Points about improving cost competitiveness of modular HTGR power plants

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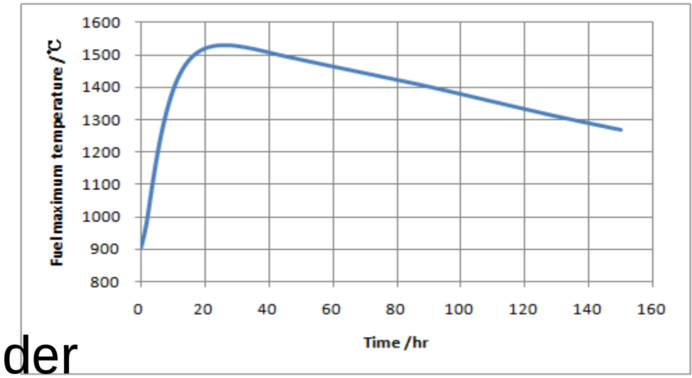
- Fundamentals and design features of modular HTGR
- Brief description of Chinese HTR-PM project
- Analysis of modular HTGR’s cost competitiveness

What is HTGR?

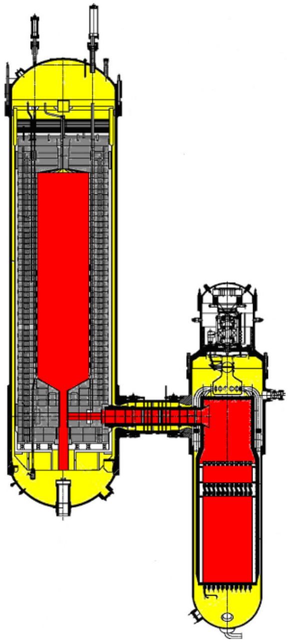
- High Temperature gas-cooled Reactor (HTGR)
  - High temperature: core outlet temperature, >700℃
  - Gas-cooled: helium coolant
- Basic features
  - Coolant: helium (single phase, good chemical stability, no neutron absorption)
  - Moderator: graphite (tolerating high temperature, large heat capacity, good compatibility with coolant)
  - Fuel: refractory ceramic coated particle fuel element (tolerating high temperature (>1600℃), 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 2×250 MWt reactor modules with a 200 MWe steam turbine, became a key government R&D project
- 2012.12: FCD the first concrete poured

HTR-PM in 2008

HTR-PM in 2009

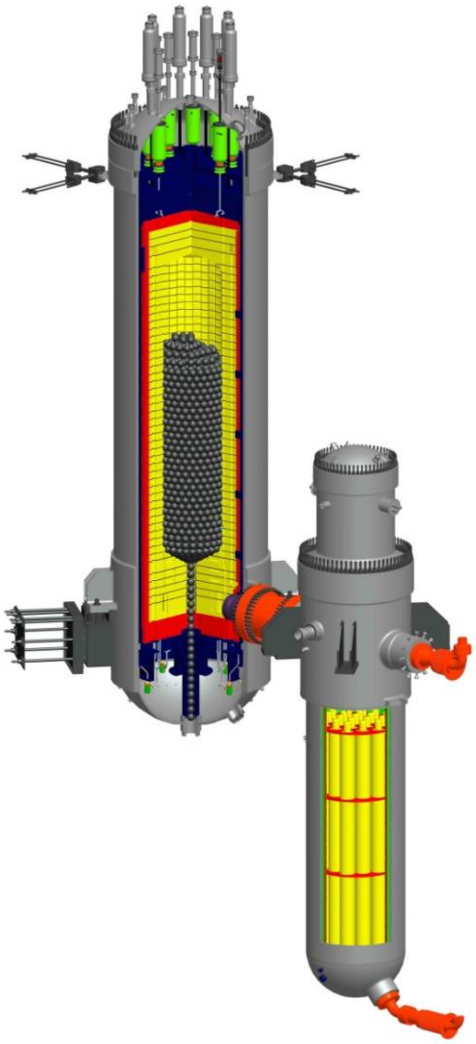
HTR-PM in 2011

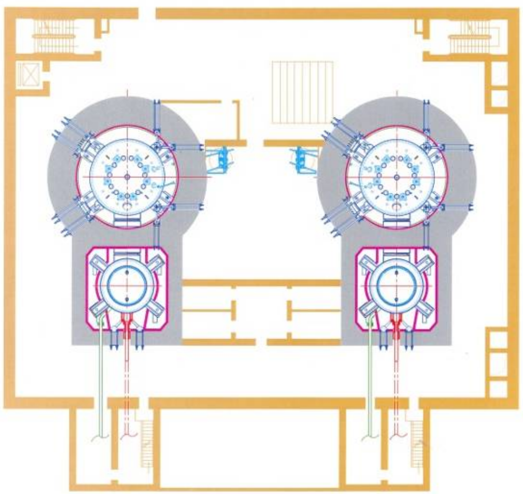
The HTR-PM after FCD

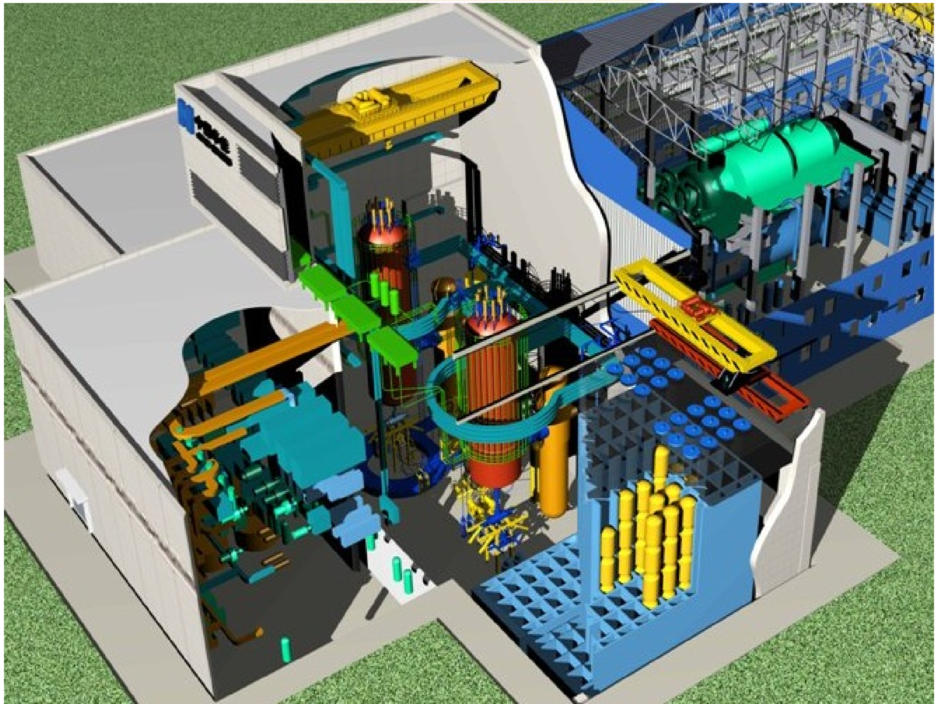
Parameters of China HTR-PM

Parameter	Value
Plant electrical power, MWe	211
Core thermal power, MW	250
Number of NSSS Modules	2
Core diameter, m	3
Core height, m	11
Primary helium pressure, MPa	7
Core outlet temperature, ℃	750
Core inlet temperature, ℃	250
Steam pressure, MPa	13.25
Steam temperature, ℃	567

Final technical solution

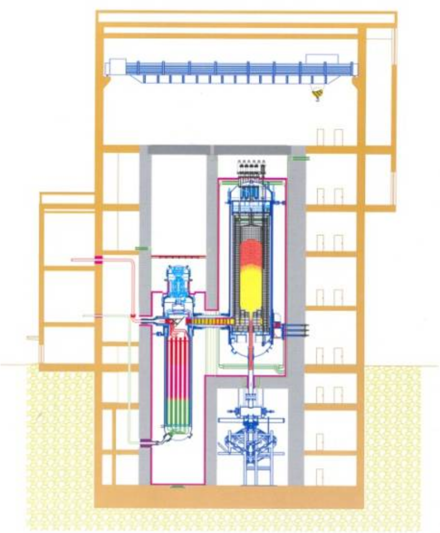


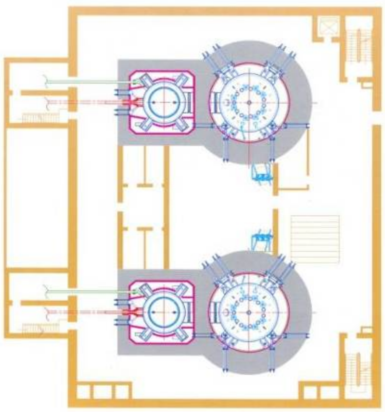


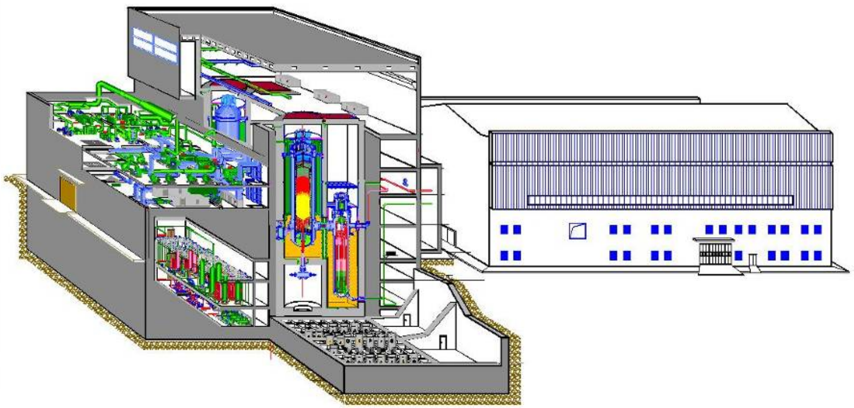


Objectives of HTR-PM

HTR-PM: multi-module reactor steam turbine plant to properly address safety, cost and technology feasibility

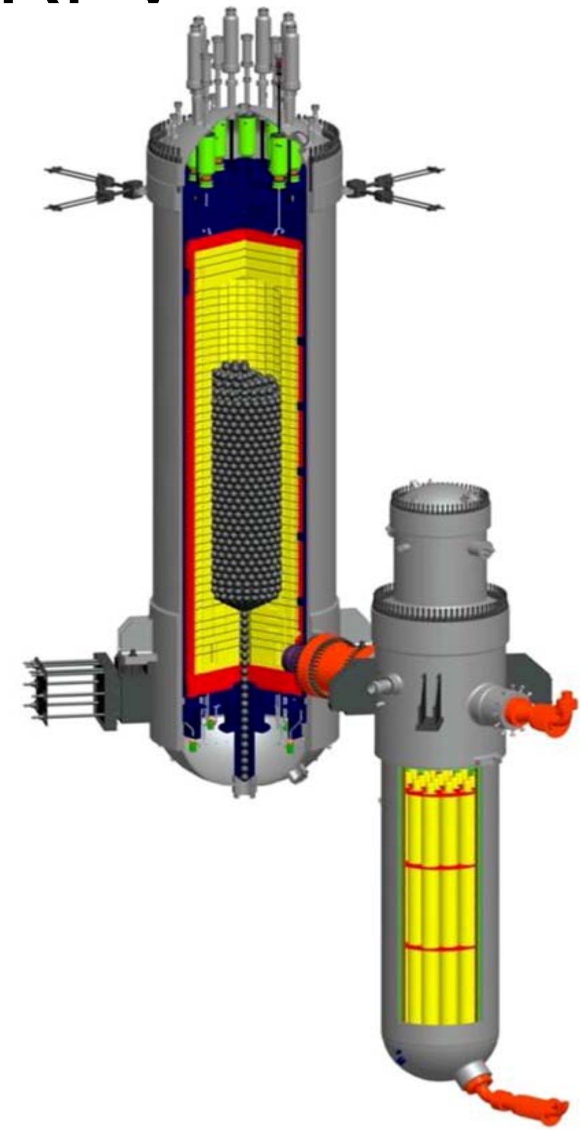






Demo. plant	***Each reactor module 100 MWe***	***two module in one reactor plant***	***Connect to one steam turbine, 200MWe***
Comm. plant	***Each reactor module 100 MWe***	***Multi-module in one reactor plant***	***Connect to one steam turbine, 200, 300, 600 MWe***

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 ℃
  - 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)*

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CR1.1: Cost competiveness

- 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 benefit brought by modularization
  - Economy of experience: the so-called learning curve. The curve will reach its minimum (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

HTR-PM RPV and reactor internals

PWR RPV and reactor internals

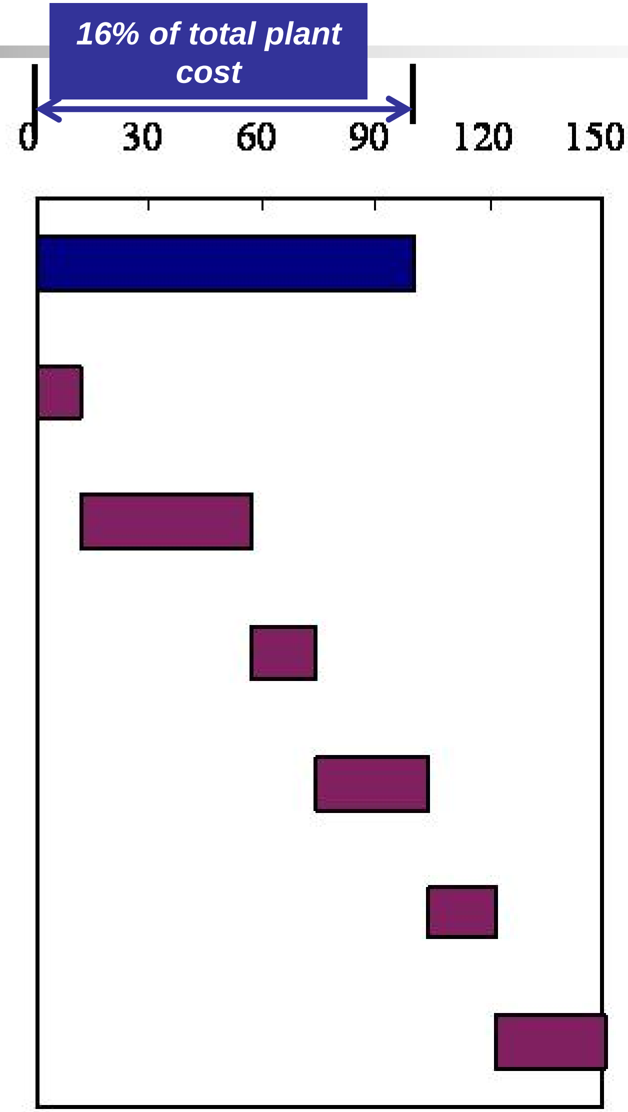
HTR-PM reduction in reactor auxiliary, I&C and electrical systems

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!