SMART Development Status and Collaboration with KSA for the Deployment

Ji-Han Chun (Technical Coordination)
J.S. Song, H.O. Kang, and K.K. Kim

SMART Development

INPRO Dialogue Forum on Legal and Institutional Issues
In the Global Deployment of Small Modular Reactors
18~21 October 2016, Vienna, Austria
Contents

- Introduction
- Design Features of the SMART in SDA
- Enhancement for the Safety of SMART
- Pre-Project Engineering Agreement with Saudi Arabia
- Summary & Conclusion
Contents

- Introduction
- Design Features of the SMART in SDA
- Enhancement for the Safety of SMART
- Pre-Project Engineering Agreement with Saudi Arabia
- Summary & Conclusion

SMART : System-integrated Modular Advanced Reactor
Small Modular Reactors (SMR) offer Several Advantages

- Enable enhanced safety
  - Easier implementation of advanced safety features
  - Passive safety
- Suitable for small or isolated electrical grids
- Lower capital cost per unit
- Siting and co-generation flexibilities
- Short construction time

Potential Demand

- New Nuclear Countries: might be interested in starting with a SMR
- Replacement of Small Old Coal Power Plants
SMART

330MWth Integral PWR
Electricity Generation, Desalination and/or District Heating

- Power: 330 MWt
- Water: 40,000 t/day
- Electricity: 90 MWe

System-integrated Modular Advanced Reactor

- Electricity and Fresh Water Supply for a City of 100,000 Population
- Suitable for Small Grid Size or Localized Power System

Plant Data
Contents

- Introduction
- Design Features of the SMART in SDA
- Enhancement for the Safety of SMART
- Pre-Project Engineering Agreement with Saudi Arabia
- Summary & Conclusion
SMART Development History Chronicle

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>Conceptual Design ('97.7~'99.3)</td>
</tr>
<tr>
<td>1998</td>
<td>Basic Design ('99.4~'02.3)</td>
</tr>
<tr>
<td>1999</td>
<td>Construction of prototype SMART ('02.7~'06.2)</td>
</tr>
<tr>
<td>2000</td>
<td>SMART Pre-Project Service ('06.7~'08.11)</td>
</tr>
<tr>
<td>2001</td>
<td>Standard Design Approval ('09.1~'12.7)</td>
</tr>
<tr>
<td>2002</td>
<td>R&amp;D to Incorporate Fukushima Action Plan into Design ('12.3~'16.2)</td>
</tr>
</tbody>
</table>

Key Events:

- NSSS & Desalination Concept (330MWt)
- Design Methodology and Computer Code
- Detailed Design (65MWt)
- Technical Validation Test
- System Optimization
- Economic Feasibility
- 330, 660MWt
- Full Passive System Validation Using SMART-ITL Code Improvement
Project Organization in SDA

- Technology Validation: $60M
- Standard Design: $85M
Integral PWR SMART

- **330 MWt (100 MWe) nominal output**
  - Small core (57 fuel assemblies) and source term
  - Unit output enough to support electricity, water and heat demand for population of 100,000

- **Integral PWR with no large RPV penetrations**
  - Less than 2” penetrations
  - In-vessel Pressurizer
  - In-vessel Steam Generator
  - Canned Motor Pump

- **Inherent Safety**
  - Elimination of LB-LOCA by design
  - No core uncovery during SB-LOCA

- **Performance proved Fuel**
  - Standard 17x17 UO$_2$ (< 5 w/o U$_{235}$) w/reduced height (2m)
  - Advanced Grid / IFM design
  - Peak Rod Burnup < 60 GWd/t
  - Performance proved @ operating PWRs

- **Improved Core Operability**
  - Cycle length: 1,000 EFPD (~ 3 years)
  - Proven reactivity control measures
    - CRDM, Soluble Boron, BP
Fuel & Core

- **Fuel Assembly**
  - Proven 17 x 17 UO₂ Ceramic Fuel
    - Active Core Length : 2 m

- **Core**
  - 57 Fuel Assemblies
  - Refueling Period : 3 years

- **Reactivity Control**
  - Control Rod Driven Mechanism
  - Soluble Boron
  - Burnable Poison
Reactor Vessel Assembly

- Reactor Vessel Assembly
  - Reactor Pressure Vessel
  - Reactor Closure Head Assembly
  - Reactor Vessel Internals

- Primary Components in RPV
  - Core
  - 8 helical once-through SGs
  - 4 canned motor pumps
  - Internal steam pressurizer
  - 25 Control Rod Drive Mechanisms
Safety Systems of SMART

- Safety Injection System (4 trains)
- Containment Spray System
- Passive Residual Heat Removal System (4 trains)
- Shutdown Cooling System (2 trains)
- Emergency Diesel Generator (2)
- Alternate AC
- Hydrogen Control
Proven Technology

- SMART basically adopts Proven Technologies of Existing PWR
- SMART-specific Technologies was fully Validated
  - Experimental Validation of SMART-specific Design Performance and Safety
    - Total of 22 Validation Experiments were Selected based on
      - PIRT (Phenomena Identification and Ranking Table)
      - Experts Opinions from Regulation, Industries, Institutes and Universities
    - Experimental Validation envelop Fuel/Core, TH/Safety, Mechanics/Components and Digital I&C
  - Software Validation of Key Design Tools and Methods
    - Core Physics, Core Thermal-Hydraulics, Safety Analysis, ....
Technology Validation (Mechanics & Components)

- Reactor Coolant Pump Performance Test
- Structural Dynamics Test and Analysis Method
- RPV Dynamics & Canned Motor Pump Tests
- SMART Steam Generator Winded With Helical Tubes
- SG Tube Material (A690) Irradiation Test
- Neutron Irradiation in HANARO
- Verification of Structural Dynamic Analysis Method
- Verification of Hydraulic Load Analysis Method
- HANARO and Capsule Including Alloy 690 Test Specimen for Neutron Irradiation
- 0.4T Compact Tension Test Specimen
- Alloy 690 Test Specimen

SMART System-integrated Modular Advanced Reactor
Technology Validation (Core & Fuel)

Subchannel Code V&V
- MATRA-5 code
  - Subchannel integral balance eq.
  - Homogeneity/1st Baseline
  - Implicit, marching scheme
  - inlet/exit boundary condition
- MATRA-5 structure
  - Flow & enthalpy distribution tests
- MATRA-5 code validation
  - Flow & enthalpy distribution tests
  - Flow blockage tests
- Subchannel test distribution tests

Fast-run DNBR Code V&V
- 4-Channel analysis model
- Code Characteristics
  - 4-channel model for SMART core
  - Non-linear marching scheme
  - Lumped channel correlation factors
- Code Applications
  - STG/BNR module in SCOPS
  - 4-channel analysis module

Core Protection/Monitoring System V&V
- Protection System (SCOPS)
  - Core Protection
  - Active/Passive
  - Other Protection Systems
- Monitoring System (SCOMS)
  - Core Protection
  - Active/Passive
  - Other Monitoring Systems

CHF Correlation System V&V
- TH Field Analysis: MATRA-5
  - Correlation of Mixing Coefficient
  - Local Parameter CHF Correlation
- Correlation Coefficients Optimization
- Limit DNBR
  - 95% tolerance limit
  - Statistical DNBR Design

1st stage (SSAR) 2nd stage (Licensed)
- Correlation
  - Conservative model for SSAR
  - BE model for SMART Test case

- Method
  - Pre-bifurcation CHF data
  - Additional correlation
  - Analysis of SMART operation
  - Development of BE correlation

- CHF Test Facility (KAERI)
  - Freon CHF Test
    - Freon-loop CHF Test
      - Fluid-to-fluid Scaling Law
      - CHF Data for SSAR CHF Correlation
      - CHF characteristics at lower velocity
      - Influence of cold wall and grid spacing
  - Water CHF/Mixing Test
    - 5x5 Test Bundle
    - Water CHF Test (Stern Lab)

Fuel Component Test
- Tests for Component Selection
  - Spacer Grid Impact Test
  - Top/Bottom Nozzle Structure Test
  - Debris Filtering Test
  - Fuel Rod Characteristics Tests
  - Control Rod Component Tests

FA Out-of-pile Test
- FAMeC
  - Tests
    - Full-size PWR FA characterization
      - Fuel cooling performance
      - Core melting and melt impact performance

- PLUTO
  - Specifications
    - Two full-size PWR fuel pins
    - High-heat flux study
      - Display: 200°C
      - Acceleration: 2g

  - Tests
    - Hydraulic compatibility
    - Flow instability
    - Endurance of two different M levels

Core Thermal-Hydraulic Tools and Methods

Fuel Performance Tests
Technology Validation (T-H & Safety)

**Smart System-integrated Modular Advanced Reactor (SMART)**

**Thermal-Hydraulic Performance Tests**

- **Design Certification for SMART Hydraulic System**
  - 1/5 Scaling
  - SG Outlet = Core Inlet Simulation
  - Condition: ATM, 60°C
  - Test Matrix
    - 1 or 2 Section SG Breakdown Test
    - FMHA Outlet Flow-Hole Optimization
  - 1/6 Scaling
  - PZR Internal Structure Simulation
  - Condition: 15MPa, Saturation Temperature
  - Test Matrix
    - Normal Condition
    - In-surge/Out-surge
    - Level Measurement Test

- **SG and PRHRS Hx Heat Transfer Test**
  - Tube Modeling Test
  - Condition: Normal and Transient
  - Scale Ratio Height/Volume: 1/2, 1/473
  - Single Loop Simulation
  - Operating Condition (Power/Pressure): 100%/15MPa

- **Safety Injection Bypass Test**
  - Scale Ratio: 1/5
  - Operating Condition: < 4MPa, Saturated Temp.

- **Safety Validation Tests**
  - SC-TS 14 UBF
  - RCP
  - Feedwater Line
  - PRHRS Makeup Tank
  - VISTA ITL
  - Integral Test Loop (ITL)

**FMHA Performance Test**

- Reactor Pressure Vessel Assembly Flow Distribution Test

**Internal Pressurizer/Level Meas. Test**

- Reactor Pressure Vessel Assembly Flow Distribution Test
Technology Validation (T-H & Safety)

**TASS/SMR-S**
(safety code)

**FMHA Performance Test**
- 1/5 Scaling
- SG Outlet - Core Inlet Simulation
- Condition: ATM, 60°C
- Test Matrix
  - 1 or 2 Section SG Breakdown Test
  - FMHA Outlet Flow-Hole Optimization

**Internal Pressurizer/Level Meas. Test**

**SG and PHRS Hx Heat Transfer Test**

**Safety Injection Bypass Test**
- Scale Ratio: 1/5
- Operating Condition: < 4MPa, Saturated Temp.

**Integral Test Loop (ITL)**
- Scale Ratio: 1/49
- Design Concept: 4 Loop, 4 Train Secondary Side
- Operating Condition (Power/Pressure): < 30% Power, 15MPa

**Reactor Pressure Vessel Assembly Flow Distribution Test**
- Scale Ratio: 1/5
- Simulation of reactor internal structure
- Operating Condition: 1 MPa, 100°C
- Test Matrix
  - Normal condition
  - 1 RCP Stop

**Thermal-Hydraulic Performance Tests**

**Safety Validation Tests**
Licensing

- Application of Standard Design Approval (Dec. 30, 2010)
  - SSAR, CDM, EOG and related documents
- Document Conformance Evaluation (~Feb. 2011)

- Questionnaires
  - 1st Round Questionnaire: April 30, 2011
  - 2nd Round Questionnaire: July 31, 2011
  - 3rd Round Questionnaire: October, 2011
  - 4th Round Questionnaire: December, 2011
  - Additional Questionnaire: Jan.~Apr., 2012

- Standard Design Approval (July 4, 2012)
Contents

- Introduction
- Design Features of the SMART in SDA
- Enhancement for the Safety of SMART
- Pre-Project Engineering Agreement with Saudi Arabia
- Summary & Conclusion
Design Enhancement after Fukushima

- **Fukushima Accident**
  - Loss of Electric Power (LOOP + EDG stop) : SBO
  - All Active Safety System Failed
  - Necessity of Fully Passive Safety System

- **Several Items Applying to SMART for Safety Enhancement**
  - Passive Safety Injection System
  - Passive Containment Cooling System
  - Passive Residual Heat Removal System
  - Passive Hydrogen Recombine System
  - Automatic Shut-down at Earthquake greater than 0.18g
  - Emergency Water Supply Line to Cool the Core
Passive Safety Injection System

- **Elimination of Active Safety Injection System**
- **4 Trains**

**Safety Injection System**
- CMT (Core Makeup Tank)
  - Low PZR Pressure Rx Trip Signal
  - Low Main Steam Line Pressure Rx Trip Signal
  - PRHRS Actuation Signal
- SIT (Safety Injection Tank)
  - Low Pressure

**ADS (Automatic Depressurization System)**
- 2 steps

**Safety Performance Requirement of PSS**
- Safe Shutdown Condition within 36 hours and core un-damaged for a minimum of 72 hours w/o AC Power or Operator Action during DBA
Passive Safety Injection System

Validation of PSIS Using SMART-ITL

Flow Distributor Design

Safety Injection Sensitivity

Experimental Facility

Experimental Data (Code Validation)
Passive Safety System

- Small Break LOCA Simulation
  - MARS Code

Contents

- Introduction
- Design Features of the SMART in SDA
- Enhancement for the Safety of SMART
- Pre-Project Engineering Agreement with Saudi Arabia
- Summary & Conclusion
SMART PPE with KSA

MOU of Partnership (Mar. 3. 2015)

Pre-Project Engineering Agreement Contract (Sep. 2. 2015)
SMART PPE with KSA

- **Pre-Project Engineering**
  - **Period of PPE**: 3 years (Dec. 1, 2015 ~ Nov. 31, 2018)
  - **Budget of PPE**: $130M
  - **Task of PPE**
    - Design of NSSS with Full Passive Safety System
    - Fuel Design
    - Balance of Plant Design
    - Design of Main Components
    - Preparation of Preliminary Safety Analysis Report
    - Human Capacity Build-up Program for K.A.CARE
    - Preparation for Construction of FOAK SMART Plant
SMART PPE with KSA

Project Owner (MSIP, K.A.CARE)

KAERI (Principal PPE execution organization)

Steering Committee (K.A.CARE, MSIP)

FOAK Engineering
- Design of NSSS, Fuel and BOP
- Preparation of PSAR

K.A.CARE HCB
- Training of K.A.CARE Expert

Preparation for FOAK Plant
- Technical Support for Site Approval
- Vendor Survey
SMART PPE with KSA

**SMART Development**
- SMART Standard Design
- Technology Validation
- Licensing
- Safety Enhancement for Post Fukushima Action Plan

**Korea & KSA**
- Pre-Project Engineering
  - FOAK Engineering Design
  - K.A.CARE HCB
  - PSAR
- 1997 ~ 2015
- ~3 Yr

**KSA**
- FOAK Plant Construction
  - 2 FOAK Plants Construction
  - Licensing (CP, OL)
- 5~6 Yr
SMART PPE FOAK Engineering

- Specific Site in KSA
- Increasing Thermal Power
- Plant Optimization
  - Optimization of Reactor Vessel
  - Optimization of Reactor Building Using New Passive Containment Cooling System Concept
- Passive Safety System
## SMART PPE FOAK Engineering (Safety)

<table>
<thead>
<tr>
<th>System</th>
<th>SDA</th>
<th>PPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRHRS * passive residual heat removal system</td>
<td>passive, ≥36 hours w/o refill</td>
<td>passive, ≥72 hours w/o refill</td>
</tr>
<tr>
<td></td>
<td>50% x 4 trains with single train failure</td>
<td>33% x 4 trains</td>
</tr>
<tr>
<td>SIS * safety injection system</td>
<td>active</td>
<td>passive, ≥72 hours w/o refill</td>
</tr>
<tr>
<td></td>
<td>100% x 4 trains</td>
<td>33% x 4 trains (CMT &amp; SIT)</td>
</tr>
<tr>
<td></td>
<td>electrically independent 2 trains,</td>
<td>electrically and mechanically independent 4</td>
</tr>
<tr>
<td></td>
<td>mechanically independent 4 trains</td>
<td>trains, gravity driven tanks (CMT &amp; SIT)</td>
</tr>
<tr>
<td>Containment Pressure</td>
<td>active : CSS</td>
<td>passive : PCCS</td>
</tr>
<tr>
<td>Protection</td>
<td>100% x 2 trains</td>
<td>33% x 4 trains</td>
</tr>
<tr>
<td></td>
<td>CSS : containment spray system</td>
<td>PCCS : passive containment cooling system</td>
</tr>
<tr>
<td>RCS Depressurization</td>
<td>SDS</td>
<td>ADS</td>
</tr>
<tr>
<td></td>
<td>2 trains, controlled by operators</td>
<td>2 trains, automatically</td>
</tr>
<tr>
<td></td>
<td>SDS : safety depressurization system</td>
<td>actuating valves under DBA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ADS : automatic depressurization system</td>
</tr>
<tr>
<td>SCS * shutdown cooling sys.</td>
<td>active, safety system</td>
<td>active, non-safety system</td>
</tr>
<tr>
<td></td>
<td>100% x 2 trains</td>
<td>100% x 2 trains</td>
</tr>
<tr>
<td>Emergency AC Power</td>
<td>active, safety system</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>
|                         | 100% x 2 trains                               | non-safety DGs are equipped
SMART PPE Human Capacity Buildup

- Class Room Training (CRT) Basic for Fundamental Nuclear Engineering
- Class Room Training (CRT) Technical for SMART Design
- On the Job Training (OJT) for SMART Design
- On the Job Participation (OJP) for SMART Design
Contents

- Introduction
- Design Features of the SMART in SDA
- Enhancement for the Safety of SMART
- Pre-Project Engineering Agreement with Saudi Arabia
- Summary & Conclusion
Summary & Conclusion

- Certified SMART Design will be available for commercial deployment

- SMART is Viable Option for Early Deployment of SMR
  - Enhanced safety by advanced full passive safety design features
  - Low licensing risks by using proven and validated technologies
  - License experience for standard design approval
  - Build-up of international competitiveness through joint research and activities with KSA
Thank You for Attention