Nuclear Innovations for Carbon Neutrality

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Contents

Current status of energy supply in Japan

- Energy supply in Japan
  - Self-sufficiency rate[*1] of energy : 12.1%
  - Composition of electric power supply[*2] : Thermal power 75.7%; Variable zero emission (solar, wind) 7.5%; Stable zero emission (stable renewables, nuclear) 16.8%
  - 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.

	Japan	France	China	India	Germany	Britain	USA
Energy self-sufficiency ratio	12%[*1]	55%[*3]	84%	65%	37%[*3]	70%[*3]	98%[*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 2021

*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 2020: 10 questions to understand the current status of energy (in Japanese)

Japan's nuclear energy policy on carbon neutrality

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 resources.
- Nuclear power can satisfy various public needs, such as harmonization with renewable energy, carbon-free hydrogen production, and heat applications for industrial use.

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

The 6th Strategic Energy Plan (excerpts on nuclear)

【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 under a consensus on ensuring safety.

【Policies for 2030】

- Promotion of R&D
  - ✓ Advance the development of fast reactors through international cooperation
  - ✓ Demonstrate small modular reactor technology with international partners.
  - ✓ Develop the basic technology of hydrogen production using high temperature reactor (HTGR)

Nuclear innovation required

- Under a consensus on nuclear safety improvement
  - ✓ Supply stable power (large scale stability + safety and supply chains + technological self-sufficiency)
  - ✓ 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

- Reduce high-level radioactive waste.
- Become a recyclable energy source through technological innovation.
- Propose solution to limited natural resources.

Flexibility

- Provide load following to maximize the use of affordable renewable energy.
- Hydrogen production, heat utilization and heat storage during low demand of electricity
- Be flexible in site locations by reducing the sizes of emergency planning zones.

Further improvement in nuclear safety

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

From materials for the Atomic Energy Sub-Committee (Apr. 2021)

Initiative to accelerate nuclear innovations

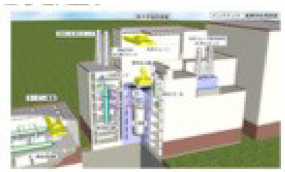
NEXIP : Nuclear Energy × Innovation Promotion

A new initiative to help accelerate the development of innovative nuclear technologies through financial support, making easy access to R&D facilities, and human resource development efforts.

METI Ministry of Economy, Trade and Industry | MEXT Ministry of Education, Culture, Sports, Science and Technology-Japan | JAEA Japan Atomic Energy Agency

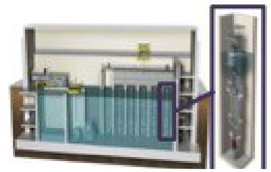
Innovative nuclear technologies

- **Fast Reactor (FR)**
  - Promote competition of various types of FR based on Strategic Roadmap (2018 Dec.)



Fast Reactor

- **Advanced Reactors**
  - Promote the innovations of nuclear technologies to meet needs in the public



Small Modular LWR

HTGR

Collaboration between research laboratories, and development support for private sectors

- **Promote private sectors' development by using JAEA facilities**
  - R&D knowledge sharing
  - Easier access to test facilities

Experimental Fast Reactor Joyo

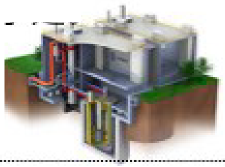
International Collaboration including Private sectors

France

- Development of sodium-cooled fast reactors (SFRs)
- R&D of various FR types
- Simulation, verification and validation

U.S.

- Promotion of nuclear innovations through GAIN initiative
- A small modular LWR will start commercial operation in 2026 with the help of GAIN
- A fast neutron reactor, Versatile Test Reactor (VTR), is newly developed to advance nuclear technologies



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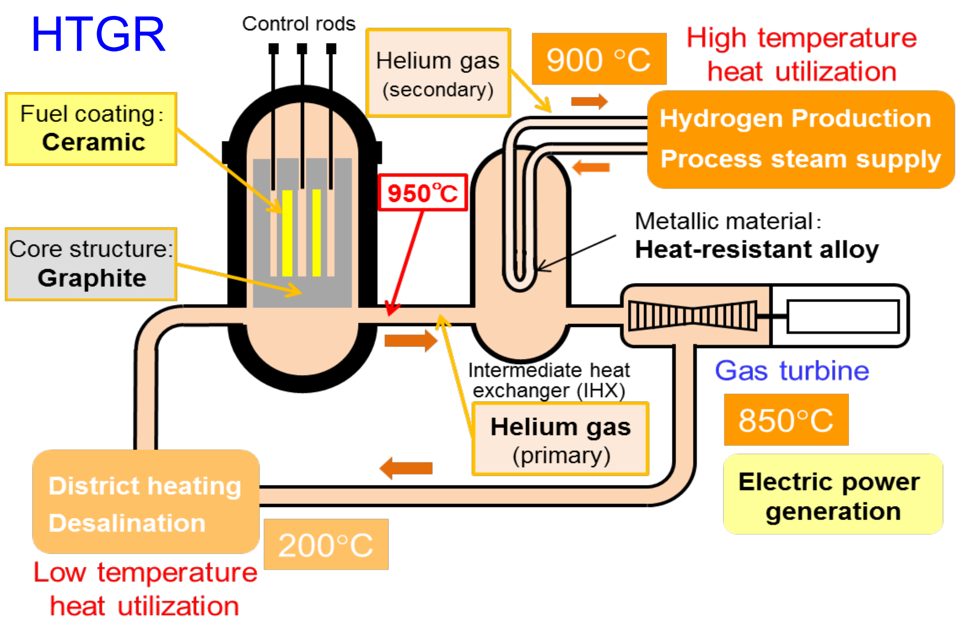
This slide is based on "Pursuing of Nuclear Innovation" (page 4) presented by Kentaro Funaki of Agency for Natural Resources and Energy, MEXT, in a session "Safety of Advanced and Innovative Nuclear Reactors and the Preparation of Regulatory Infrastructure" organized by the Safety Division of the Atomic Energy Society of Japan (September 18, 2020).

High Temperature Gas-cooled Reactor (HTGR)

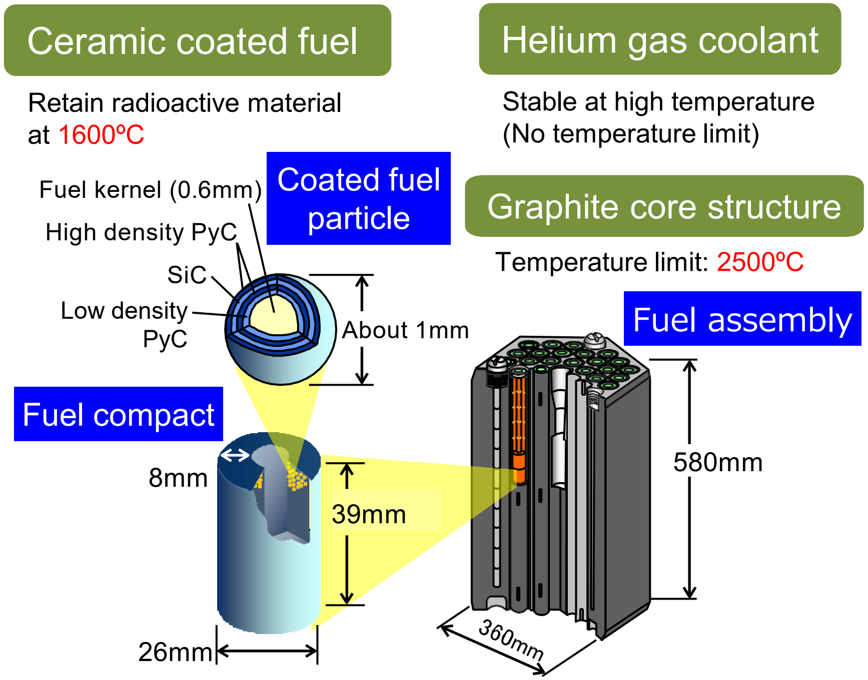
Flexibility

- HTGR can supply about 900°C of heat to various applications
  - ➢ Electric power generation
  - ➢ Hydrogen production
  - ➢ Desalination, etc



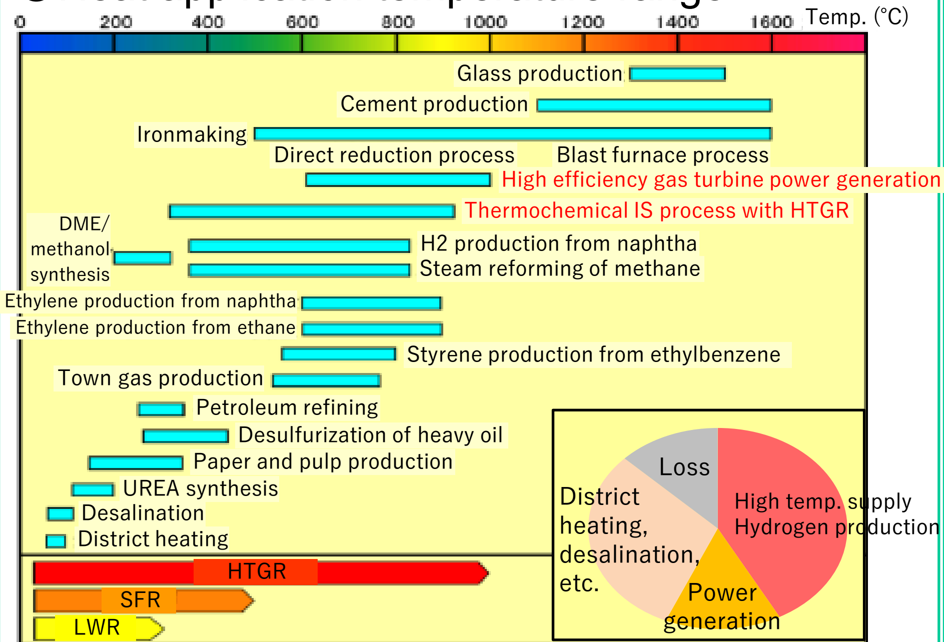
Superior inherent safety

- The reactor core is cooled by chemically inert helium gas.
  - ➢ No hydrogen explosion
- Core materials consist of ceramic coated fuel particles and graphite structures with high heat resistance.
  - ➢ No core melting
  - ➢ Slow and limited temperature transient in an accident



Various applications of heat from HTGR

○Heat application temperature range



Cogeneration system (Hydrogen, power generation, desalination, etc.

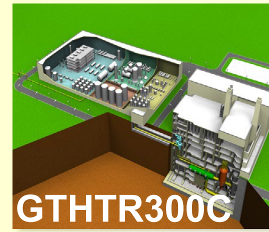
hydrogen, heat

electric power

HTGR hydrogen town

- Cogeneration system with hydrogen production, power generation and desalination
- Heat utilization efficiency: about 80%

Hydrogen production system



H_2

Fuel cell vehicle

Ironmaking

- Hydrogen production with thermochemical method (IS process) and steam methane reforming

High heat supply, cogeneration for industrial application

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 grid

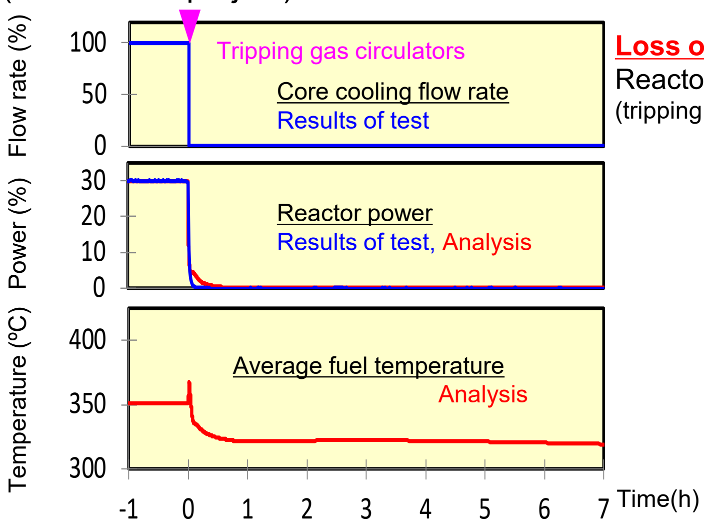
Hydrogen production

- Adjust renewable power variation by changing the ratio of HTGR power generation and hydrogen production, while keeping high power generation efficiency

Test plans using High Temperature engineering Test Reactor (HTTR)

Safety demonstration tests

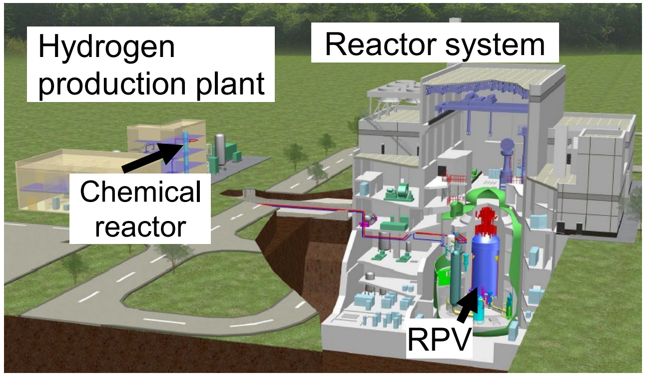
✓ Safety demonstration tests including loss of core cooling test (OECD/NEA project) and thermal load fluctuation test



Loss of forced cooling test
Reactor power: 9 MW (30%)
(tripping all gas circulators)

Demonstration of inherent safe characteristics, i.e. passive decay and residual heat removal, intrinsic reactor shutdown

HTTR-heat application test



- ✓ Couple a hydrogen production plant constructed under conventional industrial regulations with a nuclear reactor to provide a broader range of convenient applications of nuclear heat to users
- ✓ Develop the coupling technology between HTGR and a hydrogen production plant employing steam methane reforming process by 2030
- ✓ In parallel, investigate the feasibility of carbon-free hydrogen production technologies such as a thermochemical hydrogen production method
- ✓ Demonstrate the coupling technology between HTTR and a carbon-free hydrogen production plant in the future

Establishment of a safety design for coupling between HTGR and a hydrogen production plant

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
HTTR	▼Permission by NRA	▼Restart; Safety demonstration test, etc.	Thermal load fluctuation test, etc.							
HTTR-heat application test			Demonstration test for inherent safe characteristics		Technology development for carbon-free hydrogen production					
		Promotion of international cooperation using the HTTR which can provide world's highest temperature at 950°C								
		Establishment of carbon-free hydrogen production technology using high temperature heat (IS process, methane pyrolysis method, etc.)								

Demonstration of safety features and establishment of H_2 production technology with HTGR

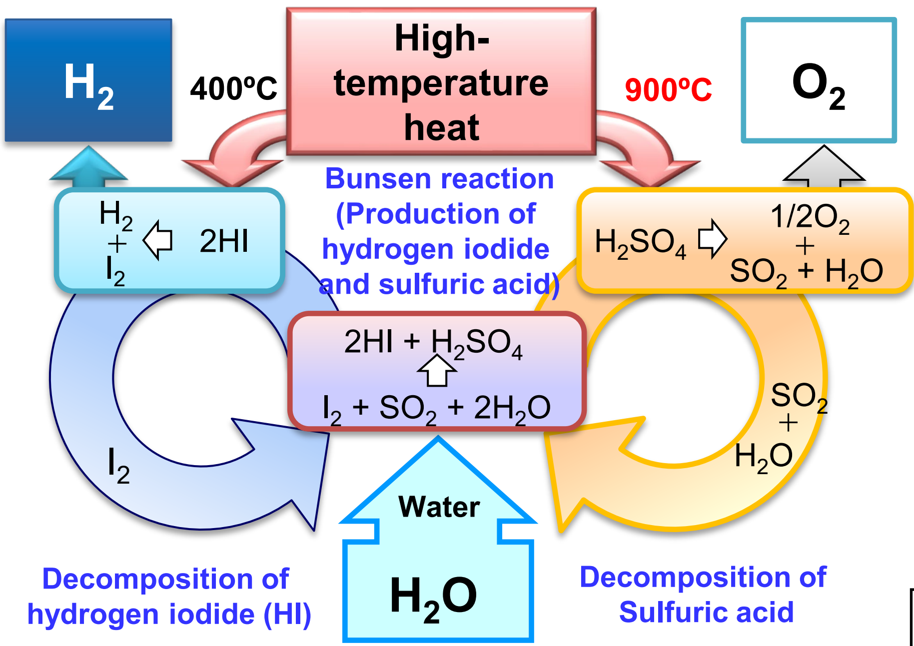
Thermo-chemical hydrogen production by IS process

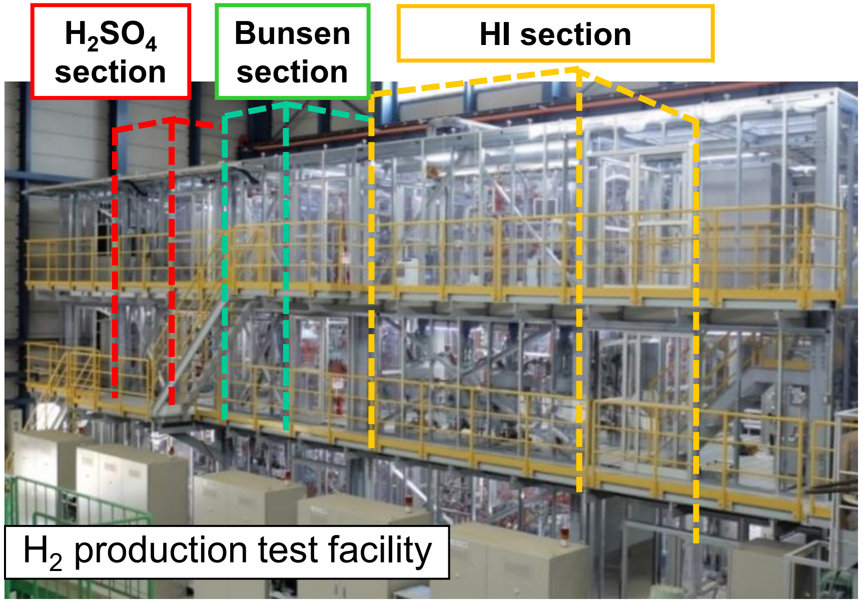
- Thermal decomposition of water requires heat 4000ºC or higher.
- IS (iodine-sulfur) process use ca.900ºC heat to decompose water through chemical reactions of iodine (I) and sulfur (S).

  Iodine and sulfur circulate in the process. ⇒ No harmful waste

  HTGR heat is used. ⇒ Zero CO_2 emission

Thermochemical hydrogen production IS process





- Constructed in 2014 March, H_2 production： ＜ 0.1 m^3/h
- W 18.5 × D 5.0 × H 8.1(m), Heated by electricity

- In FY2018, the facility made of industrial materials in practical use achieved the world's first 150-hour straight operation and produced hydrogen at a rate of 30L/h, verifying the effectiveness of the operation procedure.
- In FY2019, we confirmed that the startup and shutdown procedures used in the operation are applicable to its operation connected to HTTR, and that after operation, corrosion-resistant equipment materials had no harmful corrosion.
- In FY2020, it achieved 92L/h. Physical property data of multi-component solutions were obtained to control the composition during operation through hydrogen production tests. A solution composition calculation method using the data was proposed and validated.

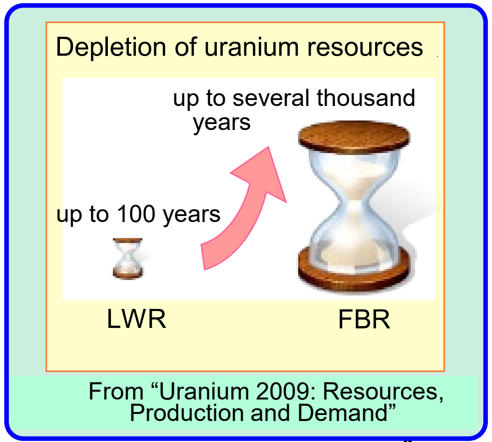
Future technical challenges

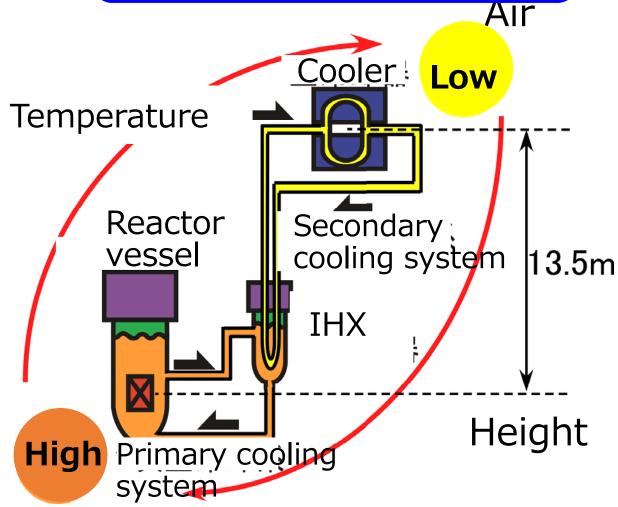
- Cation exchange membranes for higher thermal efficiency
- Ceramic reactors for higher pressure operation
- Process components for affordable hydrogen production

Fast Reactor (FR) cycle

Features

- Efficient utilization of uranium resources (x 10 more 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 emissions of CO_2
- 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 a Pu management.
  → Reduction of environmental burden
- Not only a base-load, but also a dispatchable power source that complements variable renewables (solar and wind) by combination with thermal storage.
  → Harmonize with and maximized use of 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)
  → High level of safety





Decay heat removal by natural circulation

Innovative technology that meets the requirements by the green growth strategy

Future issues

- Further improvement in safety and economic efficiency

Milestones of FR development and options

2019	Development efforts in the next 10 years	Around the mid-21st century	Late 21st century
Strategic roadmap※	Breakthrough	Operation of FR on a realistic scale at that time	Commercial use

Private sector, Universities

JAEA

Technology Innovations

- Reactor core safety
  - ✓ Elimination of core melting
  - ✓ Passive reactor shutdown
  - ✓ In-vessel retention of severe accidents
- Fuel cycle
  - ✓ Flexible use of Pu
- Economy, environment
  - ✓ Cost reduction in development, construction, etc.
  - ✓ Use of AI
  - ✓ Harmonization with variable renewables
- Maintenance
  - ✓ Reliable and risk-base design
  - ✓ Use of IoT

Address various needs and options

Options	Needs of society
Base load large reactor	• Long-term, stable base-load power supply by effective use of uranium resource (Energy security) • Use of Miner Actinides as fuel
Pu burner	• Long-term use of LWRs • Pu management • Volume reduction of High Level radioactive Waste (HLW)
Small modular reactor etc.	• SMART grids • Harmonization with variable renewables (for higher reliability of grids)

※ Decided at the Nuclear Ministerial Meeting in December 2018

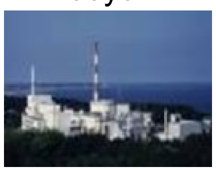
Outline of research and development in JAEA

Strategic roadmap for fast reactors

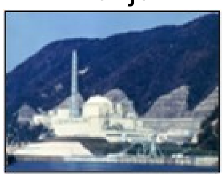
- Develop basic technologies and research infrastructures which can meet private sectors' needs in various technology development
- Establish "R&D platform", including R&D infrastructures and knowledge which have been accumulated through the development of sodium-cooled fast reactors

Design assistance tool on plant lifecycle (ARKADIA)

Joyo

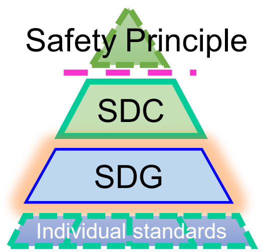


Monju



- An AI-based knowledge base that includes design, construction and R&D on Joyo, Monju and design studies
- Evaluation methods for complex phenomena using multi-physics models can be applied to various coolants and systems

Codes and Standards



Rank of SDC and SDG

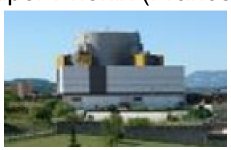
- Development of codes & standards, and design criteria applicable to various FR concepts
  - ➢ These can balance safety and economic efficiency.

Safety enhancement technology

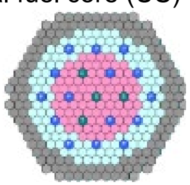
- Reactor core safety, including prevention of re-criticality and core melting accidents.
- Prevention and mitigation of specific events of FR including chemical reaction of coolant

International cooperation

Super Phenix (France)



Metal fuel core (US)



- France, having extensive experience of sodium-cooled fast reactors
- US, leading the development of metallic fuels, analysis codes, versatile test reactor (VTR) project, etc.

- Establishment of basic technologies for practical use

Support of R&D done by private sector

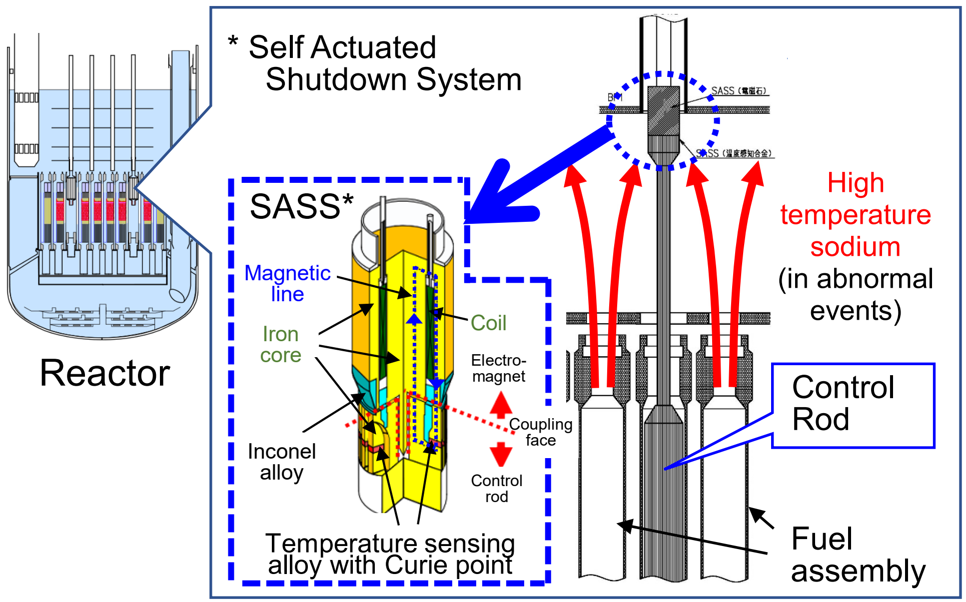
- Strengthen cooperation with industries and related ministries to narrow down technologies possibly adopted after 2024
- Promote R&D for the introduction of FRs at an appropriate time in the mid-21st century

Safety enhancement of FR

■ Example of enhanced countermeasures against core disruptive accidents (CDAs)

- Background: Since an FR core is not the maximum reactivity configuration, core material relocation caused by a CDA has a potential to induce reactivity insertion.

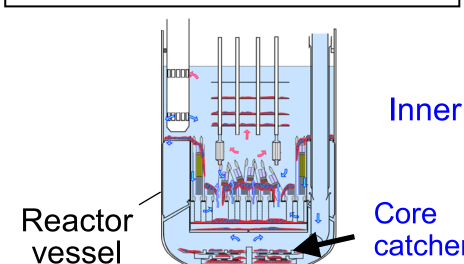
- <u>CDAs can be prevented. If a CDA should occur, re-criticality can be prevented (CDA is mitigated)</u>
  - ➢ Reactor shutdown device passively induces negative reactivity during abnormal events (spontaneous insertion of control rods using a temperature sensing alloy)
  - ➢ Mechanism to achieve and maintain subcriticality by spontaneously discharging molten fuel materials from the core (by means of Fuel Assembly with Inner-Duct Structure (FAIDUS) which enables early discharge of molten fuel from the core in a core melt accident)

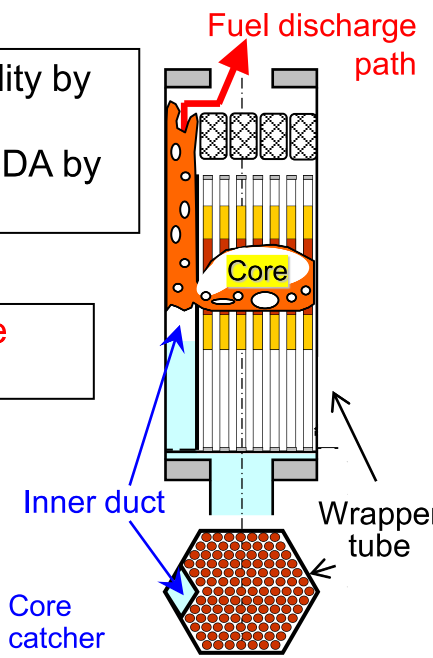


- Stability and operability of SASS during normal operation were confirmed under reactor condition at Joyo.
- Effectiveness of SASS at accident conditions was confirmed by sodium test.

- Elimination of re-criticality by using FAIDUS
- In-vessel retention of CDA by using core catcher etc.

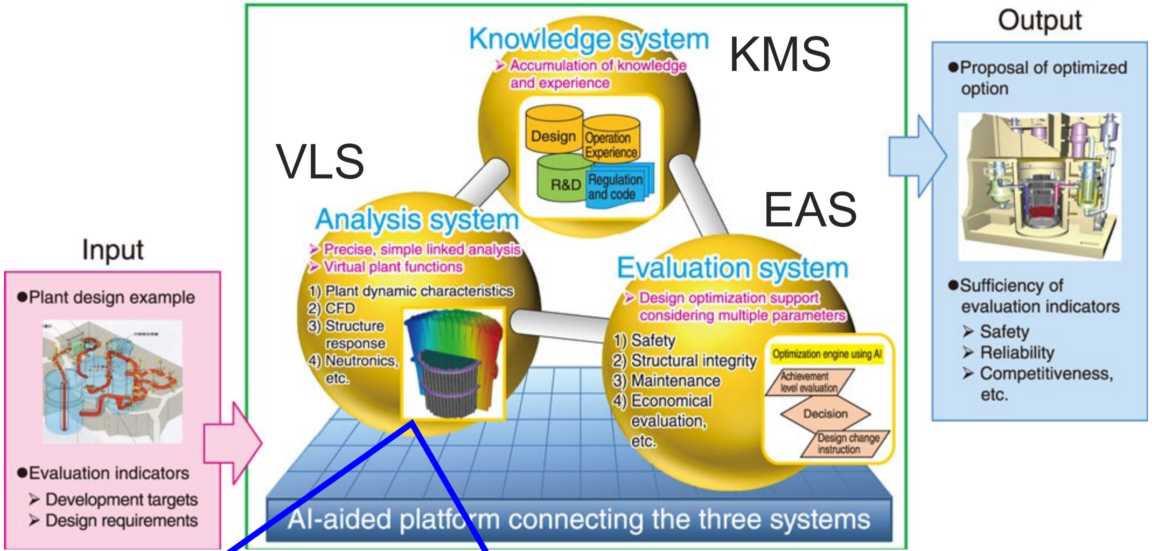
No impact on the environment

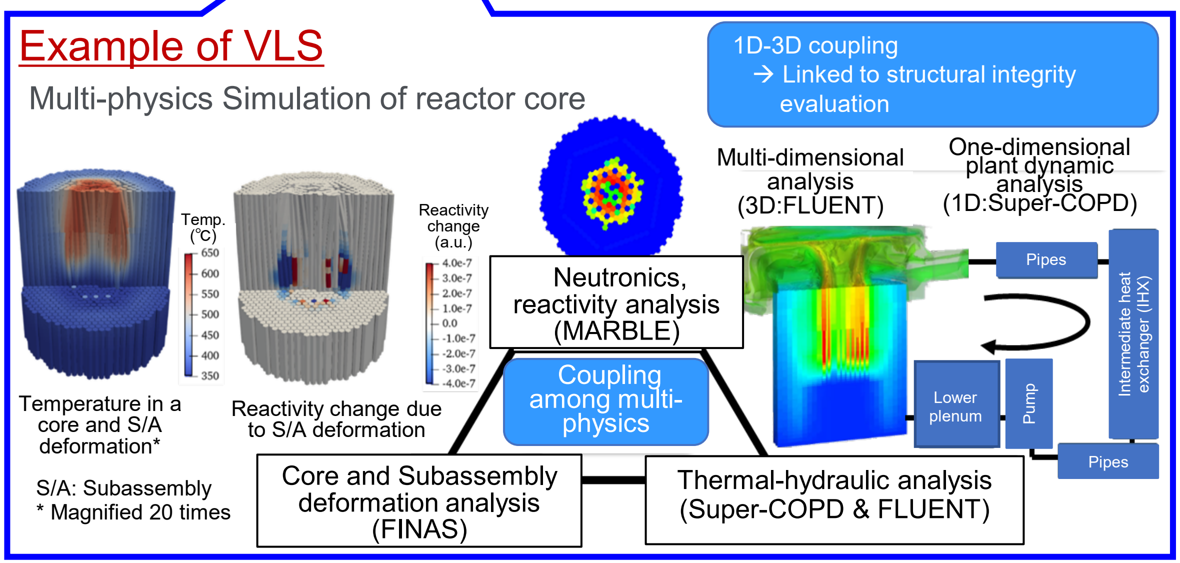




- Fuel discharge behavior was confirmed by in-pile experiments in IGR in Kazakhstan.

Platform development for innovations –ARKADIA as a Digital Triplet





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

- ARKADIA as a Digital Triplet
  1. Knowledge base for fast reactor design, construction, and R&D
  2. Advanced analysis systems
  3. Evaluation system that assists design considering a whole lifecycle of a plant

  → To improve safety, economic and decommissioning
- Improve FR design processes
  - ✓ Reduce design duration and costs as a substitute for large experiments
  - ✓ Concept construction and design for public acceptance
- Support private sector's activities for advanced reactor technologies

⇩

- Competitive plant concepts complying with “3E+S” (safety, energy security, economic efficiency, and environment)
- Reduced development period and costs
- Transfer and accumulation of technology and human resource development, rather than technology dissipation

Contribution of FR to non-energy fields

Production of medical and industrial radioisotopes: Contribution to domestic supply

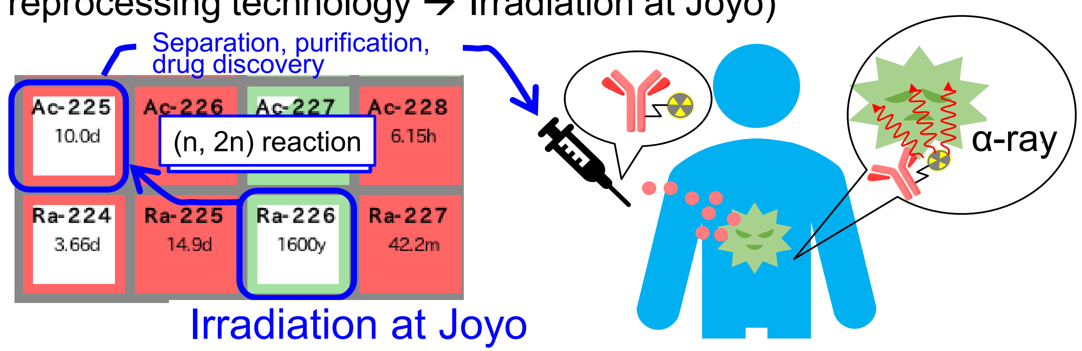
- Provide a neutron irradiation field with wide energy spectra, high flux and a large capacity
  - ✓ Neutron capture reaction (medium and slow to thermal neutrons)
  - ✓ (n, 2n) reaction (by high energy fast neutron)

  } Efficient RI production
  - ✓ Higher flux and larger capacity than accelerators allow mass production of RI

- Nearly 100% imported → Domestic production of RIs (according to its applicability to the market)
  - ✓ Industrial use: Co-60 ：Liquid level gauge, crop breeding, etc. Ir-192：non-destructive inspection
    Ni-63 ：Environment analysis Fe-55：Calibration source, etc.
  - ✓ Medical use: Co-60 ：Sterilization, cancer (gamma knife) Ir-192： Brachytherapy
    Au-198：Brachytherapy Ac-225： RI internal therapy, etc.

Contribute to the domestic RI supply system in cooperation with JRR-3 research reactor for stable supply

- ✓ Production of Ac-225 for RI internal therapy → Higher efficiency by fast neutrons
- ✓ Cooperation with universities, and utilization of JAEA's technologies (Pretreatment: reprocessing technology → Irradiation at Joyo)



Summary

■ Role of nuclear energy and advanced reactors toward carbon neutrality by 2050

- Nuclear energy, a carbon-free power source, can support variable renewables to constantly supply zero-emission energy. Promising innovative options include high temperature gas-cooled reactors (HTGRs) and fast reactors (FRs) offering enhanced safety and economic efficiency.
- Hydrogen and heat production using a HTGR can meet various needs in the public, such as reduction of greenhouse gas emissions from manufacturing and transportation sectors.
- Sustainable electricity supply using nuclear energy requires the development of a FR cycle (closed fuel cycle) system that efficiently uses natural resources and reduces the volume and toxicity of high-level radioactive waste.

■ Nuclear innovations by JAEA for carbon neutrality

Promote the development of HTGRs and FR cycle that contribute to nuclear innovations

- HTGR
  - JAEA will strongly contribute toward early deployment of HTGRs based on advanced technologies, such as the design, construction, and operation of the HTTR, the experience to meet the new regulatory requirements after 1F accident, gas turbine, hydrogen production, etc.
  - JAEA focuses to achieve international expansion of Japan's HTGR technologies.
- FR cycle
  - JAEA will establish innovative FR concepts offering enhanced safety and further develop FR basic technology and infrastructures using reactor and fuel cycle technologies accumulated through the construction and operation of Joyo and Monju, accelerating the FR development.
  - JAEA continues R&D efforts to reduce the volume and toxicity of high-level radioactive waste to achieve a closed fuel cycle.