HTGR Brayton Cycle
Technology and Operations

Xing L. Yan

HTGR Hydrogen and Heat Application Research Center
Japan Atomic Energy Agency (JAEA)

Contents

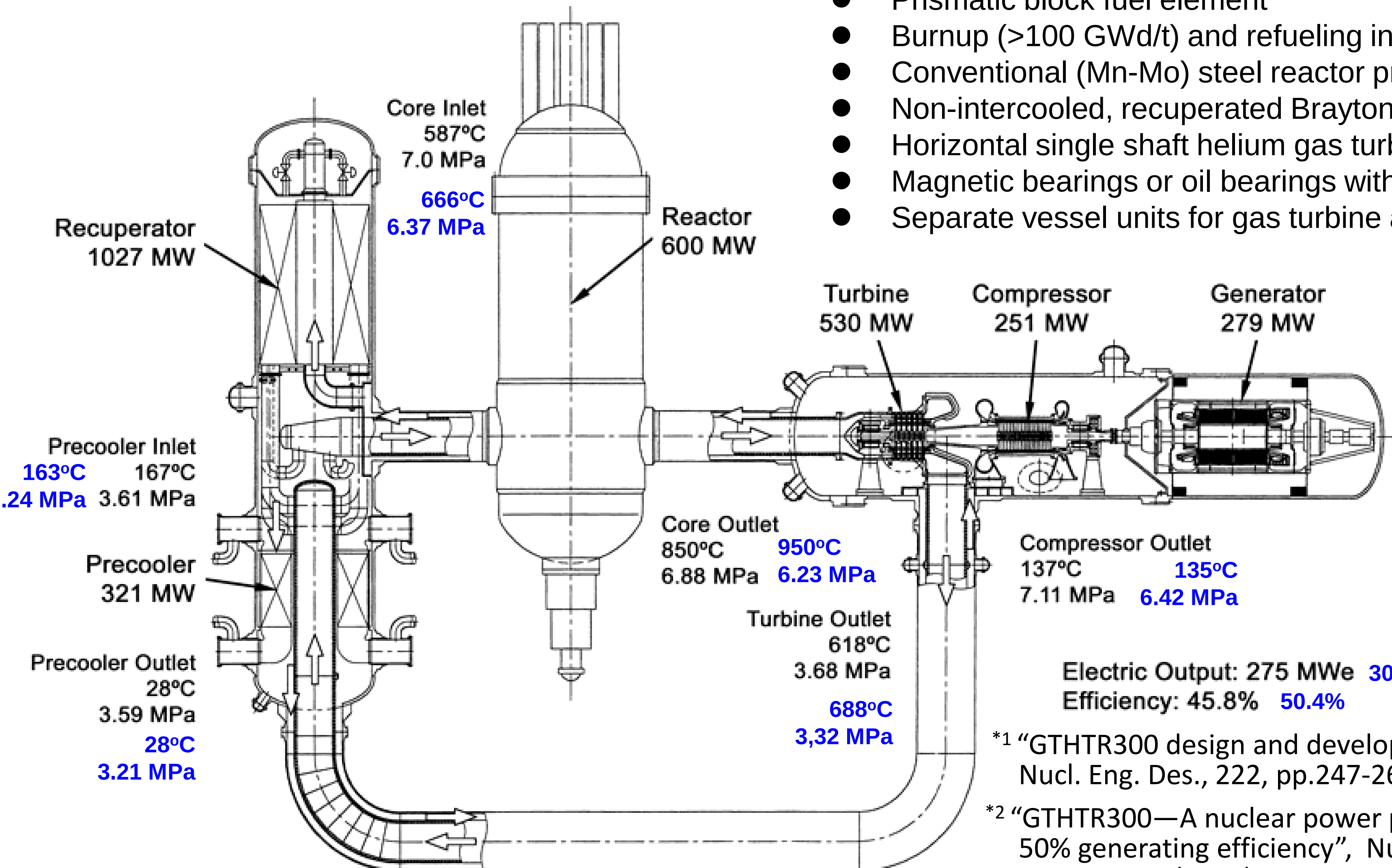
Highlighted with JAEA's GTHTR300 technology

1. **Power Conversion Cycle Parameters**
2. **Cost**
3. **Operations**
4. **Readiness and Qualification**

JAEA GTHTR300 – Power Conversion Cycle*1,*2

Reactor temp: 850 to 950°C
Brayton Cycle efficiency: 45.8 to 50.4% net

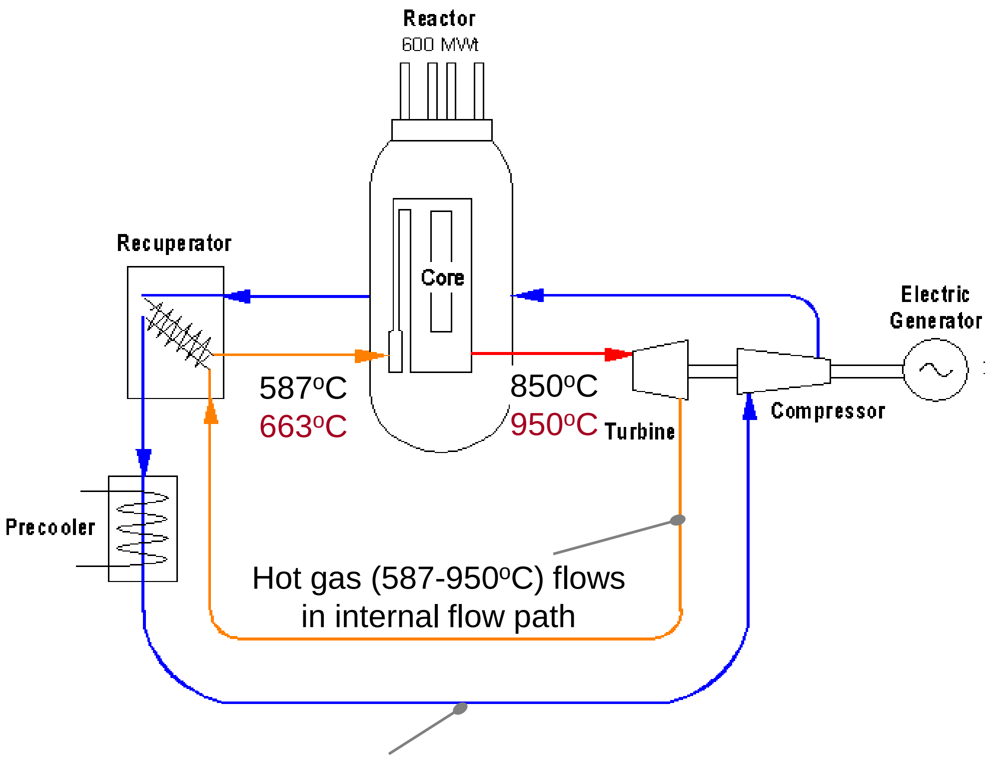
- Modular plant at 300 MWe per unit
- Inherent and passive reactor safety
- Economical dry air cooling (water free operation)
- Prismatic block fuel element
- Burnup (>100 GWd/t) and refueling interval (1.5~2 yr)
- Conventional (Mn-Mo) steel reactor pressure vessel
- Non-intercooled, recuperated Brayton cycle
- Horizontal single shaft helium gas turbine
- Magnetic bearings or oil bearings with gas seal on rotor
- Separate vessel units for gas turbine and heat exchangers

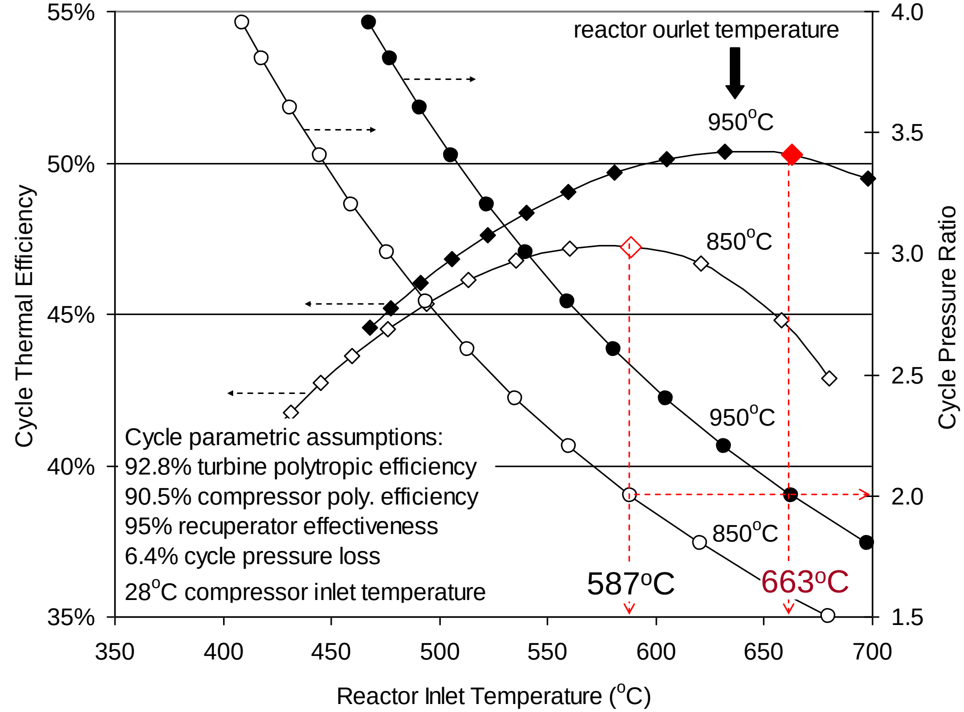


*1 "GTHTR300 design and development", Nucl. Eng. Des., 222, pp.247-262 (2003)

*2 "GTHTR300—A nuclear power plant design with 50% generating efficiency", Nucl. Eng. Des., 275, pp. 190-196 (2014)

High temperature at reactor inlet is as important as at reactor outlet for arriving at a viable point design in terms of cycle efficiency and gas turbine feasibility.





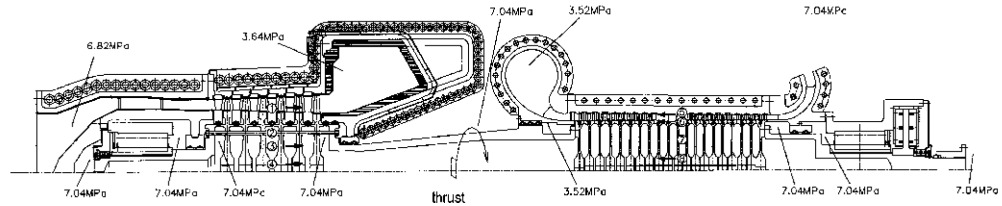
* "GTHTR300 design and development", Nucl. Eng. Des., 222, pp.247-262 (2003)

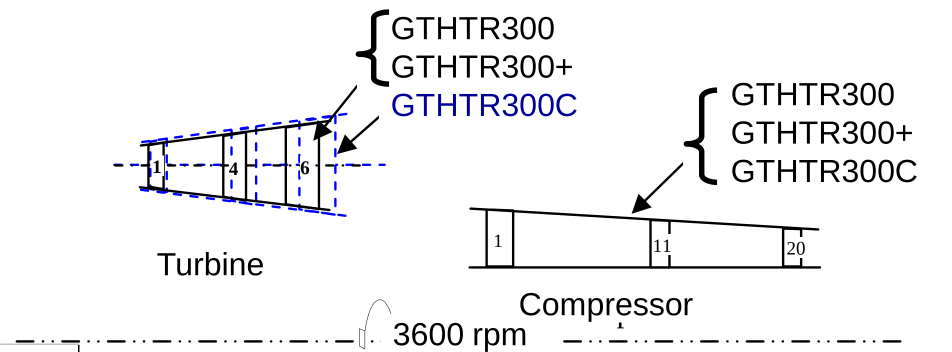
GTHTR300 helium gas turbine

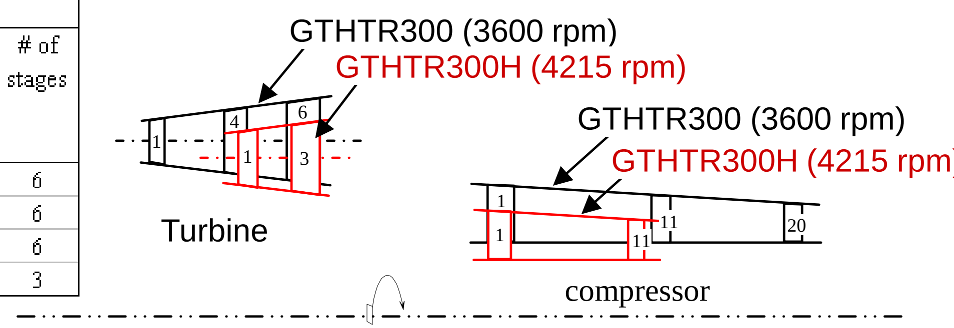
…is a line of designs scaled aerodynamically and mechanically similar from a baseline design

Baseline design: 6 turbine stages, 20 compressor stages, non-intercooled, single shaft, 3600 rpm, 300 MWe class

- Scaled from baseline gas turbine by changing inlet pressure or rotational speed while holding wheel speed constant
- Similar aerodynamics
- Similar disc stresses
- Needed to develop the baseline gas turbine only





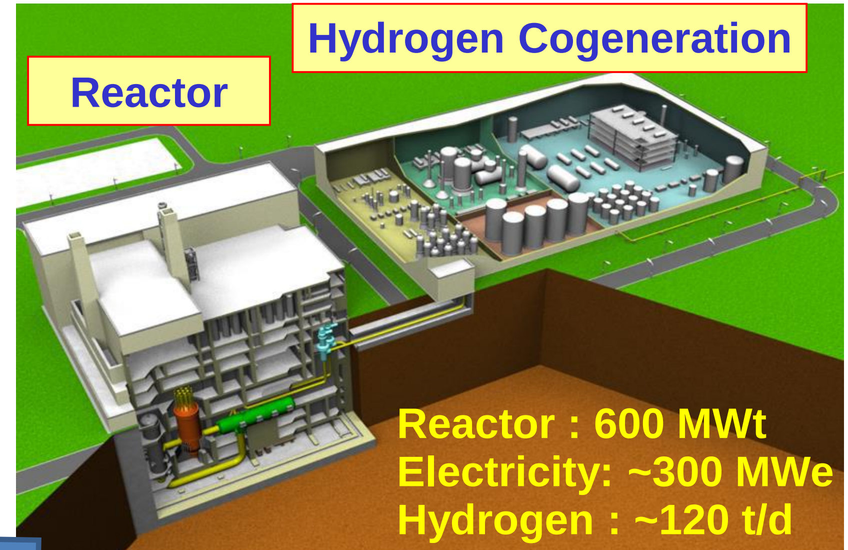


Unit	Gas turbine			Compressor section				Turbine section			
	Speed [rpm]	Pres. ratio	Mass flow [kg/s]	Inlet T [°C]	Inlet P [MPa]	rim speed [m/s]	# of stages	Inlet T [°C]	Inlet P [MPa]	mean speed [m/s]	# of stages
GTHTR300	3,600	2.00	445	28.0	3.5	282	20	850	6.8	377	6
GTHTR300+	3,600	2.00	408	28.0	3.2	282	20	950	6.2	377	6
GTHTR300C	3,600	2.00	327	26.2	2.6	282	20	850	5.0	377	6
GTHTR300H	4,215	1.47	327	26.2	3.5	282	11	730	5.0	377	3

GTHTR300 typical applications

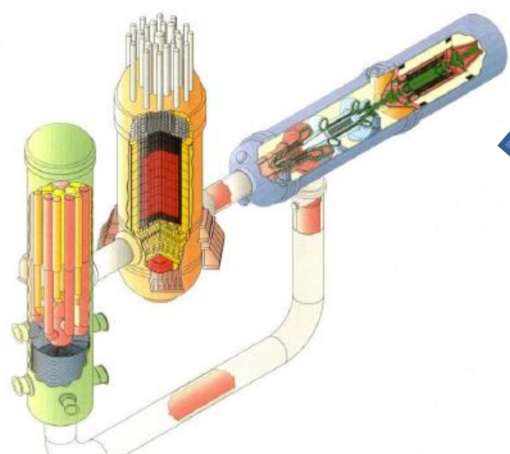
GTHTR300: Peak production parameters

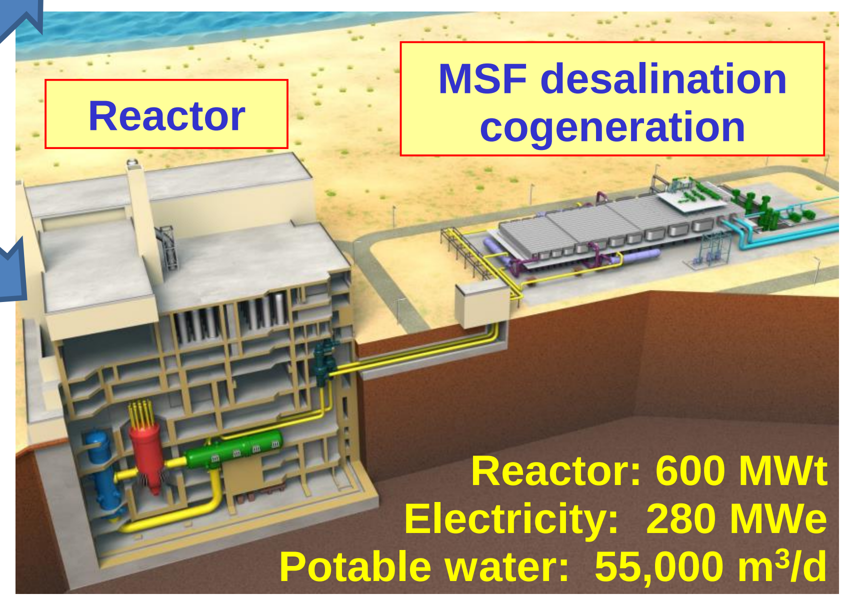
Reactor power (max. output)	600 MWt
Reactor temperature	850-950°C
Refueling interval/period	1.5-2 yrs/30 days
Plant load factor	90%
Reactor coolant pressure	7 MPa
Typical products (max. output)	
• Hydrogen (thermochemical method)	120 t/d
• Electric power (50% net efficiency)	300 MWe
• Desalination (cogenerated w/power)	55,000 m^3/d
• Steel (CO_2 free steelmaking)	0.65 million t/yr



Power Generation

Reactor thermal: 600 MWt
Net electricity: 300 MWe
Generation efficiency: 50%





GTHTR300 Cost Estimates

US$1≈J¥100

Construction Cost[*1] (per reactor unit, 4 units/plant, NOAK)

Reactor	¥17,080M
Power Conversion	¥14,011M
Auxiliary	¥ 6,723M
Electric, Instrumentation & Control	¥ 5,780M
Buildings	¥11,071M
Total	¥54,665M (~US$2,000/kWe)

Electricity Cost (3% discount rate, 40 years operation, 80% availability)

Year estimated ->	2006[*1]	2014
Capital [*2]	¥1.6/kWh	¥2.0/kWh
Operation & Maintenance	¥1.1/kWh	¥1.9/kWh
Fuel [*3]	¥1.4/kWh	¥1.4/kWh
Total	¥4.1/kWh	¥5.3/kWh

[*1] Economical Evaluation on Gas Turbine High Temperature Reactor 300 (GTHTR300) Vol. 5(2) p. 109-117 (2006)

[*2] Including decommissioning cost, [*3] Including reprocessing cost

GTHTR300 Cost Estimates (details)

US$1≈J¥100

Construction cost

Component	Million Yen	Yen/kWe
Reactor components	17,080	62,200
Reactor pressure vessel	4,095	14,900
Core components	4,229	15,400
Reactivity control system	3,060	11,100
Shutdown cooling system	956	3,500
Vessel cooling system	1,285	4,700
Fuel handling and storage system	3,101	11,300
Radioactive waste treatment system	354	1,300
Power conversion system	14,011	51,000
Turbine and compressor	3,414	12,400
Generator	1,435	5,200
Power conversion vessel	1,872	6,800
Heat exchanger	3,008	11,000
Heat exchanger vessel	2,220	8,100
Hot piping	2,062	7,500
Auxiliary system	6,723	24,400
Helium purification system	1,125	4,100
Helium storage and supply system	1,131	4,100
Cooling water system	1,479	5,400
Radiation management system	965	3,500
Ventilation and air conditioning system	1,376	5,000
Other systems	647	2,300
Electric system, control and instrumentation system	5,780	21,000
Electric system	4,000	14,500
Control and instrumentation system	1,780	6,500
Buildings	11,071	40,300
Total	54,665	198,900

Capital cost (Yen/kWh)

Load factor	80%		90%	
Discount rate	3%	4%	3%	4%
Depreciation cost	1.02	1.12	0.90	0.99
Interest cost	0.24	0.35	0.21	0.31
Property tax	0.11	0.12	0.10	0.11
Decommissioning cost	0.21	0.15	0.18	0.14
Total	1.57	1.74	1.40	1.55

Operating cost (Yen/kWh)

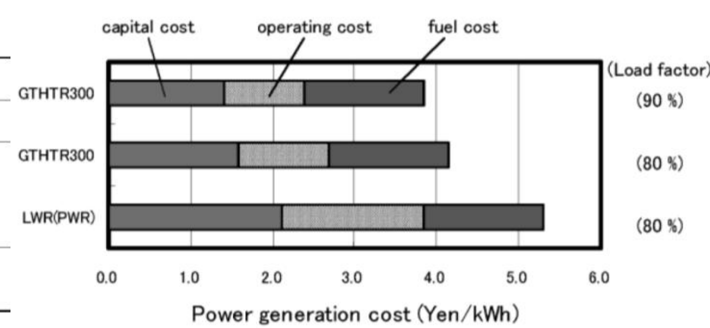
Load factor	80%		90%	
Discount rate	3%	4%	3%	4%
Maintenance cost	0.41	0.41	0.36	0.36
Miscellaneous cost	0.45	0.45	0.40	0.40
Personnel cost	0.19	0.19	0.17	0.17
Head office cost	0.01	0.01	0.01	0.01
Business tax	0.05	0.06	0.05	0.05
Total	1.11	1.11	0.99	0.99

Fuel cost (Yen/kWh)

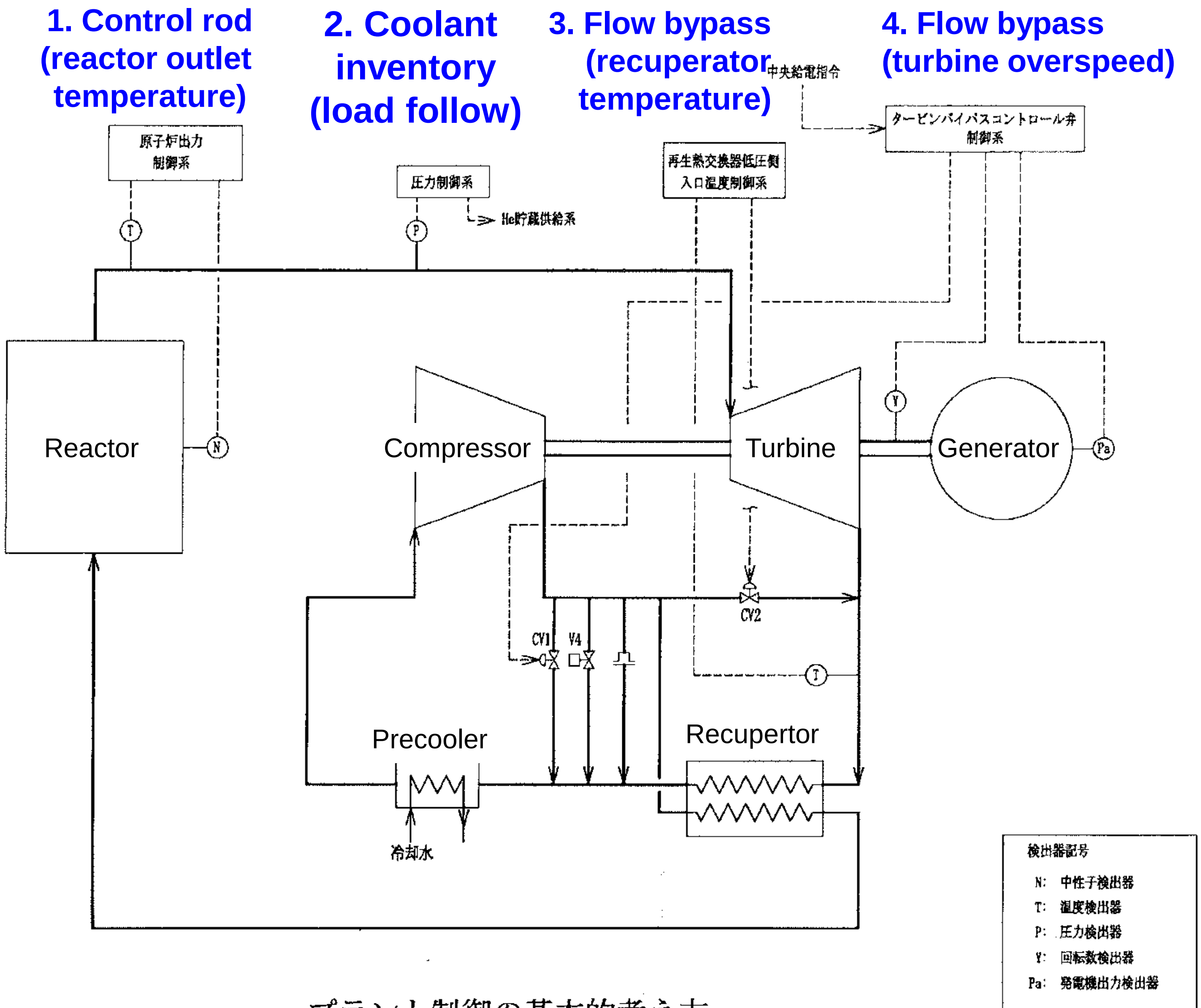
Discount rate	3%	4%
Uranium purchase and conversion cost	0.14	0.15
Enrichment cost	0.29	0.31
Fabrication cost	0.43	0.44
Storage cost	0.02	0.02
Reprocessing cost	0.40	0.38
Waste disposal cost	0.18	0.15
Total	1.46	1.44

Power generation cost (Yen/kWh)

Load factor	80%		90%	
Discount rate	3%	4%	3%	4%
Capital cost	1.57	1.74	1.40	1.55
Operating cost	1.11	1.11	0.99	0.99
Fuel cost	1.46	1.44	1.46	1.44
Total (LWR)[10]	4.14 (5.3)	4.28 (5.6)	3.84 (—)	3.97 (—)



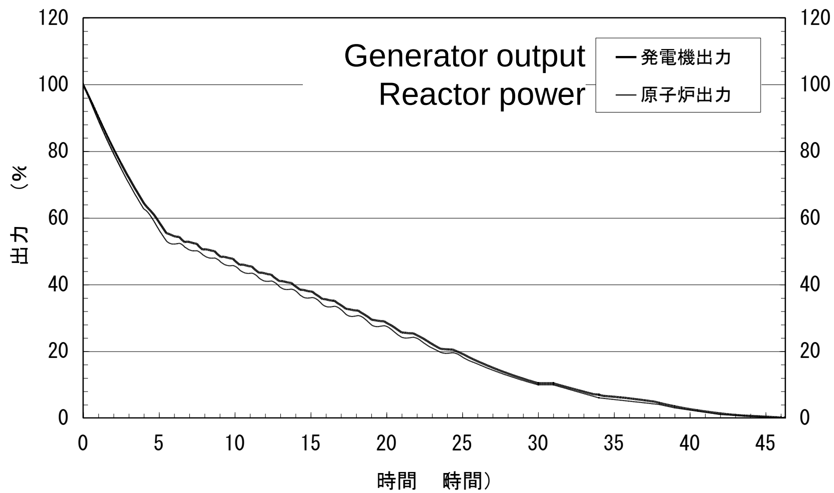
Operations – control system

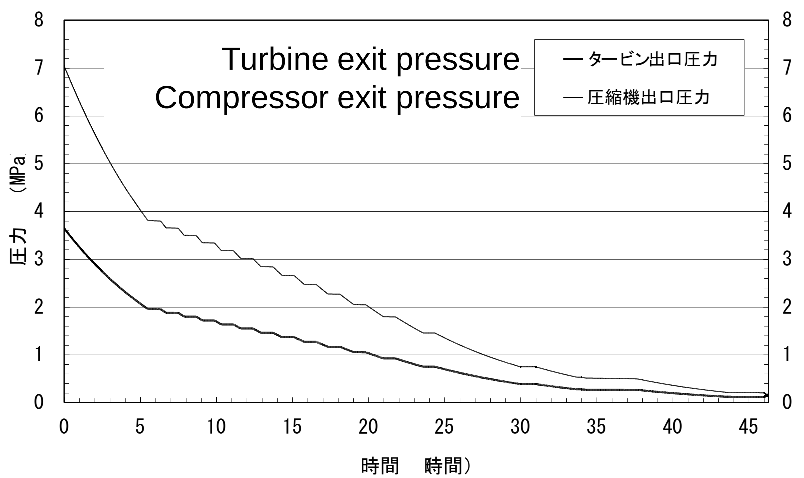


プラント制御の基本的考え方

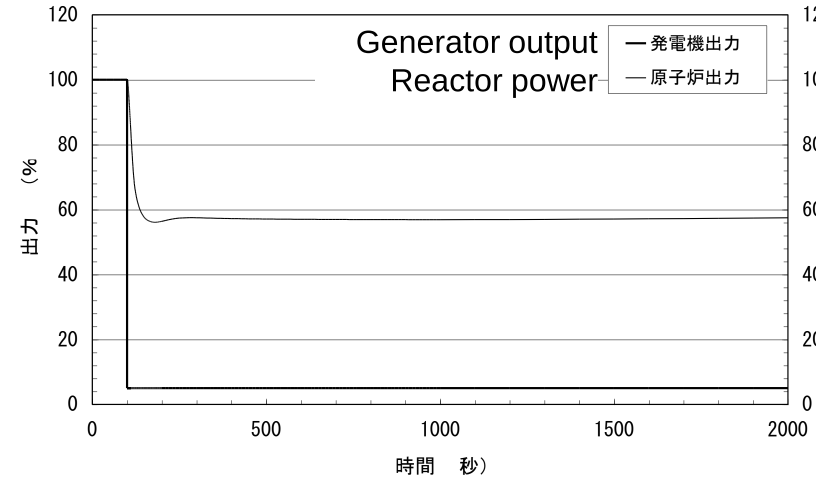
Operations – simulation results

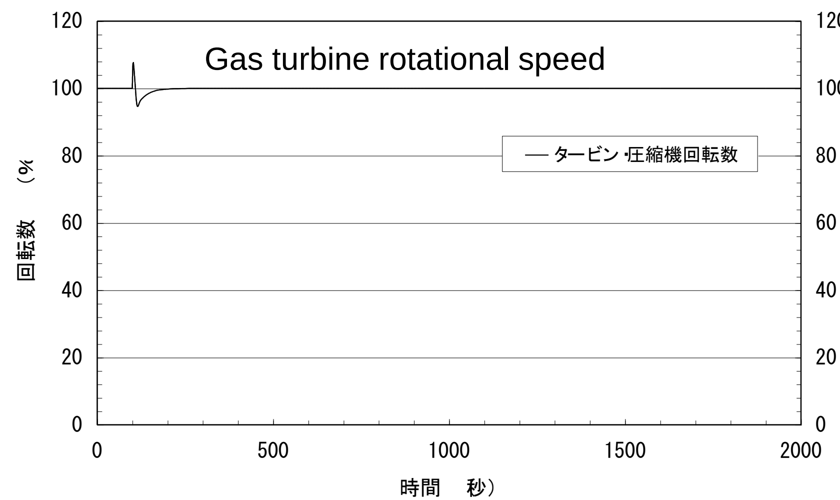
➢ Full ↔ Part load operation – with inventory control





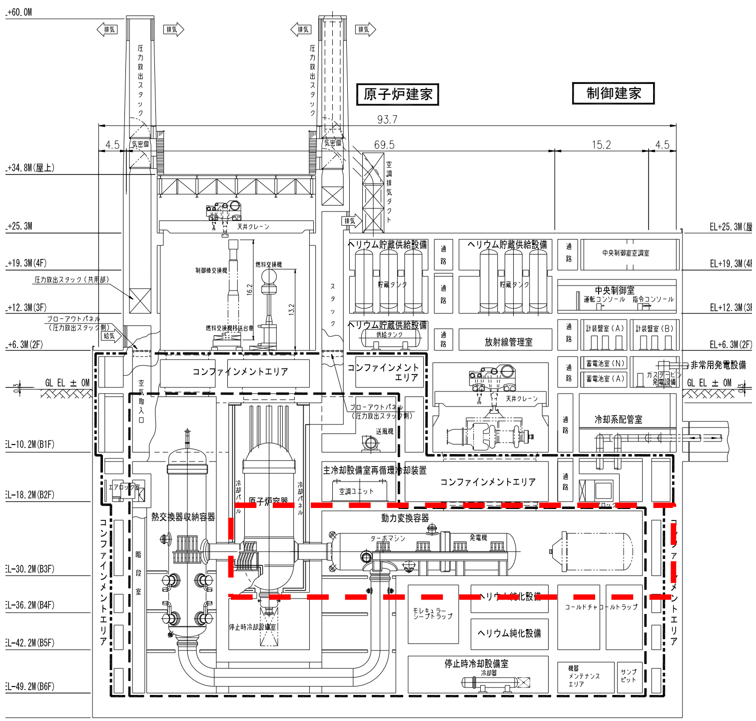
➢ Loss of load – with turbine flow bypass control



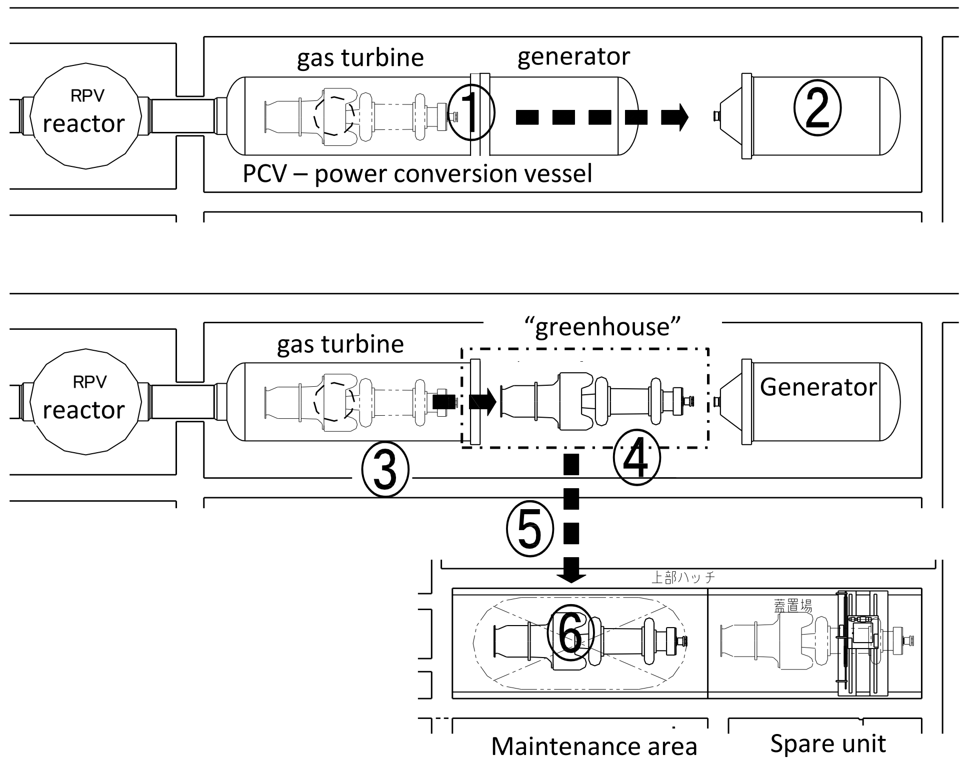


Gas turbine maintenance sequence (service period: 22 days)

① Disconnect the PCV flange
② separate the generator section
③ Disconnect the gas turbine unit supports and flanges with remote arms
④ Pull the gas turbine unit out of the PCV on rail into “greenhouse”
⑤ Move the gas turbine unit to maintenance area
⑥ Restore the PCV with pre-refurbished (spare) unit in reversed orders ⑤ -> ①



GTHTR300 reactor building



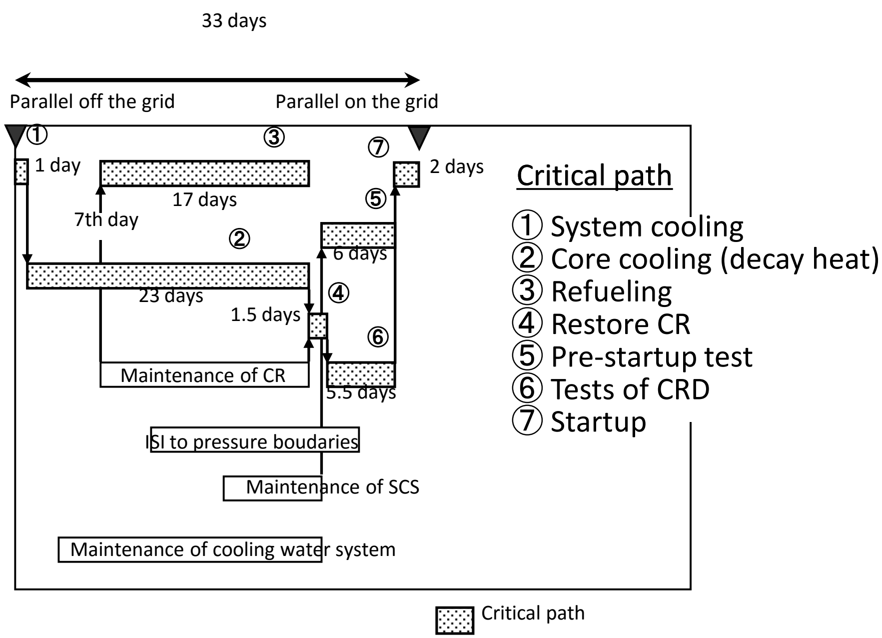
Gas turbine maintenance sequence

GTHTR300 shutdown maintenance cycles

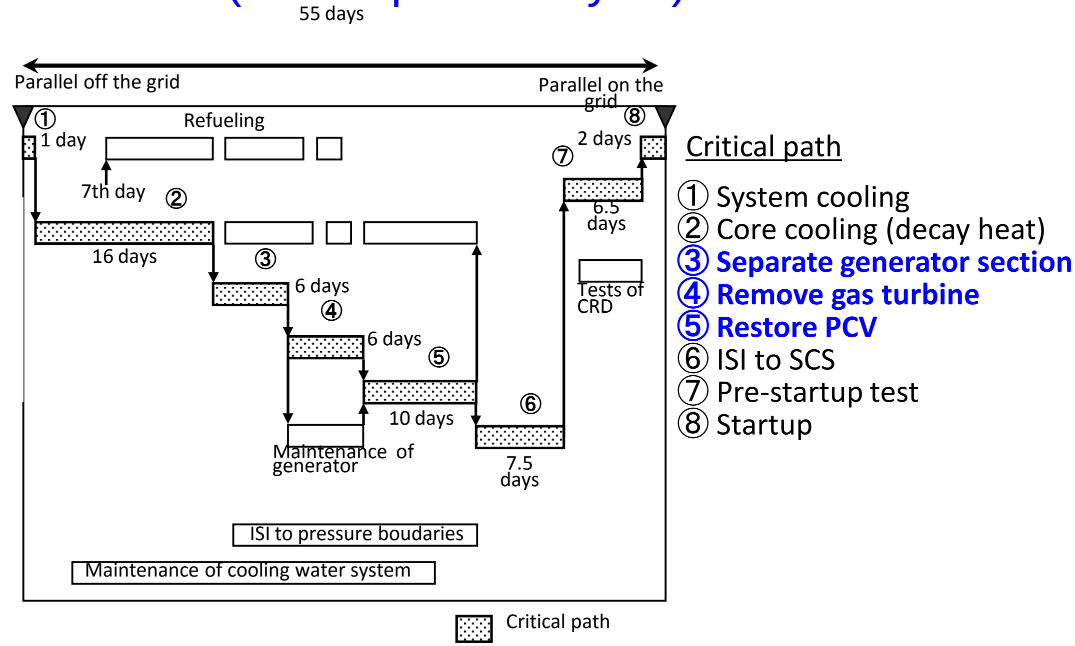
- Refuel service interval: 2 years
- Gas turbine service interval: 4 years

Downtime impact on plant availability: 6%

1st cycle: refuel



2nd cycle: refuel+gas turbine maintenance cycle (then repeat 1st cycle)



Readiness & qualification – technologies developed

(1) HTGR technology

- 30 MWt and 950°C prismatic core advanced test reactor (Operation started in 1998)
- Technology of fuel, graphite, superalloy and experience of operation, and maintenance.
- Post-F1 safety evaluation by NRA is underway.

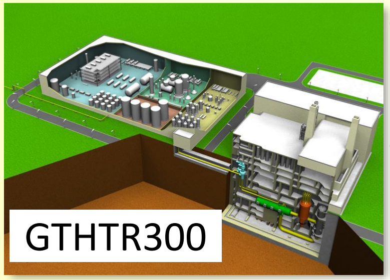
(2) GT and hydrogen technology


He compressor


hydrogen facility

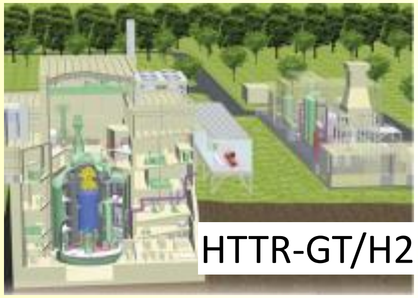
- R&D of gas turbine technologies such as helium compressor, recuperator, magnetic bearing, gas seal, maintenance, etc.
- In 2016, 31 hours of continous automated hydrogen production with a rate of 20NL/h was successfully achieved.

(3) Commerical HTGR design



- GTHTR300 for electricity generation and desalination
- GTHTR300 for cogeneration and <u>nuclear/renewable energy synergy system</u>
- HTGR with Thorium fuel
- Clean Burn HTGR for surplus plutonium burning
- Establishment of safety design philosophy

(4) System demonstration test

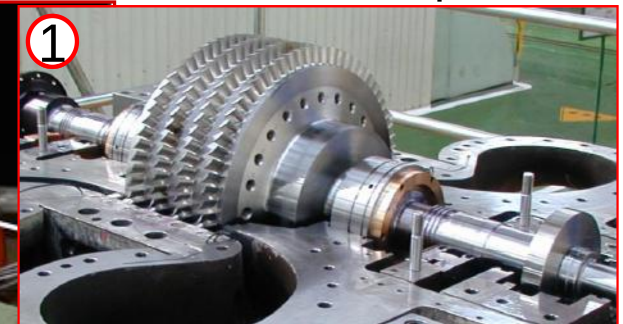


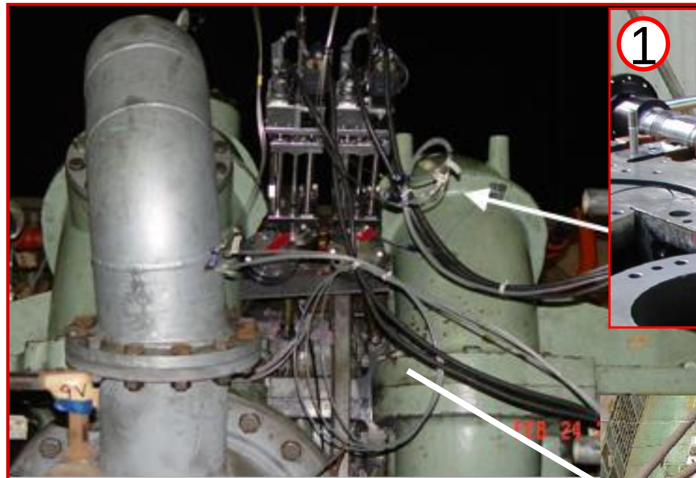
- Connection of helium gas turbine power generation system and then hydrogen cogeneration system to the HTTR.
- Basic design for the HTTR-GT/H2 test is now underway.

Helium compressor technology*

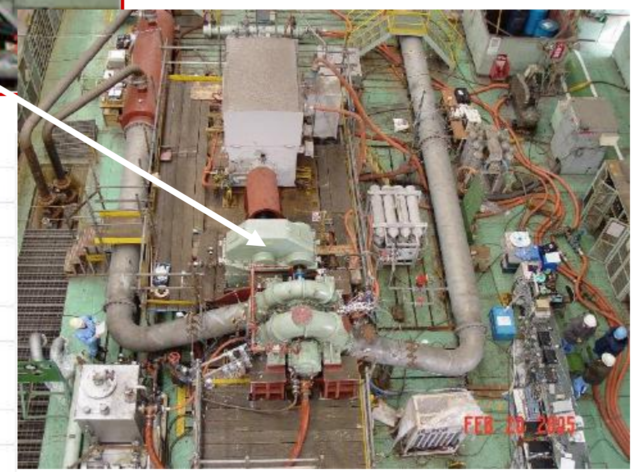
- Design method calibrated by 1/3 scale helium compressor test
- Full scale compressor adiabatic efficiency: 90.3% (polytropic efficiency 91.5%)

Helium compressor

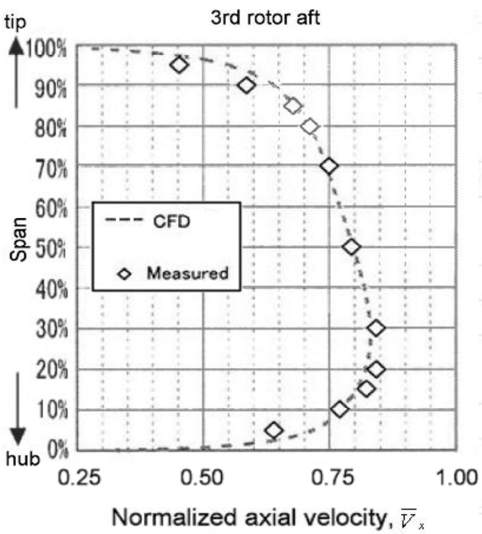


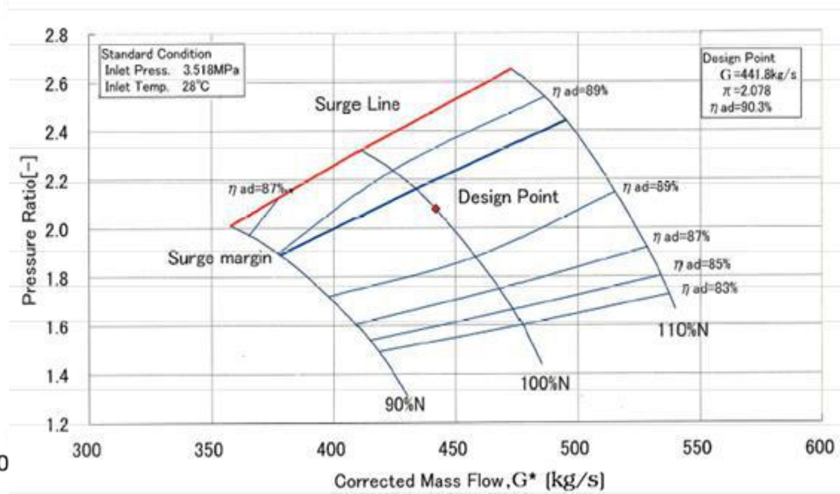


Traversed flow path probes



Helium compressor test rig



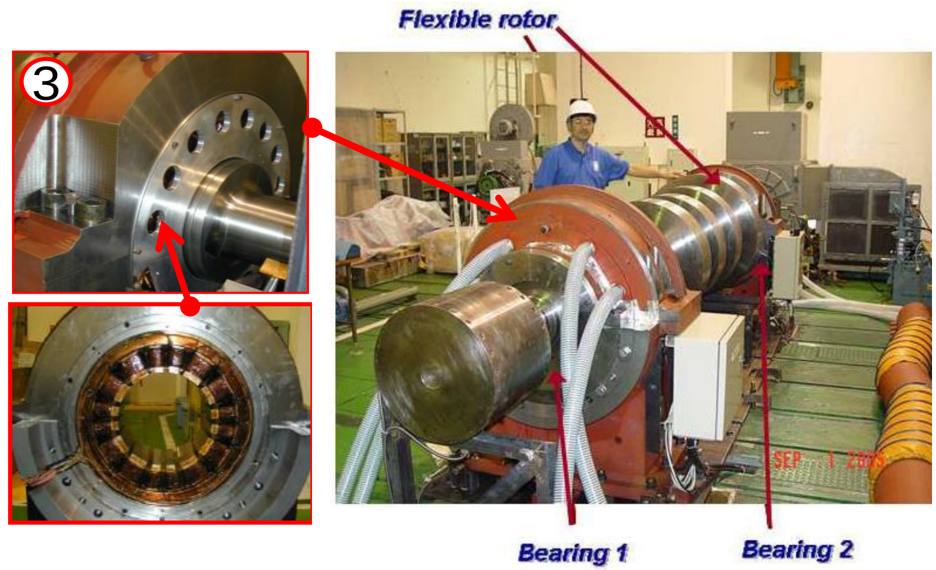


*Aerodynamic design, model test and CFD analysis for multistage axial helium compressor, Journal of Turbomachinery, 130 / 031018, pp.1-12 (2008)

Helium rotor bearing and gas seal technology

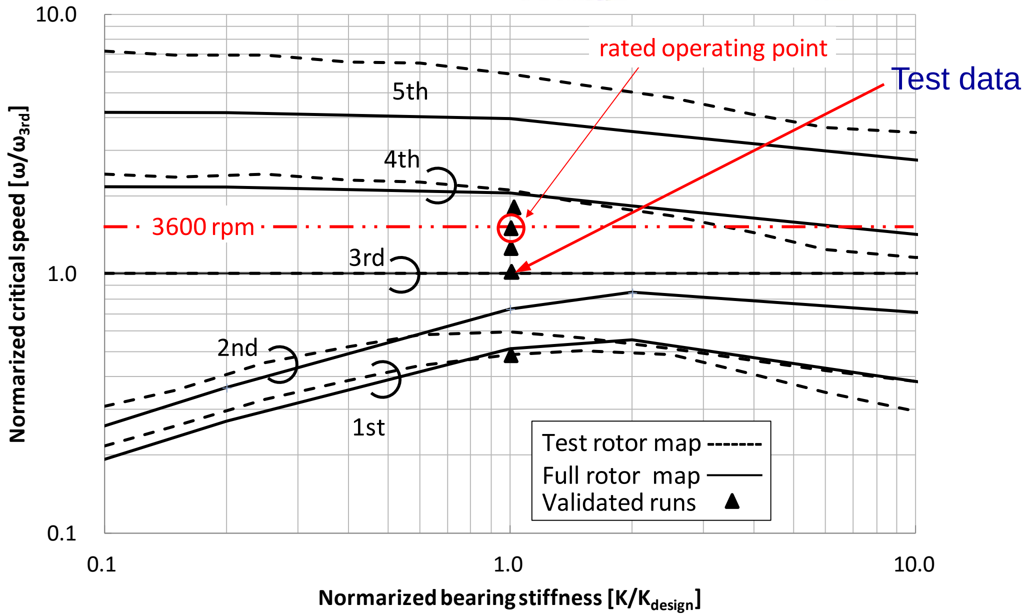
Magnetic bearing

- 1/3 scale, MB-rotor (5 tons) test rig constructed
- Test operated above first bending critical speed
- Control system tested



Gas seal (to allow use of oil bearing)

- Industrial design evaluated
- Leak expected to be minimum (<< HTTR safety license requirement)
- Verification test planned



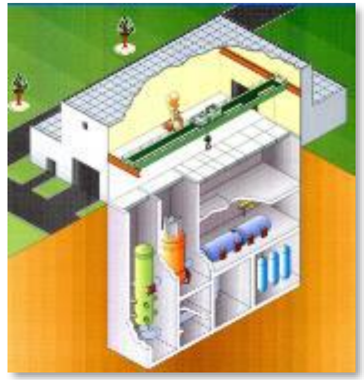
Readiness and qualification - technical roadmap

GTHTR300 basic design and component development
(2001-)

Collaborative work with MHI

- Basic design, safety design, and cost estimation
- Development of high-efficiency He compressor, compact heat exchanger, etc.
- Turbine blade alloy development

World's first successful operation of axial He compressor, He compressor design method validated



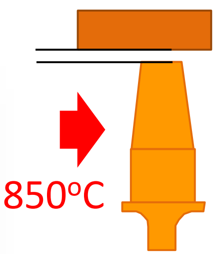
GTHTR300 Commercial lead plant
(2025)

- 850ºC reactor outlet
- Full size reactor build to allow uprate to 300 MWe without design modification

Plant uprate

Full-size turbine hot-function test

- Turbine disc/casing clearance confirmation



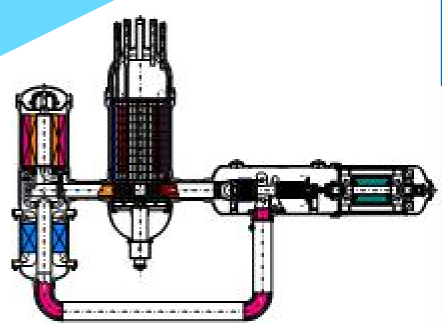
Single turbine disc

Technology transfer to private company

Present

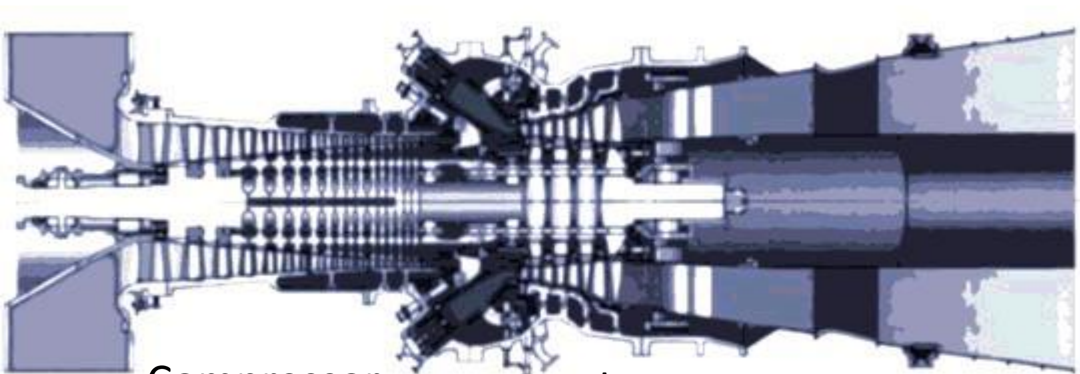
HTTR-GT/H_2 construction and operation (2015-2024)

Conceptual design for GTHTR300 power generation system
(1998-2001)



Reference materials

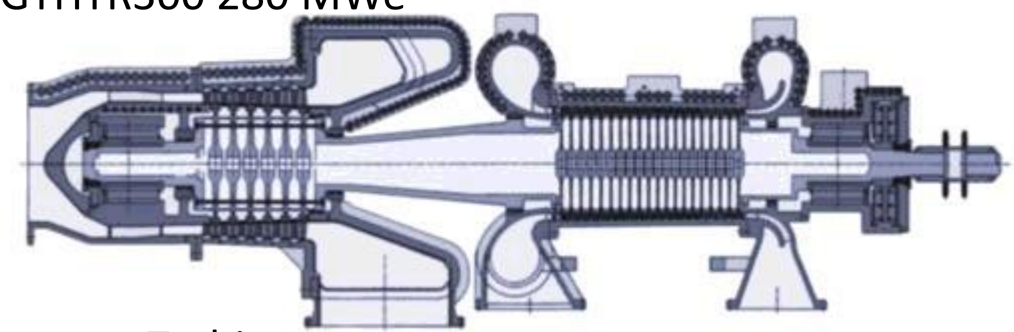
Open-Cycle Industrial Gas Turbine (Pr = 20, Ti = 1450° C)
Mitsubishi M701G 334 MWe



Compressor
17 stages

Turbine
4 stages

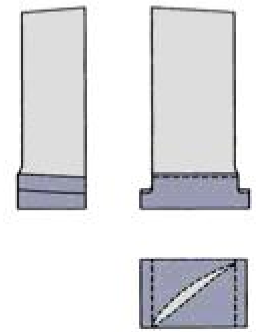
Closed-Cycle Helium Gas Turbine (Pr = 2, Ti = 850° C)
GTHTR300 280 MWe



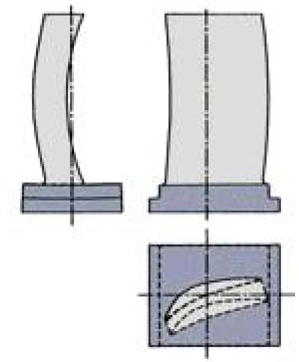
Turbine
6 stages

Compressor
20 stages

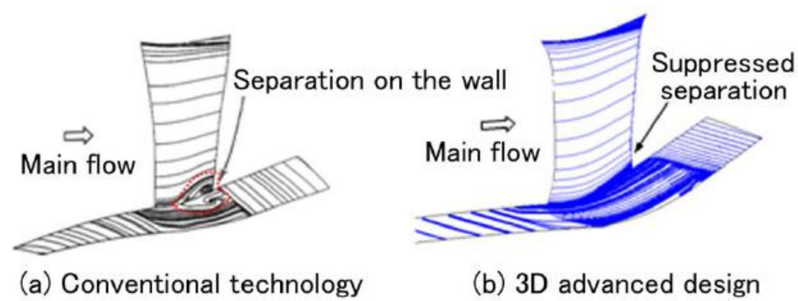
Air vane



Helium vane



Helium vane



Development status (2/2)
- Balance of plant technologies developed in Japan