Design, Applications and Siting Requirements of CGN ACPR50(S)

China General Nuclear Power Corporation (CGN)
China Nuclear Power Technology Research Institute (CNPRI)
Oct, 2017
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<th>CONTENTS</th>
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<td>3</td>
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<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
</tbody>
</table>
01
Introduction
1.1 ACPR SMR Technology

ACPR: Advanced Customer-friendly Practicable Reliable

**ACPR50**: 60MWe compact SMR NPP. Applied to onshore, mainly utilized for power generation, heating and desalination of sea water.

**ACPR50S**: 50MWe compact SMR FNPP. Applied to offshore, carried by fixed or floating platform utilized for power generation, heating and desalination of sea water.
1.2 ACPR SMR Applications

**Onshore hybrid energy supply**
- Supply power, process steam for Industrial Park
- Distributed competitive energy supplier
- Central heating or cooling for city

**Offshore hybrid energy supply**
- Power supply for sea oil production
- Provide energy of electricity, freshwater, process heat and cooling for sea shore areas and islands

**ACPR50**

**ACPR50S**
02
LNPP with SMR  ACPR50
1.1 Project duration
1.2 Design features (1/5): Mature

Based on design experience and mature industrial supply chain of large PWR:

- Take mature large commercial PWR nuclear power plant as reference, “from large to small, from single application of power generation to hybrid applications”;
- Using compact layout reactor module and mature reliable technology and equipment in order to meet the requirements of regulations and standards;
- Mature nuclear power equipment manufacturing chain.
1.2 Design features (2/5): Compact

- Main components (RPV, SG, Pumps) are connected with pipe in pipe casing.

- Advantages:
  - Eliminating the large LOCA
  - Reducing the reactor module height
  - Benefiting for maintenance
  - Reducing containment volume
1.2 Design features (3/5) : Modularity

Flexible to meet user's power requirements; shortening the construction period.

- **Single module** : NSSS, including reactor coolant system, safety system, main nuclear auxiliary and containment;
- Power generation unit: Two reactor modules with one steam turbine;
- Independent safety module: Multiple modules are in safety injection system, but they are not affect each other;
- Modular installation: Shorten the construction period.
1.2 Design features (4/5): Safety

High level Safety

- Design Safety
- Passive Safety
- Inherent Safety
- Multiple Reactivity Barriers
- Very Low Reactivity Release Frequency
- No Off-site Emergency Measure

Severe accident mitigation: Containment flooded by water

5 barriers: Fuel pellet, Fuel canning, Primary loop, Containment, Water (Containment flooding)

Negative reactivity coefficient; Low linear power density;
Coolant natural circulation in accidents.

Residual heat removal depends on natural circulation.
Water (Containment flooding) and air is used as ultimate heat sink

SG joined to the RPV with pipe in pipe which largely reduces the frequency of LOCA.
1.2 Design features (5/5): Competitive costs

Integrated energy supplier, modularity, simplified systems and compact components.
### 1.3 Research & Development (1/4): Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal output (MWt)</td>
<td>200</td>
</tr>
<tr>
<td>Main steam pressure (MPa)</td>
<td>4.68</td>
</tr>
<tr>
<td>Electrical output (MWe)</td>
<td>~60</td>
</tr>
<tr>
<td>Inner diameter of RPV (m)</td>
<td>2.3</td>
</tr>
<tr>
<td>Primary loop pressure (MPa)</td>
<td>15.5</td>
</tr>
<tr>
<td>Generation efficiency</td>
<td>~30%</td>
</tr>
<tr>
<td>Fuel arrangement</td>
<td>17×17</td>
</tr>
<tr>
<td>RPV height (m)</td>
<td>7.2</td>
</tr>
<tr>
<td>Assembly number</td>
<td>37</td>
</tr>
<tr>
<td>Primary loop design pressure (MPa)</td>
<td>17.23</td>
</tr>
<tr>
<td>Burnable poison</td>
<td>Gd</td>
</tr>
<tr>
<td>Core coolant average temperature (°C)</td>
<td>310</td>
</tr>
<tr>
<td>CR material</td>
<td>Ag-In-Cd</td>
</tr>
<tr>
<td>Designed life (Year)</td>
<td>60</td>
</tr>
<tr>
<td>Fuel enrichment</td>
<td>&lt;5%</td>
</tr>
<tr>
<td>Average reload burnup of fuel assembly (MWd/tU)</td>
<td>≥40000</td>
</tr>
<tr>
<td>CDF (One core per year)</td>
<td>&lt;1.0×10^-7</td>
</tr>
<tr>
<td>LRF (One core per year)</td>
<td>&lt;1.0×10^-8</td>
</tr>
</tbody>
</table>
1.3 Research & Development(2/4): Reactor and Fuel Design

**Fuel assembly design**
- Shorten active zone height,
- Maintain lateral dimension parameters,
- Design verification: maximum burn up, hold-down assembly verification, plenum spring design verification, internal pressure design verification, axial clearance verification, rod drop time, accident condition.

**Fuel management**
- 37 fuel assemblies in core, 16 control rod assemblies
- Gd$_2$O$_3$ as burnable poison,
- Reload burnup of fuel assembly ≥40000MWd/tU

**Thermal-hydraulic design**
- WRB-1 correlation used to calculate DNBR
- DNBR margin>150%
1.3 Research & Development (3/4): System Design

- Residual heat removal depends on passive device. Water (Containment flooding) and air is used as ultimate heat sink

- Reactor coolant system
- Engineered Safety System
- Main nuclear auxiliary system
- Containment system
- Fuel handling and storage system
- CI systems
1.3 Research & Development (4/4): Main components Design

<table>
<thead>
<tr>
<th>Main component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main pump</td>
<td>Canned-motor pump/Wet Winding Motor RCP</td>
</tr>
<tr>
<td>OTSG</td>
<td>Helical-coiled tube OTSG</td>
</tr>
<tr>
<td>CRDM</td>
<td>Electromagnetic stepping CRDM of PWR with Spring mechanism</td>
</tr>
<tr>
<td>PRZ</td>
<td>Proven technology of PWR, optimal design, miniaturization</td>
</tr>
<tr>
<td>RPV</td>
<td>Proven technology of PWR, optimal design, miniaturization</td>
</tr>
<tr>
<td>Pipe in pipe</td>
<td>Pipe in pipe casing between main components</td>
</tr>
<tr>
<td>RVI</td>
<td>Proven technology of PWR, optimal design, miniaturization</td>
</tr>
</tbody>
</table>
1.4 Verification test (1/4)

**Thermal Hydraulic test and design platforms can satisfy the tests and design of ACPR50**

- SMR safety test platform (6 test facilities)
- SMR equipment and key technology test platform (4 test facilities)
- SMR wave condition test platform (2 test facilities for FNPP)

**Thermal-Hydraulic Test Lab. in Shenzhen**

**Design software**
### 1.4 Verification test (2/4)

The following tables shows some of the experimental plans.

<table>
<thead>
<tr>
<th>No.</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor &amp; equipment tests</td>
<td>Reactor integrated hydraulic simulation test</td>
</tr>
<tr>
<td></td>
<td>Fuel assembly structural mechanics test</td>
</tr>
<tr>
<td></td>
<td>Fuel assembly hydraulics test</td>
</tr>
<tr>
<td></td>
<td>Fuel assembly CHF test</td>
</tr>
<tr>
<td></td>
<td>Once-through steam generator (OTSG) principle test</td>
</tr>
<tr>
<td></td>
<td>OTSG spiral tube heat transfer and resistance test</td>
</tr>
<tr>
<td></td>
<td>Spiral tube OTSG prototype test</td>
</tr>
<tr>
<td></td>
<td>Control rod driving system test</td>
</tr>
<tr>
<td></td>
<td>Pipe in pipe sealing &amp; flow-induced vibration test</td>
</tr>
<tr>
<td></td>
<td>Main pump component test</td>
</tr>
<tr>
<td></td>
<td>Main pump two-phase characteristics test</td>
</tr>
<tr>
<td></td>
<td>……</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety system tests</td>
<td>Passive system test</td>
</tr>
<tr>
<td></td>
<td>Passive core direct vessel injection (DVI) test</td>
</tr>
<tr>
<td></td>
<td>In-vessel retention (IVR) engineering test</td>
</tr>
<tr>
<td></td>
<td>……</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>integral performance test</td>
<td>Compact SMR integral performance test</td>
</tr>
</tbody>
</table>
## 1.4 Verification test (3/4)

<table>
<thead>
<tr>
<th>No.</th>
<th>Experiments completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Once-through steam generator (OTSG) principle test</td>
</tr>
<tr>
<td>2</td>
<td>OTSG spiral tube heat transfer and resistance test</td>
</tr>
<tr>
<td>3</td>
<td>Passive safety system experiment</td>
</tr>
<tr>
<td>4</td>
<td>Natural circulation transient experiment</td>
</tr>
<tr>
<td>5</td>
<td>The principle experiment of the suppression pool</td>
</tr>
</tbody>
</table>
### 1.4 Verification test (4/4)

<table>
<thead>
<tr>
<th></th>
<th>On going experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Control rod driving system test</td>
</tr>
<tr>
<td>2</td>
<td>Overall performance of safety system test</td>
</tr>
<tr>
<td>3</td>
<td>Heat flux density of fuel critical test</td>
</tr>
<tr>
<td>4</td>
<td>Reactor integrated hydraulic simulation test</td>
</tr>
<tr>
<td>5</td>
<td>Reactor Vessel Internal flow-induced vibration test</td>
</tr>
<tr>
<td>6</td>
<td>Pipe in pipe seal test</td>
</tr>
</tbody>
</table>
1.5 Multi-Applications

**Scenarios 1: Electricity & Water**
Electricity is supplied to the local power grid, and heating is used for meds drinking water.

**Scenarios 2: Fresh water**
Used for the production of demand of households, and the heating is used for drinking water.

**Scenarios 3: Electricity & Refrigeration**
Electricity supply to the local grid, heating for lithium bromide absorption refrigeration and for ammonia absorption refrigeration.
### 1.5 Multi-Applications

<table>
<thead>
<tr>
<th>Output</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>370 million KWh/year</td>
<td>270 million KWh/year</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>370 million KWh/year</td>
</tr>
<tr>
<td></td>
<td>Drinking water</td>
<td>44,000 tons /day</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>44,000 tons /day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Domestic water</td>
<td></td>
<td>135,000 tons / day</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>LiBr</td>
<td></td>
<td>117.3MW</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
<td></td>
<td>53.9MW</td>
</tr>
</tbody>
</table>
1.5 Multi-Applications

- **Electricity Supply**: generation and supply;

- **Thermal manufacture of fresh water**: Use MED to make water quality meet the drinking water requirements;

- **Reverse Osmosis manufacture of fresh water**: Use RO to make water quality meet domestic water requirements;

- **LiBr(lithium bromide) absorption refrigeration**: Refrigeration quality can meet the requirements of air conditioning refrigeration (above zero);

- **Ammonia absorption refrigeration**: Refrigeration quality can meet the requirements of industrial refrigeration (as low as -50°C).
1.5 Multi-Applications

Small Isolated Grid Power Supply

Load and Supply Stability is the key issue for small isolated grid System.

Stability analysis is needed to evaluate whether the power system can maintain stability under various operating conditions, protection configurations and different faults.
1.6 Siting Requirements

Siting principles of LNPP SMR ACPR50

- Construction necessity
- Safety reliability
- Economic rationality
- Technical feasibility
- Environmental compatibility
1.6 Siting Requirements

Main siting factors of LNPP SMR ACPR50

- **Earthquake**: Horizontal peak acceleration SL-2≤0.3g.
- **Transportation**: Highway transportation can meet the requirement of large and heavy equipment.
- **Site area**: Only 15hm² for 2 units.
- **Water consumption**: Circulating cooling water can, based on the site condition, be used in arid water areas.
- **Radioactive waste water**: Zero discharge can be realized.
1.6 Siting Requirements

The site selection in China is on the way.

- Two potential sites in Guangdong province: preliminary site feasibility research finished.
- One potential site in Guizhou Province: power supply for the regions of bad transportation condition.
- Three potential sites in Hebei province for combined heat and power supply.
- The preliminary site feasibility study finished.
03
FNPP with SMR ACPR50S
3.1 Status and schedule of ACPR50S project

- Technical proposal of FNPP (2012)
- Key technology research (2013~2018)
- Preliminary conceptual design of ACPR50S (2013)
- Conceptual design of ACPR50S (2015)
- Preliminary design of ACPR50S (2016~2018)
- Earlier stage preparations of demonstration project approved by China government (2015)
- Demonstration project (2017~2022)
3.2 Design Progress (1/4): Research & Development

- Design of Fuel assembly
- Design of Reactor fuel management
- Design of Reactor core thermal-hydraulic design
- Design of DBA mitigation and severe accidents mitigation design
- Design of NSSS: Reactor coolant system, safety system and nuclear auxiliary systems
- Design of R&D of main RCS components
- Design of I&C system
- Design of electric power system
- Design of floating platform and overall layout
3.2 Design Progress(2/4): Construction and Commissioning

- Environment assessment, safety evaluation of construction site and feasibility study of construction site are ongoing.
- Construction and commissioning schemes study is on the way

**Construction design**

- Ship block method
- Module installation
- Ship shaping
- Equipment and cable installation
- Launching

**Commissioning design**

- Commissioning of Main steam turbine
- Fuelling
- integrated commissioning
- Marine experiment
3.2 Design Progress(3/4): Onshore Base

The onshore base of ACPR50S contains the fuel building, the radioactive waste treatment building, and other balance buildings of plant.

- Refueling and temporary storage of spent fuels
- Disposal of nuclear waste
- Maintenance

**Completed conceptual design**
3.2 Design Progress(4/4): Licensing

- **Licensing Approaches**
  
  Apply for the license in 4 stages. Licensing stages, construction stage, fueling stage, operation stage etc.

- **Licensing Experience**
  - NNSA and other regulators are aware of ACPR50S design features
  - Making efforts to explore the new mode of regulation for FNPP
  - Promoting communication of duty between NNSA and other regulators

- **Licensing**
  - A set of design principles has been submitted to NNSA in July, which will benefit the review of PSAR.
  - The first edition PSAR will be submitted to the NNSA by the end of 2017 and the Construction Permit will be applied at the same time.

- **Review of maritime safety**
  - Through China Ship Research and Design Center (CSRDC), we are exchanging information with the maritime department about the design requirements on maritime safety.
  - Conducting research of internal / external disasters of FNPP with Lloyd's Register
3.3 Procurement Progress

Procurement contract for all primary components shall be signed by the end of 2017, the selected supplier will be involved in R&D
ACPR 50S Design Philosophy and Technical Route

• ACPR50s is a combination of industry proven PWR and floating platform technology

➢ The ACPR50S realizes design simplification with less cost and lower investment risks in order to be competitive with conventional offshore energy sources.
Considering Ship conditions

The space and resources of the ship are valuable, the design needs to meet the following requirements:

- The reactor compartment is as small as possible
- The area of the main control room is limited
3.4 Design Features (3/4)

- **Considering ocean environmental conditions**

The control rods shall be well designed and tested in order to be inserted smoothly when tilted by 45° and to remain in reactor core to control the reactivity.
8 cabins totally moulded length:~140m moulded width:~30m moulded depth:~18m
3.5 Verification test

In addition to the experiments carried out by ACPR50S, the ocean condition test and floating platforms experiments are implemented.

- **Ocean condition tests**

  1. Effect of ocean conditions on control rod driving system test
  2. Effect of ocean conditions on passive system thermal-hydraulics performance test
  3. ...

- **Experiments related to floating platforms**

  Through the experiment, the resistance curve of the platform, the natural period and the damping coefficient of the platform are obtained. Compared with the previous estimates, the result is in line with the design expectations.
3.6 ACPR50S Multi-Applications

- **Power supply**
  Offshore power supply;

- **Fresh water production**
  Producing fresh water for living or for drinking combined with offshore desalination device or ship;

- **Refrigeration**
  Air conditioning or industrial refrigeration combined with offshore refrigeration device.
3.6 ACPR50S Multiple Applications

Application scenarios

Scenarios 1: Power supply
Offshore power supply;

Scenarios 2: Electricity & Water
Offshore power supply, and product fresh water for drinking by MED;

Scenarios 3: Fresh water production
Product fresh water for living by RO;

Scenarios 4: Electricity & Refrigeration
Electricity supply to the local grid, heating for lithium bromide absorption refrigeration and for ammonia absorption refrigeration.
### 3.6 ACPR50 Multi-Applications

#### Application scenarios

<table>
<thead>
<tr>
<th>Output</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electricity</td>
<td>440 million KWh/year</td>
<td>420 million KWh/year</td>
<td>370 million KWh/year</td>
</tr>
<tr>
<td></td>
<td>Drinking water</td>
<td>22000 tons per day</td>
<td>22000 tons per day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Domestic water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Refigeration</td>
<td>LiBr</td>
<td></td>
<td>52.1MW</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
<td></td>
<td></td>
<td>24.8MW</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.6 Multiple Applications

◆ Stability is the key issue for small isolated grid

ACPR50S Platform

Isolated Grid

STABILITY

Regional Isolated Grid

Normal

Power Management System

Self-regulation

Multi-ACPR50S Platforms

Emergency Power

Energy Storage Equipment

Emergency
3.6 Multiple Applications

- **Oil Production**
  
  *Strategy for Emergency*: Emergency Power Plant, Associated Gas Turbines …

- **Isolated Island**
  
3.6 Multi-Applications

**Application Scenarios**

**Bohai Sea**

- FNPP is expected to replace the current power sources of gas turbine generators in sea oil production isolated benthosal grid.
- Analysis and calculation shows that the FNPP with multiple auxiliary devices and systems can adapt different emergency and keep stability.
3.7 Siting Requirements

The same as the LNPP SMR, siting of ACPR50S should follow the following principles:

- Construction necessity
- Economic rationality
- Safety reliability
- Technical feasibility
- Environmental compatibility
3.7 Siting Requirements

Unlike LNPPs, there are more than one site for FNPP SMR ACPR50s:
### 3.7 Siting Requirements

The difference between Small FNPP and Small LNPP in siting requirements:

<table>
<thead>
<tr>
<th>Site factors</th>
<th>Small LNPP</th>
<th>Small FNPP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Construction site</td>
<td>Operation site</td>
</tr>
<tr>
<td>hydrology, weather</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Rock-soil, earthquake</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Submerged rock, shoal</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Water intake and outlet</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Sea-route</td>
<td>×</td>
<td>√</td>
</tr>
<tr>
<td>Transportation</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Population</td>
<td>√</td>
<td>√</td>
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<tr>
<td>External man induced event</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Environmental impact and emergency</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
3.7 Siting Requirements

Main siting factors of FNPP with ACPR50s:

- Earthquake: No need to consider in floating state.
- Sea route: Need to consider the safety of navigation. Avoid running aground and stranding.
- Severe sea condition: when typhoon and other bad condition, ACPR50s can sail to the safe area.
- Mooring system: Need to select the appropriate mooring system according to operation site conditions.
International Sea Transportation of FNPP with SMR ACPR50S
4.1 Background

- In 2013, IAEA published “Legal and Institutional Issues of Transportable Nuclear Power Plants: A Preliminary Study”.
- ACPR50S is a floating NPP which need to take international ocean transportation into account in some cases.
- The two aspects below are being studied.
  - Legal issues
  - Safe, secure, efficient and reliable transportation: Safety, Security, Emergency
4.2 Legal issues

As a participant, CNPRI is studying the case of Transportation of FNPP.

Country A: (Country of origin)

Country B: (Transit country)

Country C: (Receipt country)

FNPP is designed and constructed in Country A. Country A is in charge of the transportation of FNPP.

The transportation of FNPP passes Country B's territorial waters.

Rental and use the FNPP.

The three countries are independent and interrelated.
05

Summary
CGN is developing compact SMR (ACPR 50 and ACPR50S) which are modular designed with high level safety, industry-proven and reliable NPP and sea facility technology which makes ACPR50(S) good economics.

ACPR50(S) is multiple applications and the site selection of ACPR50(S) is more flexible which makes ACPR50(S) having broad market prospects.

CGN will continue to carry out FNPP transportation research, and actively exchange results with IAEA and other countries.
Thank You For Your Attention