Small Modular Reactors: A Call for Action

Overview of Five SMR Designs

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## Current Water-Cooled SMR Designs

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Type</th>
<th>Power, MWe</th>
<th>Country</th>
<th>Vendor</th>
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<tbody>
<tr>
<td>CAP-100</td>
<td>PWR</td>
<td>100</td>
<td>China</td>
<td>CNNC</td>
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<tr>
<td>CAREM</td>
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<td>27-100</td>
<td>Argentina</td>
<td>CNEA</td>
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<td>FLEXBLUE</td>
<td>PWR</td>
<td>160</td>
<td>France</td>
<td>DCNS</td>
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<tr>
<td>KLT-40S</td>
<td>PWR</td>
<td>35</td>
<td>Russia</td>
<td>OKBM</td>
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<td>mPower</td>
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<td>B&amp;W</td>
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<td>NuScale Power</td>
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<tr>
<td>SMART</td>
<td>PWR</td>
<td>100</td>
<td>Korea</td>
<td>KAERI</td>
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<td>PWR</td>
<td>160</td>
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<td>Holtec</td>
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<tr>
<td>W-SMR</td>
<td>PWR</td>
<td>225</td>
<td>USA</td>
<td>Westinghouse</td>
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</tbody>
</table>

- Today, there are over 40 SMR designs in total in various stages of development worldwide
- Development is advanced for 17 of these: 10 light water reactors, 3 high temperature reactors, 4 fast reactors
# Selected SMR Design Parameters

<table>
<thead>
<tr>
<th>Reactor</th>
<th># Fuel Assemblies</th>
<th># Control Rod Drive Mechanisms</th>
<th>RCS Circulation</th>
<th>Chemical Shim</th>
<th>Fuel Cycle Length, yrs</th>
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</thead>
<tbody>
<tr>
<td>mPower</td>
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<td>69</td>
<td>Forced</td>
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<tr>
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<td>16</td>
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<tr>
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<tr>
<td>SMR-160</td>
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<td>37</td>
<td>Natural</td>
<td>No</td>
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<tr>
<td>W-SMR</td>
<td>89</td>
<td>37</td>
<td>Forced</td>
<td>Yes</td>
<td>2</td>
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</tbody>
</table>

- All designs use standard 17x17 PWR fuel
- All designs have 60-year design life
Generation mPower SMR
mPower Primary System

- Internal control rod drive mechanisms (CRDM)
- Canned rotor pumps (8 total)
- Once-through steam generators
- Lowest penetration is 23 ft. above top of active fuel
- Full core replacement used to achieve 4 year operating cycle

- Shortened fuel assembly (compared to commercial fuel)
- Axial graded burnable poison rods (Gd2O3 mixed with UO2)
- Control rods are aluminum carbide and B4C
mPower
Enhanced Physical Protection

- Low profile architecture (improved seismic response)
- Underground containment (more robust against external events)
- Enhanced security (from external threats)
- Underground spent fuel pool (greater integrity)

“Twin-pack” Configuration

- All safety systems underground – water tight and isolated from the environment
- No shared safety systems between units
- Spent fuel pool has 30 days coping time
- 20-year storage capacity
mPower Safety Systems

- Passive core cooling (AC power not required for safety function)
- Emergency core cooling by gravity feed
- Core remains covered during all postulated accidents
- 14 day coping time under station blackout
- 72 hour safety-related control/monitoring batteries
- 30 day+ boil off for Spent Fuel Pool
• Conventional steam cycle components
• Air-cooled condenser possible (at expense of efficiency and higher capital cost)
• One-to-one reactor to turbine-generator alignment
• 50 degree superheat in secondary
NuScale Power SMR
NuScale Primary System

- Fuel is 17x17 about 6 feet in height; design uses full core replacement with 2-year cycle at 4.95% U235 enrichment
- Standard external magnetic jack CRDMs
- Reactor Pressure Vessel is ~61 feet in height and ~9 feet in diameter
- Containment is 76 feet in height and 15 feet in diameter
- Steam Generators are 2 once-through helical-coil design with superheat
- CVCS used to add heat to the reactor coolant during startup
NuScale Modular Design
12-module, 570 MWe NuScale Plant

- Multiple modules co-located at site to create mid-to-large-size plant
- Common pool for 12 reactor modules
- Each module installed in its own seismically isolated bay
- Six reactor modules planned for initial installation

- Each module refueled underwater while others continue to operate; target refueling time is 10 days
- Roof of structure is 77 feet above grade
- Top of concrete floor is 76 feet below grade

Reactor and containment are submerged in underground steel-lined concrete pool with sufficient water to support unlimited coping period.

Any hydrogen released is trapped in containment vessel with little to no oxygen available to create a combustible mixture.
NuScale Balance Of Plant Features

Each module has an independent BOP

- The turbine-generator set is skid-mounted
- One BOP for each module and at 50 Mwe each
NuScale Long-term Containment Cooling

- **NuScale module is 160 MWth**
- **At 1 second, the decay heat is approximately 7% of rated power**
NuScale 12 Module Control Room

- Notice 12 individual reactor stations and central plant station
- Currently envision 6 total staff: 3 reactor operators and 3 supervisors
- There is significant engagement ongoing with NRC staff (regarding application of its “NUREG-711” Human Factors Engineering Program Review Model) to determine appropriate staffing
Holtec SMR
SMR-160 Primary System

- Passive Boron Injection Tank
- Passive Water Make-up Tanks
- Passive Core Cooling Heat Exchanger
- Super Heater
- Steam Generator
- Pressurizer
- Elevation 0’
- Elevation -43’
- Elevation -105’
- Spent Fuel Pool
- Single-batch cartridge core

- Full core reload as a cartridge
- 37 Full Fuel Assemblies
- 14 foot high fuel
- Up to 8 different fuel assembly types
- 8 burnable absorber segments per fuel assembly
- 4.95 wt% fuel enrichment
- Reactor Control Rod Assemblies: Shutdown – 16, Reactivity Control – 17, Axial Shaping – 4
SMR-160 Reactor Coolant System

- No reactor coolant pumps
- Purely gravitational flow in all operating modes driven by heat generated in core
- No soluble boron in coolant
- “Black Start” capability*

*Black Start means no need for off-site power

- Steam generator and CRDMs are outside the Reactor Pressure Vessel (RPV)
- Steam generator is vertical, integrally connected to RPV
- Single stages of superheat in steam generator
SMR-160 Configuration in Containment

- Cavity around the RPV (reactor well) is flooded with water
- Containment diameter of 45 feet (relatively large diameter)
- Containment height of 196 feet
SMR-160 Enhanced Physical Protection

- Underground location of safety systems
- Double protection against crashing aircraft
- Immunity from external natural events
- Maximum protection from malevolent human intervention
SMR-16 Safety Systems

- Passive Core Cooling System (PCCS)
  - Uses submerged bundle steam generator in containment and air-cooled condenser outside of the containment

- Residual Heat Removal System (RHR)
  - Lower pressure system used for normal shutdown in conjunction with the PCCS

- High Pressure Core Injection System (HPCIS)
  - Injects borated water at high pressure

- Reactor Startup System
  - Heats up reactor after fresh core load; integrated with RHR

- Passive Spent Fuel (SFP) Cooling System
  - Similar to PCCS (lower capacity, lower operating temperature)
Westinghouse SMR
W-SMR Primary System

- **Stand alone unit – no shared systems**
- **8 foot active fuel length, compared to the normal 12 to 14 foot length of currently operating reactors**
- **RPV: 81 feet height, 11.5 feet OD, 280 tons upper vessel package (heaviest)**

- **Containment: 91 feet height, 32 feet OD, steel**
- **Containment is (1) high pressure (rated at 250 psig and operates at a partial vacuum to facilitate heat removal; (2) submerged in water; (3) fully modular and prefabricated**
- 8 external horizontal seal-less pumps driven by variable speed drives
- Steam generator (1 unit) is recirculating, once-through, straight tube
W-SMR Safety Systems

- No AC power required for 7 days for plant safety – capability to add inventory to Ultimate Heat Sink (UHS) tanks for indefinite cooling
- 100% reliance on natural forces: gravity, evaporation, and condensation
CMT provides diverse shutdown, passive decay heat removal, and RCS inventory addition

ICP provides cavity flooding and long term makeup to the RCS

ICP Tanks allow gravity injection into the RCS once depressurized

Ultimate Heat Sink provides passive decay heat removal via the CMT heat exchanger and inventory makeup to the OCP
W-SMR Balance Of Plant (steam drum for secondary inventory)

- Eliminates dryout ⇒ allows compact SGs within RPV
- Increases water inventory on secondary side ⇒ lengthens heat removal through SGs in loss of feedwater event

- W-SMR has an external steam drum
- Rest of BOP is standard Rankine steam cycle with option for air-cooled condenser
W-SMR Plant Layout

• Total plant embedment is 110 feet
Entire nuclear island is modular design using composite steel structures.

Modular design drives work normally completed at the construction site to the factory where quality is better controlled, overall cost are reduced and schedule certainty increased.

All modules are designed for road and rail transport to site and scalable to other forms of transport.
KAERI SMR
SMART Primary System

- 8 helical once-through SGs with 30 degrees C superheat
- 4 canned motor pumps
- Internal pressurizer
- 25 external magnetic jack type CRDM’s
- RPV: 6.5 m diameter and 18.5 m height
SMART Steam Generator

- Reactor coolant on shell side and feedwater on tube side
- 10 meters in height
- Some have been critical of the inspectability and maintainability of helical steam generators, but KAERI has performed eddy current tests to verify the inspectability of the design
• Notice all the traditional active safety systems
• Has a passive Residual Heat Removal System on secondary side of steam generators
SMART Safety Systems

- Passive Residual Heat Removal System (4 train)
  - Natural Circulation Cooling of SG from Secondary Side
  - Only need two trains operational to cool down the plant

- Safety Injection System (4 train active)
  - Direct Vessel Injection from IRWST

- Containment Spray System (2 train active)

- Shutdown Cooling System (2 train active)

  - 10 hour vital batteries
SMART Co-generation for Desalination

- Steam Transformer for isolation of potential radioactivity in secondary plant steam from desalinated water
- Steam is supplied from secondary plant turbine extraction

- 4 units of “Multiple Effect Distillation Process with Thermal Vapor Compression” (MED-TVC) supply 40,000 tons desalinated water
- The MED-TVC evaporator is basically an MED evaporator fitted with a thermocompressor. The purpose of the thermocompression of the vapor is to take advantage of the pressure of the available steam, when this pressure is sufficient (i.e. above 2 bar abs), to enhance the units' performance.