INPRO Criterion 1.1.1
‘Robustness of Design’
Position of the EPR™ reactor
Part 1

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Contents

- EP1.1.1.1 Margins of design (& EP1.2.1.1 Margins of operation)
- EP1.1.1.2 Simplicity of design
- EP1.1.1.3 Quality of manufacture and construction
- EP1.1.1.4 Quality of materials
- EP1.1.1.5 Redundancy of systems

PART 1

- EP?.?.?.? Robustness against external hazards: not yet an INPRO criterion!

PART 2

- Conclusions on the Robustness of the EPR™ reactor design in the sense of the INPRO methodology

PART 3
EP1.1.1.1 – Margins of Design
A few facts

▶ The EPR™ reactor was designed for being capable of high performance in
  ◆ Load following and frequency variation control (up to 90% of the fuel cycle length)
  ◆ Low Power Operation

▶ The fuel cycle length is increased compared to the operating fleet (up to 24 months)

▶ The linear power rate is lower than currently operating PWRs
EP1.1.1.1 Margins of Design

- The EPR™ reactor is licensed and meets the safety requirements in:
  - France
  - China
  - Finland
  - UK

- Design certification is underway with the US NRC

- Safety margins are demonstrated and provide the highest level of confidence on how the EPR™ reactor copes with normal operation, AOO, incidents and design basis accidents
Safety margins and operation margins

**DBC events**

### Safety margins

- **Nominal values**
- **Limiting conditions of operation (LCO)**

### Initial conditions of the accident safety analyses

- **Controller range**
- **Measurement accuracy**

### Operation margins

- **DBC1 event**
- **DBC2 criterion**
- **DBC2 event**
- **DBC3 criterion**
- **DBC3 event**
- **DBC4 criterion**
- **DBC4 event**

**Result of the accident analysis**
DBC Acceptance criteria

Safety criteria

- Safety criteria are expressed in terms of radiological consequences
  - No short term countermeasures (shelters, evacuation, distribution of iodine tablets), no need for long-term relocation, No long-term restriction on the consumption of foodstuffs.
  - Effective dose (based on a 7 days exposure in 500 m distance from the plant border) < 10 mSv (sheltering)

Decoupling criteria (examples for illustration)

- No Departure from Nucleate Boiling (DNB) in any DBC-2 event, and in the DBC-3/4 events involving a failure of the secondary side shell (e.g. main steam line break)
- Fuel rods experiencing DNB in DBC-3/4 lower than 10%
- Decoupling criteria for LOCA:
  - peak cladding temperature lower than 1200°C
  - maximum cladding oxidation lower than 17% of the cladding thickness
  - maximum hydrogen generation lower than 1% of the amount that would be generated if all the active part of the cladding had reacted
Safety margins and operation margins

Balance between safety and operation margins

Impact of a modified LCO

Safety limit / Acceptance criterion

Result of the accident analysis

Conservative result

Safety analysis rules and conservatism of the method

Best-estimate result

Protection (reactor trip)

Increased safety margin

Nominal value

High level of provisions (tilt, reloads, cycle lengths, stretch-out, load-follow, ELPO)

Initial condition of the accident analysis (LCO)

Low level of provisions (tilt, reloads, cycle lengths, stretch-out, load-follow, ELPO)

Nominal value

Reduced operation margin

Conservative result

Safety analysis rules and conservatism of the method

Best-estimate result

Protection (reactor trip)
### Risk of a spurious reactor trip during a large normal transient (DBC1)

<table>
<thead>
<tr>
<th>Safety analysis rules and conservatism of the method</th>
<th>Nominal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety analysis rules and conservatism of the method</td>
<td>Best-estimate result</td>
</tr>
<tr>
<td>Protection (reactor trip)</td>
<td>Conservative result</td>
</tr>
</tbody>
</table>

#### Increased safety margin

- **Safety Limit / Acceptance criterion**
- **Result of the accident analysis**
- **Conservative result**
- **Best-estimate result**

#### Unchanged operation margin

- **Protection (reactor trip)**
- **Initial condition of the accident analysis (LCO)**
- **Nominal value**
Margins of Design vs Margins of Operation (EP1.1.2.1)

- Necessary compromise for new designs, between
  - Increased safety margins, and
  - Increased operational performance

- Most penalizing transients regarding safety function ‘Control of reactivity’
  - Steam line break
  - Rod ejection accident

- Other criterion to be considered: CR1.3.6 Sub-criticality margin
  - Reactor sub-critical in the shortest time and reliably kept sub-critical
  - Consideration of uncertainties and worst single failure in the shutdown system

- Depending on national circumstances (safety requirements vs operational requirements) adaptation may rely on
  - Design of fuel elements
  - Fuel pattern in the core
  - Efficiency and different type of control rods
  - Pattern of Rod Control Cluster Assemblies (RCCA)
  - Operation of the Safety injection System (SIS) and of the Extra Borating System (EBS)
  - Instrumentation and Control (signals + actuation of equipments)
Failure of one Reactor Coolant Pump (RCP)

- Failure of one RCP implies a partial trip to approx. 40% FP
- Plant can be operated in three-loop operation with maximum reactor power of approx. 70 % FP

When the RCP can be returned to service:

- Reactor power is reduced to approximately 30 % FP
- RCP is restarted
- Plant is returned to full load
Margins of Design – RPV Nozzle Shell

RPV Monobloc Upper Shell with 8 integral nozzle flanges

Horizontal cross section at nozzle axis level

EPR™ Safety Benefit: Higher nozzle axis improves fuel cooling in case of LOCA

LOCA: Loss of Coolant Accident
**EPR™ Innovative Feature:**
The Heavy Reflector (HR) reflects effectively a large amount of escaping fast neutrons $n$ back to the core.

### Composition:
<table>
<thead>
<tr>
<th>Composition</th>
<th>Steel Water</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>95.6 %</td>
</tr>
<tr>
<td></td>
<td>4.4 %</td>
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</tbody>
</table>

### Thickness $d$:
- between average
- 77 and 297 mm
- 194 mm

### Core height
- active
- 4200 mm

### HR height
- total
- 4752 mm

### Mass
- total
- 90 t
The enforced reactor coolant flow in the downcomer annulus generates strong turbulences in the RPV lower plenum, which are homogenized by means of the Flow Distribution Device (FDD).

- Uniform flow distribution at core inlet
- Better cooling of all fuel rods
- Decreased probability of DNB

**EPR™ Innovative Feature:**
The Flow Distribution Device results in a distinct smoothing of coolant flow.
Margins of design – Margins of operations

From reviewing the publicly available information (e.g. regulatory bodies who have licensed the EPR™ reactor or which are about to deliver Design Certification) an INPRO assessor may conclude that the evaluation parameter on ‘Margins of design’ is met.

Some examples to support this conclusion were discussed above.
EP1.1.1.2 – Simplicity of Design
The EPR™ reactor has ~ 20% less Equipment than current 4 loop US PWRs

Study based on: RCS, Pdr, Spray, RCP seal and Leakoff, SI/RHR, CVCS incl. Boration and Demin/Seal Water, SFP Cooling, CCW, FW/AFW/EFW, and MS

<table>
<thead>
<tr>
<th>Component Types</th>
<th>EPR</th>
<th>4-Loop PWR</th>
<th>% Change (Absolute)</th>
<th>% Change (Count/MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumps &amp; Turbines</td>
<td>43</td>
<td>37</td>
<td>16</td>
<td>(16)</td>
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<tr>
<td>Heat Exchangers</td>
<td>34</td>
<td>44</td>
<td>(23)</td>
<td>(44)</td>
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<tr>
<td>Tanks</td>
<td>23</td>
<td>33</td>
<td>(30)</td>
<td>(50)</td>
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<tr>
<td>Valves</td>
<td>2,044</td>
<td>2,766</td>
<td>(26)</td>
<td>(47)</td>
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</tbody>
</table>
EP1.1.1.2 Simplicity of Design
Safety injection (schematic view)
EP1.1.1.2 Simplicity of Design – SIS / RHRS
The Safety Injection System (SIS) is a 4 train system, without headers between trains ⇒ 1 train per loop

It is a 4x100 % system with respect to LOCA
- 1 train lost at the break, 1 train failed (SFC), 1 train in PM ⇒ the 4th train is sufficient to cope with the LOCA (100% of the function)

The 4 trains (LHSI,MHSI) take suction from the Internal Refueling Water Storage Tank (IRWST), so that there is no recirculation switch-over sequence in case of LOCA

The SIS can cope with all the LOCA assumed in the safety analysis (DBC 3 and 4) without Containment Heat Removal System in spaying mode. Containment spray only during severe accidents

The Low Head SIS (LHSI) performs also the Residual Heat Removal function (RHR) during plant shutdown
- Combined LHSI/RHRS functions
From reviewing the publicly available information (e.g. regulatory bodies who have licensed the EPR™ reactor or which are about to deliver Design Certification) an INPRO assessor may conclude that the evaluation parameter on ‘Simplicity of design’ is satisfied.

Some examples to support this conclusion were discussed above

- Reduced number of components
- Simplification of safety systems’ architecture
EP1.1.1.3 – 5
are discussed in PART 2 of this presentation
Robustness against external hazards – cf. PART 3 of this presentation

Thank you for your attention