2022 IAEA SMR ARIS Booklet on Advances in SMR Technology Developments

Hadid Subki
Technical Lead, SMR Technology Development
Nuclear Power Technology Development Section

Technical Officer for 2022 Booklet:
Yaolei ZOU, Y.Zou@iaea.org
Nuclear Power Technology Development Section
Division of Nuclear Power, Department of Nuclear Energy
OUTLINE

- Characteristics and Attributes of SMR
  - Major SMR technology lines
  - Key attributes
  - Salient design characteristics

- Advances on SMR Technology
  - Global map of development
  - Deployment horizon & Stage of development
  - Designs of each category
  - Examples of Fuel Cycle Approach and Waste Management Plan adopted by SMR Designs
Small Modular Reactors (SMRs)

Advanced Reactors that produce typically up to 300 MWe, built in factories and transported as Modules to sites for Installation as demand arises.

**Large, Conventional Reactor**: 700+ MW(e)

**Small Modular Reactor**: Up to 300 MW(e)

**Microreactor**: Up to ~10 MW(e)

**Small**: in size, comparing to traditional reactors.

**Modular**: factory-manufactured, installed onsite.

**Reactor**: energy generation via nuclear fission.
Key attributes of SMRs

- Enhanced Safety
- Versatile
- Modular
- Reduced Waste
- Affordable
- Non-electric 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**

**Potential Hybrid Energy System**

**Better Affordability**
- Shorter construction time

**Wider range of Users**
- Site flexibility
- Reduced CO₂ production

**Integration with Renewables**

**Enhanced Safety**

**Versatile**

**Modular**

**Reduced Waste**

**Affordable**

**Non-electric applications**

**Reduced**

**Waste**

**Affordable**

**Non-electric applications**

**Potential Hybrid Energy System**

**Integration with Renewables**
Major SMR technology lines

Water-cooled SMRs

- WCR (land based) type
- WCR (marine based) type
- HTGR type
- MSR type
- LMFR type
- Microreactor

Microreactor (U.S. DOE Glossary)

**Compact reactors** that will be small enough to transport by truck and could help solve energy challenges in a number of areas. They are capable of producing 1-20 Megawatts of thermal energy used directly as heat or converted to electric power.

Ref: [What is a Nuclear Microreactor? | Department of Energy](https://www.energy.gov/nuclear-technology-center/what-is-nuclear-microreactor)

Other Descriptions of Microreactor

1. A subset of small modular reactors of 1-20 MWe capacity;
2. Advanced reactors of power up to 10MWe, **with common features** including modularity, passive safety, flexibility, simpler designs, more factory-based manufacturing possibilities, reduced site construction time and easier and more cost-effective reproduction, etc.

Notes: Commonly seen but lacking consensus.
The 2022 IAEA SMR ARIS Booklet is a biennial publication as a supplement to the IAEA Advanced Reactor Information System (ARIS) Database. It provides a brief yet comprehensive design description of 83 different reactor designs. The 2022 version is an updated version of the 2020 booklet. It includes 11 more designs and a more comprehensive set of annexes.
Design development phases

I. Conceptual Design
   - Basic idea and goal described
   - A few calculations/sketches/data
   - Development and test needs identified
   - Rough estimates of costs and schedules

II. Conceptual Design
   - Key components and layout drawings
   - Single line diagrams
   - Brief description of key components and systems
   - Identification and preliminary analysis of concept relevant incidents and accidents

III. Basic Design
   - System descriptions for all plant systems
   - Safety analyses needed for a design approval completed
   - Licensing documents for certification
   - Procurement specifications and documentation for major components, systems, and structures
   - Itemized cost estimate and master schedule prepared

IV. Detailed Design
   - Largely completed design, complete construction schedule
   - Manufacturing, procurement specs
   - Commissioning specifications
   - Control of infrastructure (transportation routes, etc.)
   - Local cooling arrangement
   - Adjustments to adapt to site conditions
   - Final safety analysis

V. Site-specific Design & Engineering

Phases and corresponding activities during design development

Ref.: IAEA-TECDOC-936 Terms for Describing New, Advanced Nuclear Power Plants
Stage of development or deployment of SMRs
Stage of development or deployment of SMRs

The Forerunners: 2 in operation, 3 under construction. More target at deployment by 2030

KLT-40S grid connection in Dec. 2019
HTR-PM grid connection in Dec. 2021

(Planned) Connection to the Grid
### Power range of SMRs of each category

<table>
<thead>
<tr>
<th>Power range (MW(e))</th>
<th>Water-cooled reactors (land-based)</th>
</tr>
</thead>
</table>
| 301 - 450           | • IMR  
                     • Rolls-Royce SMR |
| 201 - 300           | • Westinghouse SMR  
                     • VK-300  
                     • BWRX-300  
                     • CANDU SMR |
| 151 - 200           | • SMR-160  
                     • NUWARD  
                     • i-SMR  
                     • mPower  
                     • CAP200 |
| 101 - 150           | • SMART  
                     • DHR400  
                     • ACP100 |
| 31 - 100            | • KARAT-45  
                     • RITM-200N  
                     • HAPPY200  
                     • NHR200-II  
                     • VOYGR  
                     • KARAT-100 |
| 10 - 30             | • STAR  
                     • TEPLITOR  
                     • RUTA-70  
                     • OPEN20  
                     • CAREM25 |
## Power range of SMRs of each category

<table>
<thead>
<tr>
<th>Power range MW(e)</th>
<th>Reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td>251 - 300</td>
<td>EM², SC-HTGR, GT-MHR</td>
</tr>
<tr>
<td>201 - 250</td>
<td>MHR-T, HTR-PM (2 units)</td>
</tr>
<tr>
<td>51 - 200</td>
<td>Xe-100, GTHTR300, PBMR-400</td>
</tr>
<tr>
<td>15 - 50</td>
<td>MHR-100, AHTR-100, HTMR100, FMR</td>
</tr>
<tr>
<td>&lt; 15</td>
<td>STARCORE, JIMMY, Test reactors: HTR-10, HTTR-30, PeLUIt/RDE</td>
</tr>
</tbody>
</table>

High temperature gas-cooled reactors
## Specific characteristics and applications of microreactors

- Inherent and passive safety features
- Substantially lower upfront capital costs
- Much smaller footprints, reduced-sized or even eliminated EPZ
- Rapid deployability from modularity (even an entire reactor)
- Spent fuel smaller in size (probably easier to manage)
- Scalability, Resiliency, Self-regulating
- Potential to operate in island-mode & to black-start
- High transportability from mobility
- Long refueling interval

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powering secure micro-grids</td>
<td>Powering remote off-grid areas</td>
</tr>
<tr>
<td>for critical infrastructure</td>
<td>Seawater desalination</td>
</tr>
<tr>
<td>Restoring power quickly</td>
<td>Space: powering spacecraft, supporting manned exploration</td>
</tr>
<tr>
<td>Naval: powering nuclear submarines and UUV</td>
<td>Remote mining operations: offer reliable power source</td>
</tr>
<tr>
<td>Replacement for diesel gensets</td>
<td>Hydrogen production: feasible for HTGR type</td>
</tr>
<tr>
<td>Integration with renewables: e.g. integrating solar panels</td>
<td></td>
</tr>
</tbody>
</table>
### Power range of SMRs of each category

<table>
<thead>
<tr>
<th>Power range MW(e)</th>
<th>Reactors</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 10</td>
<td></td>
<td>HOLOS-QUAD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LFR-TL-30</td>
</tr>
<tr>
<td>5 - 9</td>
<td></td>
<td>MMR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>UNITHERM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Energy Well</td>
</tr>
<tr>
<td>2 - 4</td>
<td></td>
<td>Westinghouse eVinci</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MoveluX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>U-Battery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMR</td>
</tr>
<tr>
<td>&lt; 2</td>
<td></td>
<td>MARVEL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ELENA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AURORA</td>
</tr>
</tbody>
</table>

Microreactors
## Comparison of Main Characteristics among Some HTGR-type SMR Designs

<table>
<thead>
<tr>
<th>Country of Origin</th>
<th>HTR-PM</th>
<th>GTHTR300</th>
<th>GT-MHR</th>
<th>HTMR100</th>
<th>Xe-100</th>
<th>SC-HTGR</th>
<th>EM²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design organization(s)</td>
<td>INET, Tsinghua University</td>
<td>JAEA</td>
<td>JSC “Afrikantov OKBM”</td>
<td>STL Nuclear (Pty) Ltd.</td>
<td>X-energy, LLC</td>
<td>Framatome Inc.</td>
<td>General Atomics</td>
</tr>
<tr>
<td>Reactor type</td>
<td>Modular pebble bed HTGR</td>
<td>Prismatic HTGR</td>
<td>Modular Helium Reactor</td>
<td>Pebble-bed HTGR</td>
<td>Modular HTGR</td>
<td>Prismatic HTGR</td>
<td>Modular high temperature gas-cooled fast reactor</td>
</tr>
<tr>
<td>Fuel materials</td>
<td>TRISO spherical elements with coated particle fuel</td>
<td>UO₂ TRISO ceramic coated particle</td>
<td>Coated particle fuel in compacts, hexagonal prism graphite blocks</td>
<td>TRISO particles in pebbles; LEU/Th</td>
<td>UCO TRISO/pebbles</td>
<td>UCO TRISO particle fuel in hexagonal graphite blocks</td>
<td>UC pellet / hexagon</td>
</tr>
<tr>
<td>Coolant</td>
<td>Helium</td>
<td>Helium</td>
<td>Helium</td>
<td>Helium</td>
<td>Helium</td>
<td>Helium</td>
<td>Helium</td>
</tr>
<tr>
<td>Moderator</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
<td>N/A</td>
</tr>
<tr>
<td>Thermal output, MW(t)</td>
<td>2 x 250</td>
<td>&lt; 600</td>
<td>600</td>
<td>100</td>
<td>200</td>
<td>625</td>
<td>500</td>
</tr>
<tr>
<td>Electrical output, MW(e)</td>
<td>210</td>
<td>100 - 300</td>
<td>288</td>
<td>35</td>
<td>82.5</td>
<td>272</td>
<td>265</td>
</tr>
<tr>
<td>Core inlet temp., °C</td>
<td>250</td>
<td>587 - 633</td>
<td>490</td>
<td>250</td>
<td>260</td>
<td>325</td>
<td>550</td>
</tr>
<tr>
<td>Core outlet temp., °C</td>
<td>750</td>
<td>850 - 950</td>
<td>850</td>
<td>750</td>
<td>750</td>
<td>750</td>
<td>850</td>
</tr>
<tr>
<td>Enrichment, %</td>
<td>8.5</td>
<td>14</td>
<td>14-18% LEU or WPu</td>
<td>10%</td>
<td>15.5</td>
<td>14.5 (avg)</td>
<td>~14.5 (LEU)</td>
</tr>
<tr>
<td>Core Discharge Burnup (GWD/ton)</td>
<td>90</td>
<td>120</td>
<td>100-720 (depends on fuel type)</td>
<td>80 - 90</td>
<td>165</td>
<td>165</td>
<td>~130</td>
</tr>
<tr>
<td>Refuelling cycle, months</td>
<td>Online refuelling</td>
<td>48</td>
<td>25</td>
<td>Online fuel loading</td>
<td>Online fuel loading</td>
<td>½ core replaced every 18 months</td>
<td>360</td>
</tr>
<tr>
<td>Reactivity control</td>
<td>Control rods</td>
<td>Control rods</td>
<td>Control rods</td>
<td>Control rods in the reflector</td>
<td>Control rods</td>
<td>Control rods</td>
<td>Control rods</td>
</tr>
<tr>
<td>Reactor Vessel’s height/diameter, (m)</td>
<td>25 / 5.7 (inner)</td>
<td>23 / 8</td>
<td>29 / 8.2</td>
<td>15.7 / 5.6</td>
<td>16.4 / 4.88</td>
<td>24 / 8.5</td>
<td>12.5 / 4.6</td>
</tr>
<tr>
<td>Design status</td>
<td>In operation</td>
<td>Basic design</td>
<td>Preliminary Design completed</td>
<td>Basic Design</td>
<td>Basic Design</td>
<td>Preliminary Design</td>
<td>Conceptual design</td>
</tr>
</tbody>
</table>
Fuel Cycle Approach adopted by HTGR-type SMRs

- Open fuel cycle: The majority.
  
e.g., HTR-PM will adopt close fuel cycle in the future.

- Longer refuelling cycle, e.g., GTHTR300, GT-MHR

- Fuel enrichment: all in the range of (5 – 19.75)%

- Use of Th cycle and/or Disposition of Pu: e.g., GTHTR300 (applicable), MHR-100 (possible), PBMR®-400 (flexible), EM² (capable).

- Use of Spent Fuel as Fuel: e.g., GTHTR300 (applicable), EM2 (feasible)
Volume Reduction and Conditioning:
Coated particle separation from graphite will reduce volume by up to a factor of 100.

Waste Processing:
- Low and intermediate level waste from plant operation will be conditioned by different process technologies.
  - Possible graphite recycling, $^{14}$C separation process

Storage Approach, Spent Fuel Pool Cooling Mechanism:
- With higher thermal efficiencies the radiotoxicity and decay heat will be lessened by 50% for HTGRs as compared to LWRs.
  - Dry storage with natural convection after short material active cooling.
  - Facilities for long-term storage of spent fuel and solid radwaste are in the NPP complex

Spent Fuel Take-back Option: to date not considered in HTGRs.
Thank you for your attention!

For inquiries, please contact: Small Modular Reactor Technology Development Team
IAEA Division of Nuclear Power, Nuclear Power Technology Development Section
E-mail: SMR@iaea.org