Innovative Nuclear Systems as a Solution to Small Scale Nuclear Energy

Hadid Subki
Nuclear Power Technology Development Section, Division of Nuclear Power
Outline

Motivation and driving forces

Advanced Small Reactors with Major Coolant Types

Near Term Deployable Small Generation IV Reactors

Application of Gen IV Reactors for Small Scale Energy Systems

Perceived advantages and potential challenges

Emergency Planning Zone for Small Gen IV reactors

Summary

www.IAEA.org/NuclearPower/Technology/
Motivation – Driving Forces of SMRs

Scalability of Power

Enhanced Safety

Modularity, Constructability

Flexibility of Utilization

Images courtesy of US-DOE, NuScale, KAERI, CNEA, mPower & CNNC
Advanced Small Reactors of Major Coolant Types

Samples for land-based SMRs

- Water cooled SMRs
  - CAREM
  - SMART
  - ACP100
  - NuScale

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

- Liquid metal cooled SMRs
  - PFBR
  - PRISM
  - SVBR
  - 4S

- Land-based, marine-based, and factory fuelled transportable SMRs
- Estimated power limit to be modular/transportable ≤ 180 MW(e)
Small Generation IV reactors (Examples)

### PRISM
**Fuel Cycle:** 30 years
- 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

**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**
- 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**
- 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]
## Small Generation IV reactors (Examples)

<table>
<thead>
<tr>
<th></th>
<th>PRISM</th>
<th>4S</th>
<th>SVBR 100</th>
<th>Integral MSR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Full name</strong></td>
<td>Power Reactor Innovative Small Mod.</td>
<td>Super-Safe, Small &amp; Simple</td>
<td>Lead-Bismuth Eutectic Fast Reactor</td>
<td>Integral Molten Salt Reactor</td>
</tr>
<tr>
<td><strong>Designer</strong></td>
<td>GE Hitachi Nuclear Energy USA</td>
<td>TOSHIBA, CRIEPI JAPAN</td>
<td>JSC AKME Engineering RUSSIAN Federation</td>
<td>Terrestrial Energy CANADA</td>
</tr>
<tr>
<td><strong>Reactor type</strong></td>
<td>Liquid metal cooled fast breeder reactor</td>
<td>Liquid metal-cooled fast reactor</td>
<td>Liquid metal cooled fast reactor</td>
<td>Molten Salt cooled reactor</td>
</tr>
<tr>
<td><strong>Thermal power</strong></td>
<td>840 MW</td>
<td>30 MW</td>
<td>280 MW</td>
<td>(80~600) MW</td>
</tr>
<tr>
<td><strong>Electrical power</strong></td>
<td>311 MW</td>
<td>10 MW</td>
<td>101 MW</td>
<td>(32~240) MW</td>
</tr>
<tr>
<td><strong>Coolant</strong></td>
<td>Sodium</td>
<td>Sodium</td>
<td>Lead-Bismuth</td>
<td>Molten Salt</td>
</tr>
<tr>
<td><strong>Sys. Pressure</strong></td>
<td>Low pressure</td>
<td>Non pressurized</td>
<td>6.7 MPa</td>
<td>Atmospheric pressure</td>
</tr>
<tr>
<td><strong>Sys. Temp.</strong></td>
<td>485°C</td>
<td>510°C</td>
<td>490°C</td>
<td>700°C</td>
</tr>
<tr>
<td><strong>Key features</strong></td>
<td>Uses heterogeneous metal alloy core</td>
<td>Indirect Rankine cycle</td>
<td>Indirect Rankine Cycle, Passive safety</td>
<td>Indirect Rankine Cycle, Passive safety</td>
</tr>
</tbody>
</table>
## Electric Capacity additions and required investment
### 2011 – 2035

<table>
<thead>
<tr>
<th>Regions</th>
<th>Capacity addition, GWe</th>
<th>Power generation investment, billion $</th>
<th>Transmission &amp; Distribution investment, billion $</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>880</td>
<td>1,738</td>
<td>1,271</td>
</tr>
<tr>
<td>Europa</td>
<td>938</td>
<td>1,976</td>
<td>915</td>
</tr>
<tr>
<td>East Europe, Eurasia</td>
<td>331</td>
<td>588</td>
<td>442</td>
</tr>
<tr>
<td>Asia</td>
<td>2,893</td>
<td>4,106</td>
<td>3,486</td>
</tr>
<tr>
<td>Other</td>
<td>854</td>
<td>1,383</td>
<td>978</td>
</tr>
<tr>
<td>World total</td>
<td>5,986</td>
<td>9,791</td>
<td>7,092</td>
</tr>
</tbody>
</table>

Asia has the largest capacity addition in the next 2 decades - that requires the largest investment for transmission and distribution

Application of **Hybrid Energy System of SMRs** with Cogeneration and Renewable Energy Sources

Regional Biomass (80 Km radius or ~2 million hectares)

Variable Electricity ►

Dynamic Energy Switching

Max Output of 1061 MWe to the power GRID ►►

Offsetting SMR ▲

Nuclear reactor 347 MWe (755 MWth)

Variable Electricity

Reactor Heat

Regional Biomass

1,000,000 t/DM/yr

104 GWh heat at 200°C

1169 GWh heat at 500°C

Drying and Torrefaction Processes

Torrified Product

+ Pyrolysis

Pyrolyzed oil + char + offgas

+Synfuel Production

753 m³/day bio-diesel

597 m³/day bio-gasoline

Hydrogen Electrolysis

42,000 t H₂/yr

IAEA

• **Full name**: Super-Safe, Small and Simple
• **Designer**: Toshiba Corporation, Japan
• **Reactor type**: Liquid Sodium cooled, Fast Reactor – but not a breeder reactor
• **Neutron Spectrum**: Fast Neutrons
• **Thermal/Electrical Capacity**: 30 MW(t)/10 MW(e)
• **Fuel Cycle**: without on-site refueling with core lifetime ~30 years. Movable reflector surrounding core gradually moves, compensating burn-up reactivity loss over 30 years.
• **Salient Features**: power can be controlled by the water/steam system without affecting the core operation
• **Design status**: Detailed Design
4S for Small Scale Nuclear Systems

- **Independent 4S System (base applications)**
  - Electricity/heat supply for remote area community
  - Electricity supply for mining site
  - Hot steam supply for oil sands/oil shale recovery
  - Electricity supply for seawater desalination
  - Electricity/heat supply for hydrogen production

- **Hybrid System by Combination of 4S, Smart Grid and Energy Storage System**
  - Flexible energy supply for remote area
  - Secured energy supply for "critical" area
  - Electricity/heat/water/hydrogen supply as a social infrastructure
Current electricity price at Nunavut Communities in Canada
$0.39 - $0.94 per kwh

(Doyon, Limited Report, January, 2009)
Hybrid System (4S + Smart Grid + Energy Storage)

Community
- electricity
- heat
- water

Smart Grid
- electricity
- heat

Transportation
- Hydrogen
- Energy Storage

Desalination
- 4S
- IAEA

Image Courtesy of TOSHIBA, Japan
SVBR-100

- **Designer:** JSC AKME Engineering – Russian Federation
- **Reactor type:** Liquid metal cooled fast reactor
- **Coolant/Moderator:** Lead-bismuth
- **System temperature:** 500°C
- **Neutron Spectrum:** Fast Neutrons
- **Thermal/Electric capacity:** 280 MW(t) / 101 MW(e)
- **Fuel Cycle:** 7 – 8 years
- **Fuel enrichment:** 16.3%
- **Distinguishing Features:** Closed nuclear fuel cycle with mixed oxide uranium plutonium fuel, operation in a fuel self-sufficient mode
- **Design status:** Detailed design
Regional Co-Generation Plant with SVBR

- Gradual construction of regional small and medium NPPs
- 100, 200, ... to 600 MWe
- Located close to cities and energy-intensive industries;
- sites in developing countries with small grids for transmission and distribution
- remote areas, island locations, etc.

<table>
<thead>
<tr>
<th>Example of possible Location</th>
<th>Industry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction of terminals, port “Taman&quot; (Krasnodarsky region)</td>
<td>Transportation</td>
</tr>
<tr>
<td>Oil and gas and chemical complex (Primorsky kray.)</td>
<td>Oil &amp; Gas</td>
</tr>
<tr>
<td>Zheleznorudniy Ore Mining and Processing Industrial Complex (Buryatiya)</td>
<td>Metal industry</td>
</tr>
<tr>
<td>“Peschanka” gold-copper field development (Chukotsky region)</td>
<td>Mining</td>
</tr>
</tbody>
</table>

Small Scale Nuclear System for Coastal Desalination

Comprising 2 types of onshore desalination plants: multi-layered distillation and reverse osmosis, due to flexibility and efficiency to operate in co-generation mode.

Example of an onshore desalination complex
Max. output – 200 000 tons/day per 1 unit

Image Courtesy of AKME Engineering, Russian Federation
**PRISM**

- **Full name**: Power Reactor Innovative Small Modular
- **Designer**: GE Hitachi, USA
- **Reactor type**: Liquid Sodium cooled, Fast Breeder Reactor
- **Neutron Spectrum**: Fast Neutrons
- **Thermal/Electrical Capacity**: 840 MW(t)/ 311 MW(e)
- **Fuel Cycle**: 18 months
- **Salient Features**: Underground containment on seismic isolators with a passive air cooling ultimate heat sink; recycling center for plutonium and spent nuclear fuel

© 2015 GE Hitachi Nuclear Energy

Image Courtesy of GE Hitachi, USA
PRISM for Recycling Used LWR Fuel

Benefits include:
- ‘Short’-term Waste: ~300 years versus 10,000+*
- Smaller repository
- Uranium energy: extracts 90%
- Non-proliferation: no plutonium separation
- Environmentally responsible: dry process

* Time to reach the same level of radiotoxicity as natural uranium
• **Full name**: Integral Molten Salt Reactor
• **Designer**: Terrestrial Energy, Canada
• **Reactor type**: Molten Salt
• **Neutron Spectrum**: Thermal Neutrons
• **Thermal/Electrical Capacity**: 80, 300 and 600 MW(th)
• **Fuel Cycle**: 18 months
• **Salient Features**: Underground containment on seismic isolators with a passive air cooling ultimate heat sink; recycling center for plutonium and spent nuclear fuel
I-MSR for Small Scale Energy System

- Electricity generation
- Process heat application
- Burner of LEU: MSR-Burner
- Thorium breeder: MSR-Breeder
- Utilization of plutonium from existing spent nuclear fuel as their makeup fuel source

System for consuming existing transuranic wastes

Image Courtesy of Terrestrial Energy, Canada
## Perceived Advantages & Potential Challenges

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology Issues</strong></td>
<td></td>
</tr>
<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>• Post Fukushima action items on design, safety, security and licensing</td>
</tr>
<tr>
<td><strong>Non-Techno Issues</strong></td>
<td>• Advanced R&amp;D needs</td>
</tr>
<tr>
<td>• Fitness for smaller electricity grids</td>
<td></td>
</tr>
<tr>
<td>• Options to match demand growth by incremental capacity increase</td>
<td>• Economic competitiveness</td>
</tr>
<tr>
<td>• Site flexibility → Smaller footprint</td>
<td>• Plant cost estimate</td>
</tr>
<tr>
<td>• Reduced emergency planning zone</td>
<td>• Regulatory infrastructure</td>
</tr>
<tr>
<td>• Lower upfront capital cost (better affordability)</td>
<td>• Availability of design for newcomers</td>
</tr>
<tr>
<td>• Easier financing scheme</td>
<td>• Post Fukushima action items on institutional issues and public acceptance</td>
</tr>
</tbody>
</table>
Risk-Informed approach and EPZ reduction

- Risk-Informed approach to “No (or reduced) Emergency Planning Zone”
  - Elimination or substantial reduction (NPP fences) of the Emergency Planning Zone
  - New procedure developed: Deterministic + Probabilistic needed to evaluate EPZ (function of radiation dose limit and NPP safety level)
- Procedure developed within a IAEA CRP: discussed with NRC
IAEA is engaged in SMR Deployment Issues

Twelve countries developing ~50 SMR designs with different time scales of deployment and 3 units are under construction (CAREM25, HTR-PM, KLT-40s)

Commercial availability and operating experience in vendors’ countries is key to embarking country adoption

Countries understand the potential benefits of SMRs, but support needed to assess the specific technology and customize to their own circumstances

Indicators of future international deployment show positive potential
… Thank you for your attention.

For inquiries, please contact:
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