CAP1400 IVR Related Design Features and Analysis Methodology

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2. IVR Related Design Features and Measures
3. IVR Analysis Methodology
4. Conclusion
1. Introduction

- CAP1400

- Large core thermal power

- 2 Loops PWR with passive safety design

- One of Gen-3 NPPs

- One of the 16 national science & technology key projects

- Designed by SNERDI
# 1. Introduction

- **Main Parameters of CAP1400**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core thermal power, MWt</td>
<td>4040</td>
</tr>
<tr>
<td>Electric power, MWe</td>
<td>~1500</td>
</tr>
<tr>
<td>RCS average temp, °C</td>
<td>304</td>
</tr>
<tr>
<td>RCS pressure, MPa(a)</td>
<td>15.5</td>
</tr>
<tr>
<td>Fuel assemblies</td>
<td>193</td>
</tr>
<tr>
<td>Average linear power, W/cm</td>
<td>181</td>
</tr>
<tr>
<td>Design flow-rate per pump, m³/h</td>
<td>21642</td>
</tr>
<tr>
<td>Heat transfer area per SG, m²</td>
<td>14666.5</td>
</tr>
<tr>
<td>SG outlet pressure, MPa(a)</td>
<td>6.0</td>
</tr>
<tr>
<td>Steam flow per loop, kg/s</td>
<td>1122</td>
</tr>
</tbody>
</table>
1. Introduction

- **In-Vessel Retention of core debris**
  - An important strategy for managing severe accidents of CAP1400
  - Retain the molten debris in the RPV by externally cooling water in the cavity and/or in-vessel injection
  - IVR strategy is highly compatible with CAP1400 design features
  - To make IVR strategy more efficient, some measures are taken to prevent large heat flux to RPV
  - Decomposition event tree (DET) supported by detailed analyses are used to demonstrate IVR efficiency
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2. IVR Related Design Features and Measures
3. IVR Analysis Methodology
4. Conclusion
2. IVR Related Design Features and Measures

- CAP1400 design features
  - RCS full depressurization
    - Low stresses on RPV
  - No RPV lower head penetrations
    - No other failure mechanism
  - Designed vessel insulation
    - Guide water cooling vessel and for venting steam
2. IVR Related Design Features and Measures

- Containment geometry and Cavity flooding
  - Easy to flood cavity to sufficient level with water in IRWST
  - Reflood in-vessel core debris if RCS is fully depressurized and the break locates below water level

- Passive Containment cooling
  - Condensate steam into water and return to the Cavity
2. IVR Related Design Features and Measures

- **Additional measures**
  - Core support plate sits low, beveling core radial support key, 14 feet fuel assembly
    - Lower plenum debris contacts and melts core support plate to prevent the focusing effect in transient
  - Core shroud sits on core support plate
    - Large metal mass to mitigate the focusing effect in the final state
2. IVR Related Design Features and Measures

- In-vessel injection in SAMG
  - Prevent large heat flux to vessel wall to compensate the uncertainties resulted from physico-chemical phenomena

Gravity injection from IRWST to hot leg through RNS

Injection to RCS through CVS pump
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1. Introduction

2. IVR Related Design Features and Measures

3. IVR Analysis Methodology

4. Conclusion
### Phenomenology and criterion

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<th>Criterion</th>
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<td><strong>B. Molten Corium Relocation</strong></td>
<td>Steam Explosion</td>
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<td>Structural Criterion</td>
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<td>Melt Jet Impingement</td>
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<td>Focusing Effect in Transient</td>
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<td>Heat Flux from Two-Layer Pool</td>
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<td>Structural Criterion</td>
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3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

- Detailed analyses of key phenomena

A. Core heatup and melting

A-1. Sequence Analysis by MAAP4

- Select core damage sequence from PSA and engineering judgment
- Analyze core heatup and melting
- Obtain key parameters as an input to further study
3. IVR Analysis Methodology

A-2. Detailed core heatup analysis by CFD

- Model of core shroud and barrel
- Model radial power profile
- Analyze core heatup and melting induced by decay heat and zirconium steam reaction

Temperature profile in core heatup
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

Conclusion

- Large pool formed before relocation
- Downward path blocked by frozen metal and oxide
- Core barrel fails sideward after the failure of shroud
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation and process

B-1. Steam Explosion
Potential impact of in-vessel steam explosion to vessel integrity
Not presented here

B-2. Melt jet impingement
Potential impact of melt jet impingement to vessel integrity
Not presented here

C. Corium pool in lower plenum
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

B-3. Focusing Effect in Transient

- MAAP4\CFD\hand calculation to calculate first and subsequent debris relocation
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

B-3. Focusing Effect in Transient

- Result: Debris contacts core support plate before dry out
- Focusing effect in transient (resulted from thin metal layer) therefore prevented by CAP1400 design features

![Graph showing IVR analysis methodology](image)
3. IVR Analysis Methodology

**A. Core heatup and melting**

**B. Core relocation process**

**C. Corium pool in lower plenum**

**C-1. Corium pool configuration in lower plenum**

- Thermodynamic interaction between corium and reactor internals should be considered

- Two effects to affect their contact
  - Un-oxidized zirconium has any chance to participate in thermodynamic interaction?
  - Crust effect can separate metal and oxide material?
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-1. Corium pool configuration in lower plenum

Un-oxidized zirconium has any chance to participate in thermodynamic interaction?

- The metal control rods and un-oxidized zirconium in the core melt first, and drain downward into the cooler regions of the core.
- During later phase of core melting, un-oxidized zirconium will join the metal layer, there is no pathway for it to flow to the oxide layer.
- Normally Un-oxidized zirconium does not participate in thermodynamic interaction.
- Therefore the possibility of two-layer corium pool is likely.
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-1. Corium pool configuration in lower plenum

- It is difficult to exclude the situation of any un-oxidized zirconium existence in corium pool

- If internals in lower plenum and partial (50%) un-oxidized zirconium participates in thermodynamic interaction is considered, three-layer corium pool may occur

- The possibility of three-layer corium pool is possible
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-1. Corium pool configuration in lower plenum

Crust effect can separate metal and oxide material?

- Input from SA analysis by MAAP/CFD
- Natural circulation analysis in corium pool by CFD
- Crust integrity analysis by ANSYS
- Result: Crust is likely to separate metal and oxide material from contacting
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-1. Corium pool configuration in lower plenum

Result

- Two-layer corium pool: Likely
- Three-layer pool: Possible
- Conservative three-layer pool: Unlikely

Definition of conservative three-layer pool: All un-oxidized zirconium and maximum steel is mixed into the lower plenum debris bed such that the density of heavy metal layer equals to the oxide, minimizing the upper metal pool thickness.

For detailed information, refer to accompanying PPT:

Research on Thermodynamic Interaction of Corium Materials in Lower Head
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-2. Heat transfer analysis

Two-layer pool

- Calculation for conservative conditions
  - Zirconium oxidation fraction: 75%
  - Time: 5400s
  - Metal mass: 71t

- Result
  - $q/q_{\text{crit}} = 0.74$

- $75\%$ Zr-ox
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-2. Heat transfer analysis

Three-layer pool

- Internals in lower plenum and partial (50%) un-oxidized zirconium participates in thermodynamic interaction

- Results
  - Heat flux in bottom metal layer is far below the CHF value
  - Heat flux in top metal layer is below the CHF value

![Graphs showing heat flux and CHF values for 30% Zr-Ox and 75% Zr-Ox](image_url)
3. IVR Analysis Methodology

C-2. Heat transfer analysis

Conservative three-layer pool

- All un-oxidized zirconium and maximum steel is mixed into the lower plenum debris bed such that the density of heavy metal layer equals to the oxide, minimizing the upper metal pool thickness.

- Results
  - Heat flux in bottom metal layer is below the CHF value.
  - Heat flux in top metal layer may reach at 2.4 MW/m² for accident sequences with large decay heat, exceeds the CHF value.
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-3. Effect of in-vessel Water Injection

- SAMG instructs operator to inject water to vessel
- No later than the formation of corium pool in the lower plenum
- Upward heat removal increased by evaporation of injection water, the focus effect of the upper metal layer is attenuated
- Heat flux in top metal layer may decrease to below the CHF value
3. IVR Analysis Methodology

A. Core heatup and melting

B. Core relocation process

C. Corium pool in lower plenum

C-4. RPV Structural Analysis
Refer to accompanying PPT:
Structural Integrity Research for Reactor Pressure Vessel under In-Vessel Melt Retention

C-5. CHF Testing for CAP1400
Refer to accompanying PPT:
Introduction of CAP1400 IVR Experiments
3. IVR Analysis Methodology

- Analysis Methodology
  - Decomposition event tree
  - Detailed analyses of key phenomena in each node

<table>
<thead>
<tr>
<th>DP</th>
<th>IR</th>
<th>RFL</th>
<th>Vessel Integrity in Transient</th>
<th>In-vessel Inj. in SAMG</th>
<th>Corium Pool Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCS Dep</td>
<td>Cav Fld</td>
<td>Core Rfd</td>
<td></td>
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</tbody>
</table>

- **OK**
- **F**

**Sequences**

- **Others**
  - Conservative three-layer with thin top metal
3. IVR Analysis Methodology

● Quantification of DET

<table>
<thead>
<tr>
<th>DP (RCS Dep)</th>
<th>IR (Cav Fld)</th>
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<tbody>
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<td>IVR1</td>
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<td></td>
<td></td>
<td>IVR2</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>Others</td>
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<td></td>
<td></td>
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<td>IVR3</td>
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<td>Conservative three-layer with thin top metal</td>
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<td></td>
<td></td>
<td></td>
<td>FIVR1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>FIVR2</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td>VF</td>
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<td></td>
<td></td>
<td></td>
<td>BP</td>
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</table>
3. IVR Analysis Methodology

- Quantification of DET

<table>
<thead>
<tr>
<th>DP (RCS Dep)</th>
<th>IR (Cav Fld)</th>
<th>RFL (Core Rfd)</th>
<th>Vessel Integrity in Transient</th>
<th>In-vessel Inj. in SAMG</th>
<th>Corium Pool Configuration</th>
</tr>
</thead>
</table>

IVR1

IVR2

Sequences: Several sequences

DP: RCS Depressurization, calculated from fault tree

IR: Cavity Flooding, calculated from fault tree

RFL: Core Reflooding, calculated from fault tree

Vessel Integrity in Transient: No failure from Steam Explosion or Melt Jet Impingement, no thermal failure due to the focusing effect in Transient

In-vessel Inj. in SAMG: Calculated from fault tree

Corium Pool Configuration: No thermal failure from two-layer pool or three-layer pool, no structural failure. Probability of conservative three-layer is assumed to be 0.5 conservatively
3. IVR Analysis Methodology

- Quantification of DET

<table>
<thead>
<tr>
<th>Final State</th>
<th>Meaning</th>
<th>Frequency, per year</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVR1</td>
<td>Core reflood</td>
<td>1.71E-7</td>
<td>89.92%</td>
</tr>
<tr>
<td>IVR2</td>
<td>IVR by in-vessel and ex-vessel cooling</td>
<td>5.79E-9</td>
<td>3.05%</td>
</tr>
<tr>
<td>IVR3</td>
<td>IVR by ex-vessel cooling</td>
<td>1.46E-10</td>
<td>0.08%</td>
</tr>
<tr>
<td>FIVR1</td>
<td>IVR failure due to focusing effect</td>
<td>1.46E-10</td>
<td>0.08%</td>
</tr>
<tr>
<td>FIVR2</td>
<td>IVR failure in transient</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>VF</td>
<td>Vessel failure due to failure of cavity flooding</td>
<td>5.57E-9</td>
<td>2.94%</td>
</tr>
<tr>
<td>BP</td>
<td>Containment bypass</td>
<td>7.33E-9</td>
<td>3.86%</td>
</tr>
<tr>
<td>......</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.90E-7</td>
<td>100%</td>
</tr>
</tbody>
</table>

- The result shows that IVR failure contribution is small, the efficiency of IVR is further demonstrated
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4. Conclusion

- IVR strategy is used to contain the core debris because it is highly compatible with CAP1400 design features.

- Some uncertainties, such as complex physico-chemical phenomena still exist. However, the design features and measures taken for CAP1400 to prevent large heat flux to RPV make IVR strategy robust.

- IVR efficiency is demonstrated by decomposition event tree supported by detailed analyses.

- IVR concept is extended as retaining the molten debris in the RPV by externally cooling water in the cavity and/or in-vessel injection.
Thank you for your Attention!

Any questions?