HPR1000: Advanced PWR with Active & Passive Safety Features

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China needs safe, reliable and clean energy to power its rapid growth.

Nuclear power, with its unique advantage, has been chosen by the Chinese government.

“Safety First” is the basic principle of nuclear energy development.
1. Background

Roadmap of Nuclear Power Technologies

- Self-reliance R&D of CNP300
- Self-reliance R&D of CNP600
- Introduction of Candu, VVER
- Self-reliance R&D of CP1000/ACPR1000
- Introduction of AP1000 and EPR

R&D of ACP1000/ACPR1000+ and Merged to HPR1000;
Other technologies: CAP1400, SMR, HTR-PM, FBR...

Embracing different technologies from the international market
1. Background

Roadmap of HPR1000 R&D

- CNP1000 Gen II+
  - 177 FAs in reactor core
  - Twin-unit layout
  - Single shell containment

- CP1000 Gen III-
  - 177 FAs in reactor core
  - Single-unit layout
  - Double-shell containment
  - Other 19 improvements

- ACP1000 ACPR1000+ Gen III
  - Active + passive safety features
  - DEC (BDBA+SA) countermeasures
  - Enhanced Protection Capabilities against external hazards
  - Fukushima feedbacks
  - Follows the latest safety requirement

- HPR1000 Gen III+

Timeline:
- 1999
- 2007
- 2010
- 2013
1. Background

- **General Parameters**
  - Reactor core thermal output: 3180 MWt
  - Nominal power: ≥1200 MWe
  - Design life: 60 years
  - Fuel assembly number: 177
  - Refueling cycle: 18 months
  - Average Availability: ≥ 90%
  - Nuclear island layout: Single-unit
  - Containment: Double-shell
## General Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safe shutdown earthquake (SSE)</td>
<td>0.3g</td>
</tr>
<tr>
<td>Load Following Capability</td>
<td>Yes</td>
</tr>
<tr>
<td>Operator nonintervention period</td>
<td>30 mins</td>
</tr>
<tr>
<td>Plant autonomy</td>
<td>72 hours</td>
</tr>
<tr>
<td>Occupational exposure dose</td>
<td>&lt;0.6 m-Sv/r-y</td>
</tr>
<tr>
<td>Safety Design Philosophy</td>
<td>Active+Passive</td>
</tr>
<tr>
<td>Core Damage Frequency (CDF)</td>
<td>&lt;1E-6</td>
</tr>
<tr>
<td>Large Release Frequency (LRF)</td>
<td>&lt;1E-7</td>
</tr>
</tbody>
</table>
2. Design Philosophy

- **Objectives, Principles and Safety Functions Realization**

- **General Nuclear Safety Objective**
  To protect individuals, society and the environment

- **Radiation Protection Objective**
  To ensure the release of radioactive material as low as reasonably achievable

- **Technical Safety Objective**
  To prevent accidents and mitigate their consequences.

- **Inherent safety features**

  - Proven and conservative
  - Redundancy
  - Single-failure
  - Independence
  - Defense-in-Depth
  - Diversity

- **Safety Codes & Standards**
- **Utilities Requirements**

- **Active + Passive (as Supplementary) Safety Features**

  - Control of Reactivity
  - Removal of decay Heat
  - Confinement of radioactive materials
2. Design Philosophy

From Principle to Philosophy

Principle

- **DiD**
- **Redundancy**
- **Diversity**
- **Independence**

Philosophy

- Enhance the safety configuration, especially safety features of level 4a and 4b for DEC
- Levels of DiD as far as practicable independent, i.e. 3 and 1, 3 and 4
- Safety systems for level 3 fulfill the principle of Redundancy and single-failure criterion
- Critical active equipment for level 4a are considered
- Active + Passive safety design philosophy
- Equipment: Motor-driven and Turbine-driven Pumps
- Power source, I&C, Ultimate Heat sink
- Physical separation: redundant trains
- Function separation: safety systems and normal operating systems
- Electrical, I&C and communication (data transfer) separation
2. Design Philosophy

- Redundancy or Diversity?

Why Active + Passive?
2. Design Philosophy

Risk Informed Decision Making

Complementary application of PSA for avoiding Buckets Effect. Insight from PSA point of view:

- The lower reliability of a single train, the greater contribution by increasing in redundancy for systematic reliability improvement.
- Conversely, if the reliability of a single train is high enough, the increase in redundancy has limited contribution for reliability improvement.

<table>
<thead>
<tr>
<th>Redundancy (Number of Trains)</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>0.9</td>
<td>0.99 (+10%)</td>
<td>0.999 (+1%)</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>0.19 (+90%)</td>
<td>0.271 (+43%)</td>
</tr>
</tbody>
</table>

Note: If taking common cause failure into account, the contribution of increasing redundancy for systematic reliability improvement will be lower.
## Risk Informed Decision Making

The PSA result shows that this configuration has significant effect for the safety improvement:

<table>
<thead>
<tr>
<th>Configuration of safety system</th>
<th>CDF/ reactor-year</th>
<th>ΔCDF compared to HPR1000</th>
<th>The rate of change in CDF compared to HPR1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Active Trains</td>
<td>6.11E-07</td>
<td>+4.81E-07</td>
<td>+370.00%</td>
</tr>
<tr>
<td>3 Active Trains</td>
<td>3.32E-07</td>
<td>+2.02E-07</td>
<td>+155.38%</td>
</tr>
<tr>
<td>2 Active Trains and 1 Passive Train (HPR1000, baseline configuration)</td>
<td>1.30E-07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3 Active Trains and 1 Passive Train</td>
<td>1.11E-07</td>
<td>-1.90E-08</td>
<td>-14.62%</td>
</tr>
</tbody>
</table>
3. Function Realization

Safety Configuration

- **Active**: proven with high reliability
- **Passive**: no need for power
- **Active + Passive**: diverse approaches to perform safety function
  - Emergency core cooling
  - Core residual heat removal
  - Cavity flooding and cooling (IVR)
  - Containment heat removal
3. Function Realization

Level 3: Engineered Safety Features

- Chemical Addition Tank
- Containment Spray Pump
- Heat Exchanger
- Accumulator
- IRWST
- Motor-driven Pump
- Turbine-driven Pump
- Auxiliary Feedwater Pool
- LHSI pump
- MHSI Pump
- LHSI pump
3. Function Realization

Level 4a/4b: BDBA/SA Prevention & Mitigation Measures

- Phenomena
  - Hydrogen detonation
  - High pressure molten corium ejection, direct containment heating
  - Long term overpressure
  - Basement melt-through
  - Station blackout
  - Other measures

- Countermeasures
  - Containment Hydrogen Removal System
  - Fast Depressurization System for RCS
  - Passive Containment Heat Removal System, Containment Filtered and Venting System
  - Reactor Cavity Injection and Cooling System
  - Passive systems, Diverse power sources
  - Pressure Vessel High-point Venting System, Habitability Design of Main Control Room, SAMG and etc.
3. Function Realization

- Level 4a/4b: BDBA/SA Prevention & Mitigation Measures

- Passive Residual Heat Removal (Secondary Side)
- Cavity Injection and Cooling
- Containment Filtration and Exhaust
- Passive Containment Heat Removal
- Containment Hydrogen Combination
- RPV High-point Venting
- Fast Depressurization
- IRWST
- Passive Residual Heat Removal (Secondary Side)
3. Function Realization

- **Diversity of Power Sources**
  
  **AC Power Supply**
  
  - **Turbine generator**
    - During normal operation
  
  - **Two trains of independent Off-site power**
    - If turbine tripped
  
  - **Trains of diesel generators for each unit**
    - As emergency power

  **DC Power Supply**
  
  - **SBO Diesel Generator**
    - In case of SBO
  
  - **Extra diesel generator**
    - 2 hours and 72 hours Battery
3. Function Realization

☐ Other Requirements from HAF102 or Feedback

Enhanced protection against external events

- Seismic input with peak ground acceleration of 0.3 g
- Protection against Large Commercial Aircraft Crash
- ...

✓ APC shell protection
  (for Reactor Building, Fuel Building and Electrical Building containing MCR)

✓ Physical separation of Safeguard building
  (for redundant and independent trains of safety systems) and Pumping station.
3. Function Realization

Other Requirements from HAF102 or Feedback

Fukushima Feedback

- Additional emergency water makeup and associated interfaces
- Improvements of power supply: SBO (Station Black Out) generator and DC Power
- More conservative seismic margin
- Extension of nonintervention period and plant autonomy
- Spent fuel pool monitoring and cooling
- Habitability and availability of emergency facilities

Other Requirements from HAF102 or Feedback
3. Function Realization

- Other Requirements from HAF102 or Feedback

Fukushima Feedback - Interface on Emergency Core Cooling
3. Function Realization

- Other Requirements from HAF102 or Feedback

Fukushima Feedback - Interface on Emergency SG Feedwater
3. Function Realization

- Other Requirements from HAF102 or Feedback

Fukushima Feedback - Spent Fuel Pool Cooling

- Normal Cooling
- Heat Exchanger
- Cooling Water Pump
- Spent Fuel Pool
- Evaporation
- Isolation Valve
- Mobile water makeup
- Other Requirements from HAF102 or Feedback
4. Summary

◆ **Defense-in-Depth** principle should always be respected and considered for the design of Advanced Water Cooled NPPs

◆ In the post-Fukushima era, **Diversity** is the most effective way to enhance the systematic safety of NPPs

◆ Configuring active and passive safety features in different **DiD level** is a good practice for applying **Diversity** principle, which can balance the cost and benefit for achieving the target of safety, reliability or economy
The application of the design principles, including single failure criterion, redundancy, diversity, etc. is actually a compromise between safety, reliability, economy and operability of guidelines on the basis of engineering judgement and combination of deterministic assessment and probabilistic assessment.

It's not entirely reasonable with extending each of criteria to everywhere, which could lead to imbalance in NPP design.
Appendix: R&D and Project Progress

被动系统验证测试

✓ “active” features validated by long term operation practice
✓ “passive” features verified by specific tests

Test of Passive Containment Heat Removal System

Test of Cavity Injection and Cooling System

Passive residual heat removal test for secondary side
Appendix: R&D and Project Progress

Other Verification Tests & Experiments

- Flow-induced Vibration Simulation Test of Reactor Internals
- Qualification Tests of Electrical Penetration for Double Shell Containment
- Seismic Test of Control Rod Driven Line (CRDL)
- Aging Test of CRDL
Appendix: R&D and Project Progress

- **Fuqing NPP Unit 5&6**

  - Unit 1&2 CNP1000
  - Unit 3&4 CNP1000
  - Unit 5&6 HPR1000

- Permission obtained to implement the pre-project work by Apr. 2009
- After Fukushima accident, HPR1000 was deployed for Fuqing Unit 5&6
- Approved by State Council on Apr. 15, 2015
- First Concrete Date on May 7, 2015
- Containment dome installed ahead of schedule on May 25, 2017
Benefiting from rich construction experience and operating feedback, the construction progress of HPR1000 pilot project is kept on schedule.
Appendix: R&D and Project Progress

Containment Dome Installed on May 25, 2017
Sharing experience and striving for brilliant future!

Thanks for your attention