JAEA's Missions for Deploying Next-Generation Innovative Reactors in Japan

November 17, 2022

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1. Domestic and International Situations and Requirements for Next-Generation Innovative Reactors

Energy situations of Japan

- Energy self-sufficiency*1: 11.2%
- Composition of electric power sources*2:

  Thermal 76.4%
  Variable zero emission (solar, wind) 8.8%
  Stable zero emission (stable renewables, nuclear) 14.9%
- Japan's CO_2 emissions (emission factor (gCO_2/kWh)) are 8 times higher than France!

✓ Unlike European countries with interconnected grids, Japan is an energy isolated island.

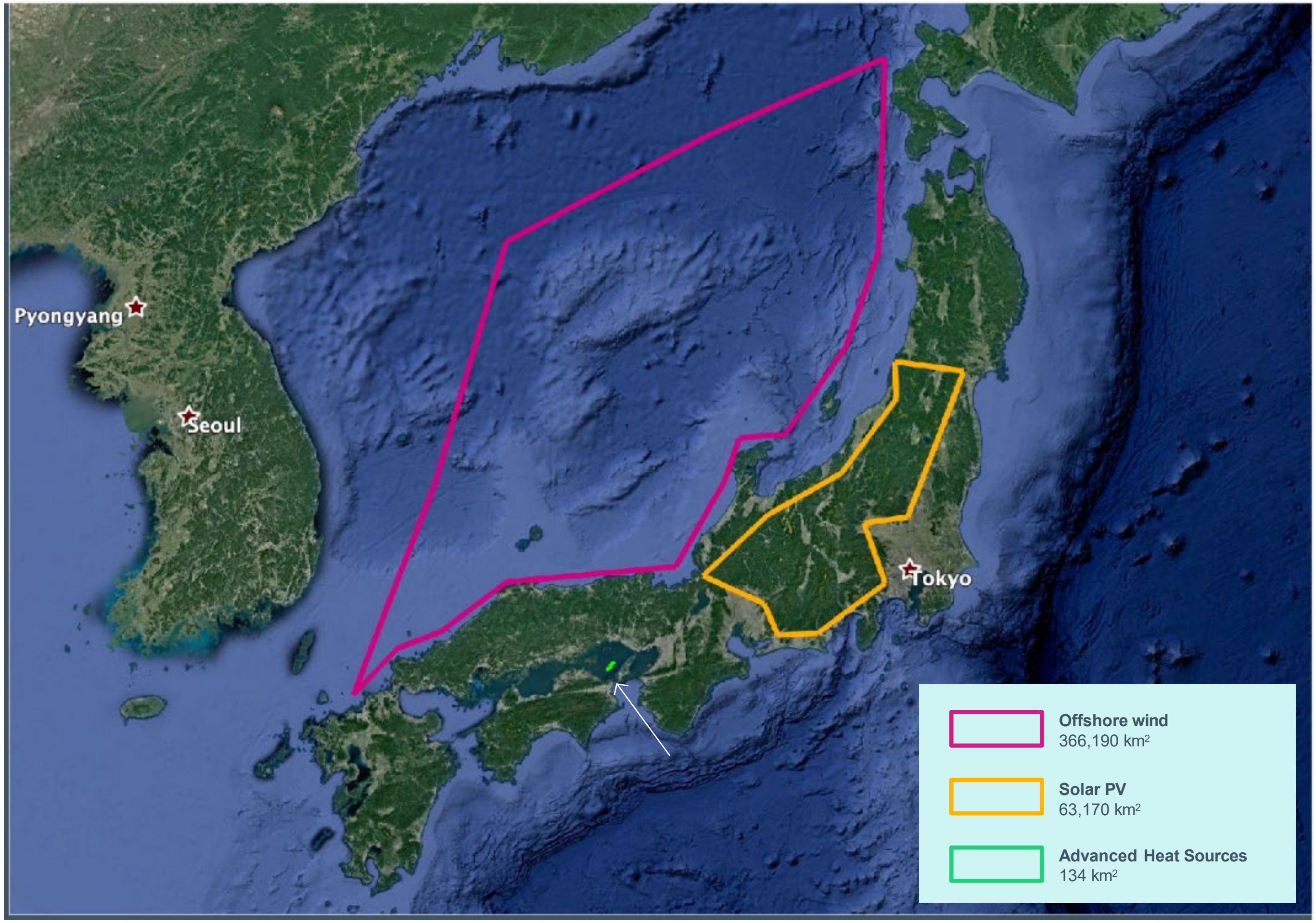
Variable zero emission: Power sources which do not emit CO_2 but whose output varies greatly depending on weather conditions
Stable zero emission: Power sources which do not emit CO_2 and can be operated stably regardless of weather conditions

	Japan	France	China	India	Germany	The U.K.	The U.S.
Energy self-sufficiency	11%*1	54%*3	84%	65%	35%*3	71%*3	104%*3
Main domestic resources	-	Nuclear	Coal	Coal	Coal	Coal Natural gas	Natural gas Petroleum Coal
Facility utilization rate (solar)	15%	14%	16%	18%	11%	11%	19%
Facility utilization rate (wind)	25%	29%	25%	23%	30%	31%	37%
International pipelines	-	✓	✓	-	✓	✓	✓
International grid connection	-	✓	✓	✓	✓	✓	✓

*1 Agency for Natural Resources and Energy, Japan's Energy White Paper 2022
*2 Website of Agency for Natural Resources and Energy, Overall results or estimated results (Total Energy Statistics), https://www.enecho.meti.go.jp/statistics/total_energy/results.html#headline7
*3 Agency for Natural Resources and Energy, Japan's energy 2021: 10 questions to understand the current status of energy (in Japanese)

Reference

■ The area needed to produce an adequate amount of hydrogen for Japan (calculated from oil consumption in 2019)



＊LUCID CATALYST, “Missing Link to a Livable Climate: How Hydrogen-Enabled Synthetic Fuels Can Help Deliver the Paris Goals”, September 2020.

Japan's nuclear energy policy

Green Growth Strategy (excerpts on nuclear)

- Nuclear power can continuously supply a large amount of carbon-free electricity. Japan has the leading-edge nuclear technology, and its technological self-sufficiency is high.
- With further innovations, we will improve nuclear safety, reliability, and efficiency, reduce the volume and toxicity of high-level radioactive waste, and enhance natural resource recycling through effective use of the resources.
- Nuclear power can satisfy various public needs, such as harmonization with renewable energy sources, carbon-free hydrogen production, and heat applications for industrial use.

⇒ Growth strategy process for 2050 related to FRs, HTGRs, and small modular reactors (SMRs) was proposed. For FR development, Japan will steadily promote it based on the *Strategic Roadmap*, established at the Ministerial Conference on Nuclear Energy in December 2018.

⇒ The experimental fast reactor Joyo can produce large quantities of medical radioisotopes, rarely found in the world. Joyo resumption will, therefore, contribute to improving cancer treatment radically.

The 6th Strategic Energy Plan（excerpts on nuclear and innovative reactors）

To achieve carbon neutrality by 2050

- Electric power sectors will use carbon-free power sources such as renewables and nuclear.
- Japan continues to use a necessary amount of nuclear power, provided that the safety is ensured.

Policies for 2030 (nuclear):

- Promotion of R&D
  - Advance FR development through international collaborative frameworks
  - Demonstrate SMR technology with international partners
  - Develop the basic technology of HTGR hydrogen production

Recent domestic activities for innovative reactors

Advanced Reactor Working Group of Nuclear Energy Subcommittee (METI)*1

- Acknowledged again the significance of nuclear energy for the nation and proposed steps for innovative reactor development in Japan
  - Technology roadmap for innovative reactor development: **An interim summary (July 2022)**

Strategic Working Group of Fast Reactor Development Council (METI)*1

- Discussed the way of fast reactor (FR) development after 2024, based on the Strategic Roadmap established in December 2018
- Discussed to improve the Strategic Roadmap, reflecting experts' feedback

Key points for the revision

- Prioritizing sodium-cooled fast reactors (SFRs) as the most promising design concept
- Proposing development milestones
- Clarifying the development strategy and the role of each player (e.g., the government, JAEA)

Study Group on R&D Infrastructure for Next-Generation Innovative Reactors (MEXT)*2

- Discussed R&D infrastructure development needed for the next decade, based on Prime Minister Kishida's directive issued at the Green Transformation Executive Conference in August 2022

Japan Atomic Energy Commission (Cabinet Office)

- Sought opinions from nuclear operators to improve the Basic Policy for Nuclear Energy established in July 2017
  - Request for establishing a government policy on the sustainable use of nuclear energy

*1 METI: Ministry of economy trade and industry
*2 MEXT: Ministry of Education, Culture, Sports, Science and Technology

International trends on nuclear energy

France

President Macron announced that France would build six next-generation EPR2 nuclear reactors and look into options to add eight more reactors. (February 2022)
France also aims at innovative reactors to close the fuel cycle and produce less waste.

The U.K.

Energy Security Strategy (April 2022): Increase nuclear power generation up to 25% by 2050. Started a demonstration program (August 2022), aiming at starting an HTGR in early 2030s. Established Great British Nuclear that supports the U.K.'s nuclear industry.

Belgium

Formulated a policy aimed at 10-year extension of the lifetime of two power plants, which will reach 40 years of operation in 2025. (March 2022)

Poland

Energy Policy of Poland for 2040 (developed in February 2021) aims to start the operation of six units by 2043, and shows that Poland may use high temperature gas-cooled reactors as an industrial heat source.

EU

European Commission decided to include nuclear energy in the EU Taxonomy, a classification framework for sustainable economic activities. (July 2022)

The U.S.

The Department of Energy started the Advanced Reactor Demonstration Program (ARDP) and awarded 10 programs its fund (October and December 2020), including an SFR named Natrium and an HTGR named Xe-100. In September 2022, the California legislature passed a bill to extend the lifetime of nuclear power plants once planned to be closed.

Korea

The administration announced a new energy policy (July 2022), which states that nuclear electricity generation will be increased to 30% or over by 2030. Korea exported four units of light-water reactors (1.4 million kW) to the UAE, of which two units are already in commercial operation, and another unit is under commissioning (as of October 2022).

China

China accelerates decarbonization by doubling (or more) its current capacity of nuclear power generation by 2030 to generate output more than 107 GW: China would be the world's biggest nuclear power producer.

Requirements for next-generation innovative reactors

- Ensure the safety, and
  - Supply stable power (in large quantities + advanced safety mechanisms + technological self-sufficiency, supply chains)
  - Achieve natural resource recycling (waste management + effective use of resources)
  - Be flexible (load-following + hydrogen and heat production + flexible siting)

Stable power supply

- As a carbon-free power source, contribute to stable, sustainable power supply across the nation.
- Achieve safety innovations for regaining the public trust.
- Innovate processes in manufacturing and procurement to stimulate nuclear supply chains, so that technological self-sufficiency will further improve.

Natural resource recycling

- As a carbon-free energy source, use innovative technology to recycle high-level radioactive waste
- Propose solution to limited natural resources
- Become a recyclable energy source through technological innovation

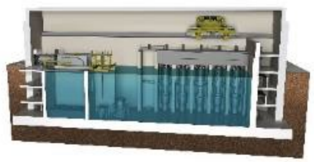
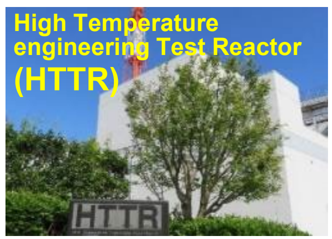
Flexibility

- Support variable renewables by adjusting nuclear power output (load-following)
- Produce hydrogen, achieve various heat application, and store heat when electricity demand is low
- Be flexible in site locations by reducing the sizes of emergency planning zones
- Contribute to improving national welfare through medical RI production

Further enhanced safety

- Develop and promote technologies for safer nuclear power by reflecting lessons learned from TEPCO's Fukushima Daiichi nuclear power plant accident.

Main categories of innovative reactors*1

Advanced Light-Water Reactor (LWR)	 Plant concept*2	Large-scale LWRs featuring new safety-enhancing technologies (e.g., a core catcher). The use of existing LWR technology allows existing LWR supply chains to actively participate in the development and us to easily predict when to start the operation.
Light-water Small Modular Reactor (SMR)	 SMR plant (a diagram provided by NuScale Power)	Electricity output up to 300 MW. Production of units (modules) in a factory reduces time and cost of construction. Using existing LWR technology, SMRs are a practical option to reduce investment risk and to meet various future needs such as load sharing.
HTGR		Provides high temperature heat (over 900ºC) which can be used for various applications such as hydrogen production as well as high efficient power generation. HTGR development is underway towards technology demonstration making the most use of international collaboration.
Fast reactor		Fast neutrons enable the nuclear fuel cycle to be achieved through the effective use of uranium resources and combustion of radioactive waste. FR development is underway using international frameworks, in which the experiences of Joyo and Monju are reflected.

References

＊1 https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/029.html
https://www.nikkei.com/article/DGXZQOUC246DB0U2A820C2000000

＊2 https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/kakushinro_wg/pdf/001_08_00.pdf

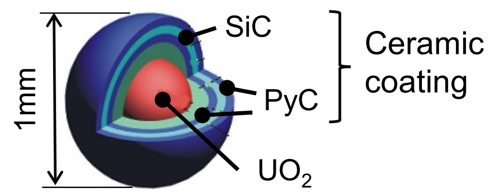
2. Development of Next-Generation Innovative Reactors in JAEA

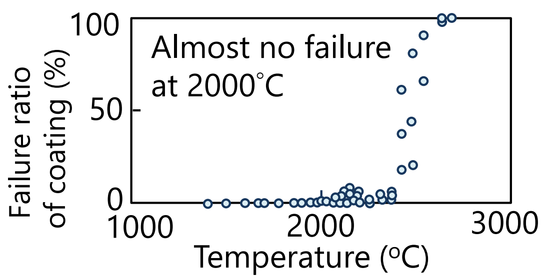
—Technology development for High Temperature Gas-cooled Reactors (HTGRs)—

Features of HTGR —Inherent safety

Ceramic-coated fuel

Resistance to high temperatures and no meltdown

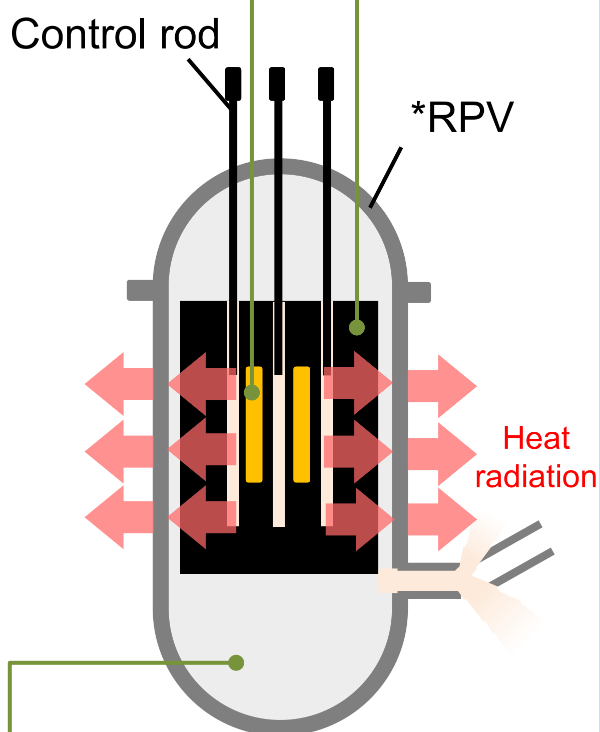




Experimental result of heated fuel particles

Helium gas coolant

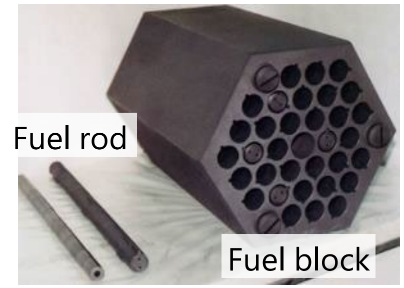
No explosions of H_2 and vapor thanks to its chemical inertness and no phase-change

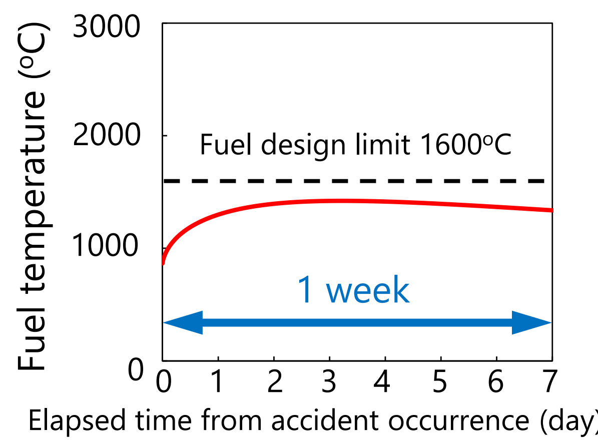


The reactor is safely shut down and cooled by passive design features that require no equipment or operator actions even if external power and coolant are lost.

Graphite components

Cooled down naturally from the outside of the RPV thanks to its large heat capacity and high thermal conductivity





Fuel temperature during loss-of-coolant accident (analytical result)

*RPV: reactor pressure vessel

Features of HTGR —Various applications of heat from HTGR

Hydrogen production

Hydrogen

Fuel cell vehicles Ironmaking

- Hydrogen production with steam methane reforming, high-temperature steam electrolysis or thermochemical method (IS process)

High temp. heat supply, cogeneration for industries

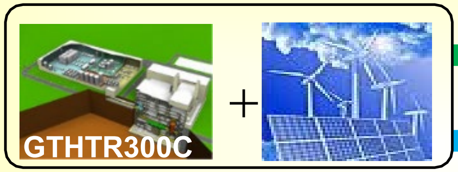
Process heat

Electric power

Chemical plant

- Process heat supply using steam (chemical plant, oil refinery, etc.)
- Electricity supply using steam turbine power generation

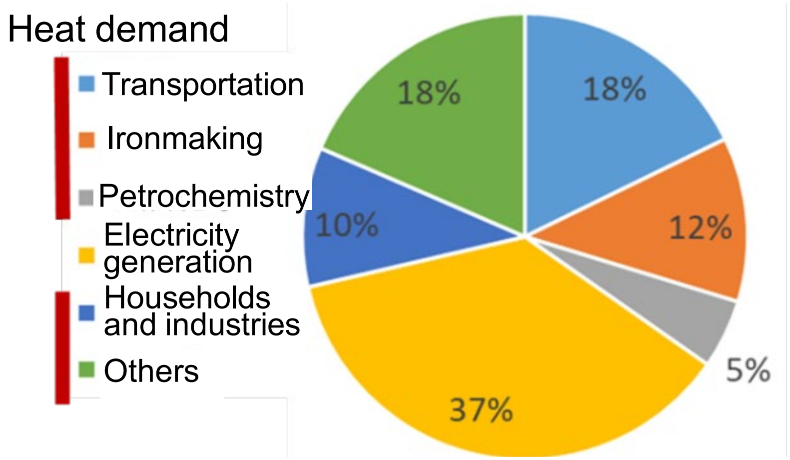
Hybrid system coexisting with renewable energy



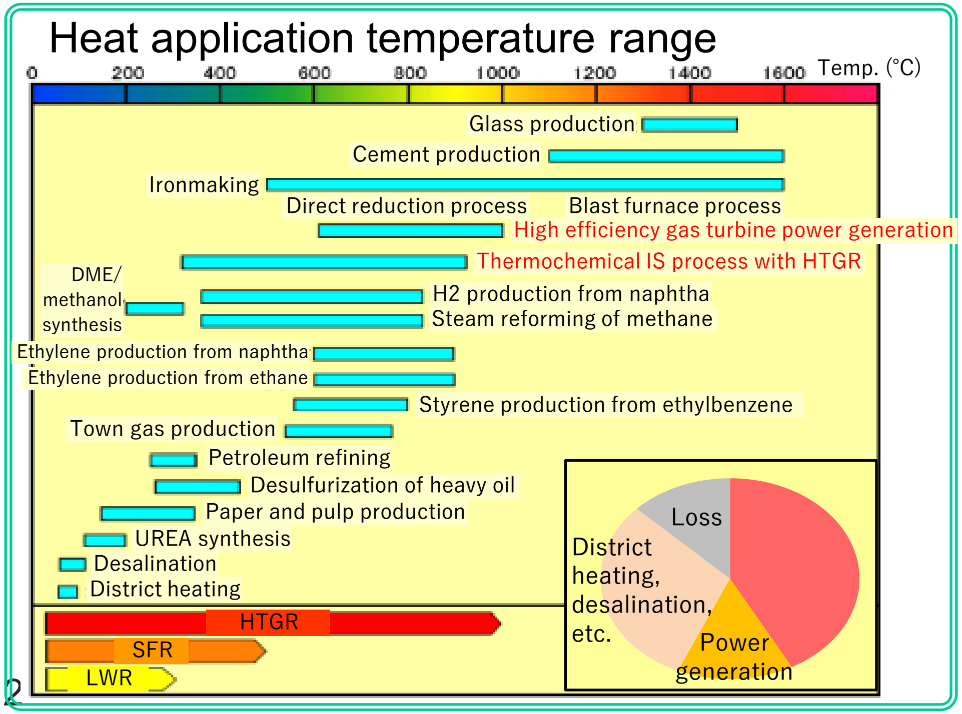
Constant power to grids

Hydrogen production

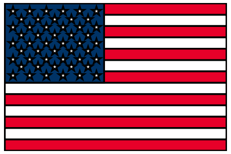
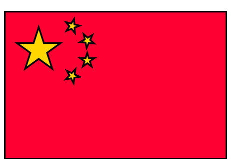
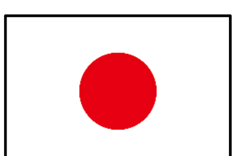
- Adjust output fluctuations of renewables by changing its electricity output or hydrogen production amount, while keeping its high power generation efficiency



Contributing factors of CO_2 emissions of Japan (2019)



Development status of HTGRs in the world

The U.S.		**<u>Supported by Department of Energy (DOE)</u>** (Advanced Reactor Demonstration Program (ARDP) since 2020) • Supporting the construction of an innovative reactor that will start operation by around 2028 • X-energy was selected. (HTGR)
The U.K.		**<u>Supported by the Department for Business, Energy & Industrial Strategy (BEIS)</u>** (Advanced Modular Reactor Research, Development & Demonstration (AMR RD&D) since 2022) • BEIS has selected HTGR as an advanced modular reactor. • Demonstration of HTGR by early 2030 • A team (incl. NNL and JAEA) has been selected to assess the feasibility of AMR RD&D.
Poland		**<u>HTGR plan by the Polish government</u>** • The National Center for Nuclear Research (NCBJ) received a budget from the Ministry of Education and Science for the design of an experimental HTGR. • Conceptual design of the HTGR is started (2022)
China		**<u>Energy technology innovation under the 13th Five-Year Plan</u>** • R&D using the research reactor, HTR-10 • A demonstration reactor (210 MWe) is in operation (Power transmission started in December 2021, and full-power operation is scheduled in 2022)
Japan		**<u>NEXIP Initiative by METI and MEXT</u>** • R&D using the High Temperature Engineering Test Reactor (HTTR) of JAEA • Commercial HTGR development by private companies (Toshiba ESS and Mitsubishi Heavy Industries)

R&D in JAEA —Outline of HTTR and R&D history

R&D

In-pile helium gas loop (OGL-1)

Very High Temperature Reactor Critical Assembly (VHTRC)

Helium Engineering Demonstration Loop (HENDEL)

The highest ever achieved

For prototypes for commercial use

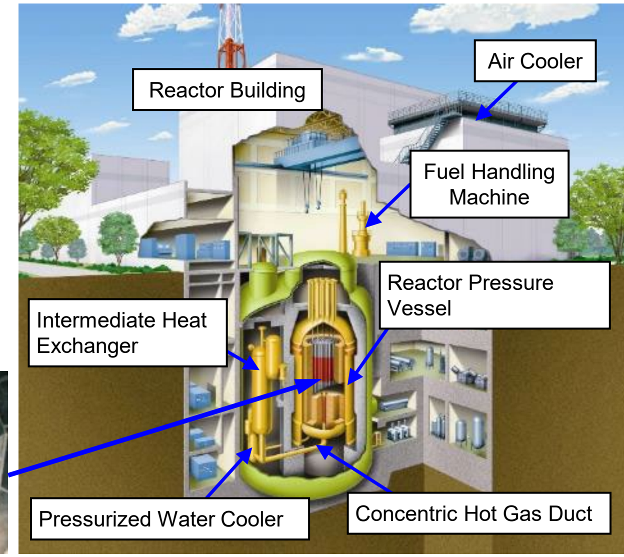
Establishment of basic technology

Reactor construction

R&D and design

2022	Safety demonstration (Loss of core cooling test)
2021	HTTR restart
2020	Obtain permission
2014	Apply for conformity review on reactor installation (New regulatory requirements)
2010	Safety demonstration (Loss of core flow test)
	50-day operation at 950°C
2007	30-day operation at 850°C
2004	Achieve reactor outlet coolant temperature 950°C
2002	Safety demonstration (Control rod withdrawal test)
2001	Achieve reactor outlet coolant temperature 850°C (30 MWt)
1998	First criticality
1997 ~ 1991	Construction
1990 ~ 1989	Application and permission of construction
1988 ~ 1985	Detailed design
HTTR	
1984 ~ 1981	Basic design
1980 ~ 1974	System integrity design
1973 ~ 1969	Conceptual design
Experimental multi-purpose very high-temperature reactor	

High temperature engineering test reactor (HTTR)



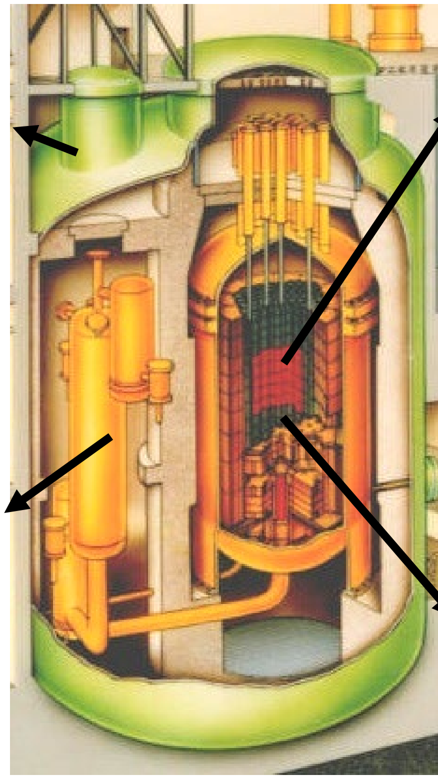
- Reactor thermal power ·················· 30 MWt
- Reactor coolant ························· Helium gas
- Reactor inlet/outlet coolant temperature ··· 395/850,950℃
- Primary coolant pressure ·················· 4 MPa
- Reactor material (moderator) ············ Graphite
- Core height/equivalent diameter ··········· 2.9m／2.3m
- Power density ···························· 2.5MW/m^3
- Fuel ···UO_2·Ceramic coated fuel particle／graphite dispersed
- Uranium enrichment ··········· 3 - 10%（average 6%）
- Fuel type ····················· Pin-in-block type
- Reactor pressure vessel ·· ······ Steel（2.25Cr-1Mo steel）
- Primary cooling circuits ········· 1 loop
  （Intermediate heat exchanger and pressurized water cooler）

HTGR technologies of Japan

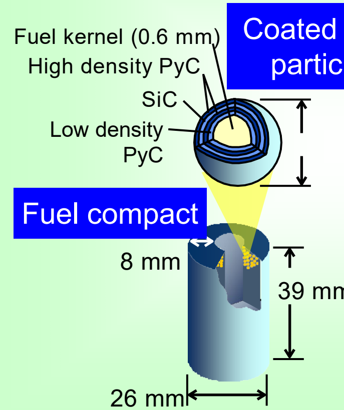
HTTR design, construction, and operation experience
(Mitsubishi Heavy Industries, Toshiba/IHI, Hitachi, Fuji Electric, Kawasaki Heavy Industries, etc.)

Accumulating a vast amount of HTGR technical data

Optimal design of commercial HTGRs



Fuel (co-developed with Nuclear Fuel Industries)



Uranium fuel using ceramics coating with high confinement performance

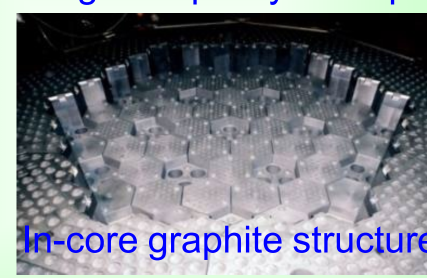
High-temperature metallic material Hastelloy XR
(co-developed with Mitsubishi Materials Corporation)

Metallic material that can be used at the world's highest temperature (950ºC) as a structural material for nuclear power plants

Capable of extracting 950ºC heat

Graphite material IG-110 (co-developed with Toyo Tanso Co., Ltd.)

The world's highest quality isotropic-graphite

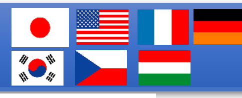


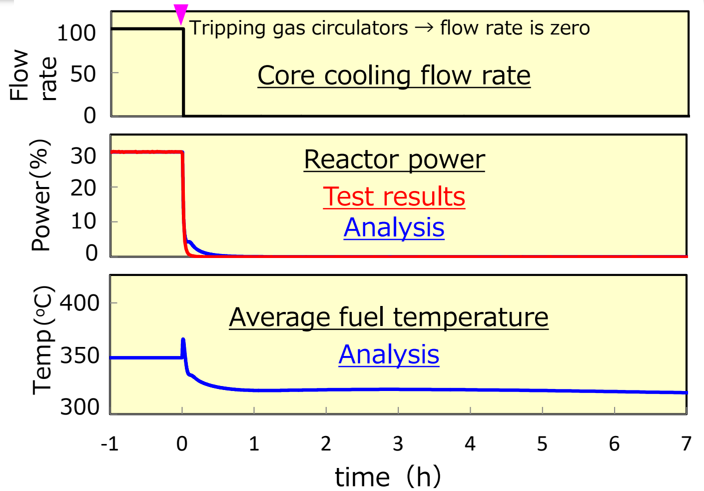
High strength, high thermal conductivity, irradiation resistance

HTGRs can be constructed using only domestic technologies

R&D in JAEA —Safety demonstration, heat application

Safety Demonstration Test



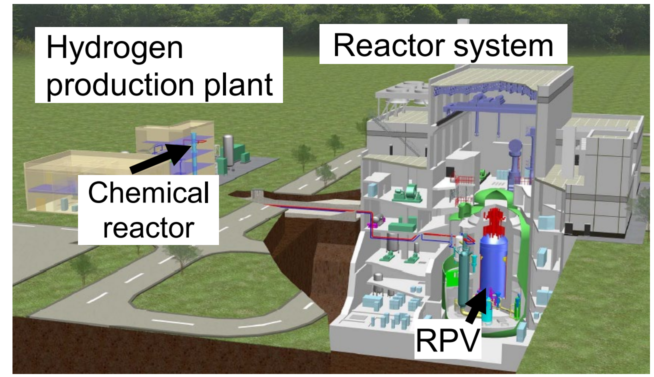


✓ Conducted safety demonstration tests including loss-of-forced-cooling test (OECD/NEA project), thermal load fluctuation tests

✓ Demonstration of inherent safety

Demonstrated inherent safety with excellent self-regulating characteristics

HTTR Heat Application Test



✓ Develop the coupling technology between HTGR and a hydrogen production plant employing steam methane reforming process by 2030

✓ Proposal for a safety concept for the connection of nuclear reactors and chemical plants

Establish safety design for connecting an HTGR and a hydrogen production plant

JAEA's HTGR technology:

- HTTR achieved the world highest 950°C outlet temperature
- HTTR demonstrated inherent safety features
- HTTR heat application test project will demonstrate hydrogen production, complying with safety regulations on heat application

The world's front-runner in HTGR technology

High expectations from other countries

- Bilateral cooperation: the U.K., Poland, the U.S., etc.
- OECD/NEA LOFC project, GIF VHTR cooperation, etc.

Collaboration with the United Kingdom

- **The U.K. advances a demonstration program for HTGR to install it in the early 2030s.**
- **A team of JAEA, the U.K.'s National Nuclear Laboratory (NNL), and Jacobs has been selected to assess the feasibility of the Advanced Modular Reactor Research, Development & Demonstration (AMR RD&D).**
- As the next stage, the U.K. government will carry out the project for the basic design of the reactor, and **JAEA will work with the Japanese government and private companies to determine how Japan can effectively collaborate with the U.K.**

Selected teams

●LOT 1 (Reactor demonstration)

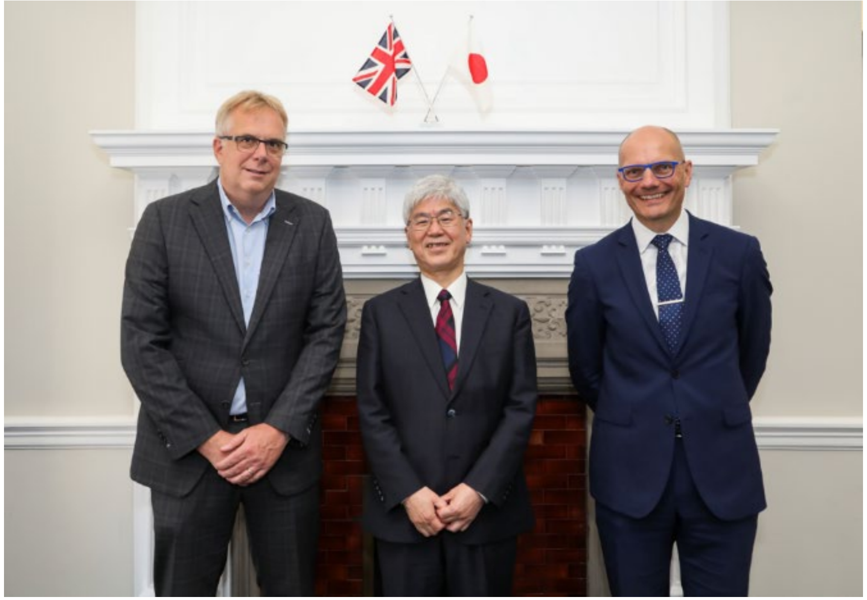
- EDF Energy Nuclear Generation
- <u>NNL (partnered with JAEA and Jacobs*)</u>
- U-Battery Developments
- Ultra Safe Nuclear Corporation UK

●LOT 2 (Fuel demonstration)

- <u>NNL (partnered with JAEA and Urenco**)</u>
- Springfields Fuels (partnered with Urenco)

*Jacobs: an American international technical professional services firm that provides engineering, technical, professional and construction services

**Urenco: a British-German-Dutch nuclear fuel consortium providing uranium enrichment services established in 1970



JAEA-NNL-Jacobs meeting

From the left: Andy (Jacobs VP), Koguchi (JAEA President), Paul (NNL CEO)

AMR RD&D

Program Overview (in three phases)

- **Phase A: Pre-FEED (Front End Engineering Design)**

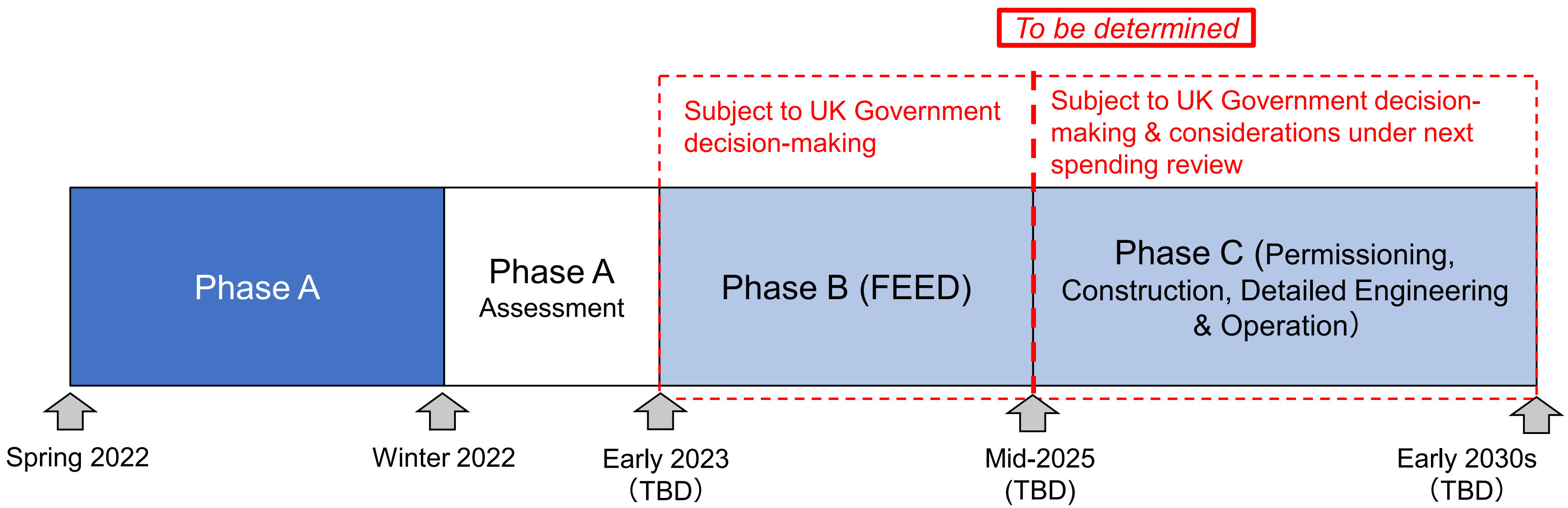
  Understand the factors (e.g., scale and cost) of the HTGR demonstration and propose solution to meet the goals

- **Phase B: FEED**

  Estimate costs (e.g., total investment cost and life-cycle cost) based on the basic design

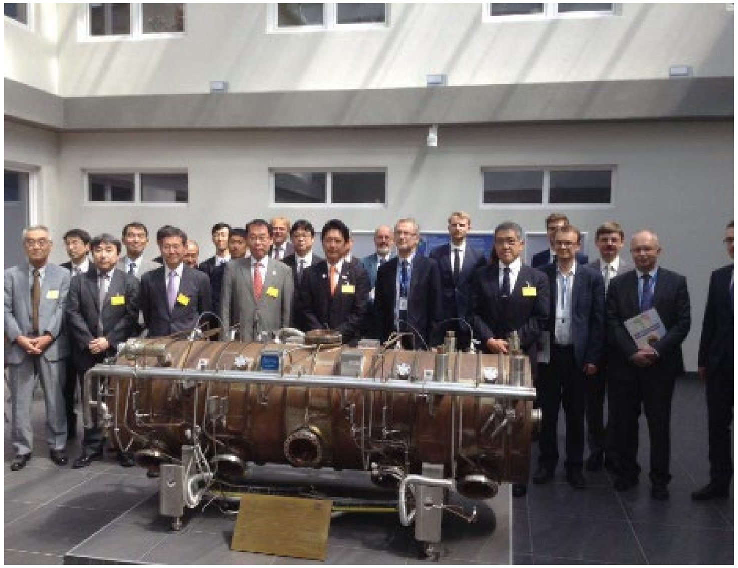
- **Phase C: Permissioning, Construction, Detailed Engineering and Operation**

  Engineering including site-specific detailed design, licensing, and construction

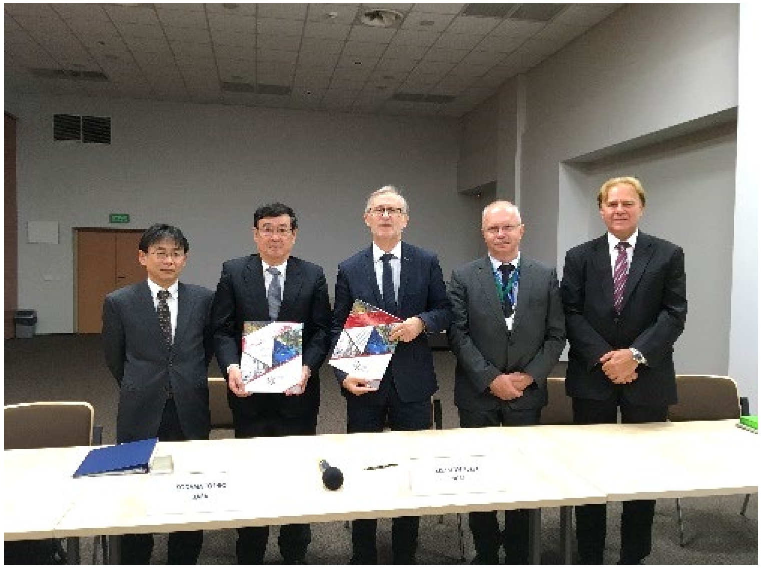


Collaboration with Poland

- Poland plans to supply process heat from HTGRs to industry.
- In May 2021, the National Center for Nuclear Energy Research (NCBJ) received a governmental funding (about 1.8 billion yen for 3 years) for the basic design of a HTGR research reactor.
- JAEA and NCBJ will revise the Implementing Arrangement regarding the HTGR R&D cooperation (made in September 2019) and proceed with the basic design of the HTGR research reactor.

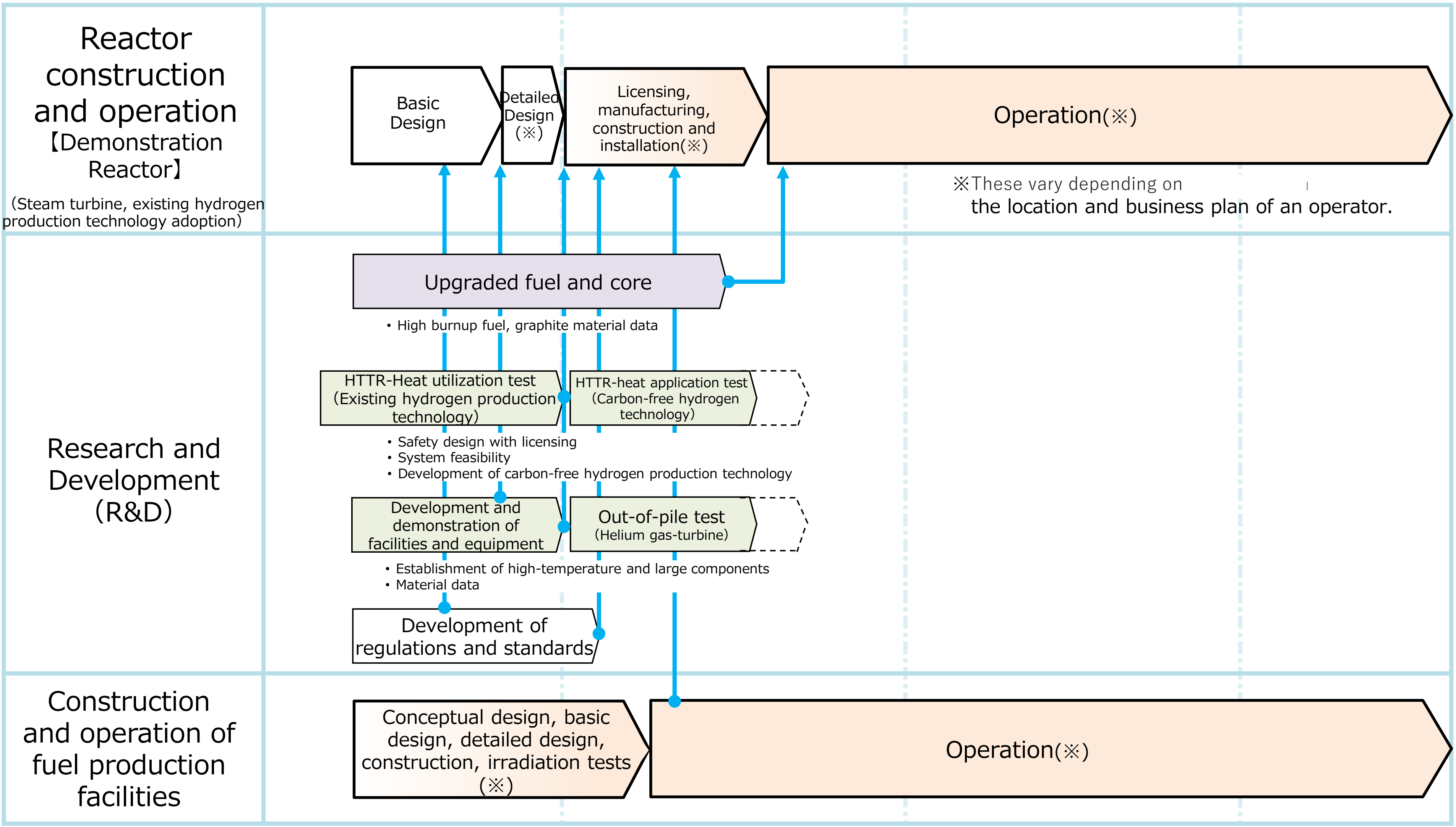


Japanese delegation (MEXT, JAEA, and industries) in Poland (July 2017)



JAEA and NCBJ signed the Implementing Arrangement (September 2019)

Technology roadmap for introduction of HTGR＊



＊reference
https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/kakushinro_wg/pdf/004_03_00.pdf

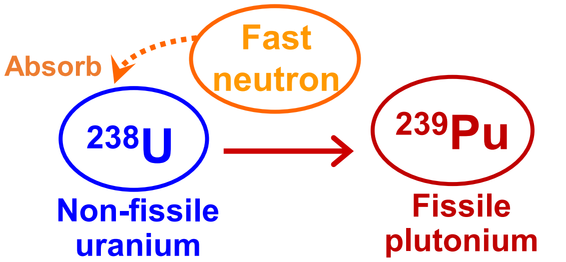
2. Development of Next-Generation Innovative Reactors in JAEA

—Technology development for fast reactor (FR) cycle—

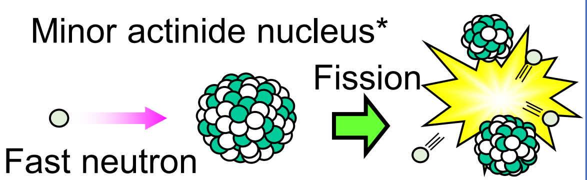
Features of FR

- Fast neutrons (high-energy neutrons)
- Liquid metal (sodium) coolant
- Sodium natural circulation removes heat from the core (Natural cooldown)

Fast neutrons



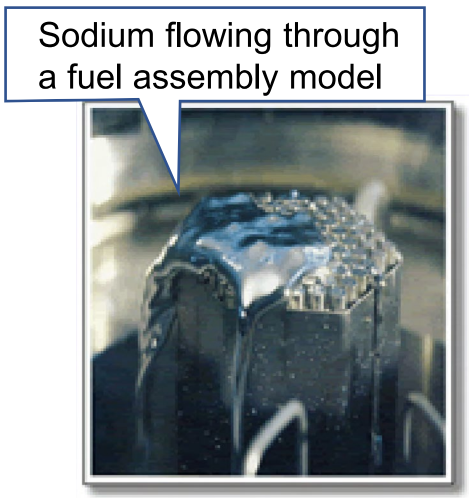
Produce new fuel



Reduce the toxicity of radioactive waste

- Fast neutrons have higher energy than the neutrons used for fission in LWRs, finding various applications.

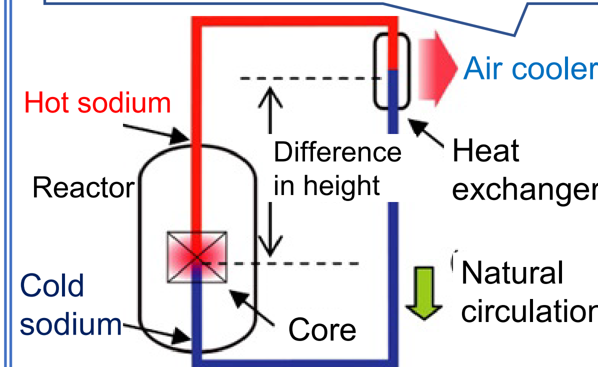
Liquid sodium



- Sodium does not moderate neutrons, enabling high-energy neutrons.
- Sodium boiling point is higher than that of water, allowing operation at high temperatures and low pressure (➔Efficient heat extraction)

Safety achieved by sodium natural circulation

Assisted by the air cooler installed at a higher place, sodium flows naturally due to its density difference caused by temperature difference.



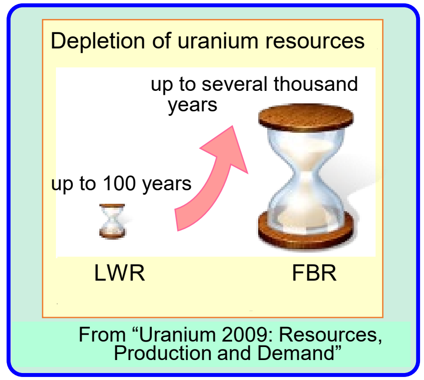
- Sodium is easily circulated naturally by convection driven by temperature difference, allowing natural cooling of the reactor even if the power source is lost.

*Minor actinides: Elements that remain highly radioactive for long periods of time and increase the toxicity of radioactive waste. Typical elements include Americium (Am), Neptunium (Np).

Significance of FR cycle

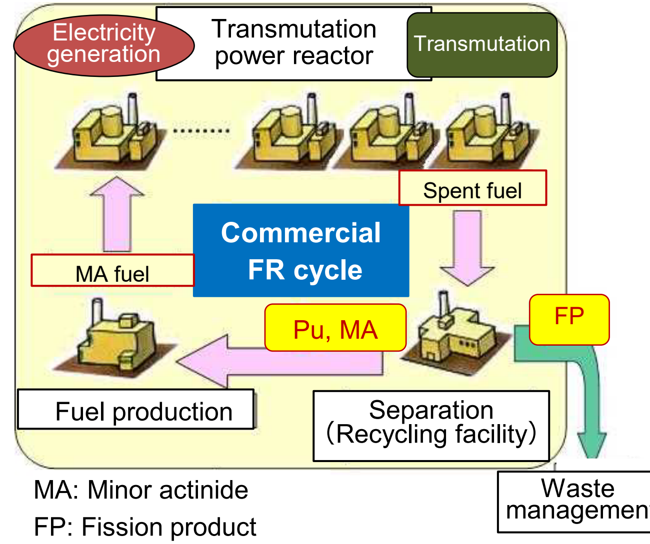
- Efficient use of uranium resources
  (Dozens of times larger than that of LWRs)
- Spent fuel recycling (no need for uranium import) and technological self-sufficiency (domestic production) ensure stable energy supply.

  ➔ Effective use of finite resources, strengthening energy security



- Zero CO_2 emissions
- Recycling minor actinides (MAs) of spent fuel as nuclear fuel reduces the amount of radioactive waste and significantly shortens the decay time of radioactive materials from 100,000 years to 300 years.
- Plutonium (Pu) can be produced or burned through Pu management.

  ➔ Reduction in environmental burden



FR transmutation system for electricity generation

Reference https://www.mext.go.jp/content/20211104-mxt_genshi-000018772_3.pdf

- Find uses as a base-load as well as a dispatchable power source that complements variable renewables (solar and wind) in combination with thermal storage.

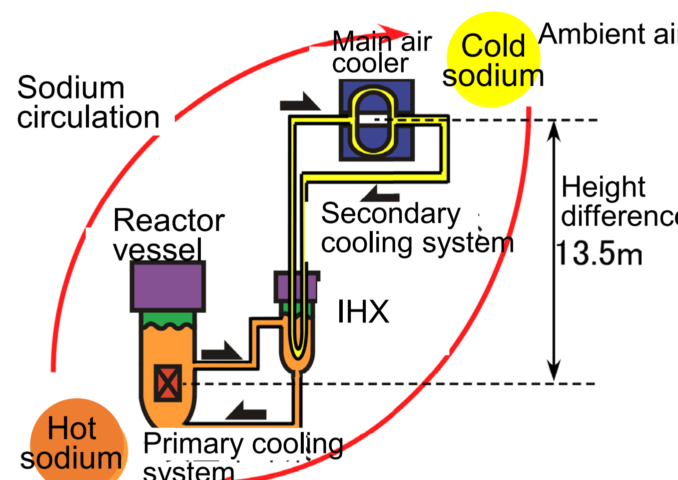
  ➔ Carbon neutrality and coexistence with variable renewables

- High natural circulation capability of coolant in combination with air coolers enables long-term stable decay heat removal even under a total blackout. (already demonstrated by the experimental fast reactor Joyo)

  ➔ Ensured safety

- Capable of producing medical radioactive isotopes using fast neutrons

  ➔ Improving cancer treatment for public well-being



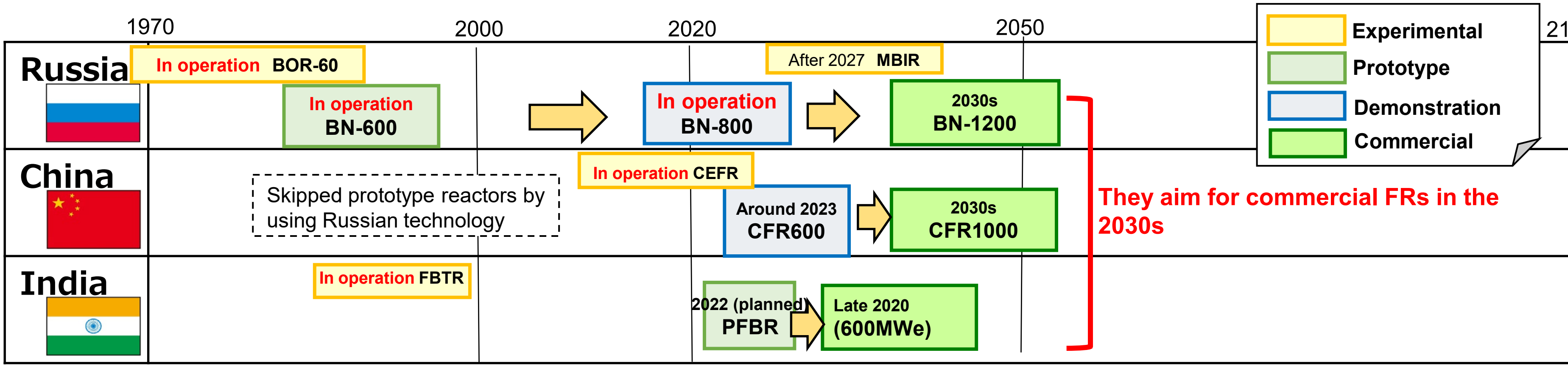
Decay heat removal by natural circulation

Achieving innovation according to the green growth strategy

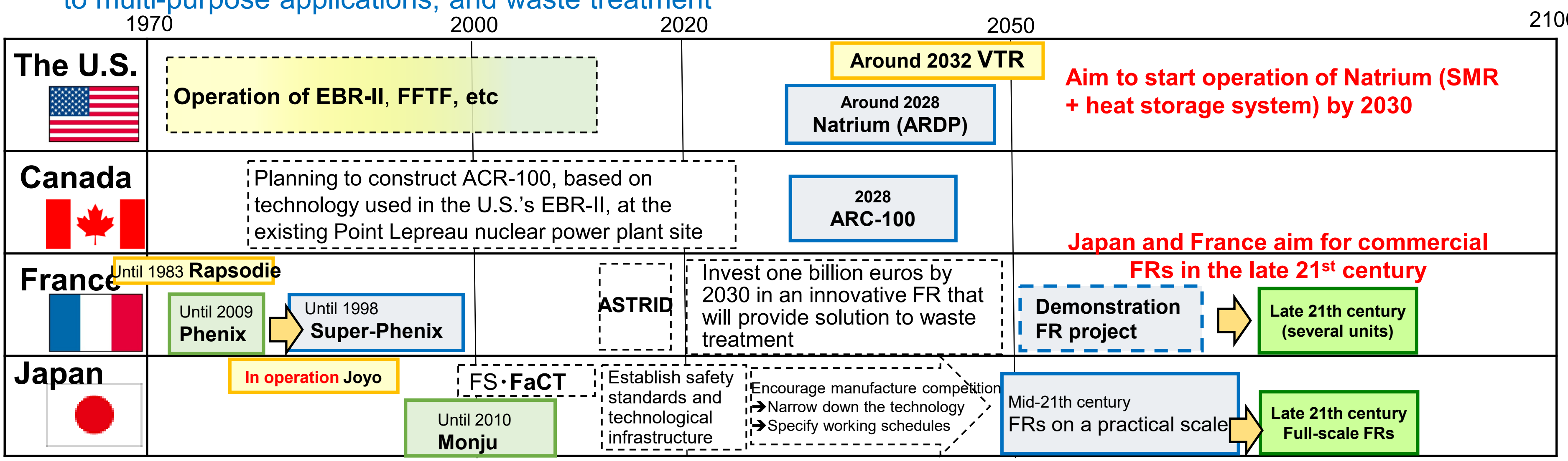
Development status of FRs in the world

- In Russia, a demonstration reactor started its operation in 2015. In China, a demonstration reactor is scheduled to achieve its first criticality in 2023.
- Public-private partnerships in the U.S. (TerraPower, etc.) and Canada (ARC, etc.) aim to start demonstration reactors in the late 2020s.

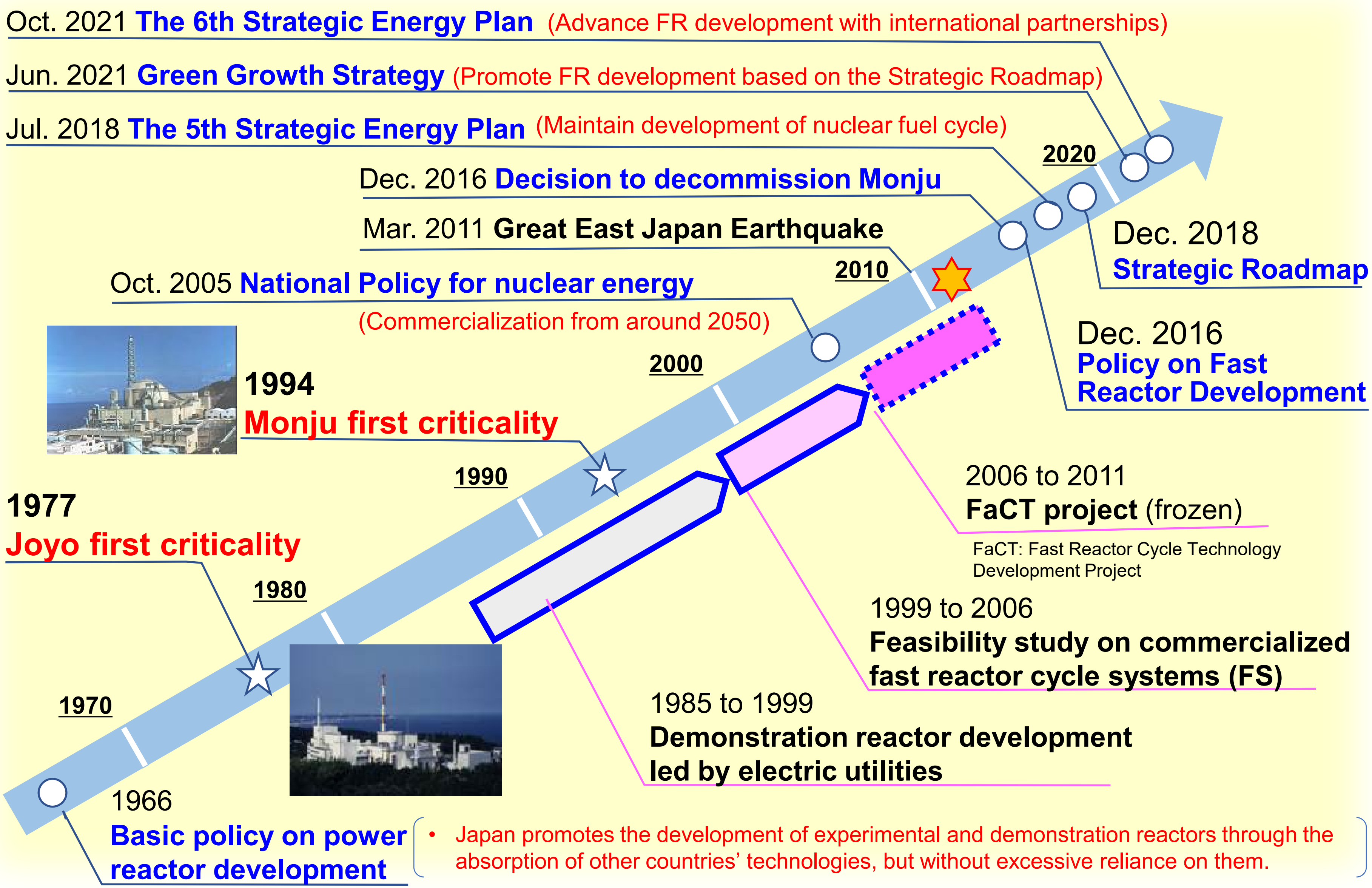
■ Russia, China, and India are rapidly developing fast-breeder reactors for energy security.



■ The U.S. Canada, France, and Japan have acquired the breeding technology, now focusing on Pu use with a view to multi-purpose applications, and waste treatment



History of FR cycle development in Japan



Achievements of the experimental fast reactor Joyo and the prototype reactor Monju

Missions of Joyo

- Demonstrate basic and fundamental technologies for FBRs
- Irradiation tests for fuels and materials
- Verify innovative technologies for the development of future reactors

- First criticality: 1977
- Total operation time: about 71,000 hrs
- Irradiation to date: about 100 test assemblies

Main achievements

- Confirmed its breeding performance
  More fuel was produced than consumed.
- Completed the fast breeder reactor (FBR) fuel cycle
  Reloaded Pu, which had been extracted from spent fuel, successfully worked as fuel.
- Demonstrated decay heat removal by sodium natural circulation
  ⇒ To be reflected in safety designs of future reactors
- Verified performance of oxide fuels
  Melting threshold in linear power density was confirmed by melting the center region of the fuel pellets.
- Served as a fast neutron irradiation field
  As of 2008, Joyo irradiated about 40,000 samples for 120 studies
- Served for the development of a self-actuated shutdown system (SASS) and SASS function tests

Expected R&D after restart of Joyo

- Reduction of radioactive waste volume and toxicity
- FR development
- Basic and fundamental research, and multi-purpose applications
- Human resource development

Missions of Monju

- Demonstrate power plant reliability
- Establish sodium handling technology

【Rated power】 280 MWe
【Operation record】

- First criticality: 1994
- Total operation time: 5,300 hrs
- Power generation time: 883 hrs
- Amount of power generated: 100 million kWh

Main achievements

- Established design approaches for FBR cores and design and manufacturing approaches for components
- Accumulated FBR operation and maintenance management technology
- Achieved power generation as Japan's first FBR system (up to 40% output)
- Confirmed the breeding performance (about 1.2 times the expected breeding ratio)
- Accumulated sodium handling techniques by operating and maintaining equipment and facilities containing sodium
- Improved sodium leak prevention technology
- Contributed to developing safety assessment methodology for SFRs

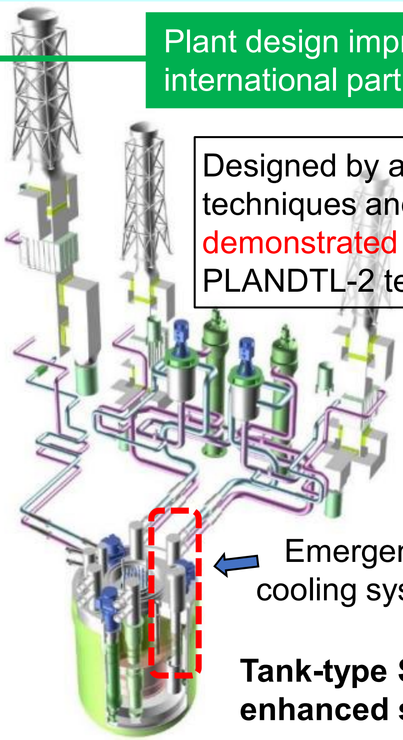
Milestones of Monju

To 1992	Design and construction
Oct. 1993	Performance tests start
Apr. 1994	First criticality
Aug. 1995	First electricity transmission
Aug. 1995	Performance tests start (40% output)
May 2010	Performance tests restart
To Dec. 2014	Preparations for restart
Dec. 2016 to date	Decommissioning

Safety improvement technologies developed through FaCT and French-Japanese cooperation, and demonstration

- Fast reactor R&D made progress for commercialization through the Fast Reactor Cycle Technology Development (FaCT) and subsequent R&D for enhancing safety and through Japan-France frameworks such as ASTRID program.
- The safety-enhancing technology was demonstrated, contributing to the development of the safety design criteria applicable to FRs around the world. Advanced fast reactor design concepts that use the technology and meet the criteria are being developed.

Plant design improved through international partnerships



Designed by applying analysis techniques and data that are demonstrated in the PLANDTL-2 tests

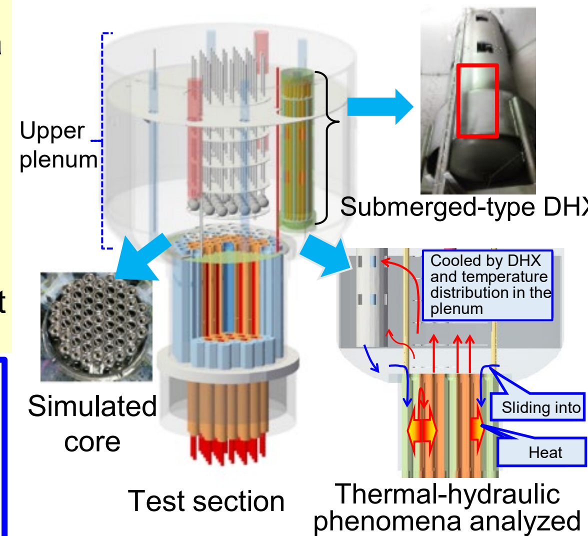
Emergency core cooling system (DHX)

Tank-type SFR featuring enhanced safety

- The collaborative work achieved the design technology for tank-type SFRs.
- The SFR uses proven safety-enhancing technology and satisfies the SDC and the SDG.

Safety enhancing technology using demonstrated data

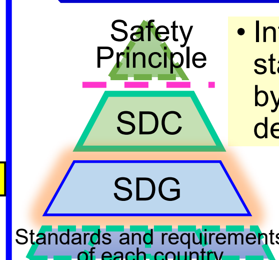
- Data was accumulated through tests on major elements such as a passive reactor shutdown system, heat removal using natural circulation of sodium, and molten fuel discharge behavior during a severe accident.
- Analysis tools were validated by using the data and applied to plant design.



PLANDTL-2 test on natural circulation heat removal

- Japan and France jointly analyzed the flow of sodium in the reactor vessel.

Safety criteria and standard



- International safety standards backed by demonstrated design technology

SDC and SDG in the hierarchy of safety standards

SDC: Safety Design Criteria

SDG: Safety Design Guideline

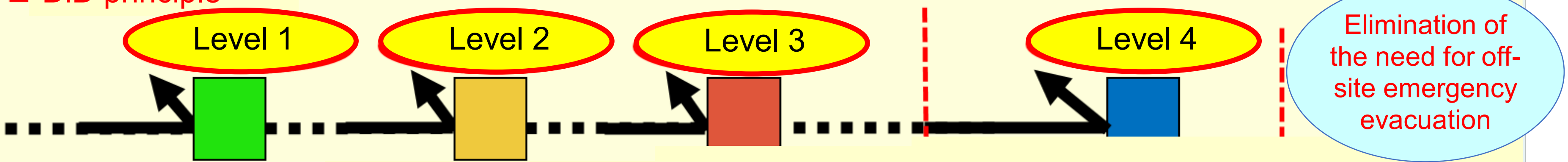
Design approach to a robust system

FR passive safety characteristics

- Natural shutdown and active shutdown of the reactor
- Natural cooldown and active cooldown of the core
- Natural termination of an accident and confinement of radioactive materials in the reactor and containment vessels

These comply with the Defense-in-Depth (DiD) principle.

■ DiD principle



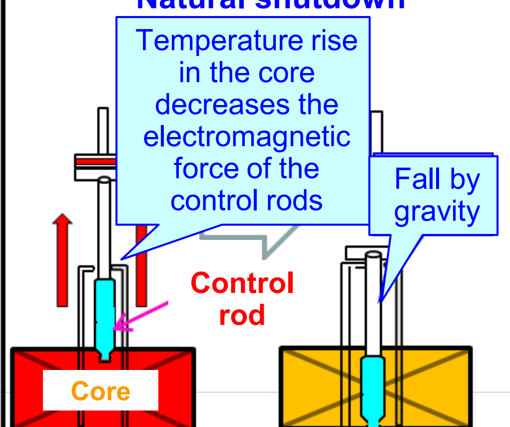
(1) Prevention of abnormal operation and failures

(2) Control of abnormal operation and detection of failures

(3) Control of accident within the design basis

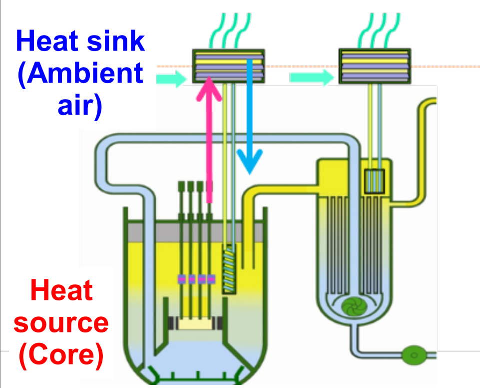
(4) Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents

Natural shutdown



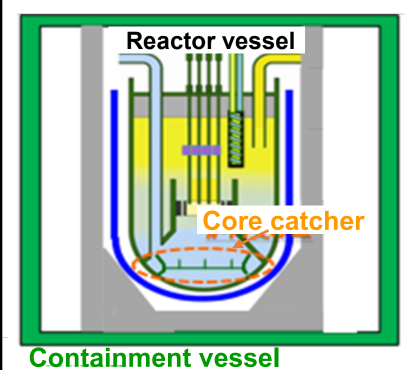
Control rods naturally fall when an abnormal event occurs

Natural cooldown



Cooled by sodium natural circulation and heat release to the ambient air

Natural termination



Contained by double layers even if the core is melted

Advanced safety features of SFRs

◆ Reflected experiences from Joyo and Monju, innovative technologies further enhanced safety.

Prevention and mitigation of a severe accident

Natural shutdown

Self-actuated shutdown system (SASS)

The alloy used in SASS has the property of losing its magnetic force at a high temperature

⇒ Control rods fall by gravity (Passive reactor shutdown)

Natural cooldown

Multiple and diverse heat removal systems

The core is cooled by sodium natural convection, in which hot sodium flows upward, and heat is released to the air even under pump failure.

Confinement

Termination of a severe accident within the vessel (In-vessel retention (IVR))

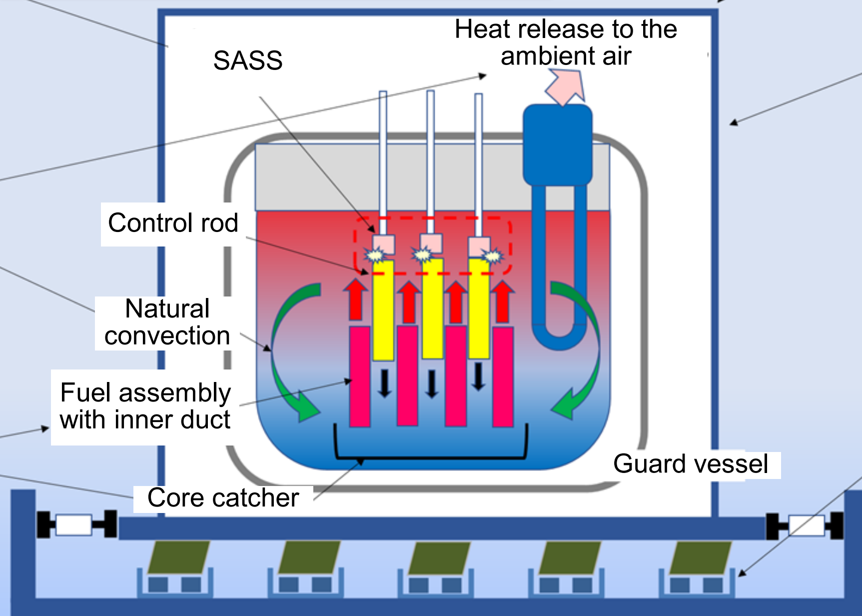
The system is designed to hold sodium and molten core. It can terminate an accident within the vessel by re-criticality prevention measures and a core catcher, eliminating the need for offsite evacuation.

Operated at around the atmospheric pressure, an SFR can maintain sodium in the RV unlike LWRs (7 to 15 MPa) that can discharge coolant from cracks in the RV. Even if leaked, sodium is retained by the guard vessel, preventing loss of coolant.

External hazard countermeasures

Additions to the regulatory requirement

Earthquake, tsunami, volcano, heavy snowfall, and more



Countermeasures against chemically active sodium (Sodium reacts with air or water)

Early detection and control of the reaction

Advanced technology can detect minor leakage of water or steam into sodium.

If leakage occurs, a double boundary between piping and equipment as well as a compartment divided by walls can limit the effects of the reaction.

Improved seismic resistance

Absorption of earthquake vibration in three dimensions

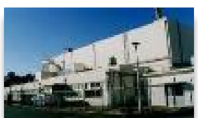
The system absorbs vibration in horizontal and vertical directions, strengthening the structure.

Achievements in the fuel cycle technology development

- ❑ Radioactive waste impact on the environment
- ❑ Geopolitical risks and stable electricity supply

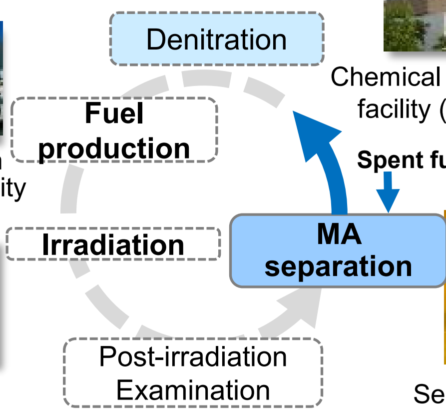
- ○ SmART cycle tests using a small amount of Minor Actinide (MA) recovered 2 grams of MA (the world's best recovery rate) for later MA-containing MOX pellet production
- ○ An irradiation test in Joyo showed the behavior of MA-containing MOX fuel
- ○ JAEA has developed long-life core materials (e.g., ODS steel cladding) that improve transmutation characteristics
- ○ MA cycle R&D is advancing through joint works with other countries such as the U.S. and France.

R&D on SmART cycle

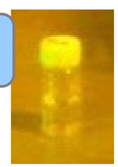


Post-irradiation examination facility (in Oarai)

Joyo (in Oarai)



Chemical processing facility (in Tokai)



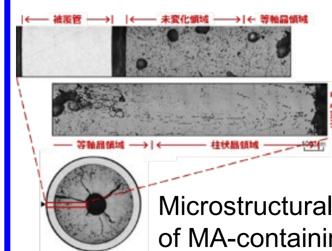
Separated MA solution

SmART cycle

SmART: Small Amount of Reuse Fuel Test Cycle

- To achieve conversion data and small-scale demonstration of the cycle feasibility
- It recovered approx. 2 grams of MA, which is worth several pellets, for fuel production and irradiation tests.

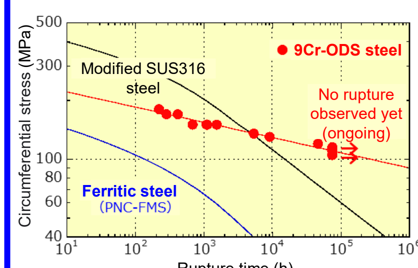
Irradiation test for MA-containing MOX fuel



Microstructural observation of MA-containing MOX fuel irradiated at Joyo

- It showed quantitative data on redistribution behavior of elements such as Am, and detailed microstructural change data needed for analyzing irradiation behavior.
- The test continues to develop a design code for MA-containing MOX fuel for the next irradiation test.

Development of long-life core materials



Internal pressure creep rupture strength of 9Cr-ODS steel cladding at 700°C

- Experiments demonstrated that ODS steel cladding maintains its world's highest creep strength level at high temperatures and long hours, equivalent to the operating conditions of a commercial FR.
- A large-scale attritor was installed to mass-produce ODS steel-coated tubes. The prototyping and performance tests have been conducted.

International cooperation in FR development

Strategic international cooperation: Leading fast reactor R&D, multinational programs, and international standard establishment by working together with the U.S. and France.

Japan-France

- R&D in 11 areas
- Digitization of plant characteristics, and sharing of test and verification data

Japan-the U.S.

- Participation in VTR/Natrium™ project*
- Co-development of structural materials, modeling & simulation, metallic fuel and pyrochemical reprocessing technologies, etc.

*Under negotiation

JAEA's International Cooperation Policy

- Japan-France and Japan-the U.S. bilateral programs develop SFR key technologies to have common technologies (e.g., design methods, safety technologies, and safety evaluation) and common plant concepts between the countries and develop them as global standards.
- Cooperation with multilateral organizations (e.g., GIF and IAEA) develops global standards, safety requirements, and design methods.

Generation-IV International Forum (GIF)

- International collaboration to develop safety design requirements
- Generation IV reactors, design methodology, data base

IAEA/NEA

- International standardization of safety design criteria
- Facilitating communication with regulatory authorities

ASME - JSME (Academic society)

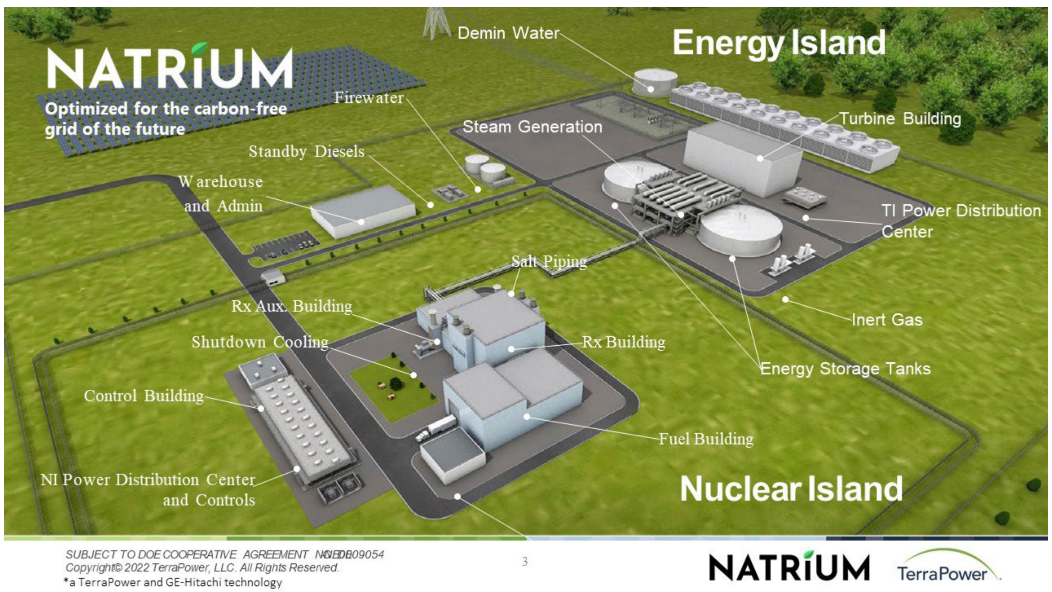
- International standardization of codes and standards, etc.

R&D cooperation with TerraPower of the U.S.

- In January 2022, TerraPower, JAEA, Mitsubishi Heavy Industries and Mitsubishi FBR Systems signed a memorandum of understanding for technical cooperation in the R&D of the Natrium* of TerraPower.

*Natrium: An SFR that uses thermal storage technology, planned to start operation in 2028

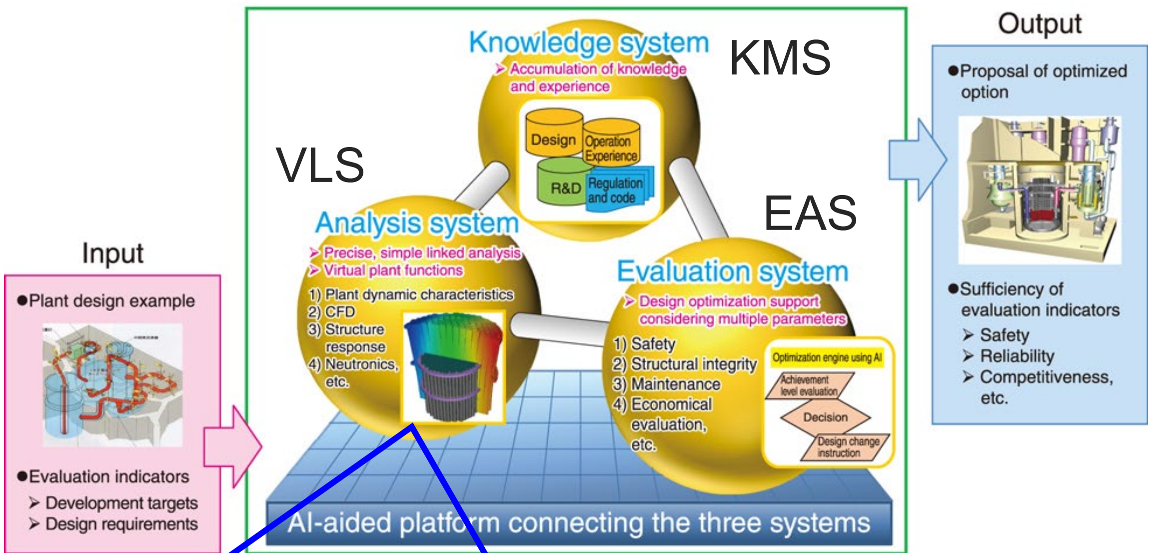
➢ The detailed cooperation areas for the demonstration of SFR technology under discussion are the following.

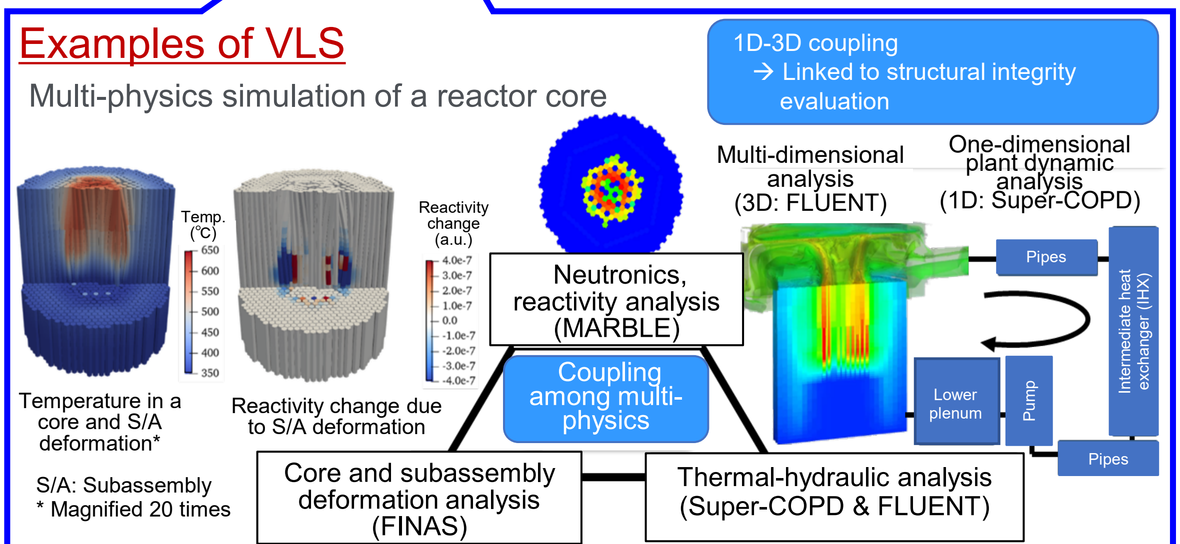


- Core and fuel
- Core components including control rods and shielding
- Reactor vessel and inner structure
- Main cooling systems including pumps and heat exchangers
- Decay heat removal system
- Fuel handling systems including fuel handling machine
- Instrumentation including failed fuel detection and location

*This slide is based on "Fast reactor development in TerraPower" presented at the 2nd meeting of the METI Advanced Reactor Working Group held on May 19, 2022

Platform development for innovations—ARKADIA





KMS: Knowledge Management System
VLS: Virtual plant Life System (Virtual Plant)
EAS: Enhanced and AI-aided optimization System

ARKADIA (Advanced Reactor Knowledge- and AI-aided Design Integration Approach through the whole plant lifecycle) = a digital triplet

1. A knowledge base for fast reactor design, construction, and R&D
2. Advanced analysis systems
3. An evaluation system that assists design work considering a whole plant lifecycle

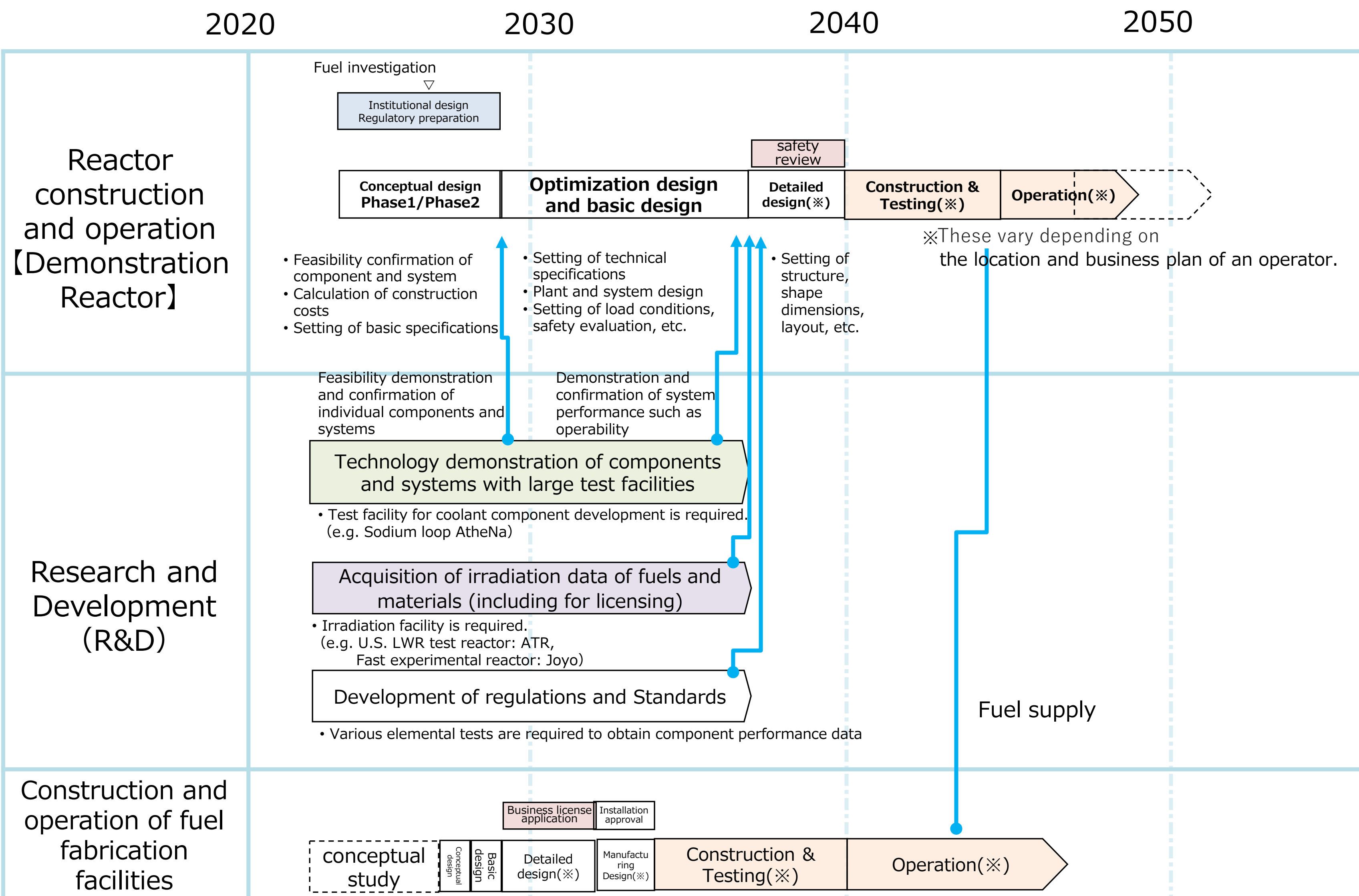
ARKADIA improves

- ➢ FR safety, economy, and decommissioning work;
- ➢ FR design processes;
  - It can substitute large experiments, thus reducing design time and cost.
  - ➔ It will enable publicly acceptable design concepts.
- ➢ private sectors' activities for advanced reactor technologies.

ARKADIA enables

- ➢ Competitive plant concepts complying with “3E+S” (Energy security, Economic efficiency, and Environment + Safety)
- ➢ Reduced development time and costs
- ➢ Transfer and accumulation of technology and human resource development, while preventing developed technologies from being broken into pieces and lost

Technology roadmap for introduction of FRs＊



＊This slide is based on *Technology roadmap for innovative reactor development: An interim summary* presented at the 4th meeting of METI Advanced Reactor Working Group held on July 29, 2022.

Contribution to non-energy fields

- The experimental fast reactor Joyo will serve not only for FR development but also medical radioisotope (RI) production. Although the RIs are crucial for advanced medical treatment, Japan is heavily relying on imports.

RI production using Joyo

Mass production: High neutron density allows mass production of RIs at a lower cost than using accelerators.

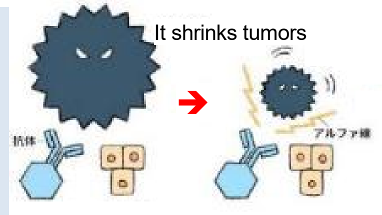
	Production (μg)	Cost (yen/μg)
Reactor (JRR-3) *per year	3,900	1,000
Accelerator *per irradiation	42	33,000

Comparison of molybdenum (Mo-99) production using nuclear reactors or accelerators

Mo-99
Used in nuclear medicine imaging to detect cancer metastasis

Rare RIs: Fast neutrons can be used to produce rare RIs such as Actinium (Ac-225)

With moderators, FRs can produce RIs that are similar to those obtained from an LWR.



Ac-225
Used in alpha internal therapy for cancer treatment

Expectations for domestic production of medical RIs by using JAEA's test and research reactors

- Submissions of requests for domestic RI production
  - from seven medical societies to MEXT* (Aug. 2020), and to ministers of relevant ministries and the chairman of Nuclear Regulation Authority (Jul. 2021)
  - from cancer patient associations and related organizations to MEXT (Aug. 2020).
  - from Japan Federation of Cancer Patient Groups to ministers of relevant ministries and the New Komeito (May 2021).
- Discussion on increasing medical RI production (the Committee on Audit of the House of Councilors, May 2021)
- Description on medical RI production using Joyo (the Green Growth Strategy, Jun. 2021)
- Establishment of the expert committee on RI production and use (the Atomic Energy Commission, Nov. 2021)
- Discussion on domestic production of medical RI (the Committee on Budget of the House of Councilors, Mar. 2022)
- An action plan (the expert committee of the Atomic Energy Commission, May 2022)

* MEXT: Minister of Education, Culture, Sports, Science and Technology

Summary

- To achieve carbon neutrality and ensure stable, inexpensive energy security regardless of situations overseas, nuclear technology is a competitive and realistic option. It has already provided more than 30% of Japan's electricity (70% in France).
- Next-generation reactors find many uses: support for renewable energy; carbon-free, stable, and inexpensive energy supply; and hydrogen and heat production. These all contribute to carbon neutrality in the industrial and transportation sectors.
- Using nuclear power inevitably requires plutonium management, reduction of the volume and toxicity of radioactive waste, efficient use of uranium resource, and commercialization of a fast reactor cycle with high safety.
  - Already achieved: MA separation, pellet production, and the understanding of in-pile irradiation characteristics in the cycle technology for waste volume reduction
- Commercialization of Japan's nuclear technologies (e.g., 950-degree heat from HTGR, and hydrogen production) will also serve national interests such as green growth.
- Russia and China are co-developing FRs and reaching commercialization with a view to exporting them. Japan has demonstrated FR technology through Monju and is attracting international attention as seen in Japan-France cooperation and cooperation with TerraPower.
- Fast reactors are capable of mass-producing Ac-225, a radioactive isotope gaining global attention for cancer treatment. The production will be demonstrated at Joyo by Japanese fiscal year 2026 based on the action plan established by the Atomic Energy Commission.

➡ With these advanced technologies, JAEA will contribute to achieving a net-zero carbon world, supplying continuous, stable, and inexpensive energy, and improving national welfare.