Current Status of JAEA's Research and Development on HTGR

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Contents

What is High Temperature Gas-cooled Reactor (HTGR) ?

Superior inherent safety

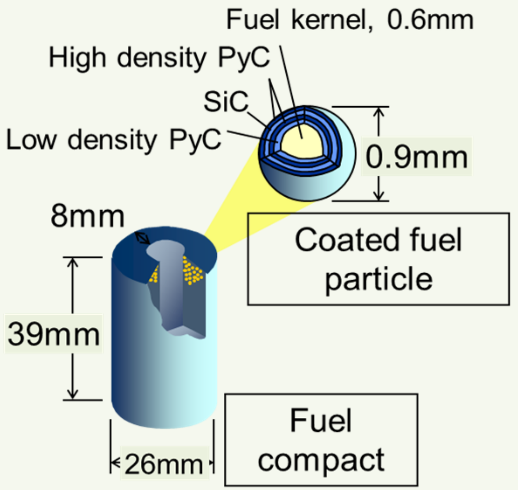
- Accidents that cause release of a large amount of radioactive materials to environment do not occur.
- A nuclear accident similar to that in the Fukushima-Daiichi Nuclear Power Station does not happen.

A wide range of heat applications

- Helium gas cooled reactor with outlet coolant temperature as high as 950°C
- A wide range of heat applications, such as hydrogen production, electric power generation, desalination, etc.

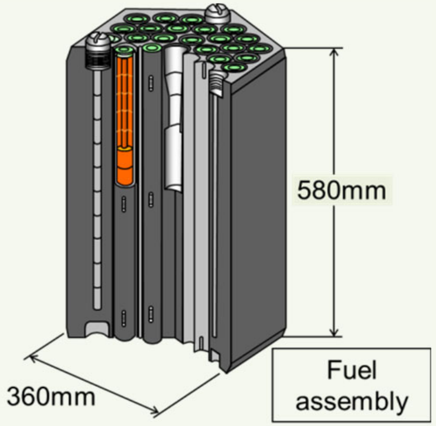
Ceramic fuel coating

Retain radioactive material at 1600°C



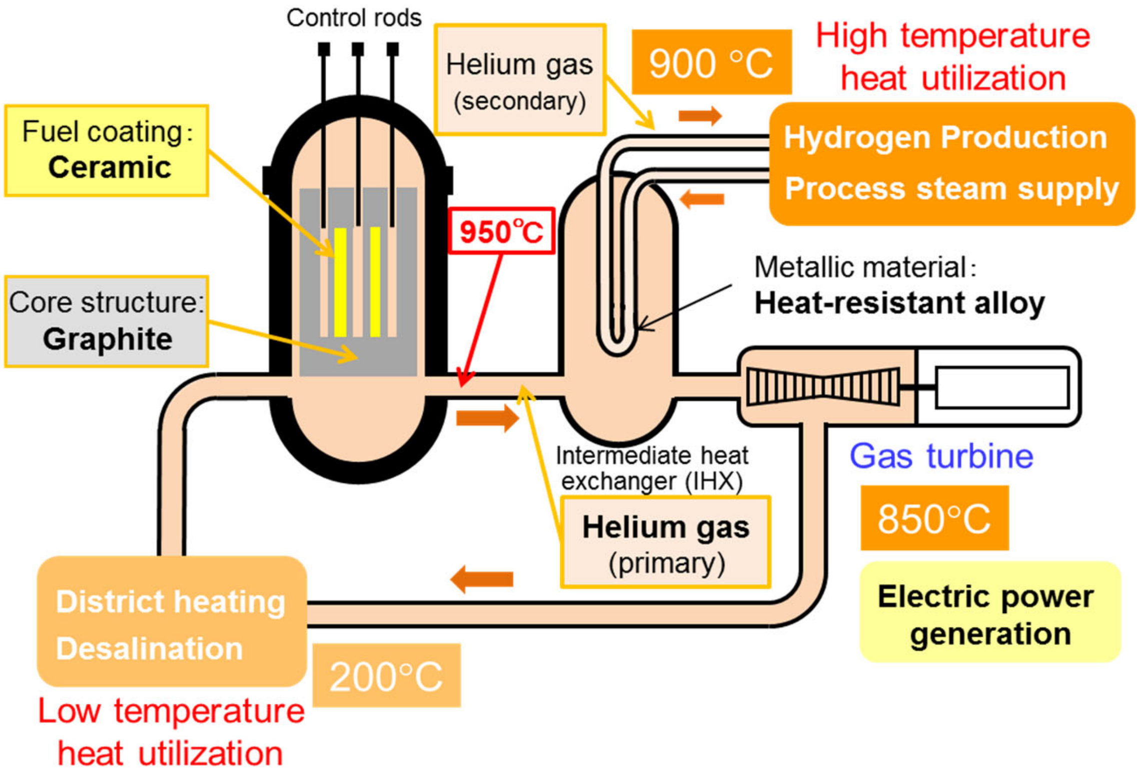
Graphite core structure

Temperature limit 2500°C



Helium coolant

Stable at high temperature (No temperature limit)


Control rods

Helium gas (secondary)

900 °C

High temperature heat utilization

Fuel coating: **Ceramic**

Hydrogen Production
Process steam supply

950℃

Metallic material: **Heat-resistant alloy**

Core structure: **Graphite**

Intermediate heat exchanger (IHX)

Gas turbine

Helium gas (primary)

850°C

District heating
Desalination

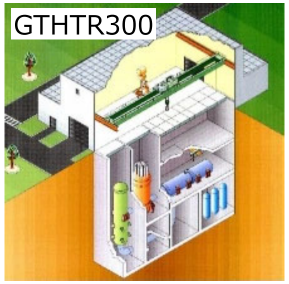
200°C

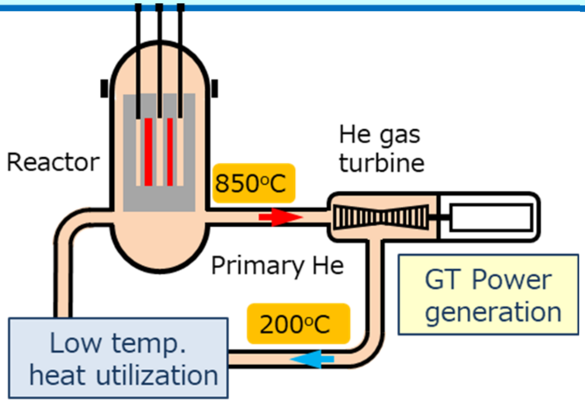
Electric power generation

Low temperature heat utilization

HTGR Systems

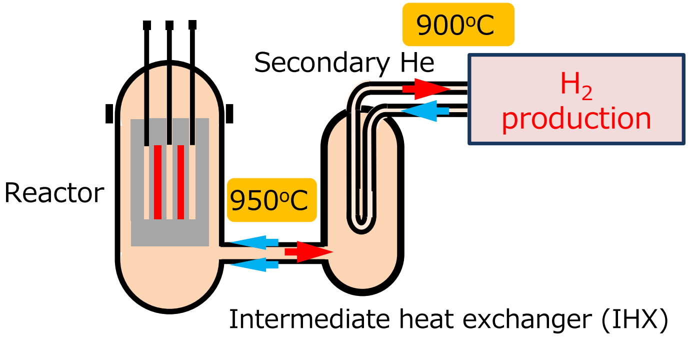
HTGR Gas Turbine (GT) System





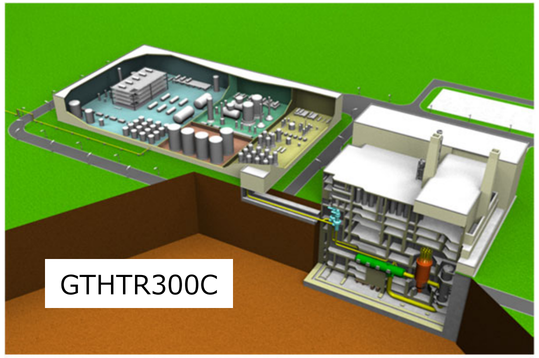
- Reactor: ～ 600 MWt (～ 300 MWe, 850°C)
- Helium gas turbine (Generation efficiency ～ 50%)
- High economy
- Deployment in 2030s

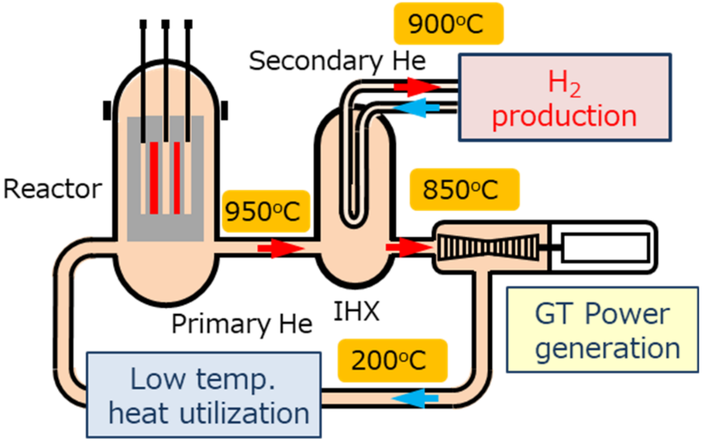
HTGR Hydrogen Production System



- Reactor: ～ 600 MWt, 950°C
- Hydrogen production ～ 85,000 Nm³/h
- Deployment in 2040s

HTGR Cogeneration System (hydrogen production & power generation by GT)





- Reactor : ～ 600 MWt, 950°C
- Cogeneration of hydrogen and electricity
- Hydrogen production ～ 50,000 Nm³/h
- Heat utilization rate is about 80%
- Deployment in 2040s

Major Specification of HTGR Hydrogen System

		Hydrogen & Electricity cogeneration (demonstration reactor)	Hydrogen & Electricity cogeneration (commercial reactor) 1,2)	Hydrogen only HTGR system3)
Thermal power of reactor	MW_t	50	600	600
Temperature of He gas output	°C	950	950	950
Electricity generation efficiency Note 1), Note 2)	%	40	47.0 / 38.0 Note2)	-
H_2 production thermal efficiency (Iodine-sulfur process) Note 3)	%	47.3	49.4 / 46.6	50.0
Electric power (at-site)	MW_e Note 4)	14	202 / 87	0
H_2 production volume 1,2)	Nm^3/h	2.66×10^3	3.19×10^4 / 6.95×10^4	8.46×10^4
	t/d	5.7	68.3 / 149.0	181.4
	t/y Note 4)	1.66×10^3	1.99×10^4 / 4.35×10^4	5.30×10^4
H_2 pressure 2)	kPa	101.3	101.3	101.3
H_2 purity 2)	mol%	98.8	98.8	98.8

Note 1) At-site value. (Thermoelectric conversion) = [(Electric power) / (Thermal power of reactor)] × 100

Note 2) In the power-hydrogen cogeneration, the turbine inlet temperature is lowered because the heat from the high-temperature part of the helium gas is used for hydrogen production. This reduces the thermoelectric conversion compared to that of power generation alone.

Note 3) [(HHV of H_2) / (required heat + heat to generate electricity)] × 100
The difference in thermoelectric conversion results in a difference in hydrogen production efficiency.

Note 4) Assuming availability of 80%

1) X. Yan et al., Nuclear Production of Hydrogen (3rd Information Exchange Meeting Oarai, Japan 5-7 October 2005) 121-139, OECD, 2006.
2) Derived using “S. Kasahara et al., Nucl. Eng. Des., 329, 213-222, 2018. ”
3) J. Iwatsuki et al., Economic Evaluation of HTGR IS Process Hydrogen Production System, JAEA-Review 2014-037.

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2. Block type and pebble bed type HTGRs
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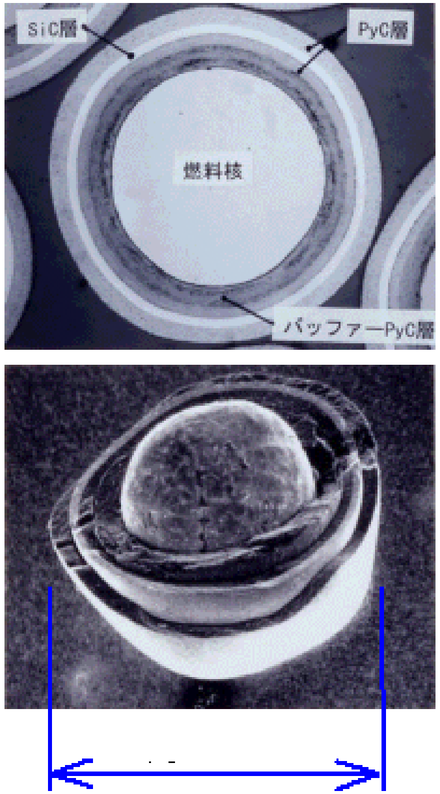
4. Current status of research and development of JAEA
   ① National policy
   ② HTGR technology
   ③ Heat utilization technology
   ④ Future plan
   ⑤ International cooperation
5. Summary

Block-type HTGR and Pebble-bed-type HTGR (1/2)

Fuel coated multiply by ceramics layers

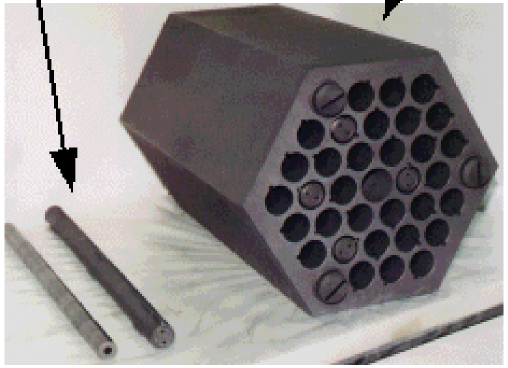


Approx. 1mm

Fuel compact

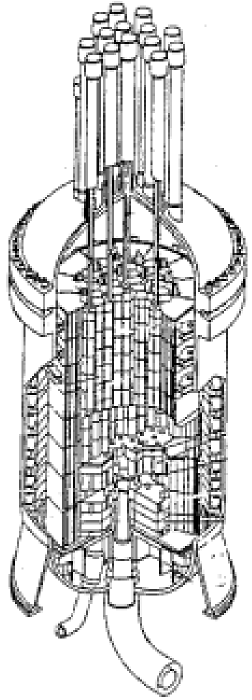
Graphite sleeve

Graphite **Block**
(Height: 600mm)



Block-type HTGR

(HTTR, FSV)

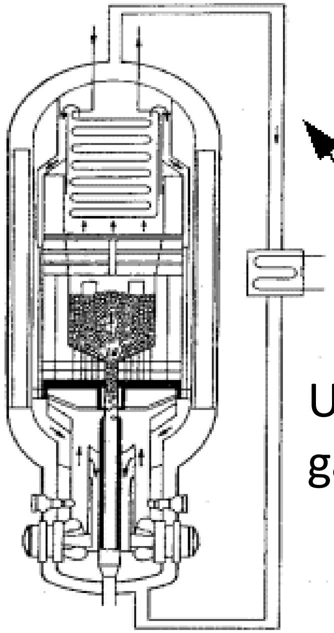


Utilization of graphite material for moderator and structural material

Fuel **Pebble**
(Diameter:60mm)

Pebble-bed-type HTGR

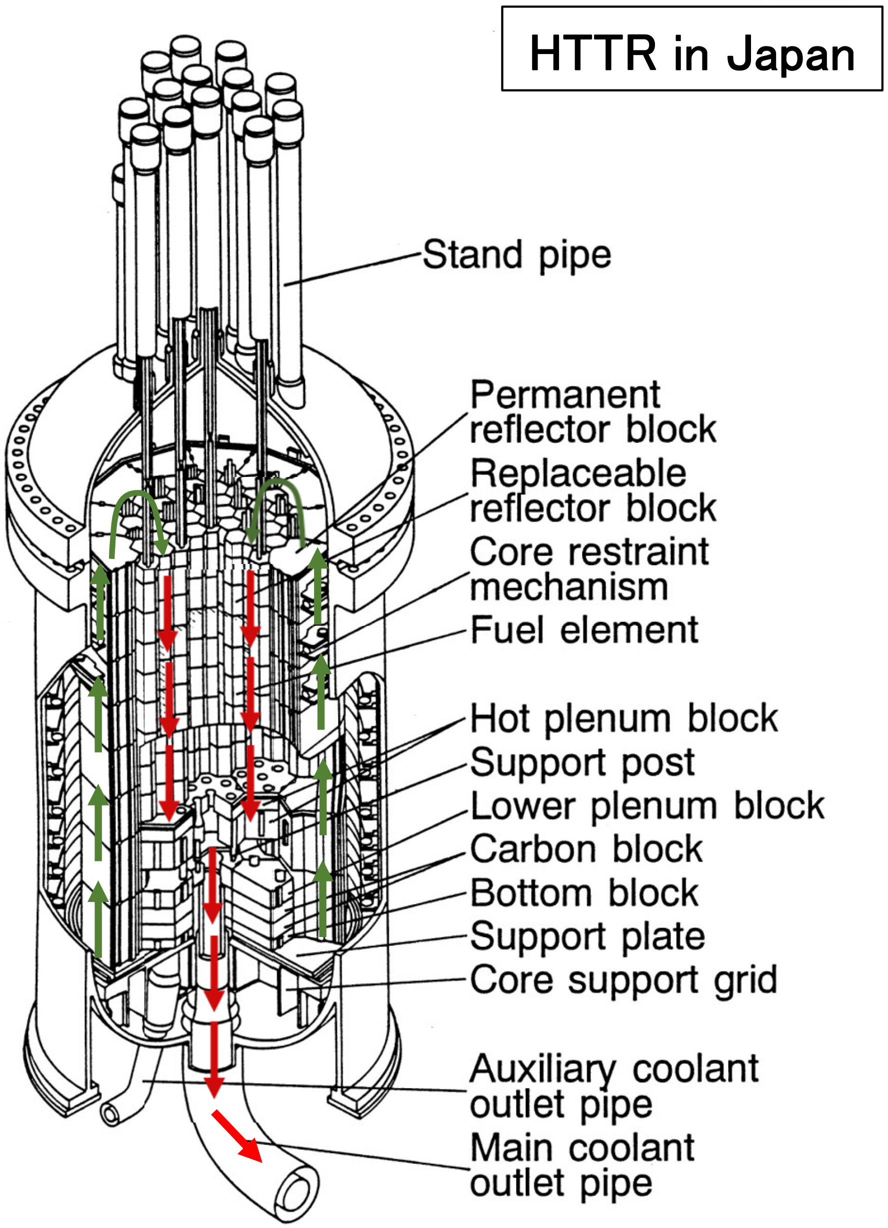
(HTR-10, HTR-PM, AVR)

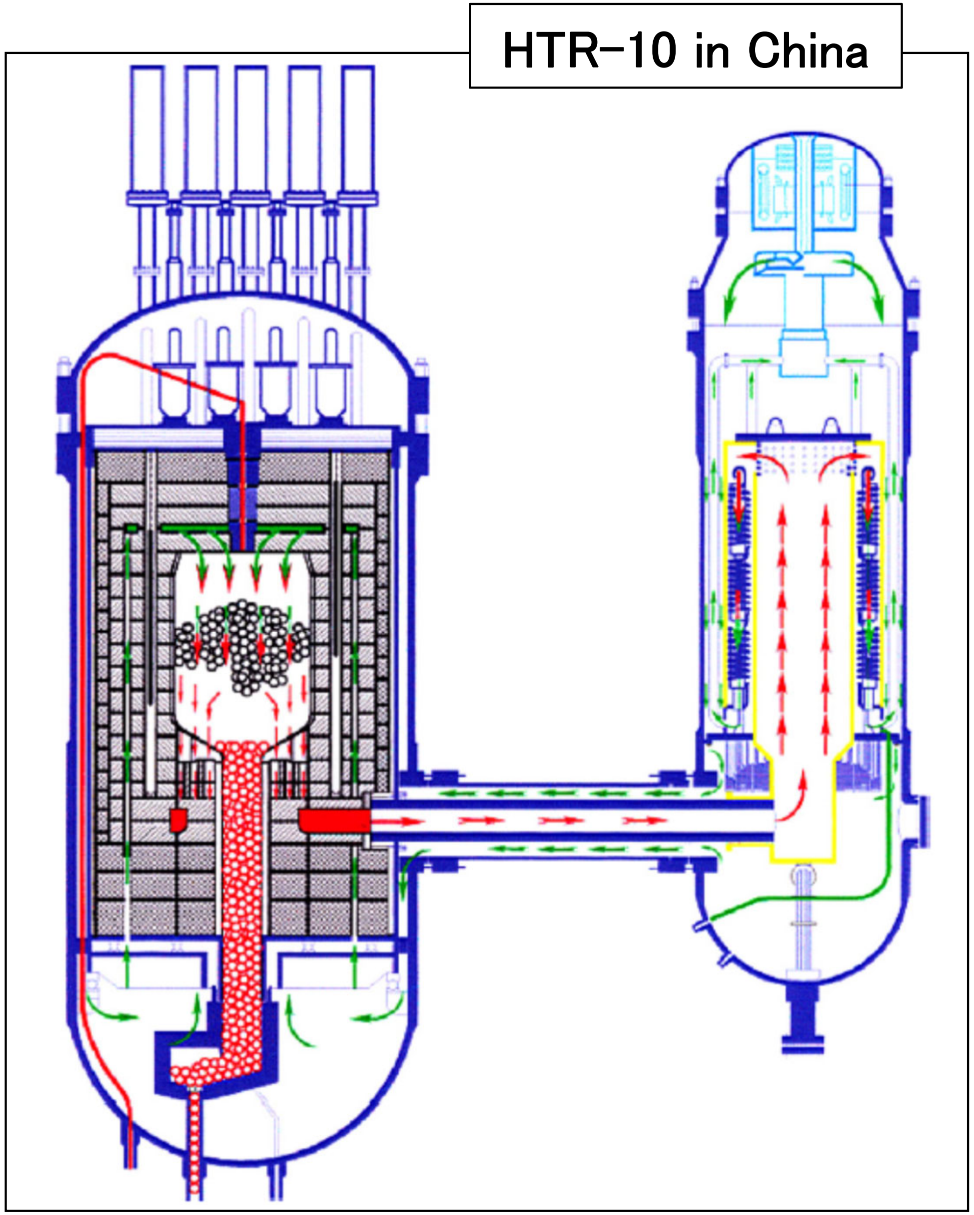


Utilization of helium gas as coolant

IAEA-TECDOC-358 Gas-cooled reactor safety and accident analysis

Block-type HTGR and Pebble-bed-type HTGR (2/2)





IAEA-TECDOC-1694 Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis Related to the PBMR-400, PBMM, GT-MHR, HTR-10 and the ASTRA Critical Facility

Block vs Pebble Bed

Items	Block type	Pebble bed type	Features of block type
Thermal power	~600 MW	~400 MW	Larger thermal power with lower fuel temperature at loss of force cooling
Fuel temperature			
• Normal operation	Higher	Lower	Lower effective coolant flow with lower core heat transfer by bypass flow
• Loss of forced cooling	Lower	Higher	Higher overall heat transfer coefficient
Discharged U^{235} in spent fuel	Higher	Lower	Discharged U^{235} in spent fuel is higher since fuels cannot be exchanged during operation.
Graphite dust in primary coolant	Negligible small amount	3 kg/y in AVR	Negligible small amount without abrasion of graphite fuel in core and friction in piping
Economics	84%~88% of pebble bed type		Better economics due to size effect with larger maximum thermal power
Experiences of earthquakes	Many	Few	Excellent seismic design with many experiences of earthquakes such as HTTR

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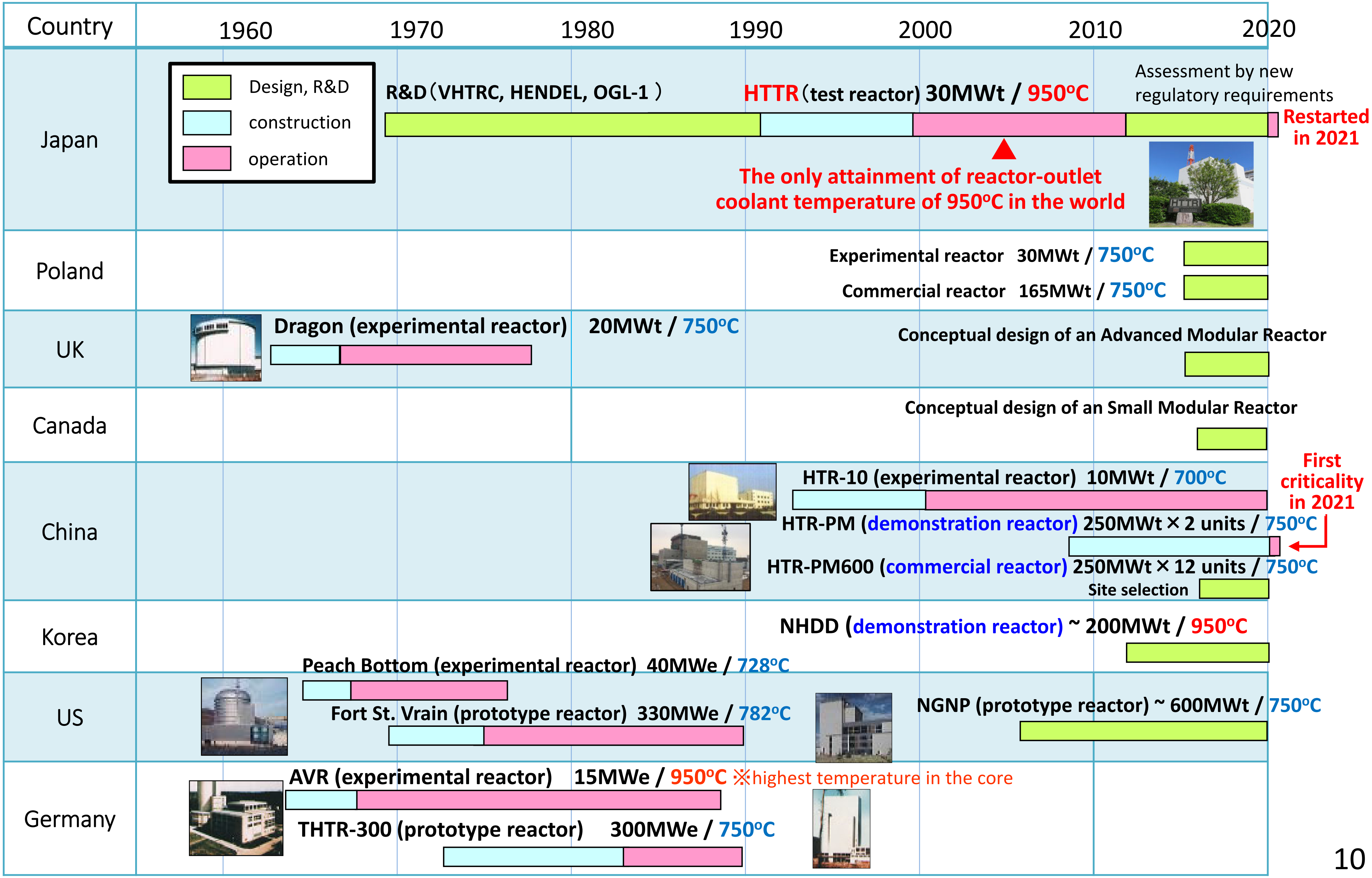
History and Plan of HTGR Development



Country: 1960, 1970, 1980, 1990, 2000, 2010, 2020

🟩 Design, R&D
🟦 construction
🟥 operation

Japan

R&D（VHTRC, HENDEL, OGL-1 ）

HTTR（test reactor) 30MWt / 950°C

Assessment by new regulatory requirements

Restarted in 2021

The only attainment of reactor-outlet coolant temperature of 950°C in the world

Poland

Experimental reactor 30MWt / 750°C

Commercial reactor 165MWt / 750°C

UK

Dragon (experimental reactor) 20MWt / 750°C

Conceptual design of an Advanced Modular Reactor

Canada

Conceptual design of an Small Modular Reactor

China

HTR-10 (experimental reactor) 10MWt / 700°C

HTR-PM (demonstration reactor) 250MWt×2 units / 750°C

First criticality in 2021

HTR-PM600 (commercial reactor) 250MWt×12 units / 750°C

Site selection

Korea

NHDD (demonstration reactor) ~ 200MWt / 950°C

US

Peach Bottom (experimental reactor) 40MWe / 728°C

Fort St. Vrain (prototype reactor) 330MWe / 782°C

NGNP (prototype reactor) ~ 600MWt / 750°C

Germany

AVR (experimental reactor) 15MWe / 950°C ※highest temperature in the core

THTR-300 (prototype reactor) 300MWe / 750°C

HTGRs in the Past and in Operation

Power Reactors

Peach Bottom
1966 – 1974
USA

Fort St. Vrain
1976 – 1989
USA

THTR
1985 – 1989
GERMANY

Research Reactors

DRAGON
1965 – 1975
UK

AVR
1968 – 1988
GERMANY

HTTR
1998 –
JAPAN

HTR-10
2000 –
CHINA

POWER MWt/MWe	115 40	842 330	750 300	20 -	46 15	30 -	10 -
He COOLANT Pressure, MPa	2.5	4.8	4	2	1.1	4	3
Inlet/Outlet Temp, ˚C	377 750	400 775	250 750	350 750	270 950	395 850/950	250 700
POWER DENSITY MW/m^3	8.3	6.3	6	14	2.3	2.5	2
FUEL TYPE	BISO Carbide	TRISO Carbide	BISO Oxide	TRISO Carbide	BISO Oxide	TRISO Oxide	TRISO Oxide
FUEL ELEMENTS	COMPACTS CYLINDRICAL	COMPACTS HEXAGONAL	COMPACTS SPHERICAL	COMPACTS CYLINDRICAL	COMPACTS SPHERICAL	COMPACTS HEXAGONAL	COMPACTS SPHERICAL
REACTOR VESSEL	STEEL	PRESTRESSED CONCRETE	PRESTRESSED CONCRETE	STEEL	STEEL	STEEL	STEEL

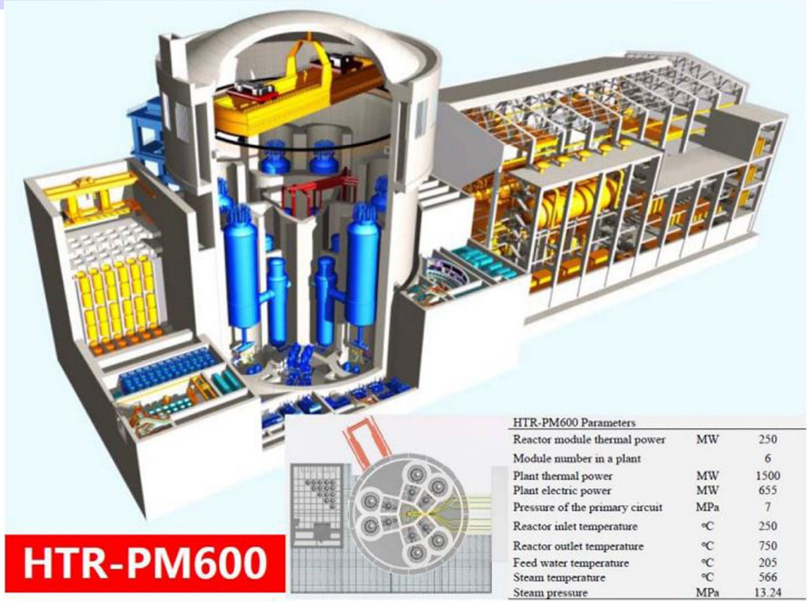
BISO refers to a fuel coating system that uses two types of carbon coatings
TRISO refers to a fuel coating system that uses three types of coatings, two carbon coatings and one silicon carbide

H. L. Brey, The Evaluation and Future Development of the High Temperature Gas Cooled Reactor, GENES4/ANP2003, Sep. 15-19, 2003, Kyoto Japan, etc.

China: Demonstration and Commercial HTGRs

HTR-PM

Demonstration HTR-PM connected to grid, world nuclear news, Dec 21, 2021.

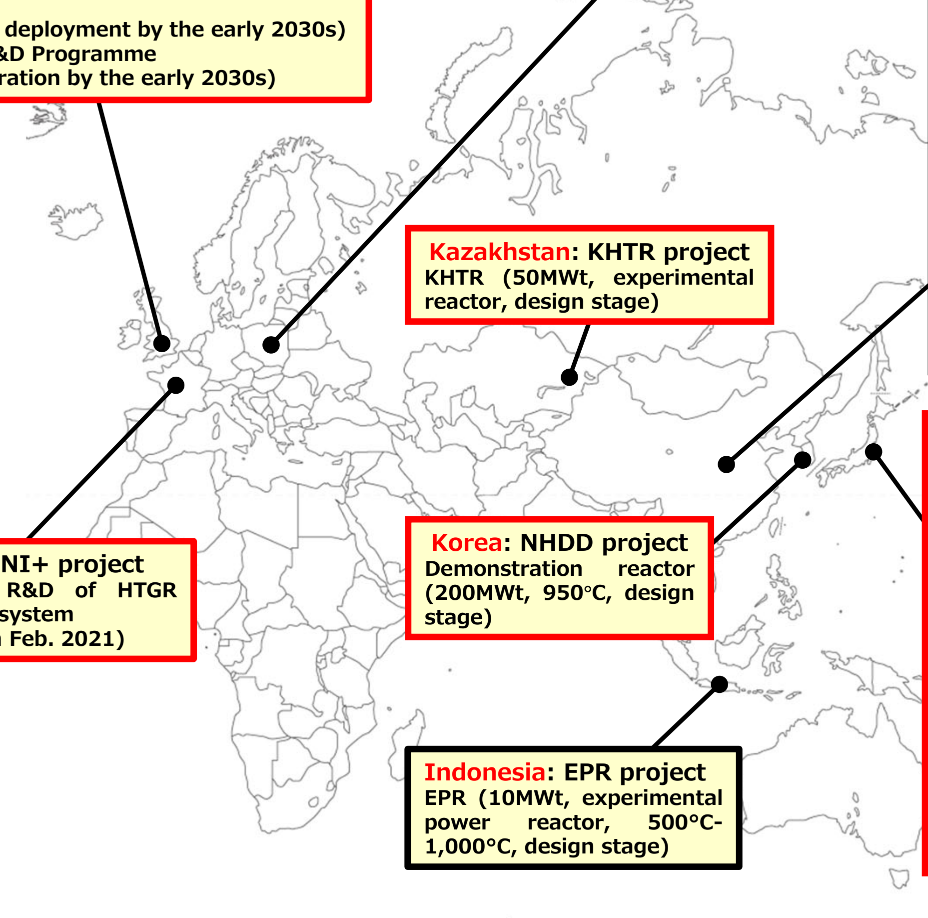


HTR-PM600 Parameters		
Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	℃	250
Reactor outlet temperature	℃	750
Feed water temperature	℃	205
Steam temperature	℃	566
Steam pressure	MPa	13.24

China's HTR-PM demonstration project advances, Nuclear News, Nov 16, 2021.

Project	HTR-PM (Demonstration reactor)	HTR-PM600 (Commercial reactor)
Major organization	Huaneng Shandong Ishijima Bay Nuclear Power (State-owned company)	China Nuclear Industry Construction Group（State-owned company), etc.
Thermal/Electric power	250MWt × 2 / 210MWe	655 MWe by six HTR-PM reactor units
Reactor outlet temp.	750 °C	750 °C
Construction/ Operation start	2009/2021	After 2021/2024
Current situation	Construction	Pre-construction (Feasibility studies)
Note	First criticality on September 12, 2021 (1st reactor) First criticality on November 11, 2021 (2nd reactor) Connection to the grid on December 20, 2021	Sanmen, Zhejiang province; Rujin, Jiangxi province; Xiapu and Wan'an, Fujian province; and Bai'an, Guangdong province

HTGR Development in the World



United Kingdom: AMR project
U-Battery (U-Battery, 10MWt, 800°C commercial reactor, design stage, BEIS AMR project; Phase 1 completion, Phase 2 (10M£) start)
UK Government: 10 Point Plan, Energy White Paper
(SMR and AMR deployment by the early 2030s)
BEIS: AMR RD&D Programme
(AMR demonstration by the early 2030s)

Poland: HTGR project
Experimental reactor (10-30MWt, 750°C, design stage)
Commercial reactor (165MWt, 750°C, FS to be started)

China
HTR-10 (10MWt, 750°C, experimental reactor in operation)
HTR-PM (2×250MWt, 750°C, demonstration reactor, criticality and grid connection in 2021, full power operation in 2022)
HTR-PM600 (2×250MWt, 750°C, commercial reactor, design stage)

Canada
MMR (USNC, 15MWt, 630°C, commercial reactor, design stage)
U-Battery (U-Battery, 10MWt, 800°C, commercial reactor, design stage)
StarCore (StarCore Nuclear, 35MWt, 750°C, commercial reactor, design stage)

Kazakhstan: KHTR project
KHTR (50MWt, experimental reactor, design stage)

EU: GEMINI+ project
Design and R&D of HTGR cogeneration system
(Completed in Feb. 2021)

Korea: NHDD project
Demonstration reactor (200MWt, 950°C, design stage)

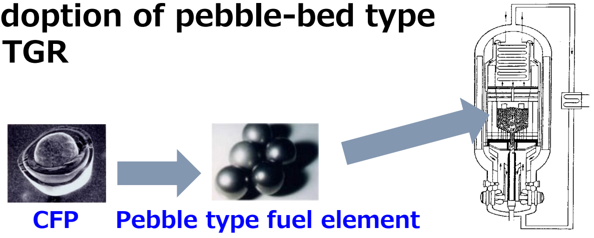
Japan
HTTR (30MWt, 950°C, test reactor in operation)
GTHTR300C (600MWt, 950°C, demonstration reactor of nuclear heat application, design stage)

USA
MMR (USNC, 15MWt, 630°C, commercial reactor, design stage)

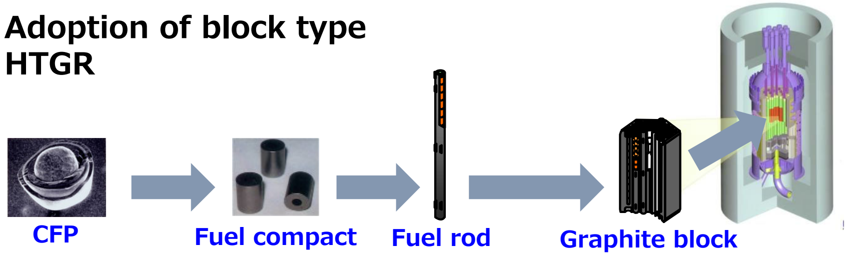
Xe-100 (X-energy, 200MWt、750°C, commercial reactor, design stage)

Indonesia: EPR project
EPR (10MWt, experimental power reactor, 500°C-1,000°C, design stage)

Adoption of pebble-bed type HTGR



Adoption of block type HTGR



HTGR Development Background

Why HTGR was developed?

- Several countries started to develop high temperature gas cooled reactor to make it higher temperature, power density and thermal efficiency as economically competitive nuclear power plants with Light Water Reactor after UK developed the first nuclear power station “Magnox” (graphite moderate CO_2 gas cooled reactor).
- US and German each developed a prototype HTGR which has steam generators and 40% of power generation efficiency by government-private sector joint research project.
- German and Japan each developed HTGR for high-temperature heat supply for coal gasification or reduced iron production aiming to less oil import.
- After Three Mile Island accident, small modular reactor (SMR) concepts were proposed which cannot cause meltdown accident and the helium gas turbine HTGR system was developed for further economical improvement.

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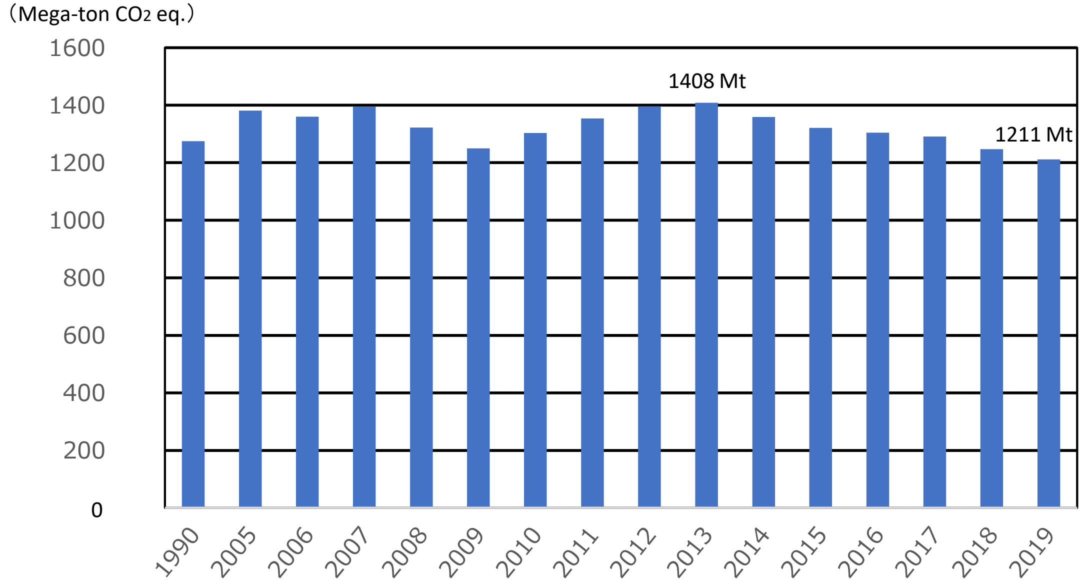
Role of HTGR for Carbon Neutrality in Japan

Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (The Ministry of Economy, Trade and Industry (METI) formulated it on December 25, 2020, and issued a new version on June 18, 2021.)

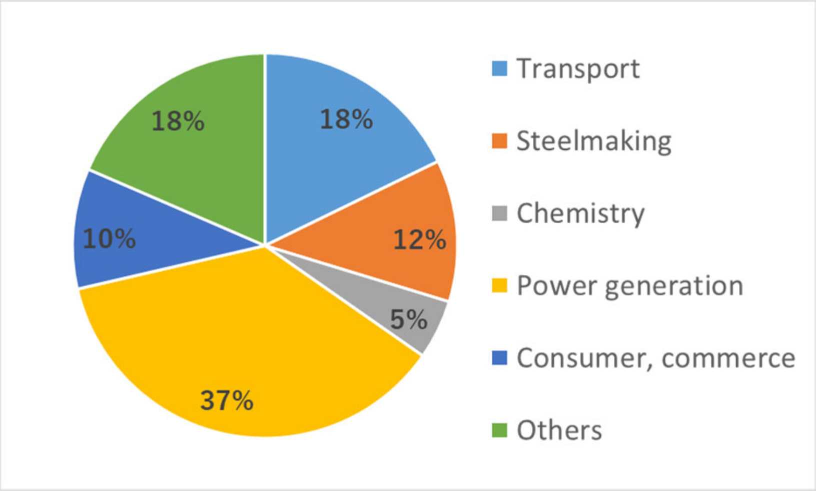
Plan for global warming countermeasures (Leaders Summit on Climate, April 22, 2021)

- Mid-term target: 46.0% reduction by FY2030 compared to FY2013

GHG emission in Japan (Final report of FY2019)



Breakdown of GHG emission (2019)



- The emission reduction in FY2019 : 14.0% compared to FY2013
- To achieve the goal,
  - ✓Reduction by additional 32% by 2030
  - ✓Reduction by additional 86% by 2050

Role of HTGR

- HTGR can produce hydrogen for nuclear steel making and fuel cell vehicle.
- HTGR can produce steam for conventional industries.
- HTGR can absorb renewable power variation.

Use of HTGR is a key to achieve the GHG reduction goal.

Deployment Effect of HTGR Hydrogen System

H_2 requirements, numbers of HTGRs, CO_2 reduction in 2050s

Sectors		H_2 requirements (Mt/y)	Number of units, installed capacity	Contribution ratio of HTGR H_2 supply (%)	HTGR H_2 supply (Mt/y)	Number of HTGRs	CO_2 reduction (Mt/y)
H_2 steelmaking		2.2	Shaft furnace 18 units※2	80 ※4	1.8	34 ※5	56.0 ※2
FCV	Car	1.8 ※1	20 million units ※3	30 ※4	0.5	17 ※5	4.2 ※2
	Truck	1.0 ※1	3.4 million units ※3		0.3		7.0 ※2
	Bus	0.1 ※1	0.1 million units ※3		0.0		0.4 ※2
Stationary FC	At-home	1.8 1)	15.3 million units ※3	30 ※4	0.5	22 ※5	4.7 ※2
	Business	2.0 1)	17.8 GW ※3		0.6		5.2 ※2
Total		9.0			3.8	73	77.6 (5.9%) ※6

H_2 requirements for H_2 steelmaking (2.2 Mt/y)
= Total in Japan (85.7 Mt-steel/y) 2) × Contribution ratio of H_2 steelmaking (40%) ※4
× H2 requirement for H_2 steelmaking (0.065 kg-H_2/t-steel) ※2

HTGR hydrogen production system has the potential to supply about 40% of H_2 needed for H_2 steelmaking, FCVs, and FCs

1) Y. Matsuo et al., Position and introduction prospects of hydrogen energy toward a low-carbon society in 2050, The Institute of Energy Economics, Japan, 2013.
2) Steel statistical yearbook 2017, World Steel Association, 2018.
3) Japan's National Greenhouse Gas Emissions（1990~2016）, National Institute for Environmental Studies, Japan.

※1：Estimated using ref. 1)
※2：Estimated value by JAEA
※3：Value from ref. 1)
※4：Assumed by JAEA
※5：Thermal power of reactor : 600MWt, H_2 production : 85,000 Nm^3/h
※6：Reduction ratio to 2013 CO_2 emission3)

Contents

The 6th Strategic Energy Plan (October 2021, Cabinet Decision)

5. Policy responses towards 2030 looking ahead to 2050

(8) Drastic enhancement of efforts towards realizing the hydrogen society

- The government will support innovative hydrogen production technology development and basic research, such as hydrogen production using photocatalysts and high-temperature heat sources such as high-temperature gas-cooled reactors, for further reduction of hydrogen supply cost and efficient mass production of hydrogen.

JAEA translation

(12) Global harmonization and global competition

- In advancing research and development of innovative technologies such as fast reactors, small modular reactors, and high-temperature gas-cooled reactors, the government will actively support the efforts of Japanese companies in collaboration with overseas demonstration projects such as the United States, the United Kingdom, France, and Canada, and expand the options to meet various social demands.

JAEA translation

6. Promotion of strategic technology development, and its societal implementation and so on, integrated with industrial, competition and innovation policies for realization of carbon neutrality by 2050

- In Japan, the government will promote the development of new technologies that drastically improve the safety, reliability, and efficiency of nuclear use for the future and human resource development. The new technologies include high-temperature gas-cooled reactors, which are expected to be utilized in various industries including hydrogen production and which have an inherent safety and other reactors with excellent safety.

JAEA translation

- By 2030, while making the most of the private sector’s ideas and wisdom, development of fast reactor will be steadily promoted by utilizing international cooperation; small modular reactor technology will be demonstrated through international cooperation; and component technologies related to hydrogen production at high temperature gas-cooled reactor will be established.

Provisional translation by METI

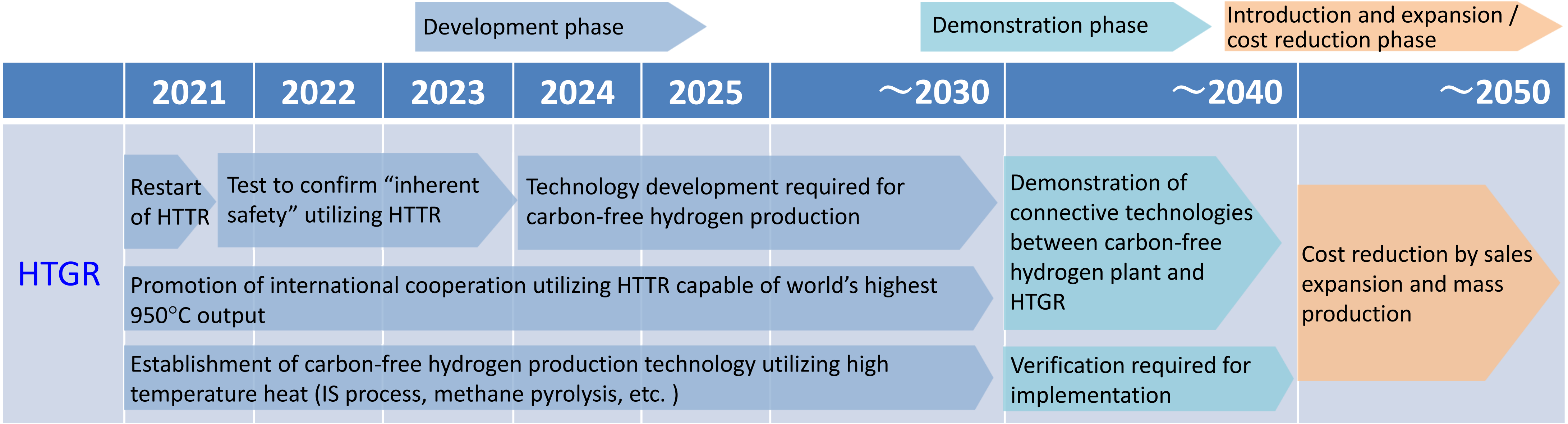
Green Growth Strategy Through Achieving Carbon Neutrality in 2050 (June 18, 2021)

4. “Action Plans” in key industrial fields (4) Nuclear industry 3) High-temperature gas-cooled reactor (HTGR)

<Future efforts>

Utilizing the HTTR which recorded world’s highest temperature, the government will support, in addition to international safety demonstration, necessary technology development for massive and low-cost carbon-free hydrogen production by 2030. Simultaneously, development of carbon-free hydrogen production method using ultra high temperature heat including IS process and methane pyrolysis method will be supported. In supporting the development, the government will participate in technology development and verification giving thoughts to safety, economy, supply chain construction, regulatory compliance and so on, and will compose overseas joint projects considering the status of preceding overseas projects.

Moreover, considering the situation where Japan is leading the world also in terms of establishment of standards through construction, operation and restart of the HTTR, cooperation with related organizations of other countries for diffusion of Japanese standards will be promoted.



Development phase

Demonstration phase

Introduction and expansion / cost reduction phase

	2021	2022	2023	2024	2025	～2030	～2040	～2050

HTGR

- Restart of HTTR
- Test to confirm “inherent safety” utilizing HTTR
- Technology development required for carbon-free hydrogen production
- Promotion of international cooperation utilizing HTTR capable of world’s highest 950°C output
- Establishment of carbon-free hydrogen production technology utilizing high temperature heat (IS process, methane pyrolysis, etc.)
- Demonstration of connective technologies between carbon-free hydrogen plant and HTGR
- Verification required for implementation
- Cost reduction by sales expansion and mass production

Contents

Overview of the HTTR Project

(1) Reactor technology: HTTR

- 30 MWt and 950 °C prismatic core advanced test reactor (Operation started in 1998)

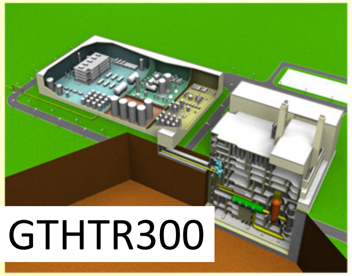
- Obtained permission of changes to reactor installation of the HTTR, restarted in July 2021.
- HTTR tests for HTGR safety demonstration.

(2) Gas turbine and H_2 technology

- R&D of gas turbine technologies such as high-efficiency helium compressor, shaft seal, and maintenance technology

- In January 2019, 150 hours hydrogen production with rate of 30L/h was achieved.

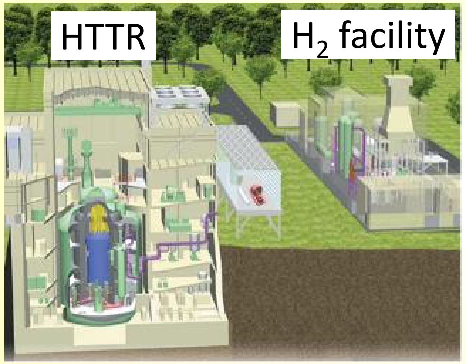
(3) Innovative HTGR design



- Design study of commercial HTGR for electricity generation and H_2 production
- Establishment of commercial HGTR safety standards

- Design study of HTGR for steam supply

(4) HTTR-heat application test

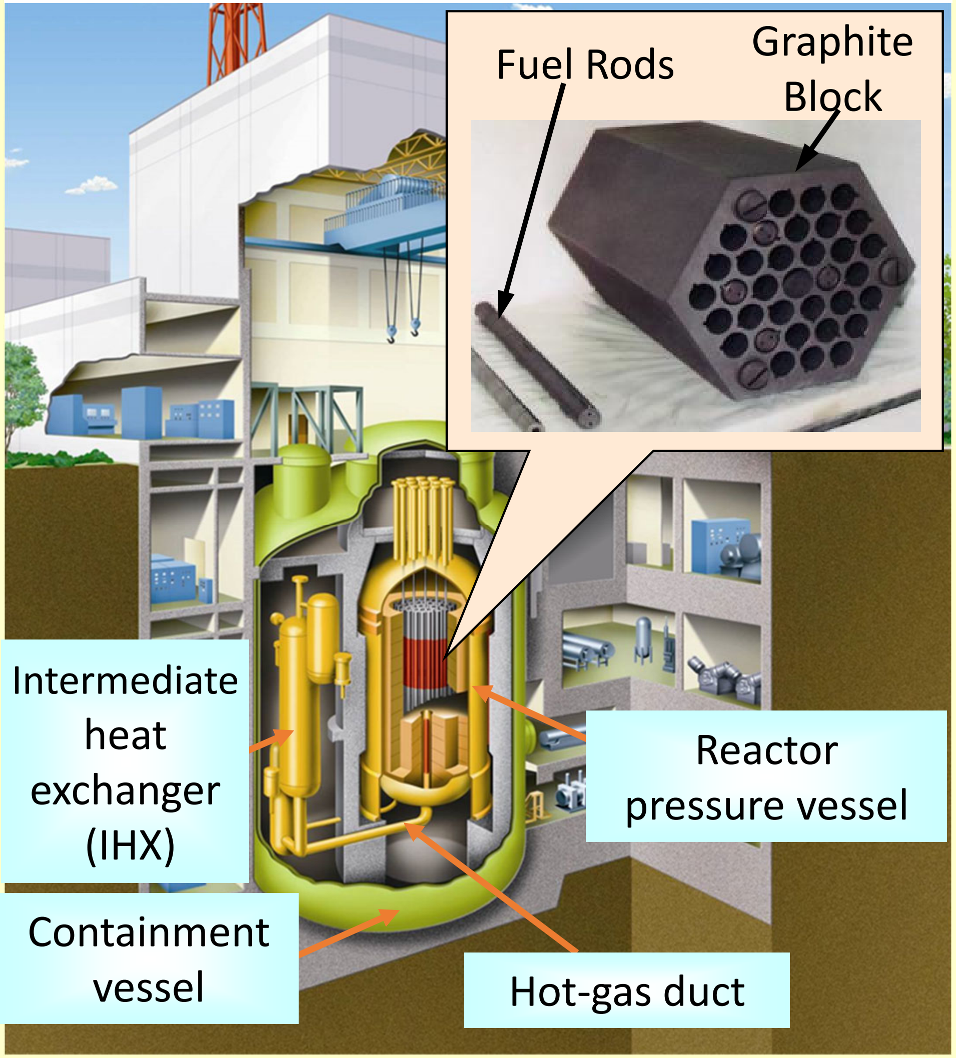


- Licensing acquisition of world’s first nuclear hydrogen production
- Demonstration test for safe & reliable HTGR heat application technologies

HTGR Development in JAEA: HTTR

HTTR(High Temperature Engineering Test Reactor)

Graphite-moderated and helium gas-cooled reactor



Major specification

Thermal power	30 MW
Fuel	Coated fuel particle / Prismatic block type
Core material	Graphite
Coolant	Helium gas
Inlet temp.	395°C
Outlet temp.	850/950°C
Pressure	4 MPa

First criticality : 1998
Full power operation : 2001
50 days continuous 950°C operation : 2010
Loss of forced cooling test at 9MW : 2010
Safety review after the 1F accident
Restart after safety approval by NRA: July 2021

HTTR's Systems

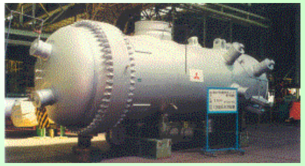
- **HTTR's design, construction and operational experiments (MHI, Toshiba/IHI, Hitachi, Fuji Electric, KHI, etc.)**

  Design optimization based on extensive technical database

- **Primary coolant system (MHI)**

  Construction of efficient transport and cooling system for very high temperature heat (950^{o}C)

Concentric hot gas duct



Primary pressurized water cooler

- **He/He intermediate heat exchanger (IHX) (Toshiba/IHI)**

Developed new heat (950^{o}C) and corrosion resistance material Hastelloy XR

HTTR

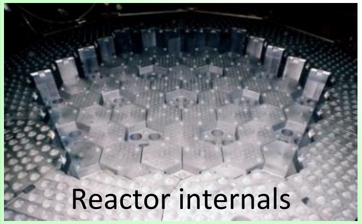
- **Reactor pressure vessel (Hitachi)**

  Developed high temperature structural design guideline for 2 1/4Cr-1Mo steel

- **Fuel (Nuclear Fuel Industries)**

Advanced coating technology

- **Reactor internals (Fuji Electric)**
- **Graphite material IG-110 (Toyo Tanso)**



Reactor internals

High strength Irradiation -resistance

History of HTTR

High Temperature Engineering Test Reactor
HTTR

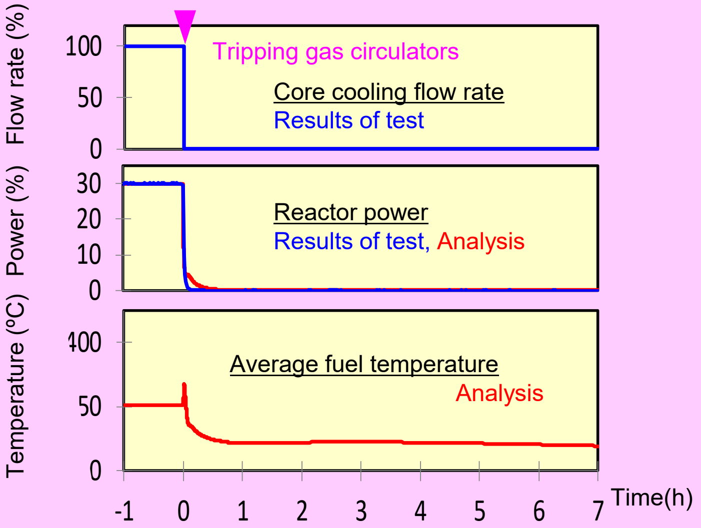
Purpose

- ☐ Establishment of HTGR technology
- ☐ Establishment of Heat utilization technology

First in the world

2021	Restart
2020	Approval of restart by NRA (June 3^{rd})
2014	Safety review on the New Regulatory Requirements toward resumption of operation
2010	Start of Loss of Forced Cooling test 950°C/ 50 days operation
2007	850°C/ 30 days operation
2004	Reactor outlet coolant temperature **950°C**
2002	Safety demonstration test (Control rod withdrawal test)
2001	Reactor outlet coolant temperature 850°C (30MWt)
1998	First criticality
1997 ～ 1991	Construction
1990 ～ 1989	Application and permission of construction
1988 ～ 1985	Detail design
H T T R	
1984 ～ 1981	Basic design
1980 ～ 1974	System integrity design
1973 ～ 1969	Conceptual design

JAEA has restarted the HTTR without significant reinforcement.



Reactor is naturally shut down as soon as the core cooling flow rate is reduced to zero.
Reactor is kept stable long after the loss of core cooling.

Research and Development

Fuels・Materials

In-pile Helium loop (OGL-1)

Reactor Physics

Very High Temperature Reactor Critical Assembly (VHTRC)

Thermal Hydraulics

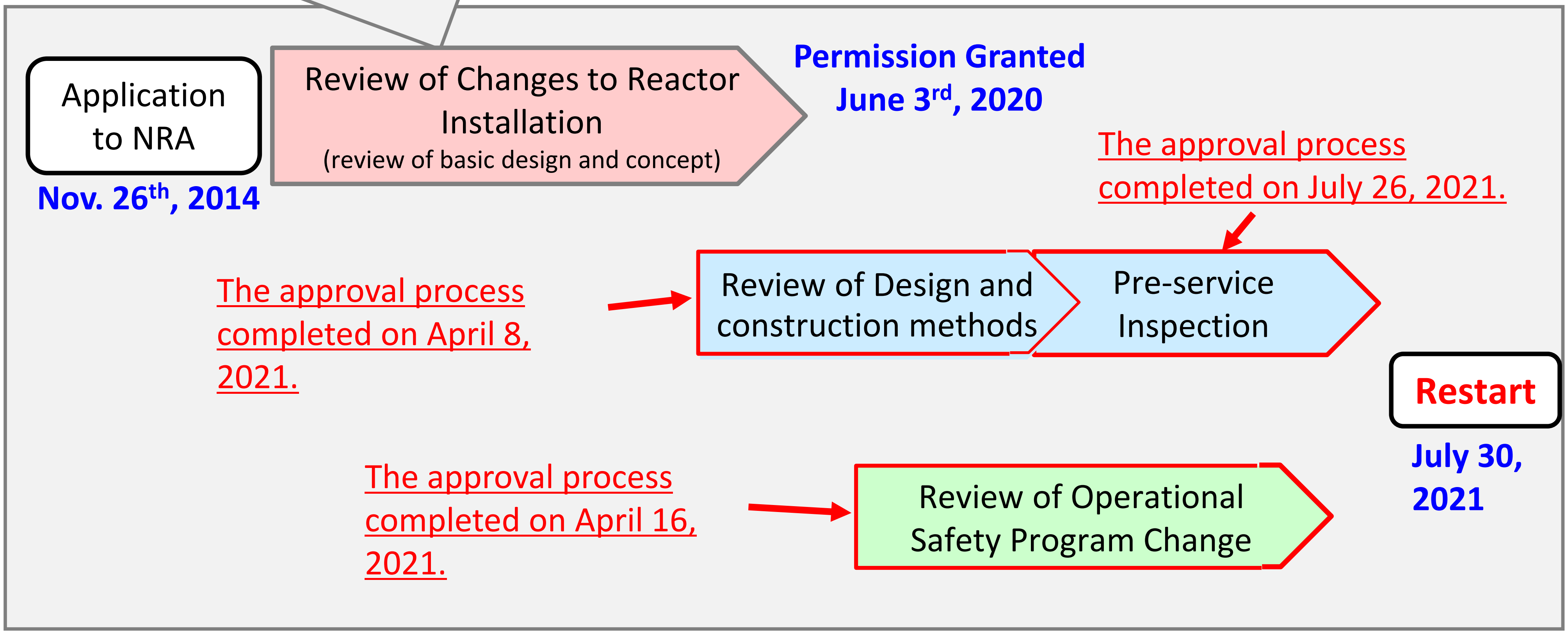
Helium Engineering Demonstration Loop (HENDEL)

Schedule towards Restart of HTTR

New regulatory requirement issued on 18 December, 2013

Major discussion items in new requirements

1. Design seismic ground motion with significantly high acceleration
2. Natural phenomena
3. BDBA



Application to NRA

Nov. 26th, 2014

Review of Changes to Reactor Installation

(review of basic design and concept)

Permission Granted

June 3rd, 2020

The approval process completed on July 26, 2021.

The approval process completed on April 8, 2021.

Review of Design and construction methods

Pre-service Inspection

Restart

July 30, 2021

The approval process completed on April 16, 2021.

Review of Operational Safety Program Change

The flow of review and inspection for checking conformity to New Regulatory Requirements

Results of Safety Review by Nuclear Regulation Authority

Major discussion item		Regulatory review condition	Regulatory review results	Additional countermeasures
Earthquake	Design seismic ground motion	Raised from 350gal to 973gal	No large-scale reinforcement due to the degradation of the SSCs.	**Not required**
	Re-evaluation of seismic design classification	**Some of safety systems, structures and components (SSCs) were classified from S to B based on results of safety demonstration tests.** ➢ **Core heat removal: S class to B class** ➢ **Reactor internal structure: S class to B class.**		
Tsunami evaluation		Assumption of tsunami height for evaluation：17.8m from sea level	Tsunami does not reach the site because siting location is 36.5 meters high from the sea level.	Not required
Evaluation of integrity of SSCs against natural phenomena such as tornado, volcano, etc.		● Design basis tornado wind speed: 100 m/s ● Thickness of descent pyroclastic material by volcano: 50 cm	● All SSCs needed to be protected are installed inside the reactor building ● Fire proof belt necessary around reactor building.	Fire proof belt was required.
Fire		Burnable materials in and around the reactor building was additionally evaluated.	● Amount of burnable materials in the reactor building is limited. ● Cables necessary to be protected against fire	Cable protection against fire was required.
Reliability of power supply		Emergency power supply failure was evaluated.	Decay heat is removable from the core without electricity.	**Only portable power generator for monitoring during accident is required.**
Beyond design basis accident (BDBA)		Postulated BDBAs ➢ **DBA + failure of reactor scram** ➢ **DBA + failure of heat removal from the core** ➢ **DBA + failure of containment vessel** ➢ Intentional aircraft crash	● **No core melt occurs in all BDBAs.** ● Intentional aircraft crash does not damage SSCs in the reactor building.	

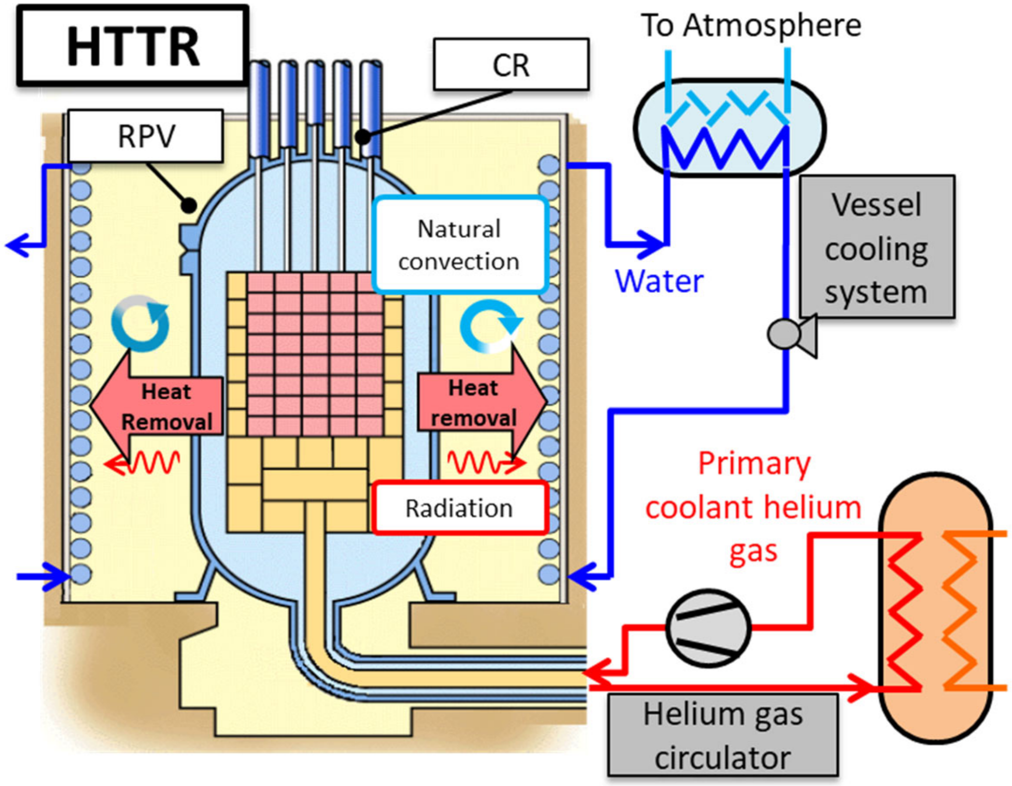
Obtained permission for changes to Reactor Installation of the HTTR by NRA on June 3rd, 2020

HTTR has restarted without significant additional reinforcements due to its inherent safety features.

Further Safety Demonstration Test

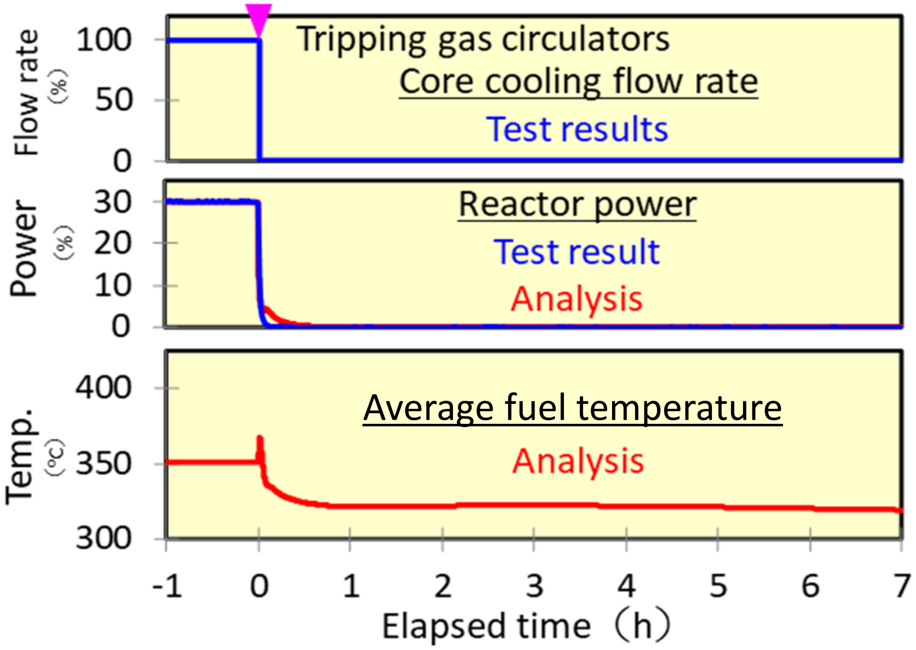
Safety demonstration test under OECD/NEA project

- ■ 30% power(9MW) Loss of forced cooling test
  (All HGC tripped) Finished (2010)
- ☐ 100% power Loss of forced cooling test
  (All HGC tripped) Planned
- ☐ 30% power Loss of core cooling test
  (All HGC + VCS tripped) Finished (Jan 2022)



Test Result

The reactor is naturally shut down as soon as the core cooling flow rate to zero.
The reactor is kept stable long after the loss of core cooling



Future test plan

- ☐ **Core physics:** Xenon stability, decay heat measurement, burnup characteristic, etc.
- ☐ **Fuel:** Iodine plate-out, integrity after long time operation, tritium behavior, etc.
- ☐ **Components:** IHX performance, etc.
- ☐ **HTTR heat application test**

Contents

1. Features of High-Temperature Gas-cooled Reactor (HTGR)
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    ① National policy
    ② HTGR technology
    ③ Heat utilization technology
    ④ Future plan
    ⑤ International cooperation
5. Summary

Helium Gas Turbine R&D

■ R&D Items

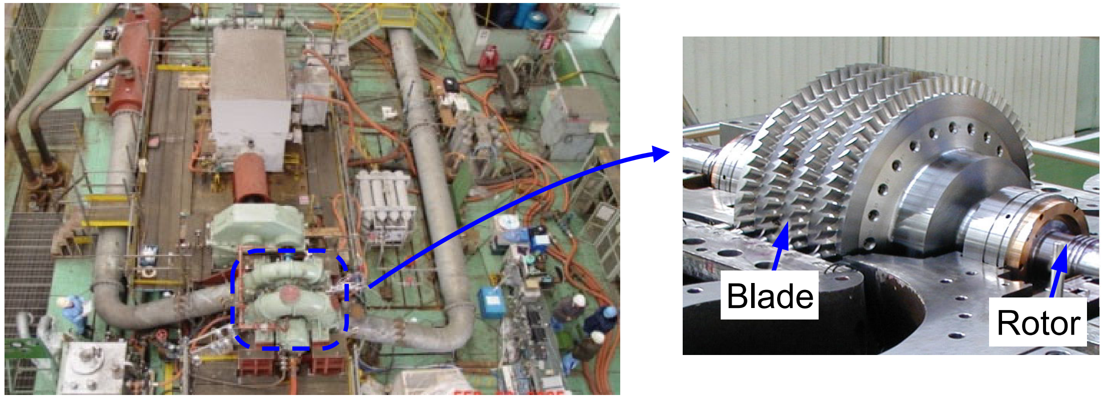
- Compressor technology
- Shaft seal technology
- Maintenance technology

■ Compressor Technology Elements

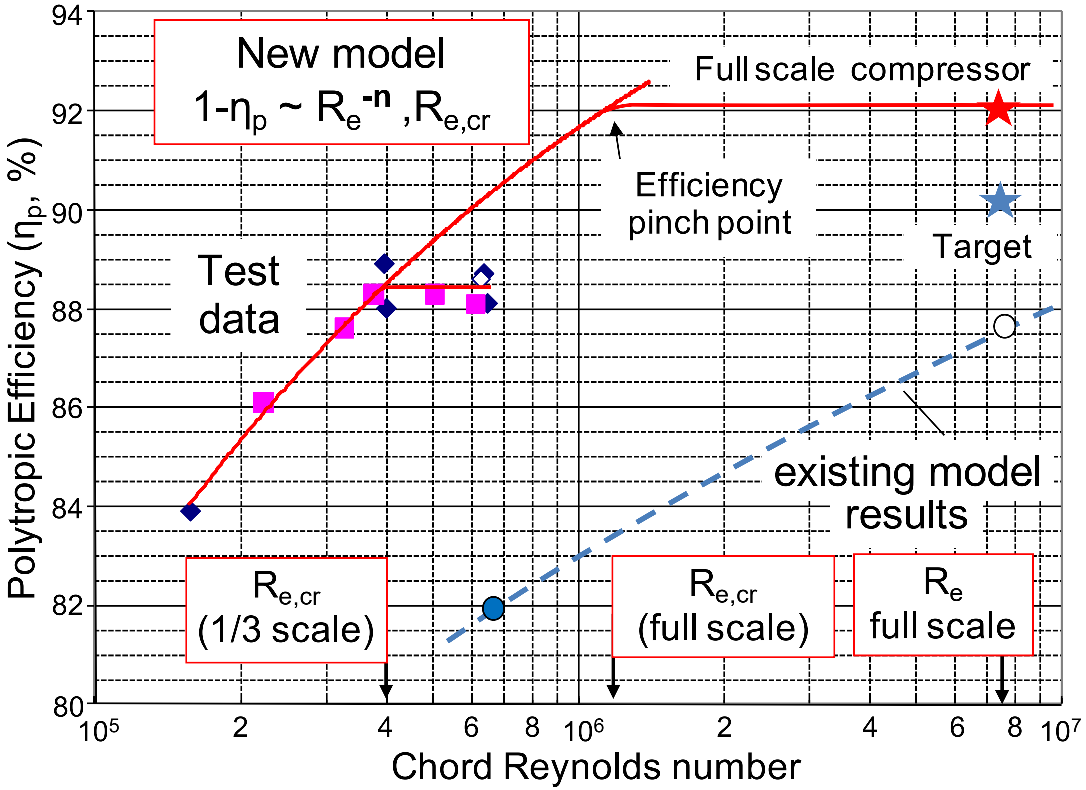
- High performance compressor flowpath
- Tight blade tip clearance
- 3D blade airfoil

■ Results

- World's first successful axial-flow helium compressor was demonstrated by 1/3 scale test rig
- Validated helium compressor design method with test data
- Efficiency significantly improved over existing air-compressor-experience based model



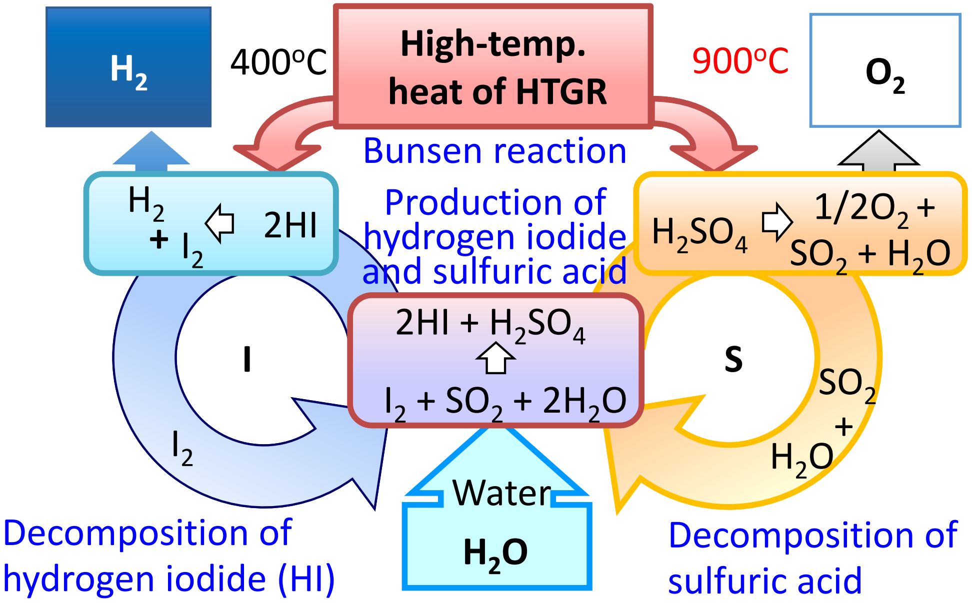
1/3 Scale Compressor Test Rig



Correlation of He Compressor Efficiency with Re

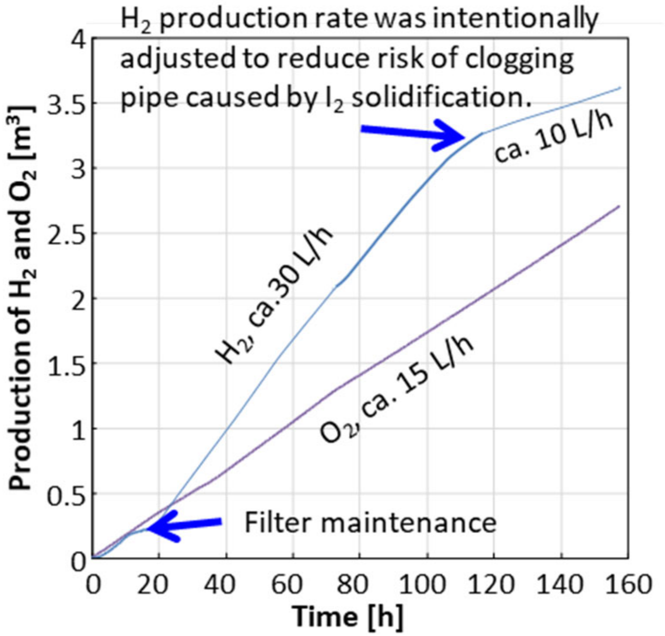
HTGR Development in JAEA -H_2 Production Technology-

Thermo-chemical water splitting Iodine-Sulfur (IS) Process

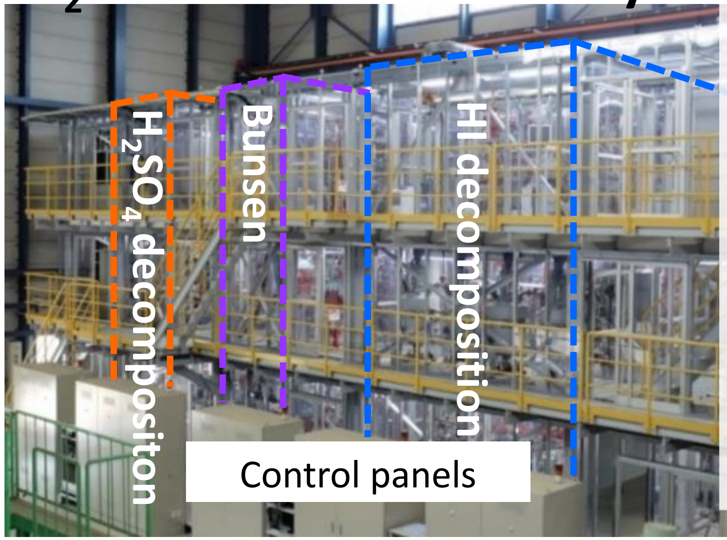


Test result

- The 150-hour and 30 L/h continuous H_2 production was performed with integration of 3 sections in January 2019.



H_2 Production Test Facility



Process
- Electric heating

Component materials

Liquid phase
- Fluoroplastic lining
- Glass lining
- Silicon carbide (SiC)
- Graphite (impervious)

Gaseous phase
- Hastelloy C-276
- JIS SUS316

Future tests

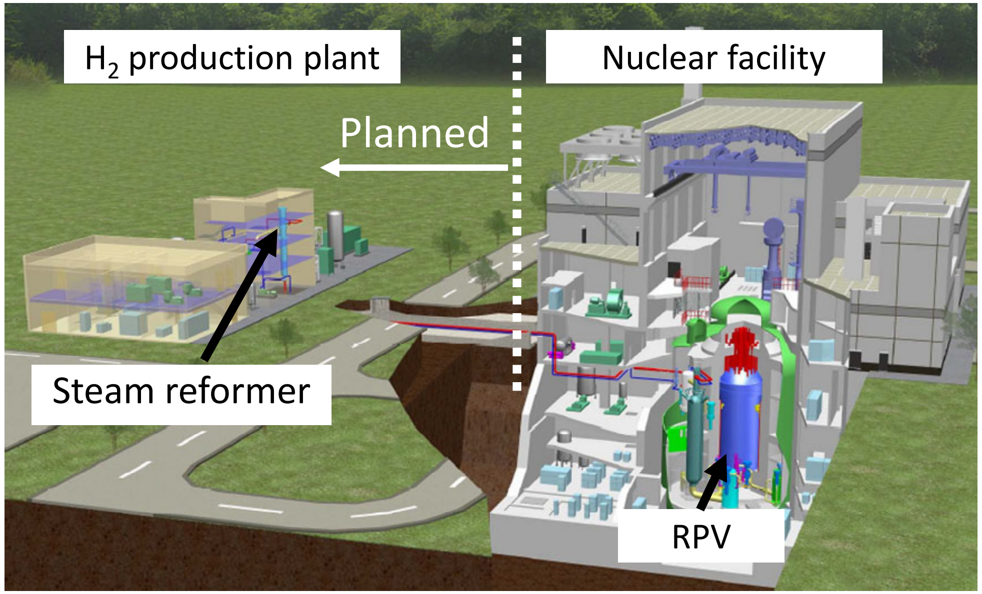
☐ 100 L/h operation, longer operation.

☐ Development of automatic control system, high performance membrane, etc.

☐ Data acquisition on reliability, durability, etc.

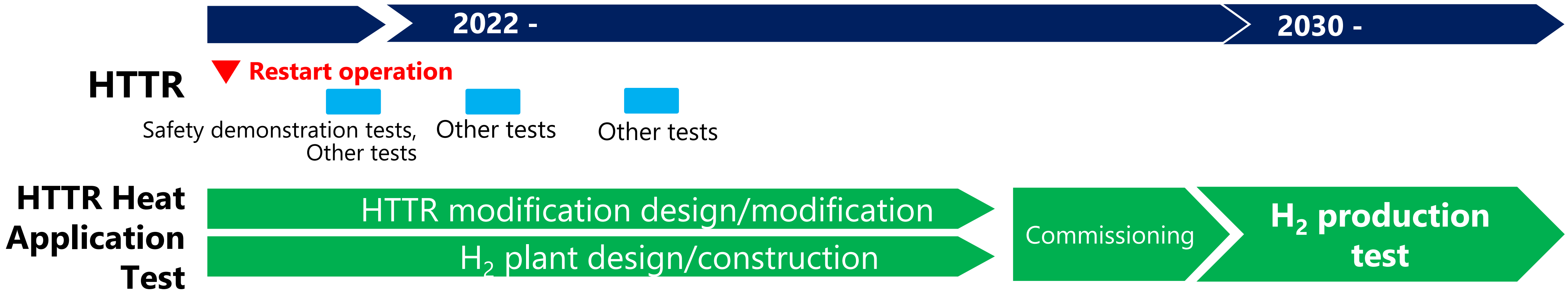
HTTR Heat Application Test

- Establish safety design for coupling of H_2 plant to HTGR
  - ✓ Obtain permission from regulatory authority for application of industrial standards to H_2 plant towards non-electric application of nuclear heat.
  - ✓ Complete development of coupling technologies for HTGR and H_2 production plant by 2030.
  - ✓ Develop carbon-free H_2 production technology such as IS process, etc., in parallel.



HTTR heat application test

Test schedule (Tentative)



2022 -

2030 -

HTTR

Restart operation

Safety demonstration tests, Other tests

Other tests

Other tests

HTTR Heat Application Test

HTTR modification design/modification

H_2 plant design/construction

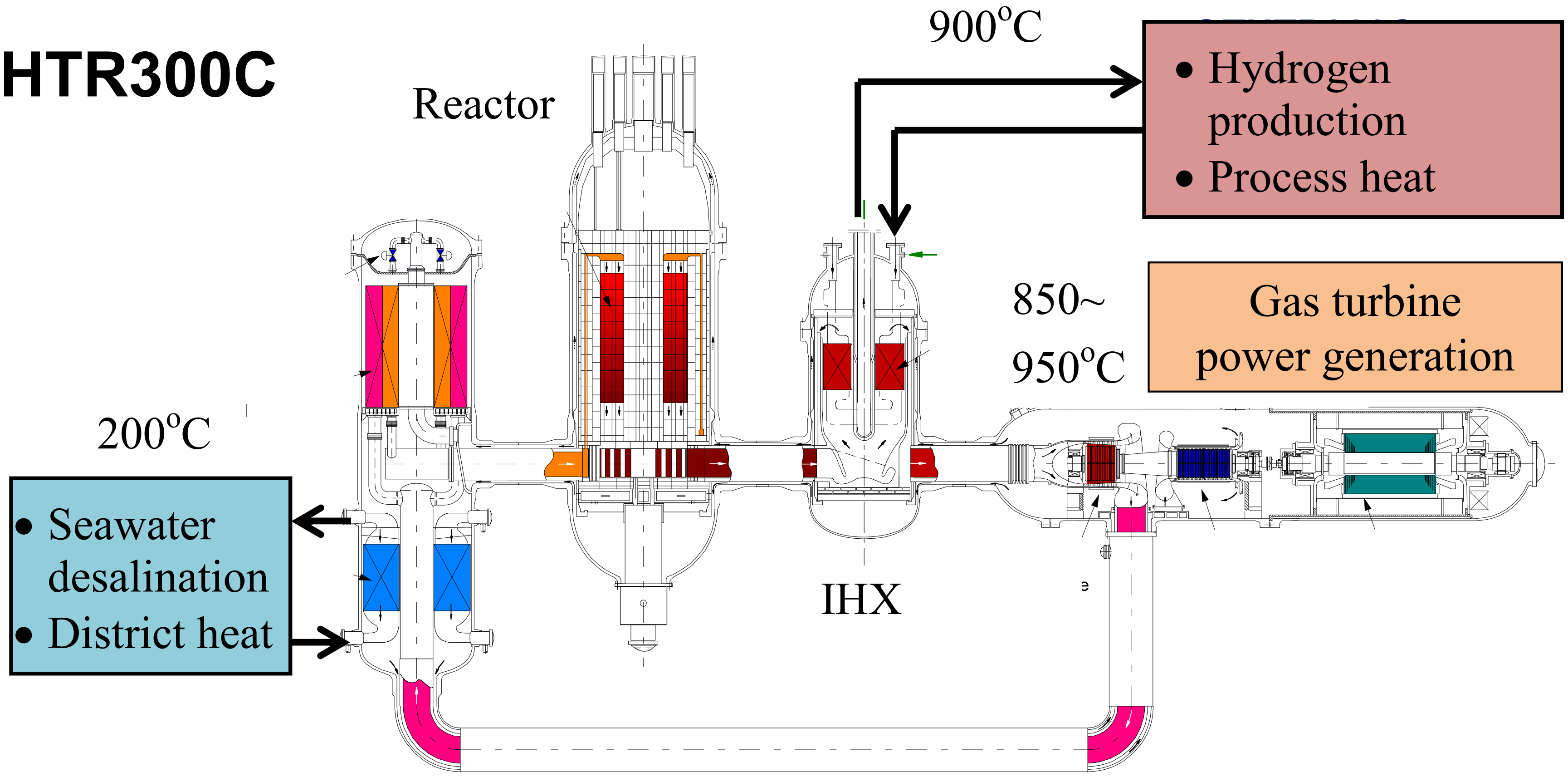
Commissioning

H_2 production test

GTHTR300C: HTGR Hybrid Energy System

- HTGR system for power generation and cogeneration of hydrogen, desalination, steelmaking, etc.
- Designed by JAEA in collaboration with Mitsubishi Heavy Industries, Fuji Electric, Kawasaki Heavy Industries, Nuclear Fuel Industries, Toshiba, IHI, others.
- Development status: Pre-licensing basic design completed.

GTHTR300C



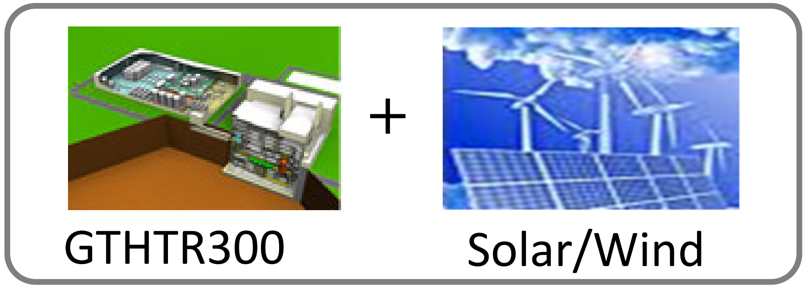
- Hydrogen production
- Process heat

Gas turbine power generation

- Seawater desalination
- District heat

Operational Flexibility - Renewable Hybrid (1/3) -

- HTGR + renewable hybrid power for grid stability & cogeneration

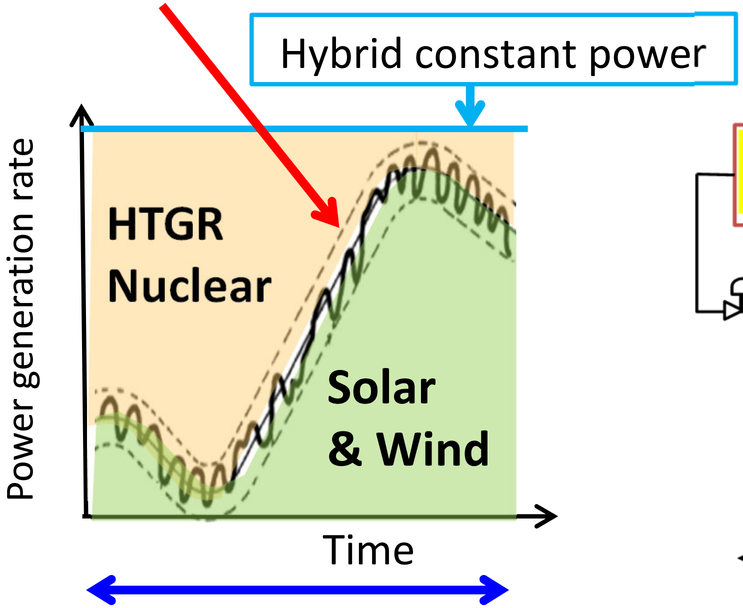


Steady constant power to grid

H_2(thermal IS, HTE, etc.)

Short time scale (sec~min) : ± 20% of reactor rated power

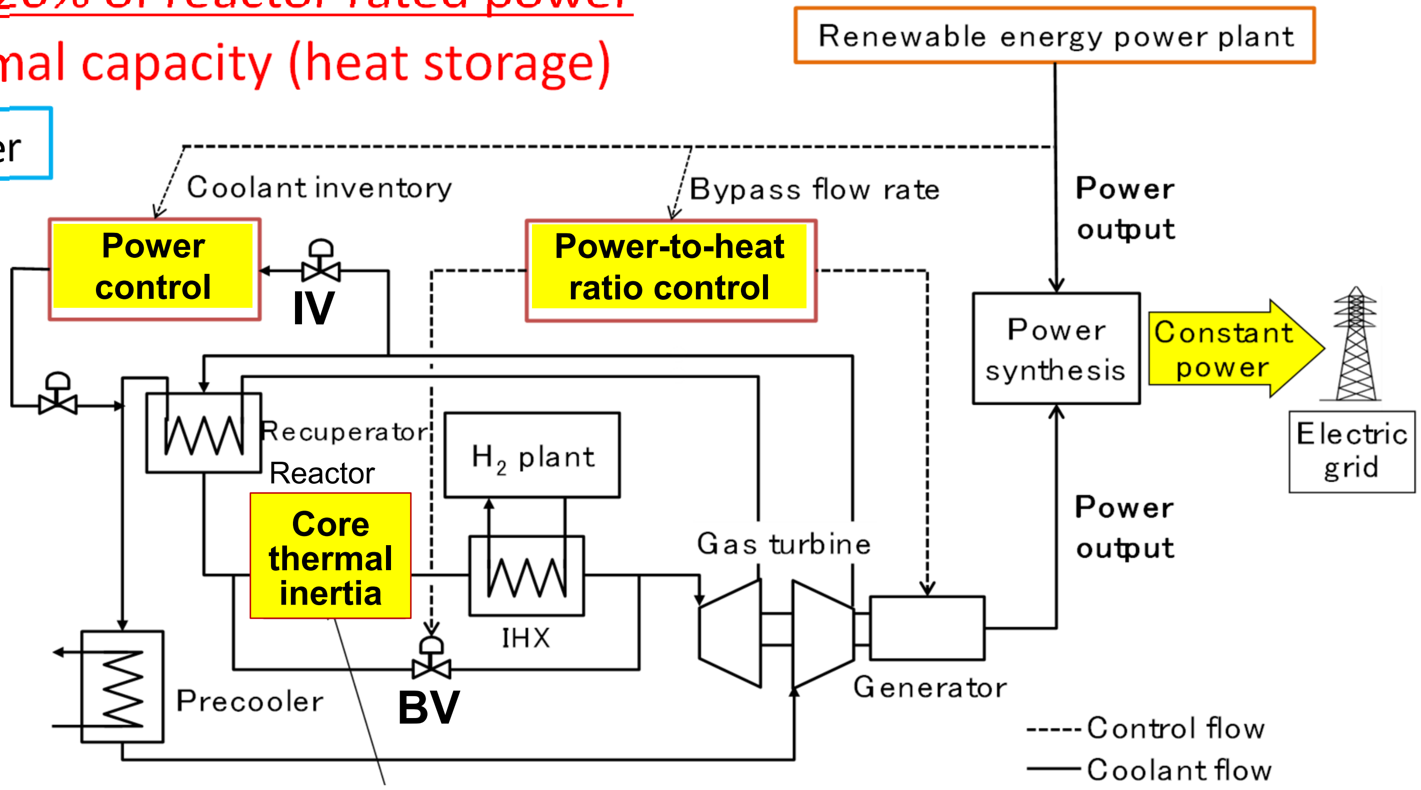
Utilize large graphite core thermal capacity (heat storage)



Long time scale (hour~day) :

± 50% of reactor rated power

(reactor gas pressure)



Core heat capacitance 370 MJ/°C

GTHTR300 renewable hybrid system

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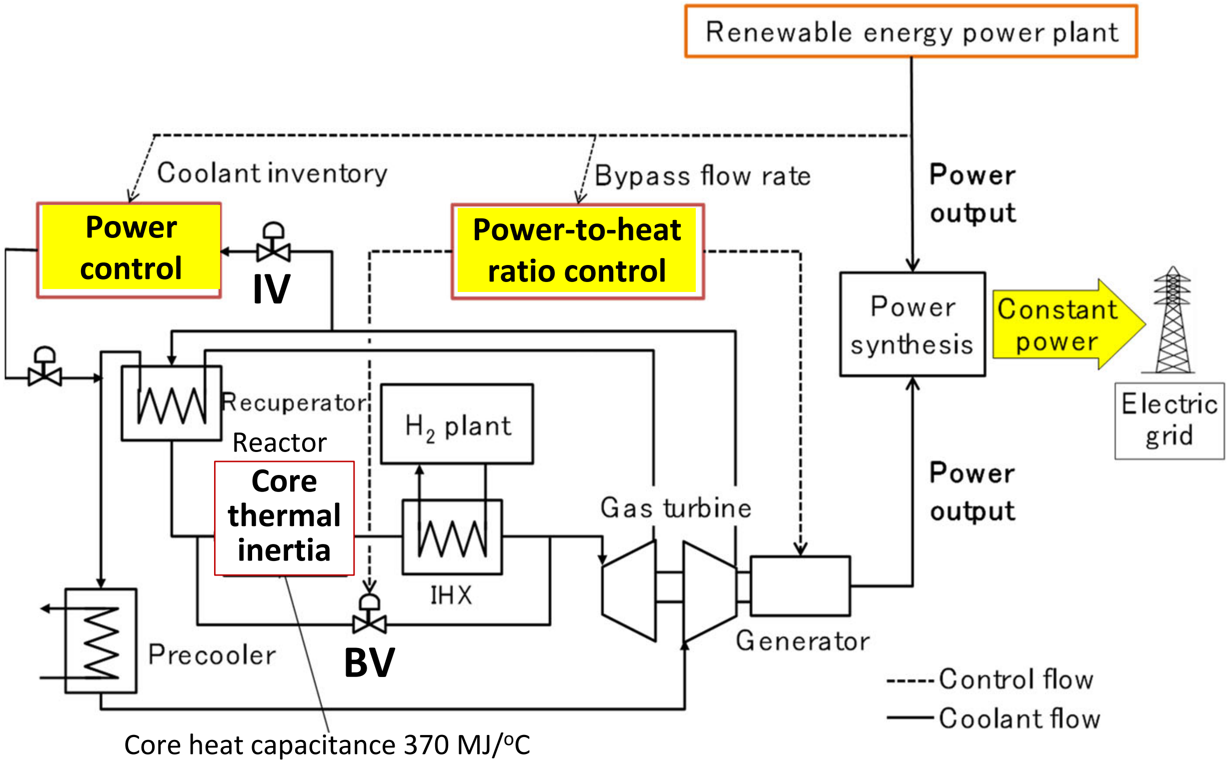
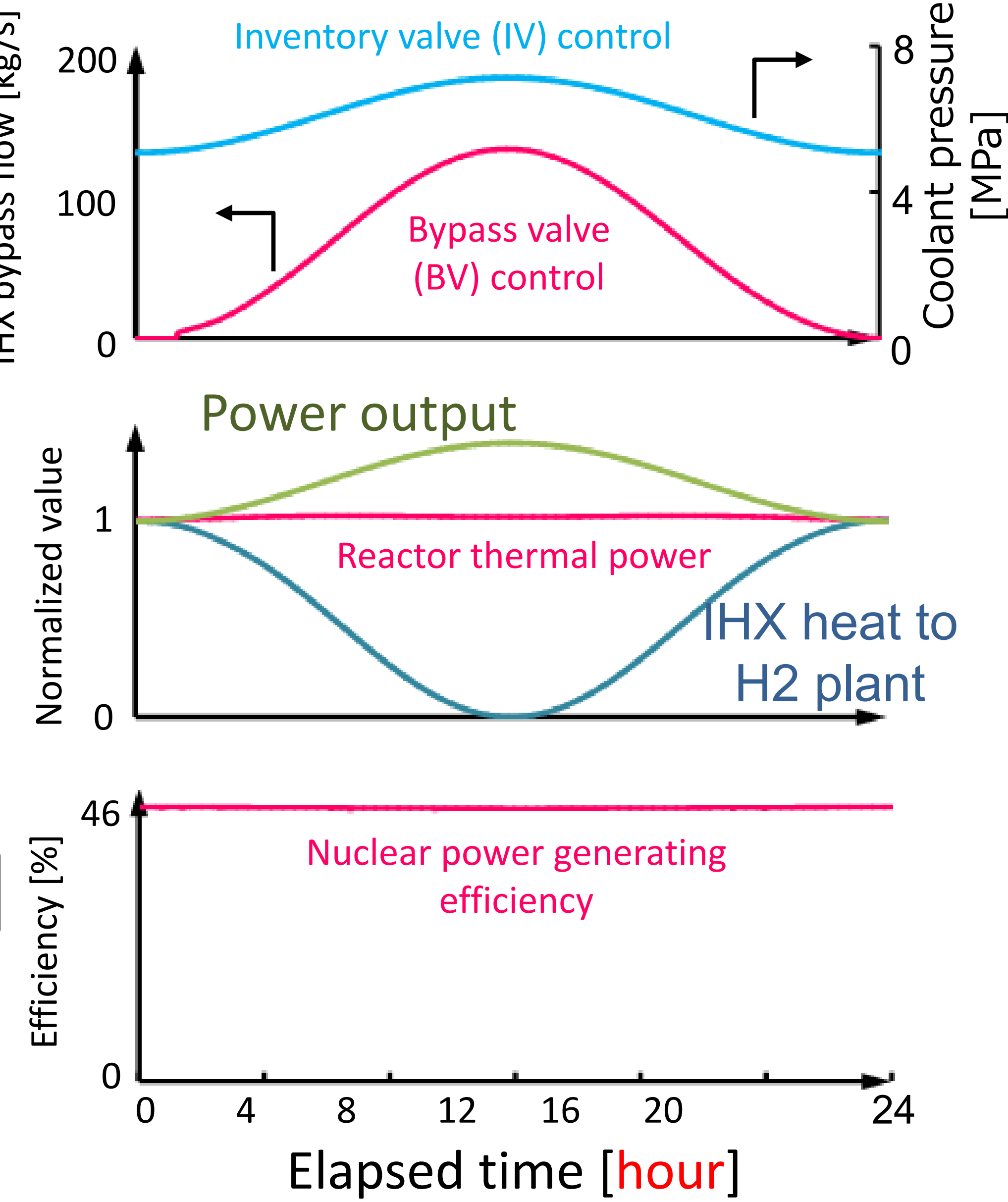
1. H. Sato & X. Yan, Study of an HTGR and renewable energy hybrid system for grid stability, Nucl. Eng. Des., 343, 178-186 (2019).
2. X. Yan, et al., GTHTR300 as SMR for nuclear-renewable hybrid system, SMR 2019 Conference, February 14, 2019, Prague, Czech Republic.

Operational Flexibility - Renewable Hybrid (2/3) -

- Reactor responds to variable renewable (solar/wind) power generation at long time scale (on the order of hour ~ day)
  - ➢ Adjusting power/H2 production ratio
  - ➢ Reactor thermal power not changed
- Power generation efficiency is constant.



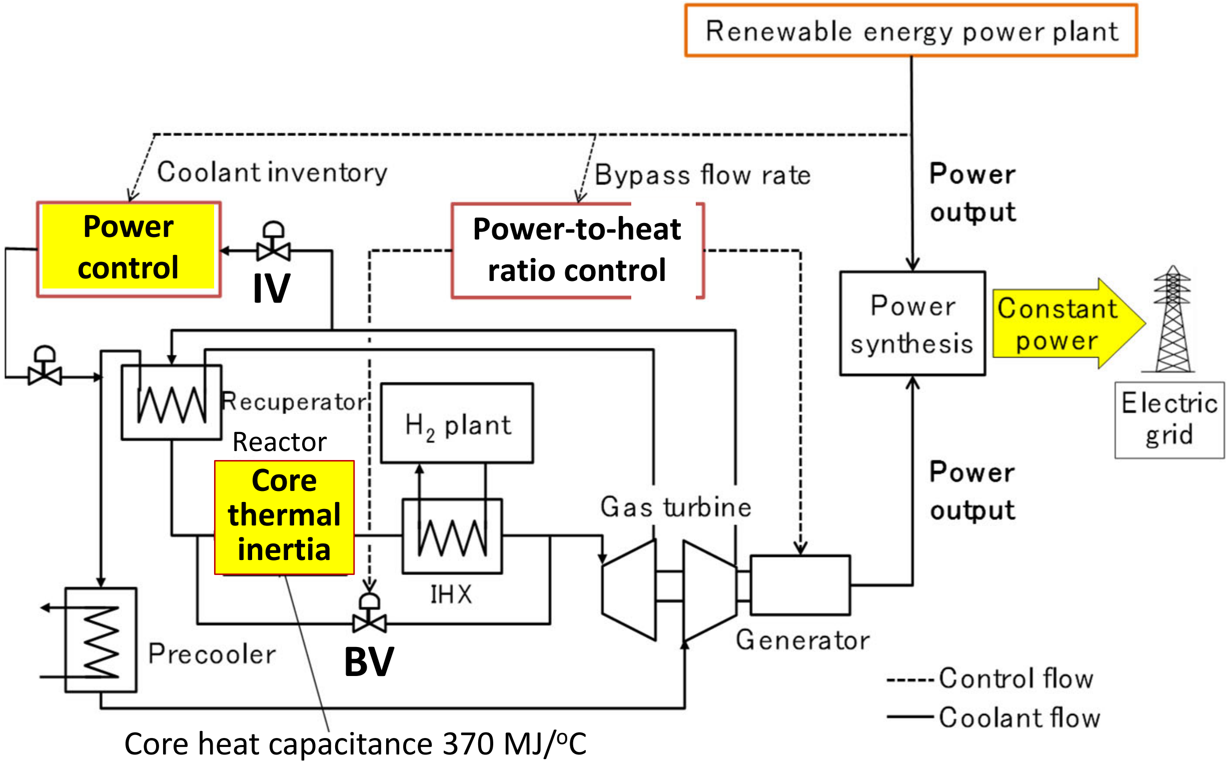


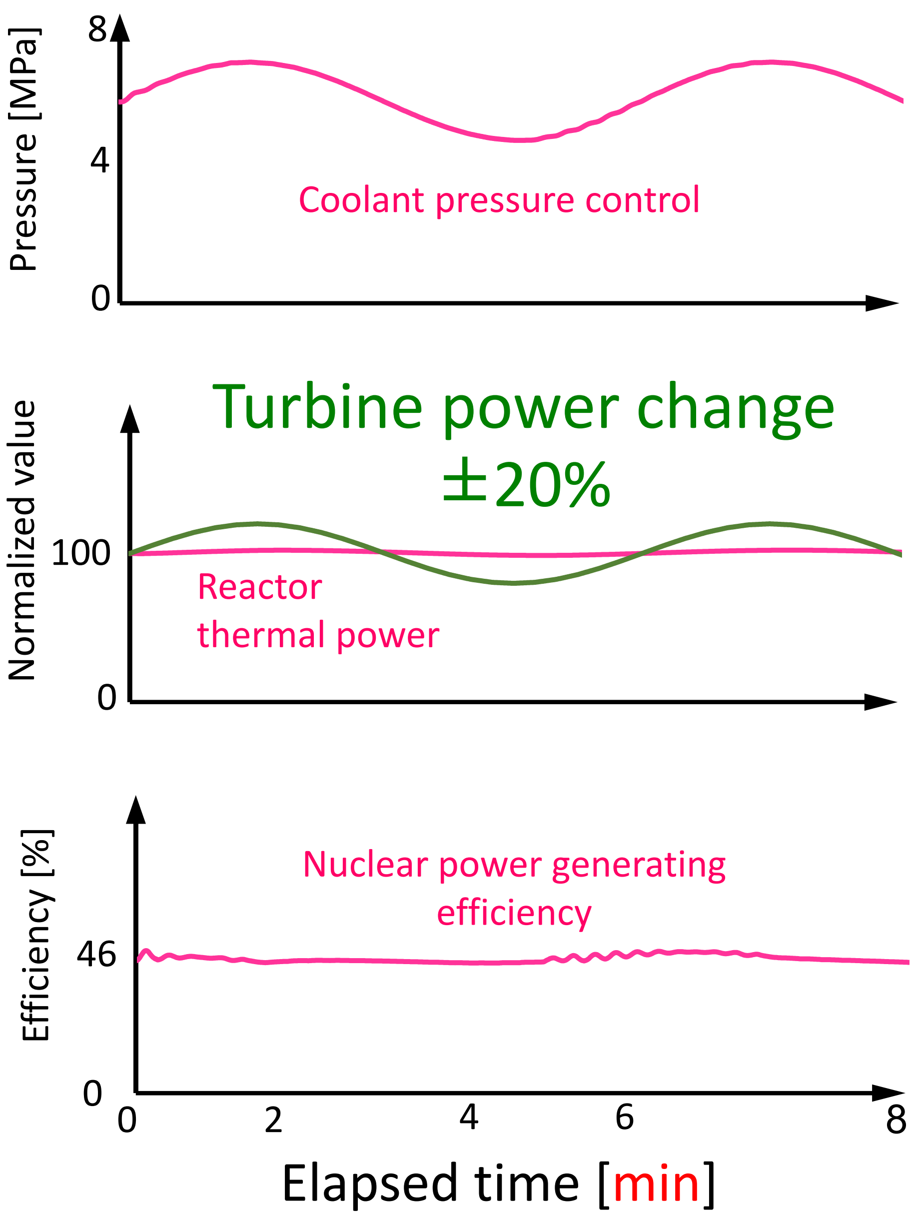
Simulation for daily load variation

1. H. Sato & X. Yan, Study of an HTGR and renewable energy hybrid system for grid stability, Nucl. Eng. Des., 343, 178-186 (2019).
2. X. Yan, et al., GTHTR300 as SMR for nuclear-renewable hybrid system, SMR 2019 Conference, February 14, 2019, Prague, Czech Republic.

Operational Flexibility - Renewable Hybrid (3/3) -

- Reactor responds to renewable (wind/solar) power generation fluctuation at short time scale (on the order of sec ~ min).
  - Utilize core thermal inertia
  - Control coolant pressure
  - Reactor thermal (fission) power is not adjusted
- Power generation efficiency is constant.

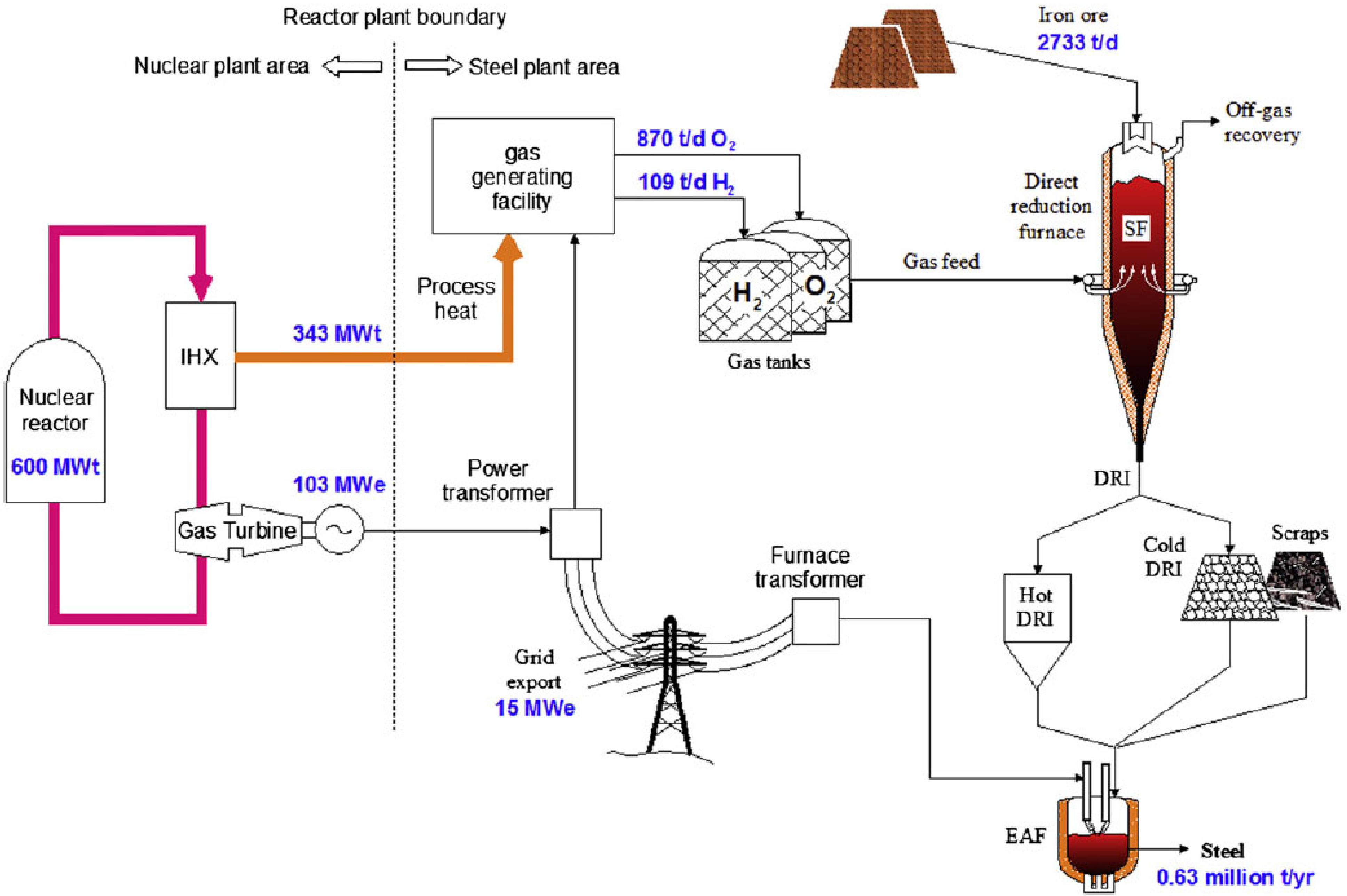




Simulation for load fluctuation

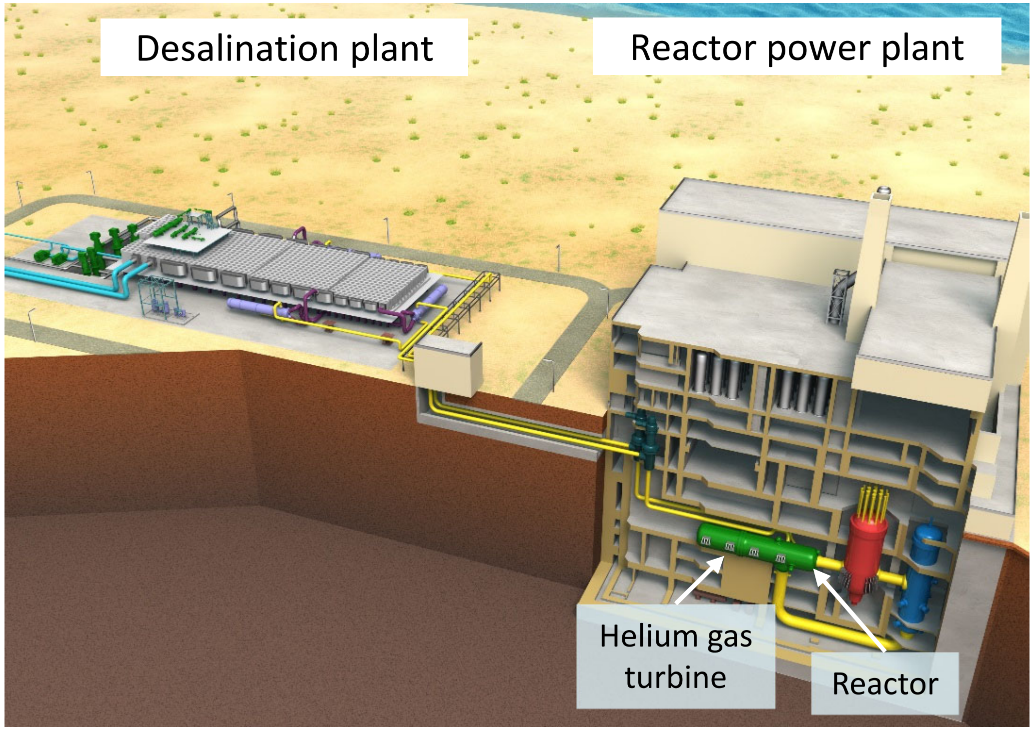
1. H. Sato & X. Yan, Study of an HTGR and renewable energy hybrid system for grid stability, Nucl. Eng. Des., 343, 178-186 (2019).
2. X. Yan, et al., GTHTR300 as SMR for nuclear-renewable hybrid system, SMR 2019 Conference, February 14, 2019, Prague, Czech Republic.

Product Flexibility - Nuclear Steelmaking -

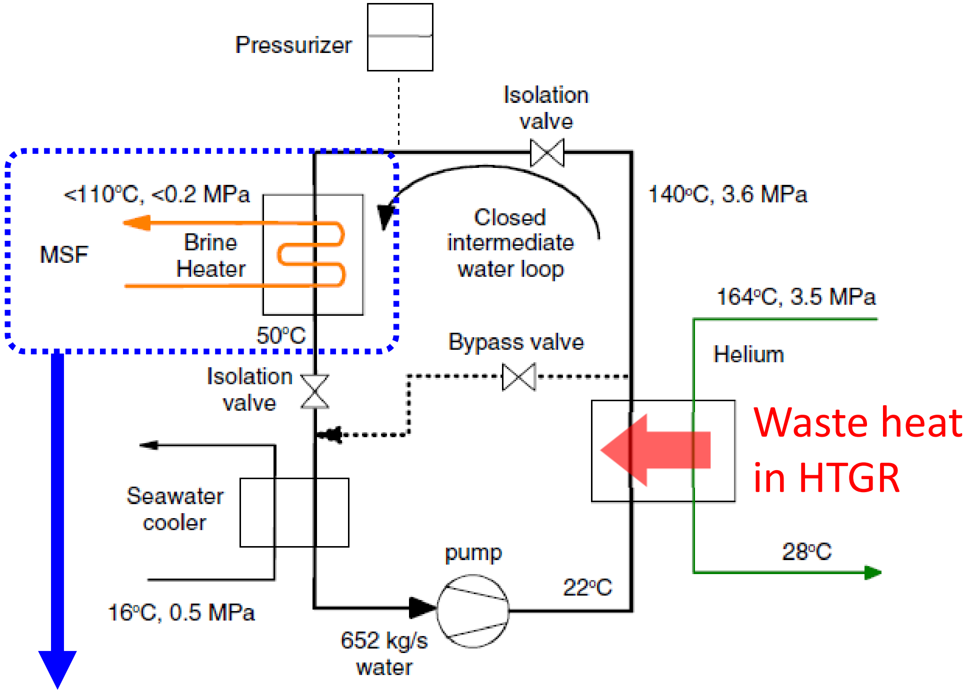


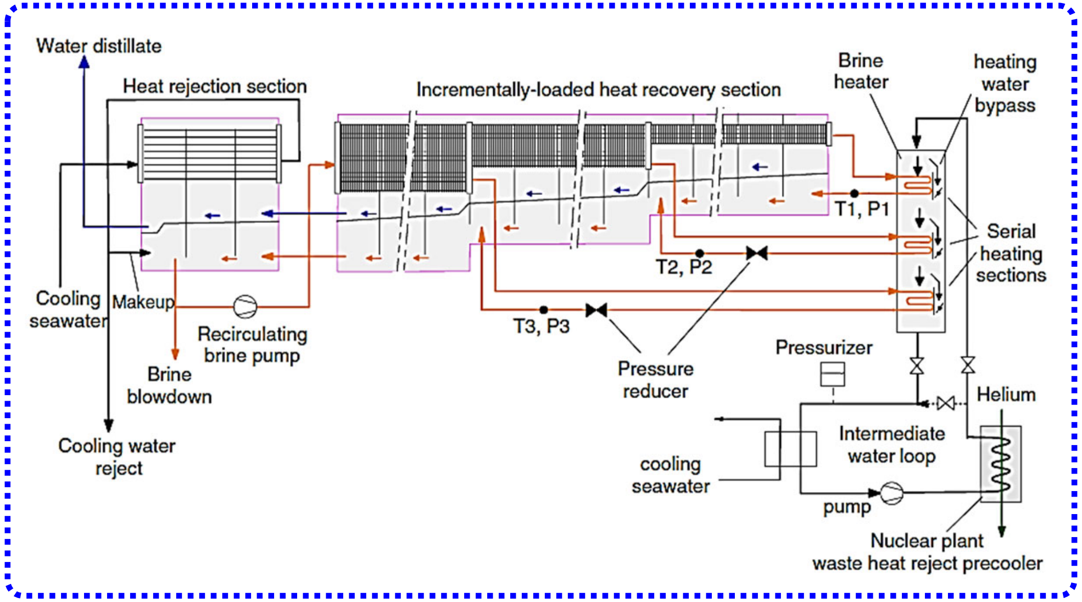
X. L. Yan, et al., Study of a nuclear energy supplied steelmaking system for near-term application., Energy, 39, 54-165 (2012).

Product Flexibility - Seawater Desalination -



Reactor power [MWt]	600
Heat supply rate [MW]	248
Reactor outlet temp. [°C]	850-950
Power generation [MWe]	Up to 300
Portable water production [m^3/d]	56,000

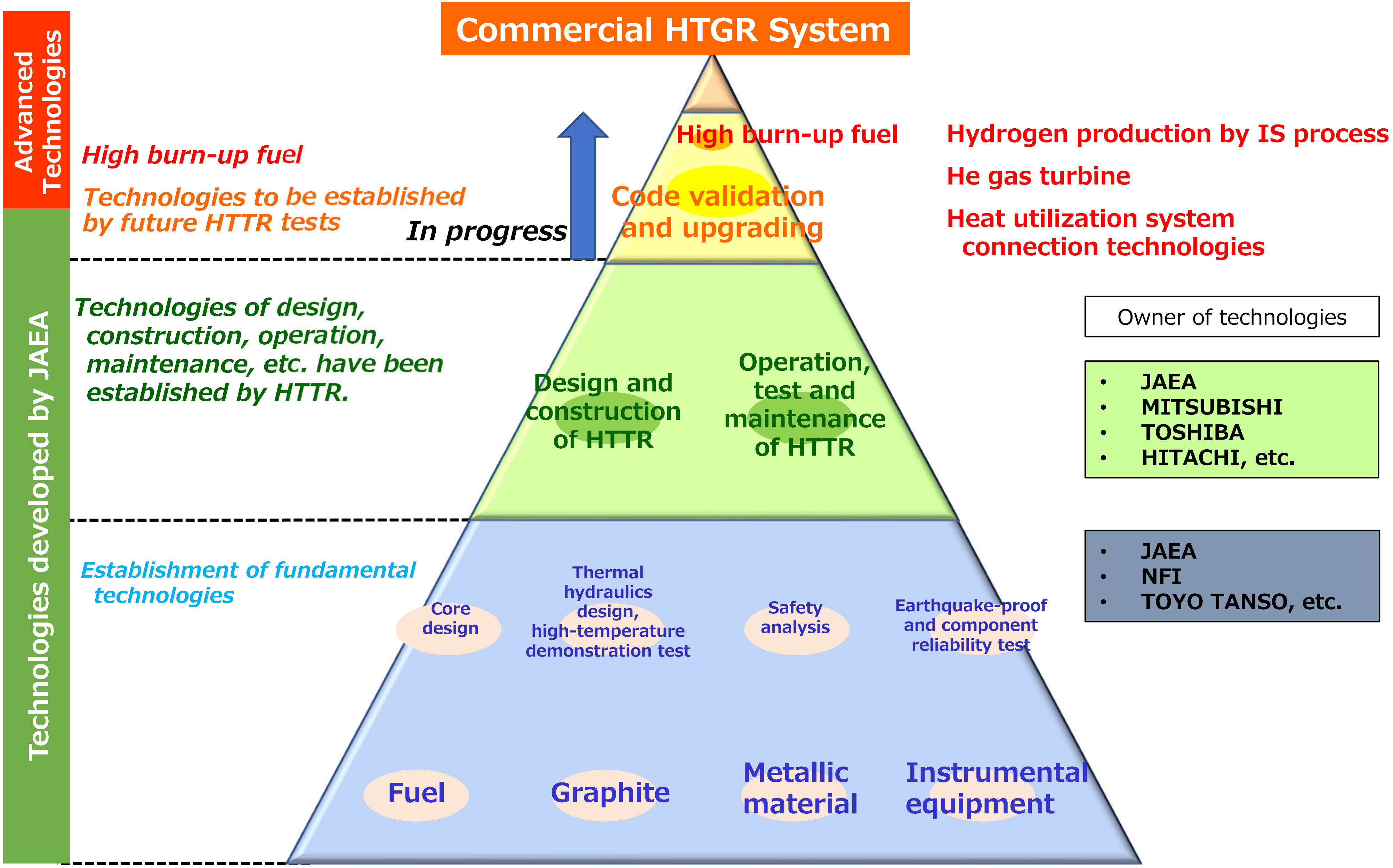




X. L. Yan, Study of an incrementally loaded multistage flash desalination system for optimum use of sensible waste heat from nuclear power plant, Int.. J. Energy Res., 37(14), 1811-1820 (2013).

Contents

Technology Readiness Level of HTGR system



Commercial HTGR System

Advanced Technologies

High burn-up fuel

Technologies to be established by future HTTR tests

In progress

High burn-up fuel

Code validation and upgrading

Hydrogen production by IS process

He gas turbine

Heat utilization system connection technologies

Technologies developed by JAEA

Technologies of design, construction, operation, maintenance, etc. have been established by HTTR.

Design and construction of HTTR

Operation, test and maintenance of HTTR

Owner of technologies

- **JAEA**
- **MITSUBISHI**
- **TOSHIBA**
- **HITACHI, etc.**

Establishment of fundamental technologies

Core design

Thermal hydraulics design, high-temperature demonstration test

Safety analysis

Earthquake-proof and component reliability test

Fuel

Graphite

Metallic material

Instrumental equipment

- **JAEA**
- **NFI**
- **TOYO TANSO, etc.**

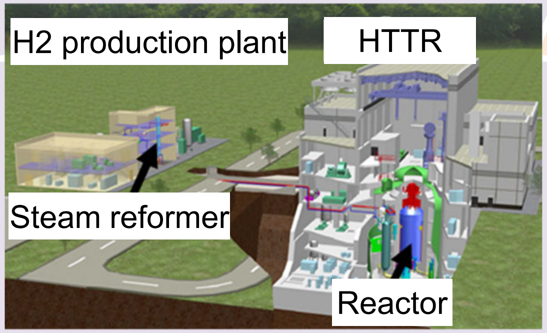
Development and Deployment Plan of HTGR *(JAEA's draft plan)*

2020 ～2030 ～2040 ～2050

Private sector

JAEA

HTTR-heat application system (SR)



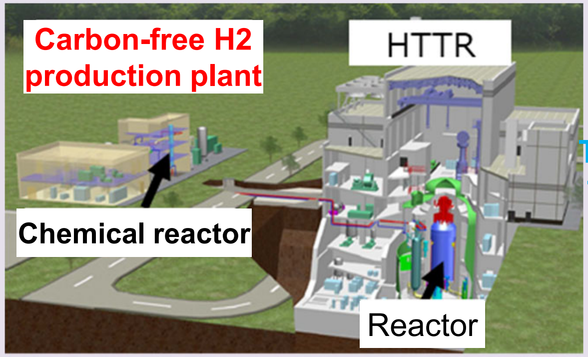
- Establishment of safety design for HTGR-H2 production system
- Establishment of connection technology between HTGR and H2 production plant

Technology development plant

- Verify reliability of all plant components and stability of long-term operation (made of metal and ceramics, 0.1 m^3/h-H2)

Overseas demonstration reactor (power generation and heat application) under international collaboration

Connection of carbon-free H2 production plant (Demonstration of technologies necessary for practical use)



HTTR-heat application test with carbon-free H2 production (100-1000m^3/h)

Reflect results of technology development

Implement components of commercial plant

- Confirmation of carbon-free H2 production
- Confirmation of overall performance in HTGR system

Technology transfer of individual elements

Technology transfer to private sector

Domestic demonstration reactor (power generation and H2 production)

Domestic commercial reactor

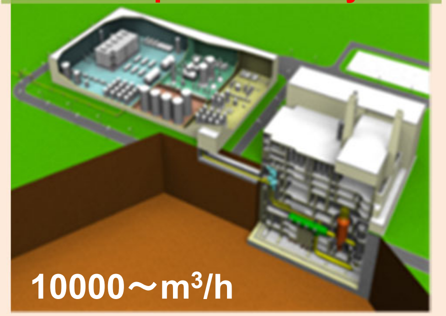
Expand to various heat sources that can utilize high-temperature heat

Establishment of supply chain

Improvement of economic efficiency

Divergence of location

HTGR H2 production system



Solar power H2 production system
100～m^3/h

Industrial waste heat utilization (mining, etc.) **H2 production system**
1000～m^3/h

Regu-lator

- **Review of HTTR heat application system** (**SR: H2 production by steam reforming of natural gas**)
- Review of HTTR heat application system (Only carbon free H2 specific part)
- Review of demonstration reactor
- Review of commercial reactor

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JAEA International Cooperation on HTGR

Multilateral cooperation

OECD／NEA

Czech France Germany Hungary Korea USA

Joint Test by HTTR, LOFC Project (Contracted Research)

- Loss of forced cooling test (Completed)
  - All three primary helium gas circulators were tripped at the initial reactor power of 30%
- Loss of core cooling test (planned)
  - All three primary helium gas circulators are tripped at the initial reactor power of 100%
  - Vessel cooling system is simultaneous tripped at reactor power of 30%

IAEA

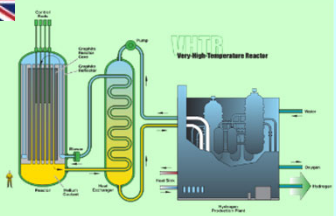
- Technical Working Group on Gas Cooled Reactors (TWG-GCR) (Number of countries: 17)
- Technical Working Group on Small and Medium Sized or Modular Reactors (TWG-SMR) (Number of countries: 21)
- Coordinated Research Project (CRP)
  - ✓ Assessing Technical and Economic Aspects of Nuclear Hydrogen Production for Near-term Deployment
  - ✓ Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for EPZ for SMR Deployment
  - ✓ Economic Appraisal of SMR Projects: Methodologies and Applications

Generation IV International Forum (GIF)

Canada China France Korea Switzer-land USA EU Australia UK

Very High Temperature Reactor (VHTR)

- Hydrogen Production System Project
- Fuel and Fuel Cycle Project
- Material Project
- Computational Methods Validation and Benchmarking Project



VHTR

EU

GEMINI+ Project (by 2021.2, under consideration of next project)

- Design and R&D of HTGR with heat application

HTTR

- **The only test and research reactor of HTGR in the world to supply heat of 950°C**
- **International joint researches for needs of each country**

Bilateral cooperation

Poland

- Information exchange and technology cooperation on HTGR based on memorandum of cooperation (2017.5-) and implementing arrangement (2019.8-) (National Centre for Nuclear Research: NCBJ)

United Kingdom

- Cooperation to U-Battery project (Commercial HTGR system) (URENCO, etc.)
- Cooperation on HTGR technology (National Nuclear Laboratory: NNL)
- Information exchange on HTGR safety (Office for Nuclear Regulation: ONR)

USA

Civil Nuclear R&D Working Group (CNWG)

- Development of simulation algorithm, validation of analytical model, study of connecting test between HTTR and heat utilization system
(Department of Energy: DOE, Idaho National Laboratory: INL)

China

- Public Information exchange
(Tsinghua University, Institute of Nuclear and New Energy Technology: INET)

Korea

- Public Information exchange
(Korea Atomic Energy Institute: KAERI)

Kazakhstan

- Design collaboration for Kazakhstan HTGR: KHTR (National Nuclear Center: NNC)
- ISTC project on irradiation research of oxidation-resistant SiC fuel compact (Institute of Nuclear Physics: INP)
- Safety research (Nuclear Technology Safety Center: NTSC)

Indonesia

- Public Information exchange
(Badan Tenaga Nuklir Nasional: BATAN)

Contents

Summary

- Government of Japan formulated “Green Growth Strategy Through Achieving Carbon Neutrality in 2050 ” positioning that HTGR as one of priority field that can contribute to achievement of goal realizing a carbon-neutral, decarbonized society by 2050.

- The HTTR restarted its operation on July 30, 2021. Loss of core cooling test was carried out as a safety demonstration test in January 2022.

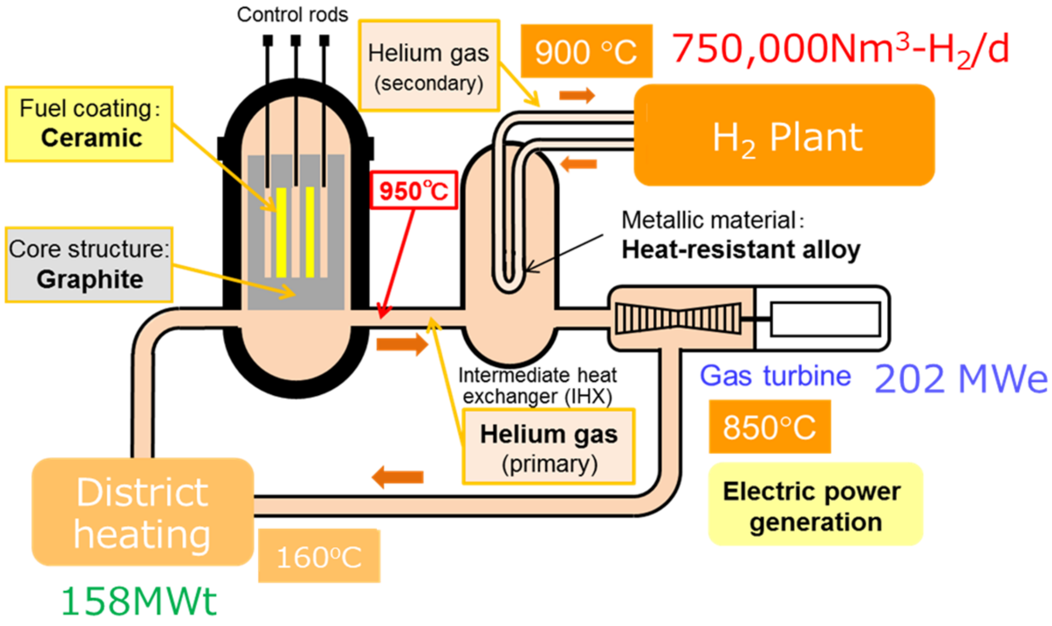
- The HTTR heat application test project will be officially started in 2022 aiming to establish safety design for coupling H_2 plant to HTGR by 2030.

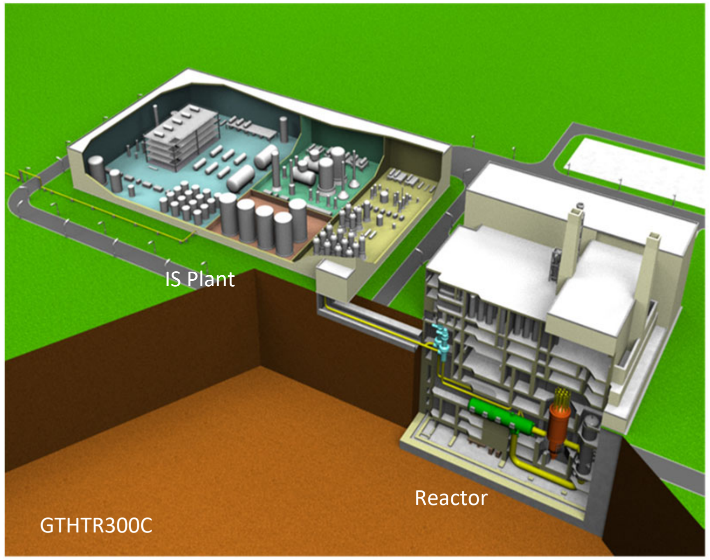
- GTHTR300C has operational flexibility: responding to variable renewable (solar/wind) power generation, and contributing to nuclear steelmaking and seawater desalination.

Thank you for your attention!

HTGR Hydrogen Cogeneration System for Steel-making

- Nuclear steel making using hydrogen as reducing agent produced by HTGR
- Reduction of 100% of CO_2 emitted from steel making factory
- First step : hydrogen by steam reforming, Future step: hydrogen by IS process





H_2 cost reduction by multi-purpose heat utilization systems.

Item	Cost reduction (USC/Nm^3)	H_2 production cost (USC/Nm^3)
H_2 production only	**-**	**24.2**
Cogeneration: H_2 and electricity	**12.4***	**11.8**
Waste heat utilization: District heating**	**11.7**	**0.1**

* Changing the share of depreciation cost of HTGR construction (by H_2 production and power generation) and selling cogenerated electricity at 8.0 JPY/kWh, whereas the original power generation cost is 5.8 JPY/kWh.,** Market production cost: 0.65 JPY/MJ

HTGR hydrogen system has economical competitiveness due to its high heat utilization rate.