Code Accuracy based Realistic Evaluation Model (CAREM) for LBLOCA Analysis of APR1400

Meeting Objective

Overview of APR1400 Design Features and LOCA

Experimental Program

Overview of CAREM

Contents of Topical Report

Summary

Meeting Objective

- To provide a preview of the APR1400 LBLOCA Realistic Evaluation Model (CAREM) Topical Report for its submittal in 3rd Qtr 2011

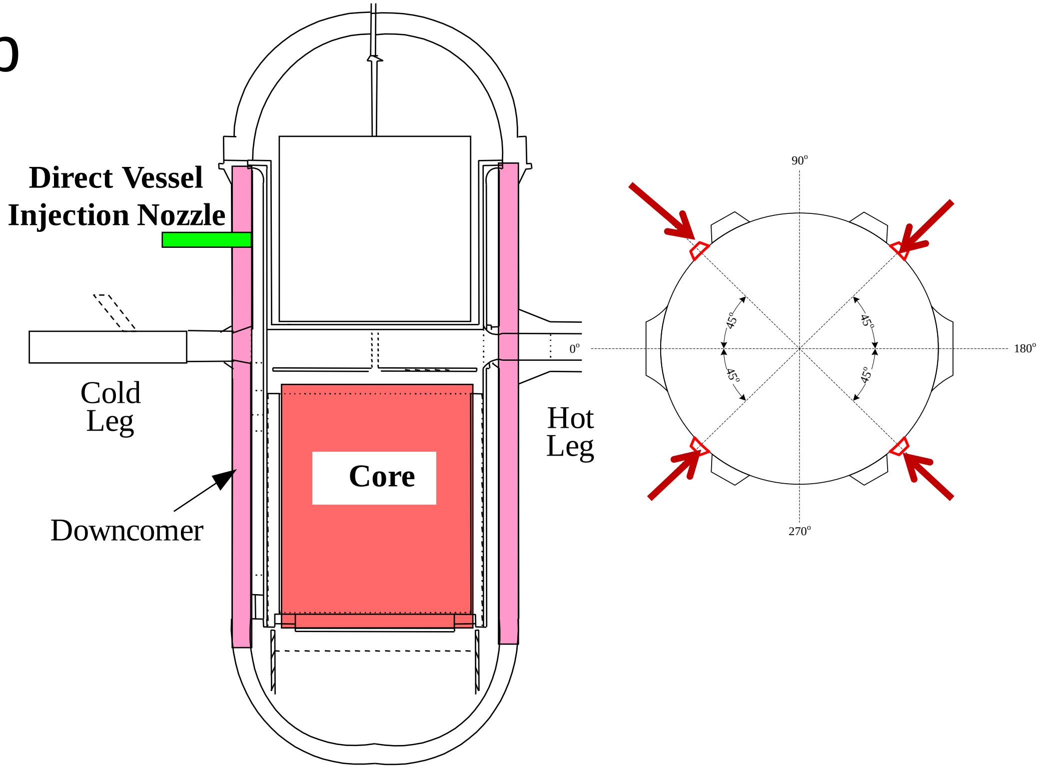
Contents

- Overview of APR1400 Design Features and LOCA Experimental Program
- Overview of CAREM
- Contents of Topical Report
- Summary

APR1400 Design Features

Direct Vessel Injection (DVI)

- SIS consists of 4 mechanically independent trains
- 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

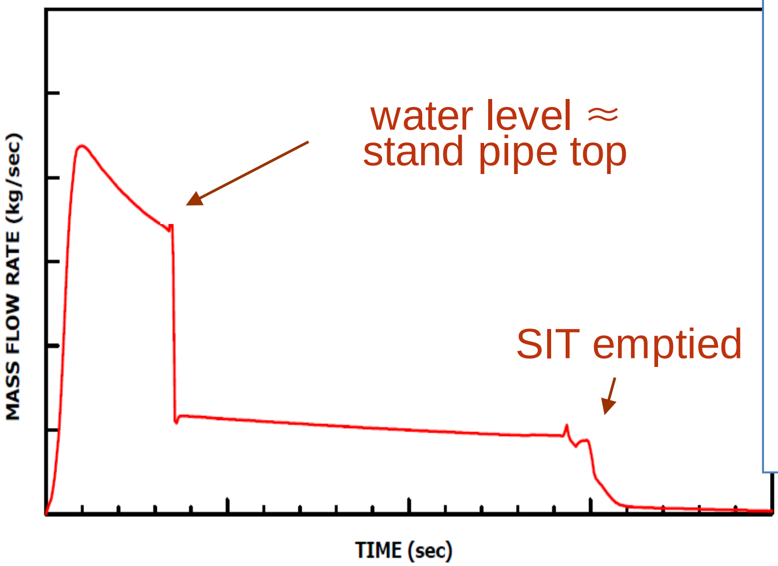


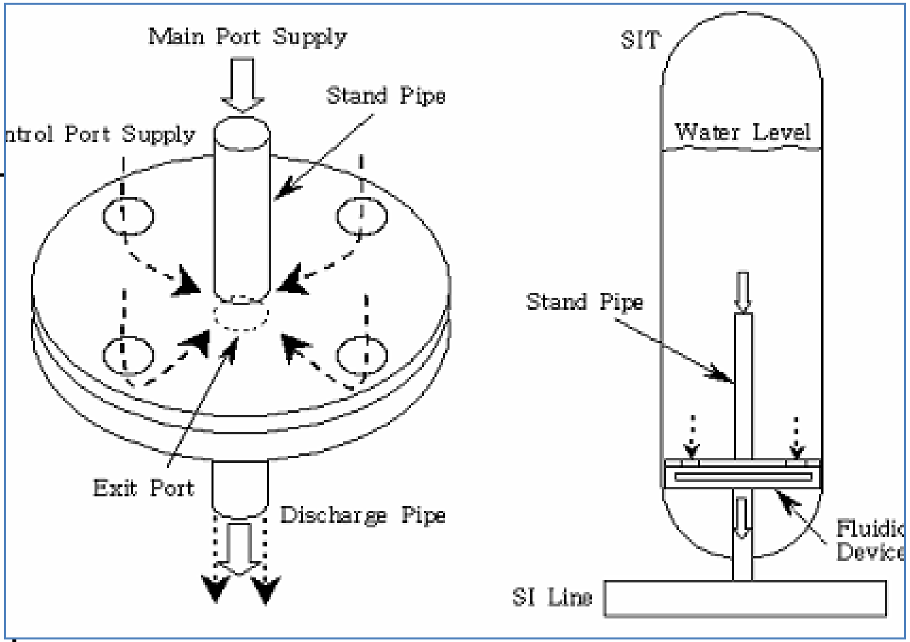
Direct Vessel Injection (DVI)

APR1400 Design Features

SIT equipped with Fluidic Device

➢ FLUIDIC DEVICE in SIT regulates the injection flow rate and enhances removal of decay heat in early reflood phase.

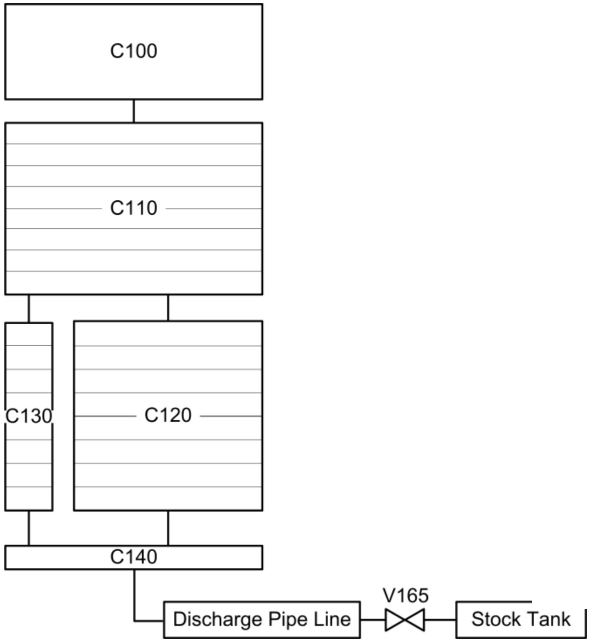


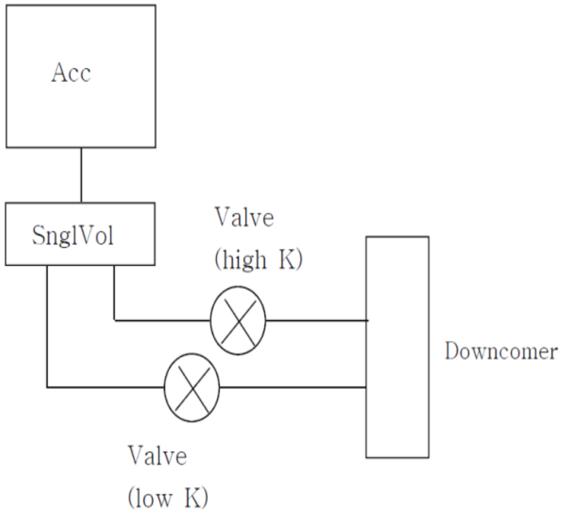


APR1400 Design Features

SIT equipped with Fluidic Device

- Sensitivity on the discharge of non-condensable gas during low flow injection period was studied.
- Downcomer water levels were enough to reach cold leg elevation in both cases.
- Negligible effect on core cooling was observed.





APR1400 Design Features

LOCA Experimental Program (1/7)

- To better understand the phenomena during APR1400 LOCA, various experiments were performed.
- Separate effect tests
  - MIDAS (Multi-dimensional Investigation in Downcomer Annulus Simulation)
  - DOBO (DOwncomer BOiling)
  - VAPER (Valve Performance Evaluation test Rig)
- Integral effect test
  - ATLAS (Advanced Thermal-hydraulic Test Loop for Accident Simulation)

APR1400 Design Features

LOCA Experimental Program (2/7)

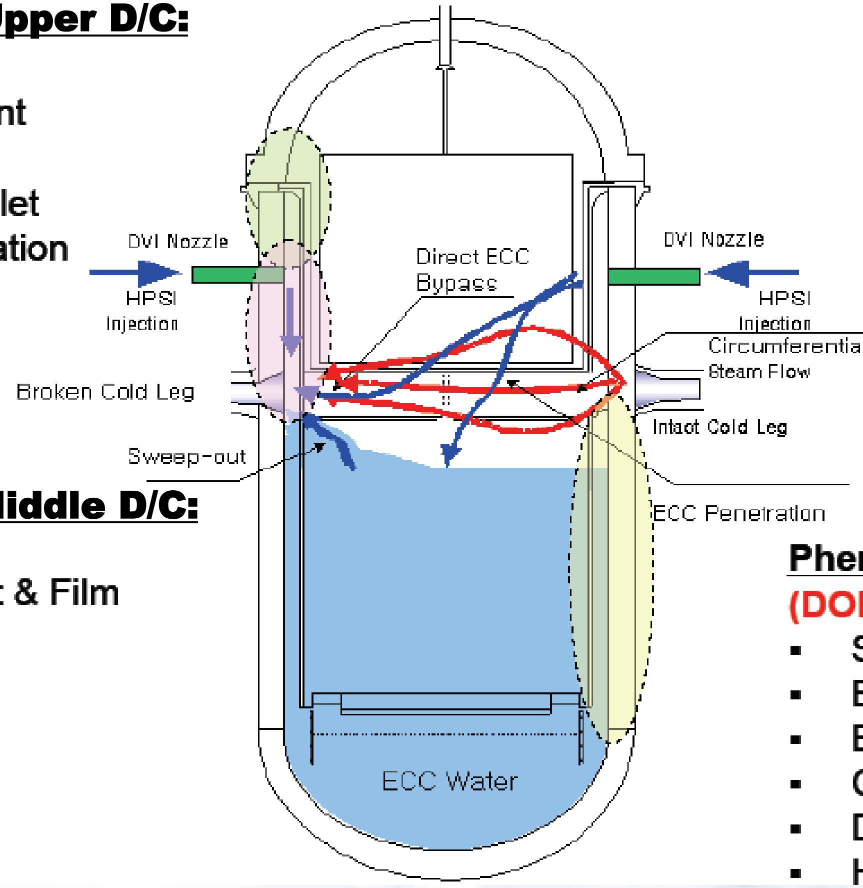
- LOCA tests confirmed the effectiveness of APR1400 SIS design and the data were utilized in the development of realistic evaluation model.
  - Effective delivery of ECC water flowing as film was observed.
  - Successful cooling of the core in late reflood was proven.

APR1400 Design Features

LOCA Experimental Program (3/7)

Phenomena in the Upper D/C:
(MIDAS)

- Water Jet Impingement
- Liquid Film Spreading
- Entrained Liquid Droplet
- H/T: Steam Condensation



Phenomena in the Middle D/C:
(MIDAS)

- Breakup of Steam Jet & Film
- Multi-D Steam-Water Interaction
- Direct ECC Bypass
- Sweep-out
- ECC Penetration

D/C-Core Interaction:
(ATLAS)

- Degree of Subcooling
- Reflood Rate
- Reflood H/T
- Manometric Oscillation

Phenomena in the *Lower* D/C
(DOBO)

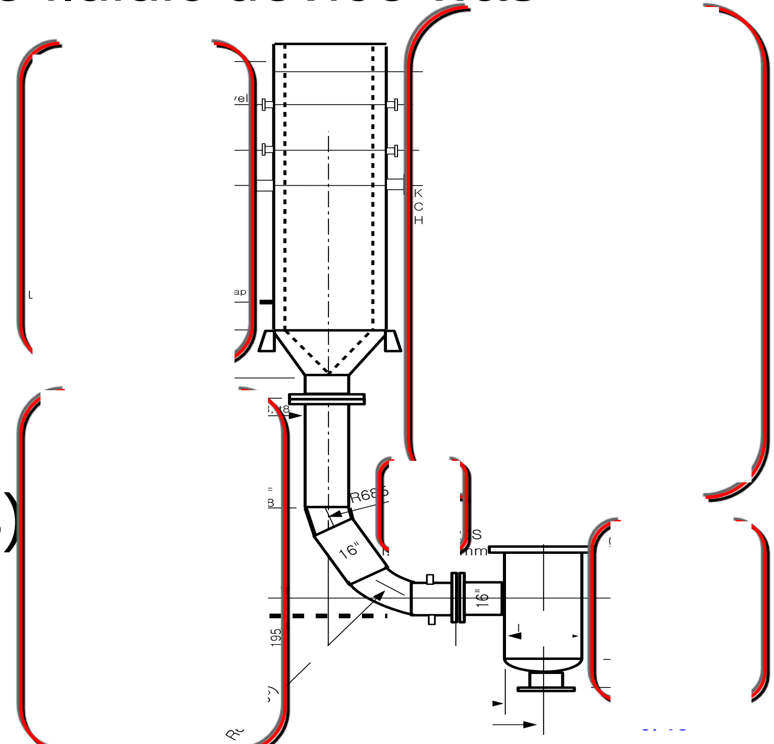
- Stored Energy Release
- Boiling H/T at Wall
- Bubble Rise
- Condensation of Bubbles
- Degree of Subcooling
- Hydro-Static Head

APR1400 Design Features

LOCA Experimental Program – SETs (4/7)

- VAPER
  - Full scale SIT experiment with fluidic device
  - Regulation of safety injection flow rate was confirmed and the flow resistance of the fluidic device was provided.

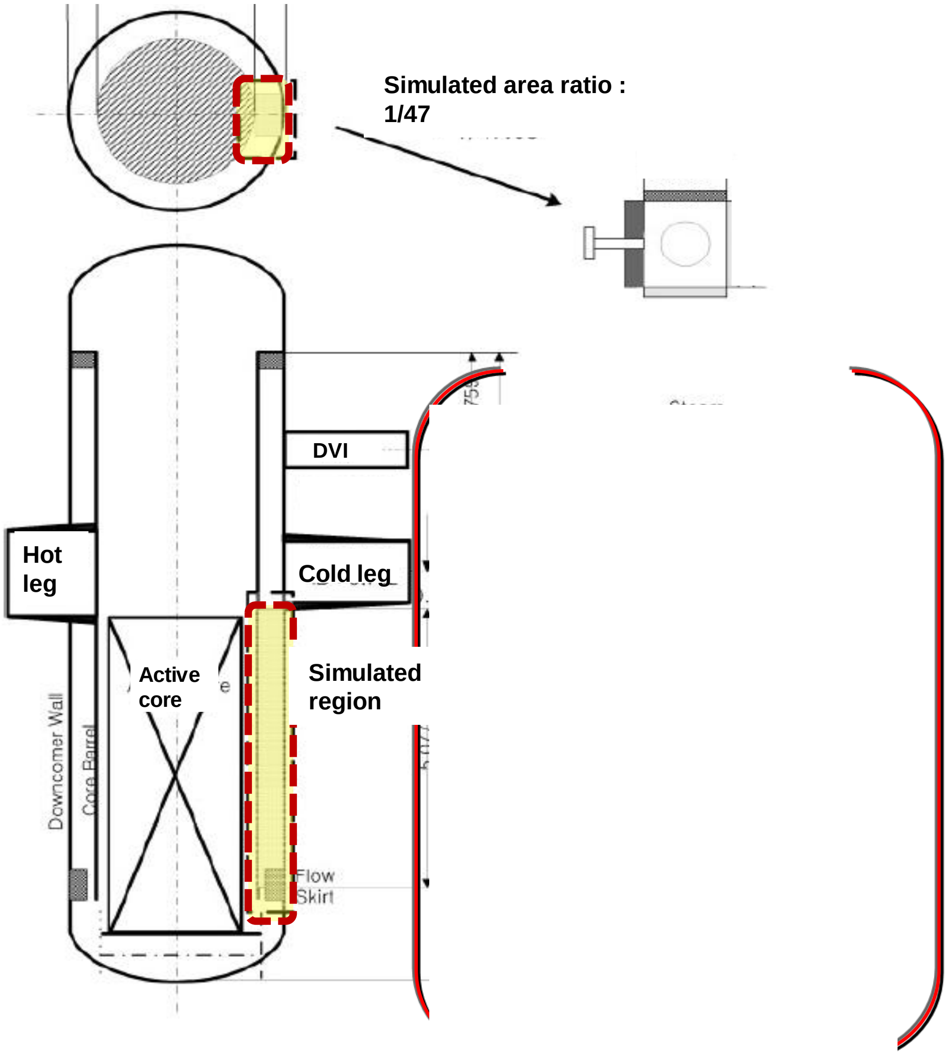
- MIDAS
  - 1/24 scale facility to study phenomena in downcomer during late reflood phase
  - Direct ECC bypass (15 tests)
  - Void height (4 tests) in the downcomer



APR1400 Design Features

LOCA Experimental Program – SETs (5/7)

- DOBO:
  - to study downcomer boiling phenomenon
  - A fraction of lower downcomer was simulated maintaining gap width and height
  - 4 tests with varying wall heat flux

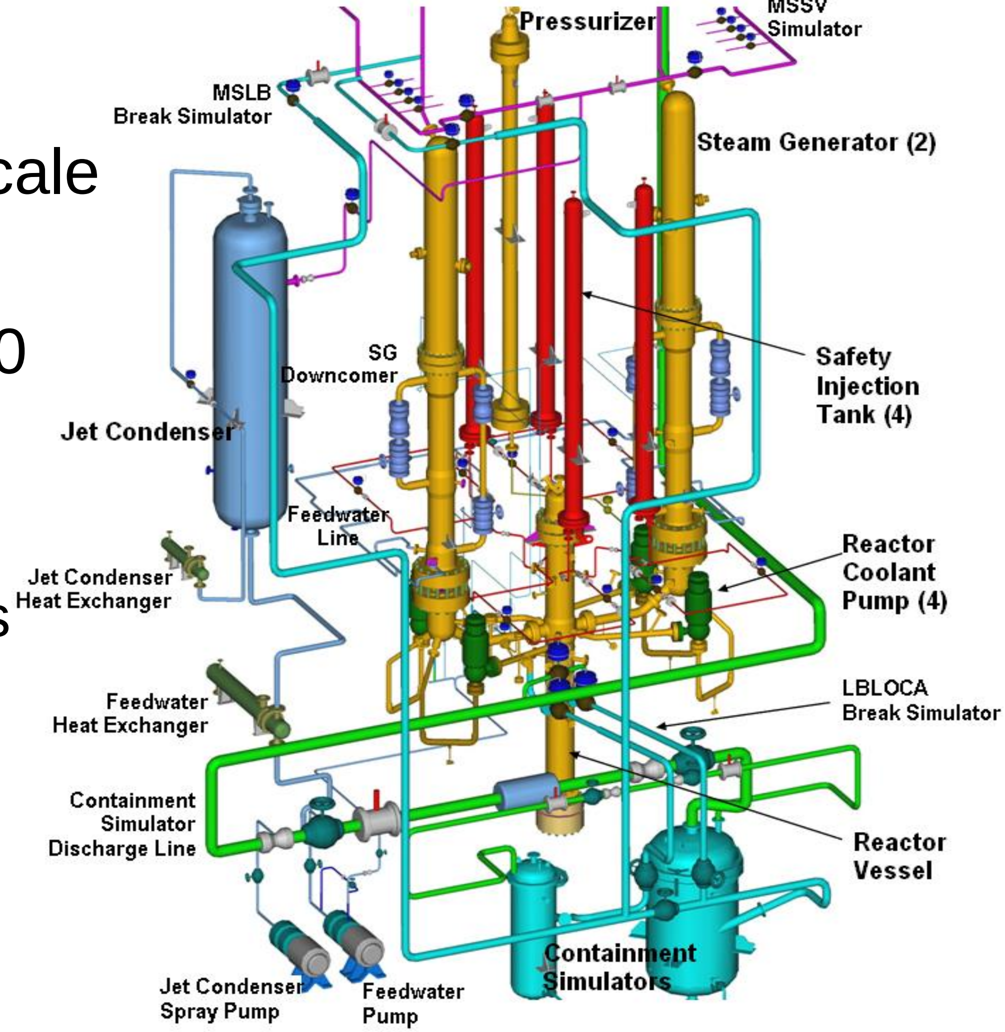


APR1400 Design Features

LOCA Experimental Program – IET (6/7)

- ATLAS: 1/2 length,
  1/288 volume scale

- Equipped with all major components of APR1400
  - RPV & Pressurizer
  - 2 Steam generators
  - 4 Reactor Coolant Pumps
  - 2 Hot Legs & 4 Cold legs
  - 4 DVI injection lines
  - 4 Safety Injection Tanks
  - 4 HPSI Pumps



APR1400 Design Features

LOCA Experimental Program – IET (7/7)

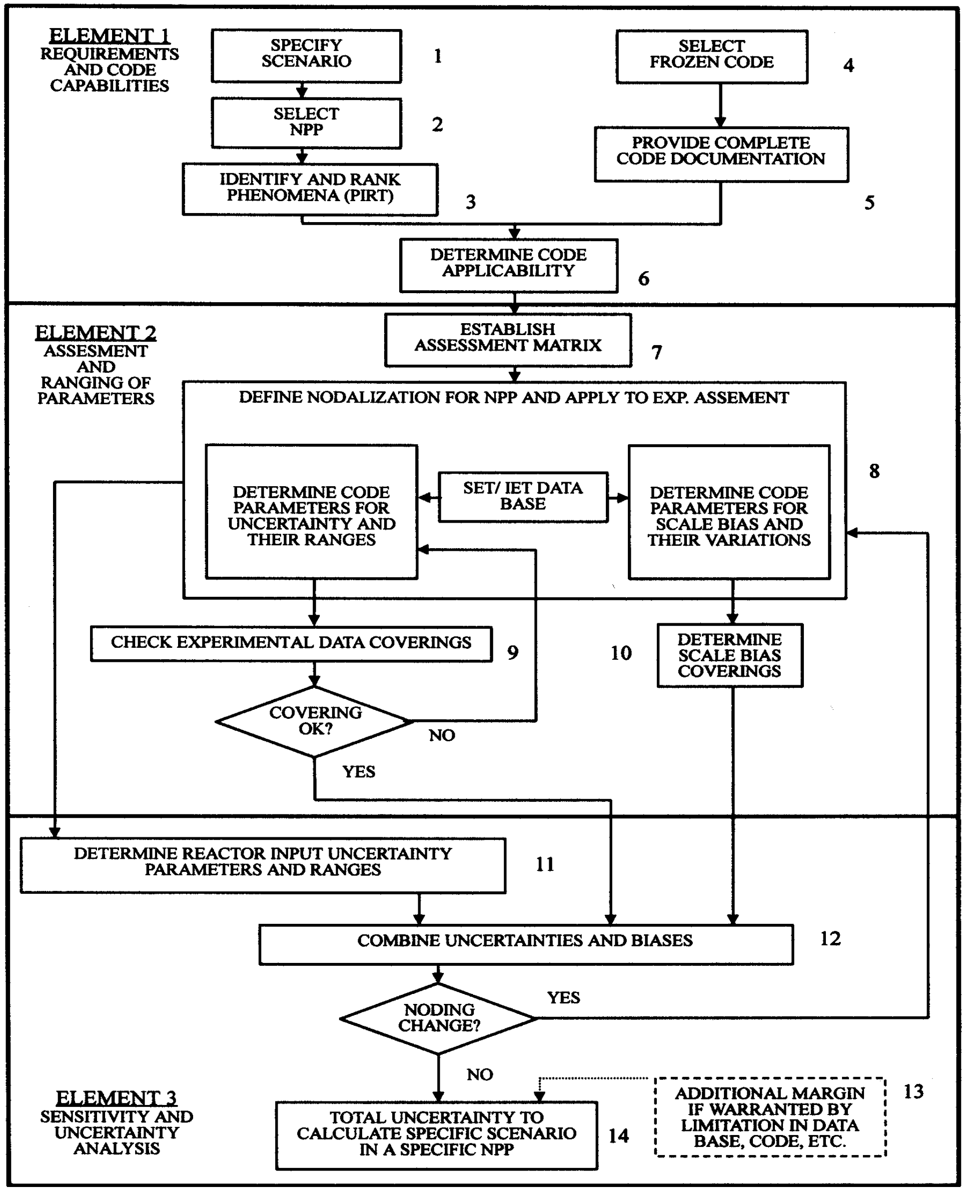
➢ ATLAS

- To understand and identify the major thermal hydraulic characteristics during the reflood phase of APR1400.
- To provide reliable data to help validate the LB-LOCA methodology.

Phase	Objectives	Test No.
Phase 1 Parametric Effect	To study the effects of wall temperature, SI flow rate, containment pressure, decay heat, etc., on core cooling	No.1 ~ No.7
Phase 2 LBLOCA Reflood	To study the reflood phenomena of DVI plant and to measure necessary data including PCT.	No.8 ~ No.15

Overview of CAREM

- 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:
  - Nuclear Tech. V.148, 3, 2004.
  - Nuclear Tech. V.158, 2007.



Overview of CAREM

Best Estimate + Uncertainty Quantification

- RELAP5/MOD3.3 + CONTEMPT4/MOD5
- CSAU Based
- Uncertainty Quantification
  - Non-Parametric Statistics

Overview of CAREM

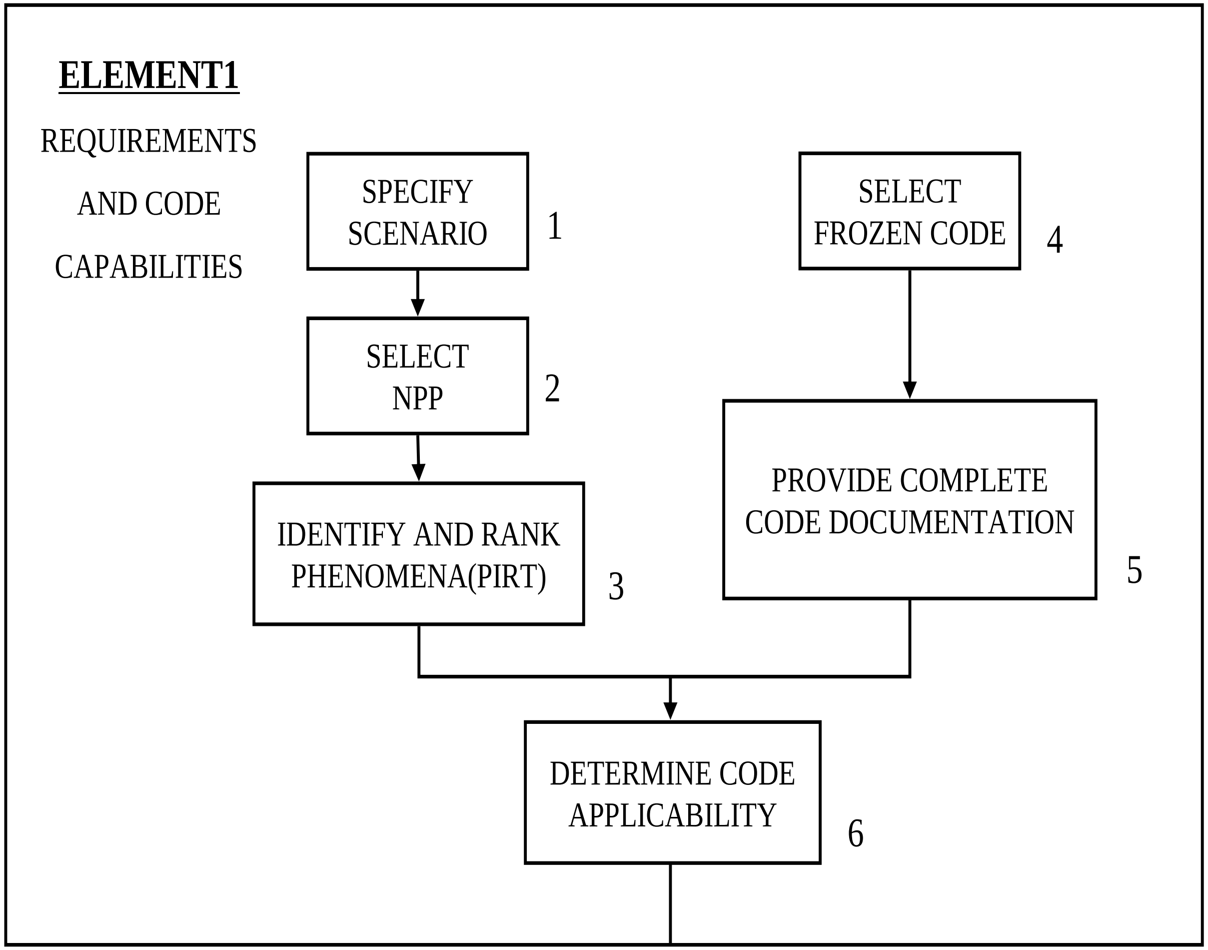
Licensing History in Korea

Plant Type	Development	Licensing Review	Approval	Remark
WH 3-Loop	1993 ~ 1996	1997 ~ 2002	Sep. 2002	CLI UEM change
OPR1000	2002 ~ 2005	2005 ~ 2007	Apr. 2007	CLI
WH 2-Loop	2005 ~ 2006	2006 ~ 2007	Dec. 2007	UPI
APR1400	2004 ~ 2008	2008 ~ 2009	Feb. 2010	DVI

- CLI: Cold Leg Injection
- UPI: Upper Plenum Injection
- UEM: Uncertainty Evaluation Method
- DVI: Direct Vessel Injection

Element 1

Requirements and Code Capabilities

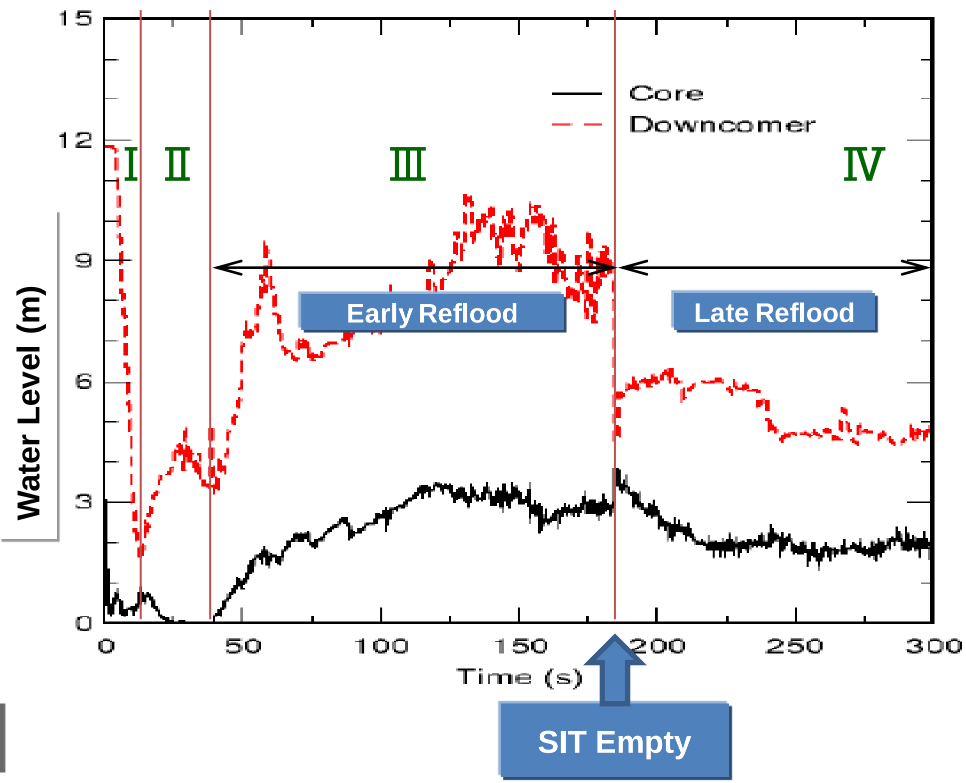


Element 1 is the same as CSAU.

Element 1

Requirements and Code Capabilities

- Scenario Specification
  - 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

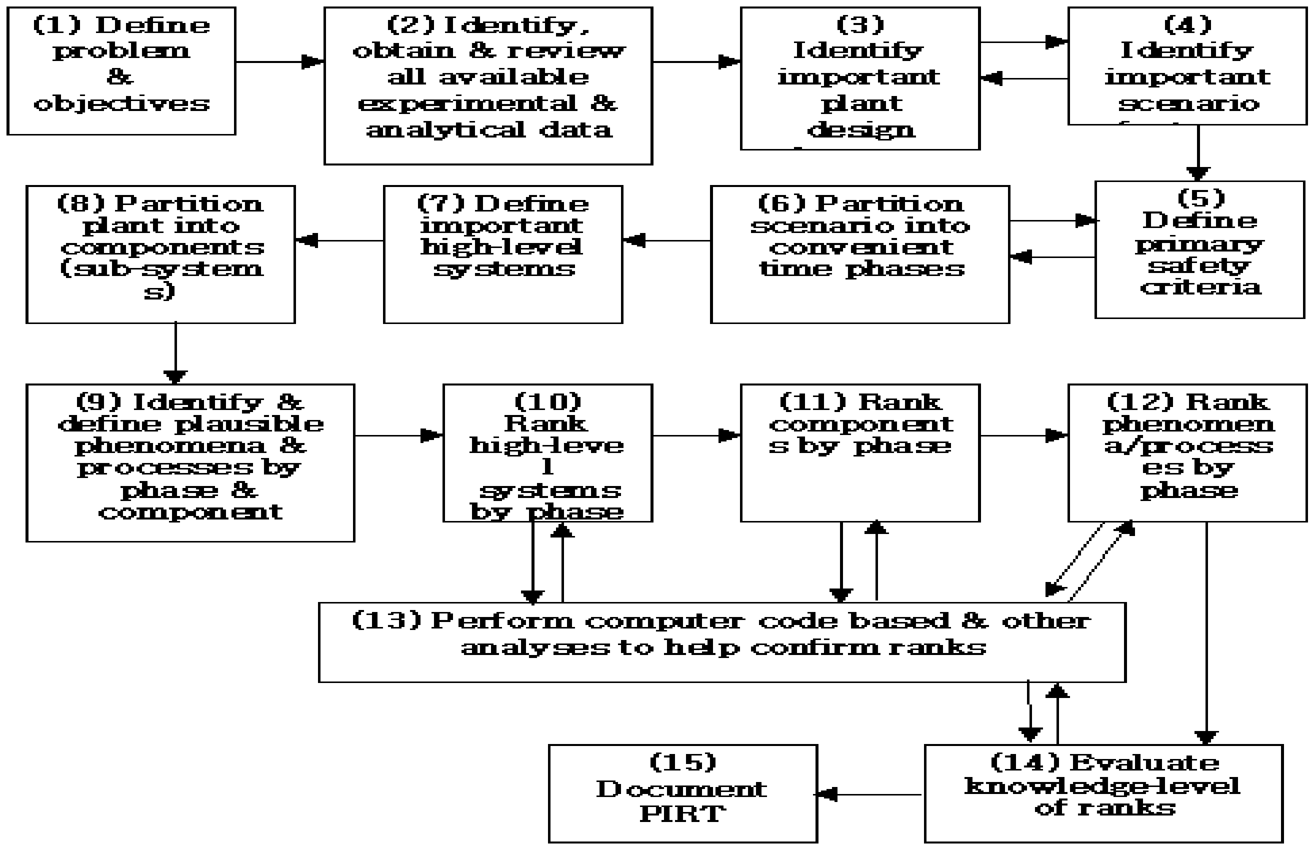
after SIT empty

Phenomena/Process Identification and Ranking (1/7)

- APR1400 LBLOCA PIRT was developed from PIRT(2001).
- APR1400 PIRT (2001)
  - Collaborative efforts between KINS and INEEL
  - Panel:
    - ✓ Mr. Gary E. Wilson (Idaho National Engineering Laboratory) – Panel Chairman
    - ✓ Dr. Brent E. Boyack (Los Alamos National Laboratory)
    - ✓ Dr. Bub-Dong Chung (Korea Atomic Energy Research Institute – KINS Customer Representative)
    - ✓ Dr. Lawrence E. Hochreiter (Pennsylvania State University)
    - ✓ Dr. Jose N. Reyes (Oregon State University)

Phenomena/Process Identification and Ranking (3/7)

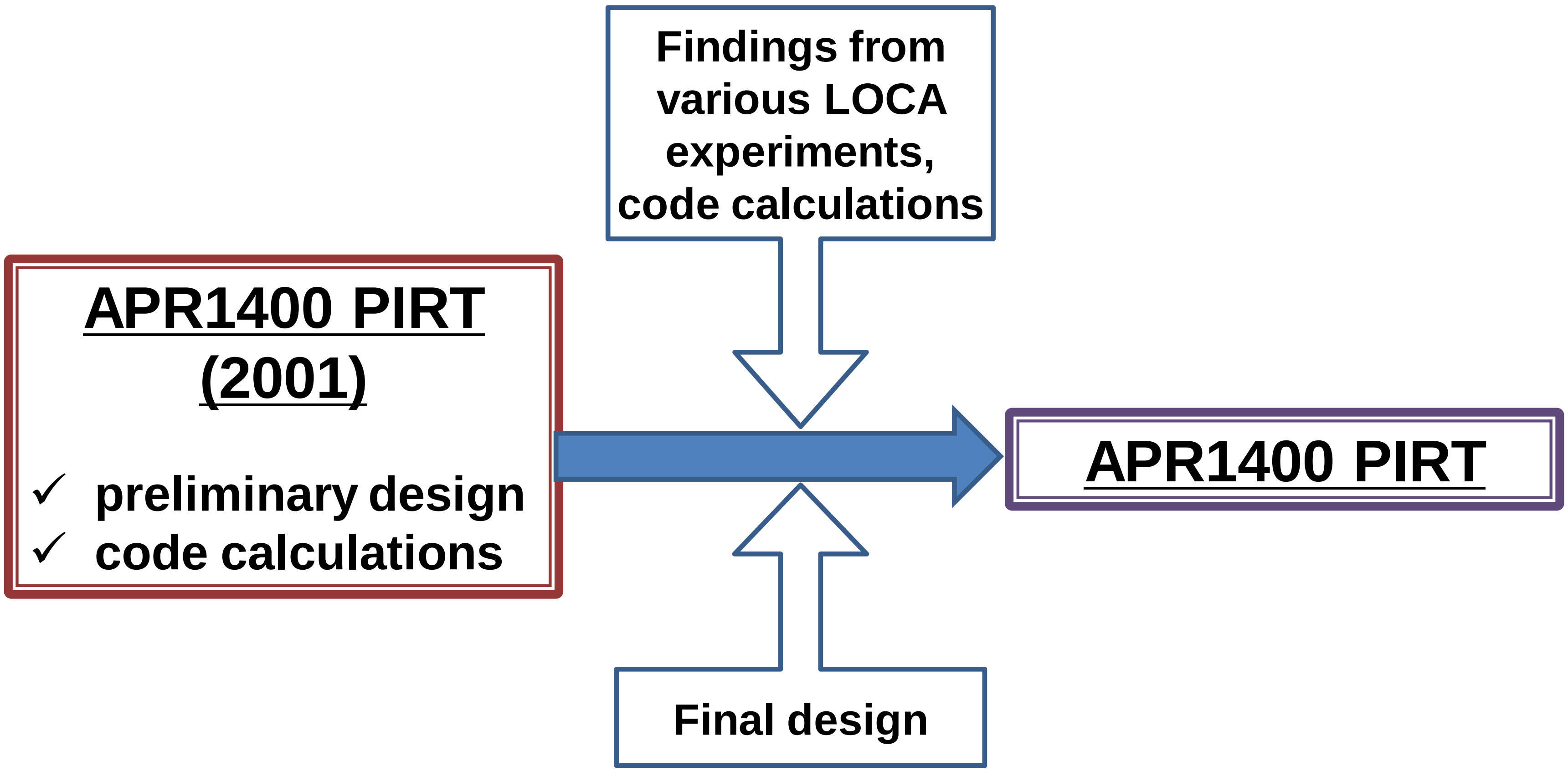
➢ APR1400 PIRT (2001) Process



- PCT was used as the primary safety criterion to judge the relative importance of a phenomenon.

● Phenomena/Process Identification and Ranking (4/7)

➢ APR1400 PIRT



Phenomena/Process Identification and Ranking (5/7)

- APR1400 PIRT

APR1400 PIRT (2001)			APR1400 PIRT		
Phase	Starts At	Ends At	Phase	Starts AT	Ends At
Blowdown	Break initiation	Initiation of LP refill	Blowdown	Break initiation	Initiation of SIT injection
Refill	End of blowdown	Initiation of core recovery	Refill	End of blowdown	Initiation of core recovery
Early Reflood	End of refill	Initial core quench	Early Reflood	End of refill	End of SIT injection
Late Reflood	Initial core quench	Stable core quench	Late Reflood	End of SIT injection	Stable core quench
Based on the assumption of fuel rod re-heating due to downcomer boiling (code calculations using preliminary design data & excessively conservative assumptions)			Based on test results and code calculations using the final design data		

Phenomena/Process Identification and Ranking (6/7)

➢ APR1400 PIRT

APR1400 PIRT (2001)

- **176 Phenomena in 30 components**

APR1400 PIRT

- **73 Phenomena in 15 components**

- Screened by ranks equal to or higher than 4
  (1: Lowest, 2: Low, 3: Middle, 4: High, 5: Highest)
- Simplification of sub-components
  (ex. SG : shell side, primary and secondary side → SG)

Phenomena/Process Identification and Ranking (7/7)

➢ APR1400 PIRT

Component	Process/Phenomena
Core/Fuel	Stored energy release
	Pellet heat transfer
	Gap conductance
	Nucleate boiling
	Critical heat flux
	Rewet
	Film boiling
	Transition boiling
	Vapor forced convection
	Radiation
	Void reactivity
	Boron reactivity effect
	Decay power
	Clad oxidation
	Clad ballooning
	Flow blockage
	Fuel relocation
	Clad burst
	Guide thimble radiation
	Spacer grid heat transfer
	Flashing
	Level
	Entrainment
	Multi-dimensional flow
	Vapor superheat
	Interfacial heat transfer

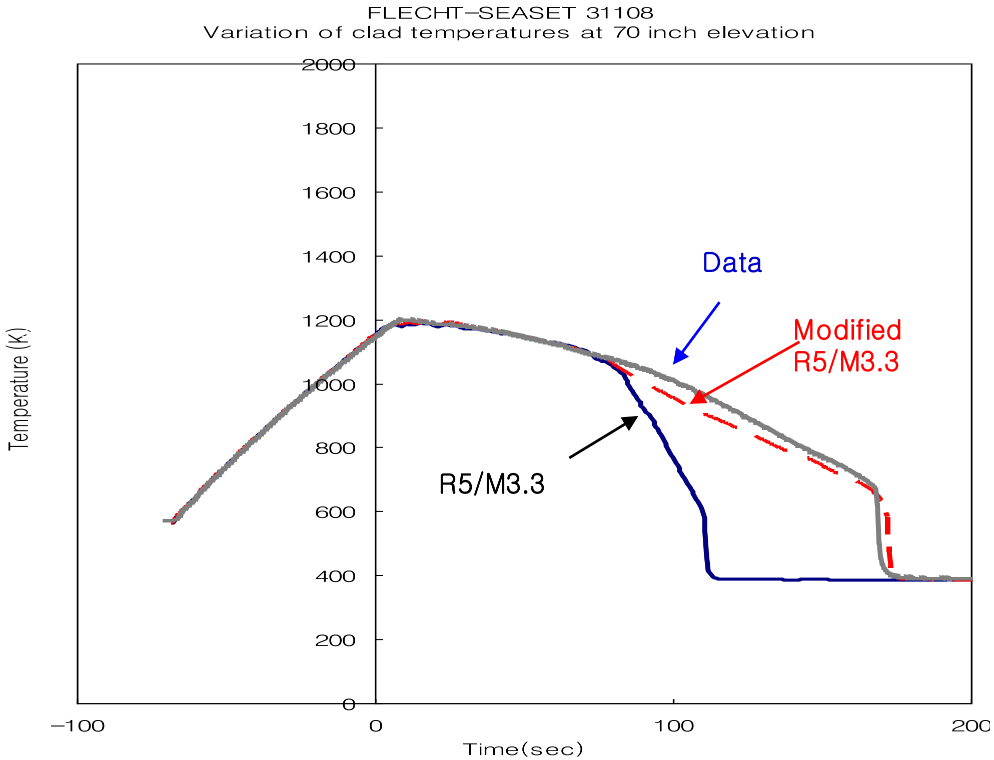
Component	Process/Phenomena
Reactor Vessel downcomer	Vessel stored energy release
	Downcomer boiling
	Direct vessel injection jet flow
	Flashing
	Level
	Entrainment
	De-entrainment
	Multi-dimensional flow
	Counter-current flow
	Condensation
	Delta-P
	Bulk mixing
	Non-condensable gas effect
Reactor Vessel lower plenum	Stored energy release
	Boiling
	Level
	Multi-dimensional flow
	Entrainment
	Bulk mixing
Reactor upper plenum	Flashing
	Level
	De-entrainment on structures
	Multi-dimensional flow
	Entrainment
Reactor upper head	Flashing

Component	Process/Phenomena
RCP	Pump performance
Hot Leg	Entrainment
	De-entrainment
Pressurizer	Flashing
	Level
SG	Vapor superheating
	U-tube heat transfer
Break	Critical flow
	Delta-P
	Cold leg-Containment flow path
Containment	Pressure history
	Temperature history
SIP	Time dependent delivery
SIT	Stored energy release
	Pressure
	Liquid temperature
	Gas temperature
	Level
	Gas discharge to piping
	FD high flow K-factor
	FD low flow K-factor
IRWST	Temperature

Frozen Codes (1/2)

- RELAP5/MOD3.3 & CONTEMPT4/MOD5
  - Two codes were consolidated to exchange P & M/E every time step.
  - RELAP5/MOD3.3 was slightly modified.
    - ■ Reflood Model (PSI Model) of RELAP5/MOD3.3
      - √ Predicts early quenching
      - √ Over-predicts film boiling HTC
    - ■ Film boiling HTC model was modified based on the assessment against FLECHT-SEASET tests.

Frozen Codes (2/2)



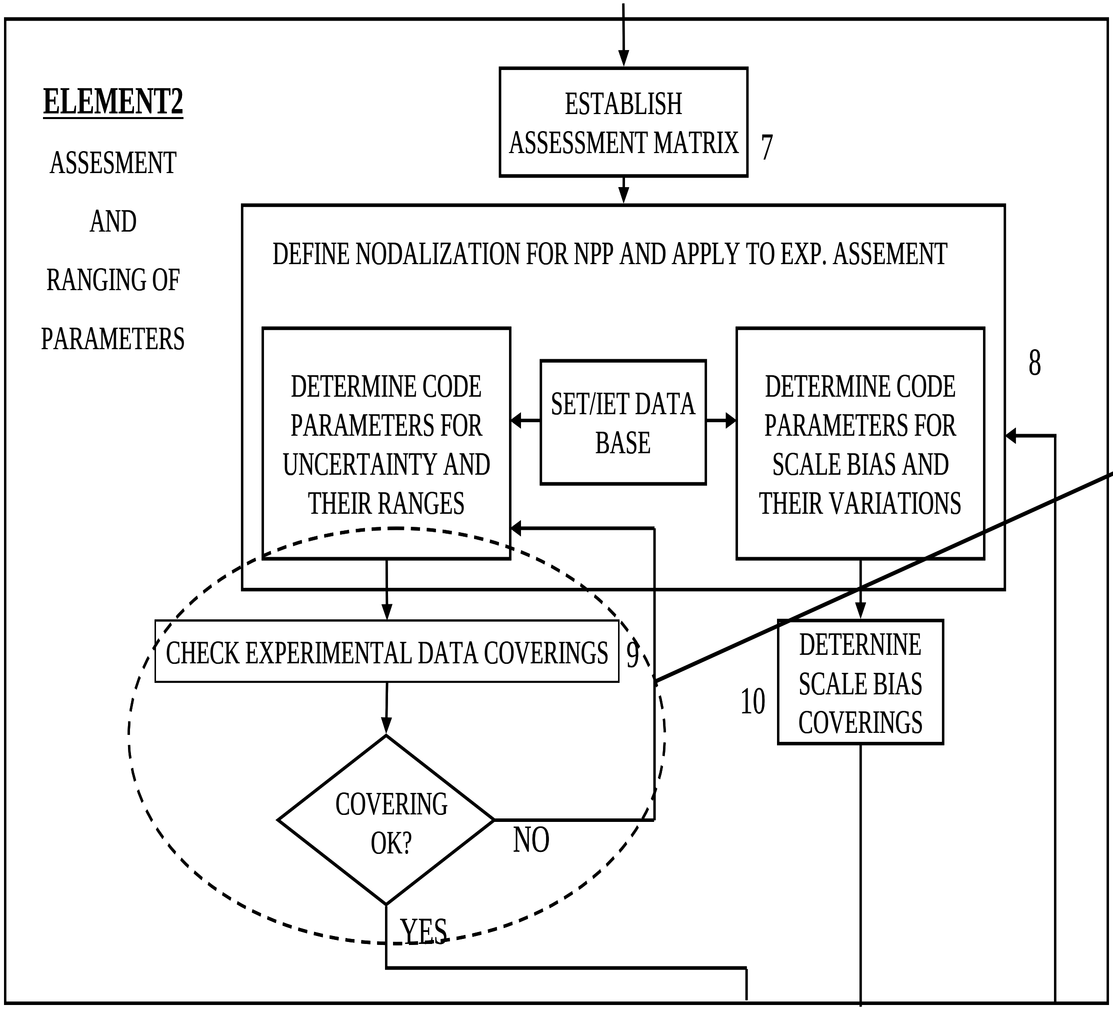
- Improved predictability of modified RELAP5/MOD3.3 was confirmed through the various assessments.

Determination of Code Applicability

- Identified phenomena and code models are compared.

Element 2

Assessment and Ranging of Parameters



EDC (Experiment Data Covering)

Basic idea is to ensure that uncertainty parameters are enough to predict all measured PCTs

Establishment of Assessment Matrix (1/2)

- Includes various SETs, IETs and tests specific to APR1400
  - to confirm code's predictability of LBLOCA phenomena
  - to assess code accuracy
  - to confirm code's scale-up capability
  - to determine nodalization
  - to range uncertainty parameters
- Includes developmental assessments as well
- Tests specific to APR1400
  - MIDAS : ECC bypass
  - VAPER : SIT equipped with fluidic device
  - DOBO : Downcomer boiling
  - ATLAS : Overall reflood phenomena including ECC bypass and downcomer boiling

● Establishment of Assessment Matrix (2/2)

	Test Facility	Phenomena	Components: Fuel Rod	Core	Pump	Downcomer	Break	Upper plenum/SG	Accumulator	Pressurizer
SET	UPTF	Lower plenum flashing, entrainment, liquid-vapor mixing with condensation, ECC bypass and DC penetration				●		●		
	CE (pump)	Two-phase pump behavior			●					
	LOFT-Wyle[1)]	Break, blowdown					●			
	GE	Entrainment and de-entrainment		●						
	Dukler Air-Water	CCFL				●				
	LOFT Accu. Blowdown	Accumulator behavior							●	
	Christensen subcooled boiling	Subcooled boiling		●						
	MIT Pressurizer test	Condensation in stratified conditions								●
	ORNL	Interfacial drag, Core heat transfer		●						
	RIT Tube Test	Critical heat flux		●						
	Bennet	Transition boiling		●						
	MINIZWOK[1)]	Metal-water reaction	●							
	Power Burst Facility	Gap conductance	●							
	FRIGG-2	Interfacial drag		●						
	THETIS	Interfacial drag		●						
	ECN[1)]	Core liquid level		●						
	MB-2[1)]	Entrainment and de-entrainment in steam generator						●		
	CREARE	Downcomer countercurrent			●	●				
	FLECHT-SEASET	Core heat transfer		●				●		
	Marviken	Critical flow					●			
	THTF	Blowdown heat transfer		●						
	NEPTUN	Core heat transfer		●						
	Semiscale Pump	Two-phase pump behavior			●					
	W Pump (1/3)	Two-phase pump behavior			●					
	CCTF	Steam binding, Core heat transfer, Quench front propagation		●				●		
	SCTF	Core level, entrainment and de-entrainment		●						
	PKL	Steam Binding		●						
IET	LOFT	Core wide void and flow distribution, Steam binding, Core heat transfer, Non-condensible gas effect		●	●	●				
	LOBI	Core wide void and flow distribution, Core heat transfer		●						
	SEMISCALE	Core wide void and flow distribution, Core heat transfer		●						

DVI Tests

	Test Facility	Components: Fuel Rod	Core	Pump	Downcomer	Break	Upper plenum/SG
SET	UPTF Test 21D				●		
	MIDAS				●		
	DOBO				●		
	ATLAS		●		●		●

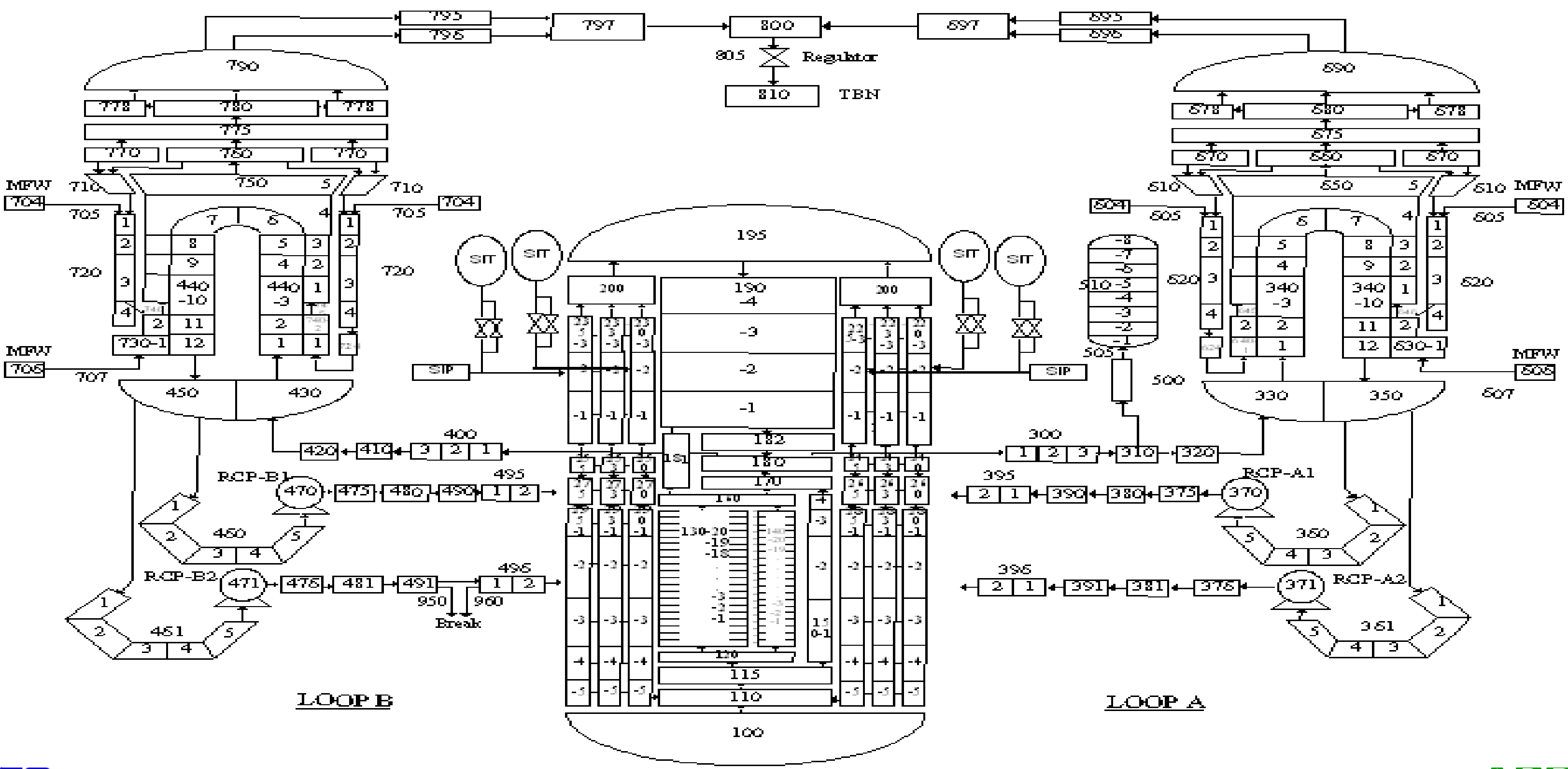
● Plant Nodalization

- ➢ 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.



Determination of Code Uncertainty Parameters

- Candidate uncertainty parameters are first determined by comparing the important phenomena and corresponding code models, and by performing the auxiliary calculations.
- The ranges of candidate parameters are first determined by assessment calculations and literature survey.

※ The parameters are confirmed as a set by way of checking Experimental Data Covering (EDC, Step 9) against SET, IET data.

■ Code Parameters, excerpted

Fuel related	Core Heat Transfer related	Critical Flow related
• Pellet Conductivity • Clad Oxidation	• CHF • Film Boiling HT • Transition Boiling HT	• 1-phase Cd • 2-phase Cd

Scale Biases

- Downcomer, lower plenum, and upper plenum of the vessel are known to have scale distortions in power-to-volume scale law.
- ECC bypass and liquid carry-over to steam generator are affected.
- The phenomena are basically multi-dimensional and have strong correlation with many parameters and flow regimes.

✓ Instead of uncertainty evaluation for these phenomena, scale biases are evaluated separately and accounted in the overall calculational uncertainty.

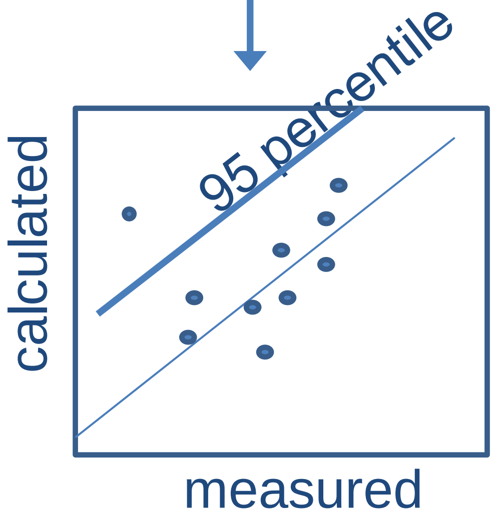
- ECC bypass during refill
- ECC bypass during reflood (downcomer level depression during reflood)
- Steam binding during reflood

Check Experimental Data Coverings (1/4)

- To confirm the uncertainty parameters as a set
- To confirm the predictability of the experiment PCT using the set of uncertainty parameters.
- To reflect the combined effect of the neglected phenomena in the PIRT.

Check Experimental Data Coverings (2/4)

Assess and determine uncertainty parameters



Data Covering against all PCT experiments

NO

YES

- 95 percentile in code accuracy
- Equivalence in EDC

(Practically all data covered in EDC)

Apply uncertainty parameters to plant calculations: ELEMENT 3

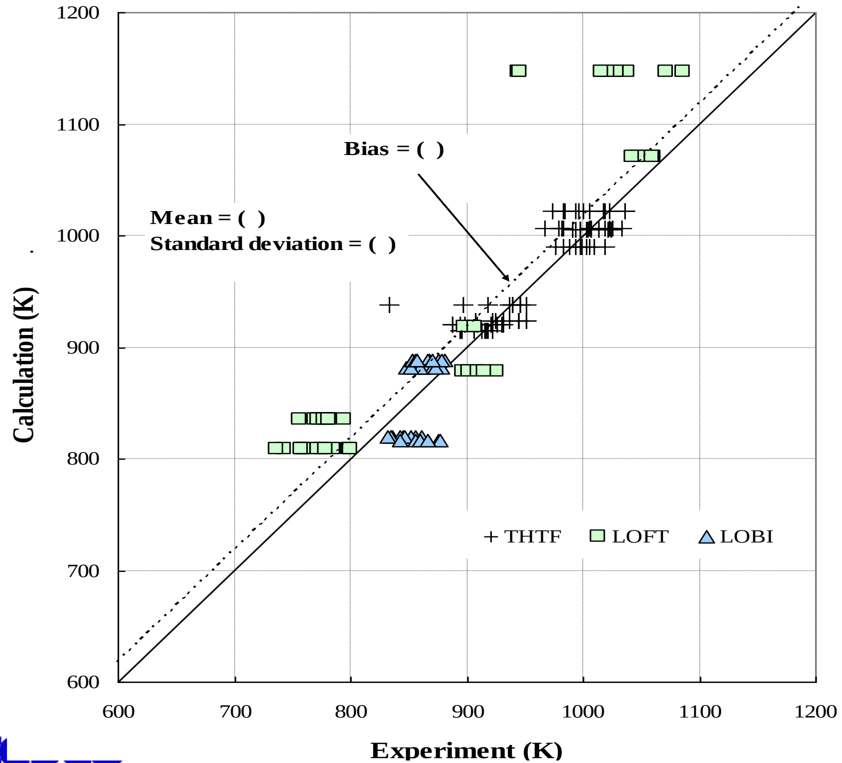
Pre-Submittal Meeting

Check Experimental Data Coverings (3/4)

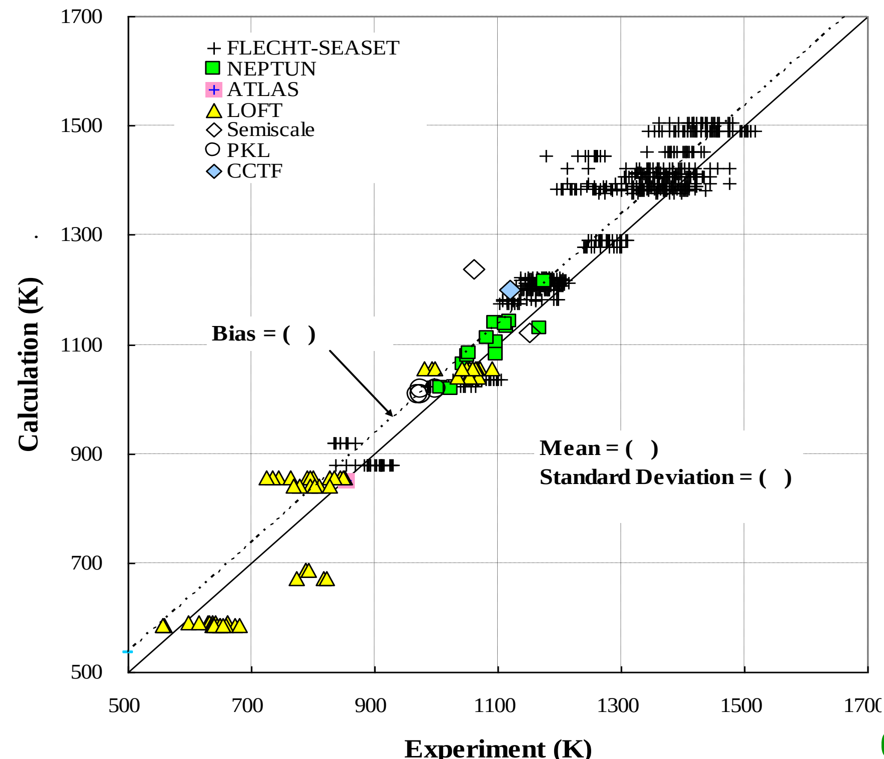
Quantification of Code Accuracy

- This step is to make an evaluation of the code predictive capability.
- Statistical analysis and scatter plots are used to determine the code accuracy.

BLOWDOWN PHASE CODE ACCURACY USING SET AND IET DATA (THTF, LOFT and LOBI, 165 Data Points)

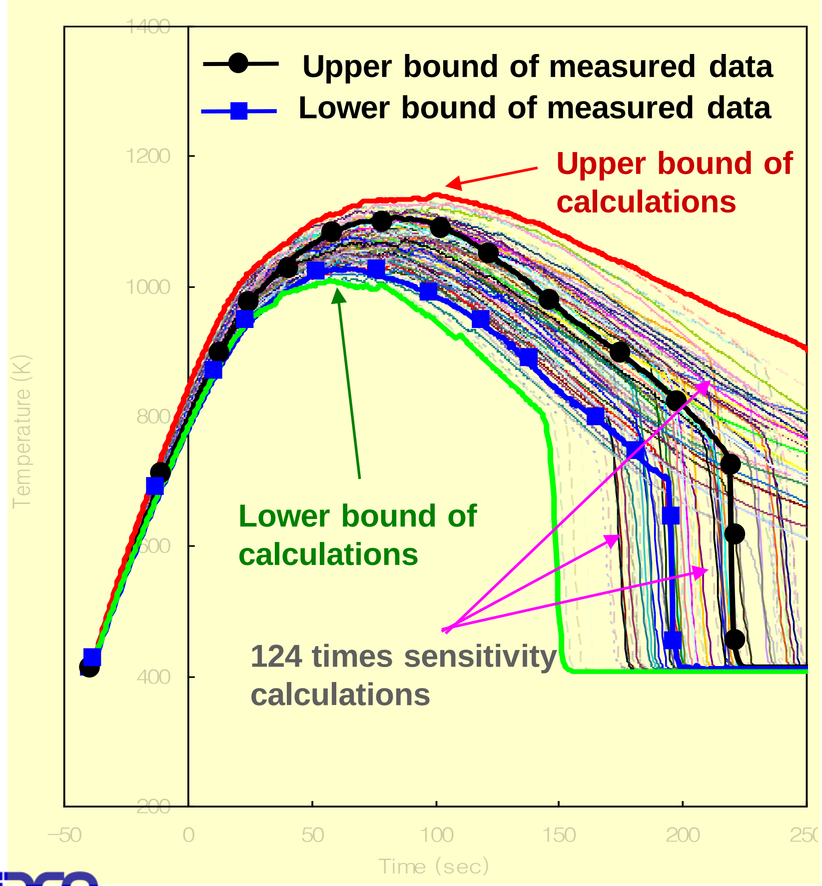


Reflood Phase Code Accuracy using SET and IET Data, 688 Data (FLECHT-SEASET, NEPTUN, LOFT, Semiscale, PKL, ATLAS and CCTF)



● Check Experimental Data Covering (4/4)

- EDC was confirmed against 39 tests where cladding temperatures were measured.
  - Flecht-Seaset, ATLAS, THTF, LOFT, Semi-Scale and so on.
  - 39 tests cover entire LBLOCA transient period.

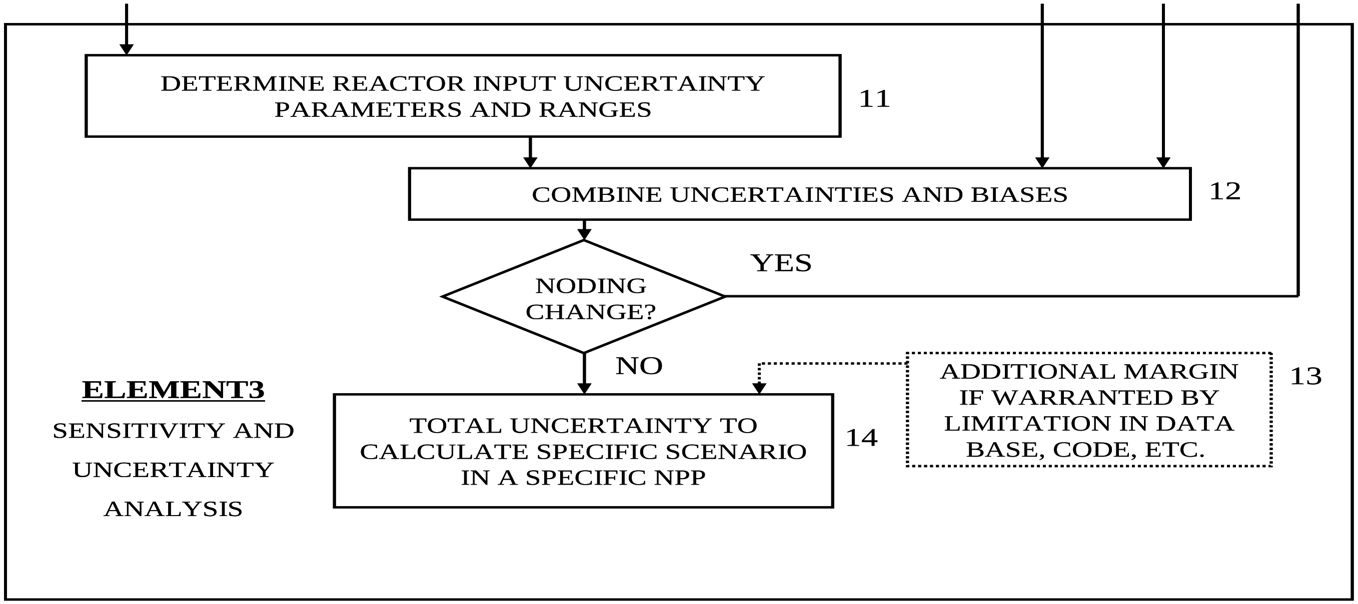


EDC of FLECHT-SEASET 30817

Using the candidate parameters, measured PCT is successfully predicted.

Element 3

Sensitivity and Uncertainty Analysis



- Important plant-specific parameters are addressed.
- Reactor input parameters and code uncertainty parameters are taken together into the plant calculations.
- Scale biases are evaluated and added to 95 percentile PCT.
- Total uncertainty is evaluated including additional uncertainties.

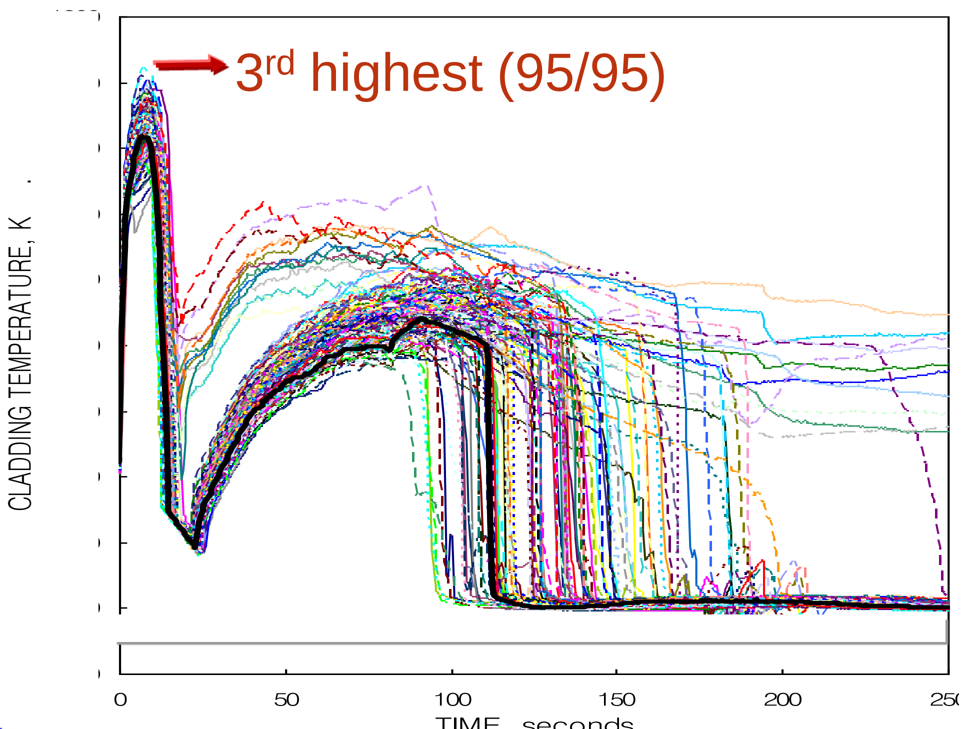
Determination of reactor input parameters

- Address plant specific parameters
  - Core power distributions, total power, Fq, Axial Power Shape
  - Decay heat
  - Safety Injection Tank pressure, temperature, volume
  - Safety Injection Pump flow rate, temperature
  - RCS loop flow rate, RCS Pump performance
  - Pressurizer pressure etc.
- Containment Back-Pressure Calculation
  - CONTEMPT4/MOD5 + conservative input and wall HTC

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

- Additional Uncertainty of Plot Frequency

- Total Uncertainty

$$\text{Licensing PCT} = PCT_{95/95} + \Delta PCT_{ECCbypass\_refill} + \Delta PCT_{ECCbypass\_reflood} + \Delta PCT_{steam\text{-}binding} + \Delta PCT_{plot\text{-}frequency}$$

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
- 9 Appendices to describe the details of
  - ✓ PIRT
  - ✓ Code modification
  - ✓ Code assessments against SETs & IETs

Topical Report Table of Contents (1/6)

Topical Report Table of Contents (2/6)

Topical Report Table of Contents (3/6)

Topical Report Table of Contents (4/6)

Appendices

- Appendix A: APR1400 PIRT
- Appendix B: Modification to RELAP5/MOD3.3 and Validation
  - ✓ Modification of a portion of reflood model
  - ✓ Modification on gap conductance calculation
  - ✓ Modification to improve code fails due to non-condensable gases
- Appendix C: Code Assessment against SETs
  - ✓ FLECHT-SEASET: 17 tests
  - ✓ CCTF: 1 test
  - ✓ NEPTUN: 7 tests
  - ✓ THTF: 4 tests
  - ✓ PKL: 1 test

Topical Report Table of Contents (5/6)

Appendices

- Appendix D: Code Assessment against IETs
  - ✓ LOFT: 4 tests
  - ✓ SEMISCALE: 1 test
  - ✓ LOBI: 1 test
- Appendix E: Code Assessment against ATLAS Test
- Appendix F: Code Assessment for ECC Bypass
  - ✓ UPTF 21D: 1 test
  - ✓ MIDAS: 15 tests

Topical Report Table of Contents (6/6)

Appendices

SUMMARY

- The effectiveness of APR1400 SIS design was confirmed by the tests specific to APR1400.
- CAREM has been developed according to the philosophy of CSAU.
- Uncertainty parameters are determined and their applicability as a set is validated by way of Experimental Data Coverage evaluation against SET and IET at various scales and at various conditions.
- Topical Report is prepared in accordance with NUREG-1379, Editorial Style Guide.
- Topical Report will be submitted in 3rd Qtr 2011.