REACTOR TECHNOLOGY DEVELOPMENT UNDER THE HTTR PROJECT

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HTTR Project

Reactor Technology

HTTR Operation and Testing

- Achievement of 950°C (April 2004)
- Safety Demonstration Tests

GTHTR Plant Design and Gas Turbine Technology R&D

- Design of GTHTR300 (electricity, 850°C) and
  GTHTR300C (cogeneration, 950°C)
- Tests of Control, Magnetic Bearing, and System Control

Hydrogen Production Technology

System Integration

- Simulation Tests, Isolation Valve Test

IS Process

- Bench-scale Tests
- Pilot-scale Test (from 2005)
- HTTR-IS (from 2010)

HTTR
High Temperature Engineering Test Reactor

Graphite-moderated, helium gas-cooled reactor

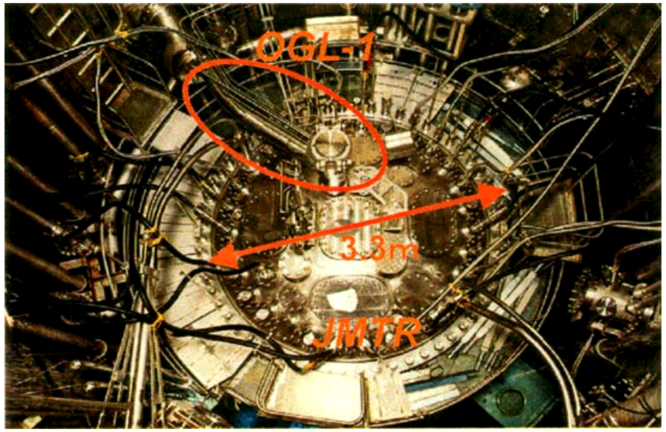
Thermal power: 30 MW
Coolant outlet temperature:
850°C in the rated operation
950°C in the high-temperature test operation

The first high-temperature gas-cooled reactor in Japan
Designed, constructed, and operated by JAERI
Located at the JAERI Oarai site

Purposes:
- to establish HTR technology
- to demonstrate HTR safety operation and inherent safety characteristics
- to demonstrate nuclear heat utilization
- to irradiate HTR fuels and materials

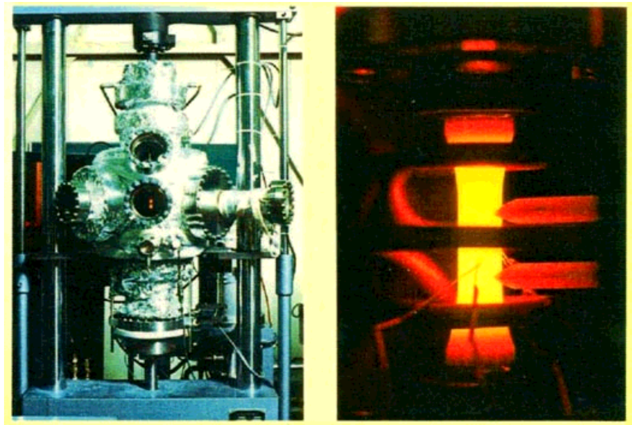
Major Technical R&D Facilities

VHTRC (Very High Temperature Reactor Critical Assembly)
Reactor Physics 1985-1995



OGL-1 (Oarai Gas Loop-1)
1000°C helium loop in JMTR
Fuel Irradiation 1985-1995

HENDEL (Helium Engineering Demonstration Loop)
Thermal Hydraulics, etc. 1982-1995

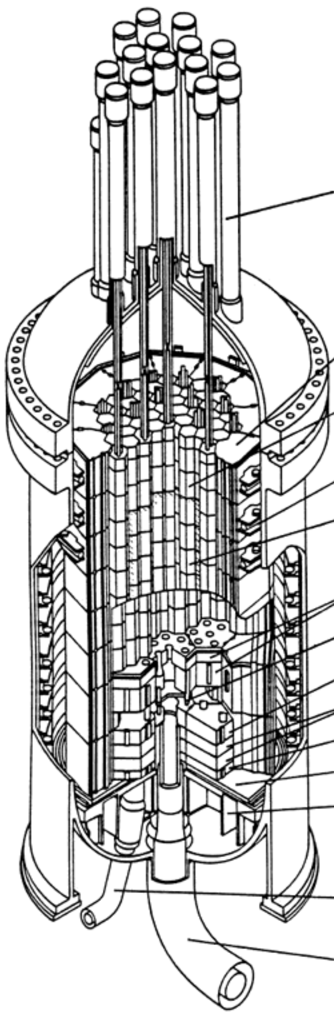


Material Test Machine
High temperature fatigue test machine for super alloy in helium gas. 1981-

HTTR Milestones

1991/03	Construction started
1996/10	Functional test started
1998/11	First criticality
1999/09	Power-up test started
2001/12	Full-power operation (single loaded) at 850°C
2002/02	Full-power operation (parallel loaded) at 850°C
2003/03	Safety demonstration test started
2004/04	High temperature operation (single loaded) at 950°C
2004/06	High temperature operation (parallel loaded) at 950°C

Cutaway View of RPV and Core of HTTR



RPV height/diameter: 13.2/5.5 m

Core height/diameter: 2.9/2.3 m

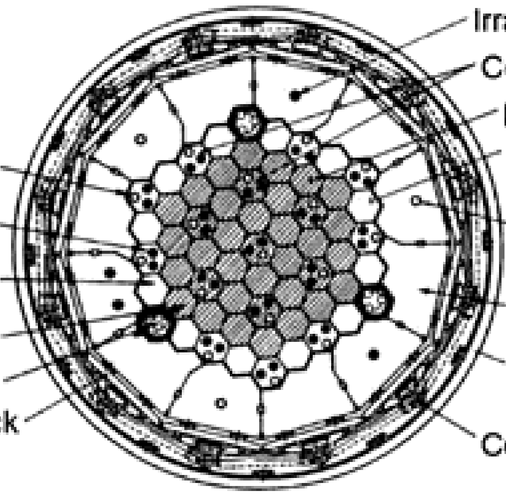
Fuel columns: 30, Control columns: 7

Fuel Element: pin-in-block type

height/across flats: 580/360 mm

Fuel: TRISO coated UO_2 (6% enrichment)

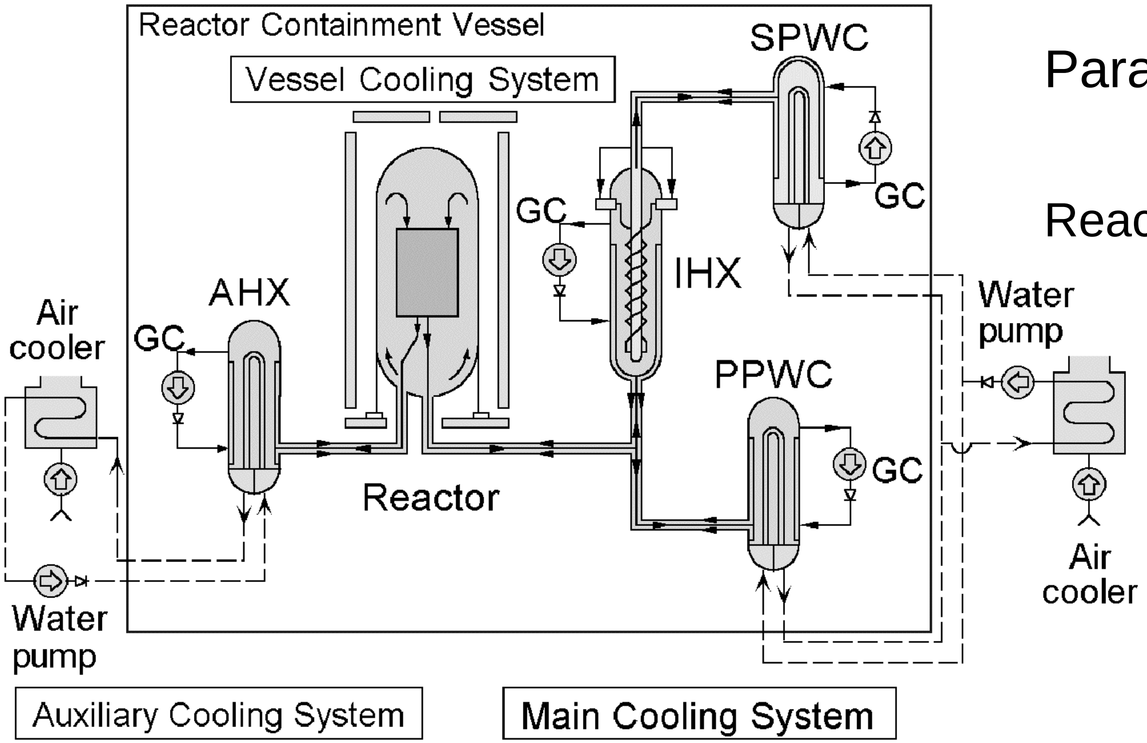
Control rods: 16 pairs



Major Specifications of HTTR

Thermal Power	30 MW
Outlet Coolant Temperature	850/950°C
Inlet Coolant Temperature	395°C
Fuel	Low Enriched UO_2 (6wt%)
Fuel Element Type	Prismatic Block
Fuel Loading	Off-load, 1 Batch
Core Diameter	2.3 m
Core Height	2.9 m
Average Core Power Density	2.5 W/m^3
Flow Direction	Downward Flow
Number of Main Loop	1
Coolant Flow Rate	10.2 kg/s (950°C Operation)
Effective Core Coolant Flow	88%
Primary Coolant Pressure	4.0 MPa

Cooling System of HTTR



AHX: Auxiliary heat exchanger
GC: Gas circulator

IHX: Intermediate heat exchanger
PPWC: Primary pressurized water cooler
SPWC: Secondary pressurized water cooler

Loop operation modes:

Single loaded operation

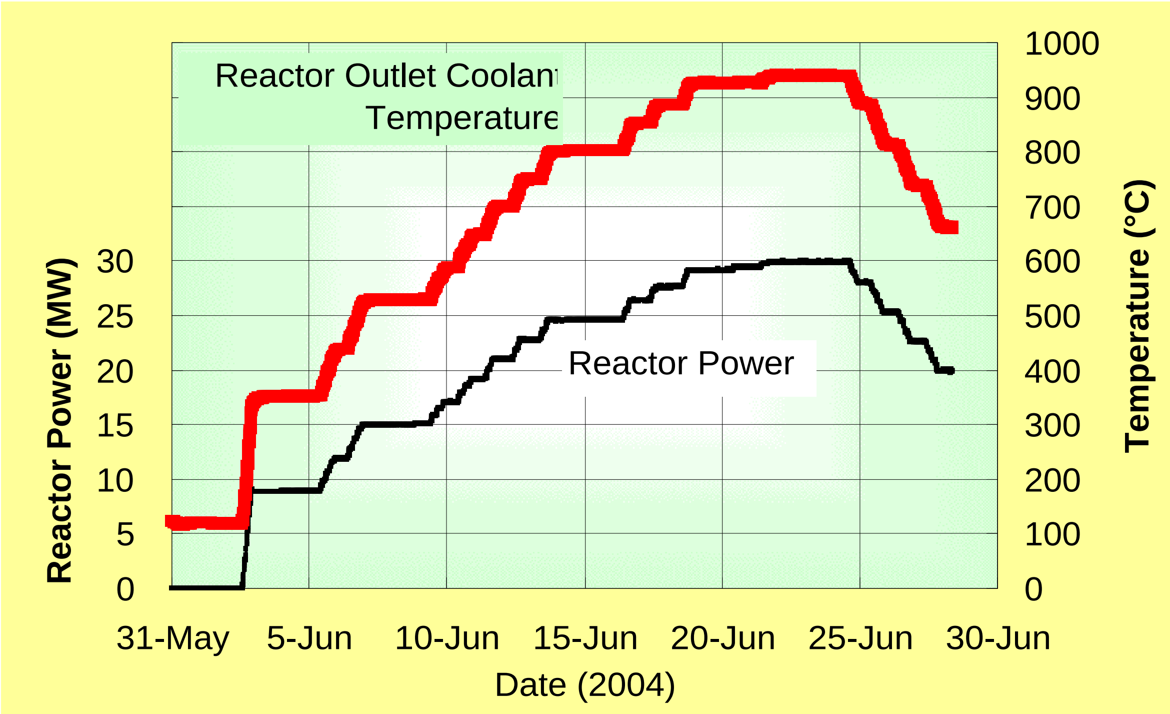
Reactor → PPWC
30 MW

Parallel loaded operation

Reactor → PPWC **20 MW**
Reactor → IHX **10 MW** → SPWC

High-temperature Test Operation at 950°C

Performance tests at 950°C were completed, and
JAERI received an operation permit for the high-temperature test operation (950°C operation) of the HTTR from the government.



Safety Demonstration Test

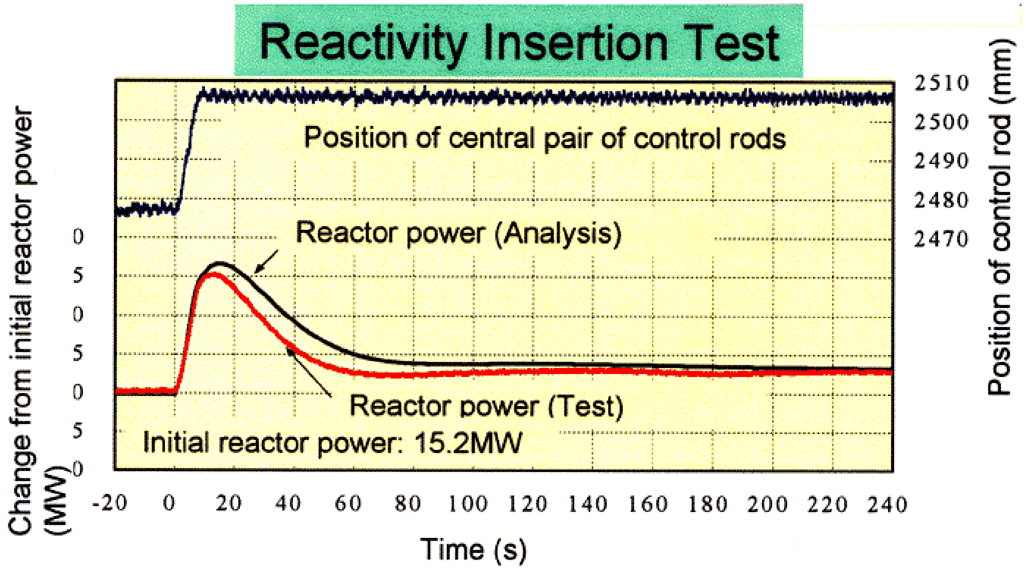
to demonstrate characteristics of HTRs
to obtain transient data for code validation
to establish safety design and evaluation technology of HTRs

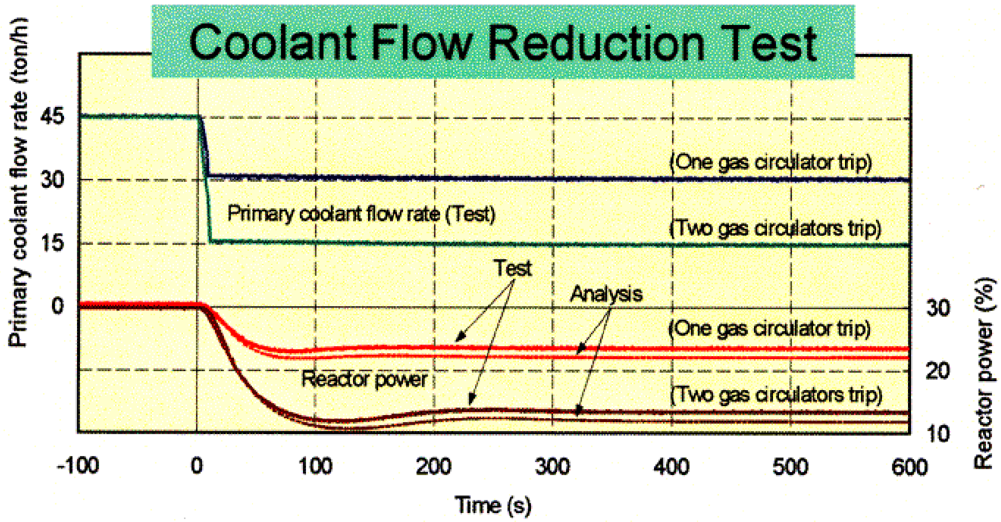
Reactivity Insertion Test

Increase of reactivity due to withdrawal of the central pair of control rods

Coolant Flow Reduction Test

Reduction of primary coolant flow due to trip of primary helium gas circulators



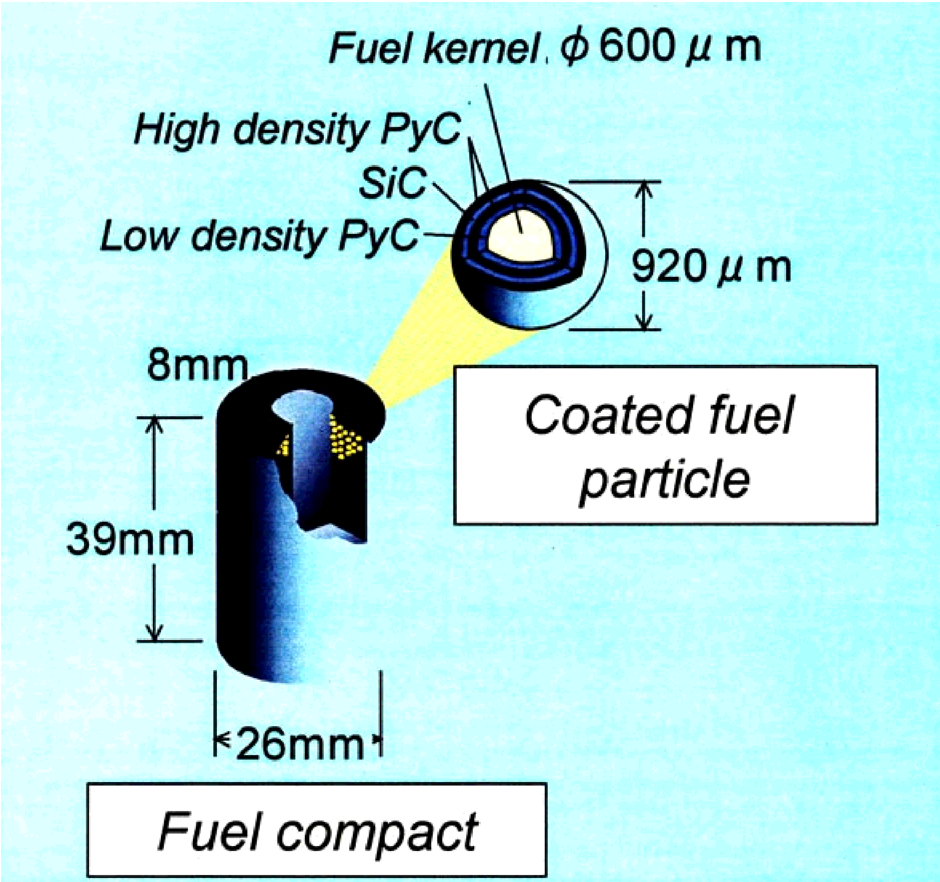


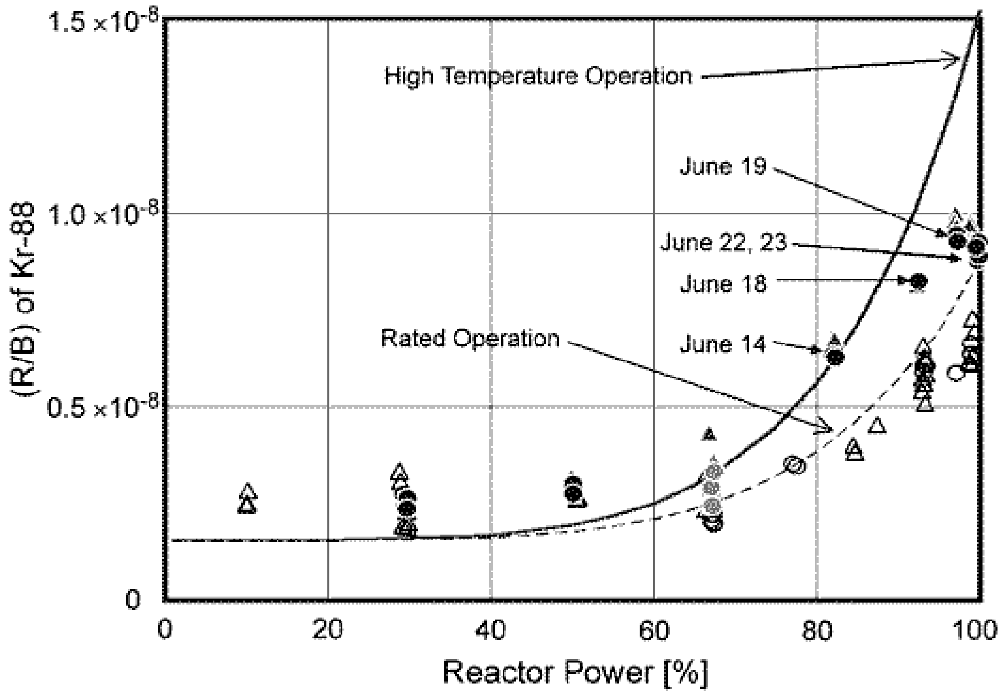
Fission Product Confinement

Failure fraction of the first-loading fuel of the HTTR

Through-coatings failure fraction: 2×10^{-6} (Design criteria:1.5×10^{-4})

SiC-failure fraction: 8×10^{-5} (Design criteria:1.5×10^{-3})





Gas Turbine High Temperature Reactor, GTHTR300

GTHTR300 Project (2001-2007)

Thermal power: 600 MW
Electric power: ~280 MW
Coolant outlet temperature: 850°C

Design of GTHTR300 plant
(Reactor, Power conversion system, Safety, Maintenance, Cost)
R&D on helium gas-turbine system
(Compressor, Magnetic Bearing, Operation & Control, Recuperator)

Purposes:
to establish feasible design of commercial power plant
to establish power conversion system technology

prototype plant in 2010's, commercial plant in 2020's
technology base for developing Advanced GTHTR and Cogeneration HTR

GTHTR300 Design Features

Modular plant

Fully inherent and passive reactor safety

Improved pin-in-block type fuel element

High burnup and long refueling interval

Conventional steel reactor pressure vessel

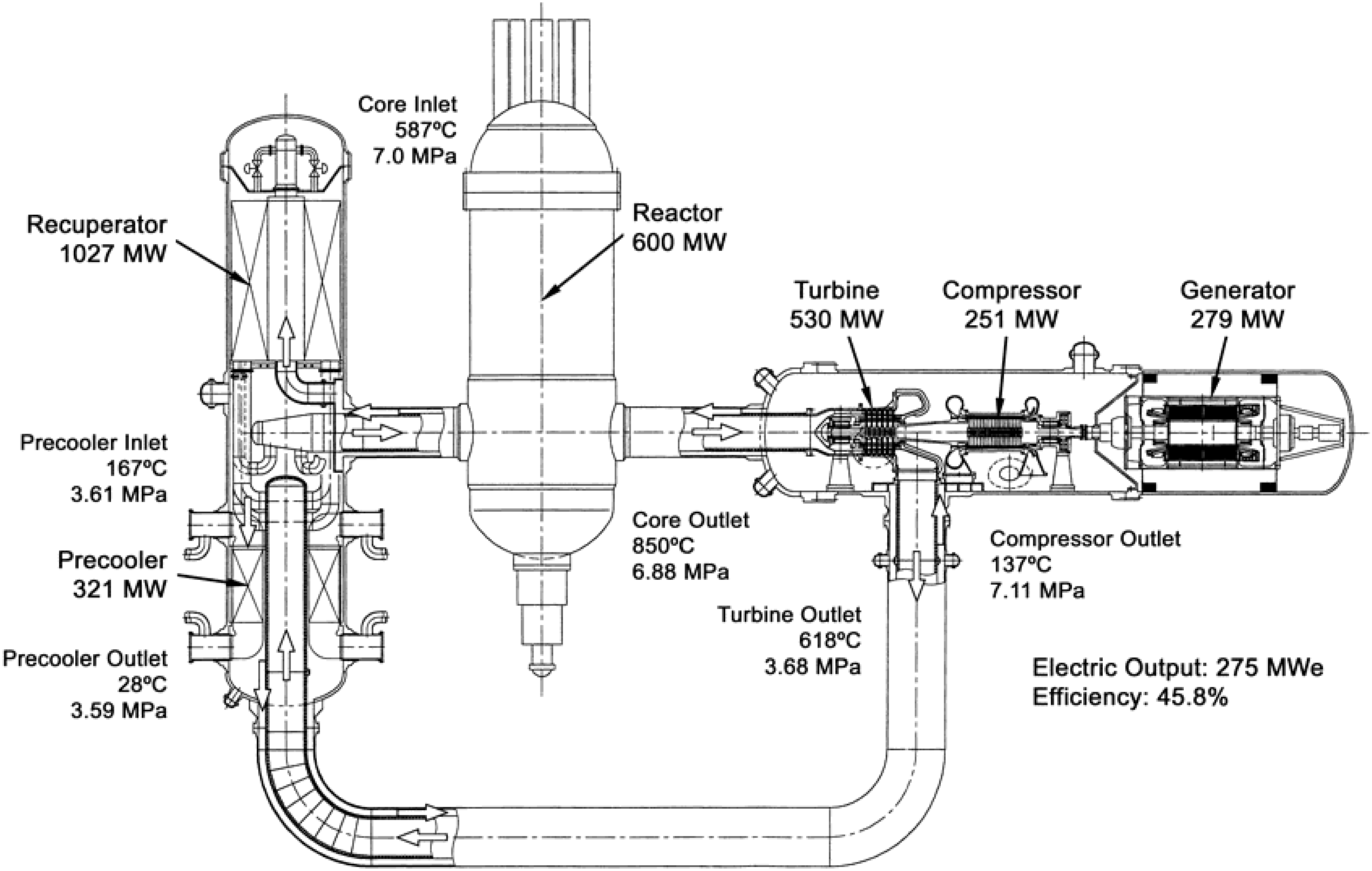
Non-intercooled Brayton cycle

Horizontal single shaft turbo-machine

Magnetic bearings to support turbo-machine rotor

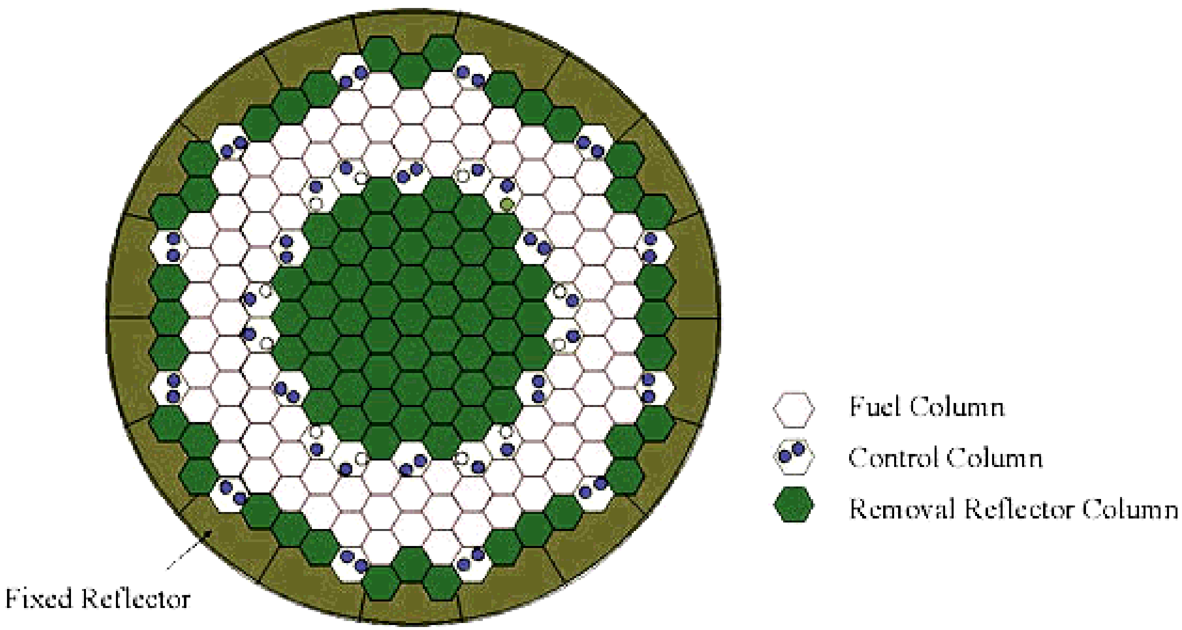
Separate containment of turbo-machine and heat exchangers

GTHTR300 Plant Layout



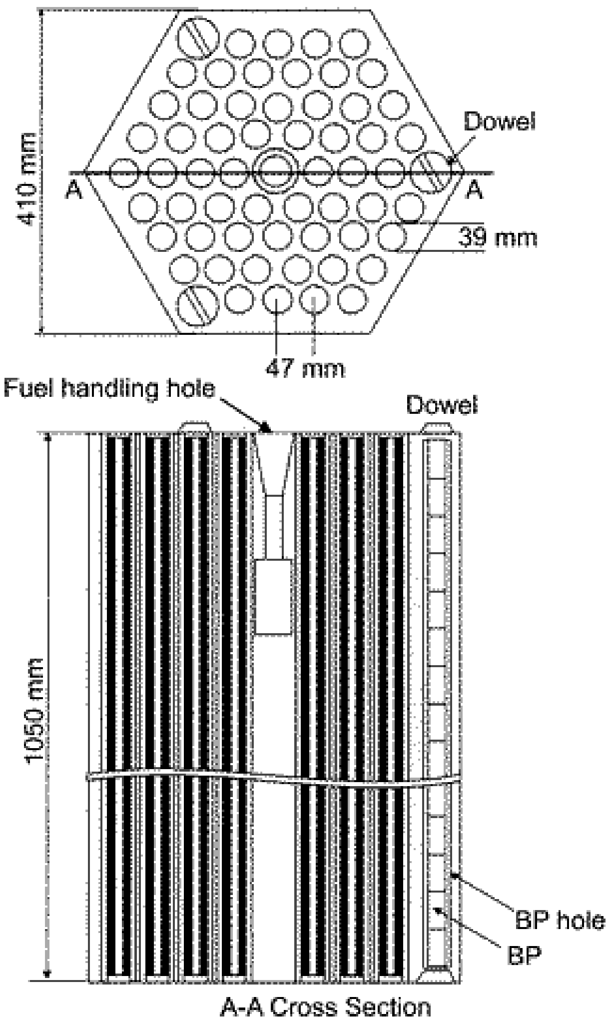
GTHTR300 Reactor Design

Thermal power	600 MWt	Fuel temperature	1379°C (max.)
Core shape	Annular	Fuel element	Pin-in-block prism
Power density	5.4 MW/m^3	Enrichment	14%
Coolant temperature	inlet: 587°C	Burnup	120 GWd/t
	outlet: 850°C	Cycle length	730 days (2 batch)
Core effective flow	82%	Pressure vessel	SA533 (Mn-Mo) steel
Core pressure drop	58 kPa		

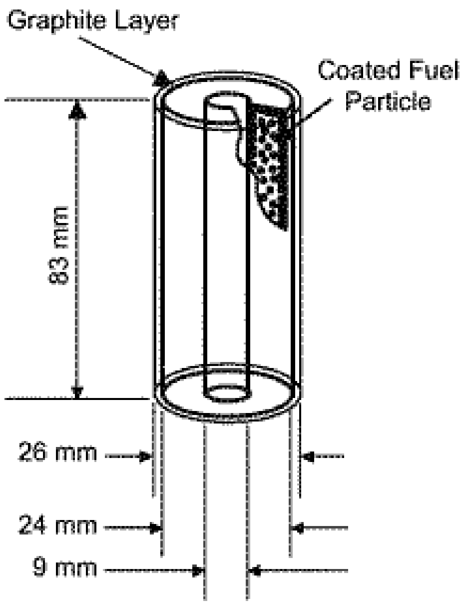


Horizontal cross section of reactor core

GTHTR300 Fuel Design



Fuel Element



Fuel Compact

Design Criteria

Maximum fuel temperature	1400°C (normal)
	1600°C (accident)
Average burnup	120 GWd/t

Coated Fuel Particle Dimension

UO_2 kernel diameter		0.55 mm
Coating layer thickness		
	Buffer layer	0.14 mm
	Inner PyC layer	0.025 mm
	SiC layer	0.045 mm
	Outer PyC layer	0.025 mm
Coated fuel particle diameter		1.01 mm

Power Conversion System Design

Helium gas working fluid, Closed-cycle

Direct cycle (no IHX)

Non-intercooled, regenerative Brayton cycle

600 MWt, 850°C, 3.5-7 MPa

Separation of PCV/HXV

Horizontal, single-shaft GT

Non-cooled 3D turbine blade

3D compressor blade

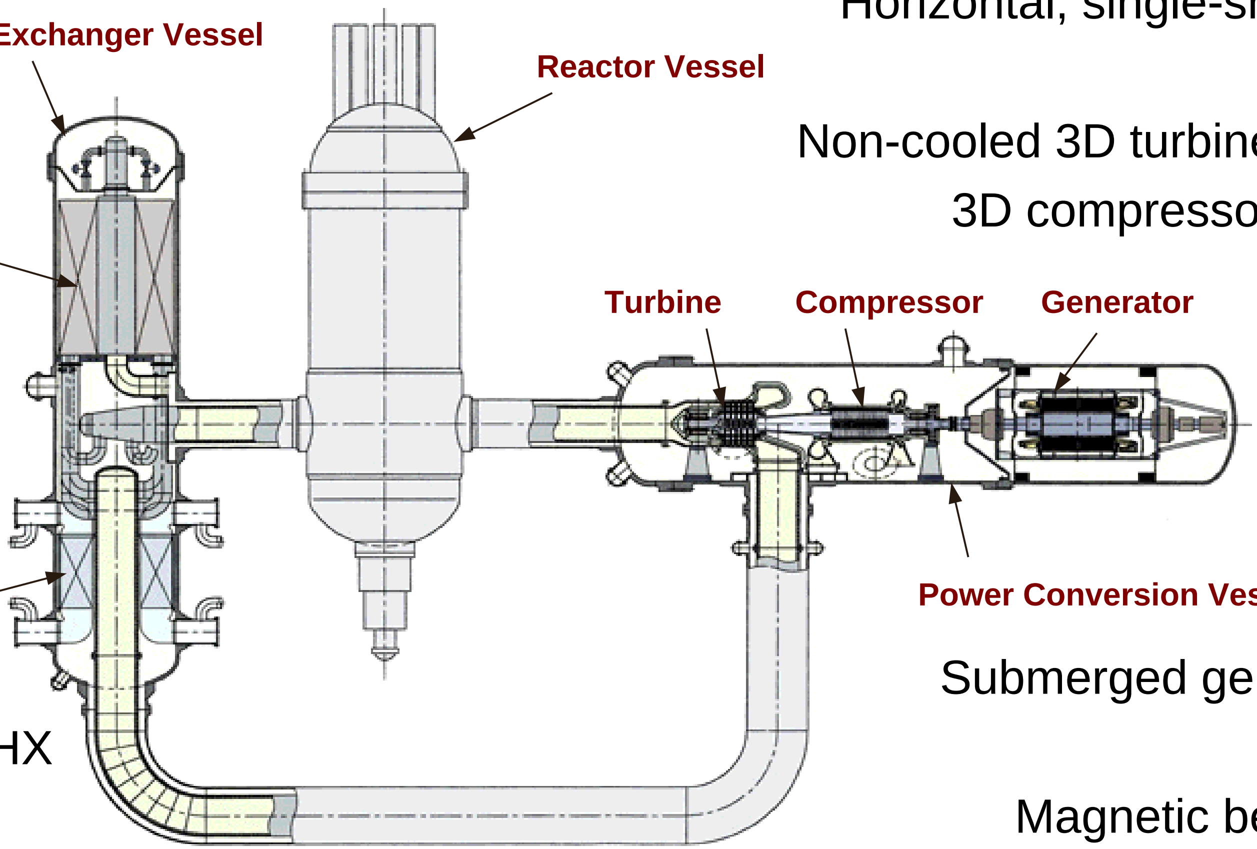


Plate-fin type, compact HX

Helical-coil type, low-fin tube HX

Waste heat dumped to sea

Submerged generator

Magnetic bearings

Flexible coupling at GT/generator

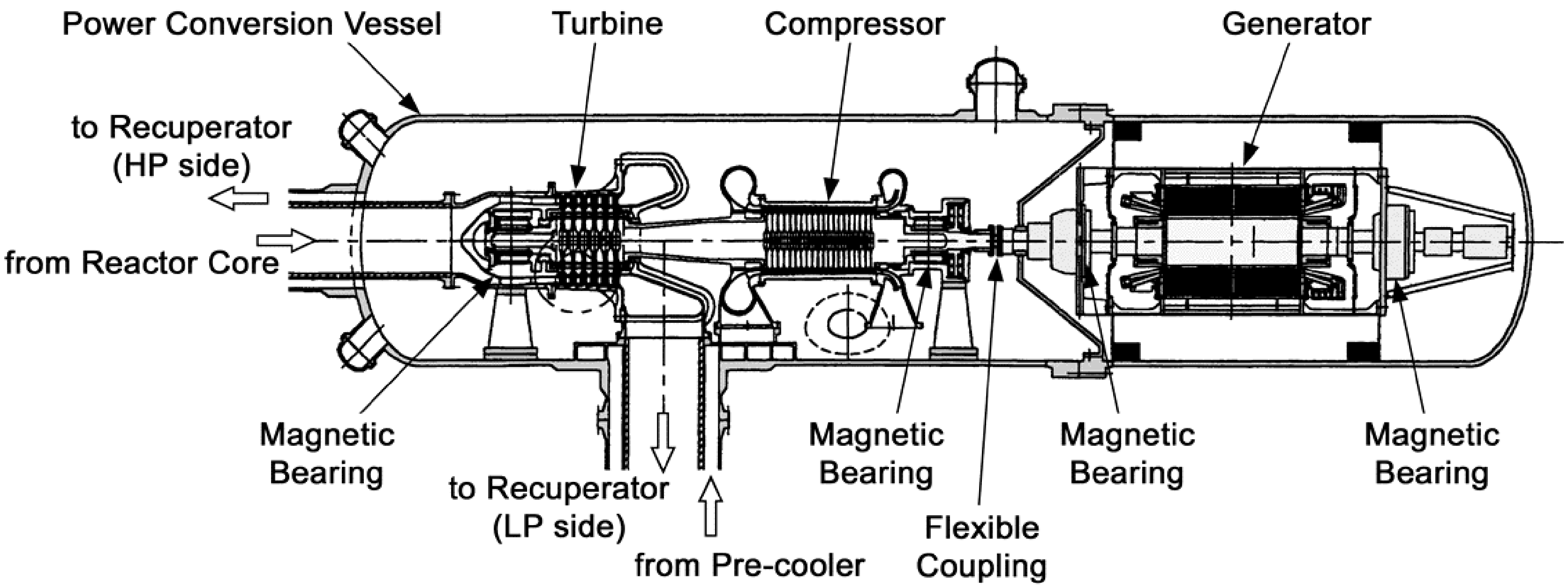
Turbo-machine design

Turbine: 6 stage, 850°C inlet temperature, 1.87 pressure ratio, 92.8% efficiency

Compressor: 20 stage, 28°C inlet temperature, 2.0 pressure ratio, 90.5% efficiency

Generator: 3-phase AC synchronous generator, helium-cooled

Electric power: 275 MW, Power conversion efficiency: 45.8%



Cost Estimation

Construction Cost per Unit (n-th plant, 4 unit/plant)

Reactor	¥17,080M
Power Conversion	¥14,011M
Auxiliary	¥ 6,723M
Electric, Instrumentation & Control	¥ 5,780M
Buildings	¥11,071M
Total	¥54,665M (¥0.199M/kW)

Electricity Cost (3% discount rate, 40 years operation)

	80% availability	90% availability
Capital *1	¥1.57/kWh	¥1.47/kWh
Operation & Maintenance	¥1.11/kWh	¥0.99/kWh
Fuel *2	¥1.46/kWh	¥1.46/kWh
Total	¥4.14/kWh	¥3.84/kWh

*1: including decommissioning cost, *2: including reprocessing cost

Electricity cost from LWR: ¥5.3/kWh (FEPC 2001)

Ongoing R&D on Power Conversion System

Scaled model tests to demonstrate key technologies for the GTHTR power conversion system

Compressor Aerodynamic Performance Test (2003-2004)

to verify aerodynamic performance and design method

Magnetic Bearing Development Test (2005-2007)

to develop technology of magnetic bearing supported rotor system

to verify rotor design

Gas-Turbine System Operation and Control Test (2007-2010)

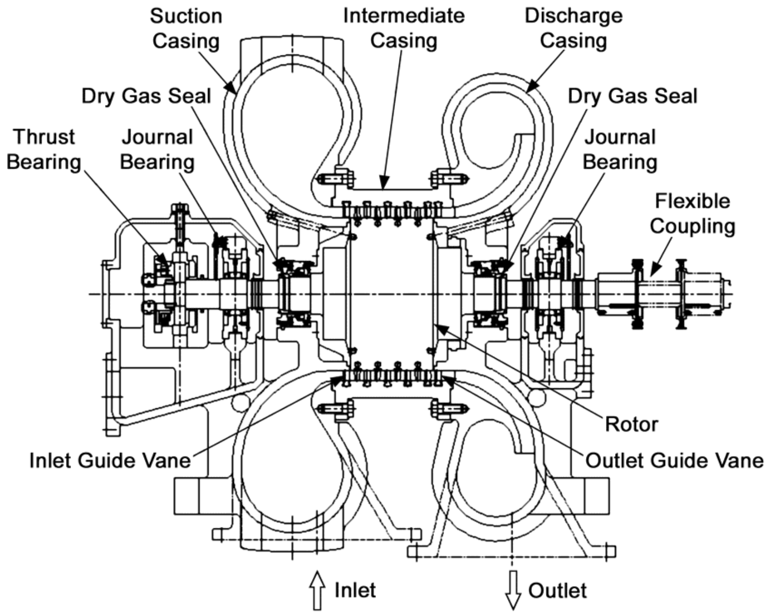
to demonstrate operability and controllability of closed-cycle gas-turbine system

Compressor Aerodynamic Performance Test

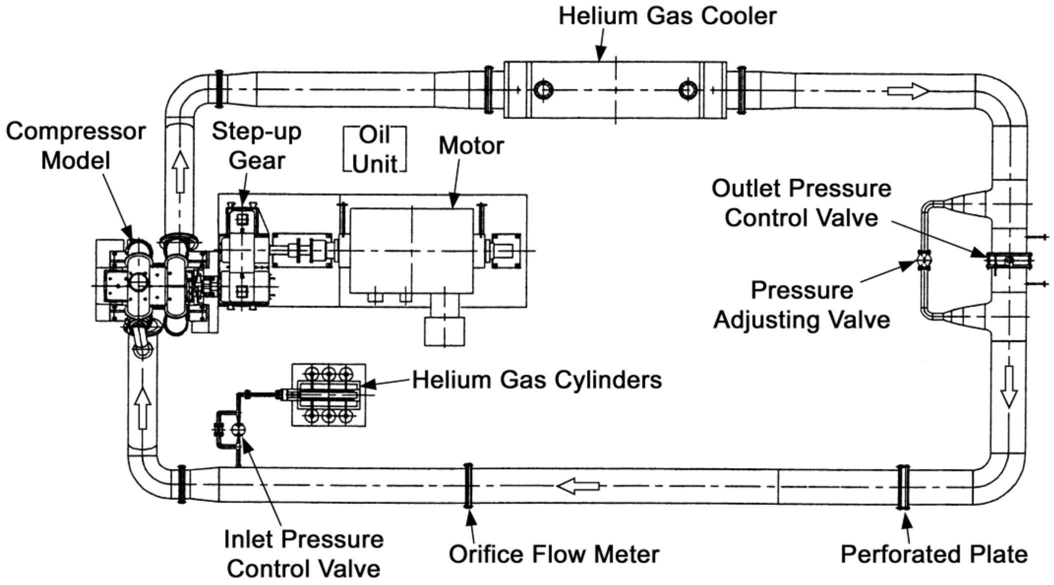
Features of helium gas compressor

high boss ratio, large number of stages, nearly parallel flow passage

high Reynolds number, low Mach number



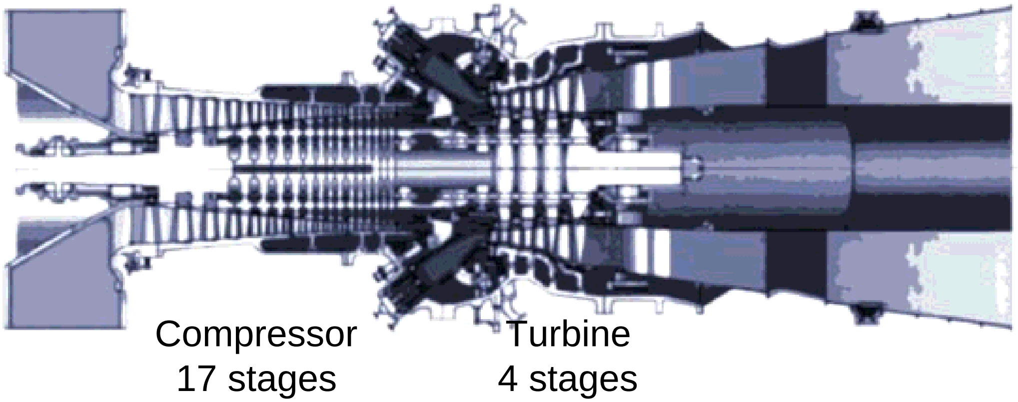
Compressor model
1/3-scale, 4-stage, 10800 rpm

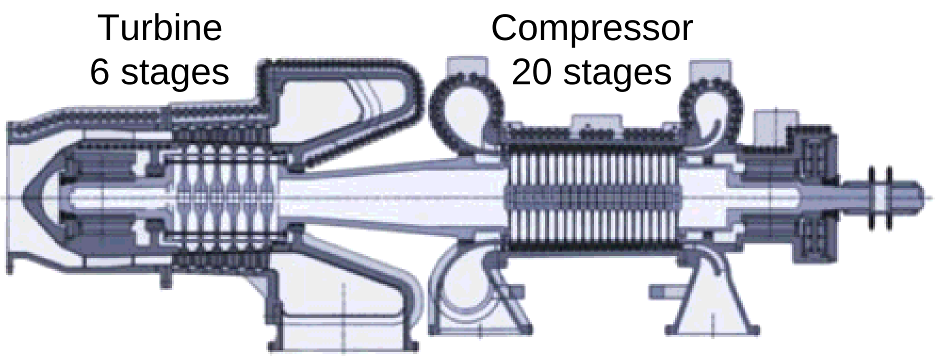


Helium gas loop
~1 MPa

Air Gas Turbine vs. Helium Gas Turbine

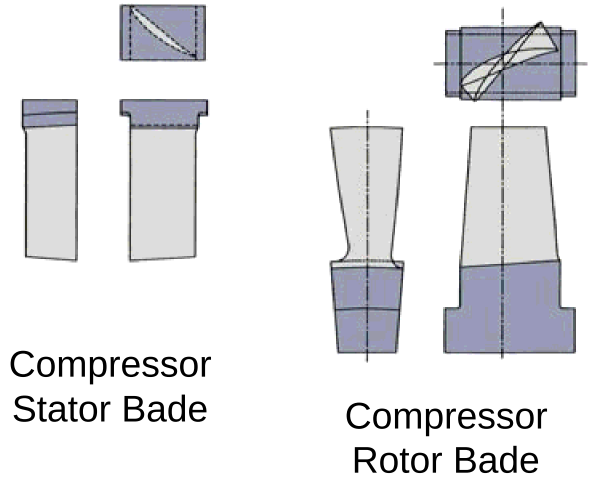
Open-Cycle Industrial Gas Turbine (π = 20, θ_{TI} = 1450°C)
Mitsubishi M701G 334 MWe, 39.5%

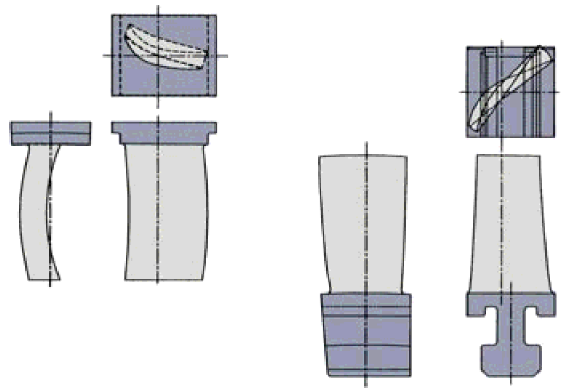




Closed-Cycle Helium Gas Turbine (π = 2, θ_{TI} = 850°C)
GTHTR300 275 MWe, 45.8%

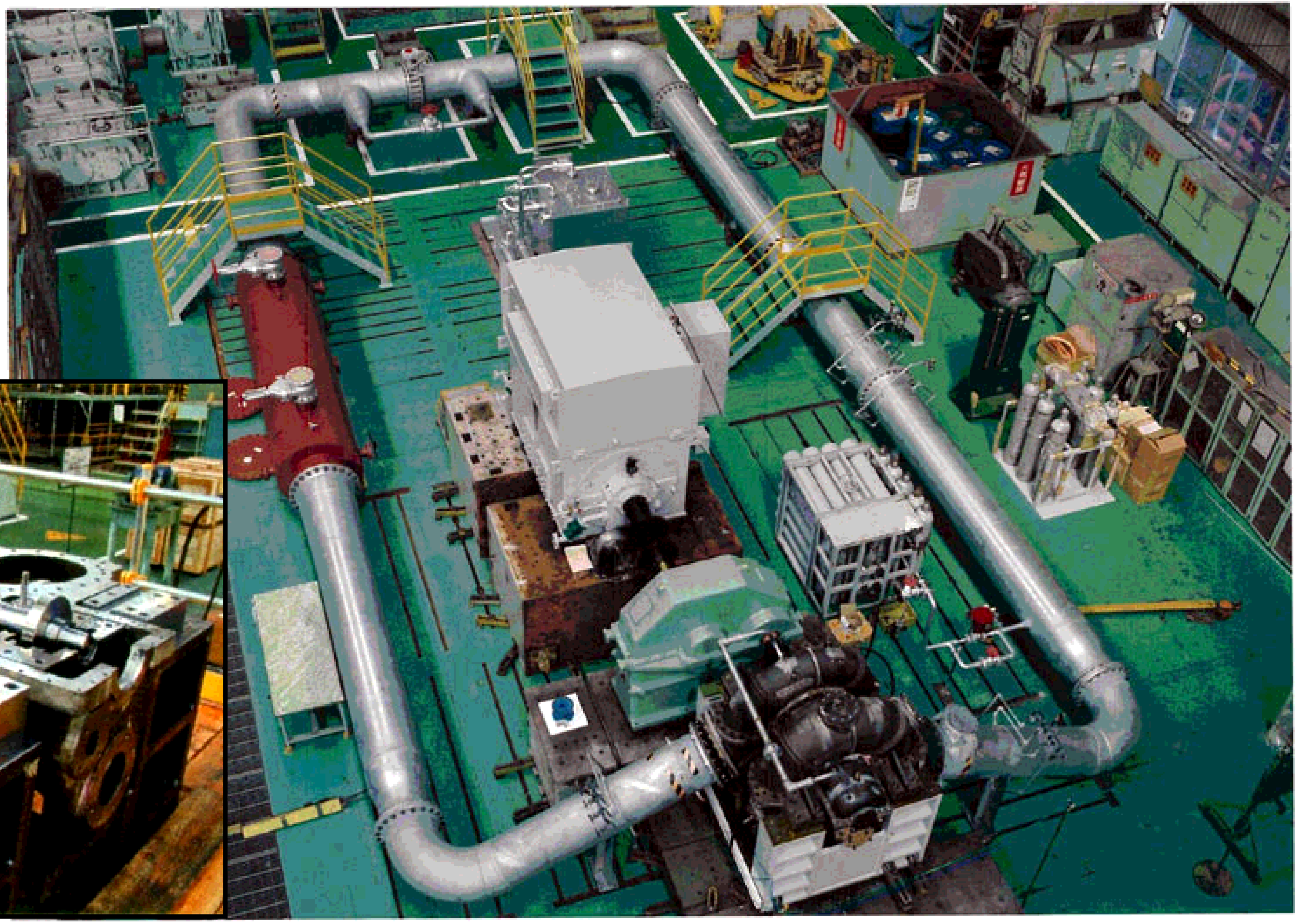
Industrial Gas Turbine

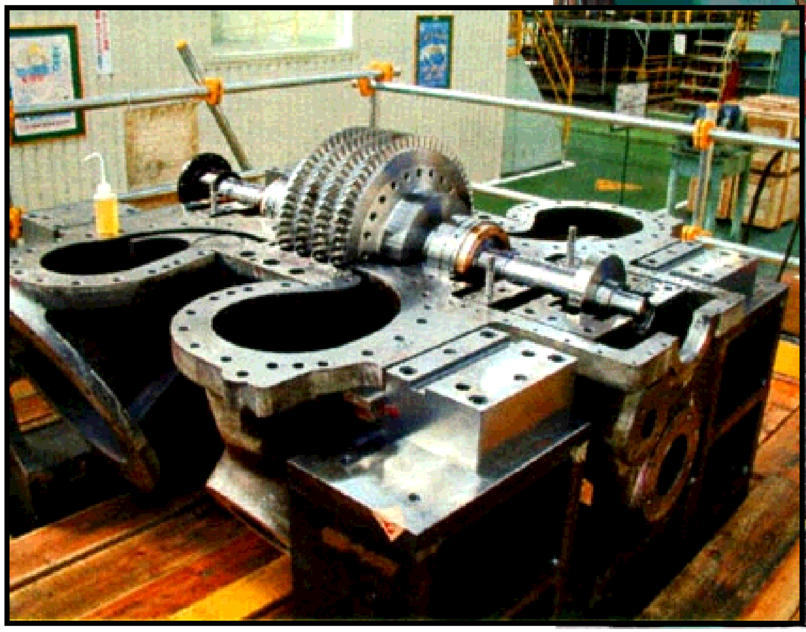




GTHTR300

Compressor Model and Helium Gas Loop





Major Design Parameters of Compressor Model

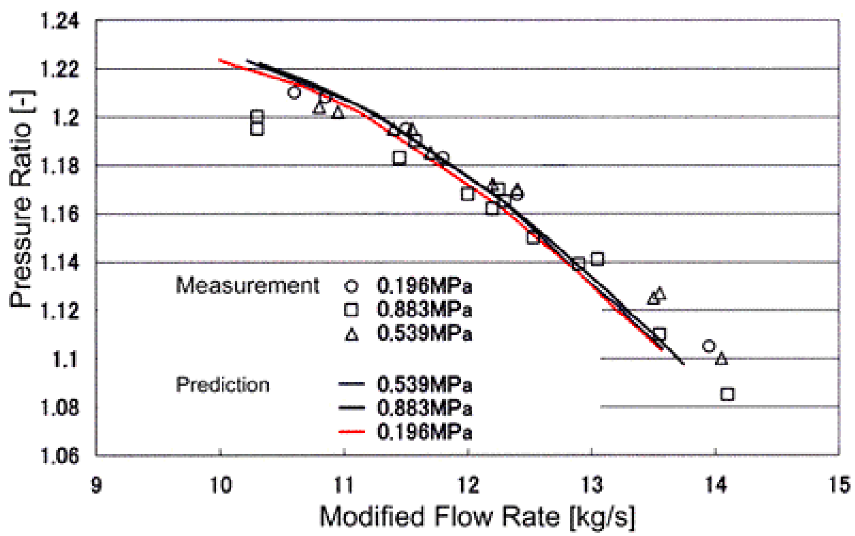
Flow rate	12.2 kg/s
Inlet temperature	30°C
Inlet pressure	0.883MPa
Pressure ratio	1.156
Base diameter	500 mm
Tip diameter (1st stage)	568 mm
Boss ratio (1st stage)	0.88
Number of stages	4
Rotational speed	10800 rpm
Peripheral speed of rotor blade	321 m/s
Number of rotor/stator blades (1st stage)	72/94
Rotor/stator blade chord length (1st stage)	28.6/35 mm
Rotor/stator blade height (1st stage)	34/33.7 mm

Aerodynamic Performance Results

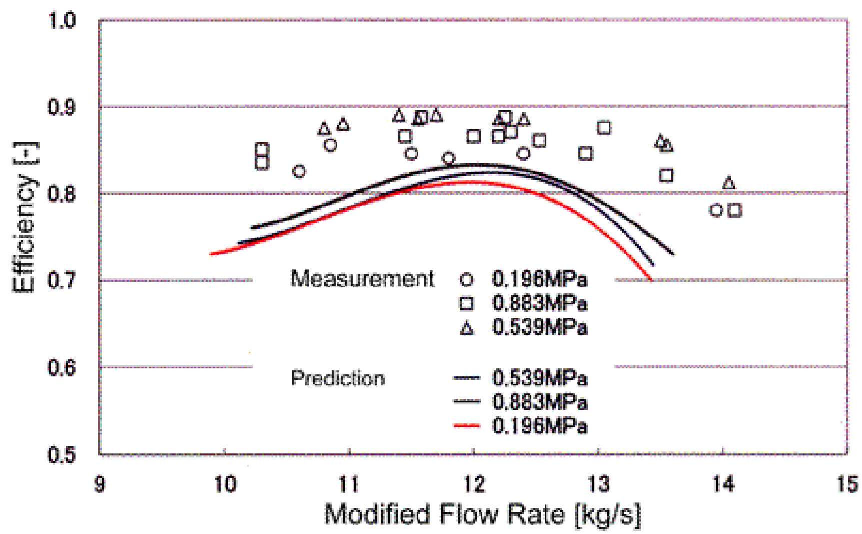
The first series of aerodynamic performance tests was completed in March 2003.

Performance results showed good agreement with the prediction.

Extrapolation to the full scale compressor condition estimated an efficiency over 90%.



Pressure ratio at the rated rotational speed



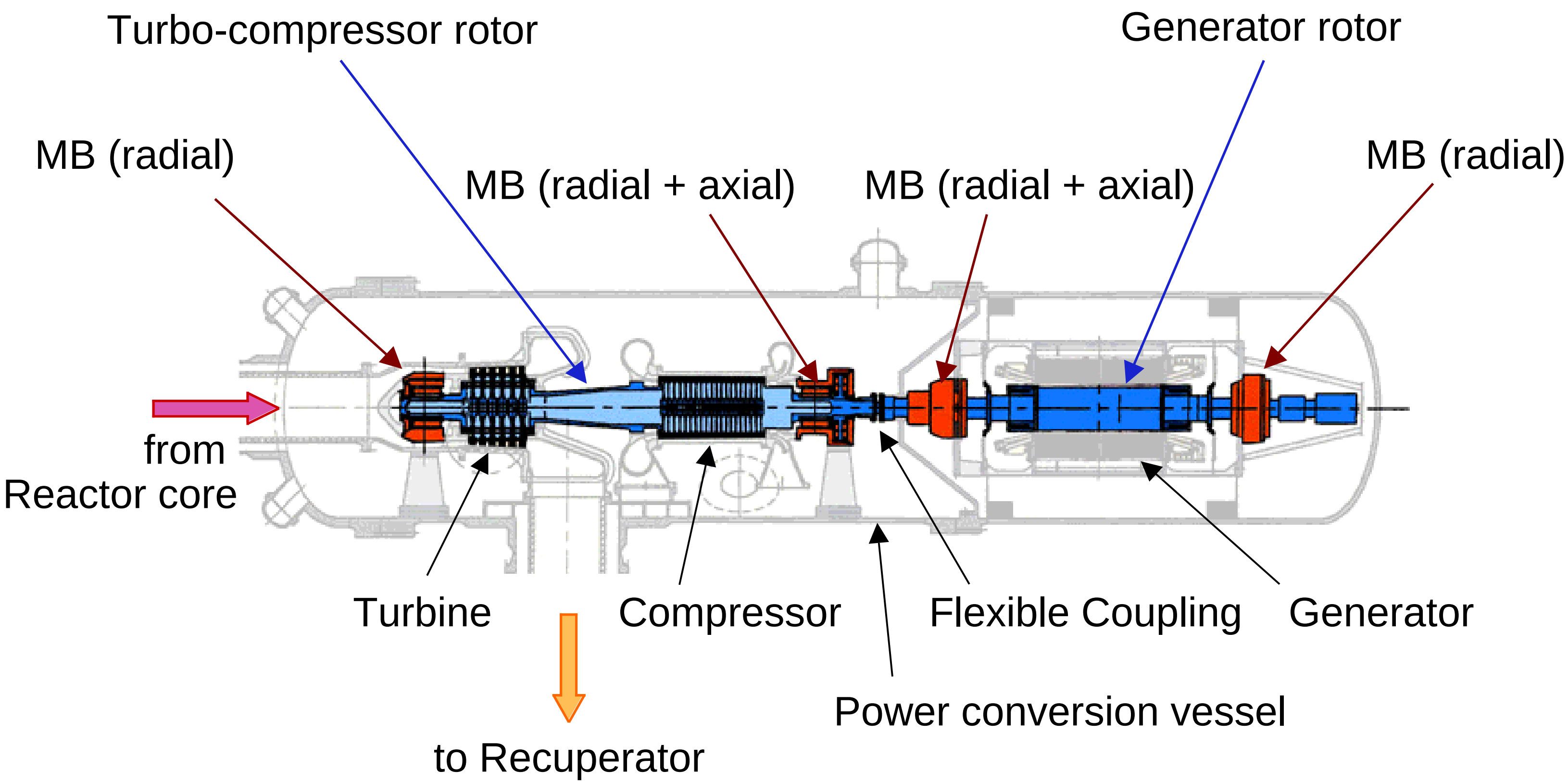
Blade section efficiency at the rated rotational speed

Turbo-machine Rotor System

Single shaft, Two span (Turbo-compressor rotor and Generator rotor), Flexible coupling connection, Magnetic bearing support

Rotational speed: 3600 rpm, Length: 12 + 13 m, Mass 46,100 + 66,500 kg

Magnetic bearings need no liquid lubricants, completely eliminating the possibility of lubricant ingress into the primary system.

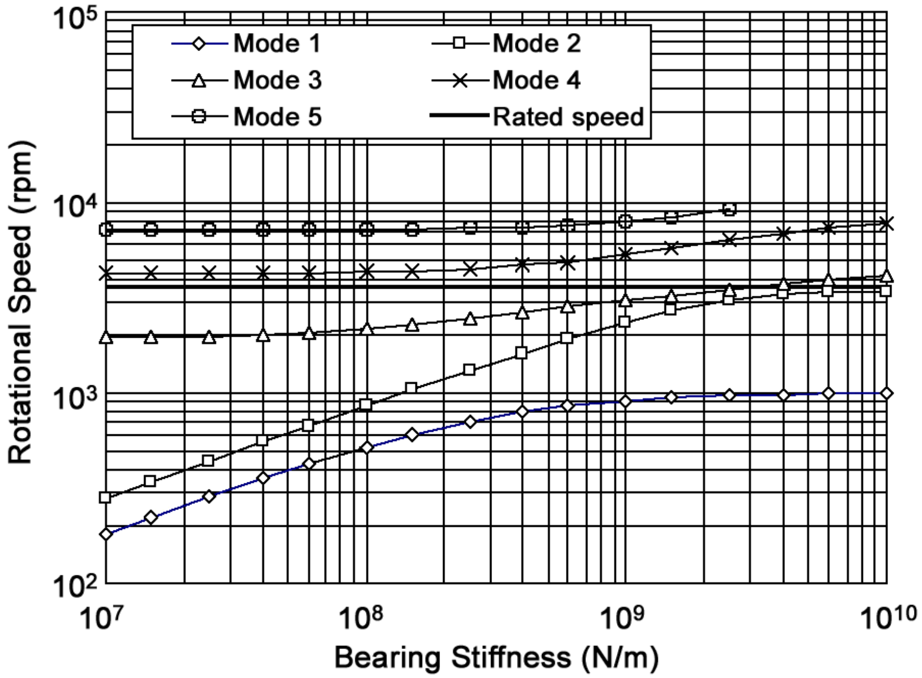


Rotor Dynamics

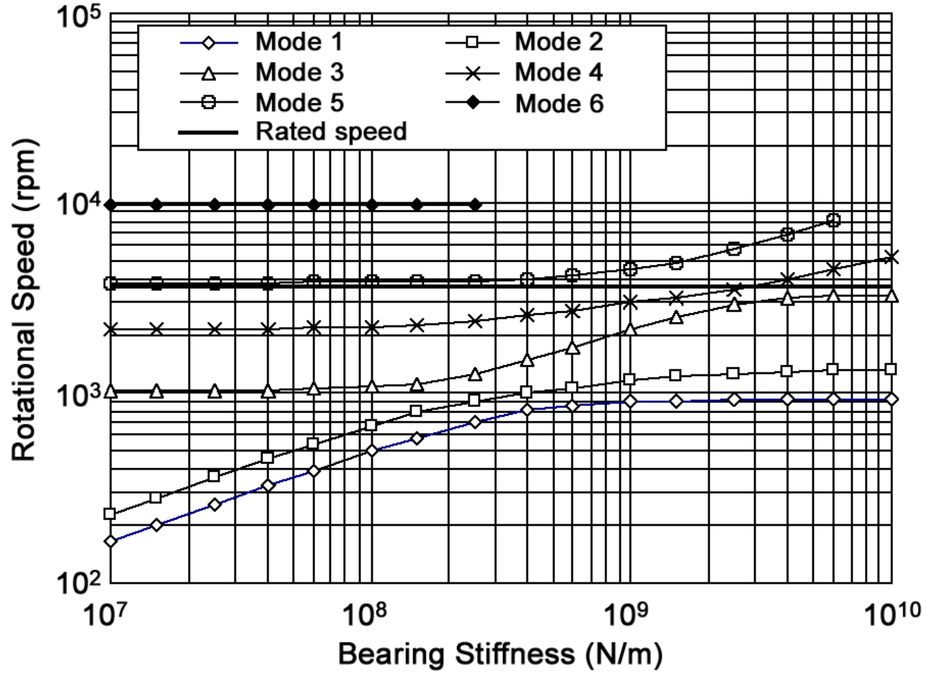
Magnetic bearings have lower load capacity and lower stiffness than oil bearings.

The stiffness of the magnetic bearings is around 10^9 N/m.

The rotors operate above bending mode critical speeds



Critical speed map for the turbo-compressor rotor

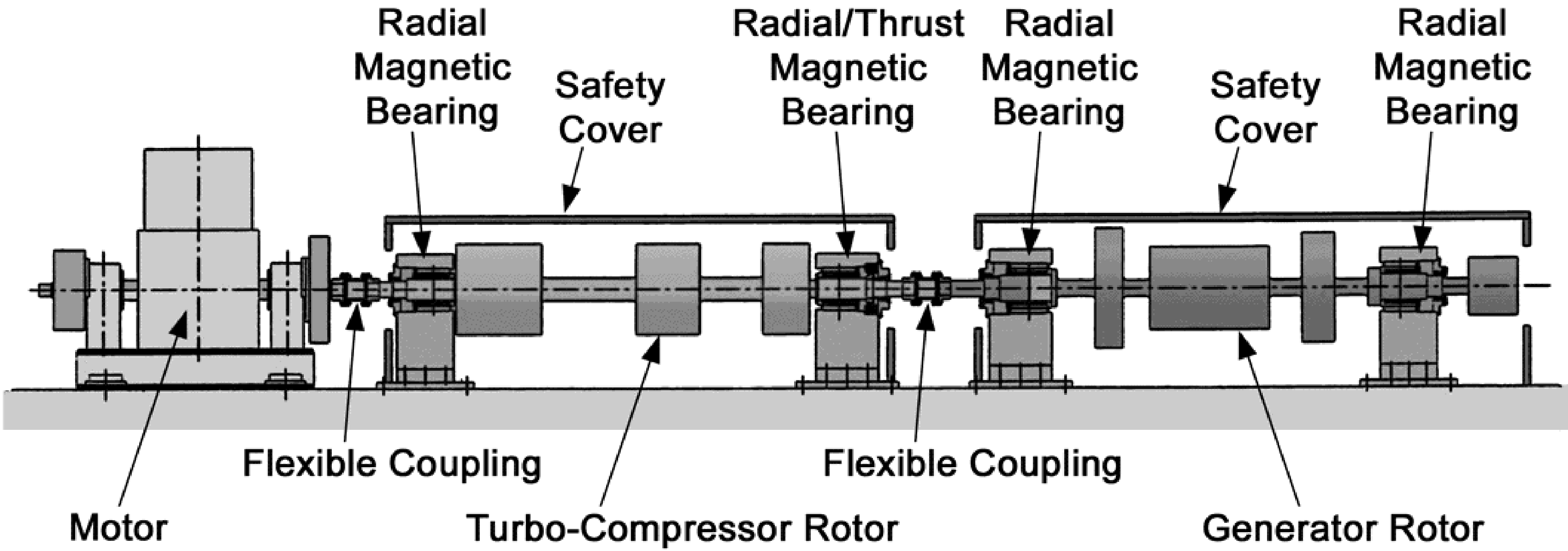


Critical speed map for the generator rotor

Turbo-machine Rotor Model Test

Testing of magnetic bearing performance, unbalance response, stability and auxiliary bearing reliability.

Development of advanced control method



Rotor model

1/3-scale (1/10 in mass), Variable speed (rated 3600 rpm)

Gas-turbine System Operation and Control Test

Test objectives;

to establish an operation and control method of closed-cycle gas-turbine systems,

to accumulate system transient data, and

to develop and verify a plant dynamics analysis code.

Operation modes;

full power steady-state normal operation,

partial power steady-state normal operation,

start-up,

shutdown

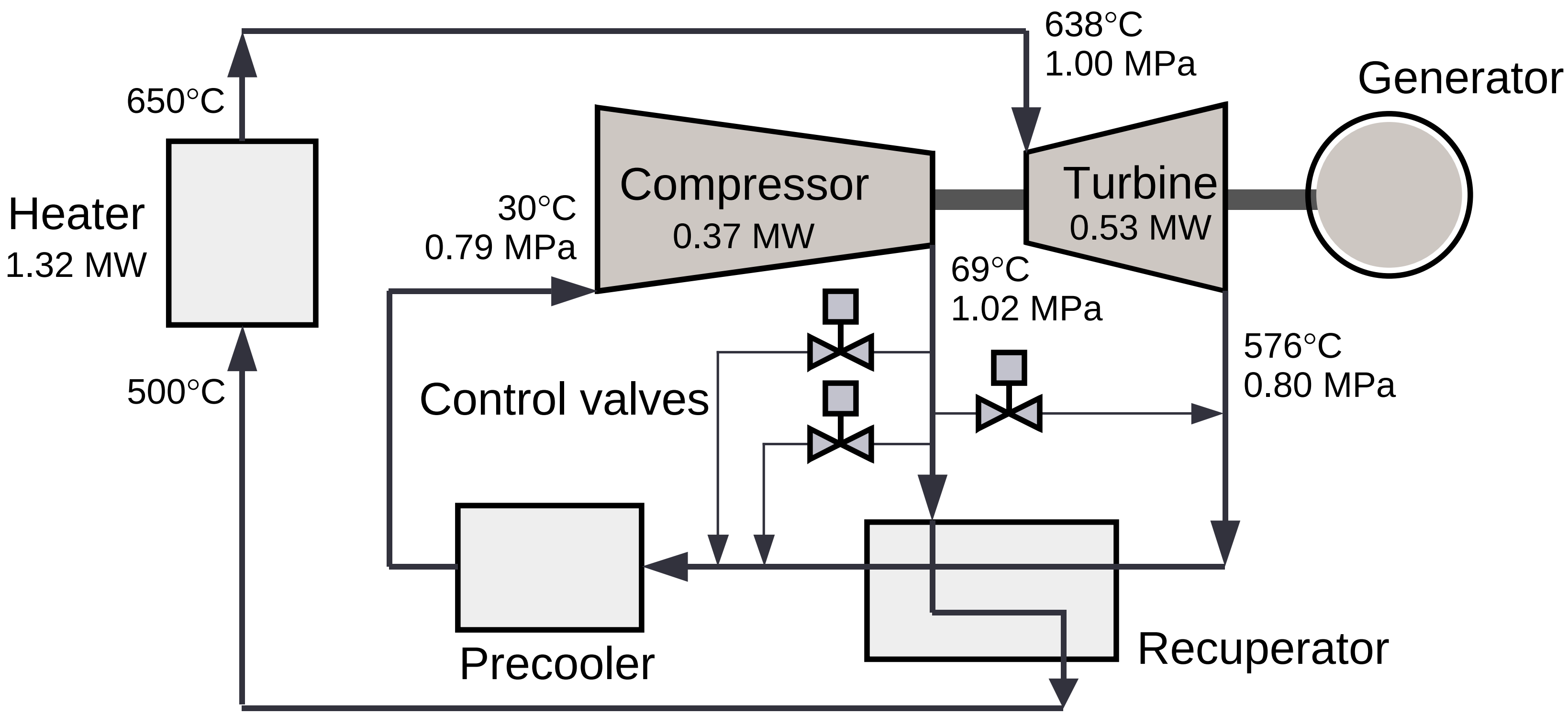
load change,

loss of load, and

emergency shutdown

Schematic Flow Diagram of the Test Facility

Integrated scaled model of GTHTR300 power conversion system

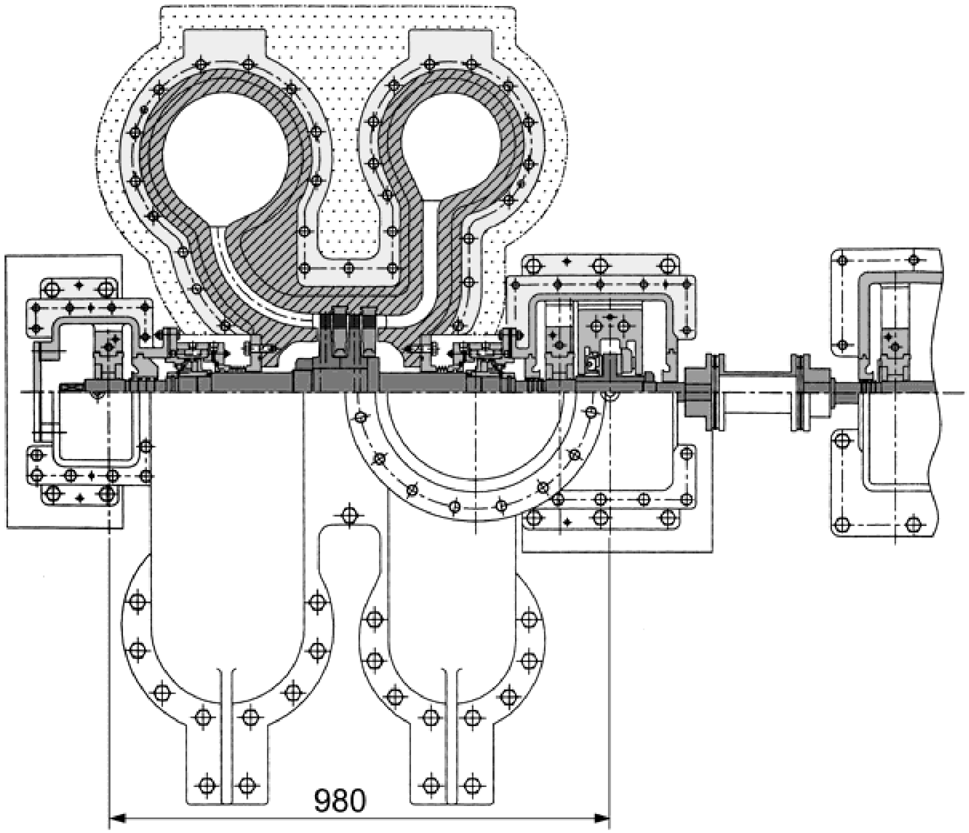


Flow diagram of the test facility (reference design)

Working fluid: Helium
Flow rate: 1.7 kg/s

Turbine Model

1/7-scale, 2-stage axial turbine (reference design)



Flow rate	1.66 kg/s
Inlet pressure	1.00 MPa
Inlet temperature	641°C
Pressure ratio	1.24
Rotational speed	23400 rpm
Number of stages	2
Inlet outer diameter	336 mm
Inlet hub diameter	281 mm
Blade height	27.5 mm

Very High Temperature Reactor (VHTR)

Very high temperature reactor with 950°C reactor outlet temperature enables;

Electricity generation at a higher efficiency around 50%,

Hydrogen production by thermo-chemical processes, and

Cogeneration of electricity and hydrogen.

HTTR and GTHTR300 offer technology base for VHTR

Preliminary design of the 950°C reactor core

Thermodynamic cycle of the 950°C power conversion system

VHTR plant for cogeneration (GTHTR300C)

950°C Reactor Preliminary Design

950°C core design with little modifications
Power distribution flattened
Fuel element design unchanged
Core internals design unchanged

	950°C core	850°C core
Thermal Power	600 MW	600 MW
Power density	5.4 MW/m^3	5.4 MW/m^3
Core outlet temperature	950°C	850°C
Core inlet temperature	587°C	587°C
Fuel temperature (max.)	1377°C	1379°C
Burnup (average)	118 GWd/t	120 GWd/t
Cycle length	550 days (2 batch)	730 days (2 batch)
Refueling bach	2	2
CFP packing fraction	21.8%	29.0%
Enrichment	5 (11.0-16.4%)	1 (14%)
BP diameter	1	2
BP concentration	2	7

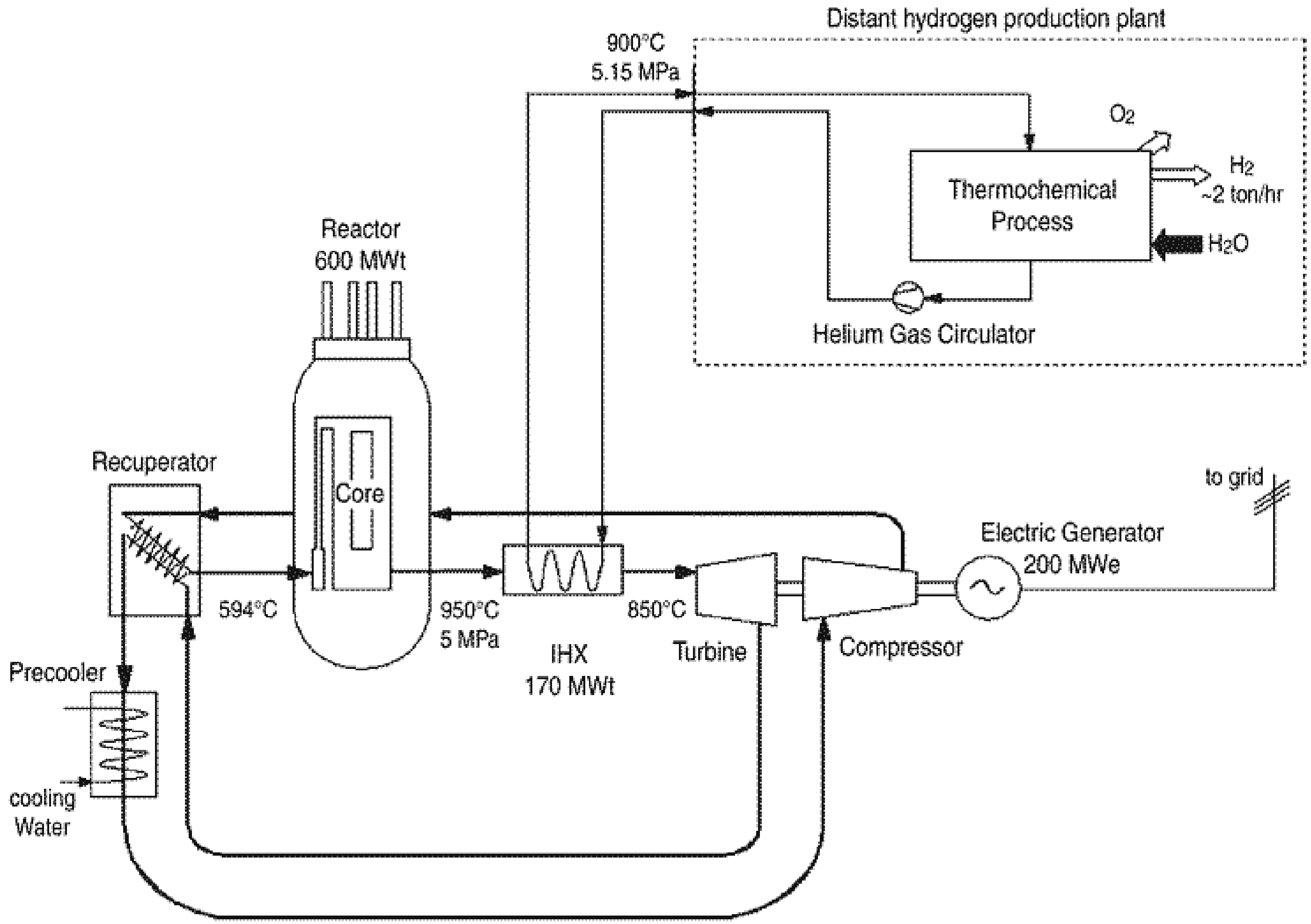
Gas Turbine Cycle for 950°C

With 950°C core, 50% Power conversion efficiency is attainable without any significant design change to GTHTR300 power conversion system.

	950°C PCS	850°C PCS
Core outlet temperature	950°C	850°C
Core inlet temperature	663°C	587°C
Pressure ratio	2.0	2.0
Turbine efficiency	94%	93%
Compressor efficiency	91.5%	90.5%
Recuperator effectiveness	95%	96%
Turbine cooling flow	1.5%	1%
Power conversion efficiency	50%	45.8%

Cogeneration Plant GTHTR300C

Least design changes from that of GTHTR300 plant
Minimum additional R&D
Topping with hydrogen production process on gas-turbine cycle



Design Features of GTHTR300C

Based on the GTHTR300 plant design

950°C core outlet coolant temperature

950-850°C for hydrogen production

850°C< for electricity generation

5 MPa coolant pressure

Helical tube-and-shell type IHX

Turbo-compressor design unchanged

Recuperator and precooler design unchanged

Comparison of Cogeneration Plant with Power Plant

	GTHTR300C cogeneration plant	GTHTR300 power plant
Reactor thermal power [MWt]	600	600
Core power density [W/cc]	5.4	5.4
Core outlet temperature [°C]	950	850
Core inlet temperature [°C]	594	587
Core coolant pressure [MPa]	5.1	6.9
Core coolant flow rate [kg/s]	324	439
GT cycle pressure ratio [-]	2.0	2.0
Power conversion efficiency [%]	46.7	45.8
Electricity production [MWe]	202	275

Intermediate Heat Exchanger (IHX)

Helical tube-and-shell type He/He IHX is operating at 950°C in HTTR

Hastelloy-XR (helium ~1000°C)

High temperature structural design guideline

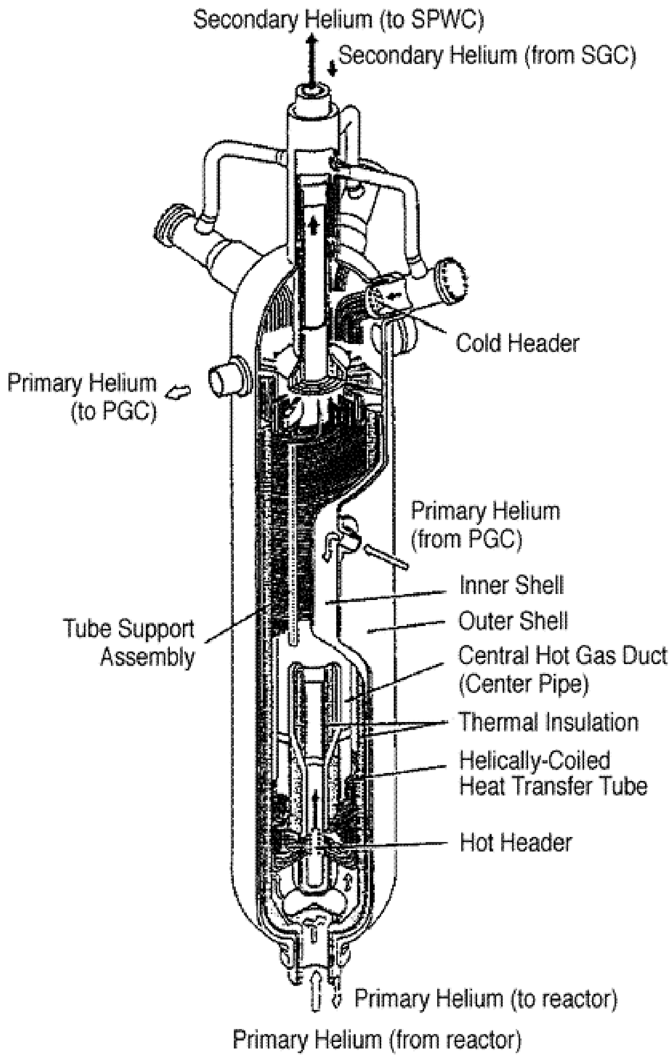
Licensing and Operating experiences

IHX design for the GTHTR300C follows that of the HTTR

Type: Helical tube-and shell

Material: Hastelloy-XR

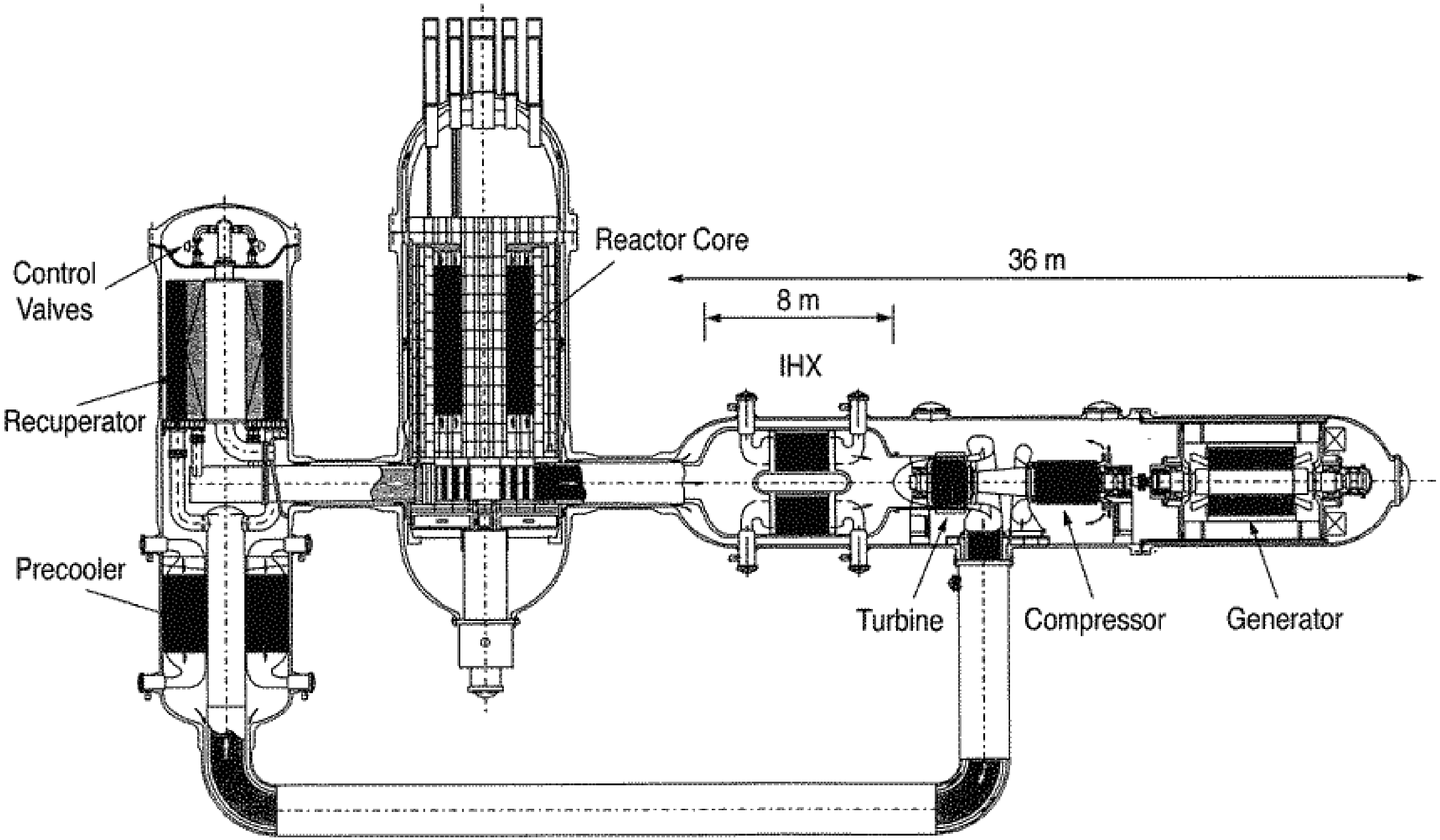
Tube sizing: 31.75 mm OD × 24.75 mm ID



Comparison of GTHTR300C IHX with HTTR IHX

	GTHTR300C	HTTR
Thermal rating [MWt]	170	10
Primary side		
Inlet/outlet temperature [°C]	950/850	950/389
Pressure [MPa]	5.02	4.06
Flow rate [kg/s]	323.8	3.4
Secondary side		
Inlet/outlet temperature [°C]	500/900	237/869
Pressure [MPa]	5.15	4.21
Flow rate [kg/s]	81.0	3.0
LMTD [°C]	154	113
Heat transfer area [m^2]	972	244
Effective tube bundle OD/length [m]	5.20/2.60	1.30/4.87

Conceptual Layout of GTHTR300C



Concluding Remarks

JAERI is carrying out the HTR technology development under the HTTR project.

The HTTR successfully achieved full power at the outlet coolant temperature of 950°C.

Design of the GTHTR300 power plant and R&D on a gas-turbine system are underway with a goal of near-term commercial deployment.

The GTHTR300 design will demonstrate competitive economy and high degree of safety. The R&D on helium gas turbines will establish technology of high-efficiency power conversion.

A concept of a cogeneration plant GTHTR300C is proposed to meet the future demand for hydrogen and electricity.