INPRO User Requirement 1.4
‘Release into the Containment’
Position of the EPR™ reactor

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► CR1.4.2 Processes

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  ◆ CR1.4.2 and CR1.4.3 will be dealt with together

► Conclusions on the position of the EPR™ reactor design regarding UR1.4 of the INPRO methodology
CR1.4.1 – Major Release into the Containment
CR1.4.1 Major release into the containment

- Indicator IN1.4.1: Calculated frequency of major release of radioactive materials into the containment / confinement

- Acceptance limit AL1.4.1: At least an order of magnitude less than existing designs

- Major release into the containment would result from severe core degradation

- CDF: Core Damage Frequency
PSA level 1 (CDF) and 2 (LERF) were performed at the design stage

- Supplement deterministic safety assessment
- Confirm soundness of the design

Standard EPR™(*) PSA

- Internal events (all reactor states)
- Internal hazards (Fire / Flooding during power states)
- Risk analysis of fuel damage in SFP

<table>
<thead>
<tr>
<th>Plant condition</th>
<th>EUR design target</th>
<th>EPR evaluation</th>
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<tbody>
<tr>
<td>Core damage frequency:</td>
<td>&lt;10^{-5} /r.y</td>
<td>~10^{-7} /r.y</td>
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<tr>
<td>- all plant states *</td>
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<td>- all type of initiators</td>
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<tr>
<td>Large Early release frequency</td>
<td>&lt;10^{-6} /r.y</td>
<td>&lt;10^{-7} /r.y</td>
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</table>

(*) Generic EPR™ design with generic site conditions
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 acceptance limit for indicator ‘Major release into the containment’ is met.

CDF is provided for the Generic EPR™ reactor
CR1.4.2 and 3 – Processes and In-Plant Severe Accident Management
CR1.4.1 Major release into the containment

- Indicator IN1.4.2: Natural or engineered processes sufficient for controlling relevant system parameters and activity levels in containment / confinement
- Acceptance limit AL1.4.2: Existence of such processes
- Indicator IN1.4.3: In-plant severe accident management
- Acceptance limit AL1.4.3: Procedures, equipment and training sufficient to prevent large releases outside containment/confine ment and regain control of the facility
**Severe Accident Approach**

**Severe accident**
- Event beyond the DBC & DEC-A accidents, leading to core damage/melt (loss of the 1st barrier) and possibly to RPV failure (loss of the 2nd barrier)
- Mitigation approach aims at ensuring containment integrity (3rd barrier)

**Practical elimination** of energetic phenomena that may lead to an early containment failure
- High Pressure core melt sequences
- Steam explosion
- Hydrogen detonation

**Commitments** to ensure the confinement integrity for any other sequences following a core melting, including those leading to the RPV failure at low pressure
- Stabilization of molten corium
- Containment heat removal
- Limitation of radioactive releases
  - Protective measures limited in area and time
  - No long term off-site contamination

*RPV melt-through at elevated pressure (FOREVER experiment, KTH Sweden)*
Typical Sequences of event

► Core uncovering, heat-up

► In-vessel core meltdown
  ◆ Cladding oxidation, with H2 production, transport, release and combustion
  ◆ Corium relocation in RPV bottom end

► RPV bottom end failure
  ◆ Reactor vessel wall attack / melt-through
  ◆ If vessel failure at high pressure, core debris and coolant ejection
  ◆ Interaction corium/water, with possible steam explosion

► Ex-vessel corium spreading
  ◆ Interaction corium-concrete
  ◆ Effective corium cooling leading to solidification
  ◆ Containment heat up and over-pressurization with failure risk
  ◆ Fission product release if confinement leaks
Should RPV fails at high pressure, core debris and coolant ejection may lead to Direct Containment Heating.

A primary depressurization system prevents high-pressure core melt sequences above 20 bar.

Dedicated depressurization valves supplement the 3 PZR safety valves and provide a safe/reliable RCS depressurization.

Redundancy and Diversification ⇒ high probability of successful operation

Practical Elimination of High Pressure Core Melt

RCS: Reactor Coolant System
RPV: Reactor Pressure Vessel
PZR: Pressurizer
Steam Explosion (SE) is a potentially destructive reaction between the molten corium and water.

**In-vessel SE**
- no risk of containment failure (reaction confined within RPV)

**Ex-vessel SE**
- Design provisions ensure dry reactor pit and corium spreading area prior to corium flooding
Practical Elimination of $H_2$ Detonation

- Oxidation of the Zr fuel cladding results in hydrogen production
  - Total oxidation of the Zr fuel cladding => 1684 kg H$_2$ (concentration > 20%)

- Global detonation is avoided as long as the average global H$_2$ concentration within containment is < 10 % H$_2$ (vol)

- Hydrogen mixing dampers installed at the wall between IRWST and annular rooms

- Large volume of containment (80 000m$^3$) with ”open” compartments

- No automatic early containment spray to avoid steam condensation

 »Integrated Rupture Foil

 »closed

 »Passively opened at 80-85°C
Practical Elimination of H₂ Detonation

- Prevention of fast deflagration or detonation ensured by Passive Autocatalytic Recombiners (PARs)

⇒ Maximum global containment pressure in the most limiting scenarios with H₂ deflagration: 4.1 to 6.3 bar abs (containment integrity up to 6.5 bar abs)
Analysis of H$_2$ Combustion

Acceleration in the SG tower: left: 0.13 s, right: 0.18 s after ignition
In the dome: deceleration with low impact on the containment shell
Strategy, should the reactor vessel fail:

- Prevent corium-basemat interaction to avoid significant releases and durable contamination of sub-soil and underground waters.

- Accumulate corium and temporarily retain it in the reactor pit after RPV failure.

- Delayed melting of a metal gate located at the bottom of the reactor pit.

- Spread the corium on a large surface outside of the reactor pit.

- Flood and cool the spreading area by IRWST water.

All stages are fully passive (retention, spreading, flooding, cooling).
Temporary Core Melt Retention in Reactor Pit

Distinct separation of functions between reactor pit (accumulation) and spreading compartment (cooling).

The core catcher is protected from loads during RPV failure (melt jets, impact of lower head).

The core melt / debris released after RPV-failure is accumulated in the Reactor Pit, with the target to:
- facilitate spreading in one event
- lower corium temperature and viscosity (Sacrificial concrete)
Passive Melt cooling

Gravity-driven overflow of water from the IRWST

At equilibrium water level, cooling is established also for debris potentially remaining within transfer channel and lower pit

Formation of a saturated water pool in the spreading compartment with steam release into containment
Core Catcher

I-beam

Sidewall cooling plate

Sacrificial concrete

Cooling channel

Bottom cooling plate (steel)

Construction concrete

Basemat Cooling

Spreading Compartment

INPRO dialogue forum 7
Vienna – 19-22 November 2013
Actuation of the CHRS after a grace period of 12 hours allows to limit the containment pressure

Possible switch between passive and active core catcher cooling (not required):

- Formation of a sub-cooled water pool above the melt avoids the need for further containment spraying after some days (atmospheric pressure reached)

Effective cooling process due to large surface-to-volume ratio of the melt, without interaction between melt and structural concrete:

- Stable state of the melt, reached within hours
- Total solidification of corium, within days

FILTERED VENTING NOT REQUIRED

CHRS : Containment Heat Removal System
Melt Cooling and Containment Heat Removal
Long Term phase (beyond 12 hours grace period)

Containment spray system

Water injection into the core catcher

Recirculation and coolant heat exchanger

Two fully redundant trains with specific diversified heat sink
Double wall containment

- outer wall is a reinforced concrete shell, resistant to external hazards
- inner wall is a pre-stressed concrete shell with a steel liner

The design leak-rate at design pressure for a 24-hour period is less than 0.5 percent by volume at 5.5 bar

All leakages are collected in the annulus and a reduction of radioactive aerosols is achieved by filtration prior to the release via the stack.
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 acceptance limits for indicators IN1.4.2 (Criterion ‘Processes’) and IN1.4.3 (Criterion ‘Accident Management’) are met.
Thank you for your attention