HTR Research and Development Program in China

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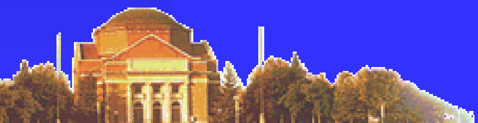
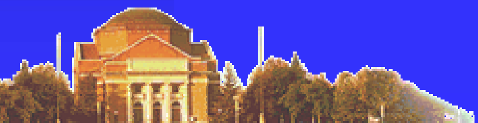


Roles of HTRs in China

- 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



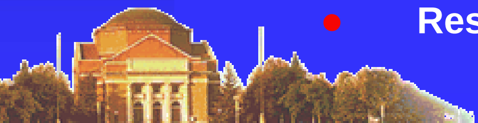
Phase I

- **In the mid-1970s**

  Target---- building a 100 MW_t 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**

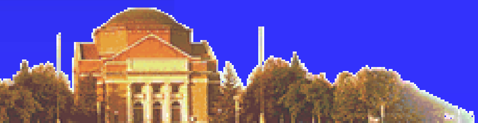
Phase III

- **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**

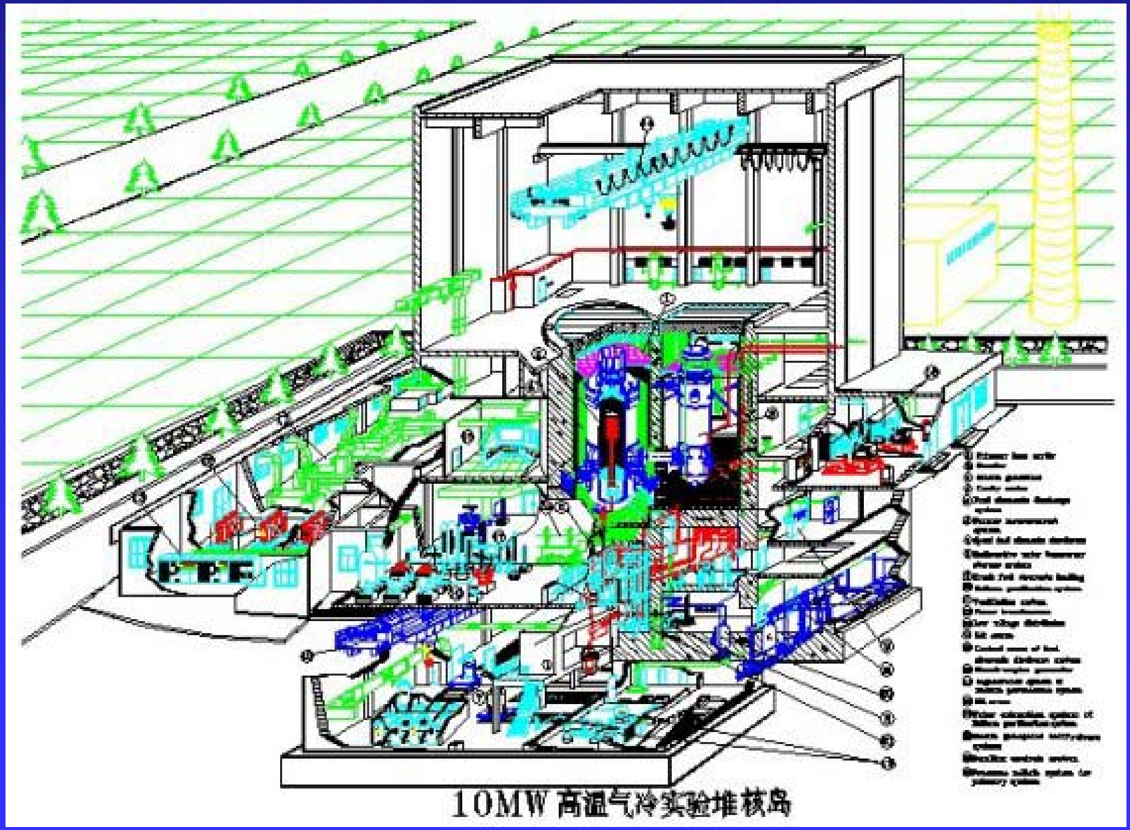


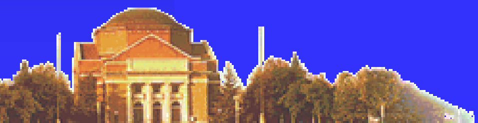
HTR-10 project

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



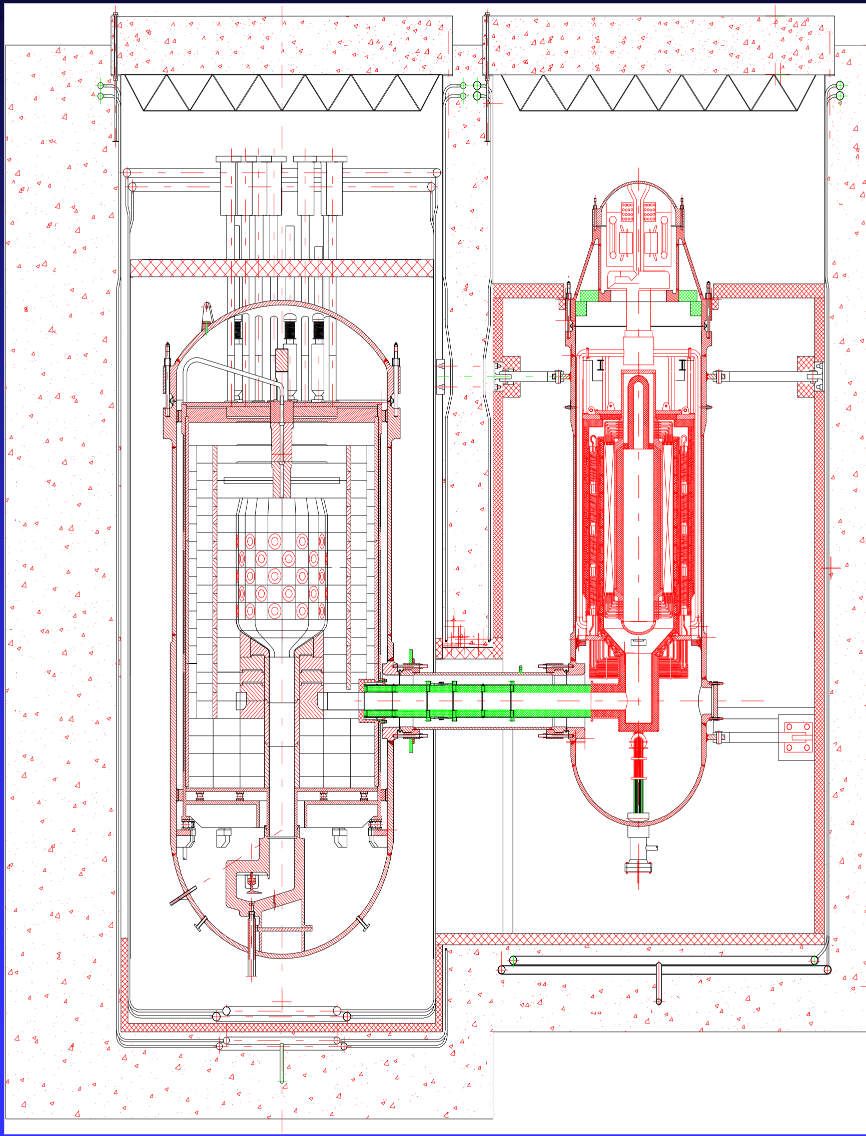


Objectives

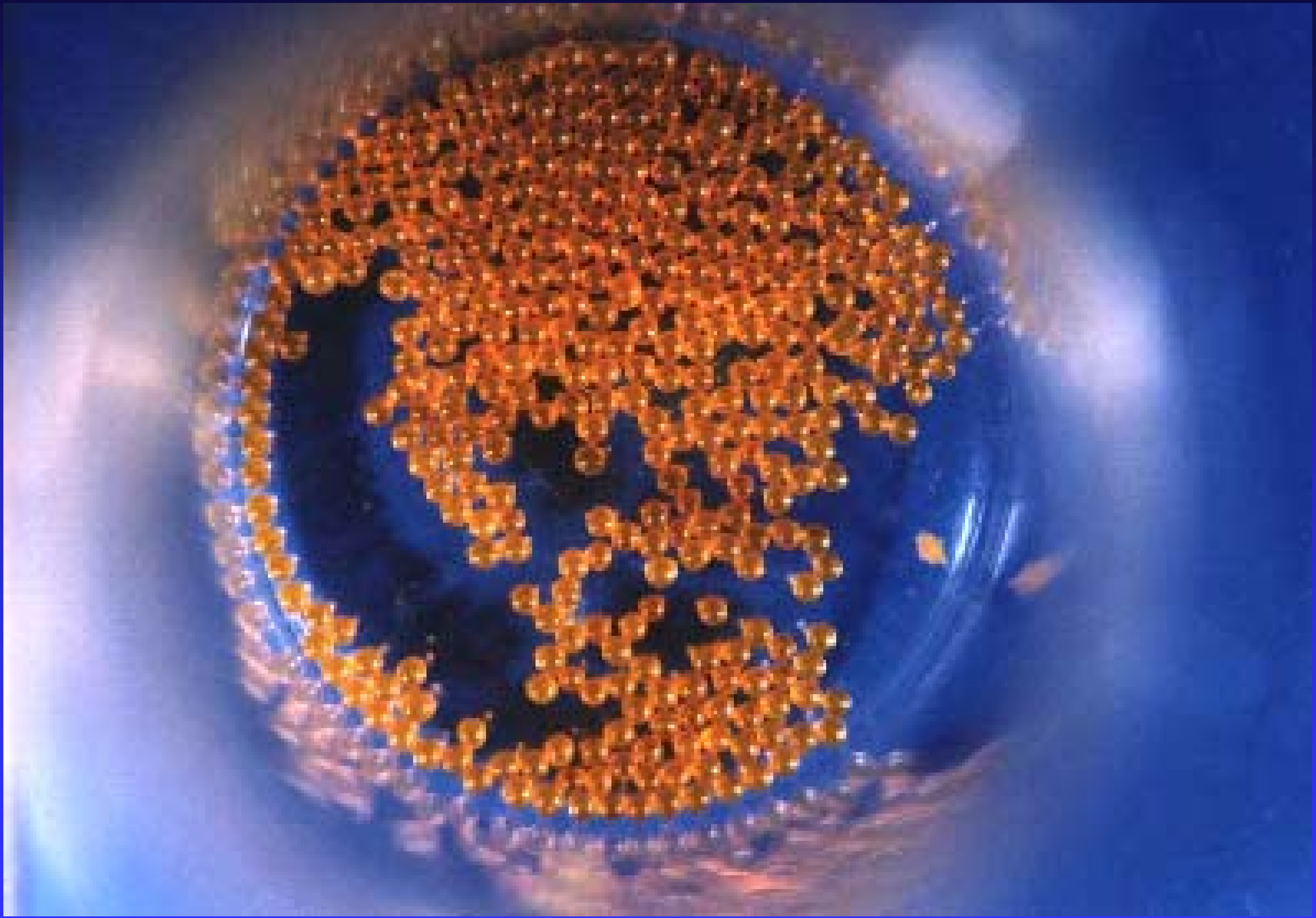
- To acquire the experience of HTRs design, construction and operation
- To carry out the irradiation tests for fuel elements
- To verify the inherent safety features of the modular HTR
- To demonstrate the co-generation and gas/steam combined cycle
- To develop the high temperature process heat utilization

Design features

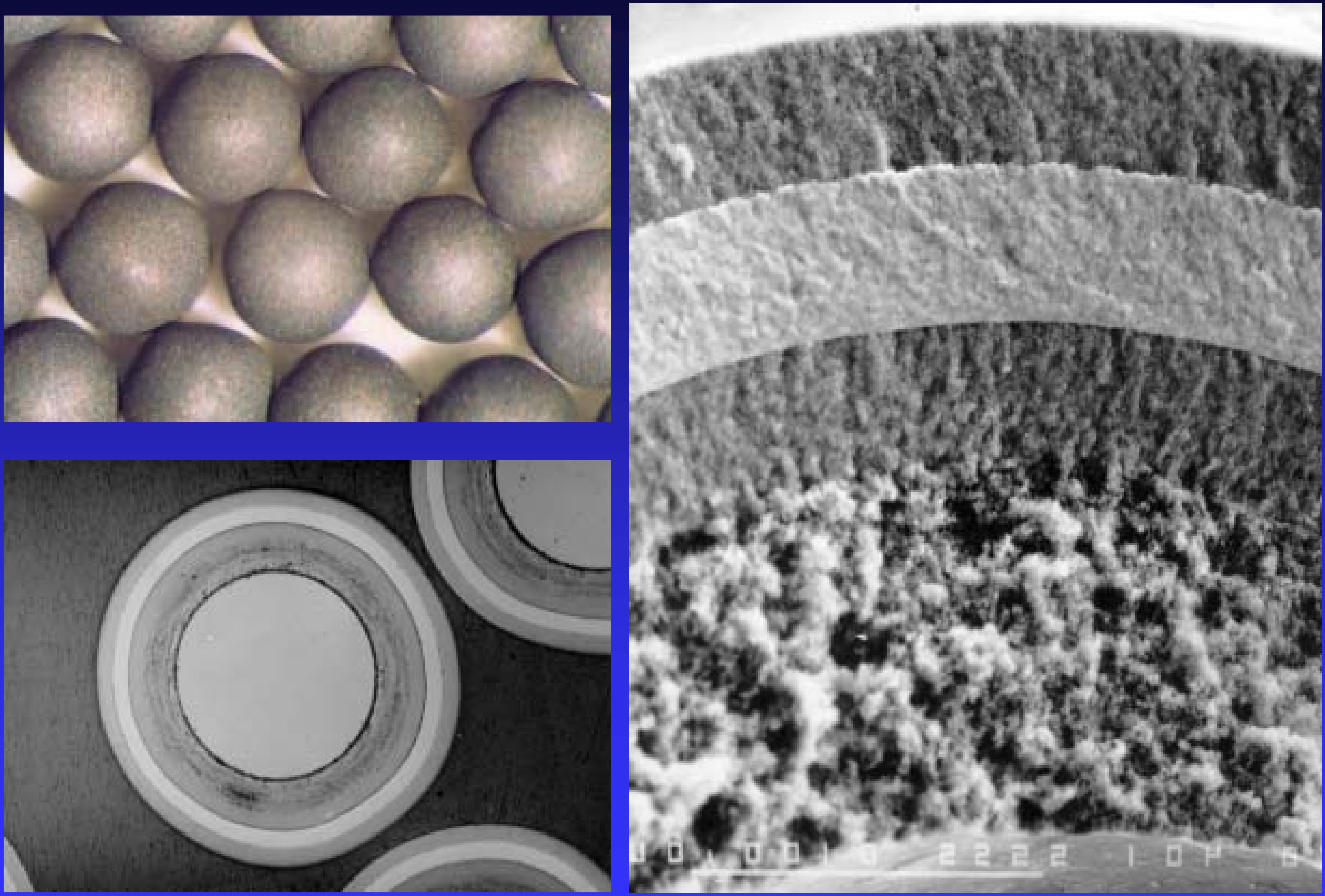
- Spherical fuel elements
- T_{fmax} lower than 1600 C^o
- Passive residual heat removal
- Multi-pass charging mode
- Side by side arrangement
- All control rods in reflectors



The cross section of the primary circui



UO_2 Kernels



Coated particles

Spherical fuel balls

Main parameters

Reactor thermal power	MW	10
Active core volume	m^3	5
Average power density	MW/m^3	2
Primary helium pressure	MPa	3
Helium inlet temperature	^oC	250/300
Helium outlet temperature	^oC	700/900
Helium mass flow rate	Kg/s	4.3/3.2
Fuel		UO_2
U-235 enrichment of fresh fuel elements	%	17
Diameter of spherical fuel elements	Mm	60
Number of spherical fuel elements		27000
Refueling mode		Multi-pass continuously
Average discharge burnup	MWd/tU	80,000

Licensing procedure

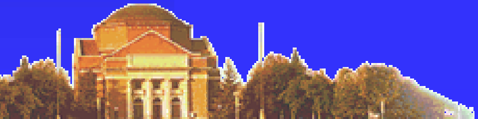
- Licensing of the construction permit

  EIR and PSAR

- Licensing of the first core loading permit

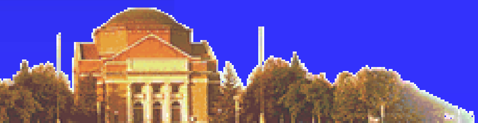
  FEIR and FSAR

- Licensing of power up



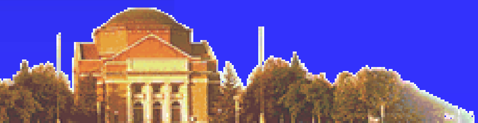
Main Licensing Safety Issues

- Fuel elements
- Source term
- Accident analysis
- Safety classification
- Containment design



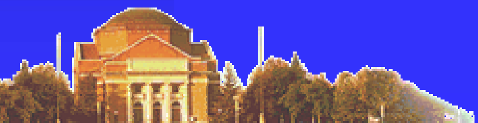
Time schedule of licensing

- 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

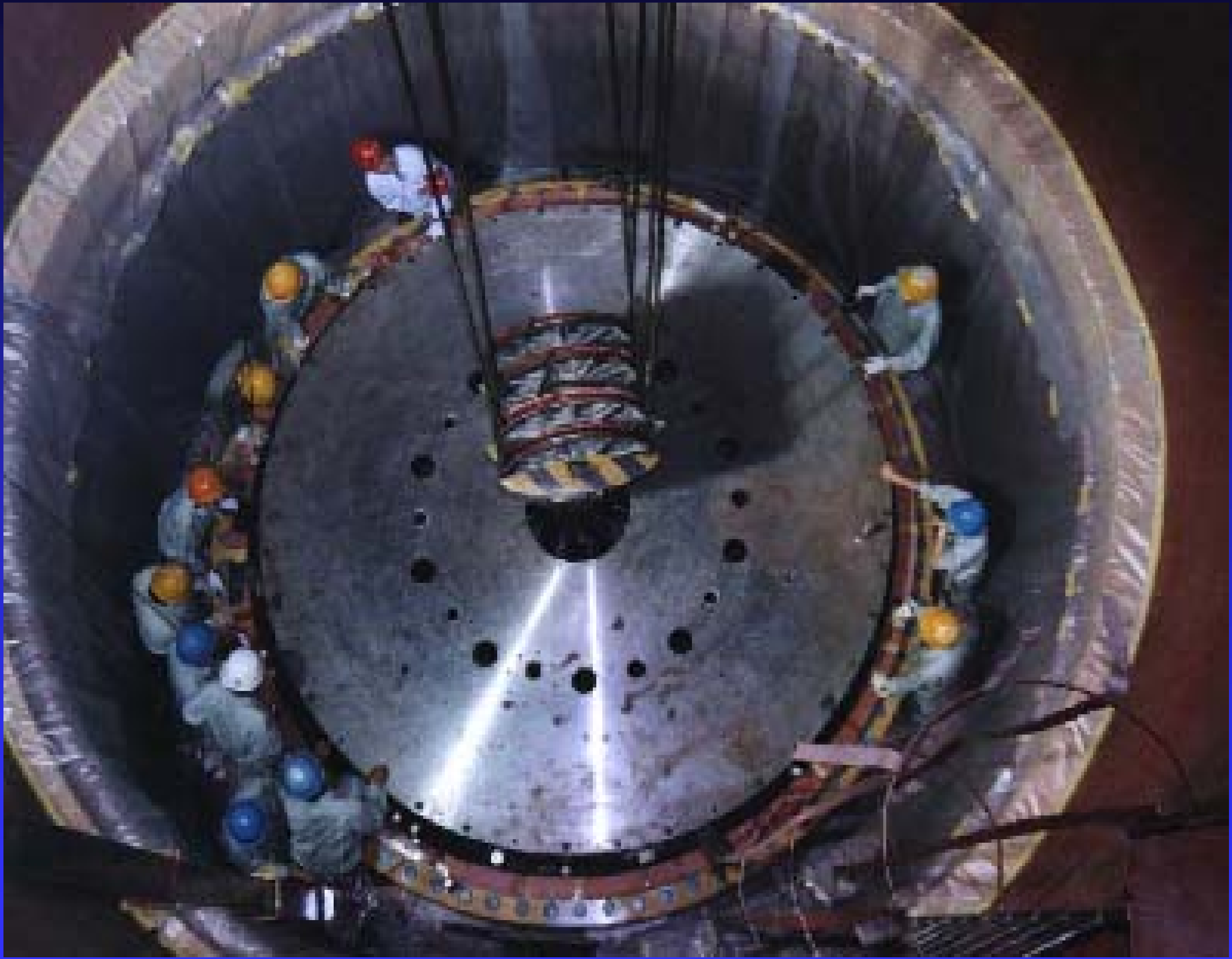


Foundation of the reactor building

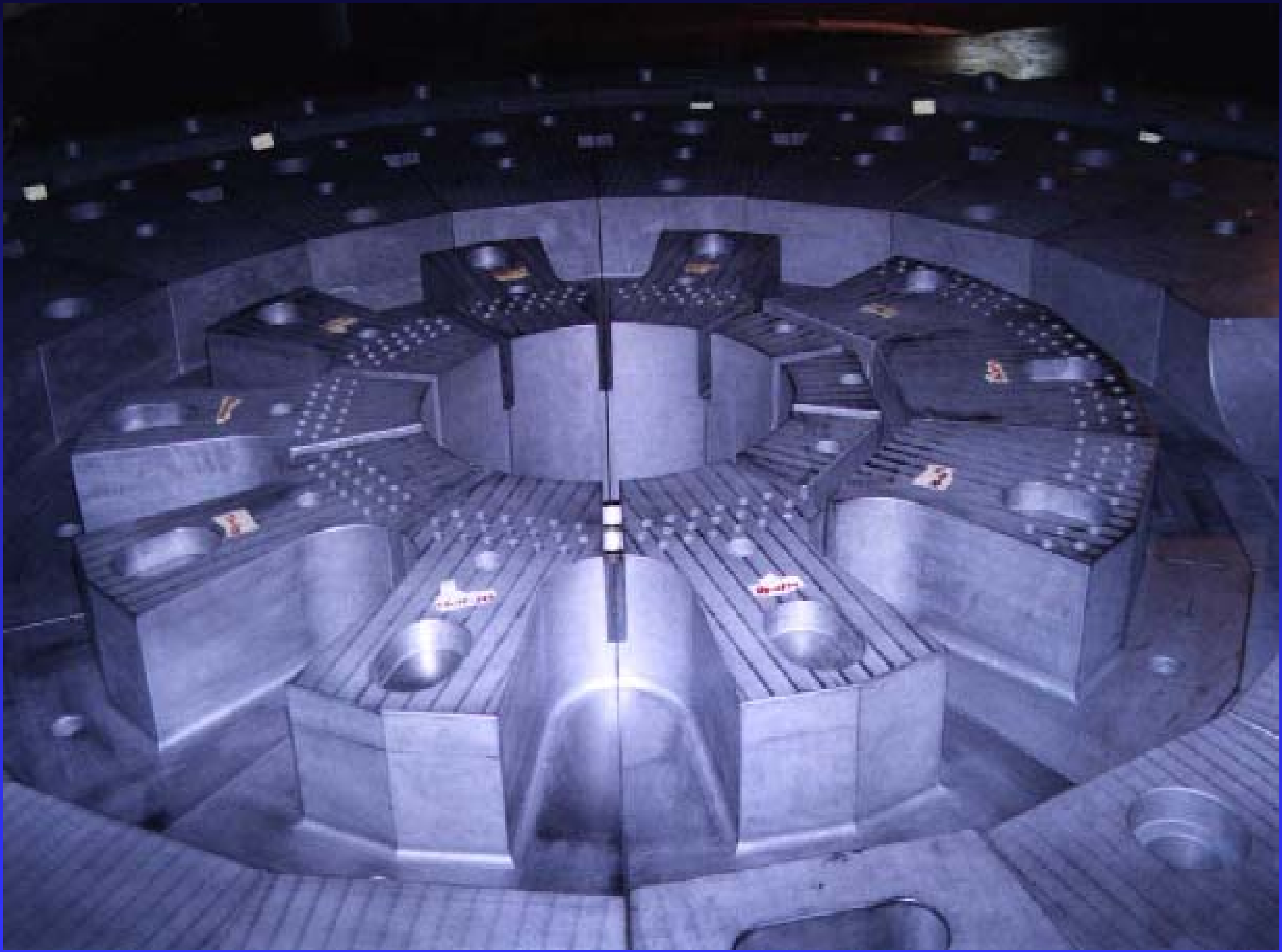
Reactor building

The HTR-10 site

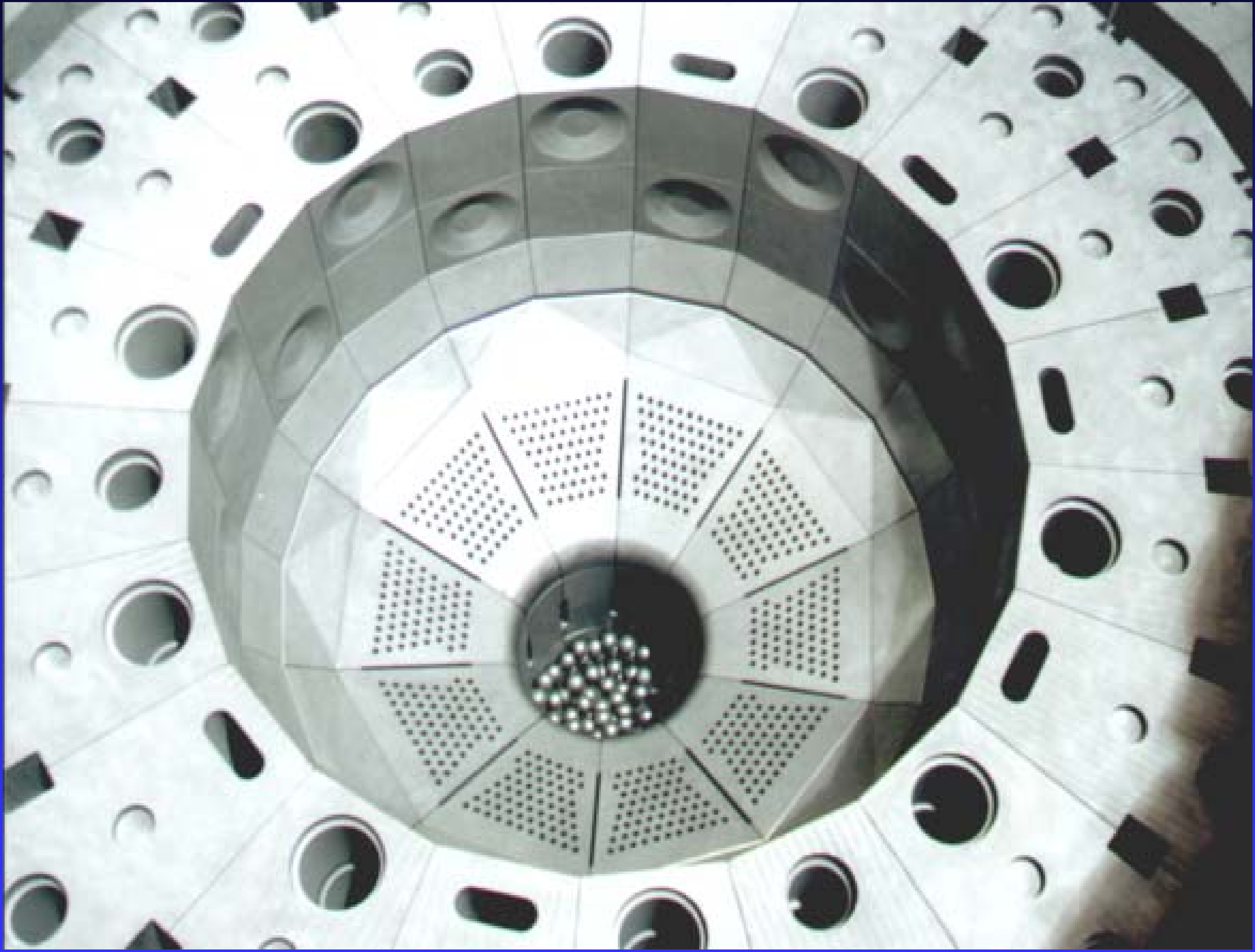
Handling RPV into reactor building



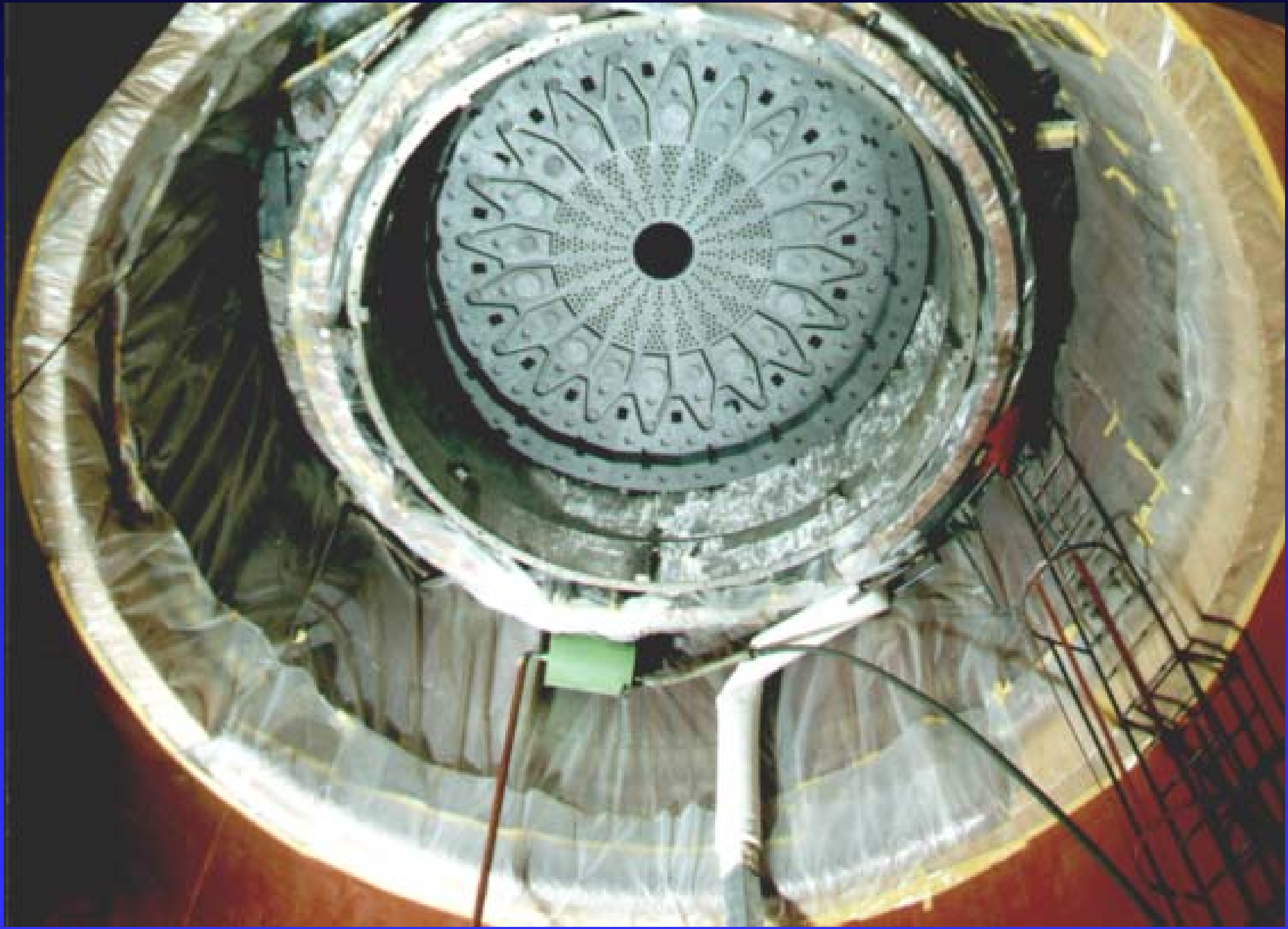
Handling reactor internal



Lower half structure of the hot gas chamber



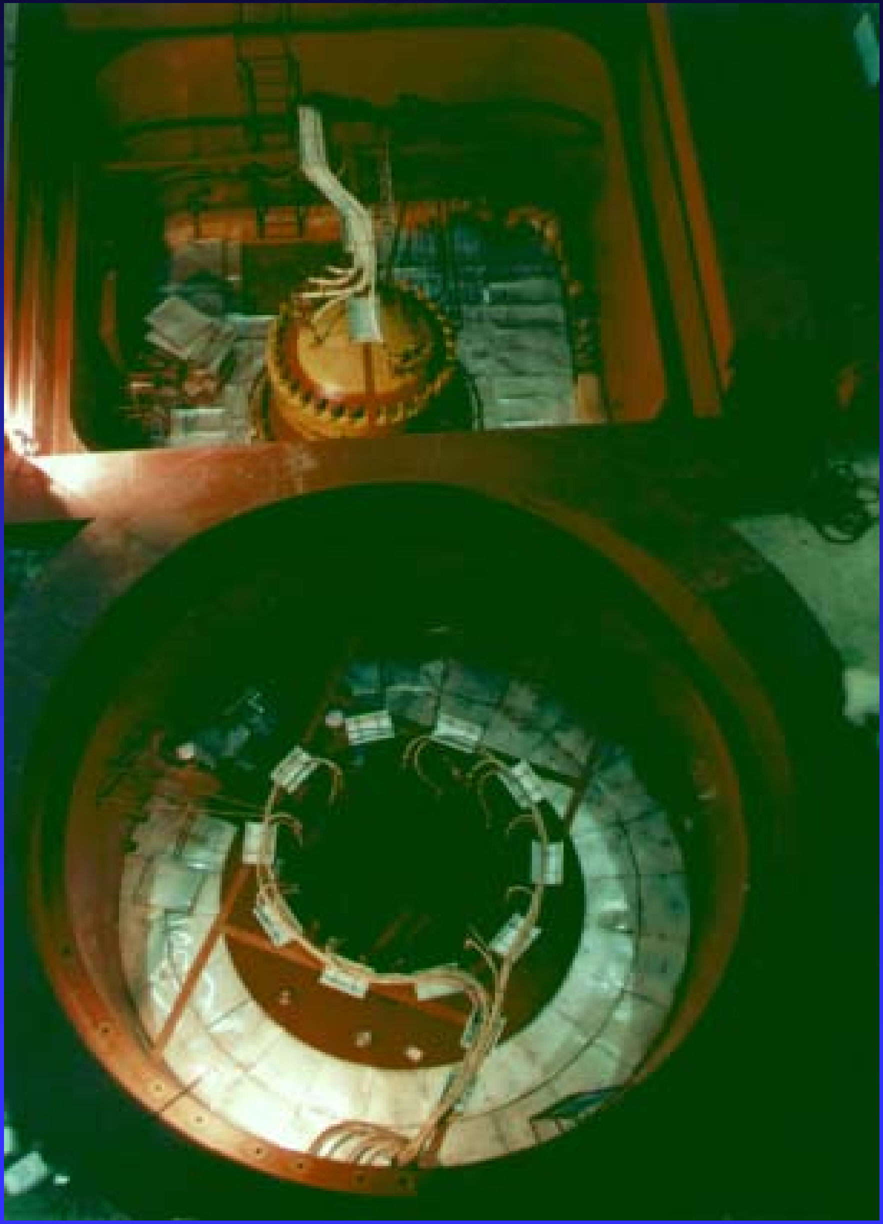
Core cross section



Top reflectors

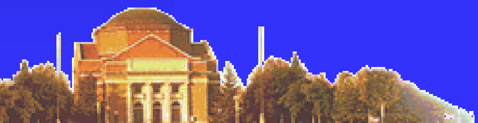
Top view of reactor pressure vessel and steam generator pressure vessel

(side by side arrangement)



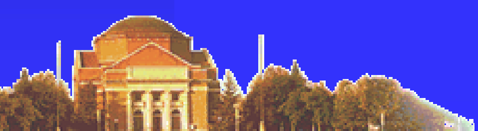
Engineering experiments

- 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



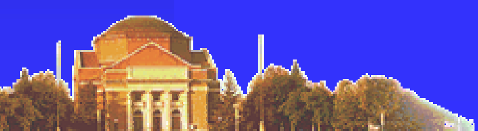
Commissioning

- **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**



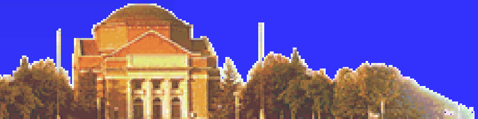
Loading the first ball

First criticality

- **Experimental critical number of balls is in good agreement with predicated one.**

Predicated number of balls: 16759

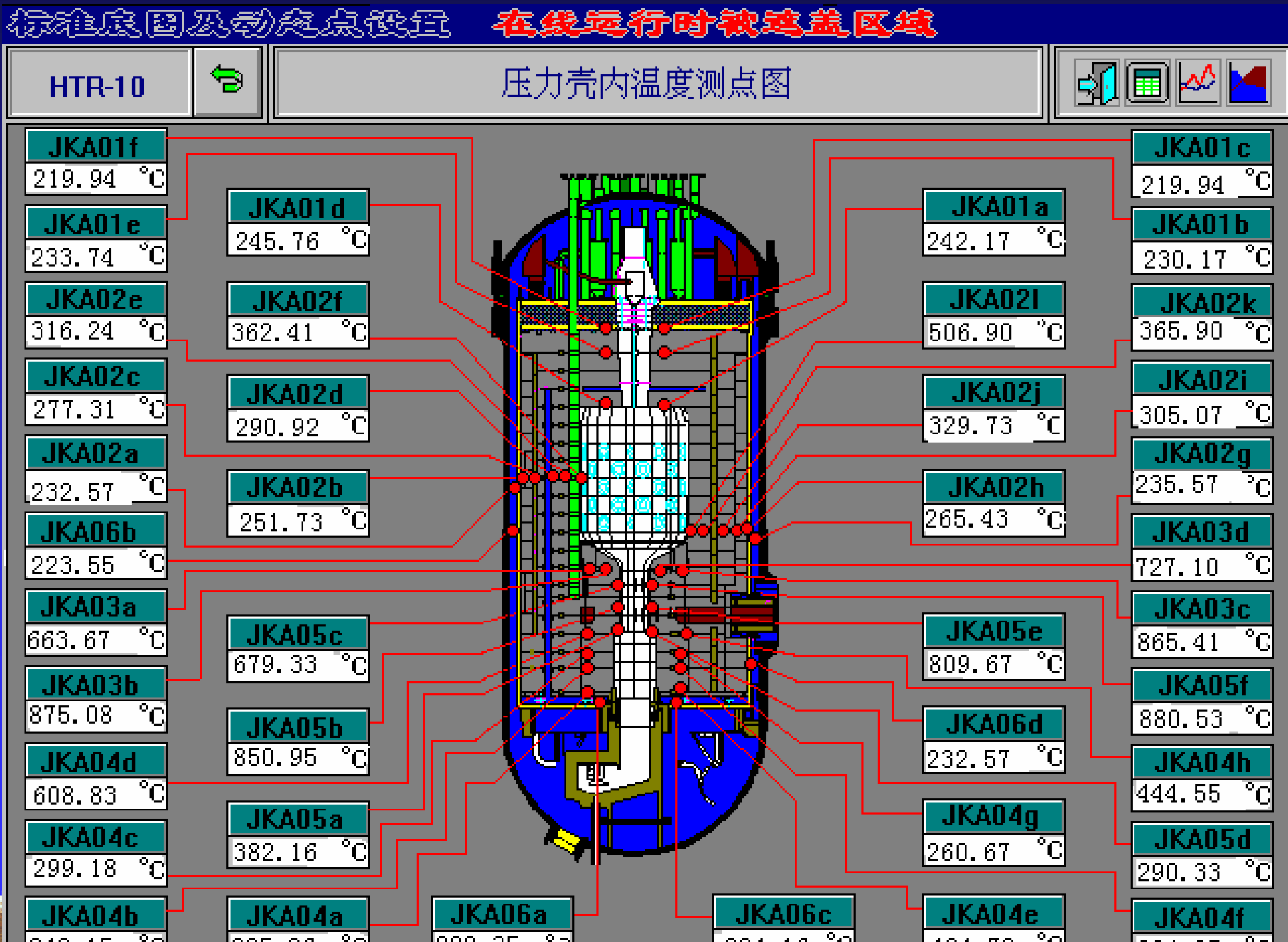
Experimental number of balls: 16890



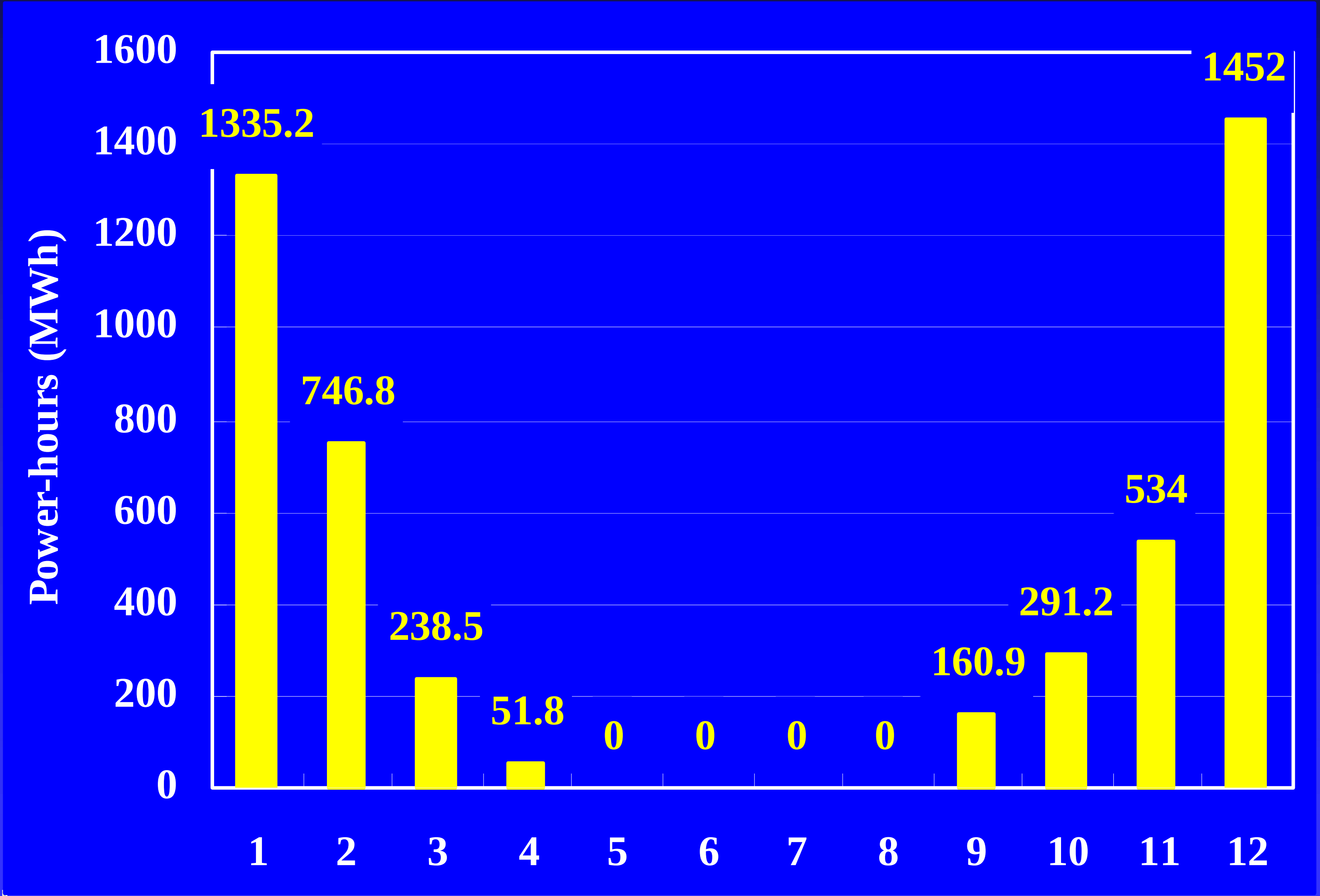
Main parameters at 10MWt

Parameters		Design	Operation
Thermal power	MW	10	10.221
Electric power	MW	2.5	2.49
Helium pressure	MPa	3.0	2.93
Inlet He temperature	ºC	250	236.2
Outlet He temperature	ºC	700	700.1
Helium flow rate	kg/s	4.32	3.99
Number of fuel elements		27000	23900
Steam pressure	MPa	3.5	3.45
Feed water temperature	ºC	104	100
Steam temperature	ºC	435	430
Water flow rate	kg/s	3.49	3.56

Temperature profile at full power



HTR-10 operation history in 2003



Total: 75 days in operation; 4810.4MWhr

Spherical fuel balls

<u>Irradiated test</u>

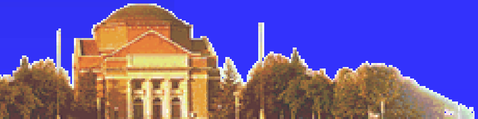
Russian IVV-2M reactor

<u>Sample</u>

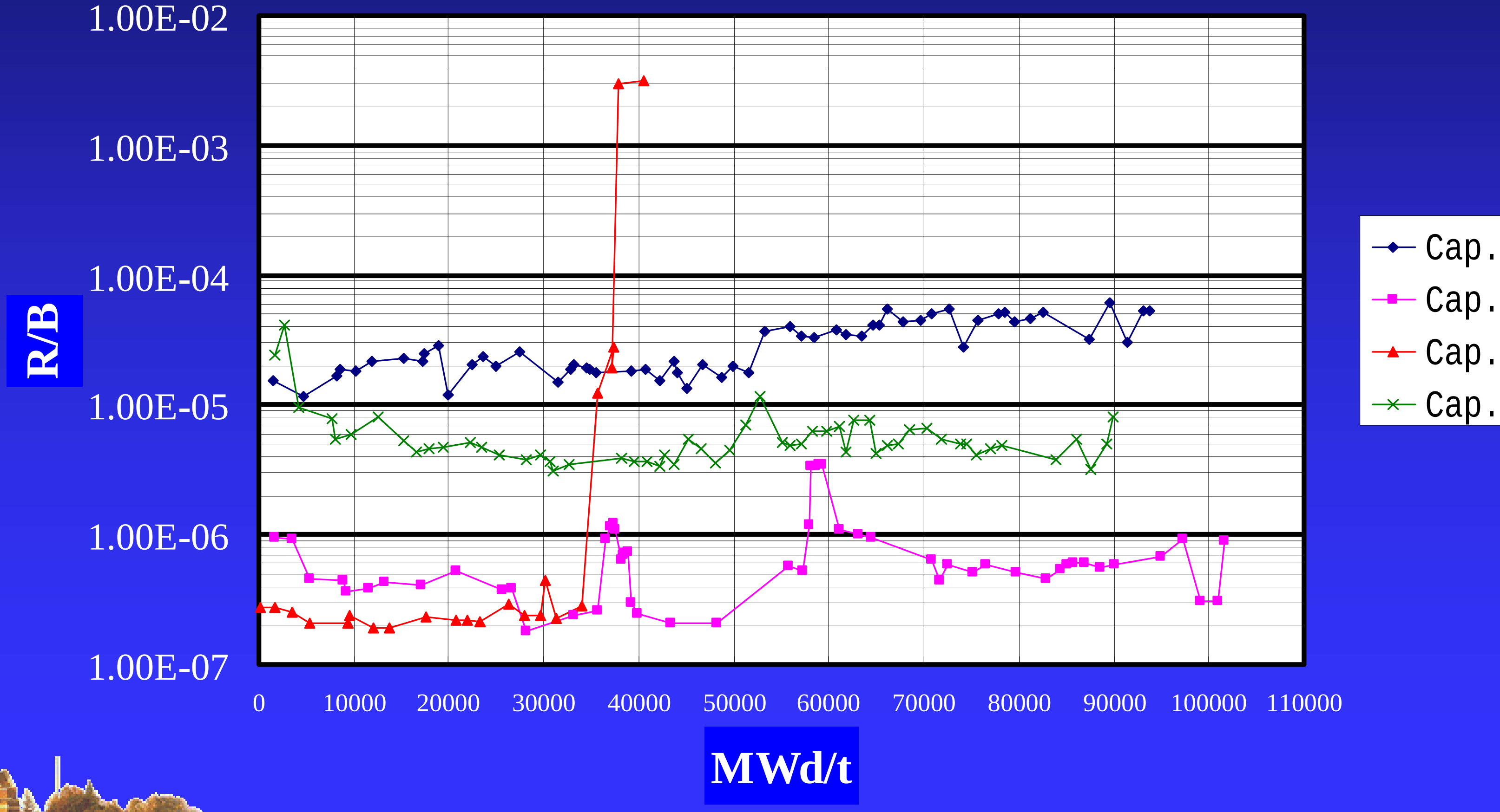
4 balls and some coated particles

<u>Irradiation condition</u>

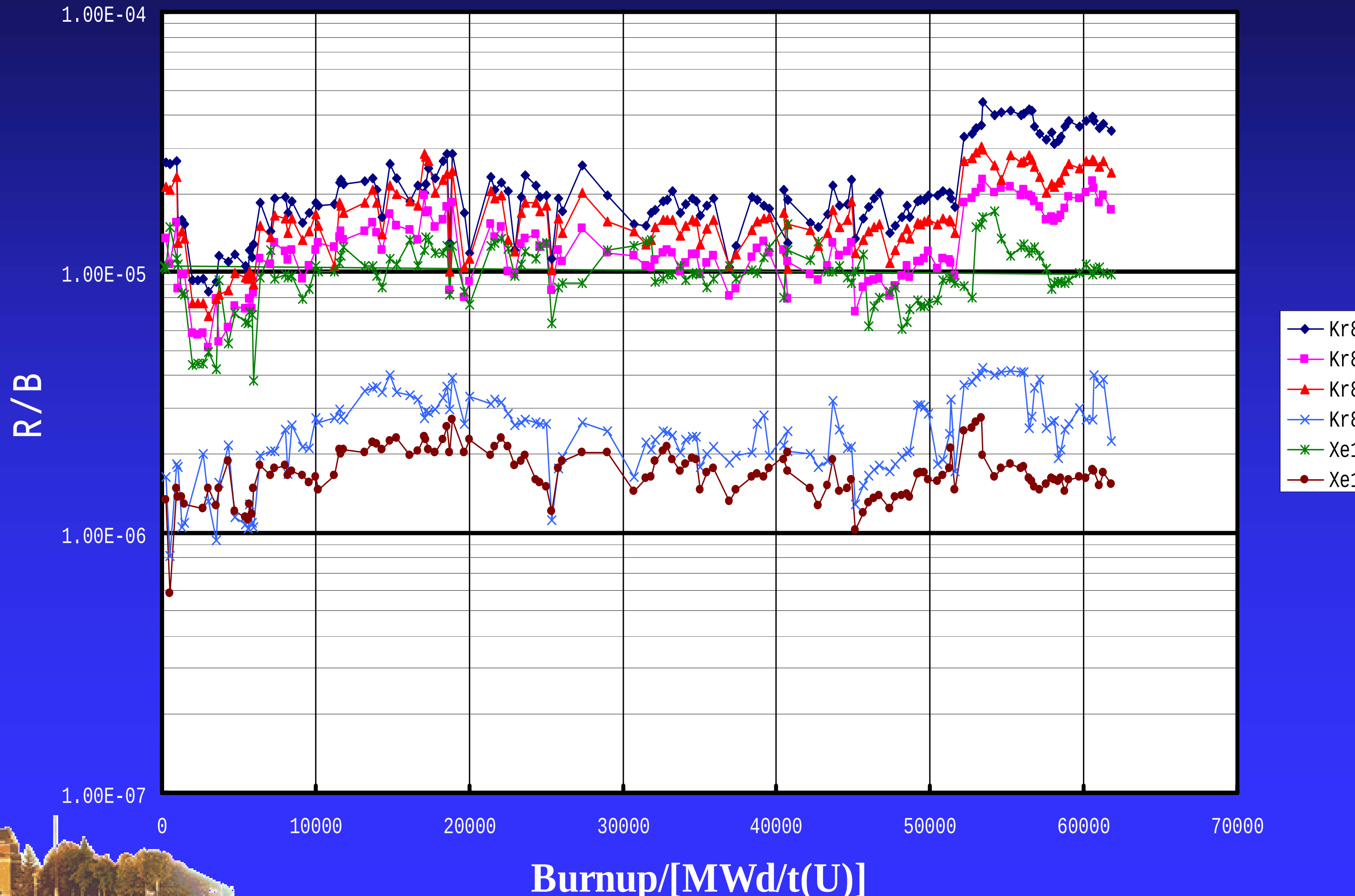
- **Temperature: 1000 $^{\circ}$C**
- **Atmosphere: Helium**
- **Burnup: about 100,000 MWd/t**
- **Heat up: 1200 $^{\circ}$C-1250 $^{\circ}$C**



Kr^{85m} Release Rate (R/B) as a Function of Burnup

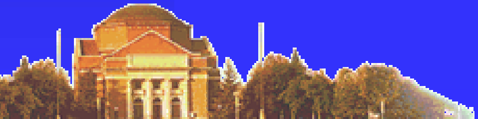


Fission Gas Release Rate (R/B) as a Function of Irradiation Time of No.5(Cap.2) Spherical Fuel Element



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

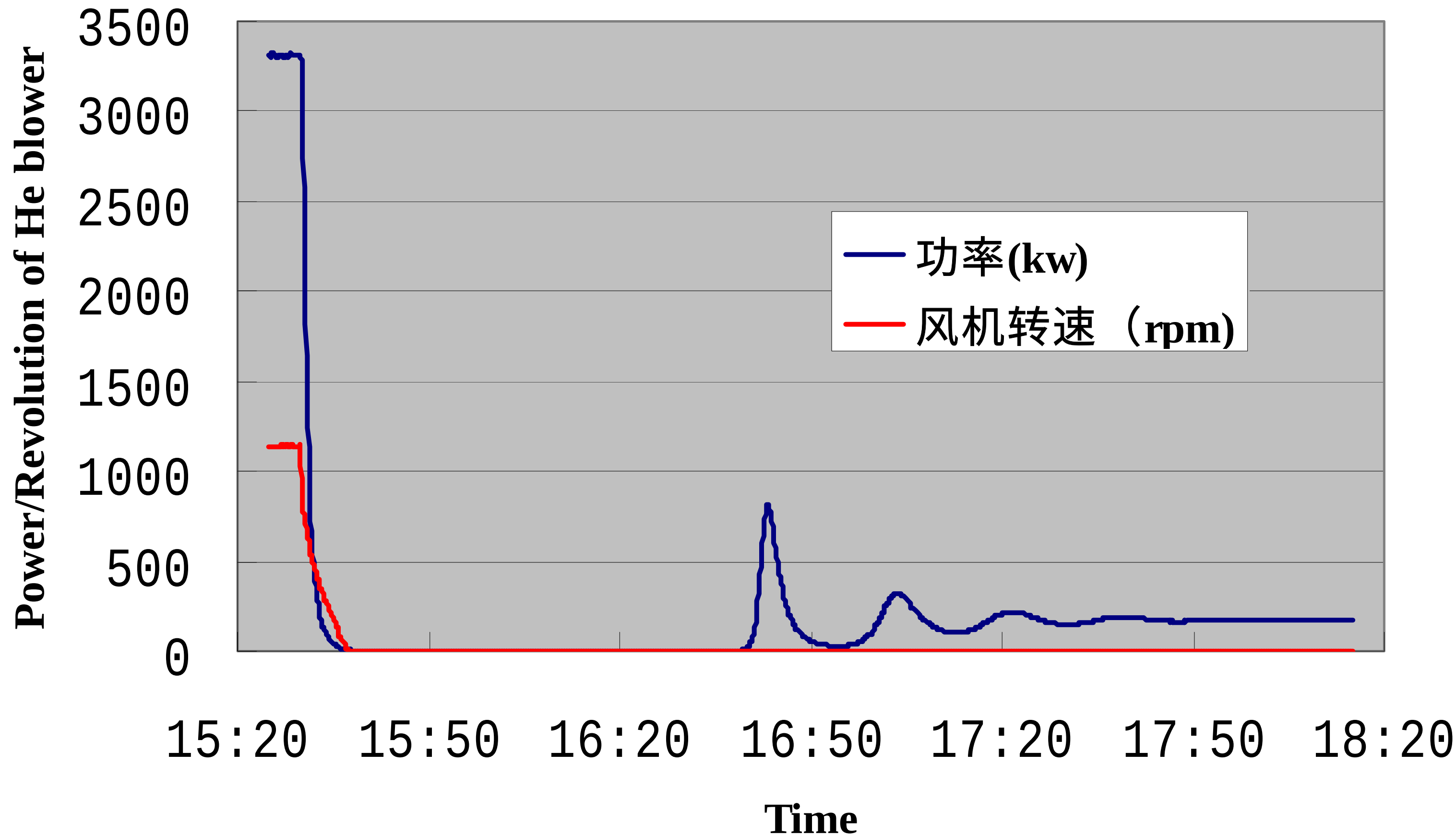
- **Initial conditions**

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

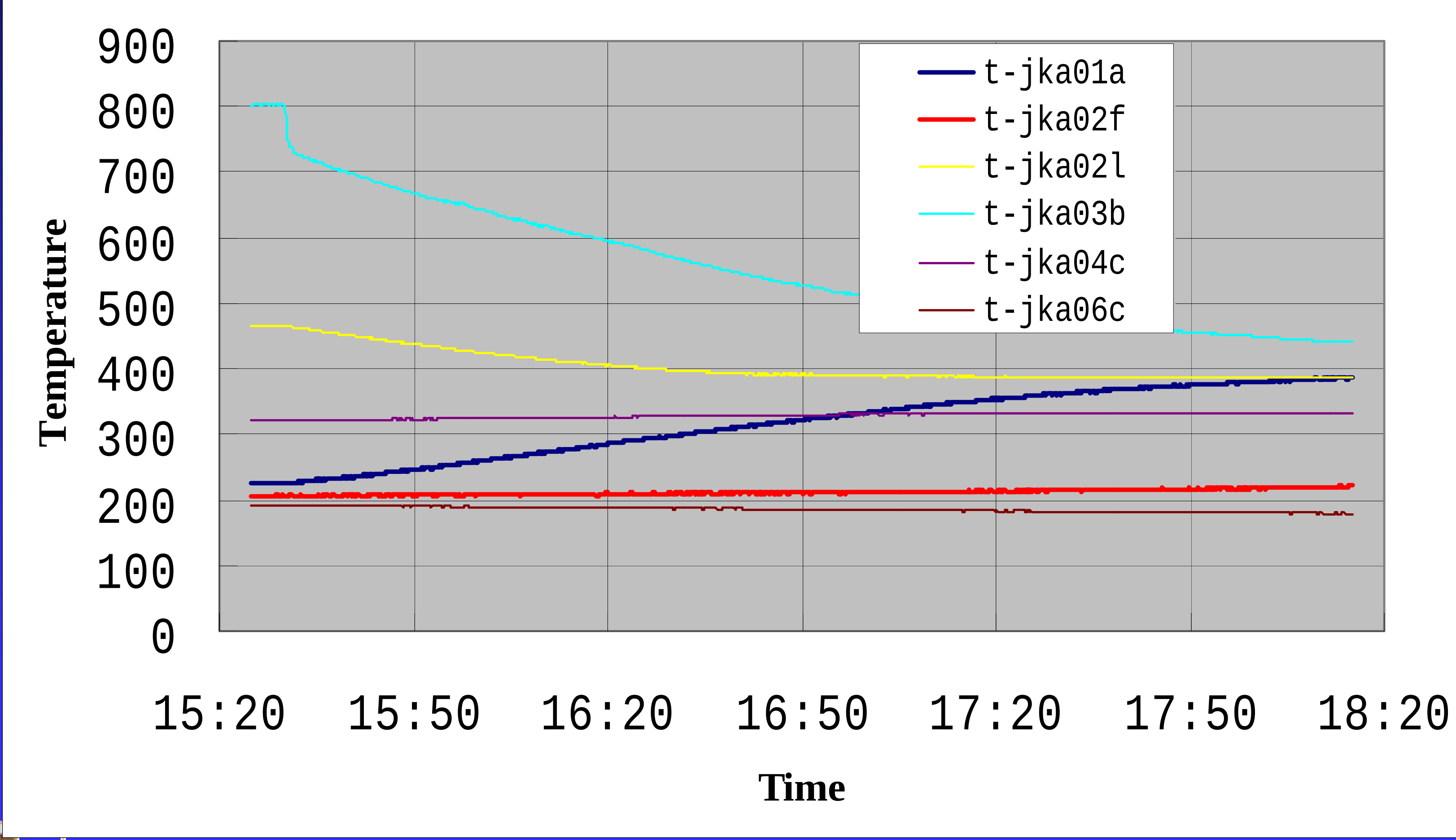
- **Results**

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



Temperature transient



Reactivity insertion (5mk) without scram

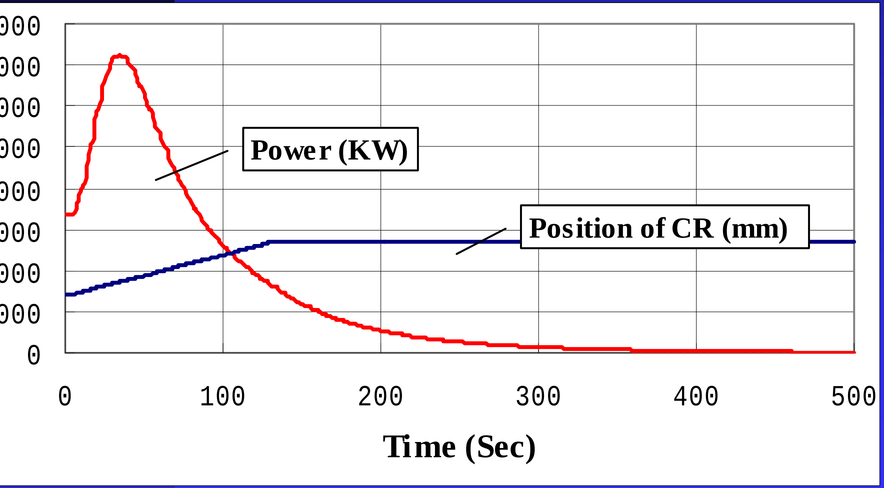
- **Initial conditions**

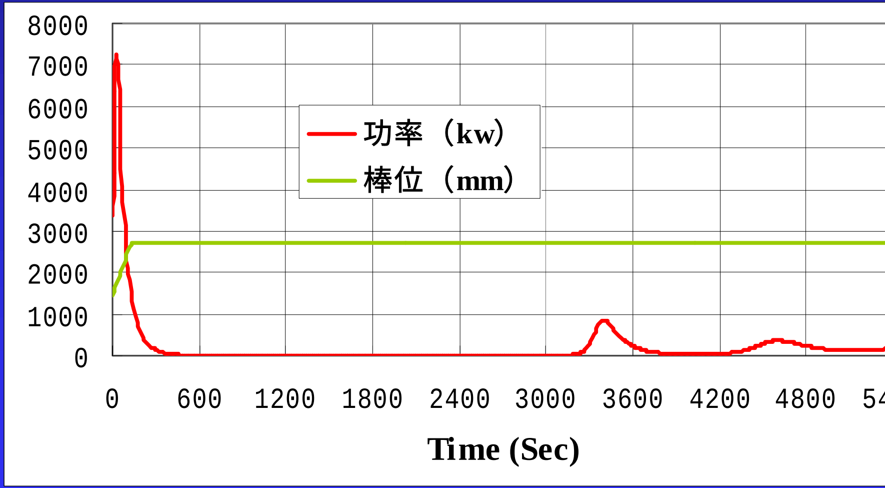
  Thermal power-3 MW
  A control rod was withdrawn at 10mm/sec.
  The maximum reactivity insert is 5mk

- **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

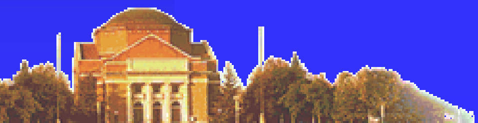
Power transient





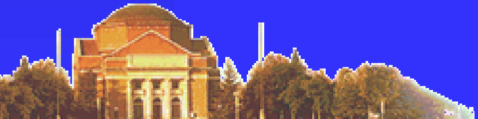
Further development

- 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



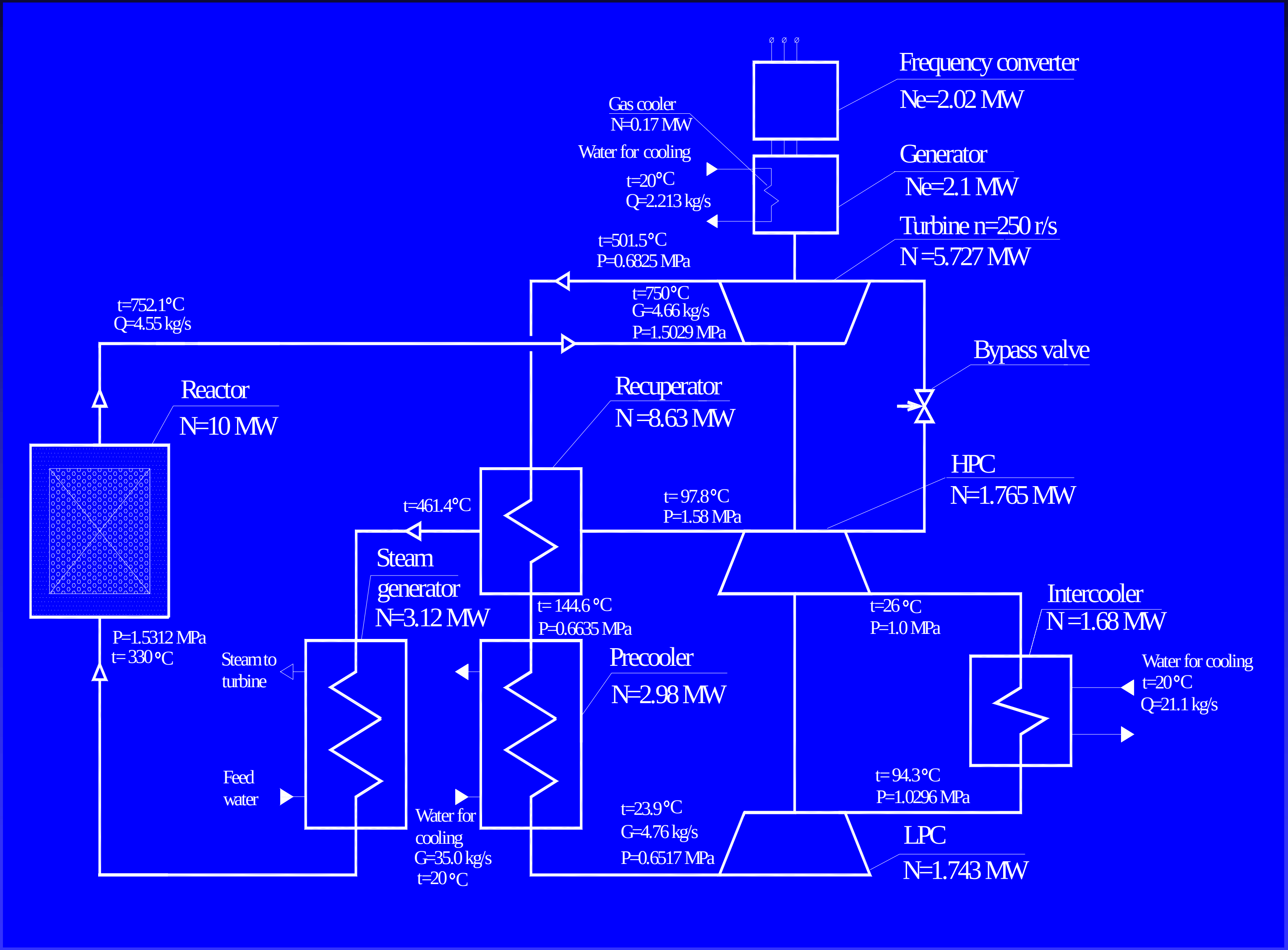
Operation of gas turbine cycle

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

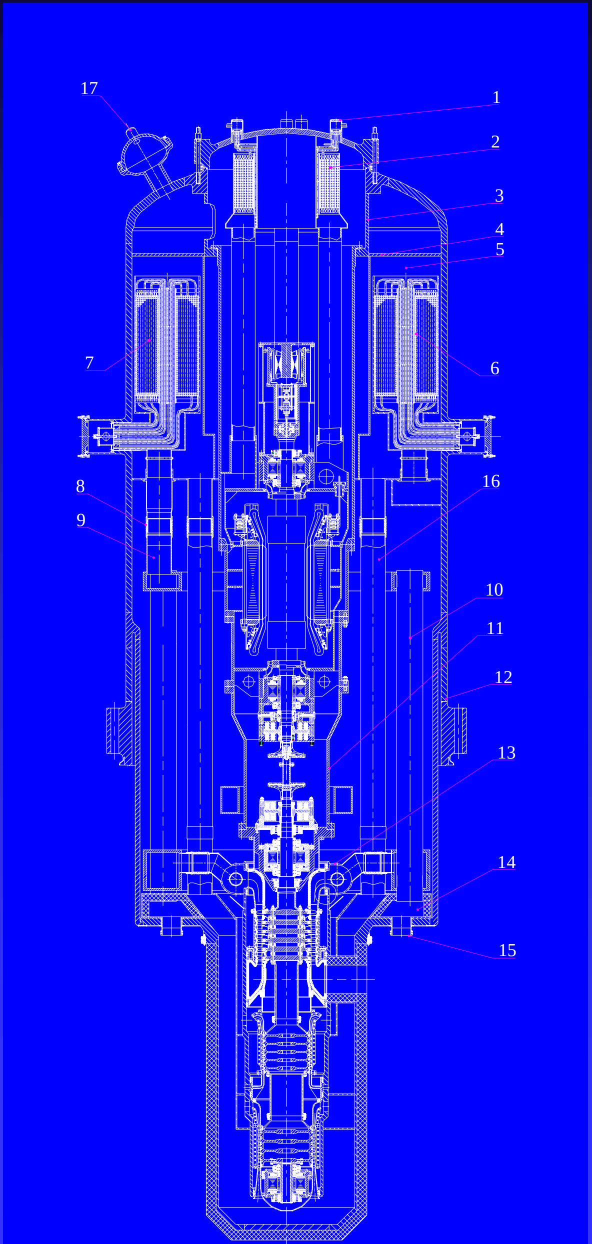


Flow diagram of the HTR-10 with gas turbine cycle

Parameters for HTR-10 with the gas turbine cycle	Value
POWER CONVERSION UNIT	
Thermal power transferred to PCU, MW	10.00
Thermal power transferred to the gas-turbine cycle, MW	6.755
Thermodynamic efficiency, %	32.247
Gross efficiency (el.) of the RP gas-turbine part, %	29.314
Total relative pressure loss, %	11.8
Total relative helium leaks, %	5.3
PCU mass, t	64
PCU height, mm	9100
Water temperature at the PCU inlet, °C	20.0
REACTOR	
Temperature at the core inlet/outlet, °C	330/752
Pressure at the inlet/outlet, MPa	1.5312/1.5159
Helium flowrate, kg/s	4.55

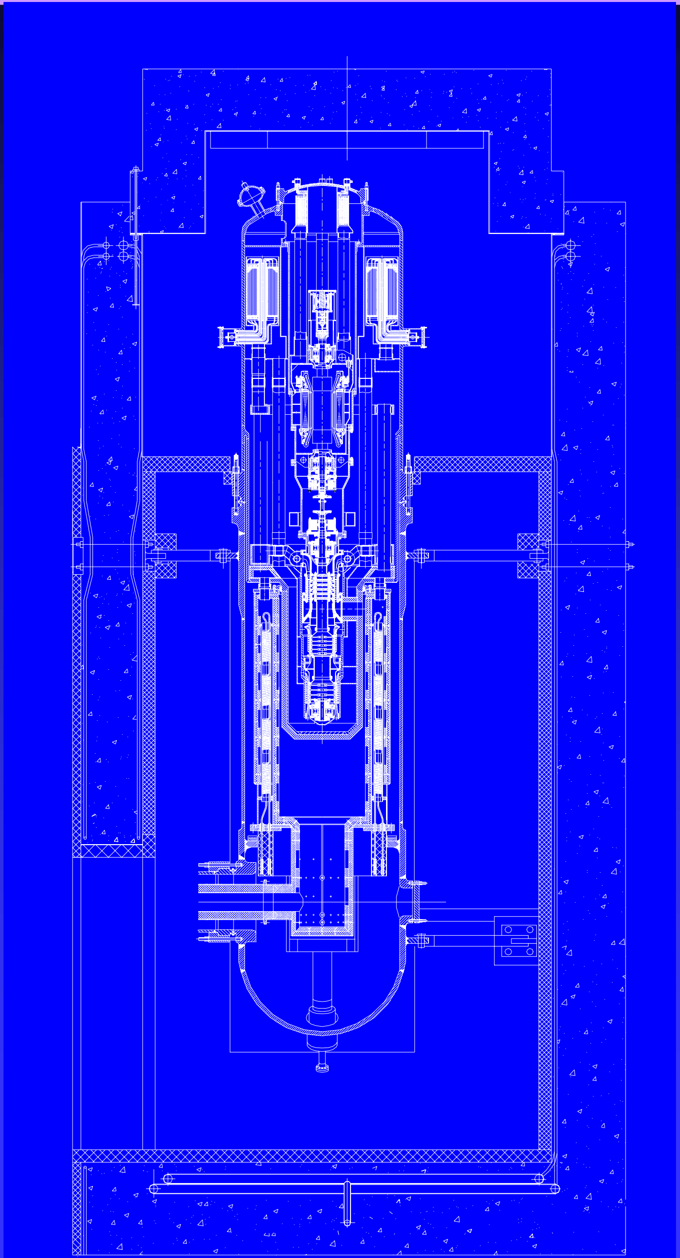
Features:

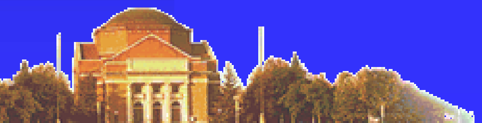
- One shaft
- Vertical configuration
- EMB
- Higher rev



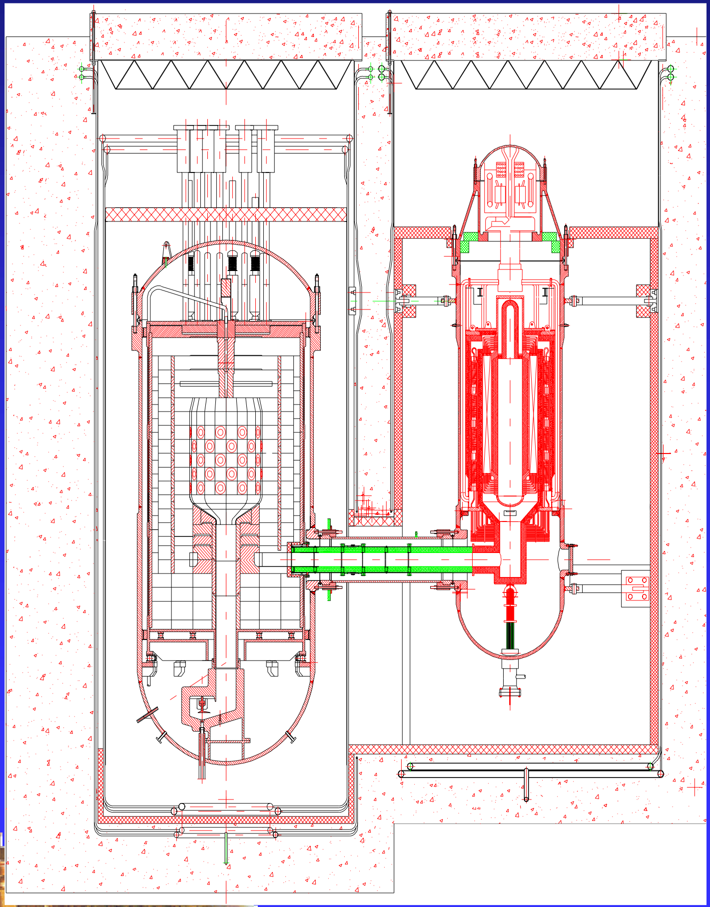
1 – Nozzle
2 – Gas cooler
3 – Shell
4 – Plate
5 – Chamber
6 – Intercooler module
7 – Precooler module
8 – Expansion pieces
9 – Pipeline
10–Rrecuperator
11–Turbomachine
12–PCU vessel
13–Header
14–Header
15–Nozzle
16–Pipeline
17–Lead-out

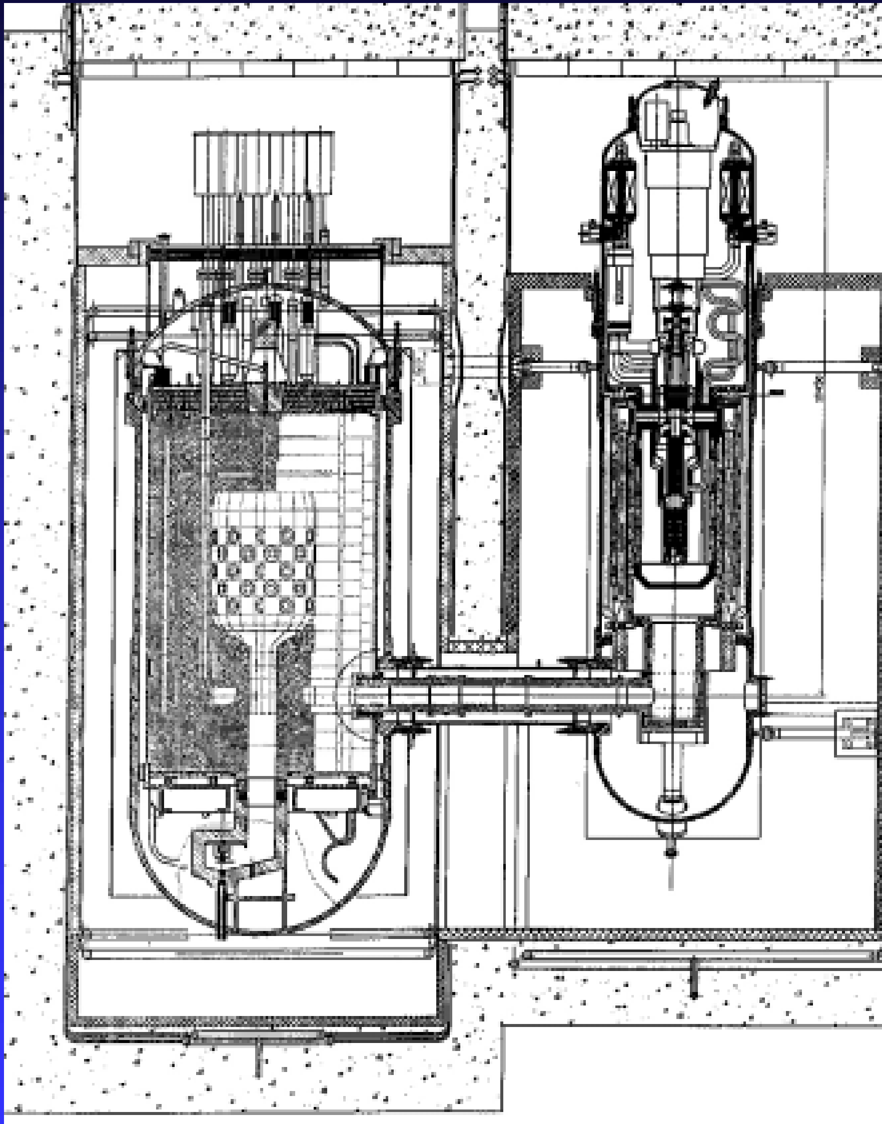
PCU in the HTR-10 steam generator pressure vessel





HTR-10 layout with PCU in steam generator vessel

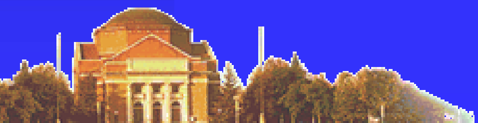




HTR-10 layout with PCU in Steam Generator vessel

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

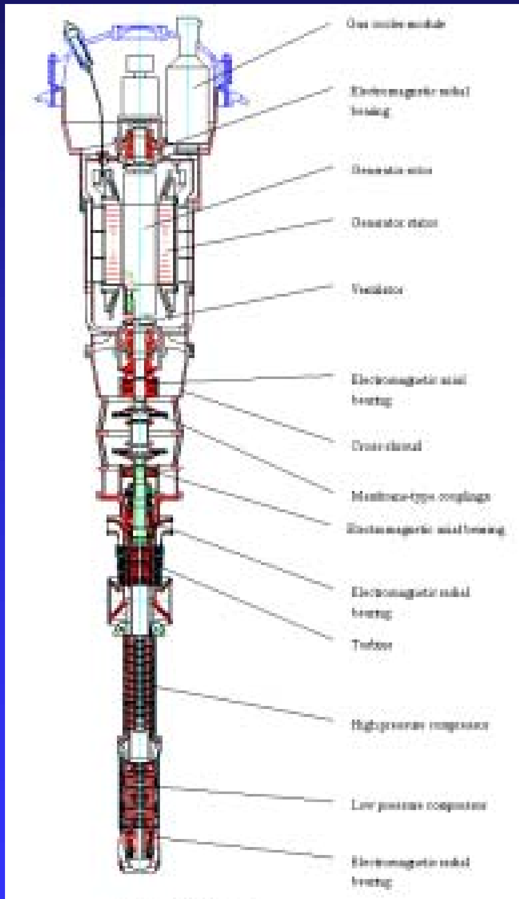


Figure 1 - Turbomachine

Generator

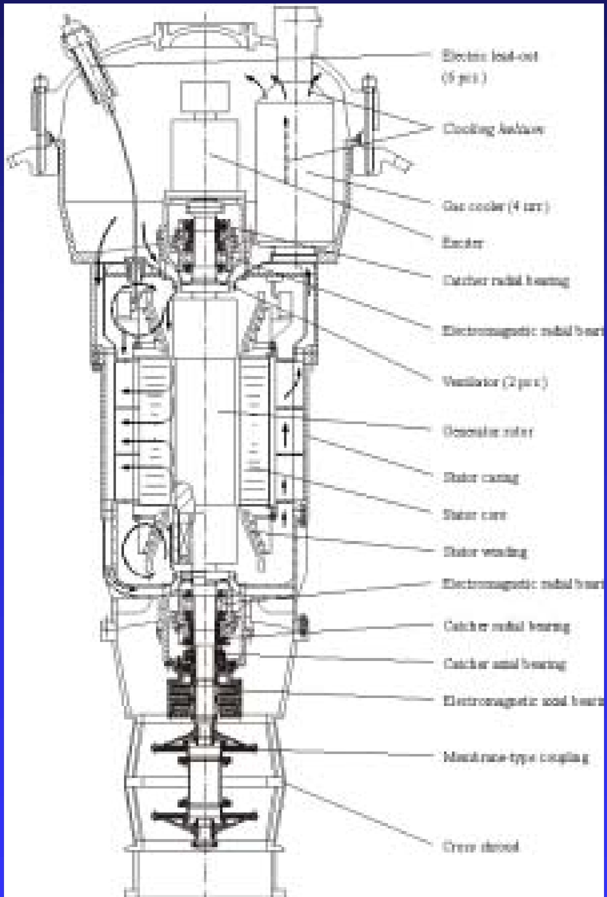
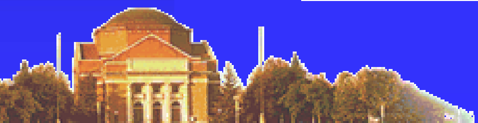


Figure 2 - Generator



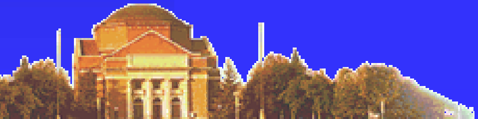
Construction of the HTR-PM

Target

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

Design features

- Pebble bed type
- Annular core
- Steam turbine cycle
- Reheat circuit
- High efficiency



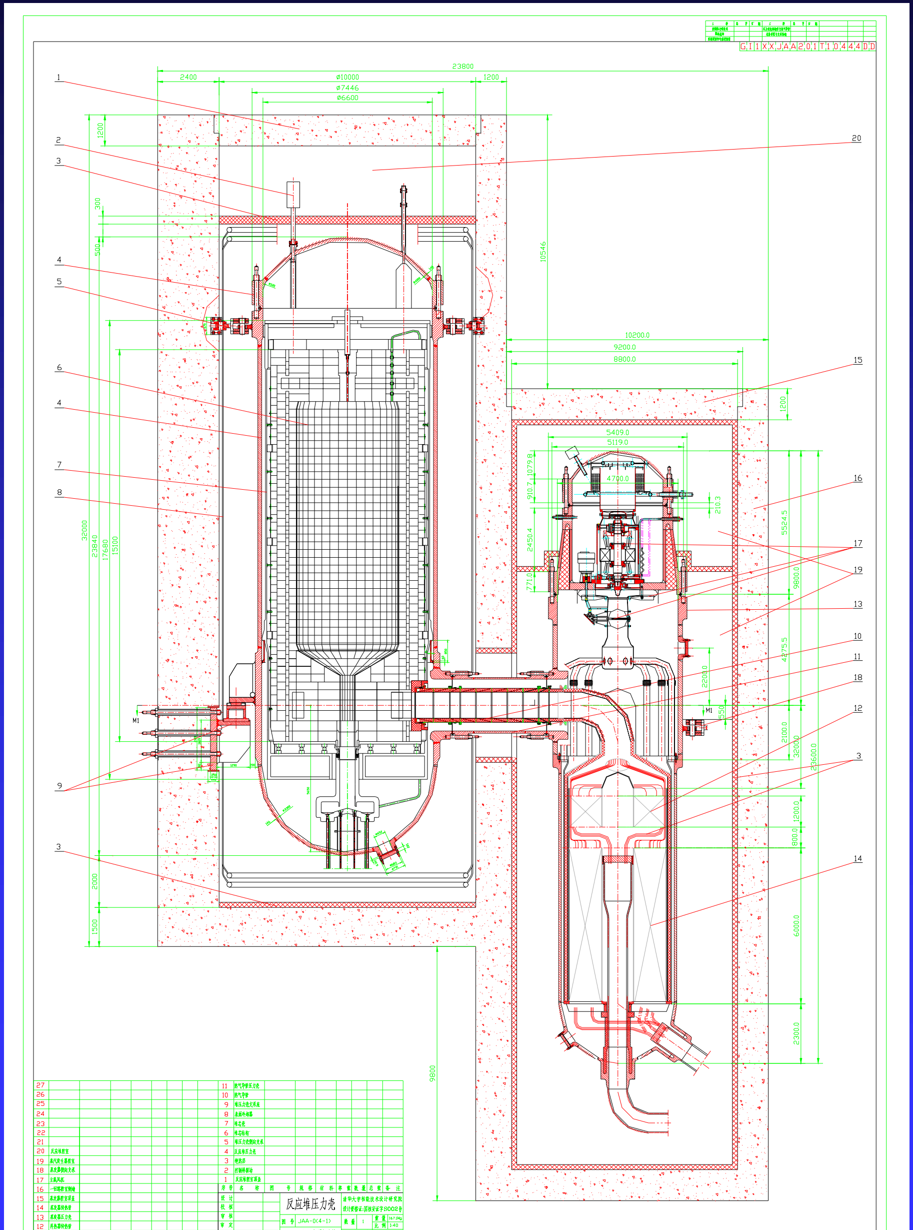
Main parameters of HTR-PM

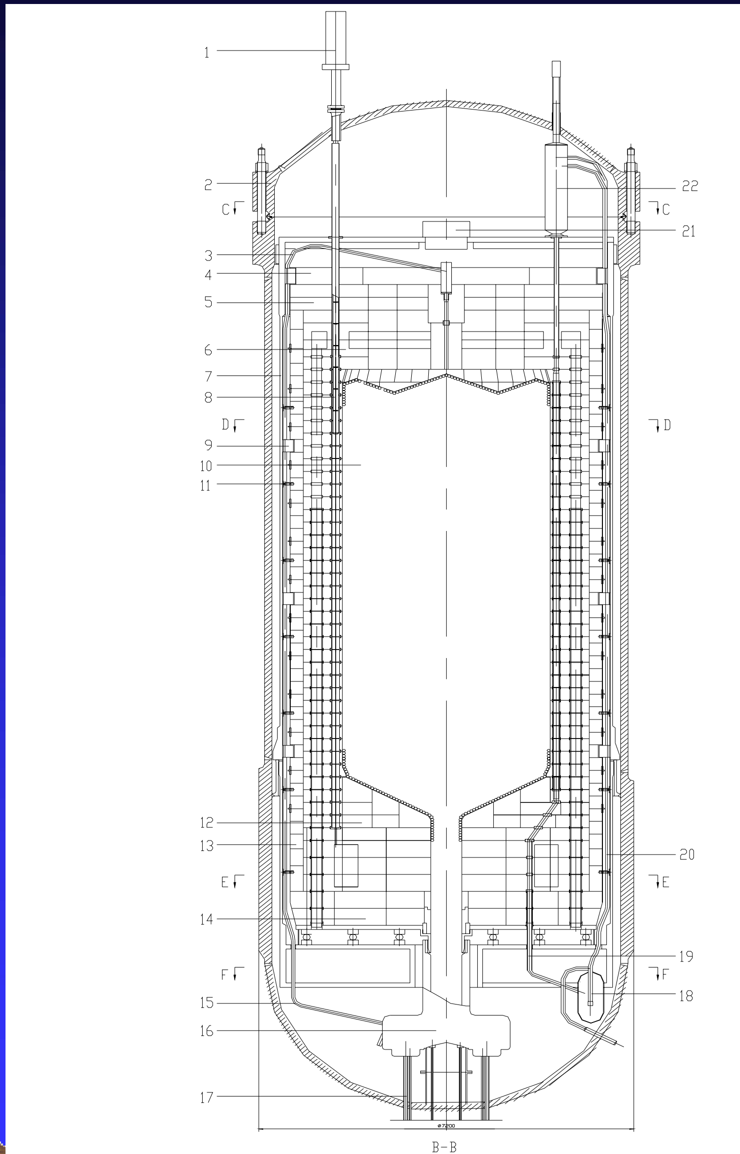
Reactor thermal power	MW	371
Active core diameter/height	m	2.00-4.00/9.43
Average power density	MW/m^3	4.28
Primary helium pressure	MPa	7.0
Helium inlet temperature	ºC	250
Helium outlet temperature	ºC	750
Helium mass flow rate	Kg/s	145
Fuel		UO_2
U-235 enrichment of fresh fuel elements	%	8.77
Diameter of spherical fuel elements	mm	60
Number of spherical fuel elements	ball	479358
Number of graphite balls	ball	159786
Average discharge burnup	MWd/tU	80,000

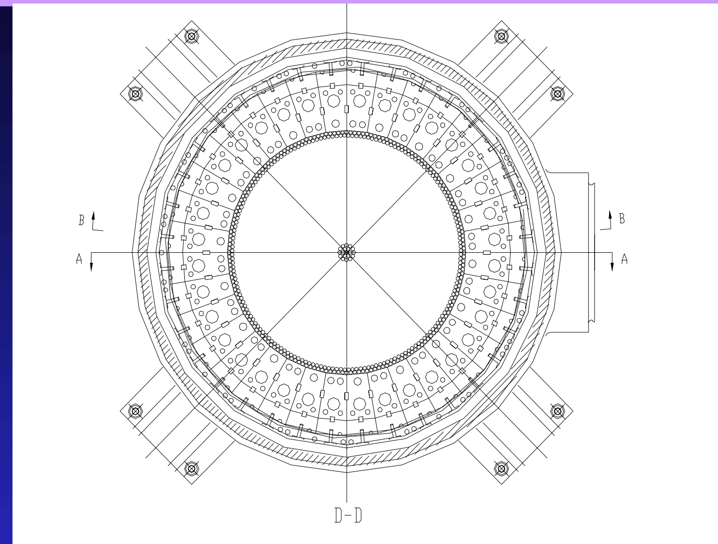
Main parameters of HTR-PM

Refueling mode		Multi-pass continuously
Number of control rods	set	18
Number of small absorb ball systems	set	18
Main steam pressure	MPa	14.2
Main steam temperature	^{0}C	538
Main steam flow rate	t/h	444.8
Feed water temperature	^{0}C	205.3
Power from steam turbine	MW	160
Gross efficiency	%	43.1
Net output power	MW	150
Net efficiency	%	40.5

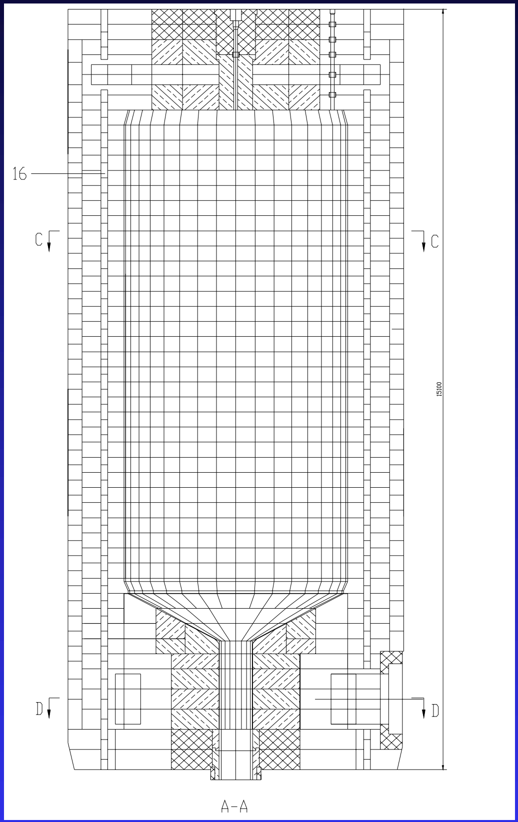
HTR-PM with the steam turbine cycle

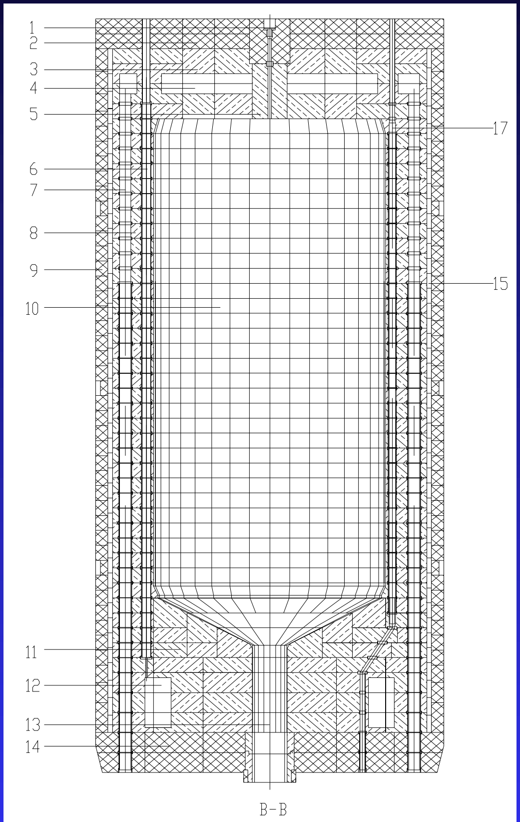


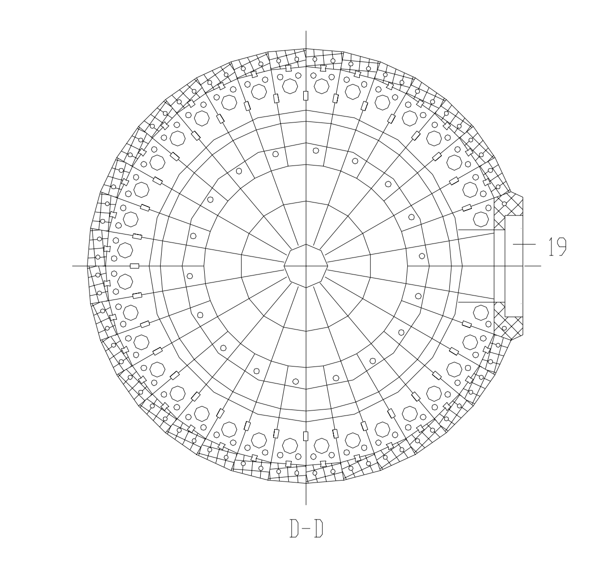




01. Control rod driving systems
02. Reactor pressure vessel
03. Charging tubes
04. Pressing blocks
05. Top insulation
06. Top reflectors
07. Reactor internal
08.Guiding tube for control rods
09. Side plates
10. Core
11. Supporting springs
12. Bottom reflectors
13. Side reflectors
14. Bottom insulators
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 channel
21. Shielding plugs
22. Top tanks for small ba



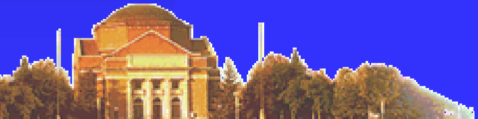




01. Charging tubes
02. Top insulations
03. Top reflectors
04. Cold gas chambers
05. Central graphite plugs
06. Channels for control rods
07. Channels for cold gas
08. Side reflectors
09. Side insulations
10. Reactor core chamber
11. Bottom reflectors
12. Hot gas chamber
13. Discharging tube
14. Bottom 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

	00	01	02	03	04	05	06	07	08	09	10
HTR-10 criticality											
HTR-10 hot commissioning											
HTR-10 power operation											
HTR-10 safety experiments											
HTR-10 gas turbine cycle test											
HTR-PM feasibility study and design											
HTR-PM Licensing and preparation											
HTR-PM Construction											

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.