HTR Research and Development Program in China

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Roles of HTRs in China

- Supplement of nuclear power generation for densely and sparsely populated regions
- Providing process steam for heavy oil recovery and petrochemical industry
- As process heat resource for coal gasification and liquefaction
- Hydrogen production
Phase I

In the mid-1970s

Target: building a 100 MWt thorium thermal breeder

Experiments

- A 1:10 pre-stressed concrete reactor vessel (PCRV) modeling test
- A 1:10 all-graphite core structure modeling seismic test
- A test for the fuel elements handling system (including the components)
- A mechanical strength or force test for the inclined specially shaped graphite support beams at the bottom of the core
- A test of the 1:2.7 and 1:1 control rod drive model
- Experiments for two-phase flow stability and vibration-induced wear of the steam generator
- Tests of oil lubricated bearings for helium blowers
- Static sealing test
- Research on chemical reprocessing of the thorium-containing spent fuel
- Nuclear graphite development
- Research of technology for fuel elements
Phase II

In the Sixth Five-Year Plan (1981-1985)

- Basic research
  - Design of the HTR-Module and other types
  - Research on safety features of the HTR-Module
  - Development of computer codes

- Application study
  - Joint study with Siemens and KFA
  - Heavy oil recovery
  - Petro-chemical industry
Phase III

In 1986-2000

- Key technology research
  - A conceptual design and the programming of computer codes
  - Development of a manufacturing process for fuel elements
  - The reprocessing of the thorium-uranium fuel cycle
  - The design of the ceramic internal together with a stress analysis
  - Development of the helium technology
  - Design of the pressure vessels
  - Development of a fuel handling system
  - Development of materials

- Building the HTR-10
Phase IV

In 2000-2010

- Target: Building a HTR-PM with power of 150MWe
  - Operation and safety demonstration tests on the HTR-10
  - Operation of the HTR-10 with the gas turbine cycle
  - Construction of the HTR-PM with power of around 150MWe
  - Hydrogen production
HTR-10 project

Target
To build a high temperature gas-cooled reactor with thermal power of 10 MW (HTR-10) by 2000 years

The sectional drawing of the reactor building
Objectives

- To acquire the experience of HTRs design, construction and operation
- To carry out the irradiation tests for fuel elements
- To verify the inherent safety features of the modular HTR
- To demonstrate the co-generation and gas/steam combined cycle
- To develop the high temperature process heat utilization
Design features

- Spherical fuel elements
- $T_{\text{fmax}}$ lower than 1600°C
- Passive residual heat removal
- Multi-pass charging mode
- Side by side arrangement
- All control rods in reflectors

The cross section of the primary circuit
UO$_2$ Kernels
Coated particles
Spherical fuel balls
## Main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Reactor thermal power</td>
<td>MW</td>
<td>10</td>
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<tr>
<td>Active core volume</td>
<td>m³</td>
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<td>Average power density</td>
<td>MW/m³</td>
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<td>Primary helium pressure</td>
<td>MPa</td>
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<td>Helium outlet temperature</td>
<td>ºC</td>
<td>700/900</td>
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<td>Helium mass flow rate</td>
<td>Kg/s</td>
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<td>Fuel</td>
<td>UO₂</td>
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<td>U-235 enrichment of fresh fuel elements</td>
<td>%</td>
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<tr>
<td>Diameter of spherical fuel elements</td>
<td>Mm</td>
<td>60</td>
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<td>Number of spherical fuel elements</td>
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<td>Refueling mode</td>
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<td>Multi-pass continuously</td>
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<tr>
<td>Average discharge burnup</td>
<td>MWd/tU</td>
<td>80,000</td>
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Licensing procedure

- Licensing of the construction permit
  - EIR and PSAR
- Licensing of the first core loading permit
  - FEIR and FSAR
- Licensing of power up
Main Licensing Safety Issues

- Fuel elements
- Source term
- Accident analysis
- Safety classification
- Containment design
Time schedule of licensing

- 1992.12 EIR and Site report
- 1993.12 PSAR for the Construction Permit
- 1994.06 EIR for the Construction Permit
- 1994.12 Issuing the Construction Permit
- 2000.10 EIR for the First Loading Permit
- 2000.10 FSAR for the First Loading Permit
- 2000.11 Issuing the First Loading Permit
- 2002.11 issuing the Power Up Permit
Construction

- 1995.06  The first tank of concrete
- 1997.10  Reactor building
- 1998.11  Installation of three PVs
- 1999.12  Installation of reactor internal
- 2000.04  Closing RPV head
- 2000.05  Power conversion unit
- 2000.11  All systems
Foundation of the reactor building
Reactor building
The HTR-10 site
Handling RPV into reactor building
Handling reactor internal
Lower half structure of the hot gas chamber
Top reflectors
Top view of reactor pressure vessel and steam generator pressure vessel
(side by side arrangement)
Engineering experiments

- A hot gas duct performance test
- Measurement of the temperature mixture degree at the core bottom
- A two-phase flow stability test for the once-through steam generator
- A performance test for the pulse pneumatic fuel handling system
- A performance test of the control rods driving mechanism
- A validation and verification test for the full digital reactor protection systems
- A test for the measurement of the neutron absorption cross-section of the reflector graphite
- A performance test for the helium circulator
Commissioning

- **Phase A:** Pre-operational tests for the Components and systems
- **Phase B:** First core loading
  - The first criticality
  - Zero power physical tests
  - Hot tests of systems
  - Low power tests
- **Phase C:** Power up tests
  - Full power operation test
Time schedule for commissioning

- 2000.12.01 First criticality at air condition
- 2002.07.16 Re-criticality at helium condition
- 2003.01.07 Synchronization at 3MWt
- 2003.01.29 Full power operation for 72h
Loading the first ball
First criticality

Experimental critical number of balls is in good agreement with predicted one.

Predicated number of balls: 16759

Experimental number of balls: 16890
### Main parameters at 10MWt

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design</th>
<th>Operation</th>
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<td>Thermal power</td>
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<td>Electric power</td>
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<td>Helium pressure</td>
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<td>Outlet He temperature</td>
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<td>23900</td>
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<td>Steam pressure</td>
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<td>3.45</td>
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<td>Feed water temperature</td>
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<td>100</td>
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<td>Steam temperature</td>
<td>435</td>
<td>430</td>
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<tr>
<td>Water flow rate</td>
<td>3.49</td>
<td>3.56</td>
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</table>
Temperature profile at full power
HTR-10 operation history in 2003

Total: 75 days in operation; 4810.4MWhr
Spherical fuel balls

**Irradiated test**
Russian IVV-2M reactor

**Sample**
4 balls and some coated particles

**Irradiation condition**
- Temperature: 1000 °C
- Atmosphere: Helium
- Burnup: about 100,000 MWd/t
- Heat up: 1200 °C-1250 °C
**Kr$^{85m}$ Release Rate (R/B) as a Function of Burnup**
Fission Gas Release Rate (R/B) as a Function of Irradiation Time of No. 5 (Cap. 2) Spherical Fuel Element

Burnup/[MWd/t(U)]
Safety demonstration tests

- Loss of helium flow
- Turbine trip
- Loss of off site power supply
- Helium circulator trip without scram
- Reactivity insertion (5mk) without scram
- Helium circulator trip without closing isolate valve
Helium circulator trip without scram

- **Initial conditions**

  Thermal power - 3 MW
  Turn off the helium circulator power
  The HTR-10 was not shut down

- **Results**

  The isolate valve of the helium circulator was closed within 15 seconds
  Isolate valves at second circuit automatically closed
  The HTR-10 was shut down by negative temperature coefficient
  The HTR-10 operated at some power level
  All of parameters met operational limited specification
Power and revolution transient

![Graph showing power and revolution transient for a blower with time on the x-axis and power/revolution on the y-axis. The graph includes a blue line for power (kw) and a red line for revolution (rpm).]
Temperature transient

![Temperature graph with time and temperature axes, showing various time periods from 15:20 to 18:20 and temperature values from 0 to 900. The legend includes markers for t-jka01a, t-jka02f, t-jka02l, t-jka03b, t-jka04c, and t-jka06c.]
Reactivity insertion (5mk) without scram

Initial conditions

- Thermal power: 3 MW
- A control rod was withdrawn at 10mm/sec.
- The maximum reactivity insert is 5mk

Results

- The power was rapidly raised
- The helium circulator was shut down by reactor protection system
- The isolate valve of the helium circulator automatically closed
- Isolate valves at second circuit automatically closed
- The HTR-10 operated at some power level by negative T coefficient
- All of parameters met operational limited specification
Power transient

![Graph showing power transient](image)

- **Power (KW)**
- **Position of CR (mm)**

Axes:
- **Time (Sec)**
- **Power (KW)**
- **Position of CR (mm)**

Values:
- **Time (Sec)**: 0, 100, 200, 300, 400, 500
- **Power (KW)**: 0, 100, 200, 300, 400, 500, 600, 700, 800
- **Position of CR (mm)**: 0, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000
Further development

- Operation and safety demonstration tests of the HTR-10
- Operation of gas turbine cycle
- Construction of the HTR-PM
- Hydrogen production
Operation and tests

- Heating mode operation
- Electricity production
- Experience feedback
- Operator training
- Benchmark calculations
- Codes validation
- Safety demonstration tests
Operation of gas turbine cycle

Objective

To get more experience for the HTR-PM

Steps

- Joint design with OKBM
- Installation of gas turbine cycle system
- Operation of gas turbine cycle
Flow diagram of the HTR-10 with gas turbine cycle
<table>
<thead>
<tr>
<th>Parameters for HTR-10 with the gas turbine cycle</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POWER CONVERSION UNIT</strong></td>
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<tr>
<td>Thermal power transferred to PCU, MW</td>
<td>10.00</td>
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<tr>
<td>Thermal power transferred to the gas-turbine cycle, MW</td>
<td>6.755</td>
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<tr>
<td>Thermodynamic efficiency, %</td>
<td>32.247</td>
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<tr>
<td>Gross efficiency (el.) of the RP gas-turbine part, %</td>
<td>29.314</td>
</tr>
<tr>
<td>Total relative pressure loss, %</td>
<td>11.8</td>
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<tr>
<td>Total relative helium leaks, %</td>
<td>5.3</td>
</tr>
<tr>
<td>PCU mass, t</td>
<td>64</td>
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<tr>
<td>PCU height, mm</td>
<td>9100</td>
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<tr>
<td>Water temperature at the PCU inlet, °C</td>
<td>20.0</td>
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<tr>
<td><strong>REACTOR</strong></td>
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</tr>
<tr>
<td>Temperature at the core inlet/outlet, °C</td>
<td>330/752</td>
</tr>
<tr>
<td>Pressure at the inlet/outlet, MPa</td>
<td>1.5312/1.5159</td>
</tr>
<tr>
<td>Helium flowrate, kg/s</td>
<td>4.55</td>
</tr>
</tbody>
</table>
Features:

- One shaft
- Vertical configuration
- EMB
- Higher rev

1 – Nozzle
2 – Gas cooler
3 – Shell
4 – Plate
5 – Chamber
6 – Intercooler module
7 – Precooler module
8 – Expansion pieces
9 – Pipeline
10 – Recuperator
11 – Turbomachine
12 – PCU vessel
13 – Header
14 – Header
15 – Nozzle
16 – Pipeline
17 – Lead-out
PCU in the HTR-10 steam generator pressure vessel
HTR-10 layout with PCU in steam generator vessel
Main components for the HTR-10 with the gas turbine cycle

- Gas Turbine
- Electrical Magnetic Bearings
- Generator
- Frequency Converter
- LP/HP Compressor
- Recuperator
- Pre-/inter- Cooler
- Generator Gas Cooler
- Pressure Vessel
Turbine machine

Generator
Construction of the HTR-PM

**Target**

Starting to build a prototype HTR (HTR-PM) with output of around 150 MWₑ in 2006 in China

**Design features**

- Pebble bed type
- Annular core
- Steam turbine cycle
- Reheat circuit
- High efficiency
## Main parameters of HTR-PM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor thermal power</td>
<td>MW</td>
<td>371</td>
</tr>
<tr>
<td>Active core diameter/height</td>
<td>m</td>
<td>2.00-4.00/9.43</td>
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<tr>
<td>Average power density</td>
<td>MW/m³</td>
<td>4.28</td>
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<td>Primary helium pressure</td>
<td>MPa</td>
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<td>Helium inlet temperature</td>
<td>°C</td>
<td>250</td>
</tr>
<tr>
<td>Helium outlet temperature</td>
<td>°C</td>
<td>750</td>
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<tr>
<td>Helium mass flow rate</td>
<td>Kg/s</td>
<td>145</td>
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<tr>
<td>Fuel</td>
<td>UO₂</td>
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<tr>
<td>U-235 enrichment of fresh fuel elements</td>
<td>%</td>
<td>8.77</td>
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<tr>
<td>Diameter of spherical fuel elements</td>
<td>mm</td>
<td>60</td>
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<td>Number of spherical fuel elements</td>
<td>ball</td>
<td>479358</td>
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<tr>
<td>Number of graphite balls</td>
<td>ball</td>
<td>159786</td>
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<tr>
<td>Average discharge burnup</td>
<td>MWd/tU</td>
<td>80,000</td>
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</table>
## Main parameters of HTR-PM

<table>
<thead>
<tr>
<th>Refueling mode</th>
<th>Multi-pass continuously</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of control rods</td>
<td>set</td>
</tr>
<tr>
<td>Number of small absorb ball systems</td>
<td>set</td>
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<tr>
<td>Main steam pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>Main steam temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Main steam flow rate</td>
<td>t/h</td>
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<tr>
<td>Feed water temperature</td>
<td>°C</td>
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<tr>
<td>Power from steam turbine</td>
<td>MW</td>
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<tr>
<td>Gross efficiency</td>
<td>%</td>
</tr>
<tr>
<td>Net output power</td>
<td>MW</td>
</tr>
<tr>
<td>Net efficiency</td>
<td>%</td>
</tr>
</tbody>
</table>
HTR-PM with the steam turbine cycle
01. Control rod driving systems
02. Reactor pressure vessel
03. Charging tubes
04. Pressing blocks
05. Top insulation
06. Top reflectors
07. Reactor internal
08. Guiding tube for control rods
09. Side plates
10. Core
11. Supporting springs
12. Bottom reflectors
13. Side reflectors
14. Bottom insulators
15. Rising tube for fuel
16. Reducer
17. Discharging tube
18. Bottom tanks for small balls
19. Discharging tubes for small balls
20. Gas carrying channels
21. Shielding plugs
22. Top tanks for small balls
01. Charging tubes
02. Top insulations
03. Top reflectors
04. Cold gas chambers
05. Central graphite plugs
06. Channels for control rods
07. Channels for cold gas
08. Side reflectors
09. Side insulations
10. Reactor core chamber
11. Bottom reflectors
12. Hot gas chamber
13. Discharging tube
14. Bottom reflectors
15. Keys
16. Square keys
17. Channels for small balls
18. Tenons
19. Hot gas tube
Project progress

- HTR-PM is supported by governmental authorities
- China Hua Neng Group, China Nuclear Engineering Group Co. and Tsinghua University signed MOU
- Selection of the site for the HTR-PM
- HTR technology will be involved in long term R&D program
# Time Schedule

<table>
<thead>
<tr>
<th>Activity</th>
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<th>02</th>
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Conclusions

- China HTR program is going well as scheduled. The HTR-10 reached full power in 2003. Measured values of main parameters are good match with predicated one.

- Preliminary safety demonstration tests show that the HTR-10 is a safety reactor, which meets design technical specification.

- Further development of the HTR-10 is planned.