Specific Design Consideration of SMART for Application in the Middle East and North Africa Region

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SMART: Integral Type Reactor with Multiple Application

**365 MW<sub>th</sub> Integral PWR**
Electricity Generation, Desalination and/or District Heating

- **Thermal Power**: 365 MWt
- **Electricity**: 90 MWe
- **Water**: 40,000 ton/day

Electricity and Fresh Water Supply to a City of 100,000 Population
Suitable for Small Grid Size or Distributed Power System
Harmonizing Innovative Concept and Proven Technology for Regulatory License and Market/Public Acceptance

Innovative Concept
- All Primary Components in Reactor Vessel
- Passive Safety Systems
- Modularization for Field Installation and Maintenance
- Fully Digitalized Control System

Proven Technologies
- 17x17 UO$_2$ Proven Fuel Technology
- Large Dry Containment Building
- Control Rod Drive Mechanism
- Reactivity Control Concepts using Burnable Poison and Soluble Boron

Comprehensive Technology Validation
- Systems, Component, and Design Tools have been fully Developed and Licensed
- Separate Effect Tests
- Integral Effect Tests
- Component Development
Generals: Integral type PWR for generation of electrical power
- Plant design life: 60 years
- Ultimate heat sink: seawater for seashore construction (or cooling tower for inland construction)
- Plant availability: more than 90%
- Reload cycle: more than 30 months
- Spent fuel storage capacity: 30 years

Safety Criteria: Fully passive system for accident mitigation
- CDF (Core Damage Frequency): less than $1.0 \times 10^{-6}$/RY
- Containment failure frequency: less than $1.0 \times 10^{-7}$/RY
- Operator response time (grace time): more than 72 hours
- Seismic Design: 0.3g (~7.0 (Richter scale))
RPV - NSSS

All Primary Components in a Reactor Pressure Vessel (RPV)
- 8 Helical Once-through SG’s
- 4 Canned Motor Pumps
- Internal Steam Pressurizer
- 25 CRDM’s
- RPV Internals
  - Upper Guide Structure &
  - Core Support Barrel, ...

RPV
- 6.5 m (D) X 18.5 m (H)
- Design Condition: 17 MPa, 360°C
- RPV Life > 60 years
Design & Safety Features of SMART (3/8)

- RPV - Internals

- Helical Steam Generator
- Flow Skirt
- Upper Guide Structure
- Core Support Barrel
- Flow Mixing Header Assembly
- Canned Motor Pump
- Impeller
- Flywheel
- Component Cooling
- Sealing Can
- Shaft
- Cooler
- Rotor
- **RPV – Fuel & Core**
  - **Fuel**
    - Proven 17 x 17 LEU Fuel with Reduced Height (2 m)
    - Peak Rod Burn-up > 60 GWD/MTU
  - **Core**
    - 57 Fuel Assemblies
    - Fuel Cycle Length > 3 years
    - Availability Factor > 95%
  - **Proven Reactivity Control**
    - 25 External Magnetic-Jack CRDM (4-Channel)
    - Soluble Boron & Burnable Poison
  - 60 years of On-site Spent Fuel Storage
RPV – Thermal-hydraulics

- Major Flow Path through Upper Guide Structure (UGS) Holes at Upper Part to minimize Cross Flow
- Flow Mixing Header Assembly (FMHA) provides Thermal/Flow Mixing in case of TH Asymmetry
- Major TH Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Thermal Power, MWth</td>
<td>365</td>
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<tr>
<td>Pressure, MPa</td>
<td>15</td>
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<tr>
<td>Core Average Mass Flux, kg/m^2s</td>
<td>2,507</td>
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<tr>
<td>Maximum Core Bypass, %</td>
<td>4.0</td>
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<tr>
<td>Average Rod Heat Flux, kW/m^2</td>
<td>360</td>
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<tr>
<td>Core Inlet Temperature, °C</td>
<td>295.7</td>
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<tr>
<td>SG Inlet, °C</td>
<td>323</td>
</tr>
<tr>
<td>Steam Superheating, °C</td>
<td>30</td>
</tr>
<tr>
<td>Fuel Thermal Margin, %</td>
<td>&gt; 15</td>
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</tbody>
</table>
Fluid Systems

- Secondary Systems (Steam, Feedwater)
- Charging, Letdown, CVCS
- Safety Systems (PRHRS, PSIS, CPRSS)
Safety Systems

Inherent Safety Features

- No Large Break: Vessel Penetration < 2” (NONE from RPV Bottom)
- Large Primary Coolant Inventory
- SG Secondary as Pressure Boundary and No Excessive Cooling
- Low Vessel Fluence

Engineered Safety Features

- Passive Residual Heat Removal System (4 Train)
  - Natural Circulation Cooling of SG from Secondary Side
  - Entry to Shutdown Cooling Condition in 36 hrs using 2 Trains
- Passive Safety Injection System (4 Train)
  - 4 trains of CMT (Core Makeup Tank) and SIT (Safety Injection Tank)
  - 2 stages of ADS (Automatic Depressurization System)
- Containment Pressure and Radioactivity Suppression System (CPRSS) functions as a Passive Containment Cooling System (PCCS)
Design & Safety Features of SMART (8/8)

- **Digital MMIS**
  - Fully Digitalized I&C System
    - 4 Channel Safety/Protection System and Communication
    - 2 Channel Non-Safety System
  - Advanced Human-Interface Control Room
    - Ecological Interface Design
    - Alarm Reduction
    - Elastic Tile Alarm
Specific Design Consideration for MENA (1/17)

MENA & Korean Nuclear Energy

MENA: Middle East and North Africa

JRTR (Jordan)  
APR1400 (UAE)  
SMART (KSA)
Nuclear cooperation between MENA and Korea

- **Hashemite Kingdom of Jordan (Jordan)**
  - Jordan Research and Training Reactor (JRTR) by KAERI & JAEC
    - Construction finished (2010.8~2017.6)
    - 5 MWt thermal power, in Irbid area (@JUST)

- **United Arab Emirates (UAE)**
  - Construction of APR1400 by KEPCO & ENEC
    - Being constructed (2012.7~2018.)
    - 4 units of 1400 MWe NPP (in Barakah area, Abu Dhabi)

- **Kingdom of Saudi Arabia (KSA)**
  - Korea-KSA SMART Partnership (2015.9~)
    - Share SMART Technology Ownership through Pre-Project Engineering and FOAK Plant Construction in KSA
    - Joint Marketing of SMART in MENA region
    - K.A.CARE Human Capability Buildup for SMART NSSS design

- **Feasibility study on SMART for Jordan together with KSA, Jordan**
Specific Design Consideration for MENA (3/17)

Site Information: Annual Temperatures and Humidity

Climate data for Riyadh, Saudi Arabia

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
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<tbody>
<tr>
<td>Record high °C (°F)</td>
<td>33 (92)</td>
<td>36 (97)</td>
<td>38 (101)</td>
<td>43 (109)</td>
<td>47 (117)</td>
<td>53 (128)</td>
<td>48 (119)</td>
<td>47 (116)</td>
<td>45 (113)</td>
<td>43 (109)</td>
<td>36 (97)</td>
<td>32 (90)</td>
<td>53 (128)</td>
</tr>
<tr>
<td>Average high °C (°F)</td>
<td>19 (67)</td>
<td>23 (73)</td>
<td>27 (80)</td>
<td>32 (90)</td>
<td>38 (101)</td>
<td>41 (106)</td>
<td>43 (109)</td>
<td>42 (108)</td>
<td>40 (104)</td>
<td>34 (94)</td>
<td>27 (81)</td>
<td>22 (71)</td>
<td>32.3 (90.3)</td>
</tr>
<tr>
<td>Daily mean °C (°F)</td>
<td>14 (58)</td>
<td>17 (62)</td>
<td>21 (70)</td>
<td>27 (80)</td>
<td>32 (90)</td>
<td>34 (94)</td>
<td>36 (97)</td>
<td>36 (96)</td>
<td>33 (91)</td>
<td>28 (82)</td>
<td>22 (71)</td>
<td>17 (62)</td>
<td>26.4 (79.4)</td>
</tr>
<tr>
<td>Average low °C (°F)</td>
<td>15 (52)</td>
<td>15 (59)</td>
<td>21 (69)</td>
<td>26 (78)</td>
<td>28 (83)</td>
<td>29 (84)</td>
<td>27 (81)</td>
<td>26 (78)</td>
<td>20 (68)</td>
<td>18 (60)</td>
<td>11 (52)</td>
<td>9 (48)</td>
<td>19.9 (67.7)</td>
</tr>
<tr>
<td>Record low °C (°F)</td>
<td>-1 (30)</td>
<td>0 (32)</td>
<td>5 (41)</td>
<td>11 (52)</td>
<td>17 (63)</td>
<td>20 (68)</td>
<td>22 (72)</td>
<td>22 (72)</td>
<td>16 (61)</td>
<td>12 (54)</td>
<td>7 (45)</td>
<td>2 (35)</td>
<td>-1 (30)</td>
</tr>
<tr>
<td>Precipitation cm (inches)</td>
<td>3 (1.2)</td>
<td>3 (1.2)</td>
<td>1 (0.4)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>1 (0.4)</td>
<td>8 (3.2)</td>
</tr>
</tbody>
</table>

Source: Weatherbase [1]

Temperatures in KSA

Humidity in KSA

Temperatures in Tunisia
Specific Design Consideration of SMART for KSA

- Following Regulatory Requirements
  - Evaluation criteria
  - Reduced LPZ for emergency planning
- Enhance safety and economic competitiveness
- Based on general data on specific site location
  - Ambient temperature, humidity
  - Seawater temperature
  - Electrical grid, city water supply
  - Precipitation, wind velocity
  - Fire protection, soil properties, ...
- Consideration for inland construction
  - Cooling Tower
- Consideration for seashore construction
  - Desalination System
SMART Passive Safety Systems

- Passive Residual Heat Removal System (PRHRS)
- Passive Safety Injection System (PSIS)
- Containment Pressure and Radioactivity Suppression System (CPRSS)
Containment Pressure and Radioactivity Suppression System (CPRSS)
- Design to reduce LPZ
- Lesser radioactivity release
- Under design
General Arrangement

- Twin units construction
  - ~20% more economical than single unit
### Required site information for site-specific design

<table>
<thead>
<tr>
<th>Required Data</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea water level (Max., Min)</td>
<td>Hydrologic data</td>
</tr>
<tr>
<td>Geotechnical engineering data</td>
<td>Soil &amp; Rock Parameter</td>
</tr>
<tr>
<td>Environmental Data in region of site</td>
<td>Location &amp; Chemical spills</td>
</tr>
<tr>
<td>Seismology data</td>
<td>Seismic design</td>
</tr>
<tr>
<td>Projected population, Individual data</td>
<td>Public dose rate</td>
</tr>
<tr>
<td>Sea water temp. &amp; Air temp.</td>
<td>HVAC, CCW, Service water</td>
</tr>
<tr>
<td>Chlorination Demand</td>
<td>Chlorination system</td>
</tr>
</tbody>
</table>
System List to consider Site Specific Data from KSA

- Ambient temperature
  - Control Room HVAC System
  - Standby Diesel Generator Building HVAC System
  - Electrical and I&C Equipment Areas HVAC System
  - Aux. Building Controlled Area HVAC System
  - Aux. Building Clean Area HVAC System
  - Control Room Emergency Habitability System
  - Reactor Containment Building HVAC System
  - Reactor Containment Building Purge System
  - Turbine Generator Building HVAC System
  - Compound Building HVAC System
  - CW Intake Structure HVAC System
  - Chlorination BLDG HVAC System
  - Plant Chilled Water System
System List to consider Site Specific Data from KSA

- Seawater temperature
  - Circulating Water System
  - Turbine Building Open Cooling Water System
  - Turbine Building Closed Cooling Water System
  - Component Cooling Water System
  - Service Water System
SMART Deployment: Seashore or Inland

Candidate locations for inland deployment

Candidate locations for seashore deployment
Nuclear Desalination using SMART (conceptual)

- The SMART reactor is coupled to four MED units, each with thermal-vapor compressor (MED-TVC) and producing total 40,000 m³/day, with 90 MWe.

- Multiple Effect Distillation (MED) Plant was considered.
  - Vapor produced by an external heating steam source
  - Vapor multiplied by placing several evaporators (effects) in series under successively lower pressures,
  - Vapor produced in each effect is used as a heat source for the next one.
Types of Cooling System

- Once-through cooling
- Closed-cycle wet cooling
- Cooling pond
- Dry cooling
- Hybrid cooling

Cooling System of NPPs

- Once through dominates (Sea-45%; Lake-15%; River-14%)
- Closed cycle with cooling tower: 26%

At present, about 43% of U.S. thermoelectric generating capacity is served by once-through systems, 42% by closed-cycle systems, 1% by dry cooling systems, and the remainder by cooling ponds.
 Cooling system options

Available water resources

40 m$^3$/s available?

Always

Most time of the year

Never

1 m$^3$/s available?

Always

Never

Once-through cooling

Once-through / wet cooling tower

Wet cooling tower

Dry cooling tower

for 3000 MWt
Specific Design Consideration for MENA (15/17)

- Once-Through Cooling vs Closed Cycle Wet Cooling

**Once-Through Cooling**
- Exhaust steam from turbine
- Condenser
- Hot water returned to source
- Cold water from source
- Condensed steam to boiler

**Wet-Cooling Tower**
- Hot water from condenser
- Fans
- Cold water to condenser
- Makeup
- Blowdown
- Ambient air
Dry Cooling & Hybrid Concepts

In-Direct Air Cooling – Trino
(Combined Cycle Power Plant, 2 × 350 MW, Italy)

Air Cool Condenser

Heller System – Yangchen TPP
(Coal Fired Power Plant, 2 × 600 MW, China)

Hybrid (Parallel Condensation)
Nuclear Dry Cooling Options (conceptual)

<table>
<thead>
<tr>
<th>Major Parameters</th>
<th>Direct dry cooling system</th>
<th>Heller system</th>
<th>Indirect dry cooling system</th>
<th>Improved indirect dry cooling system with aux. HX</th>
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<tbody>
<tr>
<td>Required heat transfer area</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>ΔT between fin tubes and air</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
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<tr>
<td>U, overall heat transfer coefficient</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
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<tr>
<td>Probability of radiation leakage</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>Leakage rate at rupture in fin tubes</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
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* Now a seashore site is considered in KSA for constructing SMART FOAK plants.
SMART Development (1997~2015)

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<tbody>
<tr>
<td>Action</td>
<td>Conceptual Design</td>
<td>Basic Design</td>
<td>SMART-P (65MWt) Design and Licensing</td>
<td>Pre-Project Service</td>
<td>Design Optimization</td>
<td>SMART Standard Design Approval</td>
<td>Safety Enhancement Research for SMART Construction</td>
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<tr>
<td>VISTA Tests</td>
<td>SMART Standard Design Certificate for SMART</td>
<td>SMART-330</td>
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<td>VISTA-ITL Tests</td>
<td>VISTA-ITL Tests</td>
<td>VISTA-ITL</td>
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<tr>
<td>Passive Safety System Validation Tests</td>
<td>SMART PPE Project Starts @ 2015. 12. 1.</td>
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<tr>
<td>Business for SMART Construction</td>
<td>VISTA-ITL Tests</td>
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<td>- Foreign Cooperation: Saudi Arabia, UK, Moldova, Malaysia, etc.</td>
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<td>- SPC : Business for SMART Export</td>
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</table>

Total 1,500 MY and ~300 M$ are invested.

Standard Design Approval @ 2012. 7. 4.

SMART PPE Project Starts @ 2015. 12. 1.
Korea-KSA SMART Partnership: Milestone

2013
- MOU (‘13.12) K.A.CARE and KAERI

2014
- Start (‘14.2) JFS (Joint Feasibility Study)

2015
- End (‘15.1) JFS (Joint Feasibility Study)

2016
- MOU (‘15.3) K.A.CARE and MSIP
- SMART 1,2 UNITS Site Finalization

2017
- PPE Contraction (‘15.9) K.A.CARE and MSIP
- SMART development and partnership & HCB

2018
- PPE phase will be completed (‘18.11.30)
- SMART 1,2 UNITS Site Finalization

2020-2025
- Construction phase started in ‘2019 (Plan)

KSA: Kingdom of Saudi Arabia
Deployment Roadmap of SMART (3/6)

Korea-KSA SMART Partnership: Plan

**Development**
- **Korea**
  - 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

**Commercialization**
- **KSA**
  - FOAK Plant Construction
    - 2 FOAK Plants Construction Licensing (CP, OL)

**Dates**
- **1997 ~ 2015**
- **2016 ~ 2018**
- **2019~2024 (Expected)**

**Abbreviations**
- HCB: Human Capability Buildup
- PSAR: Preliminary Safety Analysis Report
- CP: Construction Permit
- OL: Operation License
Deployment Roadmap of SMART (4/6)

SMART-PPE: Design Concept

- Passive Safety System
- No Emergency Diesel
- Simple Operation
- Smaller Exclusion Area Boundary

Better Safety

Cost Reduction

- Power Increment
- Smaller Building
- Less Components
### SMART-PPE: Engineering Features

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SMART-SDA</th>
<th>SMART-PPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>General Site</td>
<td>Specific Site for KSA</td>
</tr>
<tr>
<td>Safety Systems</td>
<td>Active &amp; Passive</td>
<td>Passive</td>
</tr>
<tr>
<td>Plant Power</td>
<td>330 MWt (~100 MWe)</td>
<td>365 MWt (~100 MWe)</td>
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<tr>
<td>Regulation &amp; Standard</td>
<td>Korean Norm</td>
<td>Korean Norm</td>
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<tr>
<td>Design Level</td>
<td>DL2</td>
<td>DL2</td>
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<tr>
<td>Licensing Document</td>
<td>Standard SAR</td>
<td>Preliminary SAR</td>
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</tbody>
</table>

**SDA**: Standard Design Approval  
**PPE**: Pre-Project Engineering  
**SAR**: Safety Analysis Report
SMART-PPE: Scope of Engineering

- NSSS Design
- Fuel Design
- Component Design
- BOP/AE Design

1. Core Design
2. Mechanical Design
3. System Design
4. MMIS Design
5. Reactor Coolant Pump Validation
6. Reactor vessel and Main Component Design
7. MMIS Design and Validation
8. General Arrangement
9. Containment Building
10. Aux. system Design
SMART Technology Development & Its Validation

- A variety of Technology Validation Tests have been conducted from 2009 to 2011 for the verification of the SMART Design.
- Domestic Standard Design Approval (SDA) on July 4, 2012

Specific Design Considerations for Application in MENA

- Site-specific design is being considered.
- Desalination system & Dry cooling options are discussed.

SMART Deployment Roadmap (SMART Partnership)

- SMART-KSA Joint Feasibility Study (2014.2~2015.1)
- SMART Pre-Project Engineering (2015.12~2018.11)
- FOAK Plant Construction (2019~) after successful PPE project
Thank you for your attention!