To learn more about HTGR

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Japan Atomic Energy Agency http://www.jaea.go.jp/

HTGR Research and Development Center

HTGR Hydrogen 検索

Department of High Temperature Engineering Test Reactor (HTTR)

HTTR Oarai 検索

Visit HTTR site

Welcome to visit HTTR and related facility in Oarai-machi, Ibaraki-ken.

- For inquiries:
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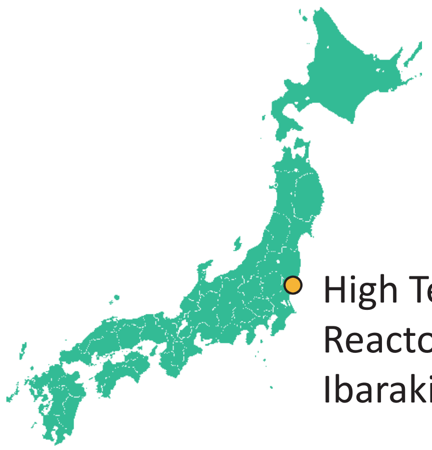
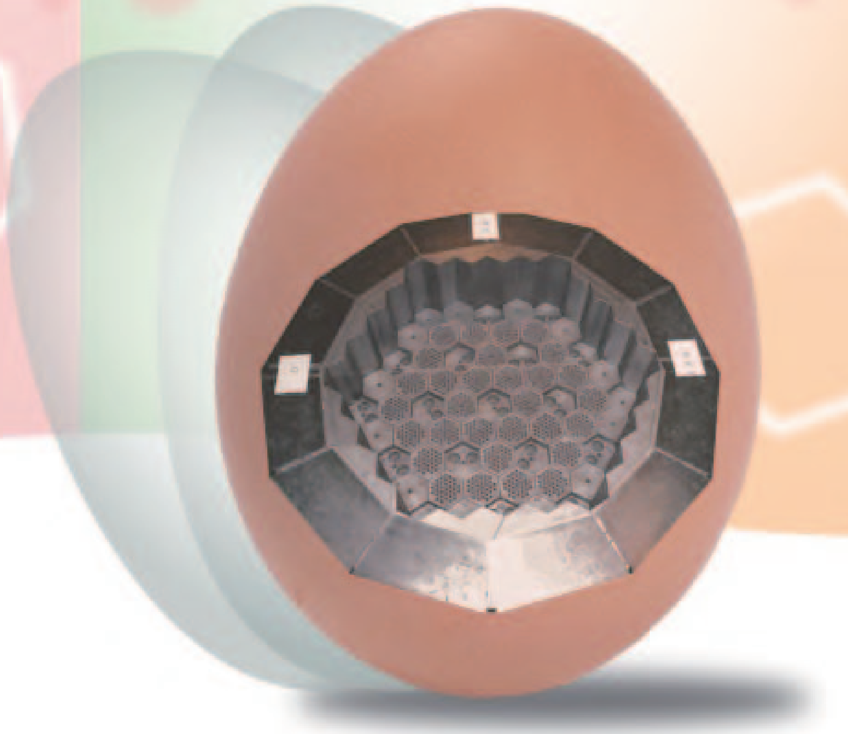
  Phone (+81)-29-267-2494



Japan Atomic Energy Agency (JAEA
4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319-1184, Japan
Phone (+81)-29-282-1122

High Temperature Gas-cooled Reactor



Safe and Eco-friendly Nuclear Reactor with Meltdown-proof design

Japan Atomic Energy Agency(JAEA)

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

"HTGR" in Government Policy

Provisional Translation

Strategic Energy Plan (July, 2018 Cabinet Decision)

Chapter 3 Basic policy and political response focusing energy system in 2030

2. Technical challenges

… Under the international cooperation with looking for trends in overseas markets, GOJ will develop technologies that contribute to the advancement of safety, such as high-temperature gas-cooled reactor with inherent safety, which are expected to be used in various industries including hydrogen production.

Growth Strategy 2018 (June, 2018 Cabinet Decision)

Chapter 2 Concrete measures 1. Energy and Environment

i) Encouragement of innovations for energy system conversion and decarbonization

… GOJ also promotes research and development for the future by utilizing experimental fast reactor and high-temperature gas-cooled reactor, etc.

Long-Term Strategy under the Paris Agreement as Growth Strategy (June, 2019 Cabinet Decision)

Chapter 3 Cross-cutting measures to focus on

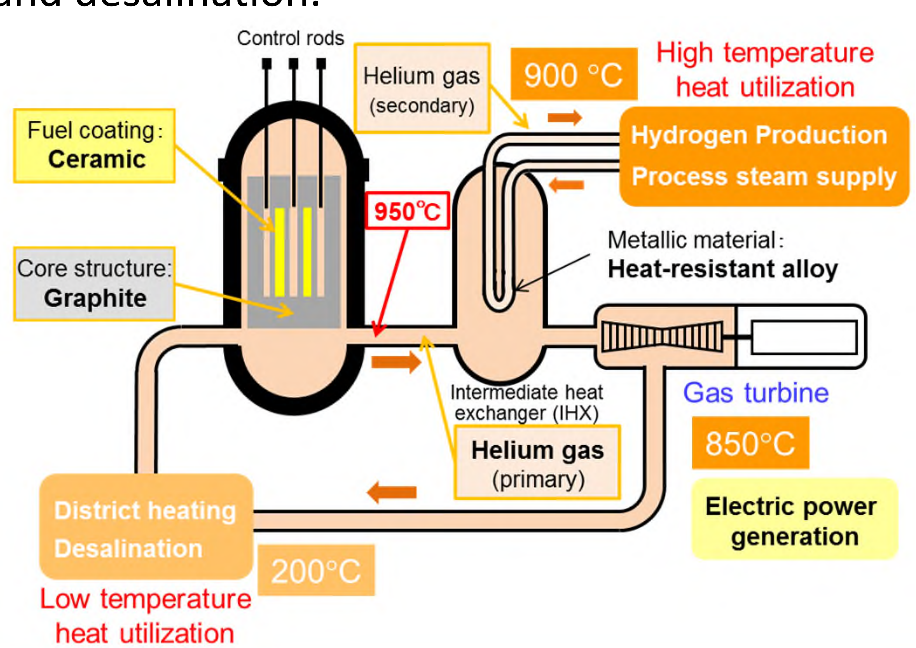
(4) Visualization of issues for practical application in individual fields

③ Examples of technologies related to Hydrogen Production: Thermochemical hydrogen production using industrial waste heat (IS Process)

⑤Examples of technologies related to Nuclear: High Temperature Gas-cooled Reactor

A flexible reactor

- HTGR can supply 950°C of heat, and can be used not only for electric power generation but also for a wide range of applications such as hydrogen production, high temperature process heat supply, district heating, and desalination.



Superior inherent safety

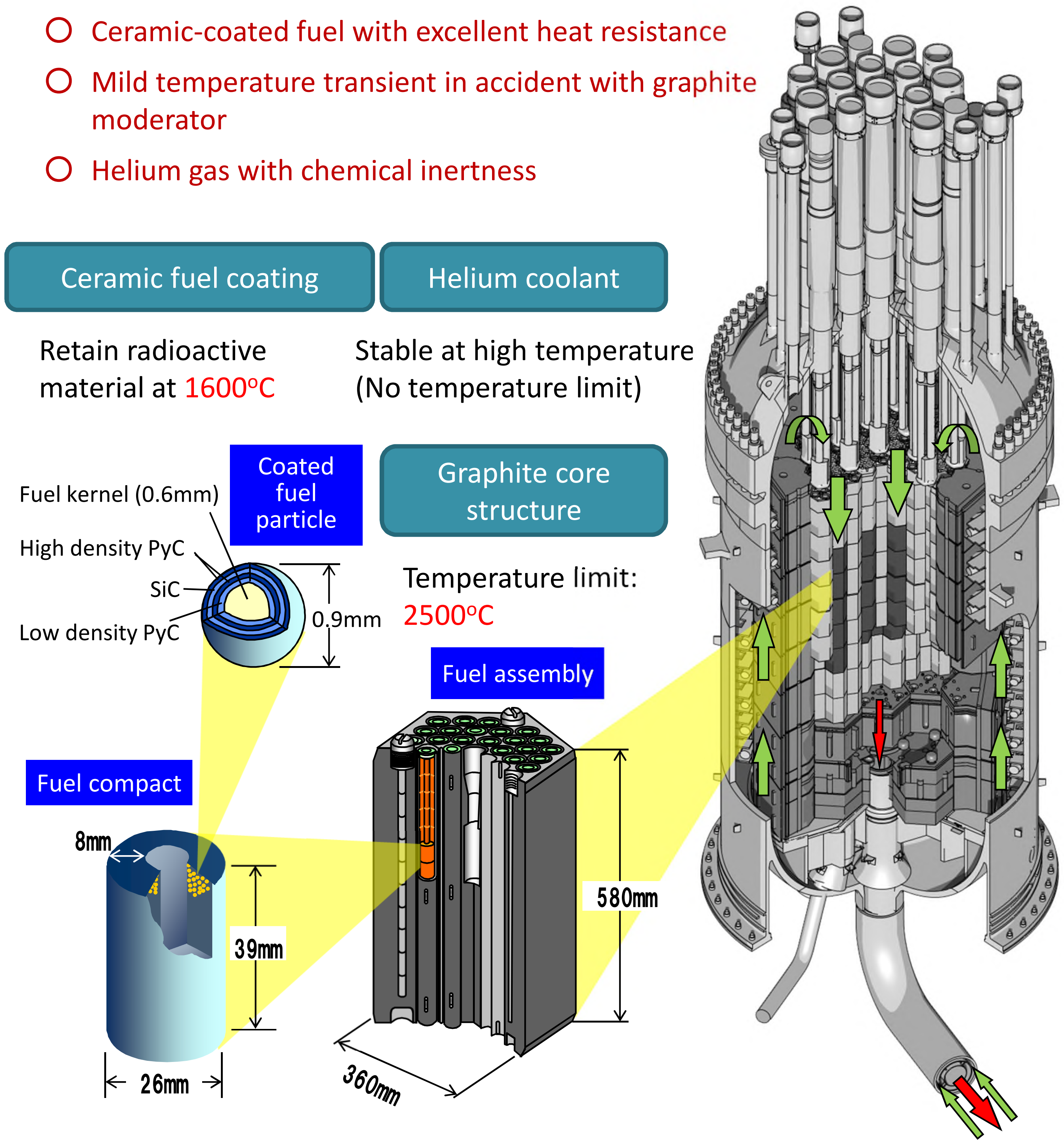
- Higher safety of nuclear power generation is requested by lessons learned from Fukushima-Daiichi Nuclear Power Station (1F) accident.
- HTGR shuts down and cools core without any equipment or operator action in case of loss of coolant or loss of off-site electric power accident.

○ Ceramic-coated fuel with excellent heat resistance

○ Mild temperature transient in accident with graphite moderator

○ Helium gas with chemical inertness

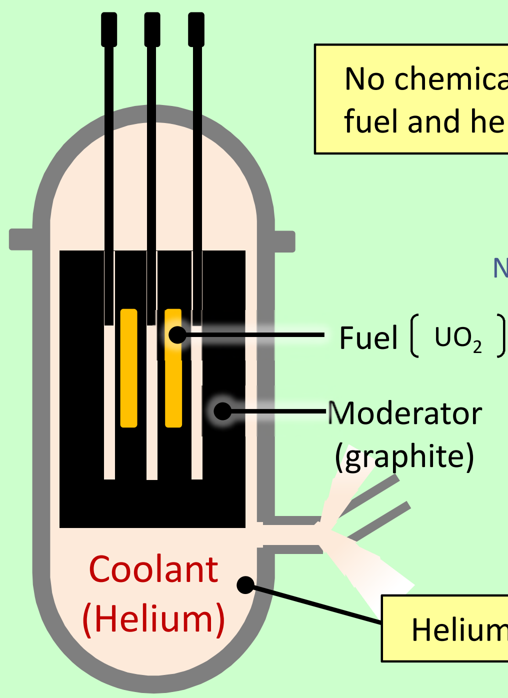
Ceramic fuel coating	Helium coolant
Retain radioactive material at 1600°C	Stable at high temperature (No temperature limit)



Superior inherent safety

Helium coolant with chemical inertness

HTGR

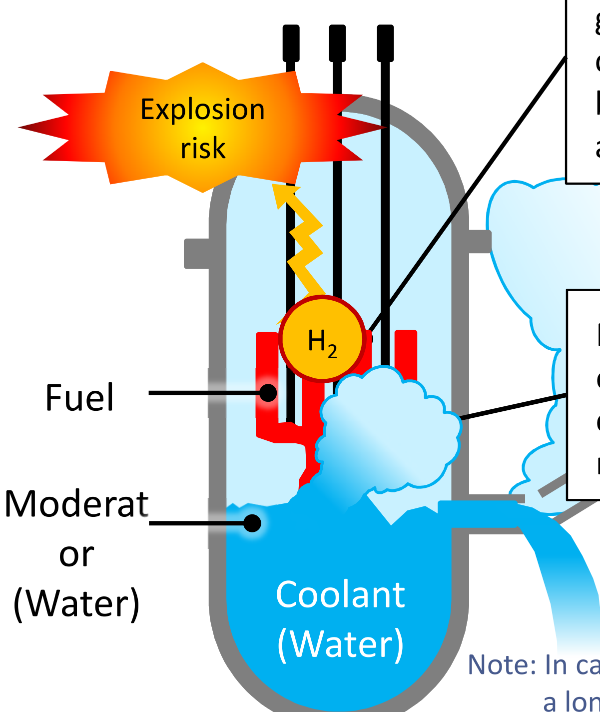


No chemical reaction of fuel and helium

Note: In case of vapor or air ingress accident, the surface of graphite oxidizes but safety of the core never be lost

Helium gas

LWR



Hydrogen gas generation due to chemical reaction between fuel (clad) and vapor

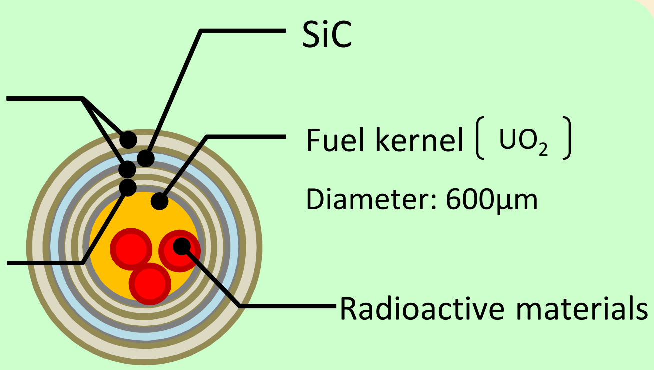
Rapid water evaporation due to contact with melting fuel

Note: In case of a station blackout for a long time like Fukushima Daiichi nuclear disaster

No hydrogen gas explosion No vapor explosion

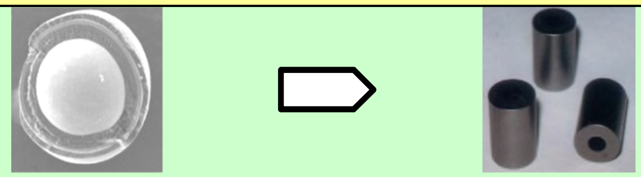
Ceramic coated particle fuel with excellent heat-resistant property

HTGR



Fission products is released from intact particles over 2200 °C. (Fuel is recyclable under 1600 °C)

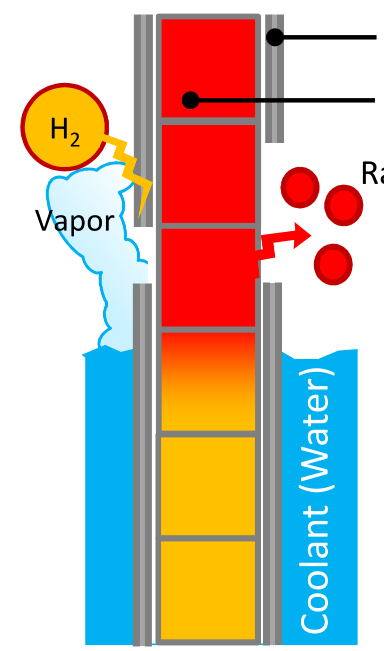
In case of a loss of coolant accident, reactor can be cooled passively and the fuel temperature never exceeds 1600 °C.



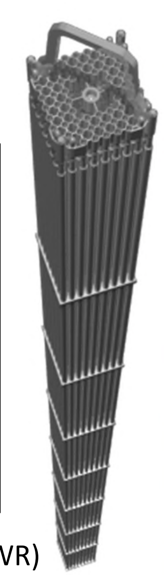
Coated fuel particle (Diameter: 920μm)

Fuel compact (Outer diameter: 26mm, Height: 39mm)

LWR



By loss of the cooling function by the evaporation of a coolant, fuel and metal cladding fuse, and it collects on the bottom of a pressure vessel.



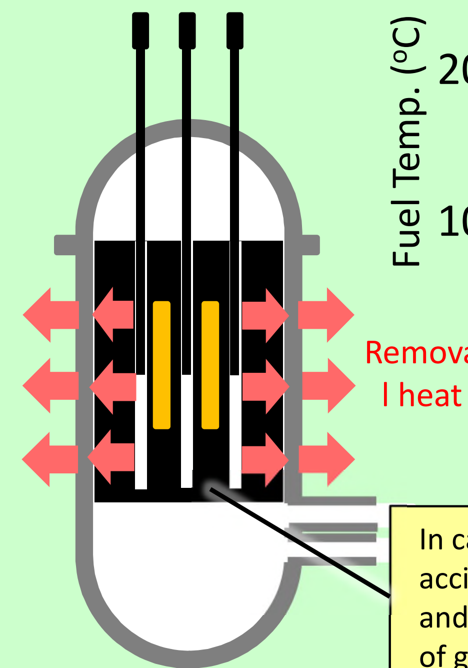
LWR(BWR) Fuel assembly (Approx.13cm x 13cm x 4m)

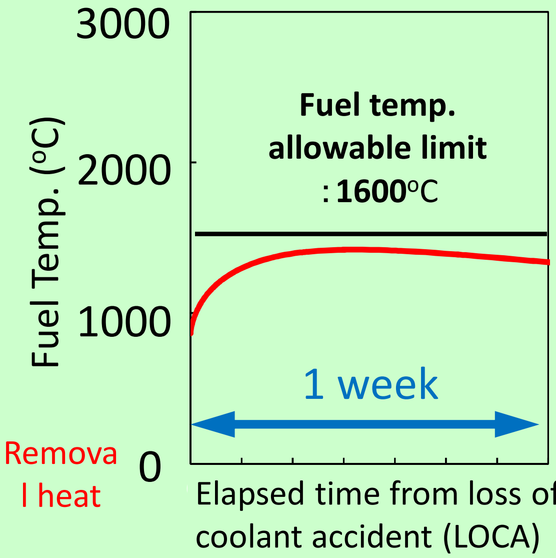
Note: In case of a station blackout for a long time like Fukushima Daiichi nuclear disaster

No fuel melting

Slow and limited temperature transient in accident with graphite moderator

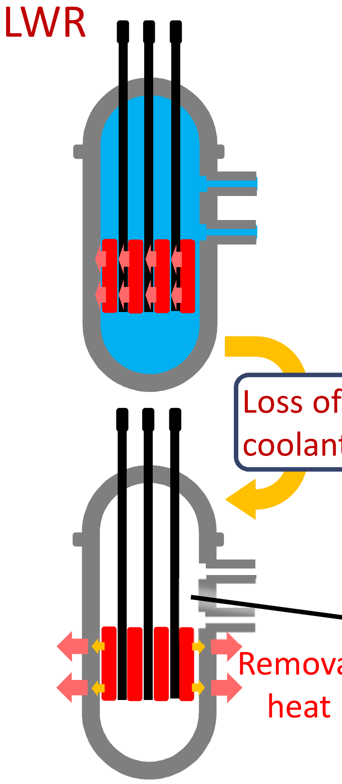
HTGR

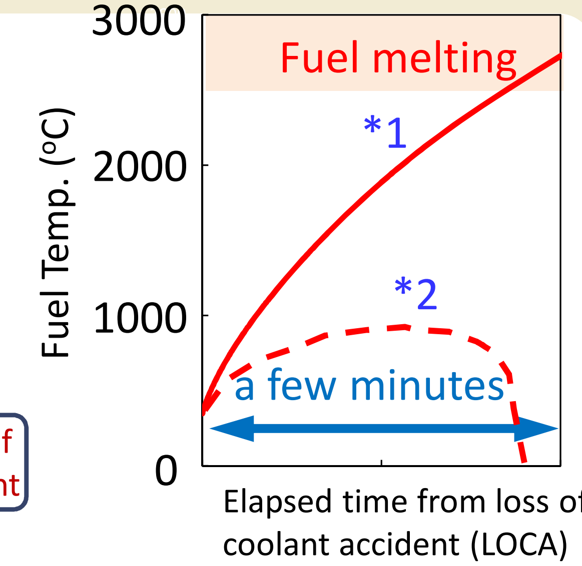




In case of a loss of coolant accident, high heat capacity and large thermal conductivity of graphite absorbs heat.

LWR





Temperature increases rapidly in a short time in case of a loss of coolant accident.

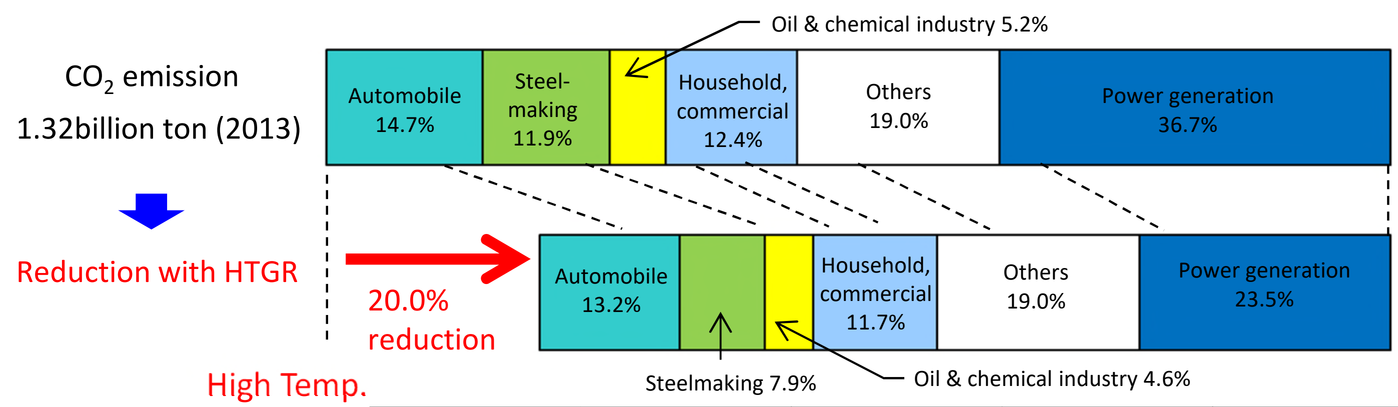
*1 ECCS is inactive (Emergency core cooling system)

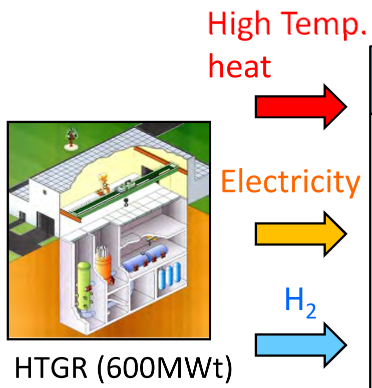
*2 ECCS is active

No immediate accident management is necessary.

Reduction of environmental loads

Contribute to reduce the CO_2 gas emission





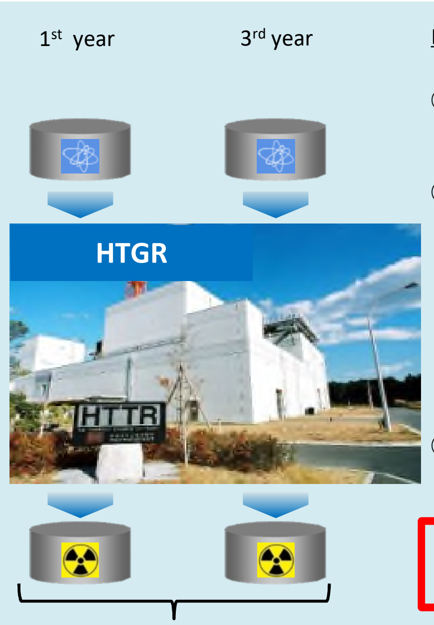
Fuel-cell powered automobile	Steelmaking with H_2 reduction	Oil refinery, chemical plant	Stationary fuel-cell	HTGR power generation
Ref.: Iwatani Corp. website		Ref.: Wikipedia	Ref.: NEDO website	
H_2 (Fuel)	Electricity (EAF*) H_2 (reduction)	High Temp. heat H_2 (raw material)	H_2 (Fuel)	Electricity
1.5% reduction	4.0% reduction	0.6% reduction	0.7% reduction	13.2% reduction
HTGR : 7 Units	HTGR : 8 Units	HTGR : 5 Units	HTGR : 10 Units	HTGR : 27 Units

* EAF = Electric Arc Furnace

1 unit = 4 HTGRs

1/4 of amount of LWRs' waste

● Amount of waste[*1] produced over 4 years operation with 1 million kWe



About 26t (About 13t per a refueling)

Preconditions

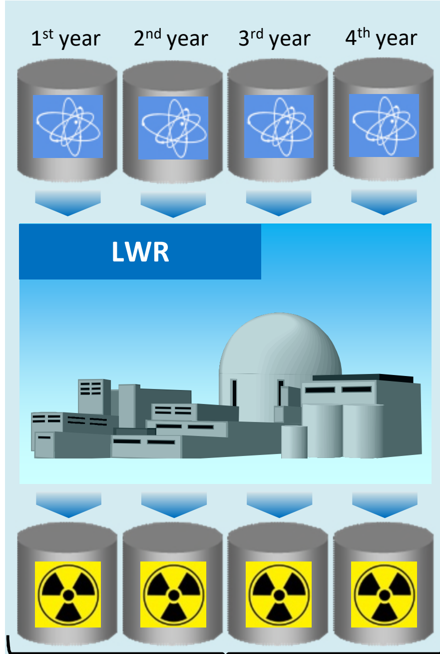
① Fuel (Enrichment: 14%)
Fuel loading: 2 times[*2]

② Burnup: 120GWd/t
(About 3 times of LWR)

High burnup is achievable by ceramics coatings with high heat and irradiation resistance

③ Power generation efficiency: 46%
(About 1.3 times of LWR)

Amount of waste in 4 years is 1/4 of LWR



PWR: About 96t (About 24t per a refueling)
BWR: About 111t (About 28t per a refueling)

Preconditions

① Fuel (Enrichment: 4%)
Fuel loading: 4 times[*3]

② Burnup[*4]
44GWd/t (PWR)
38GWd/t (BWR)

Burnup is determined by irradiation lifetime of cladding tube

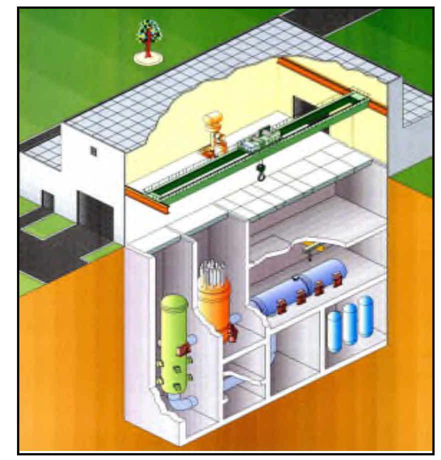
③ Power generation efficiency: 35%

Amount of waste generated in 4 years operation is about 4 times relative to HTGR

[*1] Net (Fission products, transuranic and residual uranium) weight, [*2] Refueling in 730 days, [*3] Refueling in 13 months, [*4] "Behavior o LWR fuel", Nuclear Safety Research Association [In Japanese]

Adaptable for different backend scenarios

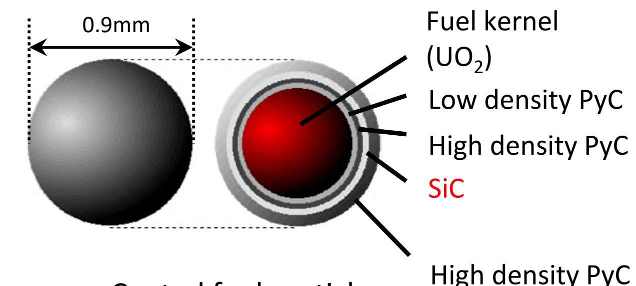
HTGR



Graphite core
Fuel (Fuel compact, Fuel rod)

Direct geological disposal

Excellent chemical stability



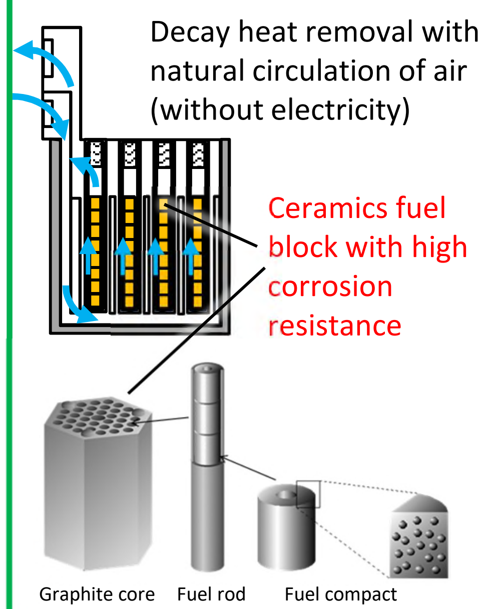
Coated fuel particle

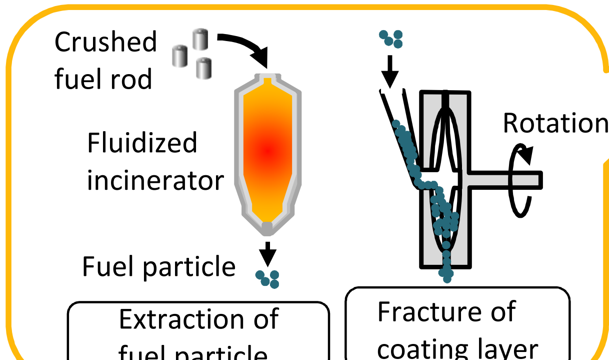
Adaptable for future nuclear politics

Temporary storage

Excellent safety

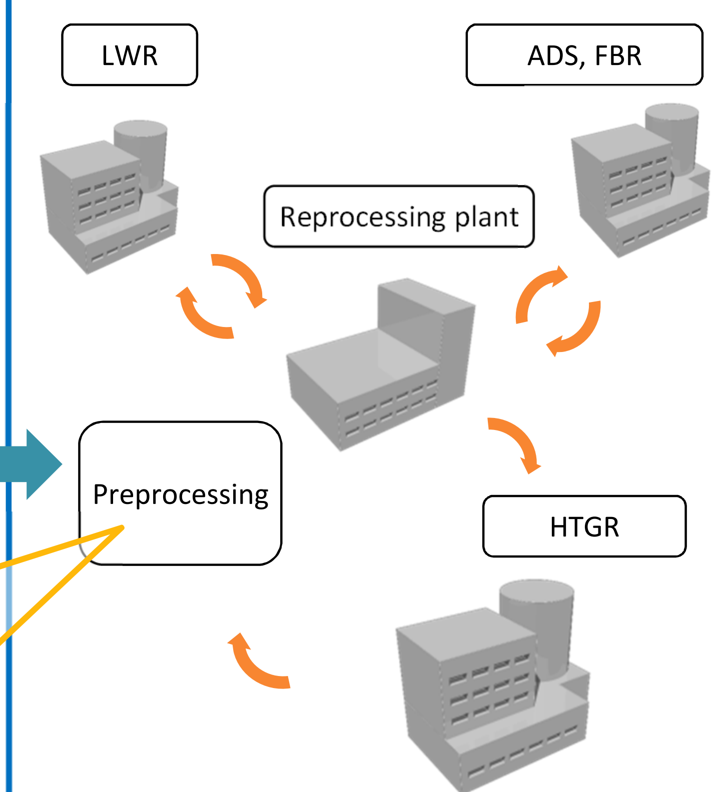
Decay heat removal with natural circulation of air (without electricity)





Connection to current fuel cycle

Adaptable for only addition of basic preprocessing



History of High Temperature engineering Test Reactor (HTTR)

R&D

In-pile Helium loop (OGL-1)

Very High Temperature Reactor Critical Assembly (VHTRC)

Helium Engineering Demonstration Loop (HENDEL)

Research development and design

Construction of Reactor

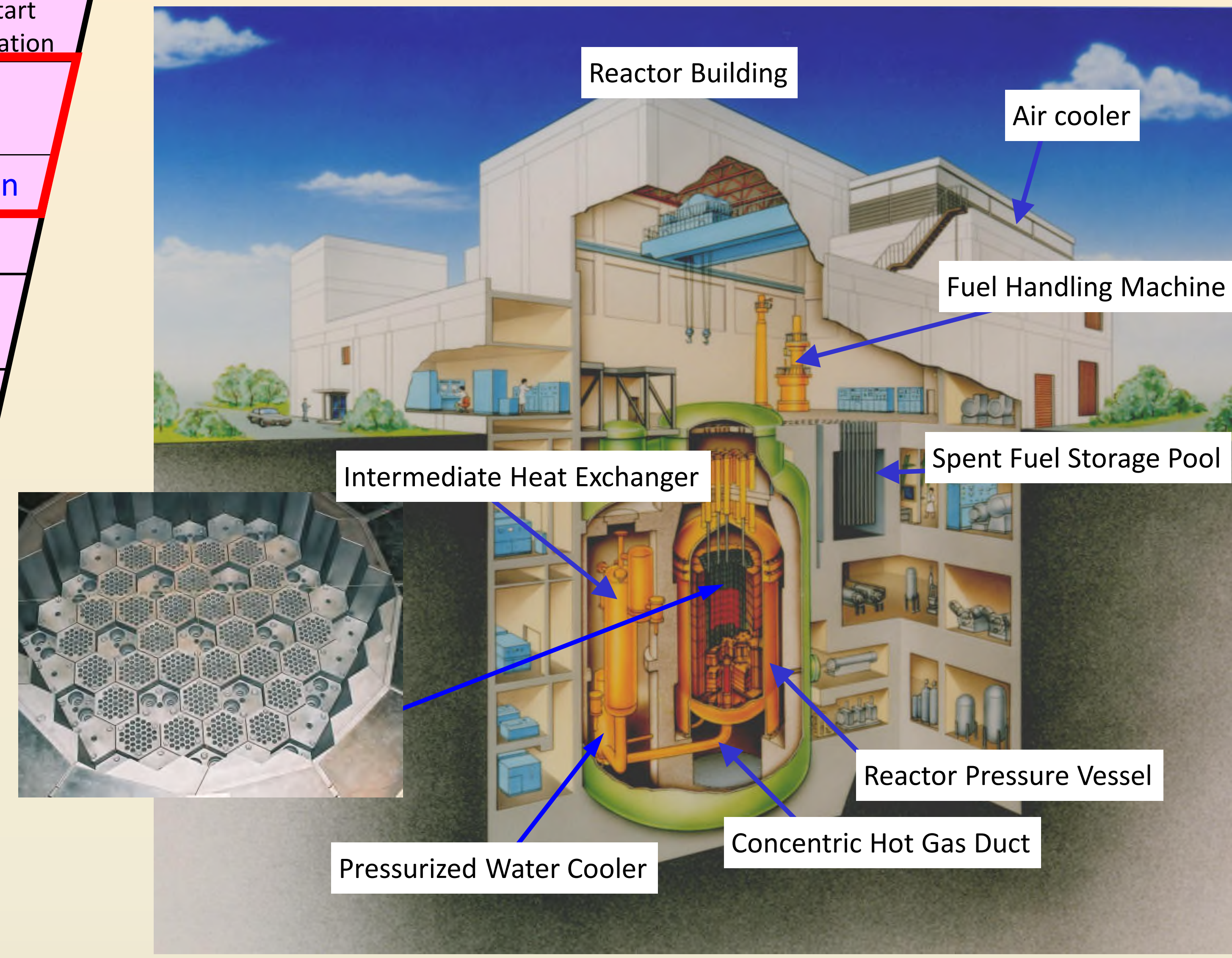
Establishment of fundamental technology

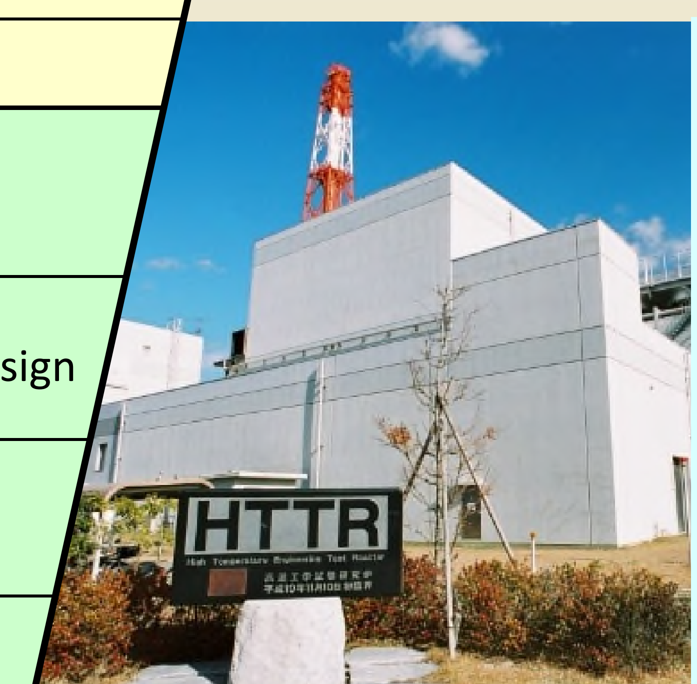
First in the world

Proposal for a prototype of commercial system

∫ 2014	Conformity review on the New Regulatory Requirements start 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
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
	HTTR
1984 ∫ 1981	Basic design
1980 ∫ 1974	System integrity design
1973 ∫ 1969	Conceptual design
	Experimental Multi-Purpose Very High-Temperature Reactor

HTTR





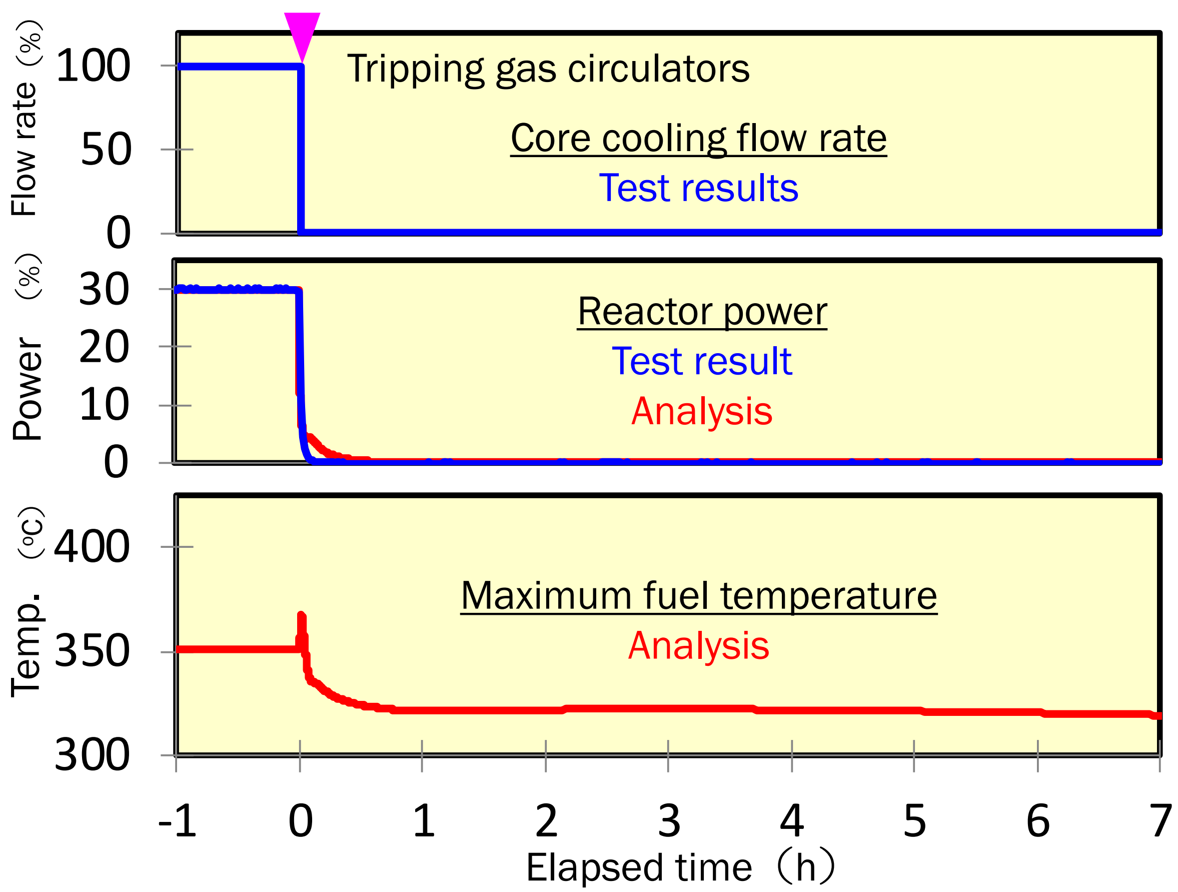
- Reactor thermal power ---------------------------------- 30MWt
- Reactor -- Helium gas
- Reactor inlet/outlet coolant temperature ---------- 395/850,950°C
- Primary coolant pressure ------------------------------- 4MPa
- Reactor material -------------------------------------- Graphite
- Reactor core height/diameter ----------------------- 2.9m/2.3m
- Average power density ---------------------------- 2.5MW/m^3
- Fuel ------------------------------------ UO_2 Coated particle fuel
- Uranium enrichment --------------------- 3~10% (average 6%)
- Fuel element type ---------------------------- Pin in block type
- Reactor Pressure vessel ------------------- Steel (2.25Cr-1Mo)
- Number of main cooling loop ----------------------------------- 1
  (Intermediate Heat Exchanger and Pressurized Water Cooler)

Safety demonstration test

OECD/NEA Project

December 21, 2010

- Reactor power 30%(9MWt)
- Tripping all gas circulators to reduce primary coolant flow rate (reactor core cooling flow rate) to zero.
  → No core cooling!
- No scram operation of reactor (No CR insertion).
  → No core reactivity control!



- Reactor is naturally shut down as soon as the core cooling flow rate is reduced to zero.
  (Scram operation unnecessary)
- Reactor is kept stable long after the loss of core cooling.
  (No fuel damage. No progress into severe accident)

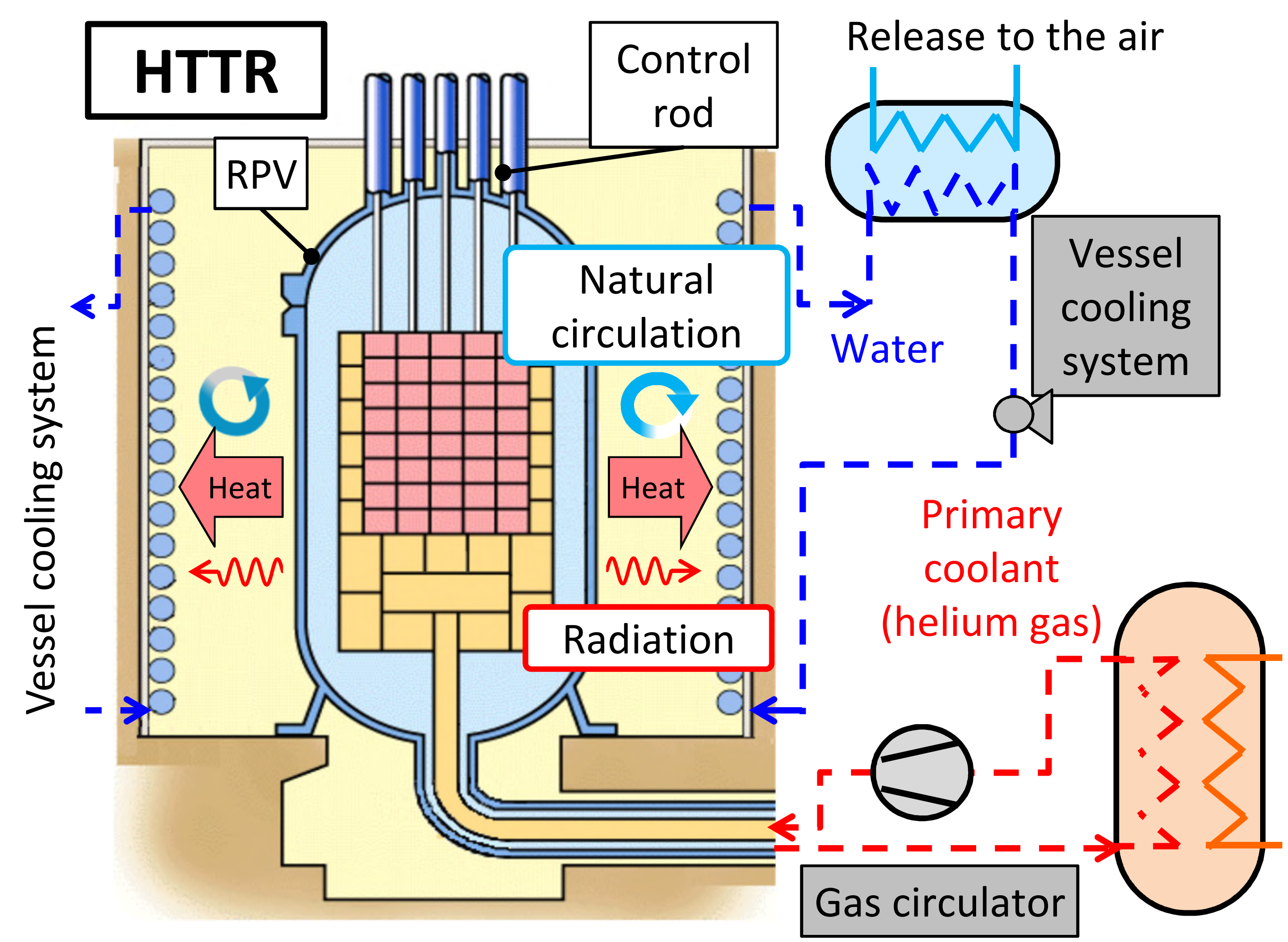
Naturally Safe!

Test plan after restarting HTTR

Toward restart of HTTR

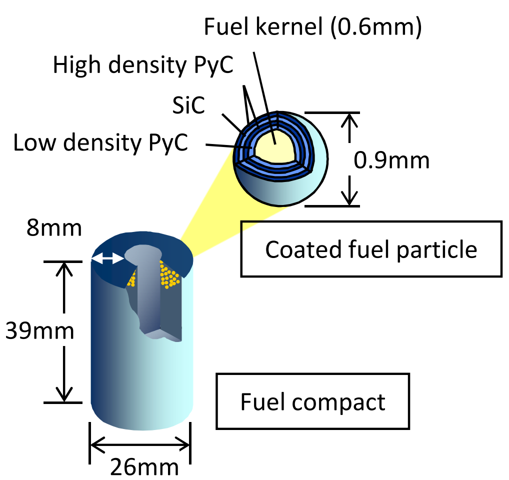
- The official safety review meeting of the application of the HTTR to the NRA to confirm the adjustability to the new regulation standard has been carried out since Nov. 28, 2014, by the Nuclear Regulation Authority (NRA).
- Discussions on main issues such as safety classification, seismic classification, forest fires and internal fires, and BDBA are almost completed.
- Discussions are being carried out for the design seismic motion, which is delayed from the expected schedule at the time of application.

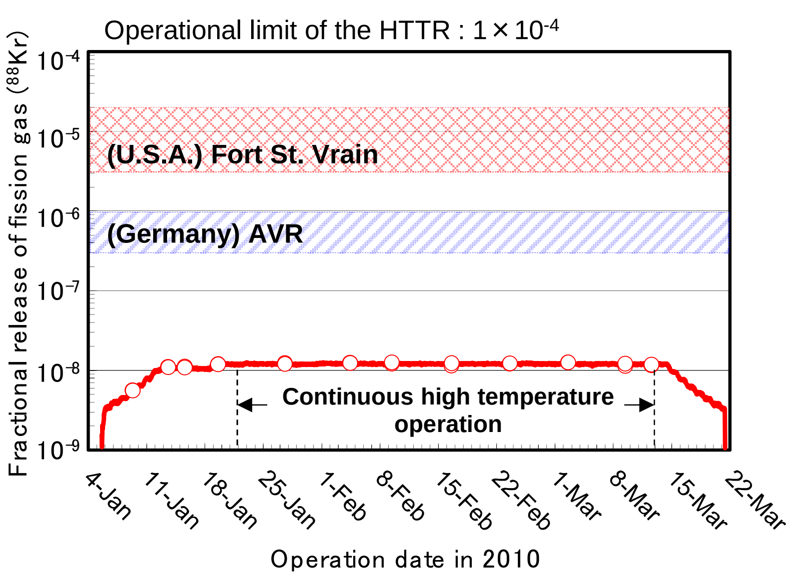
- Implementation of loss of forced cooling test simulating station blackout after restarting HTTR
- Test condition
  - ✓ Reactor power: 30% (9MWt)
  - ✓ Gas circulators stopping, Vessel cooling system stopping, No insertion of control rods



The most advanced HTGR technologies developed in Japan

Fuel Coating Technology





Purpose : High temperature strength of the ceramics coating layers to retain fission products inside the coated fuel particle

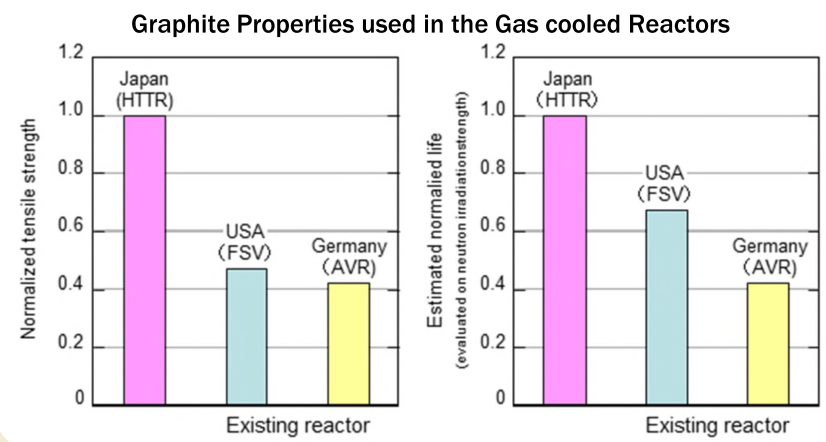
Method : The chemical vapor deposition technology used to coat four layers of ultrathin ceramics at once on the particles fluidized by gas to minimize coating failures

Results : During the continuous high temperature operation at 950ºC reactor outlet coolant temperature for 50 days, fractional release of the fission gas (^{88}Kr) was demonstrated to be 4 orders of magnitude less than the operational limit, and 2-3 orders less than those of the HTGRs operated in Germany and U.S.A.

⇒Contribute to less radioactive contamination to equipment and less radiation exposure to personnel

Graphite Material Technology

Graphite Core Component in HTTR



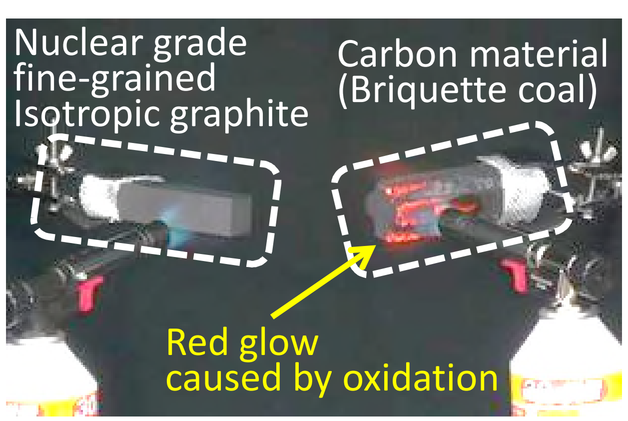
Purpose : High strength and thermal conductivity, isotropic material

Method : Application of fine-grained and isotropic graphite material using cold isotropic pressing process

Result : Domestically made fine-grained and isotropic graphite yields longer service life because of its superior strength and irradiation resistance to those of other graphite materials made elsewhere in the world (e.g. Germany and USA).

⇒Break-proof performance and highly reliable seismic resistance. Adopted for HTR-PM construction in China .

Safety Technology



Appearance of nuclear grade fine-grained isotropic graphite and carbon material during burner heating

Purpose : Inhibition of graphite component oxidation during accident

Method : Development of nuclear grade fine-grained isotropic graphite

Results : Dense and few internal pores. Impurity which catalyzes the oxidation (burning) is extremely low.

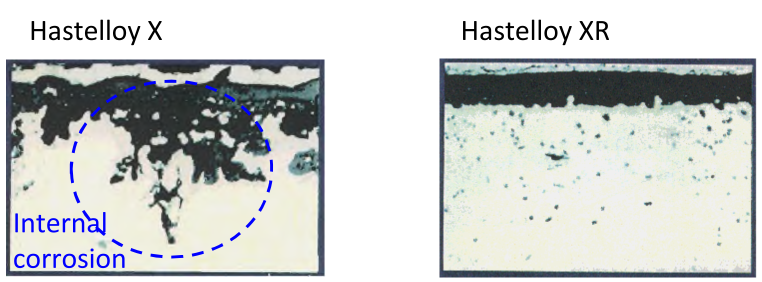
⇒ Oxidation-retardant (flame-retardant) even if the high temperature condition happens during air ingress accident.

Metallic Material Technology

Purpose : Extreme heat and corrosion resistance in high temperature

Method : Optimization of chemical composition of Si, Mn, Al, Co, and B based on Hastelloy X

Intermediate Heat Exchanger



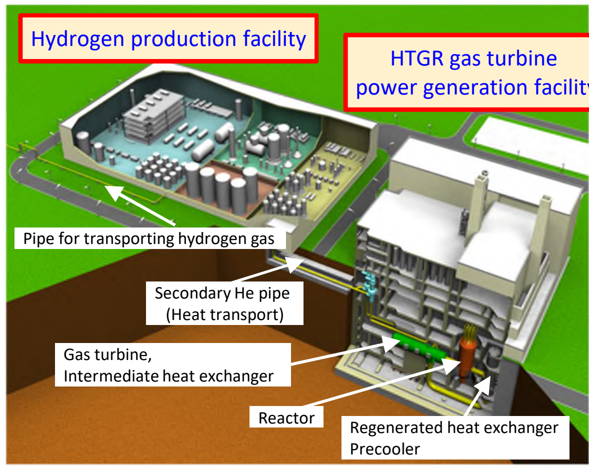
Cross-section photo after 1000℃ 10000hr corrosion test

Result : Hastelloy XR is demonstrated to be free of corrosion in the HTGR helium environment

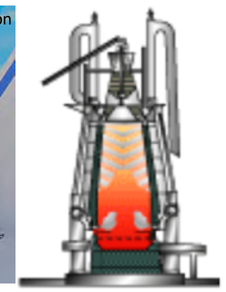
⇒Used to construct the intermediate heat exchanger of the HTTR. High temperature reactor outlet helium gas of 950ºC was attained

Various types of commercial HTGR systems

Hydrogen production system



Hydrogen

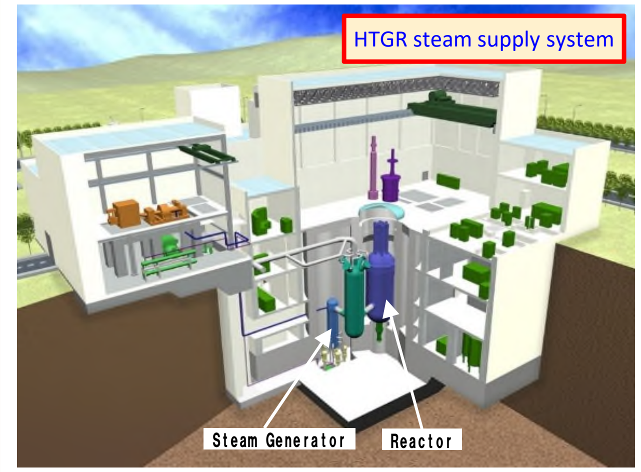


Fuel cell vehicles Steelmaking

- Thermo-chemical water splitting process (IS process)
  - ✓ Hydrogen production[*1]: 7.6ton/hr (85,000Nm^3/hr)[*2] for hydrogen production only, 2.8/6.2ton/hr (32,000/70,000Nm^3/hr)[*3,4] for cogeneration
- Steam methane reforming process for hydrogen production

*1: IS process. *2: J. Iwatsuki et al., JAEA-Review 2014-037 (2014).
*3: S. Kasahara et al.,Nucl. Eng. Des., Vol.239 (2018). *4: X. Yan et al., Nuclear Production of Hydrogen, OECD (2006).

High temperature steam for industry



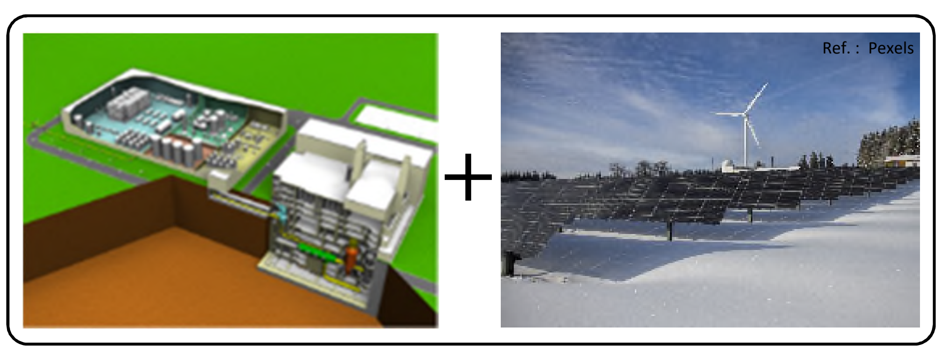
Process heat

Electricity

Chemical plant

- Process heat : Supplied to chemical plant, petroleum refining plant, etc.
- Power : Produced by steam turbine

Hybrid system with renewable energy

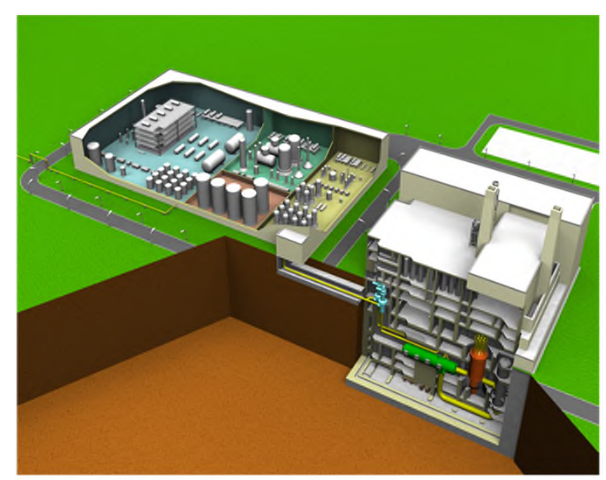


Constant power to grid

Hydrogen production

- Renewable power variation : Absorbed by HTGR power and additional hydrogen cogeneration
  - ✓ Long period (hour〜day) : Absorb up to 200MWe power variation, 25%〜100% of reactor output in 5%/min
  - ✓ Short period (sec〜min) : Absorb up to 50MWe variation
- Adjust electricity production according to renewable power variation with high electricity production efficiency

Multipurpose cogeneration



Hydrogen, Desalination

Electricity

Hydrogen town

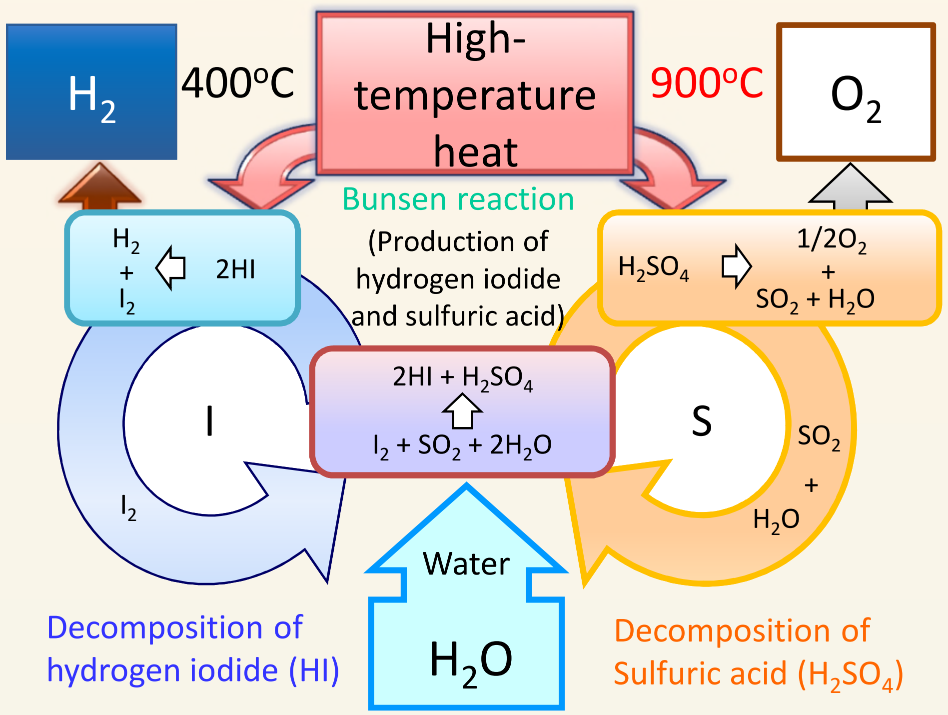
- Cogeneration : Hydrogen production, desalination, electricity production
- 50% of electricity production efficiency (produced by gas turbine), achieve 80% of heat utilization rate

Hydrogen production technology (IS process) development

Reaction scheme and features

- Thermal decomposition of water requires heat above 4000°C .
- IS process decomposes water with heat of ca. 900°C using chemical reactions of iodine (I) and sulfur (S).

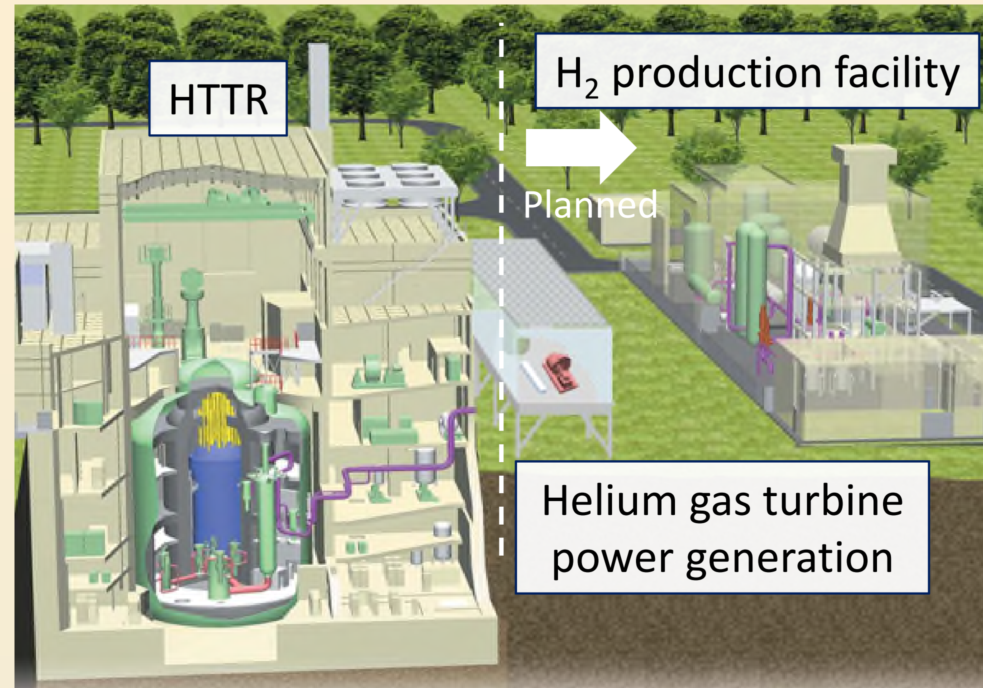
Iodine and sulfur circulate in the process. ⇒ No harmful waste
HTGR heat is used. ⇒ No CO_2 emission



Decomposition of Sulfuric acid
- H_2SO_4 is concentrated and vaporized.
- The H_2SO_4 is decomposed into SO_2, H_2O and O_2.

Decomposition of hydrogen iodide (HI)
- HI is concentrated and vaporized.
- The HI gas is decomposed into I_2 and H_2.

Bunsen reaction
- HI and H_2SO_4 are produced from I_2, SO_2, and H_2O.



Commercial use

Technology transfer to private company

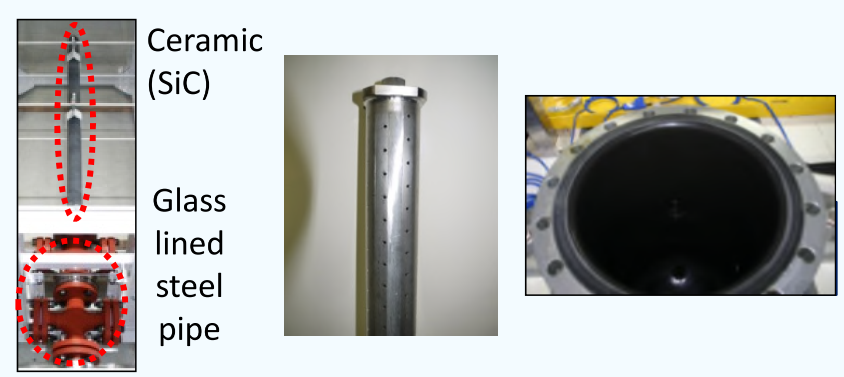
HTTR-GT/H_2 test

Continuous H_2 production for 150 hours ($0.03\ m^3/h$, Jan. 2019)

Present

Industrial material component test (2010-)

- **Integrity of components / operation stability**
- **Plant operation control system**



H_2SO_4 decomposer Ceramic (SiC) (<900°C)
HI decomposer Ni-base alloy (<500°C)
Bunsen reactor Fluoro-plastic lined steel (<100°C)

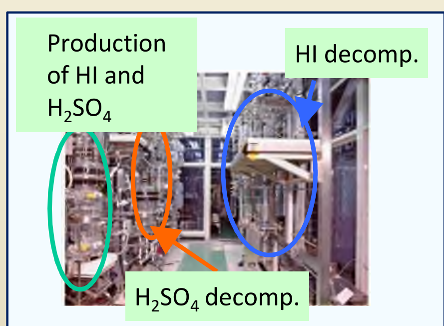
Verification of integrity of key components in the IS process environment (corrosion resistance, heat resistance)

H_2 production test facility ($0.1\ m^3/h$)

- Verification of integrity of total components and stability of hydrogen production
- Development of strength evaluation methodology for ceramic components
- Plant operation control system
  Plant maintenance techniques
- Membrane technologies to improve thermal efficiency

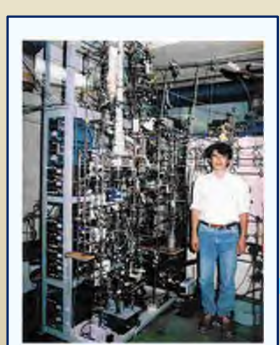
Elemental technologies (2005-2009)

- Component technology development



Bench-scale test (1999-2004)

Demonstration of one-week continuous hydrogen production by glass apparatus ($0.03\ m^3/h$-H_2)



Lab-scale test (1997)

Finding a closed-cycle continuous operation condition ($0.001\ m^3/h$-H_2)

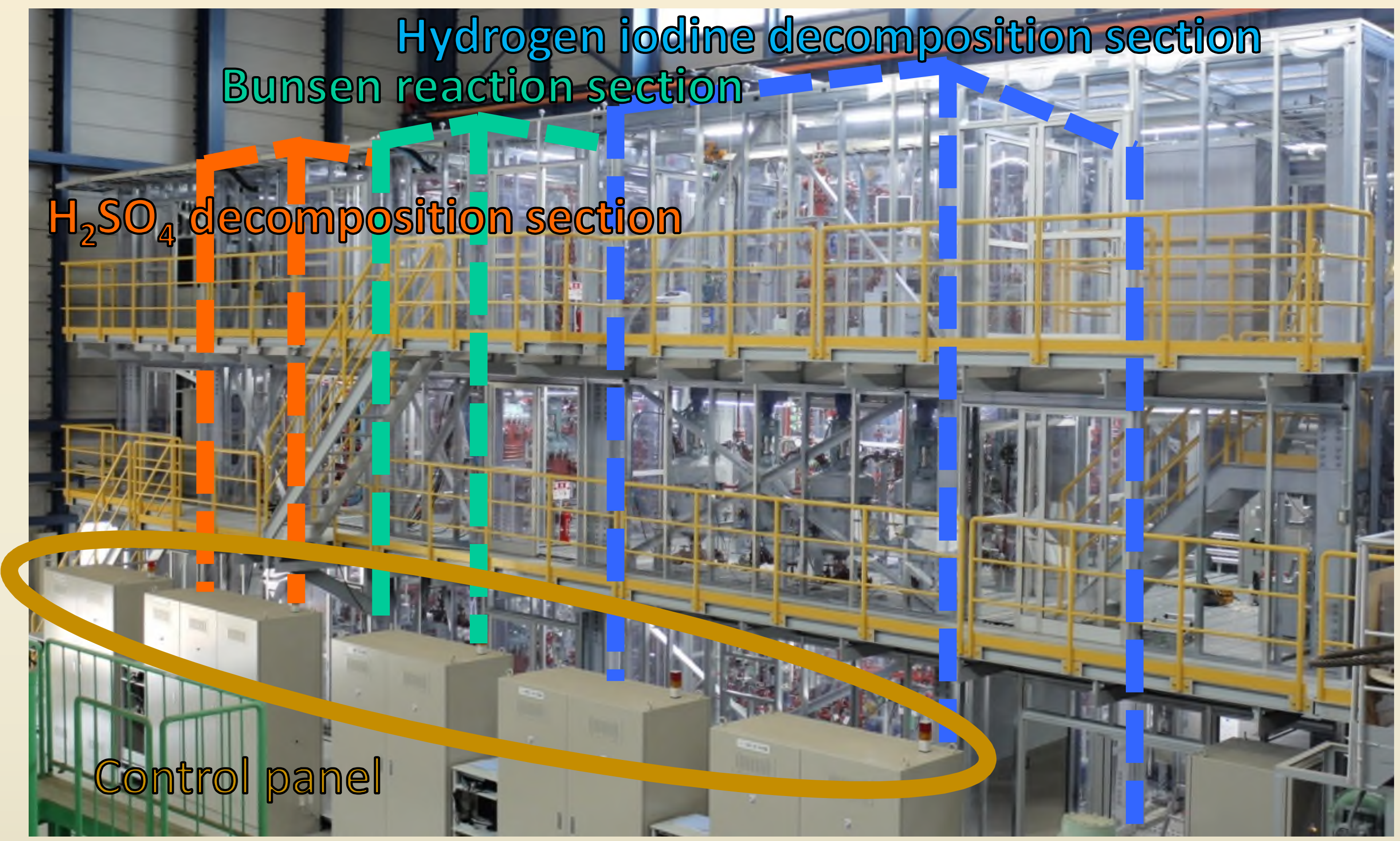
Hydrogen production test using a facility made of industrial materials

purpose

- Verification of integrity of total process components by a Hydrogen production test facility made of industrial materials

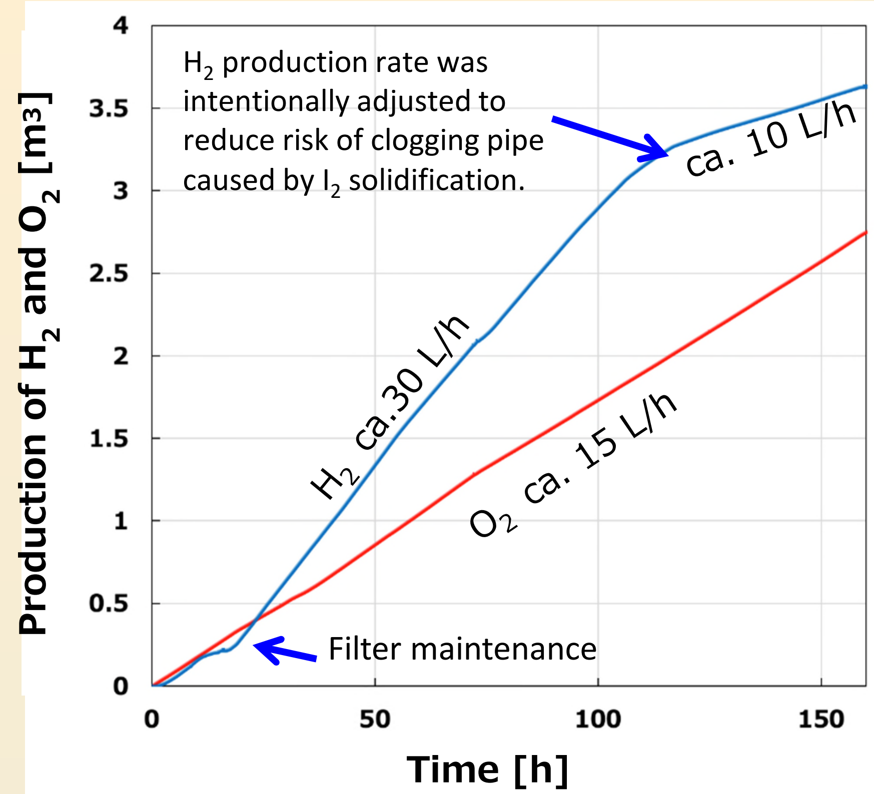
subjects

- Construction of the Hydrogen production test facility by using accumulated IS process key technologies
- Establishment of reliability of the total plant system and investigation of continuous hydrogen production performance by continuous hydrogen production tests
- Examination of operation control in start-up and shut-down assuming connection with HTTR



- Facility specification
  - Temperature: 950ºC (Max)
  - Hydrogen production capacity: 0.1 m^3/h (Rating)
  - Heating by electric heater
- Component materials
  - <liquid phase>
    - Fluoro-plastic lined steel
    - Glass lined steel
    - Ceramic (SiC)
  - <gas phase>
    - Ni-base alloy (Hastelloy C-276)
    - SUS316

～FY2015	FY2016～FY2019	FY2020～
• Operation tests of each section • Three sections integration	• Hydrogen production tests (Operation procedure and control, stable operation) • Dismantling inspection	• Automatic plant operation system



Result of operation for 3 sections integration

status

✓ H_2 was successfully produced for 150 hours by the facility made of industrial materials.

✓ Measures for technical issues previously point outed (prevention of leakage etc.) and a operation procedure to integrate 3 chemical processing sections were verified.

✓ One of important challenges is to maintain I_2 concentration in circulating solution.

Hydrogen production cost using HTGR

- Hydrogen production costs by domestic production using various energy sources were estimated.

➢ Fossil fuel (Town gas, Bunker A, LPG, Naphtha) reforming

➢ Byproduct hydrogen : Caustic soda, coke oven gas

➢ **Nuclear: IS process using heat from HTGR**

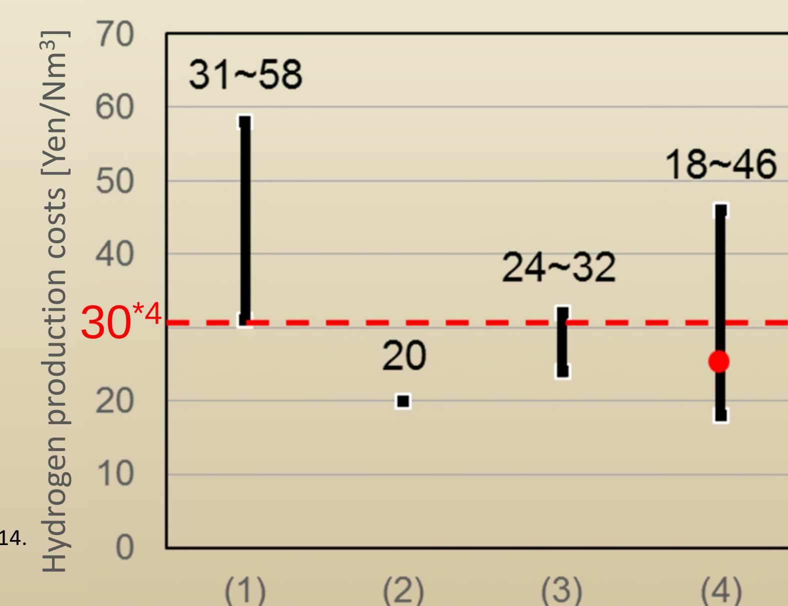
Evaluation target[*1]

(1) Fossil fuel reforming[*2]

(2) Byproduct hydrogen (Caustic soda)

(3) Byproduct hydrogen (Coke oven gas)

(4) IS process by HTGR heat[*3]

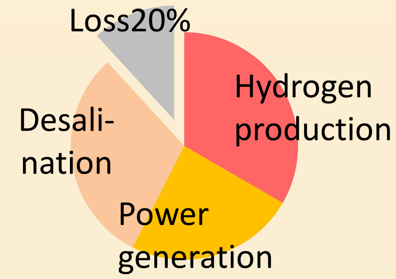


*1：Hydrogen and fuel cell strategy conference working group (5th)- handout, Agency for Natural Resources and energy, April 14th, 2014.
*2：The cost of equipment of the reformer is not included.
*3：JAEA estimation
*4：Target cost in the second half of 2020's (METI, Strategic Road Map for Hydrogen and Fuel Cells, March 22nd, 2016.)

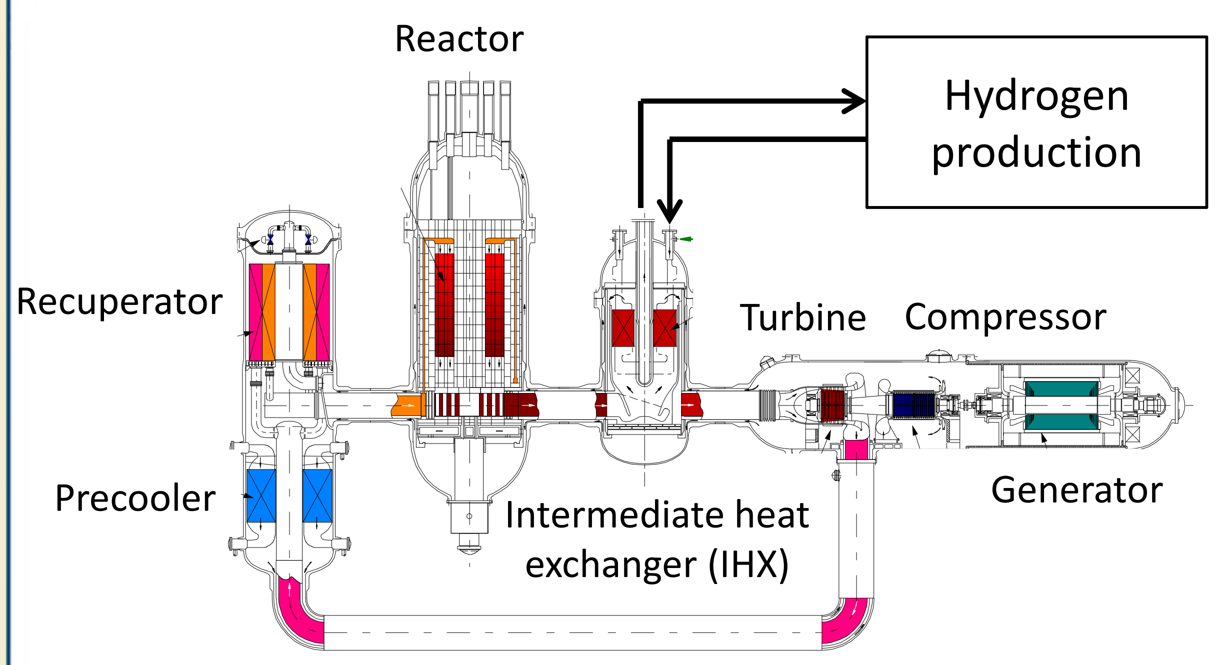
Helium gas turbine technology development

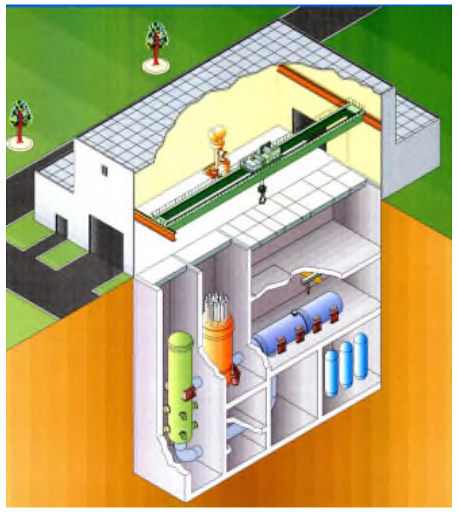
Helium gas turbine features

- Power generation with 50% efficiency owing to its high temperature
- Inland installation without needing cooling water
- Utilization of 80% reactor heat through a cascaded cogeneration system of hydrogen production, power generation and desalination



Practical use



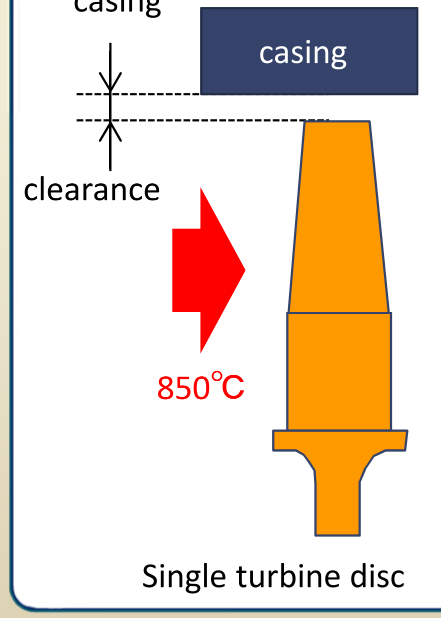


Construction of commercial demonstration plant

- 950°C reactor outlet temperature:
- 250 MWt reactor thermal power
- Demonstration of commercial plant system
  - ✓ Hydrogen production
  - ✓ Gas turbine power generation
  - ✓ Hydrogen steelmaking
  - ✓ Hybrid system with renewable energy, etc.

Hot function test of full-size turbine disc at high temperature

- Confirmation of clearance between turbine disc and casing



Technology transfer to private company

HTTR-GT/H_2 design, construction and operation

GTHTR300 basic design and component development (2001-)

Collaborative work with Mitsubishi Heavy Industries

- Completed plant basic design, safety design, and cost estimation
- Developed high-efficiency helium compressor, compact heat exchanger, etc.
- Development of turbine blade alloy

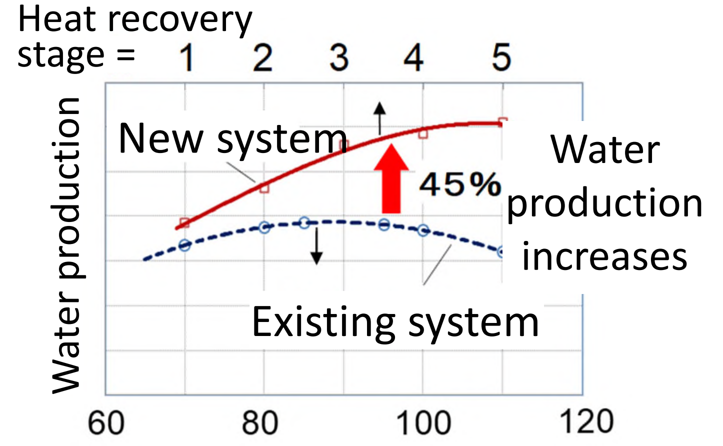
World's first successfully operated highly-efficient axial helium compressor and validated helium compressor design method

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

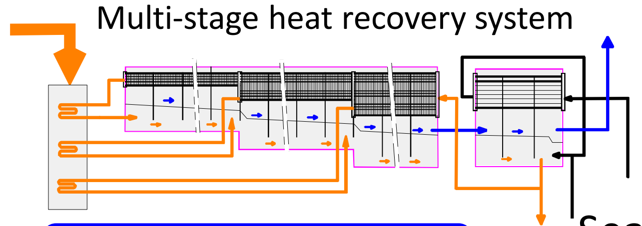
Application of HTGR - Desalination -

Enhanced performance

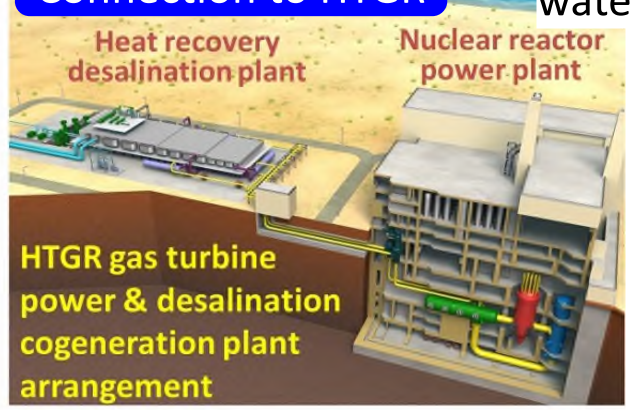
- Maximization of gas turbine heat recovery
- Reduction of more than 30% of water production cost
- Mitigation of world water shortage



New desalination system



Connection to HTGR

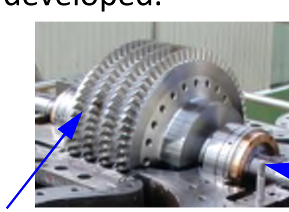


Establishment of aerodynamic design approach for helium gas turbine system

Test loop

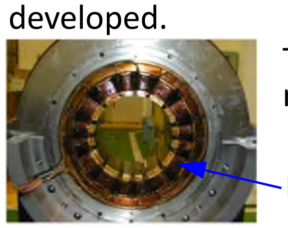
1/3 scale model of compressor

A compressor for gas turbine system circulating helium gas in high efficiency was developed.



Magnet bearing

A bearing supporting the rotary shaft of turbine, compressor, etc. without grease was developed.

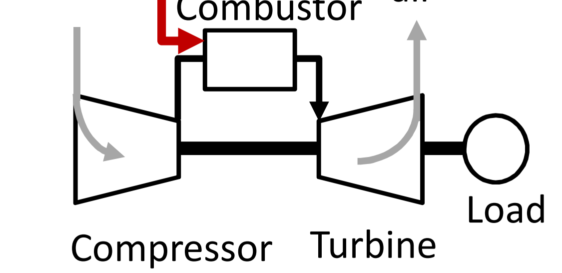


- Test condition

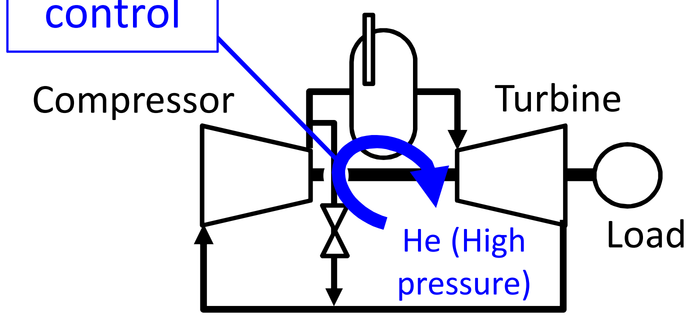
Scale	1/3 of actual size
Fluid	Helium gas
Flow rate	12 kg/s

HTTR-GT/H_2 test

- **Adjusting fuel supply for load control by combustion gas turbine is not available to nuclear-heated helium gas turbine.**



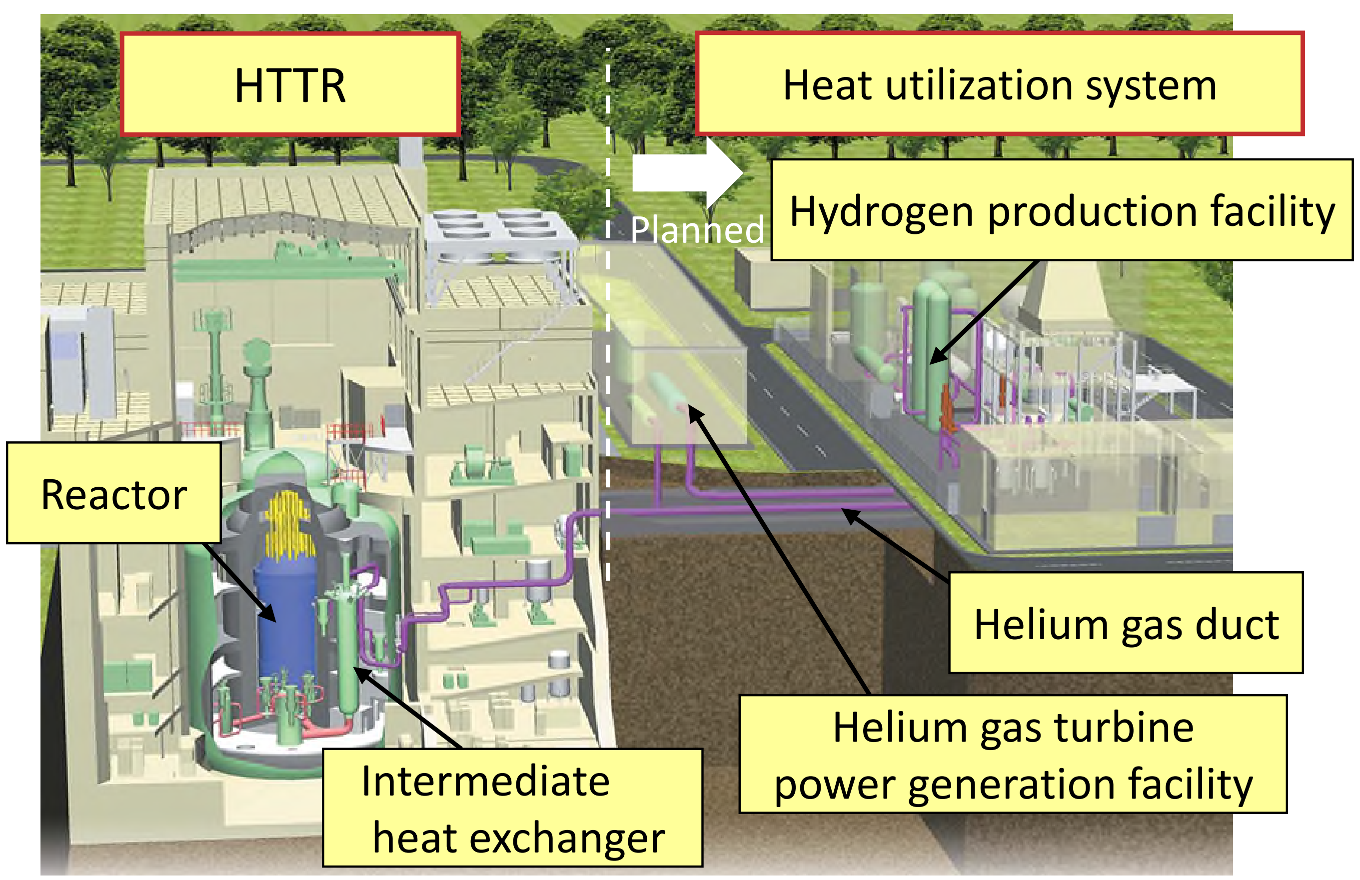
Combustion gas turbine



Helium gas turbine

A method for stable operation by system pressure control should be established

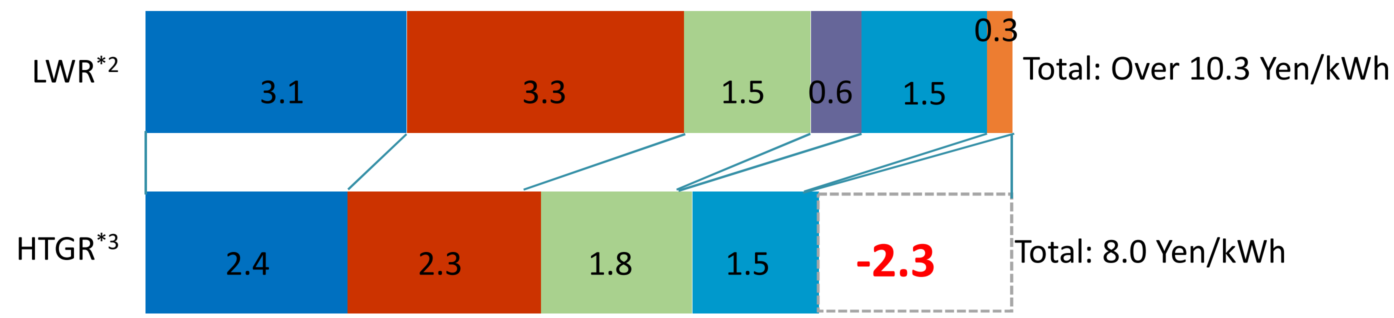
Validation of the control method by HTTR-GT/H2 tests



HTTR-GT/H_2 test facility (Planned)

HTGR's lower power generation cost than LWR

● Comparison of power generation cost[*1]



By fully utilizing advantage of HTGR of high thermal efficiency, high performance of radioactive material confinement and excellent inherent safety features,

- **Costs of management for accident risks and additional safety measures are not needed.**
- **Capital, operating and maintenance costs are lower.**

*1 In case, the HTGR was used only for power generation

*2 "Report on the Power Generation Cost for Subcommittee of Long-term Energy Supply and Demand Outlook," the Power Generation Cost Verification Working Group, Subcommittee of Long-term Energy Supply and Demand Outlook, Agency for Natural Resources and Energy (May 26th, 2015)

*3 Approximation based on M. Takei, et. al., "Economical Evaluation on Gas Turbine High Temperature Reactor 300," Transactions of the Atomic Energy Society of Japan, 5(2), pp.109-117 (2006).

Capital cost (−0.7 Yen/kWh)

The cost is lower owing to fewer number of facilities by small number of water and steam system facilities and higher thermal efficiency of the plant.

Operation and maintenance cost (−1.0 Yen/kWh)

The cost is lower owing to fewer number of facilities needed to be maintained and operated.

Fuel cycle cost (+0.3 Yen/kWh)

The cost increases owing to the more fuel production cost for complex fuel element with high retention performance of fission products.

Cost of additional safety measures (−0.6 Yen/kWh)

Emergency safety measures, emergency power generation facilities, reliability assurance of external power supply, measures for severe accidents, etc. are eliminated owing to the inherent safety design.

Expenses related to policy measures

The cost is not changed for siting, disaster prevention, public relations, development of human resources, assessment and investigation, development of current/future technology for power generation, etc.

Management cost for accident risks (−0.3 Yen/kWh)

Compensation for damage, decommissioning of accident reactor, decontamination, etc. are eliminated owing to the inherent safety design.

Milestones for commercialization

2019 — Short term — 2030 — Middle term — 2050

【HTGR technology】

R&D of core technology
- **Fuel and graphite**
- **heat and corrosion resistant super alloy**
- **Helium handling**

→ **High burn-up fuel, high power density**

HTGR for 950°C heat utilization (Hydrogen, gas turbine power generation) → **Modification of standard design**

HTGR for 750°C heat utilization (Steam, steam turbine power generation) → **Establishment of steam system technology, high core performance and safety enhancement** → **Use of reactors in oversea countries**

HTTR test → **Demonstration test of safety/Acquisition of long term operation data** → **HTTR-GT/H_2 test**

【H_2 production technology】

Fundamental engineering test

Component technology development

Integrity verification test

→ **Reliability and technology assurance test** → **Establishment of automatic control system**

Construction of a demonstration plant by private companies

(∼950℃, ∼250MWt)
Demonstration of commercial plant system
- Hydrogen production
- Gas turbine power generation
- Hydrogen steelmaking
- Hybrid system with renewable energy

→ **Construction of commercial plant for 950℃ heat utilization**

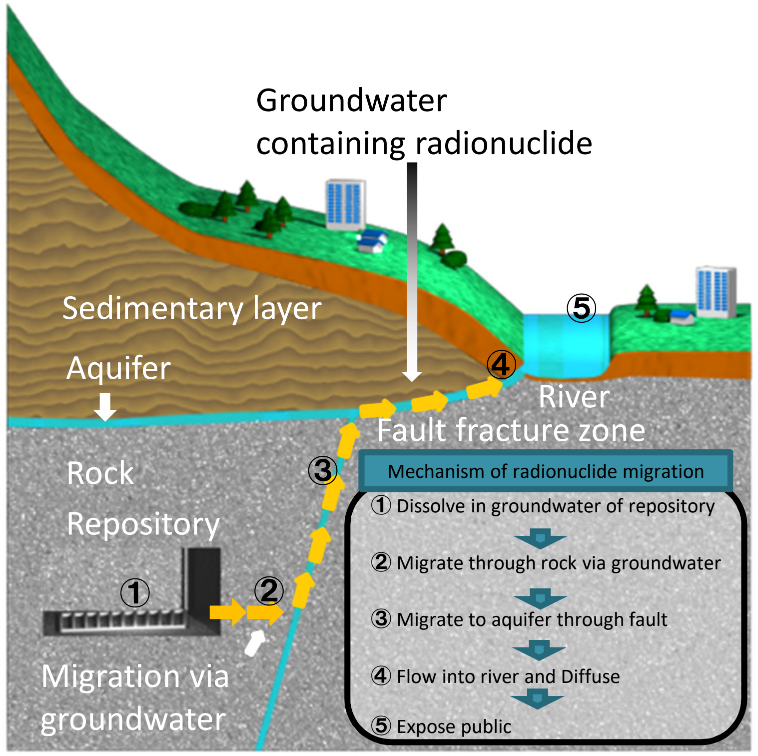
Commercial HTGR: GTHTR300C
(∼950℃、∼600MWt)
Available for various heat utilization in future
- Hydrogen production, gas turbine power generation, desalination, etc.
- Harmony with renewable energy
- Compatibility to nuclear fuel cycle, energy mix with fast reactor, etc.

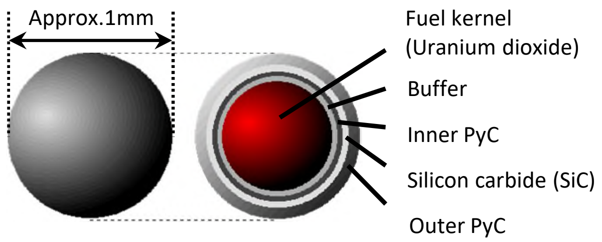
Construction of commercial plant for 750℃ heat utilization

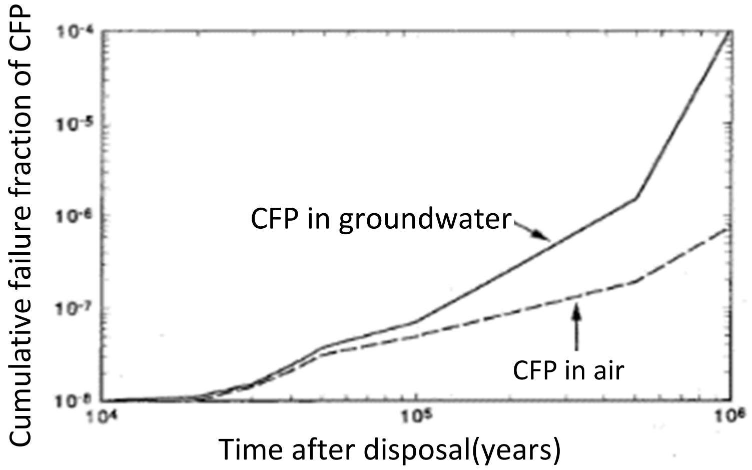
(∼750℃、∼200MWt)
Early introduction, available for various heat utilization in current society
- Steam utilization, steam turbine power generation, district heating, etc.

Disposal of Spent Fuel (Direct Disposal)

Public exposure by leaked radionuclide from geological repository should be lower (100-300μSv/year) than the exposure from nature (900-1,200μSv/year)







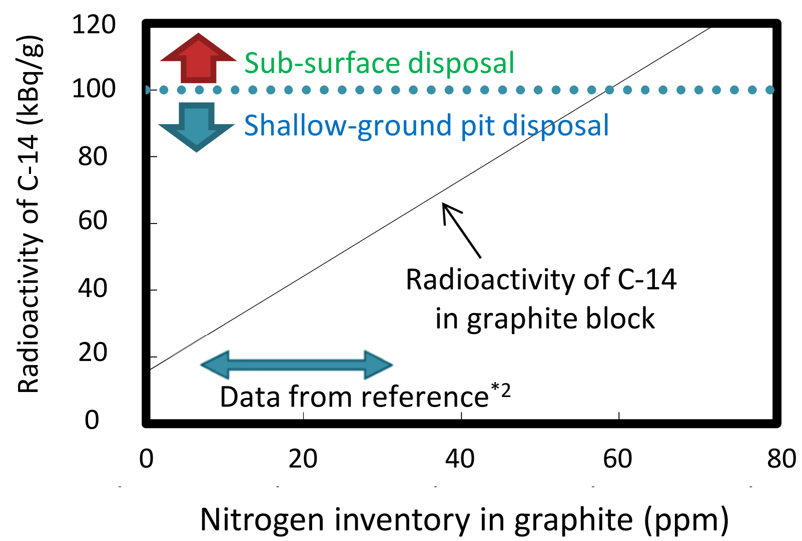
- Failure fraction of Coated Fuel Particles(CFP) increases year by year by increase of inner pressure because of helium gas generation, which is generated by α-decay (α-ray is the nucleus of helium)
- More strictly on the groundwater environment, because of corrosion of SiC layer.
- Even in the geological repository filed with groundwater, the failure fraction of CFP in spent fuels is approximately 10^{-4} after one million years due to the outstanding durability. *1
- Metallic coverpack, contains high level waste (vitrified waste), can prevent the contact with groundwater about one thousand years.*2
- The spent fuel from HTGR can reduce public exposure by preventing the dissolution of radionuclides in groundwater for several hundred thousand years.

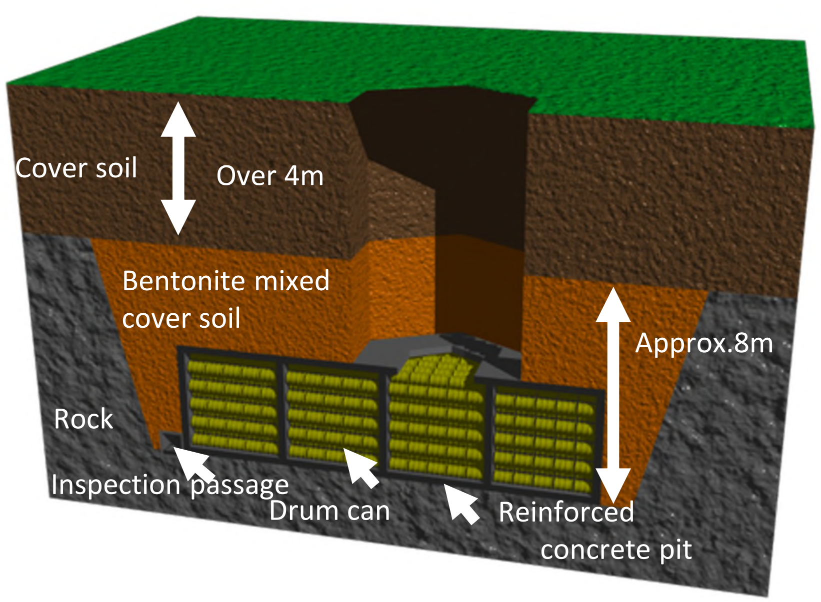
*1 Deep-Burn: making nuclear waste transmutation practical, NED 222 (2003).
*2 Second Progress Report on Research and Development for the Geological Disposal of HLW in Japan, JNC TN1410 2000-001.

Disposal of Graphite

- Volume of graphite waste from one unit of commercial HTGR for the lifetime of 60 years is equivalent to approximately two 50m swimming pools (50m*20m*1.5m).
- Disposal methods for graphite waste will be selected shallow-ground pit disposal or sub-surface disposal on the basis of the radioactivity mainly from C-14, which have a half life of 5,730 years and is generated from nitrogen.
- The site for waste disposal can be utilize for the general public after the monitoring term of 300 years.

Type of Reactor	Commercial HTGR
Number of disposed graphite blocks (#/4 years)*1	1,344
Volume of disposed graphite blocks (m^3/4 years)	205
Lifetime (year)	60
Volume of graphite waste for 60 years(m^3)	3080
Volume of 50m swimming pool (m^3) (50m x 20m x 1.5m)	1500





The waste packages contained in concrete pit are solidified by cement.*3 The pit is surrounded by clay to prevent the intrusion of groundwater.*3

*1 JAEA-Technology 2008-007
*2 JAERI-Review 2002-034
*3 Web page of Agency for Natural Resources and Energy http://www.enecho.meti.go.jp/

Status of International Cooperation in HTGR R&D

Multilateral collaboration

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%

NI2050

- Cooperation related to HTGR cogeneration

IAEA

China, France, Germany, Indonesia, Holland, Kazakhstan, Korea, Russia, South Africa, Switzer-land, Turkey, Ukraine, United Kingdom, USA

Technical Working Group on Gas Cooled Reactors (TWG-GCR)

Technical Working Group on Small Modular Reactors (TWG-SMR)

Coordinated Research Project (CRP)

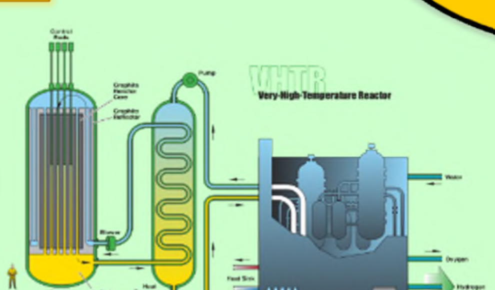
- Evaluation of Nuclear Hydrogen Production Technologies and Prospectus for Deployment
- Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for Emergency Planning Zone for Small Modular Reactor Development

Generation IV International Forum (GIF)

Canada, China, France, Korea, Switzer-land, USA, EU, Australia

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

- 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 collaboration

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)

Poland

- Information exchange based on public information under “Action Plan for the Implementation of the Strategic Partnership between Japan and the Republic of Poland (2017-2020)” (National Centre for Nuclear Research: NCBJ)

United Kingdom

- Cooperation to U-Battery project (Commercial HTGR system) (URENCO, etc.)

China

(Tsinghua University, Institute of Nuclear and New Energy Technology: INET)

Korea

(Korea Atomic Energy Institute: KAERI)

Indonesia

(Badan Tenaga Nuklir Nasional: BATAN)

- Information exchange

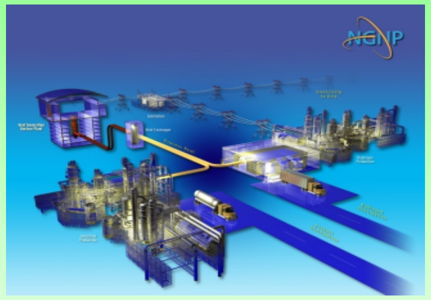
Kazakhstan

- Design collaboration for pre-FS of HTGR (National Nuclear Center: NNC)
- High burn-up fuel research (Institute of Nuclear Physics: INP)
- Oxidation-resistant graphite research (Al-Farabi Kazakh National University: KazNU, INP)
- Safety research (Nuclear Technology Safety Center: NTSC)

Research and Development in the World

United States of America

■ NGNP : Next Generation Nuclear Plant
Authorized by the Energy Policy Act of 2005 (EPACT2005)
DOE selected VHTR
Electric power / Hydrogen production
(350–600MWt, 750°C)
2011 Completion of Phase 1 (conceptual design)
Postponement of Phase 2 (detailed design & construction)
Continuation of R&D program



NGNP（HTGR）Concept
Electric power generation,
process heat supply（750°C）

High-temperature
electrolysis facility
(INL)

■ Xe-100 : High temperature gas-cooled pebble bed modular reactor
(200MWt, 750°C, Electric power generation, Design stage)
2017 Conceptual Design started

Poland

■ Research HTGR (10-30 MWt, 750°C)
■ Practical HTGR (-165 MWt, 750°C)
for heat supply to industries

United Kingdom

■ U-Battery
(Cogeneration commercial reactor)
10MWt x2, 750°C (4MWe x2)
2024 Start of operation(target schedule)

China

■HTR-10 :Test reactor
January 2003 10MWt, 700°C
(Steam turbine power generation: 2.5MWe)

Under construction of HTR-PM
Electric power (750°C)

■HTR-PM : Commercial HTGR 250MWt x2, 750°C
(Electric power generation: 105.5MWe x2)
2008 Construction (Weihai city, Shandong province)
2012 Restart of construction
2020 Start of an electric power supply

■HTR-PM600 : Power plant construction plan
250MWt x2 x3 / 600MWe, 750°C
(Ningde city, Fujian province)

Japan

■ HTTR

1998 First criticality
2001 Reactor outlet coolant temperature 850°C/30MWt
2004 Reactor outlet coolant temperature 950°C
2010 50 days continuous 950°C operation
2010 Loss of forced cooling test at 9MW

■ Hydrogen production technology (IS process) development

1997 Clarification of closed-cycle operation conditions
2004 Continuous H_2 production for a week (0.03 m^3/h)
2014 Start of Operation of Hydrogen production test facility
2018 Continuous H_2 production for 150hrs (0.03 m^3/h)

EU

■GEMINI+ Project: Design and R&D of HTGR with heat application

Indonesia

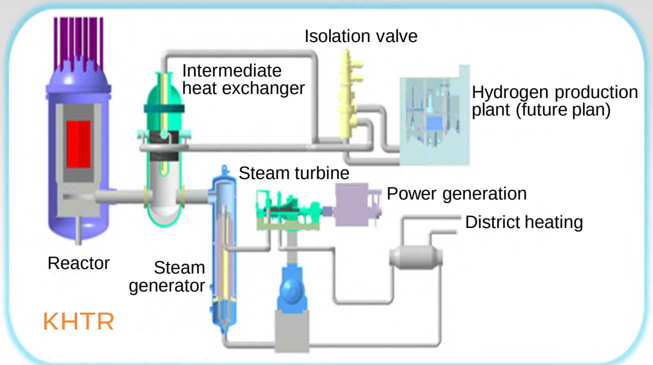
■ EPR (Experimental power reactor)
10MWt, 700-1000°C
2015 Completion of Feasibility Study

Canada

■ StarCore: 36MWt+20MWe,
Electric power generation, Design stage

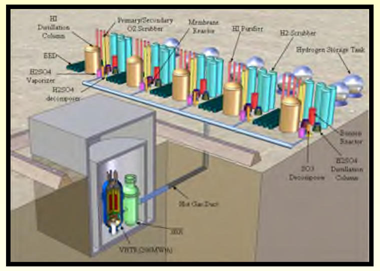
Kazakhstan

■KHTR : Electric power generation / District heating Small HTGR to be constructed
50MWt /15MWe, 750°C/950°C



Korea

■NHDD : Nuclear Hydrogen Development Demonstration
VHTR hydrogen production, 200MWt, 950°C
2012 Conceptual examination in progress
After 2019 Conceptual design to be started



NHDD Concept
Electric power,
hydrogen production
（950°C）

IS facilities (Korea Institute of Energy Research: KIER and Advanced Institute of Science and Technology: KAIST）