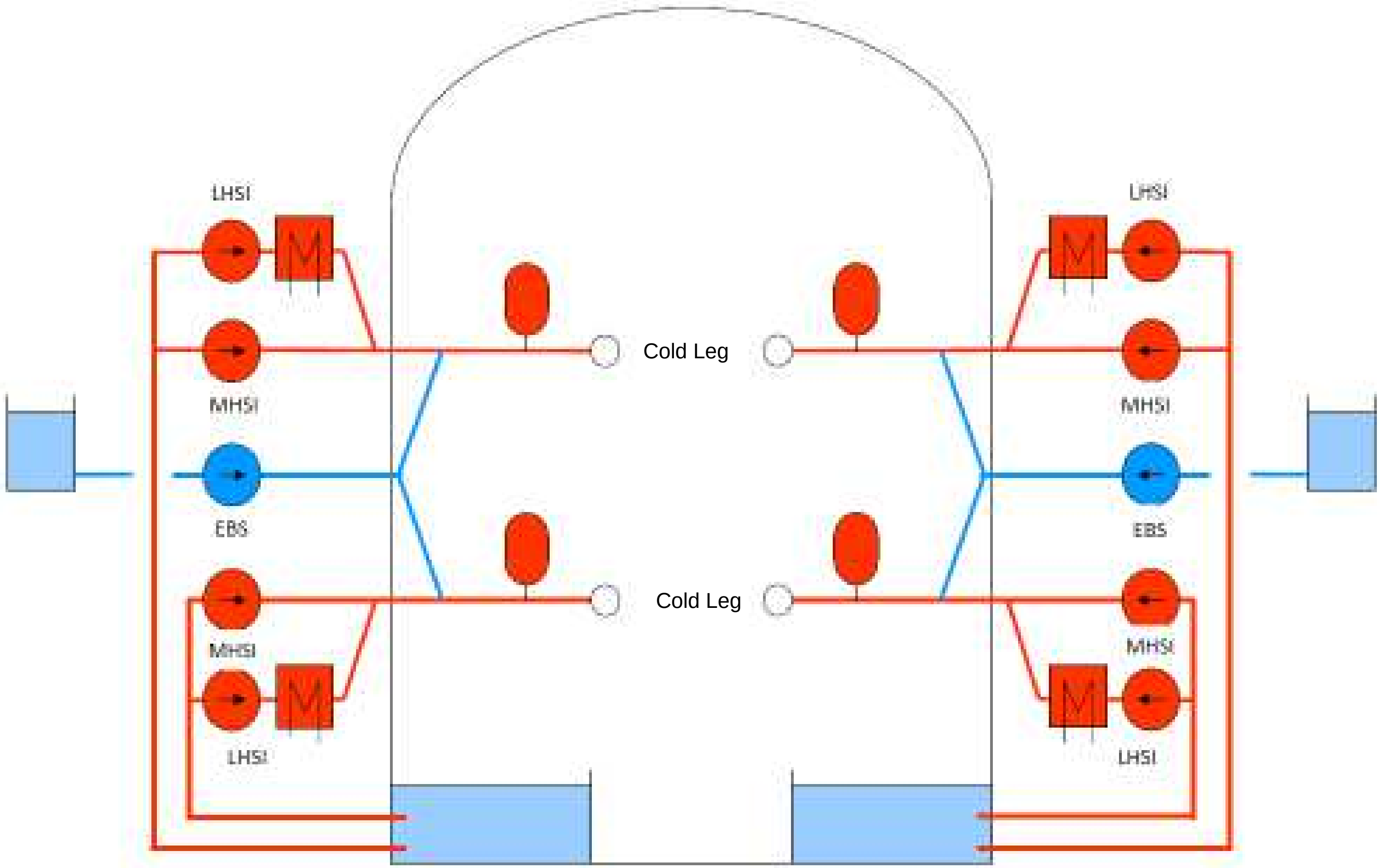
- Redundancy and functional diversity
- 24 hour autonomy
- Human-machine interface :
  - Automatic control for at least 30 minutes in accidental situations
- Are taken into account in the EPR™ design :
  - External hazards (e.g. airplane crash protection and electrical redundancy consolidated)
  - Severe accidents : radiological consequences limited (e.g. core catcher design)
  - Accident in shutdown states
  - Accident into HK



EPR™ main features



Borated water injection systems



Emergency Boration System (EBS)

1. Function

- Emergency boration for subcriticality

→ **Only used in case of accidental situations, no water inventory function**

2. Design

redundancy	2 trains 100% for subcriticality function
location	Each train injects into 2 loops Injection into the cold leg
Automatic start up signal	On low PZR pressure (after RT and before SI signal on low PZR pressure) On very low secondary (SG) pressure
Minimal Boron concentration	High (about 6 times IRWST boron concentration)
EBS design for manual cooldown	1 train necessary for 25°C/h cooldown 2 trains necessary for 50°C/h cooldown

MHSI, LHSI / RHR and ACCUMULATORS

1. Functions

- RCS mass inventory (water injection into the TCS from the IRWST)
- Borated water injection for subcriticality
- RCS cooldown in shutdown states → The RHR system is linked with the LHSI system

2. Design

redundancy	4 trains 100% for water inventory
location	MHSI and accumulators : Injection into cold legs LHSI : injection into cold or hot legs
Automatic start up signal at nominal power	MHSI/LHSI : On low PZR pressure (after RT and EBS signal on low PZR pressure) Accumulators : passive injection
Minimal Boron concentration	IRWST boron concentration
Flow rate depending on RCS pressure	MHSI : high flow rate injection at a lower pressure than the pressure reached after the PCD LHSI : high flow rate injection at low pressure Accumulators : high flow rate at medium pressure
Exchange efficiency	Designed to remove residual power in shutdown states

Subcriticality function

1. Dominant parameters

MODERATION EFFECT

- Depends on the moderator density

→ When the moderator density increases (due to a temperature decrease or a void fraction decrease), the neutron moderation is improved.

→ **Reactivity increase**

DOPPLER EFFECT (FUEL)

- Depends on the fuel temperature

→ When the fuel temperature decreases, the neutron capture in fuel (resonance of absorption cross sections) is reduced.

→ **Reactivity increase**

➔ By PWR conception, moderation and Doppler effects are auto-stabilizing effects for reactivity aspects.

2. Neutron captures

Essentially Boron (Boron 10)

- In the RCCA banks : shutdown and control RCCA
- Dissolved in the water : IRWST, ACCUMULATORS and EBS tanks

NB : critical Boron concentration : boron concentration leading the core in a critical state

Subcriticality function management in case of LOCA

<table>
<tr><th></th><th colspan="2">Design basis category accident (DBC)</th><th colspan="2">Design extension category accident (DEC-A)</th></tr>
<tr><th></th><th>Intermediate Break LOCA with MHSI/LHSI</th><th>Small Break LOCA with MHSI/LHSI</th><th>Small Break LOCA without MHSI</th><th>Small Break LOCA without LHSI</th></tr>
<tr><td>From initial state to end of PCD*</td><td rowspan="2">Reactor Trip, Accumulators and MHSI and even LHSI</td><td colspan="3">REACTOR TRIP
Designed to counterbalance reactivity brought by automatic partial cooldown</td></tr>
<tr><td>From end of PCD* to controlled state</td><td>Accumulators, MHSI and EBS</td><td>EBS</td><td>MHSI and EBS</td></tr>
<tr><td>From manual cooldown to Safe Shutdown state</td><td>Accumulators and MHSI and LHSI</td><td>Accumulators, MHSI and EBS</td><td>Accumulators and EBS</td><td>Accumulators, MHSI and EBS</td></tr>
<tr><td>At Safe Shutdown state</td><td>LHSI
(simultaneous injection and recirculation)</td><td>LHSI</td><td>LHSI</td><td>MHSI</td></tr>
</table>

Penalizing situations for subcriticality function

**PCD : Partial Cooldown*

Small break LOCA with MHSI (DBC)

1. Transient description – Short term phase

- Monophasic depressurization
- Low PZR pressure signal triggering the reactor trip
- EBS and Safety Injection start up signals on low PZR pressure levels and MCPs automatic shutdown
- **Automatic partial cooldown (PCD)** and EFWS actuation on low SG level
- **Stabilization at SGs pressure with MHSI**
- Only in case of large enough break : primary depressurization due to the break void fraction increase and stabilization at a lower pressure

→ **THE CONTROLLED STATE IS REACHED (WITHOUT BORATION NECESSITY)**

2. Transient description – Long term phase

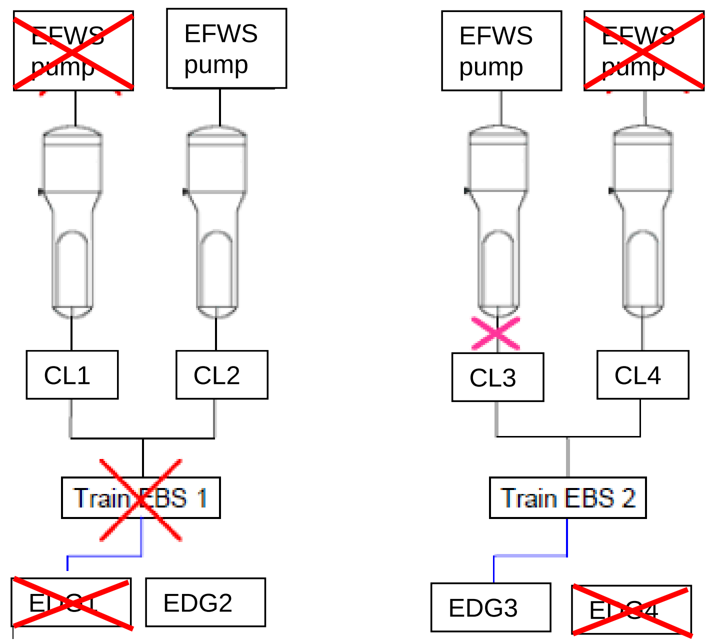
- **Manual cooldown** (depending on how many EBS trains available) and EFWS header opening if no SG unavailable
- Borated water injection by accumulators
- Accumulator isolation and LHSI injection and increase of manual cooldown speed when the EBS tank is empty
- **RHR connection**.

→ **THE SAFE SHUTDOWN STATE IS REACHED**

Small break LOCA with MHSI (DBC)

1. Study main assumptions

- Determinist and penalizing rules :
  - The loss of offsite power (LOOP) is taken into account.
  - Preventive maintenance on 1 EDG
    - → One EFWS and one EBS are unavailable.
  - Single failure assumption on another EDG
    - → Another EFWS is unavailable
  - Other conservatisms :
    - No automatic EBS start up
    - One RCCA bank is entirely stuck out of the core



→ **1 EBS is injecting into 2 loops, but one of them is ruptured**

→ **2 EFWS feed 2 SGs but one of them belongs to the ruptured loop**

→ **Only the ruptured loop is fed with one EFWS and one EBS**

Small break LOCA with MHSI (DBC)

2. Results

FROM THE INITIAL TO THE CONTROLLED STATE

- No criticality issue even if one RCCA bank is entirely stuck out of the core
- The shutdown RCCA design prevents from reaching the criticality physical conditions (moderator temperature)

FROM THE CONTROLLED TO THE SAFE SHUTDOWN STATE

- 1 MHSI and EBS train (1 EBS tank) can provide the core with boron.
- The RCS boron concentration is always higher than the critical boron concentration (which depends on temperature).
- The subcriticality is ensured at the final state (safe shutdown state).

3. Inactive loop

- Need to inject at least one EBS flowrate into the core (by an "healthy" loop) to provide it with boron and ensure subcriticality
  - → Need natural convection into at least one "healthy" loop
  - → Need to open the EFWS header in order to feed all SGs and avoid unavailable SG (and prevent SG isolation)

→ NO CRITICALITY ISSUE

Small break LOCA without MHSI (DEC-a)

1. Transient description

- Monophasic depressurisation
- Low PZR pressure signal triggering the reactor trip, then the safety injection and EBS start up and the MCPs automatic shutdown
- **Automatic partial cooldown (PCD)** and EFWS actuation on low SG level
- **Stabilization at SGs pressure without MHSI**
- Only in case of large enough break : **primary depressurization** due to the break void fraction increase and stabilization at a lower pressure
- **Manual cooldown** (depending on how many EBS trains available)
- **Fast cooldown** because of the RCS water mass inventory deterioration
- **Borated water injection by accumulators**
- **Accumulator isolation and LHSI injection**
- **RHR connection**.

→ **THE SAFE SHUTDOWN STATE IS REACHED**

2. Results

- The shutdown RCCA drop and the EBS injection ensures the core subcriticality along the PCD.
- The EBS trains and then the LHSI trains are able to provide the core with the minimal boron concentration all along the manual cooldown.

→ **NO CRITICALITY ISSUE**

Main steam line break faults

MAIN FEATURES OF MSLB TRANSIENTS

- Design basis accident
- Swift depressurization of the SGs
- Global overcooling and depressurization of the RCS
- Reactivity insertion (moderator density feedback)
- Power increase or return-to-power despite the reactor trip

SEVERAL KINDS OF BREAKS

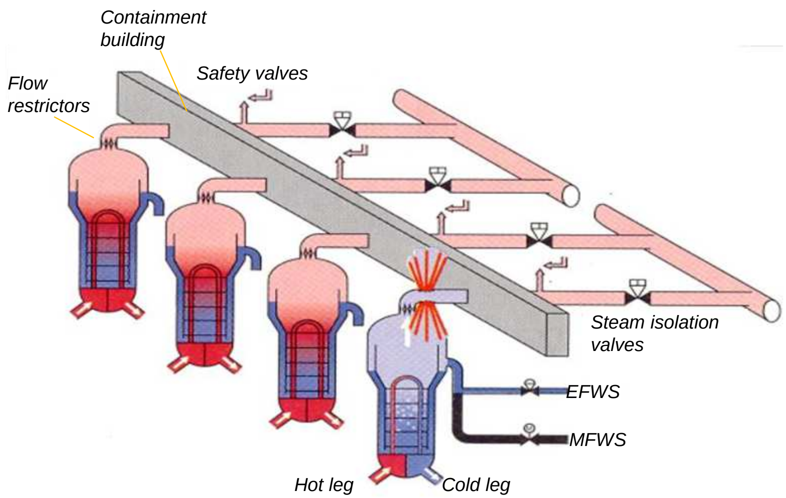
- Inside or outside the containment building
- Can be isolated or not depending on its location

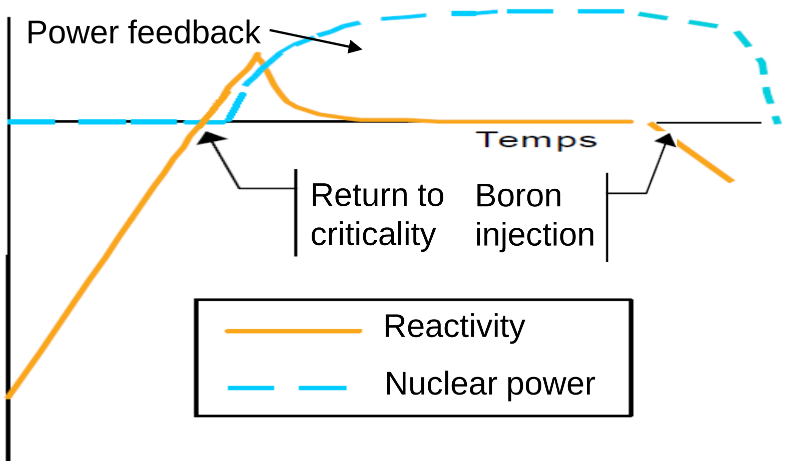
SINGLE FAILURE ASSUMPTION (EXAMPLES)

- Isolation valve failure
- One rod (RCCA) entirely stuck out of the core

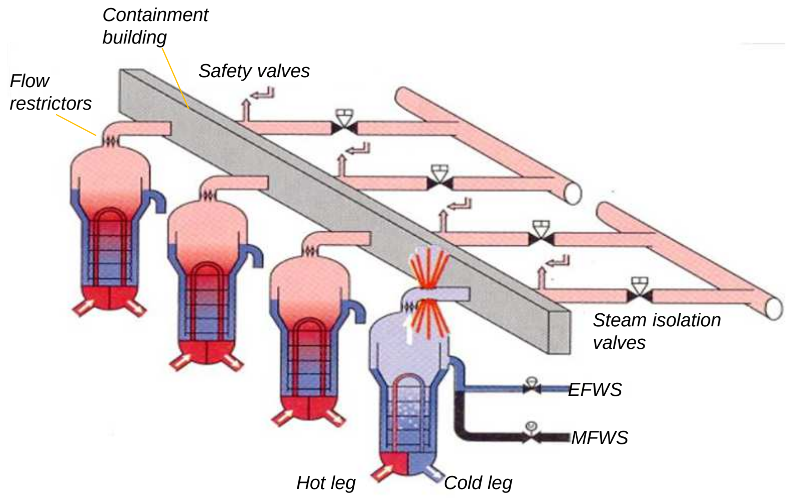
MAIN RISKS INVOLVED

- Local fuel cladding failure due to boiling crisis or high local power density





EPR™ design specificities



Design features to reduce the likelihood of occurrence

- Break preclusion on the non-isolable pipe sections (to MSIV)
- Prevention from non-isolable events (e.g. two MSRT valves in series).
- Restriction of the number of safety valve openings
- No non-isolable leakage in Reference Transient (DBC-2)

Mitigation design features to reduce the RCS overcooling

- Flow limiter at the SG outlet
- Automatic closure of the main steam isolation valves (MSIV)
- Automatic isolation of the affected SG main feed water system (MFWS)
- Restriction of the additional cooling sources, e.g. by the emergency feed water system (EFWS) on the affected SG

Mitigation design features to reduce the return-to-power intensity

- Anti-reactivity provided by the control and shutdown rod drop (reactor trip)
  - Prevent the core from damage if a MSLB occurs at full power (RT trigger design), and anti-reactivity to prevent the core from a return to criticality
  - e.g. ensures the core subcriticality after a partial cool-down even if one RCCA keeps stuck out of the core
- Automatic start up of boration systems : safety injection pumps (MHSI) and EBS
- Automatic MCP trip

EPR™ mitigation systems and triggers

Physical phenomenon	Trigger / signal	Reactor trip	MSIV closure	MFWS isolation	Boration system	MCP trip
Nuclear power	High thermal power	Achieved	-	MWF high load lines only	-	-
	Low DNBR					
	High linear power density					
Depressurization of the SGs	Fast secondary pressure loss	Achieved	Achieved	Complete isolation (SG specific)	-	Achieved
	Low or very low SG pressure				EBS start up	
Depressurization of the RCS	Low or very low PZR pressure	Achieved	-	MWF high load lines only	MHSI and EBS start up	If high containment pressure
SG water mass inventory	High SG level	Achieved	-	Complete isolation of MFWS and EFWS (SG specific)	-	

EPR™ design basis faults

Reference transients (2nd Design basis category)

- MFWS malfunction causing an increase of MFW flow rate
- Excessive steam flow increase (several causes)
  - Spurious opening of a secondary valve
  - Spurious partial cool-down
  - MSRT valve stuck open after opening

Unlikely events (3rd Design basis category)

- Spurious opening of a MSRT or MSSV valve (A-state)

Very unlikely events (4th Design basis category)

- MSLB (all sizes, all location on steam lines)
  - Despite the break preclusion design, EPR™ takes into consideration the double ended guillotine SLB
- Spurious opening of a MSRT or MSSV valve (B-state)

Multi-failure plant conditions (Design extension category)

- E.g. excessive steam flow increase and ATWS

EPR™ design basis fault management

<table>
<tr><th>Event</th><th></th><th>Core damage prevention</th><th>Overcooling mitigation</th><th>Boration</th><th>Consequences</th></tr>
<tr><td>Increase of MFW flow rate (MFWS malfunction)</td><td rowspan="2">DBC-2</td><td rowspan="5">Quick RT</td><td>Affected SG MFW isolation</td><td rowspan="3">EBS start up</td><td rowspan="2">No core damage before the reactor trip.
No return to criticality after the reactor trip</td></tr>
<tr><td>Excessive steam flow increase</td><td rowspan="4">MSIV closure
Affected SG MFWS and EFWS isolation
Affected SG MSRT isolation</td></tr>
<tr><td>Spurious opening of a MSRT or MSSV valve</td><td>DBC-3</td><td rowspan="3">No core damage before the reactor trip.
No core damage in case of return-to-criticality
Subcriticality state achievement by boration systems</td></tr>
<tr><td>Double ended main steam line break</td><td rowspan="2">DBC-4</td><td rowspan="2">EBS and MHSI pump start up</td></tr>
<tr><td>Main steam line breaks (all sizes and location)</td></tr>
</table>

Negative power reactivity coefficient impact on EPR™ SB LOCA and MSLB accidents

ADVANCED MITIGATION SYSTEM DESIGN

- **For MSLB** :
  - Reduction of the likelihood of overcooling event occurrence
  - Efficient reactor trip trigger and RCCA anti-reactivity design
  - Both overcooling mitigation and anti-reactivity providing systems (RCS boration)
- **For LOCA** :
  - Shutdown RCCA designed in order to counterbalance reactivity brought by the partial cooldown
  - EBS designed in order to counterbalance the reactivity brought by manual cooldown
  - MHSI, accumulators and LHSI help to ensure subcriticality along the transient

OVERCOOLING AND LOCA EVENT MANAGEMENT ABOUT SUBCRITICALITY FUNCTION

- Quick and efficient reactor trip and borated water injection systems triggers
- No return-to-criticality for the reference overcooling transients (DBC-2)
- No core damage in case of return-to-power after the reactor trip for DBC-3 and DBC-4 SLB events
- Achievement of safe state conditions (especially subcriticality operating conditions)

LARGE ACCIDENT SPECTRUM COVERED (DBC AND DEC-A) WITH PENALIZING ASSUMPTIONS


THANK YOU