Proven Technology for the APR1400’s Development, Licensing and Deployment: Focusing on Thermal-Hydraulic Safety Aspect

Chul-Hwa SONG *

General Project Manager (Director)
Thermal-Hydraulics Safety Research Division
Korea Atomic Energy Research Institute

1. Introduction

- Nuclear Power in Korea
- Reactors Development in Korea

Current Status of NPPs in Korea

In Operation
20 units
(17,716 MW)
(8 OPR1000)

Under Construction
8 units
(5,600 MW)
(4 OPR1000 & 4 APR1400)

Planned
10 units
(15,400 MW)
(OPR1000+, APR1400+, APR+)

Contents

1. Introduction
2. APR1400 Overview
3. Process for Development & Licensing
4. Performance Verification & Evaluation
5. Summary

From J.J. Ha (2009)
### Safe and Economic Operation of NPP

**Outstanding Performance in NPP Operation Shown in Korea !!**

<table>
<thead>
<tr>
<th>Year 2008</th>
<th>Korea</th>
<th>World Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity Factor</td>
<td>79.4%</td>
<td>93.3%</td>
</tr>
</tbody>
</table>

### Reactors Development in Korea

#### 1st Phase: Gen-II
- Turn-key Base
- Standardization
- Power Plant: APR1400 (1,400 MWe)

#### 2nd Phase: Gen-II+/III
- APR+ (1,500 MWe)
- SMART (330 MWt)

#### 3rd Phase: Gen-III+
- Evolutionary PWRs
- Self supporting Technologies

#### 4th Phase: Gen-IV
- Revolutionary
- SFR: KALIMER
- VHTR: NHDD
- Innovative Technologies

### APR1400: Design Overview

#### Safety Goals
- Seismic Design: SSE 0.3g
- Core Damage Frequency: < 10^{-5}/RY
- Containment Failure Frequency: < 10^{-6}/RY
- Coping Time for Station Blackout: > 8 Hrs

#### Performance Requirements and Economic Goals
- Plant Lifetime: 60 years
- Plant Availability: > 90%
- Occupational Radiation Exposure: < 1 man-Sv/RY
- Construction Period: 48 Month (for Nth Plant)
APR1400: Design Characteristics

- Design Improvements in APR1400
  - High Reliability & Better Performance:
    - Safety Injection System: DVI
    - Safety Depressurization/Vent System:
      - IRWST/Sparger
  - Major Specification of the APR1400

- Increased Safety Margin
  - Reduced hot-leg temp.
- Stable Operation
  - POSRVs
- Improved Maintainability
  - Integrated head assembly
- Improved SG Integrity
  - Inconel 690 tubes
  - Reduced hot leg temp.
  - Increased plugging margin
- Severe Accident Mitigation
  - IVR
  - ERVC
- Enhanced Transient Response
  - Increased Pzr volume

- THETA: Separate Effect Test Program
  - Tests for New Safety Systems Verification
  - Tests for New Safety Components Development
- ATLAS: Integral Effect Test Program

APR1400: New Safety Features

- Sparger (6x2) in IRWST
- Fluidic Device (1x4)
- DVI-SIS (1x4)
- New Design Features
  - Four trains of the safety injection system with a DVI (direct vessel injection) mode
  - A passive fluidic device (FD) in SIT's (accumulators)
  - In-containment refueling water storage tank (IRWST)
  - Safety depressurization & vent system (SDVS)
  - In-Vessel Retention (IVR) by ERVC

APR1400: Milestone

- Phase-I ('92.12 ~ '94.12): Conceptual Design
  - Reactor Type Selection
  - Development of Top-Tier Design Requirements

- Phase-II ('95.3 ~ '99.2): Basic Design
  - Development of Design Specifications for NSSS Components
  - Preparation of Standard SAR (Safety Analysis Report)

- Phase-III ('99.3 ~ '01.12): Optimization and Licensing
  - Design Optimization; Performance Verification
  - Detailed Design of Long-Lead Items
  - Licensing Application of Std. Design (Standard Design Approval: May '02)

- Phase-IV ('07.12 ~ '13.9): Construction & Comm. Operation
  - Construction Permit & F/C: '08. 4, '08. 10
  - Commercial Operation of the 1st Unit: '13. 9

APR1400: Comprehensive T-H R&Ds

- Comprehensive Thermal-Hydraulic R&D for the APR1400 Development and Licensing Support ('99~'06)
  - THETA: SET Program
  - ATLAS: IET Program
  - MARS: Safety Analysis
  - Severe Accident Mitigation Measures

- Development of New Safety Features and Their Performance Verification for APR1400
- Licensing of APR1400

3. Process for Development, Verification and Licensing

- Nuclear Organizations In Korea
- Process for Design Development & Verification
- Process for Licensing & Deployment

Nuclear Organizations in Korea (1/2)

- Governmental Organization
  - President
  - Nat. Energy Commission
  - Prime Minister
  - Atomic Energy Comm. (AEC)
  - Min. of Strategy & Finance
  - Min. of Edu., Sci. & Tech. (MEST)
  - Min. of Knowl. & Economy (MKE)
  - Min. Foreign Affairs & Trade
  - Min. of Environ.

- Nucl. Safety Comm. (NSC)
  - KAERI
  - KINS
  - KEPCO
  - KNF
  - KOPEC

- KAERI: Comprehensive R&D organization for new reactors & fuels, nuclear safety, radiation applications, etc.
- KINS: Licensing review, inspection, regulatory research

- KEPCO: Mother company of KHNP, KOPEC, KNF & KPS; electricity transmission & distribution
- KHNP: Operating NPPs
- KOPEC: NSSS & AE design
- KNF: Fuel supply
- KPS: Plant maintenance
- DOOSAN: Heavy components design & manufacturing

Nuclear Organizations in Korea (2/2)

- Key Nuclear Organizations

    - Ministry of Education, Sci. & Technol. (MEST)
    - KAERI
    - KINS

- Ministry of Knowledge & Economy (MKE)


- Industries (APR1400 Standard Design Development)
  - MKE: Formerly MOEIE
  - MEST: Formerly MOST

- KAERI (R&D) Mid-/Long-Term PJ T

- Major R&D Activities
  - Testing and Analysis for Performance Verification and Safety Evaluation of New Design Features,
  - Development of Key Technologies and Long-Lead Items,
  - Licensing Support

- Phases:
  - Phase I: '92. 12 - '94. 12
    - Selection of Reactor Type
    - Conceptual Design
  - Phase II: '95. 3 - '97. 2
    - Basic Design
    - SSAR Development
  - Phase III: '99. 3 - '01. 12
    - Design Optimization
    - Licensing the Standard Design
    - Development of Long-Lead Items
  - Phase IV: '02. 5
    - Standard Design Approval

- Request of Develop. & Testing
- Exp. Data Base and Evaluation Results
- KAERI (R&D) Mid-/Long-Term PJ T

- MKE: (PJ T Co-Funding, NPP Operation)
- MEST: (PJ T Planning, NPP Licensing)

- Mid-/Long-Term PJ T

- R&D Projects
- Exp. Data Base and Evaluation Results

- KAERI (R&D) Mid-/Long-Term PJ T

- MKE: (PJ T Co-Funding, NPP Operation)
- MEST: (PJ T Planning, NPP Licensing)
Process for Licensing & Deployments

Design Developments ('92.12~'01.12)
- Phase-I ('92~'94): Design Require., Design Concepts
- Phase-II ('95~'98): Design Development, Design Spec. & SSAR
- Phase-III ('99~'01): Design Optimization, Long-lead Item Development

As of Jan. 2010

R&D for 'Proven Technology'

Std. Design Approval ('02.5)

Construction ('07.9~'12.12)
- HFT: Hot Func. Test
- CHT: Cold Hydro Test
- Set RV: Rx Vessel Set
- F/C: First Concrete

CP: Construct. Permit ('08.4)

Commercial Operation ('13.9~)

Final SAR (FSAR)

~ 50 months

OL: Operation Licensing (~'12.12)

In-Plant Testing ('12)

OL: Operation Licensing (~'12.12)

Set RV: Rx Vessel Set

F/L: Fuel Loading ('13.1)

Pre-Operation

Commissioning ('13.1~'13.8)

SET: (1) Overview

- **DVI Test**
  - Focused on Unique T-H Phenomena in a RPV Downcomer Due to the DVI Type
  - T-H Evaluation Relevant to the Safety:
    - LBLOCA: ECC Bypass, Downcomer Boiling
    - SBLLOCA: DVI Line Break
    - MSLB: Boron Mixing

- **Fluidic Device (FD) Test**
  - Small-scale Test for the Design Develop.
  - Full-scale Tests for:
    - Design Confirmation, and
    - Performance Evaluation/Verification

- **IRWST/Sparger Test**
  - IRWST along with the SDVS Actuation for a RCS Depressurization
  - To Provide Exp. Data for Evaluating their TH & Mechanical Behaviors

4(A) THETA Program: T-H Separate Effect Tests (SET)

SET: (2) DVI Type of Safety Injection

- **Complete Set of Experiments for the LBLOCA Reflood**

**Phenomena in the Upper D/C:**
- Water Jet Impingement
- Liquid Film Spreading
- Entrained Liquid Droplet
- H/T: Steam Condensation

**D/C-Core Interaction:**
- Degree of Subcooling
- Reflood Rate
- Reflood H/T
- Manometric Oscillation

**Phenomena in the Lower D/C:**
- Stored Energy Release
- Boiling H/T at Wall
- Bubble Rise
- Condensation of Bubbles
- Degree of Subcooling
- Hydrostatic Head
Comprehensive Research for DVI

- Systematic Approach for LBLOCA ECC Bypass (‘99~’02)
  - Liquid Film Spreading Test
  - Steam-Water Test (MIDAS)
  - B.E. Codes Evaluation & Assess.
  - E.M. Method Analysis

SET: (3) Passive S.I. (FD: Fluidic Device)

- FD Design Development and its Performance Verification
  - Development and Performance Verification of the Full-scale Fluidic Device (FD), as a Passive Flow Controller, for APR1400 (‘97~’01)
  - Determination of the characteristic curve of S.I. flow for safety analysis
  - Manufacturing Sensitivity Tests: Uncertainties in Manufacturing (’03~’06)

SET: (4) Safety Depressurization Sys.

- Hydrodynamic Loads on the Internal Structures inside IRWST
  - Air Clearing Load
  - Condensation-induced Load

- Thermal Mixing in a Pool
  - Direct Contact Condensation of Steam Jets
  - Thermal Mixing
    - Local Hot Spot

4(B). ATLAS Program: T–H Integral Effect Test (IET)
**IET: (1) ATLAS Program**

- **Integral Effect Test Program: ATLAS**
  - Tests for safety issues and/or interests of APR1400
  - Simulation of APR1400 transients & accidents for assessment & validation of system analysis codes

  - Reference NPP: APR1400
  - Geometric Scale:
    - 1/2 H, 1/144 A, 1/288 V
  - Loop Configuration:
    - 2 Hot Legs & 4 Cold Legs
    - Integrated Annular DC

  - Operating Conditions:
    - Full Press./Temp.
    - Max. 8% of Scaled Power

**IET: (2) ATLAS Tests**

- **ATLAS: Application & On-going Projects**
  - Verification of safety concerns for APR1400
  - Validation of regulatory & industrial safety analysis codes:
    - MARS, SPACE Codes
  - Domestic cooperative programs
    - DSP
    - DOOSAN: FLB
  - Int’l cooperative program
    - OECD/NEA ISP-50:
      - Verification of APR1400 LBLLOCA Analysis Methodology
    - Counterpart tests:
      - LSTF, PKL, etc.

**Measures for Severe Acc. Mitigation**

- **Hydrogen Management System (HMS)**
  - Passive Auto-catalytic Recombiners (PAR) limits the average H2 concentration

- **IVR-ERVC**
  - In-Vessel corium Retention through External Reactor Vessel Cooling

- **Cavity Flooding System (CFS):**
  - Cooling and scrubbing the core debris

**4(C). Severe Accident Research Program**
5. Summary

Current Status of APR1400

- Two Commercial Projects:
  - Domestic Pjt.: KNU #25–26 (SKN #3&4)
  - International Pjt.: UAE #1–4

- Key Milestones: SKN #3&4
  - Design Certification (DC): May 2002
  - Construction Permit (CP): Dec. 2007
  - First Concrete (F/C): Nov. 2008
  - Set Reactor Vessel: Aug. 2010
  - Fuel Loading (F/L): Jan. 2013
  - #1 COD (SKN #3): Sep. 2013
  - #2 COD (SKN #4): Sep. 2014

- Another DC Application: US-NRC
  - Pre-Application Review Process: Started from Early 2010

Application of APR1400 R&D Results

- Understanding New T-H Phenomena
- Physical Models/Correlations Developed
- Resolving Safety Issues
- Technology Transfer

Evaluation, Validation and Improvements of the Best-Estimate Codes for Safety Analysis (MARS, TRACE, etc.)

Support of APR1400 Standard Design Approval and Construction Permission

- Support of APR1400 Development and Securing the Key Technologies for Advanced LWR's
- Support of Evaluation/Validation of Design Codes (E.M.) and their Localization

Engg'g Progress (SKN #3): ~45% of Construction (As of Jan '10)
Concluding Remarks

- APR1400 Has Been successfully Developed Based on New Technologies and the Abundant Experiences of the ALWR Design, Construction and Operation in Korea
  - OPR1000 → APR1000 → (APR1000+)
  - APR1400 → APR+
- ARP1400 Has Been fully Verified in Terms of Performance and Safety.
  - Enhanced Nuclear Safety and Improved Economic Competitiveness
- APR1400 Is now Being Deployed in Commercial Markets:
  - Two (2) Units are Under Construction, and Another Four (4) Units are Planned in Korea.
  - Capable of Providing Competitive Cost and High Reliability
  - Four (4) Units are Planned to Construct in UAE.
- Advancements In Technologies Are Now In Progress for Gen-III+ such as APR1000 (’09~) and APR+ (’07~) in Korea.

References

- IAEA, Status of Advanced Light Water Reactor Designs, IAEA-TECDOC-1391 (Chap. 4.9), May 2004

Acknowledgements

- This Work Has Been Done by KAERI and Financially Supported Over 10 Years:
  - Mostly by MOST (Ministry of Science & Technology) and MOCIE (Ministry of Commerce, Industry & Energy) of the Republic of Korea, and
  - Partly by KINS (Korea Institute of Nuclear Safety) and Industries (KHNP, KOPEC, etc.).
- The Author deeply Appreciates It for their Technical Contributions from the Colleagues in the THSR Division at KAERI.