Small Modular Reactors
Design Specificities of LWR- and HTGR-type SMRs, identification of issues of their deployments

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SMR: definition & rationale of developments

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

**Economic**
- Lower Upfront capital cost
- Economy of serial production

**Modularization**
- Multi-module
- Modular Construction

**Flexible Application**
- Remote regions
- Small grids

**Smaller footprint**
- Reduced Emergency planning zone

**Replacement for aging fossil-fired plants**

**Better Affordability**
- Shorter construction time

**Wider range of Users**

**Site flexibility**

**Reduced CO₂ production**

**Potential Hybrid Energy System**

Integration with Renewables
## Status and major accomplishment in Member States

<table>
<thead>
<tr>
<th>Countries</th>
<th>Recent Milestone</th>
</tr>
</thead>
<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>
<tr>
<td>Canada</td>
<td><strong>CNSC</strong> is performing design reviews for several innovative SMR designs, mostly non-water cooled, including molten salt reactors (MSR)</td>
</tr>
</tbody>
</table>
| China                      | • **HTR-PM** is in advanced stage of construction. Commissioning expected in 2018.  
                             • **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**, **ACPR50S** and **CAP-F**)                                                                                   |
| Korea, Republic of         | **SMART** (100 MWe) by KAERI certified in 2012. SMART undertakes a pre-project engineering in Saudi Arabia, for near-term construction of 2 units.                                                                  |
| Saudi Arabia               | • **K.A.CARE** performs a PPE with **KAERI** to prepare a construction of 2 units of **SMART**                                                                                                               |
|                            | • An MOU between K.A.CARE and CNNC on HTGR development/deployment in KSA                                                                                                                                          |
| Russian Federation         | • Akademik Lomonosov floating NPP with 2 modules of **KLT40S** is in advanced stage of construction. Aiming for commissioning 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                                                                                                      |
| United States of America   | • The US-NRC has started design review for **NuScale** (600 MW(e) from 12 modules) from April 2017, aiming for FOAK plant deployment in Idaho Falls.  
                             • **TVA** submitted early site permit (ESP) for Clinch River site, design is still open.                                                                              |
# Power Range of SMRs

Power Range MW(e) | Reactor Designs |
------------------|----------------|
> 301             | IMR, AHWR-300, VBER-300, GTHTTR300, IRIS, DMS, GT-MHR, EM², BREST-OD-300, SC-HTGR |
251-300           | Westinghouse SMR, FUJI, MHR-T, ThorCon, LFTR |
201-250           | mPower, SMR-160, PBMR-400, IMSR, Flexblue |
151-200           | CAP150, HTR-PM, MSTW, MkI PB-FHR, SmAHTR |
101-150           | ACP100, SMART, MHR-100, SVBR100, ACP50S |
51-100            | CAREM25, NuScale, KLT-40S, HTMR-100, G4M |
0-50              | **Reactors** |
SMRs for immediate & near term deployment

Water cooled SMRs
- CAREM
- SMART
- ACP100
- NuScale

Gas cooled SMRs
- HTR-PM
- GTHTR300
- HTMR100
- EM²

Liquid metal cooled SMRs
- PFBR
- PRISM
- SVBR
- 4S
Water cooled SMRs (Examples)

**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
- Target commissioning: October 2018

**SMART**
- Licensed/Certified
- Integral PWR type SMR
- Forced circulation
- 100 MW(e) / 330 MW(th)
- Core Outlet Temp: 323°C
- Fuel Enrichment: 5% UO₂
- Multi-purpose application: electricity production, sea water desalination, district heating and process heat for industries
- Passive safety systems along with severe accident mitigation features
- Standard Design Approval: 4 July 2012

**ACP100**
- Basic Design
- Integral PWR type SMR
- Forced circulation
- 100 MW(e) / 310 MW(th)
- Core Outlet Temp: 323°C
- Fuel Enrichment: (2-4)% UO₂
- Underground nuclear island and spent fuel pool-enhanced protection against external hazards
- Containment vessel installed in water pool with fully passive safety facilities
- Modules per plant: (1 – 8)
- Undertaking IAEA’s Generic Reactor Safety Review.

**NuScale**
- Under development
- Integral PWR type SMR
- Naturally circulation
- 50 MW(e) / 160 MW(th) per module
- Core Outlet Temp: 302°C
- Fuel Enrichment: 4.95% UO₂
- Modules per plant: 12
- Containment vessel immersed in reactor pool that provide unlimited coping time
- Underground installment of containment vessel
- Submit Design Certification Review Application: 12/2016
Marine-based SMRs (Examples)

**KLT-40S**
- 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**
- 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
High Temperature Gas Cooled SMRs

**HTR-PM**

**Modular Pebble Bed High Temperature Gas Cooled Reactor**

- Helium/Graphite cooled
- 210 MW(e) / 500 MW(th)
- Core Outlet Temp: 750°C
- Fuel Enrichment: 8.5% UO₂
- TRISO coated particle
- No. of fuel spheres: 420,000 /module
- Modules per plant: 2
- Advanced stage of construction- expected to be commissioned by 2018

**Prismatic High Temperature Gas Cooled Reactor**

- Helium/Graphite cooled
- 100-300 MW(e) / 600 MW(th)
- Core Outlet Temp: 850-950°C
- Fuel Enrichment: 14% UO₂
- TRISO ceramic coated particle
- Fuel temperature limit: 1600°C
- Modules per plant: 4
- Inherent safety features
- Multi-purpose application: power generation, hydrogen production, process heat, steelmaking, desalination and district heating

**HTMR100**

**High temperature Gas Cooled Reactor**

- Helium cooled / graphite moderated
- 35 MW(e) / 100 MW(th) per module
- Core Outlet Temp: 750°C
- Fuel Enrichment: 15% Th/Pu, <10% U₂₃₅ Th/LEU and Th/HEU
- Module per plant: (4-8) pack
- Number of Fuel units: ~150,000 pebbles
- Better load following capability and flexibility in multi-module configuration

**EM²**

**High Temperature Gas Cooled Fast Reactor**

- Helium cooled
- 240 MW(e) and 500 MW(th)
- Refuelling cycle: 30 years
- Core Outlet Temp: 850°C
- Fuel enrichment: 1% U₂₃₅ - 1% Pu, MA coated particle
- Efficiency: 48%
- Fully enclosed in an underground containment
- Utilization of spent fuel
- Simplified power conversion system and 30% reduction in material requirements than that of current NPPs
Other Generation IV SMRs
(Examples)

**PRISM**
- Power Reactor Innovative Small Modular
- Liquid Sodium-cooled Fast Breeder Reactor
  - 311 MW(e) / 840 MW(th)
  - Core Outlet Temp: 485°C
  - Fuel Enrichment: 26% Pu, 10% Zr
  - Underground containment on seismic isolators
  - For complete recycling of plutonium and spent nuclear fuel

**4S**
- Super Safe Small Simple Sodium-cooled Fast Reactor
  - Fuel Cycle: 30 years
  - 10 MW(e) / 30 MW(th)
  - Core Outlet Temp: 510°C
  - Fuel Enrichment < 20%
  - Negative sodium void reactivity
  - Hybrid of active and passive safety features
  - Designed for remote locations and isolated islands, close to towns

**SVBR100**
- Heavy Metal Liquid Cooled Fast Reactor 100 MW
  - Lead Bismuth Eutectic cooled Fast Reactor
  - 101 MW(e) / 280 MW(th)
  - Core Outlet Temp: 490°C
  - Fuel Enrichment 16.5%
  - Fuel Cycle: 8 years
  - Hybrid of active and passive safety features
  - Prototype nuclear cogeneration plant to be built in Dimitrovgrad, Ulyanovsk

**IMSR**
- Integral Molten Salt Reactor
  - Molten Salt Reactor
  - 80, 300 and 600 MW(th)
  - Core Outlet Temp: 700°C
  - Fuel Cycle: 7 years
  - MSR-Burner: Efficient burner of LEU
  - MSR-breeder: Thorium breeder
  - Ideal system for consuming existing transuranic wastes (Long lived waste)
  - Passive decay heat removal in situ without dump tanks

*Images Courtesy of:*
- GE Hitachi, USA
- TOSHIBA, Japan
- AKME Engineering, Russia
- Terrestrial Energy, Canada
# SMR – iPWR type: integration of NSSS

<table>
<thead>
<tr>
<th>Integration of components</th>
<th>ABV-6M</th>
<th>CAREM</th>
<th>NuScale</th>
<th>ACP100</th>
<th>SMART</th>
<th>mPower</th>
<th>W-SMR</th>
<th>IRIS</th>
<th>IMR</th>
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<td>NC</td>
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<td>100</td>
<td>180</td>
<td>225</td>
<td>335</td>
<td>350</td>
</tr>
</tbody>
</table>
Concept of Integral PWR based SMRs

SMART

Westinghouse SMR

CRDM

Steam generators

pumps

pressurizer

core + vessel

Steam generators

Reactor coolant pump

Pressurizer

Reactor vessel

Main coolant pipe
Benefits of integral vessel configuration:

- eliminates loop piping and external components, thus enabling compact containment and plant size → reduced cost
- Eliminates large break loss of coolant accident (improved safety)
SMR Key Design Features (1)

- Multi modules configuration
  - Two or more modules located in one location/reactor building and controlled by single control room
    - → reduced staff
    - → new approach for I&C system

Images reproduced courtesy of NuScale Power Inc. and BWX Technology, Inc., USA.
SMR Key Design Features (2)

- Underground and marine based deployment
  - Underground sites offer:
    - Better protection against the impacts of severe weathers
    - Better seismic strength
    - Enhanced protection against fission product release
    - Improved physical security, aircraft impacts and conventional warfare
  - Marine based deployments offer:
    - Infinite heat sink (sea)
    - Site flexibility
Design Features of iPWR-SMRs

• Enhanced performance engineered safety features:
  Natural circulation primary flow → No LOFA
  – Reactivity control
    • Internal CRDM
      – No rod ejection accident
    • Gravity driven secondary shutdown system
  – Residual heat removal system
    • Passive Residual Heat Removal System
    • Passive Residual heat removal through SG and HX submerged in water pool
  – Safety injection System
    • Passive Injection System
    • Active injection System Flooded containment with recirculation valve
SMR Site Specific Considerations

- Site size requirements, boundary conditions, population, neighbours and environs
- Site structure plan; single or multi-unit site requirements

- What site specific issues could affect the site preparation schedule and costs?
- What is the footprint of the major facilities on the site?
SMR Key Design Features (3)

- **Containment**
  - Passively cooled Containment:
    - Submerged Containment (Convection and condensation of steam inside containment, the heat transferred to external pool) (NuScale, W-SMR)
    - Steel containment (mPower)
  - Concrete containment with spray system (SMART)
  - Pressure suppression containment (CAREM, IRIS)

- **Severe Accident Feature**
  - In-vessel Corium retention (IRIS, Westinghouse SMR, mPower, NuScale, CAREM)
  - Hydrogen passive autocatalytic recombiner (CAREM, SMART)
  - Inerted containment (IRIS)
Innovative Nuclear Systems
Revolutionary designs
(Very) High Temperature Gas Cooled Reactors

VHTRs; HTRs; HTGRs

For inquiries on HTGR, contact: F.Reitsma@iaea.org
Graphite Moderated Gas Cooled Reactors

For inquiries on HTGR, contact: F.Reitsma@iaea.org

- X-10 Reactor, Windscale Piles
  - Air coolant
  - Gas outlet temperature >~500°C

- Magnox, AGR
  - CO2 coolant
  - Gas outlet temperature >~500°C

- HTGR
  - Helium coolant
  - Coated particle fuel
  - Gas outlet temperature >~700°C
  - Gas outlet temperature >~900°C

- Steam Generator

- Heat Application (IHX, Gas turb.)

- Block Type Reactors

- Pebble Bed Reactors
High Temperature Gas Cooled Reactors is an advanced reactor system (part of GEN-IV) with the following main characteristics:

- High temperatures (750-1000°C)
- Use of coated particle fuel
- Helium coolant
- Graphite moderated
- Small reactor units (~100 - 600 MWth)
- To be deployed as multiple modules
- Low power density (typically 3-6 W/cc compared to 60-100W/cc for LWRs)
- Two basic design variations – Prismatic and pebble bed design

For inquiries on HTGR, contact: F.Reitsma@iaea.org
Prismatic (block-type) HTGRs

For inquiries on HTGR, contact: F.Reitsma@iaea.org
Pebble type HTGRs

- Spherical graphite fuel element with coated particles fuel
- On-line / continuous fuel loading and circulation
- Fuel loaded in cavity formed by graphite to form a pebble bed

For inquiries on HTGR, contact: F.Reitsma@iaea.org
HTGRs - benefits

- Higher (↑20-50%) efficiency in electricity generation than conventional nuclear plants due to higher coolant outlet temperatures
- Potential to participate in the complete energy market with cogeneration and high temperature process heat application
  - Process steam for petro-chemical industry and future hydrogen production
  - Market potential substantial and larger than the electricity market
  - Allows flexibility of operation switching between electricity and process heat
- Significantly improved safety
  - Decay heat removal by natural means only, i.e. no meltdown
  - No large release - radioactivity contained in coated particle fuel
  - EPZ can be at the site boundary
- Position close to markets or heat users
  - Savings in transmission costs
- Can achieve higher fuel burnup (80-200 GWd/t)
  - Flexible fuel cycle and can burn plutonium very effectively

For inquiries on HTGR, contact: F.Reitsma@iaea.org
HTGRs Challenges

- The low power density leads to large reactor pressure vessels (but site requirements not larger)
  - Forging capability can also set limit on RPV diameter and power (e.g. Ø6.7 m → < 350 MWth in South Korea)
- helium coolant has low density and thus requires high pressurization
- helium coolant is non-condensable – so a traditional containment cannot be used
- coated particle fuel costs are expected to be higher

For inquiries on HTGR, contact: F.Reitsma@iaea.org
Interest in HTGRs

- 14 member states in the TWG-GCRs
- Active projects
  - China (HTR-10 and HTR-PM)
  - Japan (HTTR and hydrogen project)
  - USA, South Africa, Korea, Russian Federation
  - EU research projects

Newcomer countries:

- Indonesia
  - Indonesia completed the concept design and safety analysis of a 10MW(th) experimental power reactor
  - Ideal technology for deployment on remote areas / islands

- Saudi Arabia
  - signed an MoU with China for HTR-PM deployment
  - The use of 210 MW(e) HTGR for cogeneration of electricity and industrial process heat, e.g. hydrocarbon and petrochemicals

- Member states that recently expressed interest
  - Poland – new committee to prepare for the possible future implementation of HTGRs
  - Other countries in Asia-Pacific

For inquiries on HTGR, contact: F.Reitsma@iaea.org
## SMR for Non-Electric Applications

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high temperature reactors</td>
<td>100-1200</td>
</tr>
<tr>
<td>Gas-cooled fast reactors</td>
<td>100-1200</td>
</tr>
<tr>
<td>Molten Salt reactors</td>
<td>100-1200</td>
</tr>
<tr>
<td>Supercritical water-cooled reactors</td>
<td>100-1200</td>
</tr>
<tr>
<td>Sodium-cooled fast reactors</td>
<td>100-1200</td>
</tr>
<tr>
<td>Liquid metal cooled reactors</td>
<td>100-1200</td>
</tr>
<tr>
<td>Water cooled reactors</td>
<td>100-1200</td>
</tr>
</tbody>
</table>

### Applications

- District heating
- Seawater desalination
- Pulp & paper manufacture
- Methanol production
- Heavy oil desulfurization
- Petroleum refining
- Methane reforming hydrogen production
- Thermochemical hydrogen production
- Coal gasification
- Blast furnace steel making
Cogeneration Concept of SMART

330 MW$_{th}$ 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 Distributed Power System

Images courtesy of KAERI, Republic of Korea
Cogeneration Concept of ACP100

- **Electricity Generation for Remote Area**
- **Electricity Generation and District Heating**
- **Electricity Generation and Industrial Process Heat**
- **Electricity Generation and Desalination in Coastal Area**

Images courtesy of CNNC, China
KLT-40S FNPP and its Application

Floating plants to supply heat and power to the consumers in coastal zone of hard-to-reach areas of oil-and-gas production

Floating nuclear desalination complexes

Autonomous power supply to sea oil-production platforms

Ground-based plants for autonomous power supply

Images courtesy of OKBM Afrikanov, Russian Federation
Advantages of Cogeneration

• Improve economics of NPPs (Better Revenue due to):
  – Better utilization of fuel
  – Sharing of infrastructures
  – Production of more than one product

• Improve NPP efficiency (Energy saving):
  – Recycling of waste heat
  – Accommodate seasonal variations of electricity demand
  – Rationalization of power production (use of off-peak)
  – Improve the value of heat (use low-quality steam)
  – Meet demand for energy-intensive processes (desalination, hydrogen, etc.).

• Sustain the environment (keep Clean):
  – Reduce use of fossil fuel
  – Reduce Impacts

For Non-Electric Applications, contact: I.Khamis@iaea.org
Safety Aspects and Challenges of Nuclear Desalination

- Safety issues of ND are similar to NPP
- Additional specific safety considerations for the coupling schemes between the reactor and the desalination plant (DP)
- Issues related to environment, shared resources, and siting...etc.

- Disparity: Countries & technology
- Public acceptance: Safety, Public health, Environmental issues
- Economics: competitiveness with fossil
## Preliminary Identification of Issues (1)

<table>
<thead>
<tr>
<th>No.</th>
<th>Infrastructure Elements</th>
<th>Potential Advantages due to SMR Specificities</th>
<th>Potential Challenges due to SMR Specificities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>National Position</td>
<td>o May facilitate decision making: lower radiological risk and lower capital cost for countries with small grid</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Nuclear Safety</td>
<td>o Enhanced levels of safety that incorporate lessons-learned from major nuclear accidents</td>
<td>o No reference SMR plant with passive safety features in operation as yet</td>
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<tr>
<td>3</td>
<td>Management</td>
<td>o Enhanced levels of safety that incorporate lessons-learned from</td>
<td>o O&amp;M management for multi-unit SMR nuclear power plants</td>
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<tr>
<td>4</td>
<td>Funding &amp; Financing</td>
<td>o Easier to finance, phased-built for multi-module SMRs may alleviate project load</td>
<td>o Untested; the 3 SMR under construction are industrial demonstration plants</td>
</tr>
<tr>
<td>5</td>
<td>Legal framework</td>
<td>o To be identified/addressed</td>
<td>o Marine-based SMRs may require non-nuclear legislative framework to address transport &amp; maritime security issues</td>
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<tr>
<td>6</td>
<td>Safeguards</td>
<td>o To be identified/addressed</td>
<td>o May need novel approaches to safeguard due to: underground construction, integral primary circuit</td>
</tr>
</tbody>
</table>

**References:**
- Joint NIDS-NPTDS Consultancy Meeting on Infrastructure required for SMR Deployments, 8 – 11 December 2014, Participating MS: China, France, Indonesia, Republic of Korea, Saudi Arabia, Russian Federation, United States of America
- Technical Meeting on Technology Roadmap for SMR Deployments, 5 – 8 October 2015
- Technical Meeting on Technology Assessment of SMR for Near-Term Deployments, 5 – 9 September 2016, Beijing, China
SMRs in terms of Safeguards (1)

- Each design, technology, deployment site or region may introduce specific safeguard, security and environmental issues/challenges;
- Embarking countries are not familiar on establishing a secure perimeter around floating or submersible NPP;
- The issue of responsibility for safeguards for supplier vs. operator States is new.

<table>
<thead>
<tr>
<th>SMR Designs</th>
<th>Type</th>
<th>Power MW(e)</th>
<th>Fuel</th>
<th>Enrichment (%)</th>
<th>Refueling Interval (months)</th>
<th>Burn-up (GWD/T)</th>
<th>Siting Orientation</th>
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<tbody>
<tr>
<td>HTR-PM</td>
<td>HTGR</td>
<td>210</td>
<td>UO₂ Spherical TRISO</td>
<td>8.5</td>
<td>On-power refuelling</td>
<td>90</td>
<td>Above ground</td>
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<tr>
<td>KLT-40S</td>
<td>PWR Compact Loop</td>
<td>35 x 2</td>
<td>UO₂ Silumin-matrix</td>
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<td>PWR</td>
<td>60</td>
<td>UO₂ 17x17</td>
<td>&lt; 5</td>
<td>30</td>
<td>&lt; 52</td>
<td>Floating</td>
</tr>
<tr>
<td>FLEXBLUE</td>
<td>PWR</td>
<td>160</td>
<td>UO₂ 17x17</td>
<td>4.95</td>
<td>38</td>
<td>38</td>
<td>Submerged</td>
</tr>
<tr>
<td>CAREM25</td>
<td>i-PWR</td>
<td>30</td>
<td>UO₂ Hexagonal</td>
<td>3.1</td>
<td>14</td>
<td>24</td>
<td>Above ground</td>
</tr>
<tr>
<td>ACP100</td>
<td>i-PWR</td>
<td>100</td>
<td>UO₂ 17x17</td>
<td>2.4 ~ 4</td>
<td>24</td>
<td>45</td>
<td>Above ground</td>
</tr>
<tr>
<td>SMART</td>
<td>i-PWR</td>
<td>100</td>
<td>UO₂ 17x17</td>
<td>&lt; 5</td>
<td>36</td>
<td>&lt; 60</td>
<td>Above ground</td>
</tr>
<tr>
<td>NuScale</td>
<td>i-PWR</td>
<td>50 x 12</td>
<td>UO₂ 17x17</td>
<td>&lt; 4.95</td>
<td>24</td>
<td>-</td>
<td>Under ground</td>
</tr>
</tbody>
</table>
### SMRs in terms of Safeguards (2)

<table>
<thead>
<tr>
<th>Specific Features</th>
<th>Potential Safeguard Aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pebble-bed fuel for HTGR-SMRs</td>
<td>• Accounting for loading, circulating and unloading fuel pebbles is still a challenge in pebble-bed HTGR?</td>
</tr>
<tr>
<td>Fuels with high enrichment and burn-up for marine-based SMRs</td>
<td>• Attractiveness of fresh fuels with over 10% $\text{U}_{235}$ enrichment</td>
</tr>
<tr>
<td>Marine-based SMRs, however, designed for <strong>without on-site refuelling</strong></td>
<td>• Safeguards will need to monitor if the reactor has been tampered with</td>
</tr>
<tr>
<td>Marine-based SMRs for remote region have (very) long refuelling interval</td>
<td>• Reduced chances for misuse or material diversion as the reactor vessel opened less frequently</td>
</tr>
<tr>
<td>SMRs are intended for remote locations</td>
<td>• Present new challenges for safeguard inspection access</td>
</tr>
<tr>
<td>Smaller physical footprint (plant layout)</td>
<td>• May be difficult to verify integral reactor vessel due to difficulty to access for design verification</td>
</tr>
<tr>
<td>Several water-cooled SMRs adopt <strong>underground construction</strong></td>
<td>• Enhanced security but more difficulty to verify reactor design and location</td>
</tr>
</tbody>
</table>
## Preliminary Identification of Issues (2)

<table>
<thead>
<tr>
<th>No.</th>
<th>IAEA Infrastructure Elements</th>
<th>Potential Advantages due to SMR Specificities</th>
<th>Potential Challenges due to SMR Specificities</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Regulatory framework</td>
<td></td>
<td>❖ Depending on designs/technologies, licensing reviews may be accelerated or delayed due to FOAK components</td>
</tr>
<tr>
<td>8</td>
<td>Radiation protection</td>
<td>❖ To be identified/addressed</td>
<td>❖ To be identified/addressed</td>
</tr>
<tr>
<td>9</td>
<td>Electrical grid</td>
<td>❖ Deployable on smaller grids with less reserve capacity and less dependent on off-site power for safety function</td>
<td>❖ Multi-unit plants with multi balance of plants</td>
</tr>
<tr>
<td>10</td>
<td>Human resource development</td>
<td>❖ Modular construction technology reduce peak construction workforce</td>
<td>❖ HRD for FOAK plants with no reference plant; HRD for non water-cooled in newcomer countries</td>
</tr>
<tr>
<td>11</td>
<td>Stakeholder involvement</td>
<td>❖ Need to evaluate whether SMRs may even develop conducive environment for nuclear power programme</td>
<td>❖ Marine-based SMRs may require non-nuclear legislative framework to address transport &amp; maritime security issues</td>
</tr>
<tr>
<td>12</td>
<td>Site and supporting facilities</td>
<td>❖ Smaller footprint may expand availability of sites, lower water usage and lower transmission requirements</td>
<td>❖ Site and supporting facilities for deployment in remote regions</td>
</tr>
</tbody>
</table>
### Preliminary Identification of Issues (3)

<table>
<thead>
<tr>
<th>No.</th>
<th>IAEA Infrastructure Elements</th>
<th>Potential Advantages due to SMR Specificities</th>
<th>Potential Challenges due to SMR Specificities</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Environmental protection</td>
<td>o Allows for geographically distributed power production</td>
<td>❖ May require additional environmental assessments</td>
</tr>
<tr>
<td>14</td>
<td>Emergency planning</td>
<td>o Low power and safety features expected to reduce EPZ size</td>
<td>❖ Depending on deployment scheme, e.g. # of units per site, regulatory framework may differ on EPR between countries</td>
</tr>
<tr>
<td>15</td>
<td>Security &amp; physical protection</td>
<td>o Intrinsic design features (e.g. additional barriers) may limit vulnerabilities for sabotage</td>
<td>❖ Cyber security for deployment in remote regions (in newcomer countries)</td>
</tr>
<tr>
<td>16</td>
<td>Nuclear fuel cycle</td>
<td>o No impact to most SMRs with refueling interval of 12 to 36 months</td>
<td>❖ some SMRs have long fuel cycle up to 7 years with higher enrichment (in LEU)</td>
</tr>
<tr>
<td>17</td>
<td>Radioactive waste</td>
<td>o To be identified/addressed</td>
<td>❖ Spent fuel management may be different for some non-water cooled SMRs</td>
</tr>
<tr>
<td>18</td>
<td>Industrial involvement</td>
<td>o Simplification may reduce safety grade components enable diverse supply chain, increase local content</td>
<td>❖ Manufacturers qualification for novel/FOAK components</td>
</tr>
<tr>
<td>19</td>
<td>Procurement</td>
<td>o Potential for simplified supply chain due to the smaller components and enhanced standardization</td>
<td>❖ Untested, no complete case as yet ❖ need to ensure: suppliers can provide novel system, equipment and services specific for SMRs</td>
</tr>
</tbody>
</table>
Identified R&D needs for SMRs

- Human factor engineering, control room staffing and operational procedures for multi-module SMRs plant
- Core flow stability for natural circulation iPWR based SMRs
- Reliability, Uncertainty and Sensitivity Analyses for integrated Control Rod Drive Mechanism in iPWRs
- Hybrid engineered safety system development for iPWR type SMRs
- PSA for a multi-module SMR Plants considering Common Cause Failures
<table>
<thead>
<tr>
<th>Advantages</th>
<th>Issues and Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Shorter construction period (modularization)</td>
<td>• Licensability (first-of-a-kind structure, systems and components)</td>
</tr>
<tr>
<td>• Potential for enhanced safety and reliability</td>
<td>• Non-LWR technologies</td>
</tr>
<tr>
<td>• Design simplicity</td>
<td>• Operability and Maintainability</td>
</tr>
<tr>
<td>• Suitability for non-electric application (desalination, etc.).</td>
<td>• Staffing for multi-module plant; Human factor engineering;</td>
</tr>
<tr>
<td>• Replacement for aging fossil plants, reducing GHG emissions</td>
<td>• Supply Chain for multi-modules</td>
</tr>
<tr>
<td></td>
<td>• Advanced R&amp;D needs</td>
</tr>
<tr>
<td>Non-Techno Issues</td>
<td></td>
</tr>
<tr>
<td>• Fitness for smaller electricity grids</td>
<td>• Economic competitiveness</td>
</tr>
<tr>
<td>• Options to match demand growth by incremental capacity increase</td>
<td>• Plant cost estimate</td>
</tr>
<tr>
<td>• Site flexibility</td>
<td>• Regulatory infrastructure</td>
</tr>
<tr>
<td>• Reduced emergency planning zone</td>
<td>• Availability of design for newcomers</td>
</tr>
<tr>
<td>• Lower upfront capital cost (better affordability)</td>
<td>• Physical Security</td>
</tr>
<tr>
<td>• Easier financing scheme</td>
<td>• Post Fukushima action items on institutional issues and public acceptance</td>
</tr>
</tbody>
</table>
Prospects of SMR for Asia Pacific Region
Potential for Southeast Asia:
(1) Developing an Integrated Regional Energy Market; (2) Transitioning to a Low Carbon Economy; (3) Synergy of renewables with small nuclear reactors for remote regions and small islands.
Total Primary Energy Demand and GDP in selected Southeast Asian countries, 1971-2013

Source: Southeast Asia Energy Outlook, OECD/IEA 2015

Note: Mtoe = million tonnes of oil equivalent.
Case: SMR for Saudi Arabia

Source: K.A.CARE Presentation at the IAEA’s 59th General Conference Side Event on SMR Deployment

- Bilateral nuclear cooperation agreement signed between governments of Saudi Arabia and Republic of Korea in November 2011
- Pre-Project Engineering for 2x100 MWe SMART plant construction
- An on-going cooperation between K.A.CARE and KAERI; MoU signed in September 2015
- Desire for full IP ownership of NSSS technology
- Future SMR export market in MENA
- Nuclear cogeneration for remote cities & industry
- Coastal and inland SMR site availability

Gradual Offsetting of Fossil 50% by 2040

Day-night load variation for Saudi Arabia
Case: SMR for Indonesia

Through an open-bidding, an experimental HTR-type SMR was selected in March 2015 for a basic design work aiming for a deployment in 2024 – 2025.

Time constraint for land acquisition and licensing.

Site: National R&D Complex in Serpong where 30 MW(th) in operation

BATAN works with the regulatory body on licensing

Potential SMR for cogeneration, i.e. for mineral processing following 2014 ban on export of unprocessed minerals. To be promoted as international project.
Elements to Facilitate Deployment

Design Development and Deployment Issues

Average Ranking

1. SMRs with lower generating cost
2. SMRs inexpensive to build and operate
3. SMRs with flexibility for cogeneration
4. SMRs with automated operation feature
5. Passive safety systems
6. SMRs with enhanced proliferation resistance
7. Multi-modules SMR deployment
8. Build-Own-Operate project scheme
9. Transportable SMRs with sealed-fueled
10. Modification to regulatory, licensing

Average Ranking (1 is Most Important)
NEW: integral PWR Simulator

- Integral PWR
- 14 Systems Simulated
  - Primary Systems
  - Secondary Systems
  - Tertiary Systems

Main Thermohydraulic parameters:
- Reactor thermal power ~ 150 MW
- Electrical power ~ 45 MWe
- PZR pressure ~ 15.5 MPa

Passive safety
- Automatic Depressurisation system (ADS)
- Pressure Injection system (PIS)
- Gravity Injection system (GIS)
- Passive heat removal system (PDHR)

For SMR simulator training, contact: Chirayu.Batra@iaea.org
Multiple interactive screens

For SMR simulator training, contact: Chirayu.Batra@iaea.org

Summary

- IAEA is engaged to support Member States in SMR Technology Development and has started addressing challenges in applying Design Safety Requirements for NPPs to SMRs.

- SMR is an attractive option to enhance energy supply security:
  - In newcomer countries with smaller grids and less-developed infrastructure.
  - In advanced countries for power supplies in remote areas and/or specific applications.

- Innovative SMR concepts have common technology development challenges, including regulatory and licensing frameworks.

- Studies needed to evaluate the potential benefits of deploying SMRs in grid systems that contain large percentages of renewable energy.

- Studies needed to assess “design standardization” and “target costs” in cogeneration markets, the benefits from coupling with renewables to stabilize the power grid, and impacts on sustainability measures from deployment.
Thank you!

For inquiries on SMR, please contact:
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