Points about improving cost competitiveness of modular HTGR power plants

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Contents

- Fundamentals and design features of modular HTGR
- Brief description of Chinese HTR-PM project
- Analysis of modular HTGR’s cost competitiveness
What is HTGR?

- **High Temperature gas-cooled Reactor (HTGR)**
  - High temperature: core outlet temperature, >700°C
  - Gas-cooled: helium coolant

- **Basic features**
  - **Coolant**: helium (single phase, good chemical stability, no neutron absorption)
  - **Moderator**: graphite (tolerating high temperature, large heat capacity, good compatibility with coolant)
  - **Fuel**: refractory ceramic coated particle fuel element (tolerating high temperature (>1600°C), good compatibility with coolant, nearly complete retention of all fission products)
Concept of Modular HTGR

- **Design philosophies**
  - To restrict core power density (power density is about 1/30 of normal PWR)
  - To restrict power level of each reactor module (core size)
  - Appropriate geometry of core, e.g. slender core

- **Inherent safety characteristics**
  - Complete passive removal of decay heat
  - Large negative temperature coefficient of reactivity
  - Large heat capacity
  => Fuel temperature lower than limiting value under any accident conditions; gentle response characteristics, providing for long times for operator actions
Application of modular HTGRs

- High efficiency electricity generation due to high core outlet temperature
  - Steam turbine
  - Gas-turbine
  - Cogeneration
- Flexible unit output: multiple modules plant, meeting requirement of various grid
- Process steam: supply to heavy oil recovery, etc.
- Process heat supply to chemical process, hydrogen production, etc.
HTR-PM
200 MWe High Temperature gas-cooled Reactor Pebble-bed Module

- 2004: industry investment agreement was signed
- 2006: decided to use $2 \times 250$ MWt reactor modules with a 200 MWe steam turbine, became a key government R&D project
- 2012.12: FCD the first concrete poured
The HTR-PM after FCD
## Parameters of China HTR-PM

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Plant electrical power, MWe</td>
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<td>Core thermal power, MW</td>
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<tr>
<td>Number of NSSS Modules</td>
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<td>Core diameter, m</td>
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<td>Core height, m</td>
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<tr>
<td>Primary helium pressure, MPa</td>
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<tr>
<td>Core outlet temperature, °C</td>
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<tr>
<td>Core inlet temperature, °C</td>
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<tr>
<td>Steam pressure, MPa</td>
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<tr>
<td>Steam temperature, °C</td>
<td>567</td>
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</tbody>
</table>
Final technical solution
HTR-PM: multi-module reactor steam turbine plant to properly address safety, cost and technology feasibility

Demo. plant
Each reactor module 100 MWe

Comm. plant
Each reactor module 100 MWe

Connect to one steam turbine, 200 MWe

Multi-module in one reactor plant

Connect to one steam turbine, 200, 300, 600 MWe

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Components manufacture, as an example - RPV
Hot test of blower

- A full-size prototypical helium blower with active magnetic bearing has been tested for 100 hours in hot conditions.

Data

- Power, 4.5MW
- Temp., 250 °C
- Rotator, ~4t
Schedule

- 2014, finish the key components demonstration tests
- 2015, key components to the site
- 2017, connect to the grid
Question

- Technical advantages of modular HGTRs
  - Inherent safety (no core meltdown)
  - Can be used beyond electricity generation

- Can modular HTGR compete with large-scale PWR whose power output is more than ten times as large? Commercially feasible?

- Try to answer it based on Chinese practice of HTR-PM demonstration plant

- Reference: INPRO METHODOLOGY FOR SUSTAINABILITY ASSESSMENT OF NUCLEAR ENERGY SYSTEMS: ECONOMICS (2014)
CR1.1: Cost competitiveness

- In the INPRO methodology in the area of economics, four requirements and eight criteria are developed.

- One of the criteria, CR1.1, is “Cost Competitiveness”. Overnight cost is one of the most important parameters used for calculation of the economic function, such as LUEC, IRR, etc.

- This presentation is primarily focused on the discussion of overnight cost of HTR-PM.
Costs of HTR-PM

- One of main technical objectives of HTR-PM is to help reveal the potential economic competitiveness.

- So far, more than 90% (in costs) of HTR-PM’s equipment has been ordered through bidding process.

- Analysis has been done based on detailed costs databank for HTR-PM and also the China’s PWR projects.
Module concept

- One large system is divided into several identical subsystems – “modules”

Characteristics

- The subsystems are completely identical
- Each subsystem is relatively simple
- As far as reactors are concerned, it is best that they have independent safety functions

*(Comparison: another concept, one large system is divided into different subsystems, “package”)*
Benefits due to modularization

- For such modules, it can take maximum advantages of the benefits brought by modularization.
  - **Economy of experience**: the so-called learning curve. The curve will reach its minimum \((\text{equilibrium})\) after about the 10\(^{th}\) module. Cost-decrease is around 30%.
  - **Economy of scale**: brought by the increase of production.
    - Cost divided into fixed and variable part, when the output increases, the specific fixed cost decreases.
Multi-module HTGR power plant

- Modular HTGR provide the utilities with flexibility in unit size, i.e., various unit capacities, such as 200, 300, 600, even 1000 MWe.

- In order to compare the cost between HTGR power plant and large PWR power plant, a ten-module HTGR plant is adopted, i.e. 10 NSSS (reactor, S/G, etc.) modules feed one steam turbine.
Multiple NSSS modules

- Main control room is shared among all the modules
- The turbine-generator and its auxiliary systems are shared
- Most auxiliary systems are shared, with the exception of the reactor protection system and other nuclear safety-relevant systems
Break-down of PWR capital costs

- NI components: 23~28%
  - RPV + Internals: 9% (9%*23~28%=2~3%)
  - Other NSSS components: 28%
  - Reactor auxiliary systems: 23%
  - I&C and electrical systems: 26%
  - Fuel handling and storage: 5%
  - Other components: 9%

- CI: 12%; BOP: 3%

- *RPV and internals of PWR exhibit only a limited influence on the total plant cost*
RPV and internals of HTGR

- Lower power density
  - inherent safety
  - large RPV, large masses of graphite

- Consequently, specific weight of the HTGR RPV is about 10 times that of a PWR in terms of power

- Taking the difference of manufacturing process into account (e.g. no resurfacing welding of stainless steel for the HTGR RPV), the cost of RPV and reactor internals for an HTR-PM plant is about eight times that of PWR
Other NSSS components of HTGR

- **S/G**
  - smaller heat transfer coefficients, balanced by
  - larger temperature difference
  - Similar specific heat transfer area to PWR’s

- **Blower**
  - non-safety grade
  - lower density helium as working fluid
  - large temp. difference between inlet and outlet
  - Collectively, specific motor power for HTGR is similar to main pump of PWR
Other NSSS components of HTGR

- CRDM
  - **Factor:**
    - temp. difference between shutdown and operating conditions
    - negative temperature coefficient of reactivity
    - continuous fuel charging
  - **Result:** the number of control rod systems is similar to PWR

- Summing up, other NSSS components has no great difference from PWR
Reactor auxiliary systems

- **HTGR**
  - less than 10 auxiliary systems

- **PWR:**
  - 40–50 auxiliary systems for a generation II+ NPP
  - 60–70 nuclear grade pumps and blowers
I&C and electrical systems

- For HTGR
  - Capacity of an HGTR emergency power supply system is very small
  - Allowed start-up time of the system is much longer (many hours)
  - Number of reactor auxiliary systems is decreased

- I&C equipment becomes significantly less
Capital cost estimates of NI Components

- An HTGR cost estimate for NI Components is found to be a factor two compared to the costs of those for PWRs.
  - RPVs and reactor internals: much higher. However, the NOAK plant will get an about 30% cost reduction due to mass production.
  - Other NSSS components: for the NOAK plant these costs will approach to the same level as for PWRs.
Capital cost estimates of HTGR plants - other part

- **CI components**
  - 25% due to a conventional T/G used

- **BOP, Buildings and structures, construction and commissioning, First load fuel**
  - no significant difference

- **Engineering**
  - standardization resulting in reduction of engineering work
Capital cost estimates of HTGR plants – collective cost

- Under the above assumptions, the maximum costs of HTGR plant will not exceed the costs of an PWR by more than 20%.

- Potentially, the component costs can be compensated partially by reduction of management, engineering, schedule, etc.
HTR-PM economic potential

16% of total plant cost

HTR-PM RPV and reactor internals
PWR RPV and reactor internals
HTR-PM reduction in reactor auxiliary, I&C and electrical systems
HTR-PM reduction in turbine plant equipments
HTR-PM reduction in mass production of RPV and reactor internals
HTR-PM reduction in project management and engineering
HTR-PM reduction in schedule and financial cost
Power plants of small-scale

- Modularization of HTGR plants tends to bring benefits in terms of cost reduction when down scaling seems to be desirable.

- Smaller HTGR plants with a fewer number of modules would show better cost competitiveness.
Summary
Way to cost effective HTR-PM plants

- Adopt **multiple NSSS modules** and one turbine generator for one plant to achieve large capacity
- Reduce the costs of RPVs and reactor internals through **mass production**
- **Share auxiliary systems** in one plant
- Reduce the workload of design and engineering management through **standardization**
- **Shorten construction schedule**
Thank you for your attention!