Accident Sequence Analysis of Unit 1 to 3 Using MELCOR Code

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2. Problems of previous analysis
3. MELCOR modeling
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1. Motivation

- Understand accident progression
- Evaluate core damage, MCCI, PCV integrity, etc., to establish the decommissioning plan
- Evaluate source term, for estimation of external and internal exposure
- Apply lessons learned from TEPCO's Fukushima Dai-ichi NPS accident to severe accident management of other nuclear power plants
1. Motivation

2. Problems of previous analysis

3. MELCOR modeling

4. Results

5. Further investigation

6. Conclusions
Previous Analysis of Unit 1

In this calc., temp. of RPV gas phase was very high. It was possible that gas phase leakage occurred before lower head failure.

Preliminary Analysis of Unit 2

If PCV boundary is intact, very high D/W pressure is predicted.

PCV leakage was assumed (approx. 50 cm²)

Calc.: After S/RV opened, D/W pressure rose simultaneously. Temp. of S/P was almost saturation temp.

D/W pressure increased slowly. Steam via S/RV condensed in S/P?

Previous Analysis of Unit 3


Difference during RCIC operation
Both RPV pressure and D/W pressure decreased simultaneously after HPCI started
1. Motivation
2. Problems of previous analysis
3. MELCOR modeling
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MELCOR Model

- MELCOR 1.8.5 on Linux was used
- S/RV was implemented using control function (CF)
- RCIC and HPCI were implemented using flow path (FL)
  - using CF in previous calc.
- Release of radionuclides from the core components: CORSOR-M
- S/P scrubbing model: SPARC
Nodalization of BWR4 Mark-I

Analyses are under going using precise nodalization
Thermal Stratification of S/P

Thermal stratification was examined when S/RV was opened continuously.

Thermal Stratification of S/P

Similar conditions during RCIC operation in Unit 2 and 3

1/400 volume of SBWR-600


Thermal stratification

Uniform

Only steam

Steam with NCG
Thermal Stratification of S/P

Thermal stratification of S/P was assumed during RCIC operation.

Flow of high-temp. water

RCIC exhaust pipe

Water level increased by RCIC injection (+0.6 m)

S/C

RCIC exhaust

downcomer

ca. 0.5 m

4.15 m

Top view

To simulate higher temp. of pool surface, control volume of S/P was divided vertically.
Preliminary CFD Analysis Model

s/c

Cylinder

half

r = 4.45 m
h = 4.095 m

対称条件
対称条件
断熱、Slip
円外周:
断熱、Non-slip

初期水温: 32℃

RCIC 模擬
SR 弁模擬
発熱部

内部発熱部

53.31 m
1.45 m
1.54 m
CFD Analysis on Thermal Stratification of S/P

RCIC exhaust  time = 20 h
General Assumptions

• External water injection via fire protection
  – adjusted based on preliminary analysis, but less than the record

• PCV boundary
  – leakage, if D/W temp. exceeds 350°C¹

• Venting
  – opening is adjusted based on preliminary analysis
  – timing is basically based on the record, but adjusted based on observed D/W press.

• Decay heat
  – TEPCO’s calculation²

• MCCI is not considered
  – original model (CORCON) overestimates

¹http://www.nisa.meti.go.jp/shingikai/800/28/007/7-2.pdf
²http://www.nisa.meti.go.jp/shingikai/700/12/001/1-4.pdf
1. Motivation
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Assumptions for Analysis of Unit 1

- **RPV boundary**
  - gas phase leakage is assumed (possible candidate is graphite gaskets*)
  - RPV is depressurized before lower head failure

- **Thermal stratification of S/P**
  - a particular S/RV opened repeatedly

- **MCCI is not considered**
  - original model (CORCON) overestimates

- **Hydrogen explosion**
  - Leak path from top of R/B to the environment at 15:36 on Mar. 12

RPV Press. and Water Level of Unit 1

- **Pressure (MPa)**
- **Water level (mm)**
- **Relative time (h)**

**Actual time**
- Mar. 12 0:00
- Mar. 13 0:00
- Mar. 14 0:00
- Mar. 15 0:00

*(○, △) Observed data*
D/W Press. and Temp. of Unit 1

PCV leakage due to over temp.

2nd vent also opened partially

1st vent partly succeeds

Nitrogen

Steam

Mar. 12 0:00

Mar. 13 0:00

Mar. 14 0:00

Mar. 15 0:00

Mole fraction (-)

Cumulative steam leakage (ton)

Relative time (h)

Actual time

Nitrogen

Steam

Hydrogen

Steam leak from RPV to D/W

PCV leakage due to over temp.

2nd vent also opened partially

1st vent partly succeeds

Nitrogen

Steam

Mar. 12 0:00

Mar. 13 0:00

Mar. 14 0:00

Mar. 15 0:00

Mole fraction (-)

Cumulative steam leakage (ton)

Relative time (h)
External Water Injection of Unit 1

Mar. 12 0:00  Mar. 13 0:00  Mar. 14 0:00  Mar. 15 0:00

Rate (m$^3$/h) vs. Accumulated volume (m$^3$)

Solid line: record  Dotted line: calc.

Rate

Accumulated volume

Relative time (h)
Temp. of Steam Dome of Unit 1

- **Temp. of steam dome**
- **Water level**
- **inner shroud**
- **(○,△) Observed data**
- **Mar. 11 18:00**
- **Actual time Mar. 12 0:00**
- **Mar. 12 6:00**

*Graph showing temperature and water level changes over time.*
Temp. and Mass of the Core of Unit 1

- **Max temp. (K)**
- **Mass of UO₂ (ton)**

**Actual time**
- Mar. 12 0:00
- Mar. 13 0:00
- Mar. 14 0:00
- Mar. 15 0:00

**Relative time (h)**
- 0 20 40 60 80

- **Cooled by steam flow from RPV to D/W**
- **Discharged to pedestal floor**
- **In core**

**Graph notes:**
- Lower plenum
- In RPV
- Temp.
Hydrogen Generation of Unit 1

![Graph showing hydrogen generation over time]
## Summary on Unit 1

<table>
<thead>
<tr>
<th>Previous work</th>
<th>Assumption/ analysis conditions</th>
<th>Rational</th>
<th>Irrational / questionable</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV boundary fails by lower head failure</td>
<td>RPV depressurization</td>
<td>Primary boundary integrity</td>
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</tr>
<tr>
<td>This work</td>
<td>Gas phase leakage of RPV to D/W</td>
<td>RPV depressurization</td>
<td></td>
</tr>
<tr>
<td>D/W head leakage due to over temperature</td>
<td>Hydrogen leak path to refueling bay</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assumptions for Analysis of Unit 2

- PCV boundary was intact during early period
  - D/W leakage was assumed when D/W press. decreased

- Heat removal of S/P by possible flooding of sea water in torus room
  1) simplified calc. (subtract enthalpy)
  2) calc. heat transfer (right fig.)

- Water injection rate via RCIC
  - adjust the time when water level decreases below TAF

- Thermal stratification of S/P
Water injection rate via RCIC was adjusted

RPV press. showed good agreement with observed data

adjust the time when water level decreases below TAF

Water injection rate via RCIC was adjusted

RPV press. showed good agreement with observed data

adjust the time when water level decreases below TAF
Thermal Stratification of S/P (Unit 2)

- **S/RV opened**
- **S/P remained subcooled**
- **D/W press. rises simultaneously when S/RV opens**

**Previous calc.**
- **Observed data**
- **Calc.**

- **S/P temp. is uniform distribution**
**RPV Press. and D/W Press. of Unit 2**

Calculated D/W press. showed good agreement with observed data.

- **PCV leakage was assumed**
- **Thermal stratification of S/P and heat removal from S/P were assumed**
- **Subcooled water remained lower S/P**
- **Small PCV leakage was assumed**

*will be discussed at next slide*
RPV Press. and D/W Press. of Unit 2

- Sea water flooding is modeled
- PCV leakage is assumed
- Thermal stratification of S/P and heat removal from S/P are assumed
- Subcooled water remains at lower S/P

S/P temp. decreases
Steam discharge stops but heat removal continues
External Water Injection of Unit 2

- Rate (m$^3$/h)
- Accumulated volume (m$^3$)
- Relative time (h)

Actual time:
- Mar. 12 0:00
- Mar. 13 0:00
- Mar. 14 0:00
- Mar. 15 0:00
- Mar. 16 0:00
- Mar. 17 0:00

Accumulated volume:
- Rate

Graph showing the rate and accumulated volume over time.
Temp. of Steam Dome of Unit 2

(○,△) Observed data

Temp. of steam dome

TAF

Water level

Mar. 12 0:00
Mar. 13 0:00
Mar. 14 0:00
Mar. 15 0:00
Mar. 16 0:00
Mar. 17 0:00

0 50 100 150
Relative time (h)

0 500 1000 1500
Water level (mm)

0 500 1000 1500
Temp. (K)

Observed data

Actual time

Mar. 12
0:00
Mar. 13
0:00
Mar. 14
0:00
Mar. 15
0:00
Mar. 16
0:00
Mar. 17
0:00

Mar. 12
0:00
Mar. 13
0:00
Mar. 14
0:00
Mar. 15
0:00
Mar. 16
0:00
Mar. 17
0:00

Temp. of steam dome

TAF

Water level
Hydrogen Generation of Unit 2

Actual time

Mar. 12 0:00  Mar. 13 0:00  Mar. 14 0:00  Mar. 15 0:00  Mar. 16 0:00  Mar. 17 0:00

H\textsubscript{2} conc. (v/v\%) vs. Relative time (h)

H\textsubscript{2} generated in the core (kg)

S/C  D/W

total amount

Mar. 12
Mar. 13
Mar. 14
Mar. 15
Mar. 16
Mar. 17
## Summary on Unit 2

<table>
<thead>
<tr>
<th>Assumption / analysis conditions</th>
<th>Rational</th>
<th>Irrational / questionable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Previous work</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early PCV leakage</td>
<td>D/W pressure during RCIC operation</td>
<td>Rapid decrease of D/W press. after S/RV opens</td>
</tr>
<tr>
<td>Uniform temp. of S/P</td>
<td></td>
<td>simultaneous increase of D/W press. at RPV depressurization</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCV integrity</td>
<td>Keep high D/W pressure after RPV depressurization</td>
<td></td>
</tr>
<tr>
<td>Sea water flooding</td>
<td>Slow increase of D/W press. during RCIC operation</td>
<td></td>
</tr>
<tr>
<td>Thermal stratification of S/P</td>
<td>Response of D/W press. at RPV depressurization</td>
<td>RCIC operated by circulation mode</td>
</tr>
</tbody>
</table>
Assumptions for Analysis of Unit 3

- Injection rate via RCIC and HPCI using test line
- Reduce HPCI injection
- Thermal stratification of S/P
- Flow rate of S/C and D/W spray at 50 m³/h
Water level when HPCI stopped (Unit 3)

- No water injection into RPV
- No steam draw from RPV

- RPV pressure increases according to water level at HPCI stop

- HPCI started
- S/RV opened
- Open: Fuel range
- Filled: wide and narrow

- Water level was not measured
- HPCI stopped

- Observed data

- TAF
- TAF+1m
- TAF+2m
- TAF+5m
RPV Press. and Water Level of Unit 3

Injection rate via RCIC and HPCI using test line

RPV press. decreases by continuous operation of HPCI

- Actual time
- Mar. 12 0:00
- Mar. 13 0:00
- Mar. 14 0:00
- Mar. 15 0:00
- Mar. 16 0:00
- Mar. 17 0:00

(O, △, □) Observed data

Pressure (MPa)

Collapsed water level (mm)

Relative time (h)
**RPV Press. and D/W Press. of Unit 3**

Thermal stratification of S/P is assumed

Temp. difference between surface and bottom of S/P is 20°C in preliminary CFD analysis

S/C spray suppresses D/W press.
D/W Press. and Temp. of Unit 3

Actual time

Mar. 12 0:00
Mar. 13 0:00
Mar. 14 0:00
Mar. 15 0:00
Mar. 16 0:00
Mar. 17 0:00

(○) Observed data

D/W press.
D/W temp.

Temp. (K)
D/W pressure (MPa)
Relative time (h)
External Water Injection of Unit 3

Rate (m$^3$/h)

Accumulated volume (m$^3$)

Relative time (h)

Mar. 12 0:00
Mar. 13 0:00
Mar. 14 0:00
Mar. 15 0:00
Mar. 16 0:00
Mar. 17 0:00

solid line: record
dotted line: calc.

rate

accumulated volume

0 50 100 150 200 250 300 350

0 500 1000 1500 2000 2500 3000

0 100 150 200 250 300 350 400

0 10 20 30 40 50 60 70
Temp. of Steam Dome of Unit 3

- **Actual time**
  - Mar. 12 0:00
  - Mar. 13 0:00
  - Mar. 14 0:00
  - Mar. 15 0:00
  - Mar. 16 0:00
  - Mar. 17 0:00

- **Observed data**
  - (○,△,▽,□)

- **Temperature of steam dome**
  - TAF
  - BAF

- **Collapsed water level (mm)**
  - 0 50 100 150

- **Relative time (h)**
  - 0 50 100 150
**Temp. and Mass of the Core of Unit 3**

- Maximum core temp.
- Discharged to pedestal floor

**Actual time**

- Mar. 12: 0:00
- Mar. 13: 0:00
- Mar. 14: 0:00
- Mar. 15: 0:00
- Mar. 16: 0:00
- Mar. 17: 0:00

**Temp. (K) vs. Relative time (h)**

- In core
- In RPV

**Fuel (%)**

- Discharged to pedestal floor

**Temp. and Mass of the Core of Unit 3**

- Discharged to pedestal floor
- Maximum core temp.
Hydrogen Generation of Unit 3

Hydrogen is released to the environment via venting

Actual time

Mar. 12 0:00  Mar. 13 0:00  Mar. 14 0:00  Mar. 15 0:00  Mar. 16 0:00  Mar. 17 0:00

0
0.02
0.04
0.06
0.08
0.1

Hydrogen (kg)

Mar. 14 11:01 explosion

R/B

H$_2$ from core

Mar. 14 11:01 explosion
# Summary on Unit 3

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</tr>
<tr>
<td>HPCI operation</td>
<td></td>
<td>RPV press. during HPCI operation</td>
</tr>
<tr>
<td>Uniform temp. of S/P</td>
<td></td>
<td>Significant deference between observed D/W press. and calculated one</td>
</tr>
<tr>
<td><strong>This work</strong></td>
<td></td>
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</tr>
<tr>
<td>Thermal stratification of S/P</td>
<td>D/W press. rises fast</td>
<td></td>
</tr>
<tr>
<td>Test line operation</td>
<td>Depressurization of RPV during HPCI operation</td>
<td></td>
</tr>
<tr>
<td>PCV spray operation</td>
<td>Both RPV press. and D/W press. decreases simultaneously</td>
<td></td>
</tr>
<tr>
<td>Venting</td>
<td>Fluctuation of D/W press.</td>
<td></td>
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</tbody>
</table>
Leakage from upper part of RPV to D/W is predicted by calculation.

After depressurization via S/RV (Unit 2 and Unit 3)
PCV leakage

Temperature distribution

<table>
<thead>
<tr>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.2 h</td>
<td>90.3 h</td>
<td>54.9 h</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1u</th>
<th>2u</th>
<th>3u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimation from plant parameters</td>
<td>~13 h</td>
<td>~90 h</td>
<td>&lt;60 h</td>
</tr>
<tr>
<td>MELCOR prediction</td>
<td>16.7 h</td>
<td>-</td>
<td>53.2 h</td>
</tr>
</tbody>
</table>
Time Line

- Core uncovery
- Core damaged
- RPV gas phase leak
- Lower head failure
- PCV failure

Relative time (h)

Unit 1
Unit 2
Unit 3
1. Motivation
2. Problems of previous analysis
3. MELCOR modeling
4. Results
5. Further investigation
6. Conclusions
5. Further investigation

• Accident sequence has been clear qualitatively

• But we need quantitative estimation

• Especially,
  – Core damage
  – MCCI

• Source term
  – Consist with monitoring data

• Uncertainty of measured data

• Aftershock
Credibility of Measured PCV Press.

RPV pressure and D/W pressure indicated almost same values.

- D/W pressure is credible
- S/C pressure is unreliable

S/RV opened
S/P remained subcooled
Abnormal Measurement

Credibility of measured data should be discussed in detail.
6. Conclusions

- RPV depressurized by gas phase leakage (Unit 1)
- It is reasonable that PCV boundary was intact in the early period of the accident (Unit 2)
- S/C was possibly cooled by sea water flooding to torus room (Unit 2)
- D/W pressure rose rather rapidly due to thermal stratification of S/P (Unit 3)
- S/C spray suppressed D/W pressure (Unit 3)
- Injected water via HPCI was not so much (Unit 3)

- We need further investigation to find core damage, MCCI, radionuclides released to the environment, etc.
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