CAREM for LBLOCA Analysis of APR1400

- Objective
- APR1400 Design Features
- Overview of CAREM
- RELAP5/MOD3.3 Modifications
- Assessment Matrix
- Plant Nodalization
- Uncertainty Parameters
- BIAS Evaluation & Licensing PCT
- Contents of Topical Report

CAREM: Code Accuracy based Realistic Evaluation Model
Objective

➢ To provide a preview of the APR1400 LBLOCA Realistic Evaluation Model (CAREM) Topical Report

CAREM : Code Accuracy based Realistic Evaluation Model
APR1400 Design Features (1/3)

- SIS consists of 4 mechanically independent trains
- Direct Vessel Injection (DVI)
- A safety injection pump and a safety injection tank are installed in each train.
- All the ECC water is injected into the upper annulus of reactor pressure vessel
Fluidic Device in SIT regulates the injection flow rate and enhances removal of decay heat in early reflood phase.
APR1400 Design Features (3/3)

- LBLOCA Scenario Specification for APR1400
  - Cold leg guillotine break
  - LOOP and Single failure of a DG assumed

I : Blowdown (~ 20 sec) break open ~ initiation of SIT
II : Refill (~ 35 sec) until water level is reached to the bottom of active core
III : Early Reflood (~ 190 sec) until SIT empty
IV : Late Reflood after SIT empty
Overview of CAREM (1/3)

- CAREM consists of 3 elements and 14 steps as in CSAU.
- Step 9 checks Experimental Data Covering (EDC) using the uncertainty parameters determined in step 8. If it fails, step 8 repeats until the covering is satisfied.
- Non-parametric statistics is used in EDC as well as in plant calculations.
- References:
Overview of CAREM (2/3)

Best Estimate + Uncertainty Quantification

- RELAP5/MOD3.3 + CONTEMP4/MOD5
- Two codes were consolidated to exchange P & M/E
- CSAU Based
- Uncertainty Quantification
  - Non-Parametric Statistics
- RELAP5/MOD3.3 was slightly modified
## Overview of CAREM (3/3)

### License History in Korea

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Development</th>
<th>Licensing Review</th>
<th>Approval</th>
<th>Remark</th>
</tr>
</thead>
</table>

- CLI: Cold Leg Injection
- UPI: Upper Plenum Injection
- DVI: Direct Vessel Injection
RELAP5/MOD3.3 Modifications (1/5)

- Modifications to improve the predictability of quenching time
  - Results of code assessment against various SETs and IETs
    - Over-prediction of film boiling HTCs
    - Under-prediction of quenching time

- Modifications
  - Logic for selecting dry-/wet-wall
  - Film boiling heat transfer calculation

Reference:
Logic for selecting dry-wall & wet-wall

- Definitions of tgsat, pfinrg in subroutines vertdragreg and verthifreg were modified.

Before:  
- Becomes wet-wall when steam super heating is below 51 K

After:  
- Restored the selection logic of the previous versions
  
- Becomes wet-wall when steam super heating is below 2 K
RELAP5/MOD3.3 Modifications (3/5)

- Film Boiling Heat Transfer
  - Subroutine: pstdnb.f

Before

\[ h_{FB} = \max(h_{FBB}, h_{FBNB}, h_{FR}) \]

where,

\[ h_{FBB} = \left[ 1400 - 1880 \min(0.05z_g, F) \right] \min(0.999 - \alpha_g, 0.5) + h_{FR} \left(1 - \alpha_g\right)^{0.5} \]

\[ h_{FBNB} = \text{Bromley correlation} \]

\[ h_{FBNB} = 0.62 \left( \frac{g k_f \rho_f (\rho_f - \rho_g) [h_{fg} + 0.5(T_w - T_{sp}) C_{gf}]}{L(T_w - T_{sp}) Pr_g} \right)^{0.25} \]

\[ h_{FR} = \text{Forslund-Rohsenow correlation} \]

\[ h_{FR} = 0.4 \left(\frac{\pi}{4}\right) \left(\frac{6(0.999 - \alpha_g)}{\pi}\right)^{2/3} \left[ \frac{g \rho_f \rho_g L h_{fg} k_f^3}{(T_w - T_{sp}) \mu_g d \left(\frac{\pi}{6}\right)^{1/3}} \right]^{0.25} \]

\[ h_{FB} \text{ calculated by } h_{FBB} \text{ is much higher than the data.} \]
Relap5/MOD3.3 Modifications (5/5)

- Effect of Modifications (Wet-wall selection and FB HT)

- Improved predictive capability was validated from the assessments against various SETs and IETs.
Assessment Matrix (1/10)

- Includes various SETs, IETs and tests specific to APR1400
  - MIDAS : ECC bypass
  - VAPER : SIT equipped with fluidic device
  - DOBO : Downcomer boiling
  - ATLAS : Overall reflood phenomena, ECC bypass, DC boiling

- Includes developmental assessments in RELAP5 documents as well

- Comprehensive and broad range of T/H conditions and scales
<table>
<thead>
<tr>
<th>Scale</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semiscale</td>
<td>1:1600</td>
</tr>
<tr>
<td>ATLAS</td>
<td>1:288</td>
</tr>
<tr>
<td>LOFT</td>
<td>1:50</td>
</tr>
<tr>
<td>CCTF</td>
<td>1:25</td>
</tr>
<tr>
<td>UPTF</td>
<td>1:1</td>
</tr>
</tbody>
</table>

- Results of assessments against ※ marked experiments are described in TR.
Assessment Matrix  (3/10)

- MIDAS
  - Direct ECC Bypass Test
  - Modified linear scaling law
    length $1/4.9$,  area $1/24.3$,  velocity $1/2.2$,  flow rate $1/53.9$
  - Superheated steam & water
  - Steam flow rate
    $0.7 \sim 1.8 \text{ kg/s}$
    ($37 \sim 100 \text{ kg/s APR1400}$)
  - SI injection
    $\sim 1.36 \text{ kg/s per DVI nozzle}$
    ($\sim 74 \text{ kg/s APR1400}$)
Assessment Matrix (4/10)

- **MIDAS**
  - Test 100 ~ 108: SI from DVI 2 & 4
  - Test 109: SI from DVI 2
  - Test 110 ~ 114: SI from DVI 4

FT-CL: CL steam flow, FT-DV: SI flow

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Assessment Matrix (5/10)

- **MIDAS**

- **DVI 4**
  - Broken CL

- **DVI 2**

- **Injection from DVI 4**: bypassed
- **Injection from DVI 2**: bypassed
- **Injection from DVI 4 & DVI 2**: bypassed
Assessment Matrix (6/10)

- **DOBO**
  - Downcomer Boiling Test
  - Circumferential length 1:47
    - Height 1:1
  - gap-size 0.25m,
    - height 6.4m
  - One-side of DC heated
  - Constant heat flux was simulated in each test
  - Window for visual investigation

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Assessment Matrix (7/10)

- DOBO

TS

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Assessment Matrix (8/10)

■ DOBO

TS

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Assessment Matrix (9/10)

- ATLAS
  - IET facility equipped with all major components of APR1400
  - Length 1/2, volume 1/288
  - Total 1250 instrumentations for measurements of physical parameters and facility control
Assessment Matrix (10/10)

- ATLAS Test 15

  ✓ Studied typical core reflood phenomena after SIT empty in ATLAS.
Plant Nodalization

- Plant model must be nodalized finely enough to capture both the important phenomena and design characteristics.
- But needs to be coarse to make the calculations practical and economical.
- Establishment of standard nodalization is needed to diminish nodalization uncertainty.

- APR1400 Nodalization
  - Guidelines and the various nodalizations of NPP & test facilities in RELAP5 documents and international experiences were referenced.
  - NPP nodalization is kept in the test facility nodalization.
APR1400 Nodalization

- Each loop and its components are modeled separately.
- Downcomer is modeled with 6 channels and 10 axial nodes.
- Core is modeled with 2 hydraulic channels and 20 axial nodes.
- Explicit and fine noding of SG primary and 2ndry sides.
Uncertainty Parameters (1/3)

- All phenomena in PIRT were considered in determination of uncertainty parameters.
- Uncertainties of parameter/phenomena were
  - treated statistically
  - treated conservatively
  - treated in bias evaluation
## Uncertainty Parameters (2/3)

<table>
<thead>
<tr>
<th>Component</th>
<th>Process/Phenomena</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core/Fuel</td>
<td>Stored energy</td>
<td>Fq, gap conductance, pellet thermal conductivity, Dittus-Boelter liquid forced convection HT correlation</td>
</tr>
<tr>
<td></td>
<td>Pellet heat transfer</td>
<td>Pellet thermal conductivity</td>
</tr>
<tr>
<td></td>
<td>Nucleate boiling</td>
<td>Chen nucleate boiling HT correlation</td>
</tr>
<tr>
<td></td>
<td>Critical heat flux</td>
<td>Zuber CHF correlation, Groeneveld CHF correlation</td>
</tr>
<tr>
<td></td>
<td>Rewet (Transition boiling HT)</td>
<td>Weismann transition boiling HT correlation</td>
</tr>
<tr>
<td></td>
<td>Film boiling HT</td>
<td>Bromley film boiling HT correlation, Forslund-Rohsenow film boiling HT correlation</td>
</tr>
<tr>
<td></td>
<td>Radiation HT</td>
<td>Conservatively</td>
</tr>
<tr>
<td></td>
<td>Boron reactivity</td>
<td>Conservatively</td>
</tr>
<tr>
<td></td>
<td>Decay power</td>
<td>ANS-79 DH</td>
</tr>
<tr>
<td></td>
<td>Clad oxidation</td>
<td>Cathcart-Pawel oxidation correlation</td>
</tr>
</tbody>
</table>

Example of the determination of uncertainty parameters
BIAS Evaluation
Combination of Uncertainties and Biases

- Plant Calculations
  - Limiting Break Size was determined from sensitivity calculations.
  - 124 sensitivity calculations for the limiting break.
  - Code parameters and reactor operational parameters are considered together.

- Bias Evaluation
  - Biases are evaluated for selected cases from plant sensitivity calculations.
  - 3 biases are evaluated separately.
    - ECC bypass during refill
    - ECC bypass during reflood
    - Steam binding during reflood
Licensing PCT

Total Uncertainty

Licensing PCT = PCT_{95/95} + \Delta PCT_{ECC\text{bypass\_refill}}
+ \Delta PCT_{ECC\text{bypass\_reflood}}
+ \Delta PCT_{\text{steam-binding}}
+ \Delta PCT_{\text{additional}}

※ \Delta PCT_{ECC\text{bypass\_reflood}} \text{ neglected}

\Delta PCT_{\text{additional}} \text{ Uncertainty due to plot frequency, time step, .. etc.}
Contents of Topical Report

- TR is prepared in accordance with NUREG-1379, Editorial Style Guide
- Structured in the order of CAREM procedures of 3 Elements and 14 Steps
- 10 Appendices to describe the details of
  - PIRT
  - Code modification
  - Code assessments against SETs & IETs
  - Coupling RELAP5 and CONTEMPT4
  - Uncertainty Parameter Values for APR1400 Plants
1. Introduction
   ▪ General introduction of CAREM, APR1400 design feature, acceptance criteria

2. Methodology Roadmap

3. Requirements and Capabilities
   3.1 Scenario Specification (Step 1)
   3.2 NPP Selection (Step 2)
   3.3 Phenomena Identification and Ranking Table (Step 3)
   3.4 Frozen Code Selection (Step 4)
   3.5 Code Documentation (Step 5)
   3.6 Code Applicability Determination (Step 6)
      ✓ constitutive equations, numerical solution method, component models, control functions, and overall code capability
4. Assessment and Ranging of Parameters

4.1 Establishment of Assessment Matrix (Step 7)
   ✓ Includes RELAP5 developmental assessments

4.2 Plant Nodalization and Experiment Evaluation (Step 8)
   ✓ Plant nodalization (Step 8.1)
   ✓ Determination of code uncertainty parameters and their ranges (Step 8.2)
   ✓ Determination of code parameters for scale bias evaluation (Step 8.3)

4.3 Check Experimental Data Coverings (Step 9)
   ✓ Code accuracy evaluation (Step 9.1)
   ✓ Check data covering (Step 9.2)

4.4 Determination of scale bias coverings (Step 10)
5. Sensitivity and Uncertainty Analysis

5.1 Determination of Plant Input Uncertainty (Step 11)
5.2 Combine Uncertainties and Biases (Step 12)
  ✓ Plant base calculation and SRS calculations
  ✓ Evaluation of scale biases

6. Quantification of total uncertainties (Step 13, 14)

7. Conclusion
Topical Report Table of Contents (4/6)

Appendices

- Appendix A: Identification and Ranking of Phenomena or Processes
- Appendix B: Freezing of RELAP5/MOD3.3/K
  - Modification of a portion of reflood model
  - Modification on gap conductance calculation
  - Modification to improve code fails due to non-condensable gases
- Appendix C: Assessment of RELAP5/MOD3.3/K against SETs
  - FLECHT-SEASET
  - CCTF
  - NEPTUN
  - THTF
  - PKL

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Appendices

- Appendix D: Assessment of RELAP5/MOD3.3/K against IETs
  - LOFT
  - SEMISCALE
  - LOBI

- Appendix E: Assessment of RELAP5/MOD3.3/K against Reflood Test

- Appendix F: Assessment of RELAP5/MOD3.3/K against ECC Bypass Test
  - UPTF 21D
  - MIDAS (Multi-dimensional Investigation in Downcomer Annulus Simulation)

- Appendix G: Assessment of RELAP5/MOD3.3/K against Downcomer Boiling Test
  - DOBO (DOwncomer BOiling)
Appendices

- Appendix H: Assessment of RELAP5/MOD3.3/K against FD/SIT
  - VAPER (VAIve Performance Evaluation Rig)
- Appendix I: Coupling RELAP5/MOD3.3/KJ and CONTEMPT4/MOD5
- Appendix J: Sampled Uncertainty Parameter Values for 124 Plant Calculations
Information for RAI

- A complete set of drawings of the reactor primary system, including the reactor vessel, reactor core, cold leg and hot leg piping, steam generator, pressurizer and the accumulator; a diagram of the emergency core cooling system piping; A set of full size hard copies and copies in PDF format

  : All set will be prepared.

- A complete set of code manuals including the theory manual, the input manual and the testing manual. If these manuals are identical to NUREG reports issued by NRC associated with RELAP-5 Mod 3.3, provide a reference list of these NUREG reports

  : All set will be prepared.
Information for RAI

- A CD containing all the source code, executables, input deck for Shin-Kori (SKN) unit 3 and unit 4. PVM package used to link the CONTEMPT4/MOD5 with RELAP-5 code
  
  : It needs to be discussed.
Thank you for your attention