46th Meeting of the Radiation Safety Standards Committee (RASSC)
24-26 June 2019 (Agenda Item Nr R9.1)

Technology Status and Designs of SMRs

Stefano Monti
Head of Nuclear Power Technology Development Section
Division of Nuclear Power
Department of Nuclear Energy
**Definition, motivation, target applications**

Advanced Reactors to produce up to 300 MW(e), built in factories and transported as modules to sites for installation as demand arises.

A nuclear option to meet the need for flexible power generation for wider range of users and applications.

<table>
<thead>
<tr>
<th>Economic</th>
<th>Better Affordability</th>
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<tbody>
<tr>
<td>• Lower Upfront capital cost</td>
<td>• Shorter construction time</td>
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<tr>
<td>• Economy of serial production</td>
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<table>
<thead>
<tr>
<th>Modularization</th>
<th>Wider range of Users</th>
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<tbody>
<tr>
<td>• Multi-module</td>
<td>• Site flexibility</td>
</tr>
<tr>
<td>• Modular Construction</td>
<td>• Reduced CO₂ production</td>
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<table>
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<tr>
<th>Flexible Application</th>
<th>Integration with Renewables</th>
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<tbody>
<tr>
<td>• Remote regions</td>
<td></td>
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<td>• Small grids</td>
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</table>

<table>
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<tr>
<th>Smaller footprint</th>
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<tr>
<td>• Reduced Emergency planning zone</td>
<td></td>
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<th>Replacement for aging fossil-fired plants</th>
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<th>Potential Hybrid Energy System</th>
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Salient Design Characteristics

Simplification by Modularization and System Integration

Multi-module Plant Layout Configuration

Underground construction for enhanced security and seismic

Enhanced Safety Performance through Passive System

- Enhanced severe accident features
- Passive containment cooling system
- Pressure suppression containment

Image courtesy of IRIS 7.

Image courtesy of NuScale Power Inc.

Image courtesy of BWX Technology, Inc.

Image courtesy of BWX Technology, Inc.
SMRs for immediate & near term deployment

- SMR designs overview
- Selection of SMRs considered ready for deployment
- Some characteristics
Main Features

- Design description and main features of 56 SMR designs
- SMRs are categorized in six (06) types based on coolant type/neutron spectrum:
  - Land Based WCRs
  - Marine Based WCRs
  - HTGRs
  - Fast Reactors
  - MSRs
  - Others
- MANY designs not included / not submitted
**SMRs Under Construction for Immediate Deployment – the front runners ...**

<table>
<thead>
<tr>
<th>Country</th>
<th>Reactor Model</th>
<th>Output (MWe)</th>
<th>Designer</th>
<th>Number of units</th>
<th>Site, Plant ID, and unit #</th>
<th>Startup Commissioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>CAREM-25</td>
<td>27</td>
<td>CNEA</td>
<td>1</td>
<td>Near the Atucha-2 site</td>
<td>2022</td>
</tr>
<tr>
<td>China</td>
<td>HTR-PM</td>
<td>210</td>
<td>Tsinghua Univ./Harbin</td>
<td>2 mods, 1 turbine</td>
<td>Shidaowan unit-1</td>
<td>2019</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>KLT-40S (ship-borne)</td>
<td>70</td>
<td>OKBM Afrikantov</td>
<td>2 modules</td>
<td>Akademik Lomonosov units 1 &amp; 2</td>
<td>2018</td>
</tr>
<tr>
<td></td>
<td>RITM-200 (Icebreaker)</td>
<td>50</td>
<td>OKBM Afrikantov</td>
<td>2 modules</td>
<td>RITM-200 nuclear-propelled icebreaker ship</td>
<td>2019</td>
</tr>
</tbody>
</table>
SMRs: Under Construction

CAREM

Under Construction

Integral PWR type SMR

Naturally circulation

• 30 MW(e) / 100 MW(th)
• Core Outlet Temp: 326°C
• Fuel Enrichment: 3.1% UO₂
• In-vessel control rod drive mechanisms
• Self-pressurized system
• Pressure suppression containment system
• First Criticality: 2022

KLT-40S

Under Commissioning

Floating PWR type SMR

Forced circulation

• 35 MW(e) / 150 MW(th)
• Core Outlet Temp: 316°C
• Fuel Enrichment: 18.6% UO₂
• Floating power unit for cogeneration of heat and electricity; onsite refuelling not required; spent fuel take back to the supplier
• Commercial Start-up: 2019-20

HTR-PM

Under Construction

HTGR type SMR

Forced circulation

• 210 MW(e) / 2x250 MW(th)
• Core Outlet Temp: 750°C
• Fuel Enrichment: 8.5% TRISO coated particle fuel
• Inherent safety, no need for offsite safety measures
• Multiple reactor modules can be coupled with single steam turbine
• Commercial operation: 2019
• The HTR-PM 600 (6 modules) are under design and several potential sites identified

Image Courtesy of CNEA, Argentina

Image Courtesy of Afrikantov, Russia

Image Courtesy of Tsinghua University, China
SMRs: Near Term Deployable

NuScale

Under regulatory review
Integral PWR type SMR

Naturally circulation
- 60 MW(e) / 200 MW(th) per module
- Core Outlet Temp: 314°C
- Fuel Enrichment: <4.95% UO₂
- 0.5 g peak ground accelerations
- Modules per plant: 12
- Containment vessel immersed in reactor pool that provide unlimited coping time for core cooling
- Multi-purpose Energy use: Electricity and process heat applications

SMART

Standard design approval (2012)
Integral PWR type SMR

Forced circulation
- 100 MW(e) / 330 MW(th)
- Core Outlet Temp: 323°C
- Fuel Enrichment: <5% UO₂
- Coupling with desalination and process heat application
- Pre-project engineering agreement between Korea and Kingdom of Saudi Arabia for the deployment of SMART in the Gulf country
- Design update (increased power and more passive safety features) to be submitted for design approval

ACP-100

Basic Design Completed
Integral PWR type SMR

Forced circulation
- 125 MW(e) / 385 MW(th)
- Core Outlet Temp: 319°C
- Fuel Enrichment: <4.95% UO₂
- In-vessel control rod drive mechanisms
- Nuclear Island underground
- Preliminary safety assessment report (PSAR) finished
- An industrial demonstration plant with one 385 MW(t) unit is planned in Hainan Province
- IAEA conducted a generic safety review
SMRs: Generation-IV Designs

**SEALER**

**Conceptual Design**

**Small lead-cooled battery**

Forced circulation

- 3 MW(e) / 8 MW(th)
- Core Outlet Temp: 432°C
- Fuel Enrichment: <20% UO₂
- Non-pressurized
- The primary market for SEALER is constituted by Arctic communities and mining operations which today depend on diesel generators for production of power and heat

**Conceptual Design**

**EM2**

**Modular high temperature gas-cooled fast reactor**

Forced cooling with helium

- 265 MW(e) / 500 MW(th)
- Core Outlet Temp: 850°C
- Fuel Enrichment: 14.5% UO₂
- Silicon carbide composite cladding and fission gas collection system
- Use a combined power conversion cycle - direct helium Brayton cycle and a Rankine bottoming cycle
- Modules per plant: 4

**Conceptual Design**

**IMSR**

**Molten Salt Reactor**

**Conceptual / Basic Design**

Forced circulation

- 190 MW(e) / 400 MW(th) per module
- Core Outlet Temp: ~700°C
- Fuel Enrichment: < 5%
- Completely sealed reactor vessel with integrated pumps, heat exchangers and shutdown rods; core-unit is replaced completely as a single unit every seven years
- Conceptual design complete – basic engineering in progress
Water Cooled SMR Designs for district heating

DHR-400

- 0 MW(e) / 400 MW(th)
- Core Outlet Temp: 98°C
- Fuel Enrichment: <5% UO₂
- Designed to replace traditional coal plants for district heating
- Multi-purpose applications including district heating, sea water desalination & radioisotope production
- Seeking a construction license in 2019
- First plant that is expected to be built in Xudapu, Liaoning, China.

RUTA-70

- 0 MW(e) / 70 MW(th)
- Core Outlet Temp: 102°C
- Fuel Enrichment: 3% UO₂
- Designed for low temperature process heat, coupling with desalination system, radioisotope production or other applications

Basic Design
Pool Type SMR
Forced circulation

Conceptual Design
Pool type SMR
Natural / Forced circulation

Image Courtesy of CNNC, China

Image Courtesy of NIKIET, Russian Federation
Marine-based SMRs (Examples)

**KLT-40S**
- Floating Power Units (FPU) Compact-loop PWR
  - 35 MW(e) / 150 MW(th)
  - Core Outlet Temp.: 316°C
  - Fuel Enrichment: 18.6%
  - FPU for cogeneration
  - Without Onsite Refuelling
  - Fuel cycle: 36 months
  - Spent fuel take back
  - Advanced stage of construction, planned commercial start: 2019 – 2020

**ACPR50S**
- FPU and Fixed Platform Compact-loop PWR
  - 60 MW(e) / 200 MW(th)
  - Core Outlet Temp.: 322°C
  - Fuel Enrichment: < 5%
  - FPU for cogeneration
  - Once through SG, passive safety features
  - Fuel cycle: 30 months
  - To be moored to coastal or offshore facilities
  - Completion of conceptual design programme

**FLEXBLUE**
- Transportable, immersed nuclear power plant
  - PWR for Naval application
  - 160 MW(e) / 530 MW(th)
  - Core Outlet Temp.: 318°C
  - Fuel Enrichment 4.95%
  - Fuel Cycle: 38 months
  - passive safety features
  - Transportable NPP, submerged operation
  - Up to 6 module per on shore main control room

**SHELF**
- Transportable, immersed NPP Integral-PWR
  - 6.4 MW(e) / 28 MW(th)
  - 40,000 hours continuous operation period
  - Fuel Enrichment: < 30%
  - Combined active and passive safety features
  - Power source for users in remote and hard-to-reach locations;
  - Can be used for both floating and submerged NPPs

Images reproduced courtesy of OKBM Afrikantov, CGNPC, DCNS, and NIKIET
Prospects for SMR deployment

- Some Technology Developer Member State activities
- New-comers interest
- Elements to Facilitate Deployment
## Status and major accomplishment in Technology Developer Countries

<table>
<thead>
<tr>
<th>Countries</th>
<th>Recent Milestone</th>
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<tbody>
<tr>
<td>Argentina</td>
<td><strong>CAREM25</strong> is in advanced stage of construction. Aiming for fuel loading &amp; start-up commissioning in 2019</td>
</tr>
</tbody>
</table>
| Canada                | **CNSC** is performing design reviews for several innovative SMR designs, mostly non-water cooled, including molten salt reactors (MSR)  
First Canadian SMR licence application submitted: Global First Power (GFP), with support from Ontario Power Generation and Ultra Safe Nuclear Corporation (USNC), to deploy a Micro Modular Reactor plant at Chalk River in Ontario |
| China                 | • **HTR-PM** is in advanced stage of construction. Commercial operation expected in 2019.  
• **ACP100** completed IAEA generic reactor safety review. CNNC plans to build **ACP100** demo-plant in **Hainan Provence** in the site where NPPs are already in operation.  
• China has 3 floating SMR designs (**ACP100S**, **ACP50S** and **CAP-F**) |
| France                | • Propose a new French SMR design (Consortium of TechnicAtome, CEA, EDF, Naval Group, Investir L`Avenir)                                                                                                                                                                                                                                     |
| Republic of Korea     | **SMART** (100 MWe) by KAERI certified in 2012.  
• SMART undertakes a pre-project engineering in Saudi Arabia, for near-term construction of 2 units.  
• Updated design with increased power and more passive safety features developed  
• New design will be submitted for certification in Korea in parallel with KSA licensing application |
| Russian Federation    | • Akademik Lomonosov floating NPP with 2 modules of **KLT40S** has completed construction and commissioning. Aiming for criticality and test operations in 2019.  
• AKME Engineering will develop a deployment plan for **SVBR100**, a eutectic lead bismuth cooled, fast reactor.                                                                                                                                                    |
| United Kingdom        | • **Rolls-Royce** recently introduced **UK-SMR**, a 450 MW(e) PWR-based design; many organizations in the UK work on SMR design, manufacturing & supply chain preparation  
• Identifying potential sites for future deployment of SMR;  
• Government supporting 8 advanced designs (Phase I) to determine its feasibility                                                                                                                                  |
| United States of America | • The US-NRC has started design review for **NuScale** (720 MW(e) from 12 modules) from April 2017, aiming for FOAK plant deployment in Idaho Falls |
## Status and major accomplishment in Embarking Countries

<table>
<thead>
<tr>
<th>Countries</th>
<th>Recent Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saudi Arabia</td>
<td>• <strong>Vision 2030 → National Transformation Program 2020</strong>: Saudi National Atomic Energy Project:&lt;br&gt;  • K.A.CARE performs a PPE with KAERI to prepare a construction of 2 units of SMART&lt;br&gt;  • An MOU between K.A.CARE and CNNC on HTGR development/deployment in KSA</td>
</tr>
<tr>
<td>Indonesia</td>
<td>• Through an open-bidding, an experimental 10 MW(th) <strong>HTR-type SMR</strong> was selected in March 2015 for a basic design work aiming for a deployment in mid 2020s&lt;br&gt;  • Site: R&amp;D Complex in Serpong where a 30 MW(th) research reactor in operation&lt;br&gt;  • BAPETEN, the regulatory body has issued a site license</td>
</tr>
<tr>
<td>Jordan</td>
<td>• Jordan, Saudi Arabia and Republic of Korea is to conduct a feasibility study for a deployment of SMART in Jordan</td>
</tr>
<tr>
<td>Poland</td>
<td>• <strong>HTGR</strong> for process heat application to be implemented in parallel to large LWRs&lt;br&gt;  • 10 MW(th) experimental <strong>HTGR at NCBJ</strong> proposed possibly with EU cooperation</td>
</tr>
<tr>
<td>Tunisia</td>
<td>• STEG, the National Electricity and Gas Company is active in performing technology assessment for near-term deployable <strong>water-cooled SMRs</strong></td>
</tr>
<tr>
<td>Kenya</td>
<td>• Requested support on human capacity building for Reactor Technology Assessment that covers SMRs through IAEA-TC Project</td>
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Perceived advantages and potential challenges
## Advantages, Issues & Challenges

### Technology Issues
- Shorter construction period (modularization)
- Potential for enhanced safety and reliability
- Design simplicity
- Suitability for non-electric application (desalination, etc.).
- Replacement for aging fossil plants, reducing GHG emissions

### Non-Techno Issues
- Fitness for smaller electricity grids
- Options to match demand growth by incremental capacity increase
- Site flexibility
- Reduced emergency planning zone
- Lower upfront capital cost (better affordability)
- Easier financing scheme

### Technology Issues
- Licensability (FOAK designs)
- Non-LWR technologies
- Operability and Maintainability
- Staffing for multi-module plant; Human factor engineering;
- Supply Chain for multi-modules
- Advanced R&D needs

### Non-Techno Issues
- Economic competitiveness
- Plant cost estimate
- Regulatory infrastructure
- Availability of design for newcomers
- Physical Security
- Post Fukushima action items on institutional issues and public acceptance
A small selection of IAEA SMR activities...
International Technical Working Group on SMR

- To advice and support IAEA programmatic planning and implementation in areas related to technology development, design, deployment and economics of SMRs
- 20 Member States and two International Organizations: European Commission and OECD-NEA as invited observers:

- Three technical subgroups established:
  - **SG-1**: Development of Generic Users Requirements and Criteria (GURC)
  - **SG-2**: Research, Technology Development and Innovation; Codes and Standards
  - **SG-3**: Industrialization, design engineering, testing, manufacturing, supply chain, and construction technology
- TWG will also address SMR for Non-Electric Applications and coupling with renewables
- 1<sup>st</sup> TWG Meeting for SMR held on 23 - 26 April 2018 in Vienna
- 2<sup>nd</sup> Meeting scheduled for 8 – 11 July 2019 in Vienna
SMR: Ongoing Support to Member States through TC

Ongoing SMR/HTGR Missions
- Indonesia
- Jordan
- Saudi Arabia

Technical Cooperation Project: Europe/Eurasia
- Armenia
- Azerbaijan
- Croatia
- Czechia
- Hungary
- Lithuania
- Poland
- Romania
- Russia
- Slovakia
- Tajikistan
- Ukraine

Common Themes / actual activities:
- Design and technology status of water-cooled SMRs / non-water cooled SMRs
- Non-electric nuclear applications, options, technology readiness and toolkits
- Technology Assessment training
- Infrastructure, economic and financing aspects of SMRs
- Design Specific Issues on Engineering Project, Construction and Industrial Supply Chain for Small Modular Reactor Deployments
- Siting of SMRs
- SMR deployment scenarios in global energy portfolio
- Design safety and safety assessment of SMRs
- Principles for Emergency Preparedness & Response for SMRs
- SMR fuel cycles and waste management (specifically also for HTGRs)
CRPs relevant to SMRs

1. High Temperature Gas Cooled Reactor Physics, Thermal-Hydraulics and Depletion Uncertainty Analysis

2. High Temperature Gas Cooled Reactors Safety Design

3. Development of Approaches, Methods and Criteria for Determining Technical Basis for EPZ for SMR Deployment (joint project – presented later)


5. HTGRs applications for energy neutral sustainable comprehensive extraction and mineral products development (T11006 - with NEFW-NFCM)

NEW CRPs proposed:

- New coordinated research project on ‘Technologies to enhance the competitiveness and early deployment of SMRs and HTRs’ to start in 2020.
INPRO Dialogue Forum 17 in Coordination with NPTDS

- INPRO Dialogue Forum (DF) 17 on “Opportunities and Challenges in Small Modular Reactors”
- Venue: Ulsan, Republic of Korea, Jul 2019
- Opening, Technical Plenaries, Wrap Up and Closing Sessions
- Plenary Technical Sessions:
  - Market Opportunities
  - Design Requirements
  - Research & Technology Development
  - Near Term Deployment Designs (presented by design authorities – designs in licensing, construction or recent deployment)

- Technology Exhibition Space
- Technical Tours to local nuclear sites and industry
- Over 130 current expressions of interest for participation (DFs are usually less than 100 participants)
Recent Publications and Forthcoming Ones

- NES Technology Roadmap for Small Modul Reactor Deployment
- TECDOC: Status of Approaches for Environmental Impact Assessment for SMR Deployment
- TECDOC: Options to Enhance Energy Supply Security using Hybrid Energy Systems
TECDOC: “Options to Enhance Energy Supply Security using HES based on SMRs

HES: Hybrid Energy Systems integrate energy conversion processes to optimize energy management, reliability, security, and sustainability.

ESS: Energy Supply Security is a reliable continuous supply of energy at an affordable cost.
Joint ICTP-IAEA Workshop on Physics and Technology of Innovative High Temperature Nuclear Energy Systems | (smr 3281)

Starts 14 Oct 2019

Ends 18 Oct 2019

Central European Time

ICTP
Kastler Lecture Hall (AGH)
Strada Costiera, 11
I - 34151 Trieste (Italy)
Considerations for Radiation Safety in SMRs

- Few thoughts on Radiation Safety for SMRs
- What is different.. If anything
Radiation Protection: considerations for SMR designs

• Water cooled SMRs (should be very similar to large NPPs)
  – In iPWR all main equipment is integrated in vessel that may present challenges when doing maintenance
  – Many designs will require opening the vessel to get access to equipment (steam generator, primary pumps, pressurizer etc.)
  – Some SMRs with compact designs may consider new shielding materials to reduce required thickness and weight
Radiation Protection: considerations for SMR designs

• Non-water cooled SMRs
  – Different reactor spectrum / source terms composition and chemical form (not associated with steam)
  – In molten salt reactors the source term is circulating, some fissions will take place outside the core as well as some delayed neutrons… activation; remaining fuel/coolant after draining for maintenance
  – Graphite moderated / reflected HTGRs behave differently as a neutron reflector / shield compared to water (and need ~ 1 meter thickness)
  – Special techniques and designs required for in-core graphite shield designs (and behaviour over lifetime as graphite shrink and expand with irradiation)
Thank you!

For inquiries on SMR, please contact:

Mr Frederik Reitsma
Team Leader: SMR Technology Development
IAEA Nuclear Power Technology Development Section

F.Reitsma@iaea.org