HTR-PM of 2014: toward success of the world first Modular High Temperature Gas-cooled Reactor demonstration plant

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Vice Chairman of Chinergy Co. and Vice Chairman of HSNPC
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1, Introduction: HTR-PM Milestones

- 2003: finished pre-concept design and decided to use steam turbine
- 2004: signed industry investment agreement
- 2006.01: became a key government R&D project
- 2006.09: decided to use $2 \times 250$ MWt reactor modules with a 200 MWe steam turbine,
- 2008.02: government approved the HTR-PM project budget
- 2008.10: issued procurement contracts of the lead components
- 2012.12: government issued construction permit and we poured the first concrete
乏燃料厂房
1#反应堆舱室
2#反应堆舱室 核辅助厂房

混凝土浇筑完成
正在进行钢筋绑扎

±0.0m
-5.0m
-11.0m
-15.5m
+7.5m
+11.3m
+16.6m
+20.5m
+28.1m
+42.1m

Schedule：2012/09 FCD
2013/03 -15.5m
2014/03/28 0m
2014/8/12 +7.5m
2014/10 +20.5m
2014/11 +14.5m
Schedule：2015/07 +42.1m

2012/12/09 FCD

形象目标
HTR-PM on October, 2014
2, Key Technical Decision
## HTR-PM Designs Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant electrical power, MWe</td>
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</tr>
<tr>
<td>Core thermal power, MW</td>
<td>250</td>
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<tr>
<td>Number of NSSS Modules</td>
<td>2</td>
</tr>
<tr>
<td>Core diameter, m</td>
<td>3</td>
</tr>
<tr>
<td>Core height, m</td>
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<tr>
<td>Primary helium pressure, MPa</td>
<td>7</td>
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<tr>
<td>Core outlet temperature, °C</td>
<td>750</td>
</tr>
<tr>
<td>Core inlet temperature, °C</td>
<td>250</td>
</tr>
<tr>
<td>Fuel enrichment, %</td>
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</tr>
<tr>
<td>Steam pressure, MPa</td>
<td>13.25</td>
</tr>
<tr>
<td>Steam temperature, °C</td>
<td>567</td>
</tr>
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</table>
HTR-PM Technical Basis

- Chinese HTR-10 engineering experience, published knowledge of German HTR-Module, as well as world developments in HTGR.
- There is no technical know-how transfer from Germany even if we were trying to establish such a co-operation.
- HTR-PM is an optimized design using Chinese engineering and manufacturing capability, INET and its partner established their own IP.
(1) Reactor: $2 \times 250\text{MWt}$ with one $210\text{MWe}$ steam turbine
(2) Steam generator: 19 helical heat transfer tube bundles
(3) Helium circulator: electric-magnetic bearings
(4) Reactivity control: 24 control rods and 6 SARs
(5) Fuel handling system: improved HTR-10 design
(6) Spent fuel storage: canister based dry storage system
Reactor Design: $2 \times 250\text{MWt}$

- **Technical uncertainties of the annual core:**
  - Dynamic annual core: fuel flow demonstration, increased helium outlet temperature difference, reactivity control, etc..
  - Solid annual core: graphite replacement, complicated fuel flow at the bottom, increased pressure drop, etc..

- The experience until now showed the difference of reactor plant costs of the $2 \times 250\text{MWt}$ and $458\text{MWt}$ plant will be smaller than 10%. Considering the future multi-module plants, the difference of the total plant costs will be smaller than 5%.

- This is a key decision to the HTR-PM’s success.

<table>
<thead>
<tr>
<th></th>
<th>$2 \times 250\text{MW}$</th>
<th>$458\text{MW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV weight</td>
<td>$2 \times 0.57$</td>
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</tr>
<tr>
<td>Graphite weight</td>
<td>$2 \times 0.60$</td>
<td>1</td>
</tr>
<tr>
<td>Metallic reactor internals weight</td>
<td>$2 \times 0.86$</td>
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</tr>
<tr>
<td>Blower power</td>
<td>$2 \times 0.57$</td>
<td>1</td>
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</tbody>
</table>
HTR-PM’s steam generator has 19 steam generator helical tube assemblies.

The advantages:

- every assembly has the heat transfer capability of 13MWt, and can be tested and verified in a 10MWt helium test facility (ETF-HT, ETF-SG).
- able to be inspected.
- can be manufactured using limited experience in Chinese industry.
- mass production.
Helium Circulator

Solution A: Helium Circulator with magnetic bearing

- INET has experience in magnet bearing technology in HTR-10GT project and tested a helium circulator for HTR-10 in 2006.
- The IT technology innovation since 1980's.
- Use the best bearing in the world market.
- Conduct an intensive and comprehensive R&D program.

Backup Solution: Helium Circulator with dry gas sealing

- Tsinghua University has a team in dry gas sealing technology. The dry gas sealing and bearing used are the commercial available products.
- Test a full scale prototype.

HTR-PM is designed to use the both helium circulator.
Reactivity Control

Original design: 8 CRDMs and 22 SARs (driven by 11 systems)

The difficulties we can not solve in limited time and resource are:

- To stat-up the reactor until ~40% power through SARs, at the same time use CRDs to control the reactor power,
- Meanwhile the helium circulator will impose a strong helium bypass between the reactor core and SARs, if we considering the possible change of graphite structure in the later reactor life time,
- SARs structure inside the reactor can not be maintained.

We decide to change the reactivity control to 24 CRDs and 6 SARs. The reactor can be started up only through CRDs. SARs become a reserved shut-down system.

The change has been approved by the licensing authority and executed in manufacture.
Fuel Handling System

We tested a full scale prototyping of the integrated discharge machine. In nearly 2 years we find the unsolved difficulties:

1. no qualified bearing found in our conditions,

2. difficult to replaced and maintained in irradiated condition.

We changed to an improved HTR-10 design, that is to separate the discharge machine and broken sphere separator, make the bearing in the system simple. The system has been tested and proved to be successful.
Spent Fuel Storage

Canister:
- 40000 spent fuel spheres,
- Could be transported by standard LWR transport cask.

Spent fuel storage building:
- Capability of 40 years storage,
- To be cooled by closed air forced flow in closed condition for the demonstration plant,
- If the forced flow failed, the open air natural flow can keep the fuel temperature under limit.
# Nuclear safety review

## Before 2011/03/11

<table>
<thead>
<tr>
<th>Stage</th>
<th>Report</th>
<th>Questions</th>
<th>Action sheets</th>
<th>Review meetings</th>
<th>Special issues</th>
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</thead>
<tbody>
<tr>
<td>Site selection</td>
<td>Site safety analysis report</td>
<td>41</td>
<td>18</td>
<td>1</td>
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<td></td>
<td>Environmental impact assessment report</td>
<td>80</td>
<td>31</td>
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<tr>
<td>Design</td>
<td>Preliminary safety analysis report</td>
<td>1515</td>
<td>541</td>
<td>9</td>
<td>8</td>
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<tr>
<td></td>
<td>Environmental impact assessment report</td>
<td>93</td>
<td>39</td>
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## After 2011/03/11

<table>
<thead>
<tr>
<th>Stage</th>
<th>Report</th>
<th>Questions</th>
<th>Action sheets</th>
<th>Review meetings</th>
<th>Special issues</th>
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</thead>
<tbody>
<tr>
<td>Earthquake design input change</td>
<td></td>
<td>47</td>
<td>10</td>
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<td></td>
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<tr>
<td>Construction permit conditions</td>
<td></td>
<td>107</td>
<td>22</td>
<td>8</td>
<td></td>
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<tr>
<td>Reactivity control scheme change</td>
<td></td>
<td>111</td>
<td>26</td>
<td>5</td>
<td></td>
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</tbody>
</table>
Defend in depth measures after Fukushima Daichii accident

- Measures to protect the reactor under seismic and tsunami as well as station blackout conditions according to the nuclear safety roles
- Station blackout
- +ATWS (HTR-10 safety demonstration test)
- +Loss of the coolant
- +Loss of the passive cavity cooling systems.
3, R&D

Started construction in 2009 and finished in 2010

The laboratory

The facility is ready in 2011
## Test Facilities of HTR-PM Project

<table>
<thead>
<tr>
<th>Facility Code</th>
<th>Facility Name</th>
<th>Key Parameters</th>
<th>Description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETF-HT</td>
<td>Engineering Test Facility- Helium Technology</td>
<td>10MWt, 7.0MPa, 250-750 °C, helium</td>
<td>Heat source to verify steam generator and other systems</td>
<td>Facility finished</td>
</tr>
<tr>
<td>ETF-SG</td>
<td>Engineering Test Facility- Steam generator</td>
<td>One full scale assembly, 10MWt, 13.25MPa, 205-570 °C, water</td>
<td>Secondary loop and third loop to verify steam generator</td>
<td>Facility finished</td>
</tr>
<tr>
<td>ETF-HC</td>
<td>Engineering Test Facility- Helium Circulator</td>
<td>Full scale, 4.5MWe, 7.0MPa, 250 °C, helium</td>
<td>Verification of helium circulator</td>
<td>Facility finished</td>
</tr>
<tr>
<td>ETH-FHS</td>
<td>Engineering Test Facility- Fuel Handling System</td>
<td>Full scale, 7.0MPa, 100-250 °C, helium, two chain</td>
<td>Verification of fuel handling system</td>
<td>Components tested, final installation of the whole system</td>
</tr>
<tr>
<td>TH-FHS</td>
<td>Test Facility- Fuel Handling System</td>
<td>Full scale, air, 0.1Mpa</td>
<td>Verification of the fuel movement in the FHS system</td>
<td>Most tests finished</td>
</tr>
<tr>
<td>ETF-CRDM</td>
<td>Engineering Test Facility- Control Rods Driving Mechanism</td>
<td>Full scale, 1MPa, 100-250 °C, helium</td>
<td>Verification of Control Rods Driving Mechanism</td>
<td>Tests finished</td>
</tr>
<tr>
<td>ETF-SAS</td>
<td>Engineering Test Facility- Small Absorber Sphere System</td>
<td>Full scale, 7.0MPa, 100-250 °C, helium</td>
<td>Verification of small absorber sphere system</td>
<td>Tests of absorber sphere flow finished</td>
</tr>
<tr>
<td>ETF-SFS</td>
<td>Engineering Test Facility- Spent Fuel System</td>
<td>Full scale, air, 0.1 Mpa</td>
<td>Verification of major components of spent fuel storage system</td>
<td>Most tests finished</td>
</tr>
<tr>
<td>TF-SFCD</td>
<td>Test Facility- Spent Fuel Canister Drop</td>
<td>Full scale</td>
<td>Verification of spent fuel canister drop</td>
<td>In final installation</td>
</tr>
<tr>
<td>ETF-HPS</td>
<td>Engineering Test Facility- Helium Purification System</td>
<td>7.0MPa,25-250 °C,helium Purification flow rate: 40kg/h</td>
<td>Verification of purification efficiency (greater than 95% and system resistance less than 200kPa).</td>
<td>Tests finished</td>
</tr>
<tr>
<td>TF-PBEC</td>
<td>Test Facility- Pebble Bed Equivalent Conductivity</td>
<td>3m diameter, 60mm graphite sphere, 1600 °C, vacuum</td>
<td>Measurement of pebble bed equivalent conductivity</td>
<td>Facility commissioning</td>
</tr>
<tr>
<td>TF-PBF3D</td>
<td>Test Facility- Pebble Bed Flow 3D</td>
<td>0.1 MPa, room temperature, air, 1:5 scale</td>
<td>Three-dimensional simulation test for pebble bed flow</td>
<td>Facility manufacturing</td>
</tr>
<tr>
<td>TF-HGM</td>
<td>Test Facility- Hot Gas Mixing</td>
<td>0.1 Mpa, 20-150 °C, air, 1:2.5 scale</td>
<td>Verification of hot gas mixing at reactor core outlet</td>
<td>Tests finished</td>
</tr>
<tr>
<td>ETF-DCS</td>
<td>Engineering Test Facility- Distributed Control System</td>
<td>Full scale</td>
<td>Verification of DCS architecture and major control Systems</td>
<td>Facility finished, under testing</td>
</tr>
<tr>
<td>ETF-RPS</td>
<td>Engineering Test Facility- Reactor Protection System</td>
<td>Full scale, 4 channels</td>
<td>Verification of Reactor Protect System</td>
<td>Tests finished</td>
</tr>
<tr>
<td>ETF-MCR</td>
<td>Engineering Test Facility- Main Control Room</td>
<td>Full scale</td>
<td>Verification of Man-Machine Interface</td>
<td>Facility finished, V&amp;V ongoing</td>
</tr>
</tbody>
</table>
Reactor Pressure Vessels (RPVs), will be delivered in 2015.07

The key difficulty which was overcome is the 460 tons forge.
Helium Circulator with Magnetic Bearing

- Prototype No.1: full scale motor with oil lubrication bearing,
- Prototype No.2: motor with domestic magnetic bearing,
- Prototype No.3: full scale helium circulator with domestic bearing, finished hot state 100 hours in nitrogen July, 2014, Shanghai, and to be tested in hot helium condition in ETF-HC,
- Prototype No.4: full scale motor with the magnetic bearing of the final product, tests the catch-down capability.
100 hours hot state in nitrogen, July, 2014, Shanghai

The shaft track of the upper and lower radial bearing
Steam Generator

- Tube fabrication
- Bending
- Welding
- Helical tube assembly
- Vessel fabrication
- Installation of the 19 assemblies to the vessel
- Material tests

Steam generator is the most delaying components in the project, however until now the all fabrication technologies have been finished and tested, the fabrication was started and will be ready in 2016.
5, Fuel fabrication

- INET demo production facility, 100000/Year, 2010.10 finished the first production
- Irradiation test of fuels, Petten, Netherlands, 2014.12.30 to finish irradiation test, results until now are good
- Commercial fuel plant, 300000/Year, finished equipments installation, to start production in 2015
### 6. Costs

<table>
<thead>
<tr>
<th>Feature</th>
<th>Challenging question</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small reactor module power (~100 MWe)</td>
<td>How a 100 MWe HTR-PM can be competed with the large PWR plant, which is 10 times more?</td>
<td>Multi-module plant</td>
</tr>
<tr>
<td>Power density of the HTR-PM is only 1/30 of those in PWRs</td>
<td>HTR-PM RPV is even bigger than a EPR.</td>
<td>The costs of the RPV is only 2% of the total plant cost in PWRs</td>
</tr>
</tbody>
</table>
Multi-module plant: HTR-PM600 as commercial plants for next deployment

- 6 reactor modules (250MWt, 250/750 ℃, 7.0MPa each) connecting to 1 steam turbine (13.25Mpa, 566 ℃), provide a 650 MWe nuclear plant.
- Co-generation of electricity and steam.
- Nearly the same site footprint of PWR plants.
- Capital costs will no exceed 110-120% of the same power generation II+ PWR plants.
HTR-PM600 as commercial plants for next deployment
The costs of RPV is only 2% of the total plant cost in PWRs

1st Decay: 1/10

2nd decay: 1/4
7, Concluding Remarks

- Key components and technologies have been tested and verified. The remain full scale demonstration tests will be finished in months: helium circulator, steam generator, and fuel handling system.
- There are no foreseen difficulties in manufacturing major components. The components will be shipped to the site started from 2015.
- Fuel irradiation test will reach target burn-up in the end of 2014. The equipment installation of the fuel fabrication plant has been finished.
- The concept design of the commercial 600 MWe HTR-PM600 has been finished.
- We are working for the target to connect grid in 2017.