Development of Next-Generation Sodium-Cooled Fast Reactor

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Outline

1. Nuclear Energy Development in Japan
2. Strategic Roadmap of Fast Reactor Development
3. Development of SFRs in Japan
4. Pool-type SFR for demonstration reactor
5. SFR-related activities in JAEA

Nuclear Energy Development in Japan

August 24, 2022, GX (Green Transformation) Implementation Council

- Prime minister Kishida expressed that making up for the delay in energy policies is a pressing issue in implementing GX.
- Items requiring political decisions to expand the introduction of renewable energy were presented today, including
  - drastically accelerating the development of power systems,
  - speeding up the installation of fixed storage batteries, and
  - promoting offshore wind power and other electricity sources.
- At the same time, items requiring future political decisions concerning nuclear power were also put forward, such as
  - combined efforts by the concerned parties to resume operations,
  - maximum utilization of existing nuclear power plants including the extension of their operation period with ensuring their safety being a major precondition, and
  - development and construction of next-generation innovative reactors that incorporate new safety mechanisms.
- We have discovered additional, distinct advantages of next-generation advanced reactors such as coexistence with renewables and hydrogen usage. Given these and the global circumstances, we will identify challenges that Japan's reactor development will face, and build a technical roadmap that solves all of them.

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Basic policy for Nuclear in Green Transformation (GX)

Dec. 22, 2022, Japanese government's GX Implementation Council

- Basic policy with a ten-year roadmap issued in Dec.
  - The maximum use of nuclear power, given that it treats it as "a power source contributing to energy security and highly effective for decarbonization."
  - Actualization will be embarked upon starting with the replacement of reactors for which decommissioning has been decided."
  - The development and construction of reactors other than those to be replaced will be considered
  - Additional extensions may be allowed where reactor operation was suspended for certain specified reasons," building on the current approach of a reactor operating lifetimes of 40 years, possibly to be extended to up to 60 years.

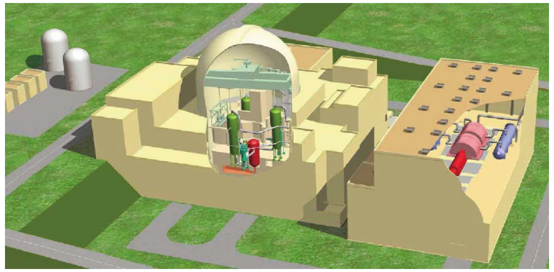
Feb. 10, 2023, Japanese government's GX Implementation Council

- Basic policy toward GX realization
  - To achieve decarbonization, stable energy supplies and economic growth simultaneously.
  - Public-private GX investments exceeding JPY150 trillion (approximately USD1.14 trillion) during the coming decade

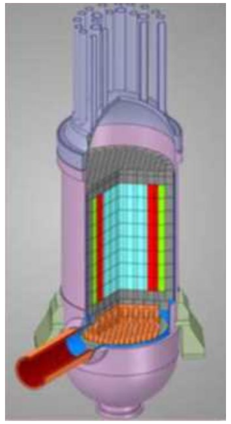
Technical roadmap for innovative reactors in Japan

- Apr.-Nov. 2022, the direction of innovative reactors was discussed in METI
- Nov. 2022, Japan developed the technical roadmap that shows timeline and milestones of detailed processes, and update it as necessary.

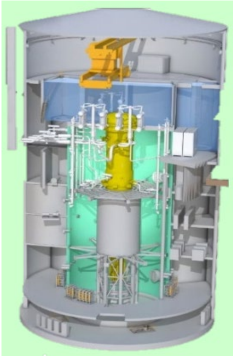
- Advanced light water reactors (LWRs)
- Light water-cooled small modular reactors (LW SMRs)
- Fast reactors
- High temperature gas-cooled reactors (HTGRs)
- Fusion reactors



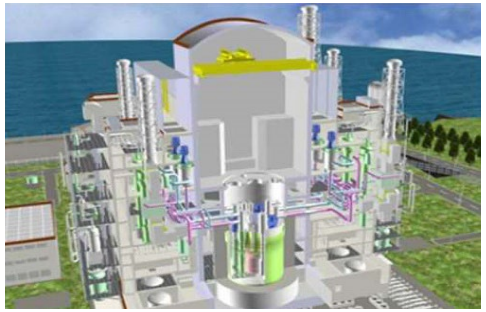
Large-scale advanced LWR



HTGR



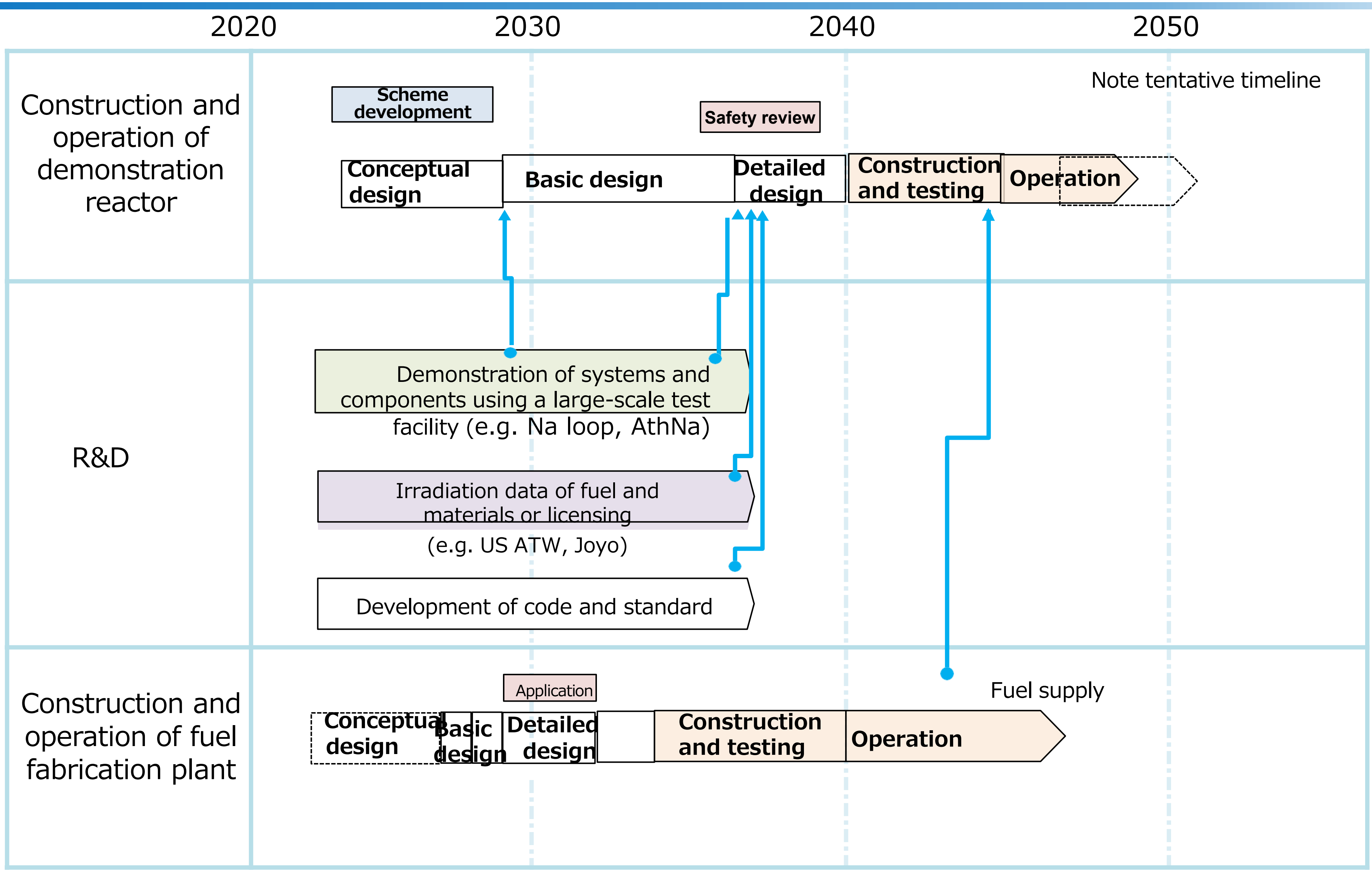
LW SMR



Fast reactor

Preliminary Roadmap as of 29th Nuclear Energy Subcommittee (Aug. 9, 2022)

Technical roadmap (Fast reactor)



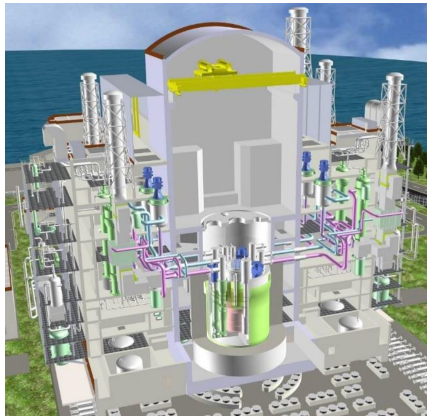
Strategic Roadmap of Fast Reactor Development (2022) Demonstration fast reactor

- A revised strategic roadmap was approved by a ministerial meeting on December 23th, 2022.

  - ✓ 2023 Summer: selection of a demonstration reactor concept and a core company.
  - ✓ 2024-2028: conceptual design and related R&D
    - Severe accident experiments
    - Irradiation in Joyo
    - Material experiments
    - AtheNa experiment (component demonstration)
  - ✓ 2026: fuel selection (oxide or metal)
  - ✓ 2028-: Basic design study and licensing application
  - ✓ 2040s: start operation

July 12, 2023, METI

- ➢ Selected Mitsubishi Heavy Industries, Ltd.
  - ➢ as the core company in charge of the conceptual design of the demonstration fast reactor
- ➢ The pool-type sodium-cooled fast reactor plant concept proposed by Mitsubishi FBR Systems, Ltd. was selected as the target concept of the demonstration reactor.
- ➢ The electric output of the demonstration reactor is 650MWe.



Tank-type sodium-cooled fast reactor
(https://www.mhi.com/news/23071202.html)

https://www.meti.go.jp/shingikai/enecho/denryoku_gas/genshiryoku/pdf/036_01_00.pdf
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https://www.mhi.com/news/23071202.html

Development of sodium cooled fast reactors (SFRs) in Japan

Development led by JAEA

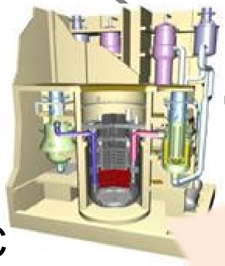
led by Private sector

JSFR

Design Study for Commercialization

Power：600~1500 MWe

Temperature ：500~550ºC



Commercialization

- Demonstration of economics
- Demonstration of reliability

<u>Scheduled operation by ~2050</u>

Power：650 MWe (demonstration)

Temperature ：500~550ºC

Innovative Technologies for Safety Enhancement

Joyo

Experimental

(under safety review by regulator)

- Basic and fundamental study
- R&D of advanced technologies

<u>Initial Criticality in 1977</u>

Power：50MWt → 100MWt → 140MWt → 100MWt (Mk-IV Core)

Temperature：435ºC → 500ºC → 500ºC

Monju

Prototype

(decided decommissioning in 2016)

- Demonstration of reliable operation
- Demonstration of innovative technologies

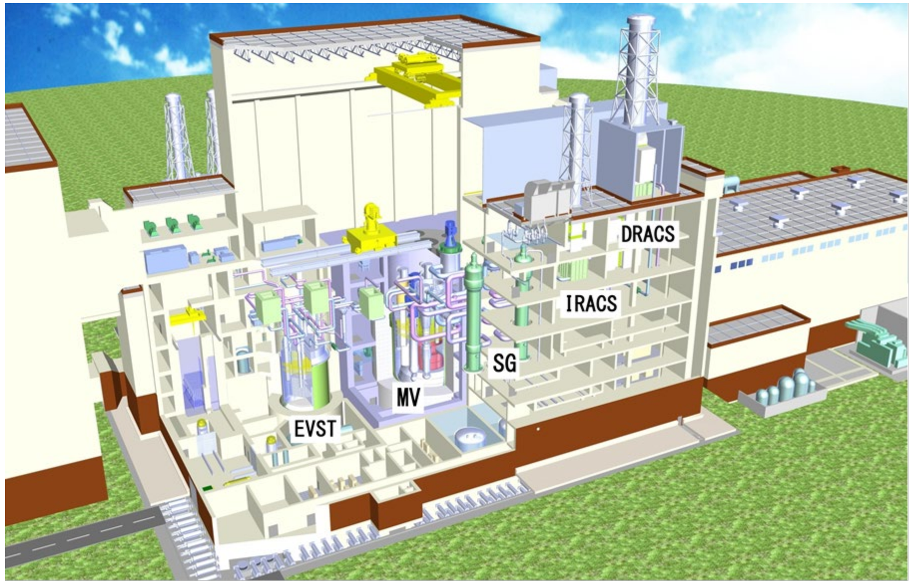
<u>Initial Criticality in 1994</u>

Power：714MWt / 280MWe, Temperature：529ºC

Main design specifications of the pool-type SFR for demonstration reactor

Item	Values or Systems
Power	1500MWt / 650 MWe
Core inlet / outlet coolant temperature	550/400 deg. C
Fuel type / Assembly	MOX fuel / Assembly with inner duct which discharges molten fuel
Primary pumps	Three mechanical pumps

Item	Values or Systems
Intermediate Heat Exchangers (IHXs)	Four IHXs (Straight tubes containing secondary coolant inside)
Secondary pumps	Four mechanical pumps
Power conversion systems	Four steam generators, one water-steam turbine



Higurashi, K., et al., Joint IAEA-GIF Workshop on the Safety of Non-Water Cooled Reactors, Vienna, Austria, 30 May-2 June 2023

Main safety features of the pool-type SFR for demonstration reactor

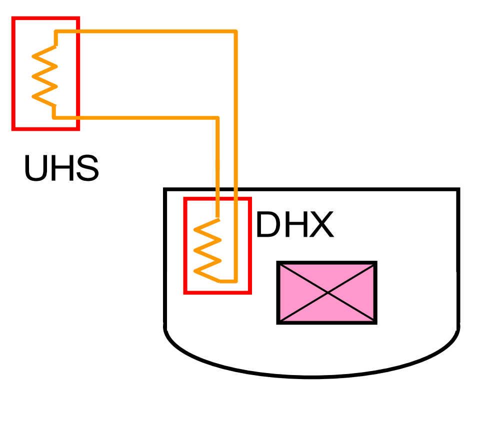
	Safety features
(i) Reactor shutdown measures	● Two active reactor shutdown systems ● Passive reactor shutdown measure: Self-Actuated Shutdown System (SASS) using a Curie point electromagnet
(ii) Measures to achieve IVR of damaged core	● Measures to mitigate the consequence of core damage resulting from anticipated transients without scram (ATWS) (reduction of void reactivity to approximately 6$ or less, provision of the fuel assembly with inner duct structure, transfer of re-molten fuels from the control rod guide tube, and stable cooling and retention using a core catcher)
(iii) Measures for decay heat removal	● Prevent complete loss of decay heat removal function: Decay Heat Removal System (DHRS) configuration considering the use of natural circulation capability: ➢ One immersed Direct Reactor Auxiliary Cooling System (DRACS) ➢ Four Intermediate Reactor Auxiliary Cooling Systems (IRACS) ➢ One penetrated DRACS ● Prevent core uncovering and ensure primary coolant paths for decay heat removal: practical elimination of double leakage by securing high reliability of the main vessel and the safety vessel

Higurashi, K., et al., Joint IAEA-GIF Workshop on the Safety of Non-Water Cooled Reactors, Vienna, Austria, 30 May-2 June 2023

Type of decay heat removal system

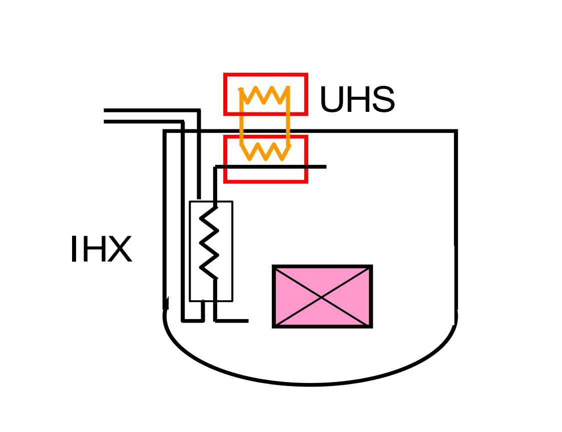
DRACS

Direct Reactor Auxiliary Cooling System



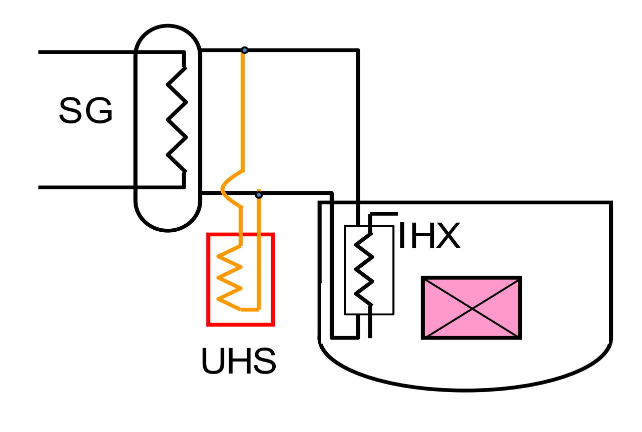
PRACS

Primary Reactor Auxiliary Cooling System



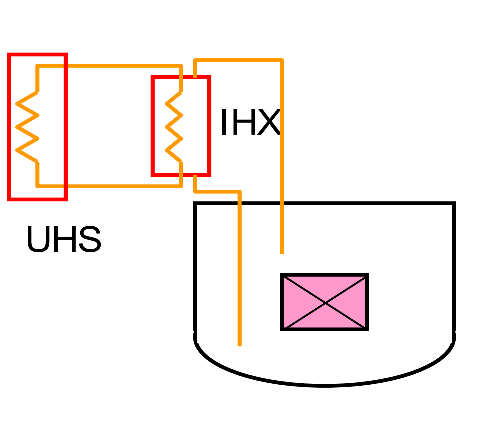
IRACS

Intermediate Reactor Auxiliary Cooling System



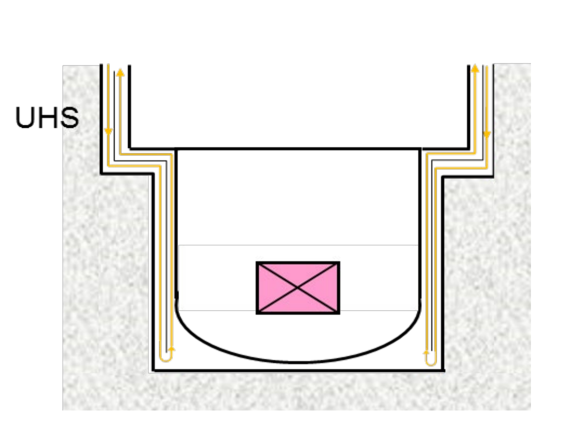
RACS

Reactor Auxiliary Cooling System



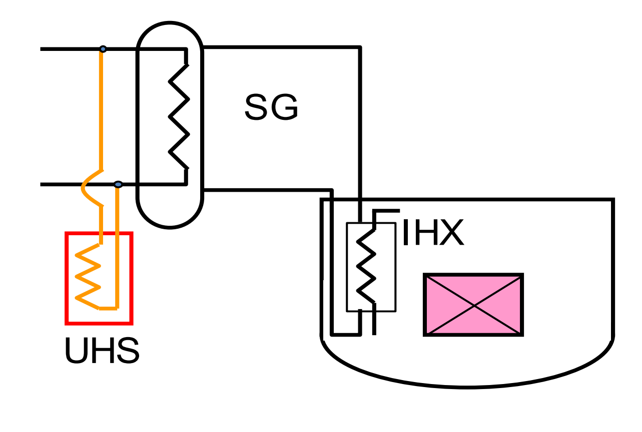
RVACS

Reactor Vessel Auxiliary Cooling System



SGACS

Steam Generator Auxiliary Cooling System



Ref.: S. Kubo et al., A conceptual design study of pool-type sodium-cooled fast reactor with enhanced anti-seismic capability, Bulletin of the JSME Mechanical Engineering Journal Vol.7, No.3, (2020)

Safety design of Decay heat removal system (DHRS)

Safety design

- ✓ Passive reactor shutdown
- ✓ Measures against CDAs
- ✓ <u>Measures to secure decay heat removal</u>
- ✓ Containment vessel
- ✓ Measures against sodium leak and sodium fire
- ✓ Measures against sodium-water reaction

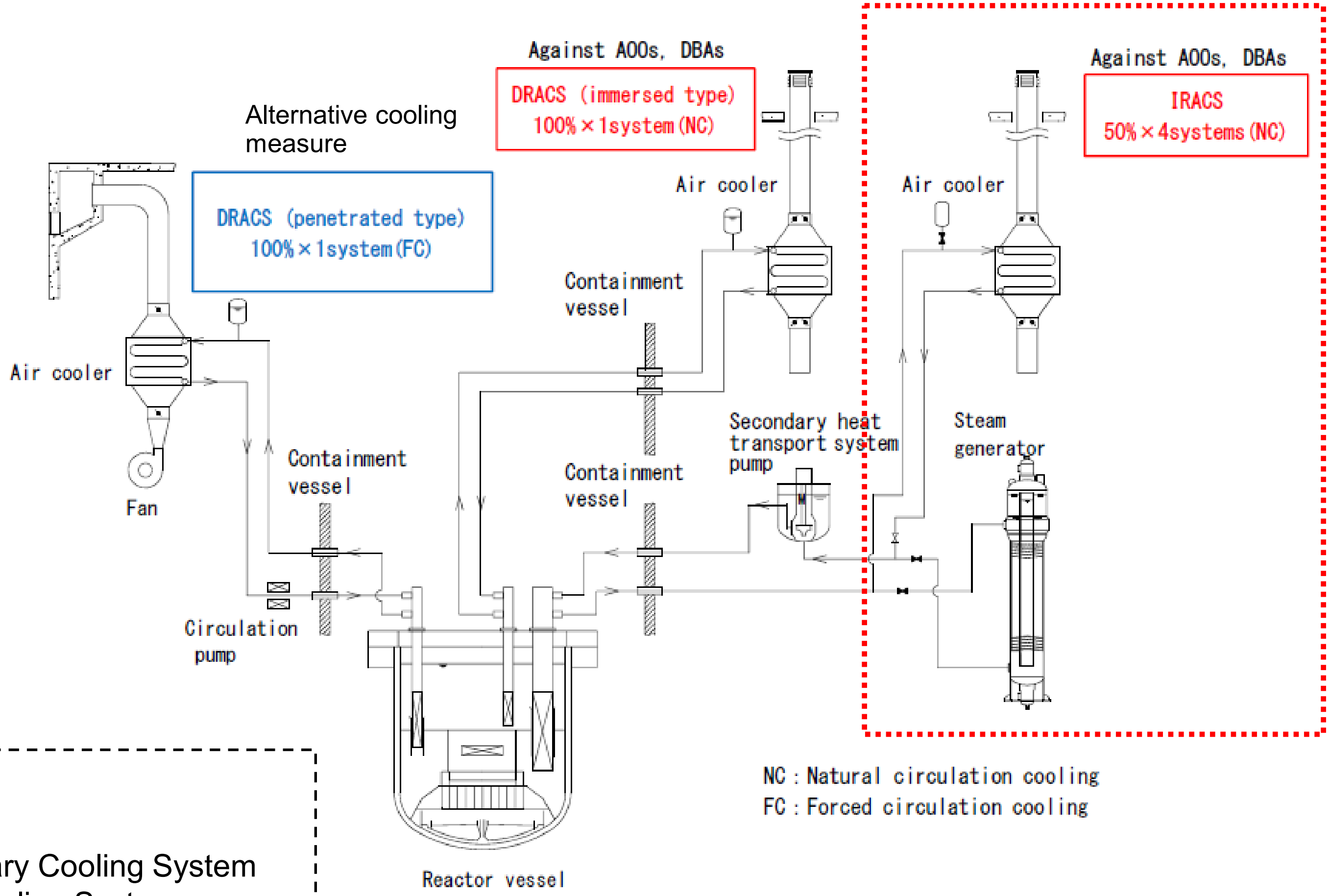
- **SDC/SDG**
  - ✓ Situations of complete loss of heat removal function that could lead to core damage and failure of the reactor coolant boundary should be practically eliminated.
  - ✓ Natural circulation capability should be incorporated into the whole decay heat removal system as an SFR's merit.
- **Policy**
  - ✓ Diverse and redundant design
  - ✓ Incorporate natural circulation capability
  - ✓ For AOOs and DBAs
    - Secure enough heat removal capacity in the case of single failure
    - Adopt different types of cooling systems to reduce a possibility of common cause failure
  - ✓ DHRS in addition to measures for AOOs and DBAs
    - Have an alternative cooling measure against the loss of cooling systems for AOOs and DBAs

Higurashi, K., et al., Joint IAEA-GIF Workshop on the Safety of Non-Water Cooled Reactors, Vienna, Austria, 30 May-2 June 2023

Safety design of DHRS for AOOs and DBAs

<u>IRACS</u>

- Provided for AOOs and DBAs
- Has a capability of NC
- Connected to the secondary heat transport system, and core cooling by IRACS relies on the main flow of the primary heat transport system.



Configuration of DHRS

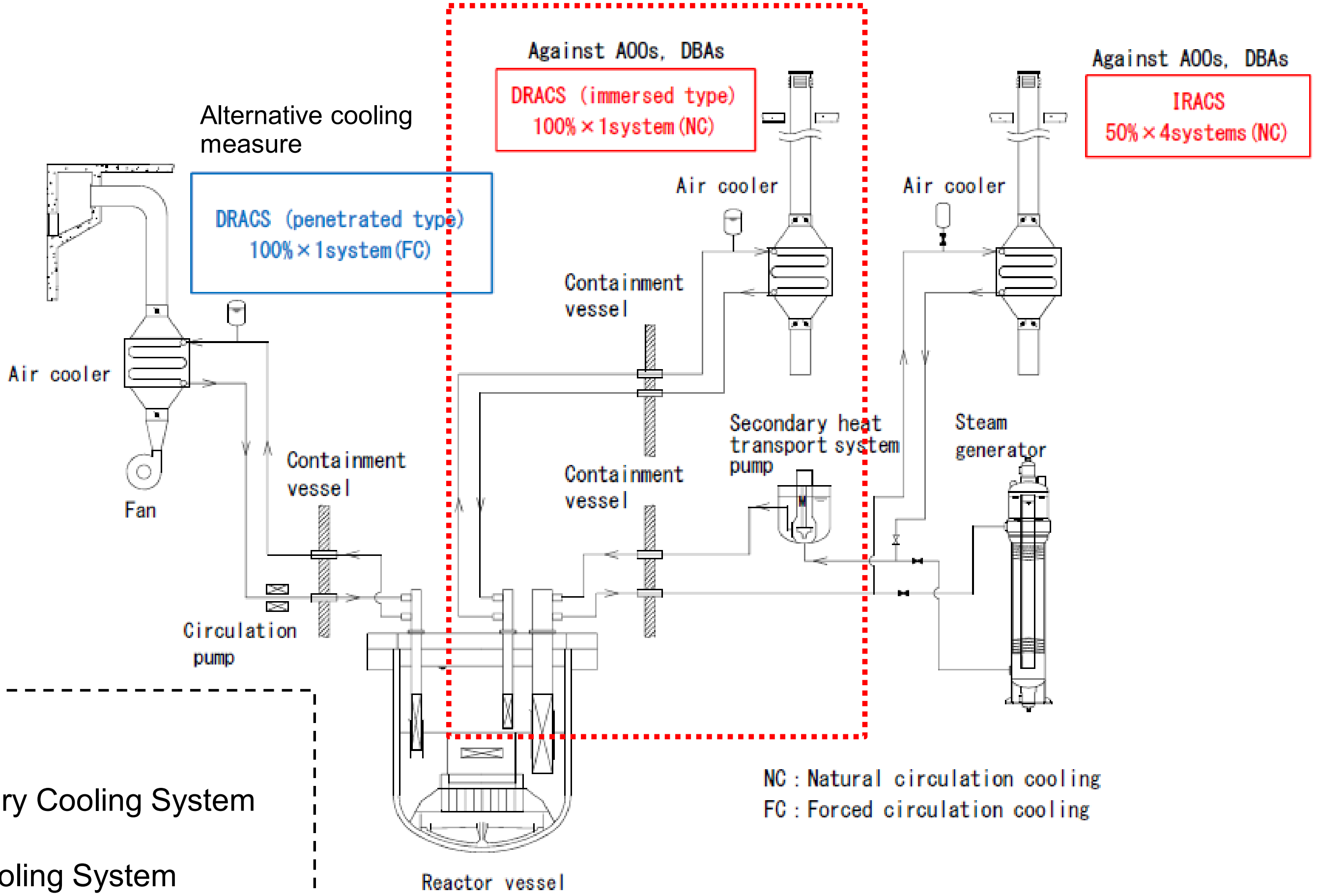
NC: Natural circulation cooling
FC: Forced circulation cooling
IRACS: Intermediate Reactor Auxiliary Cooling System
DRACS: Direct Reactor Auxiliary Cooling System

Ref.: S. Kubo et al., A conceptual design study of pool-type sodium-cooled fast reactor with enhanced anti-seismic capability, Bulletin of the JSME Mechanical Engineering Journal Vol.7, No.3, (2020)

Safety design of DHRS for AOOs and DBAs

DRACS (immersed type)

- Provided for AOOs and DBAs
- Provided with IRACS from a viewpoint of single failure and diversity
- Has a capability of NC
- Has DHX in the hot pool for NC through IHXs etc.



Configuration of DHRS

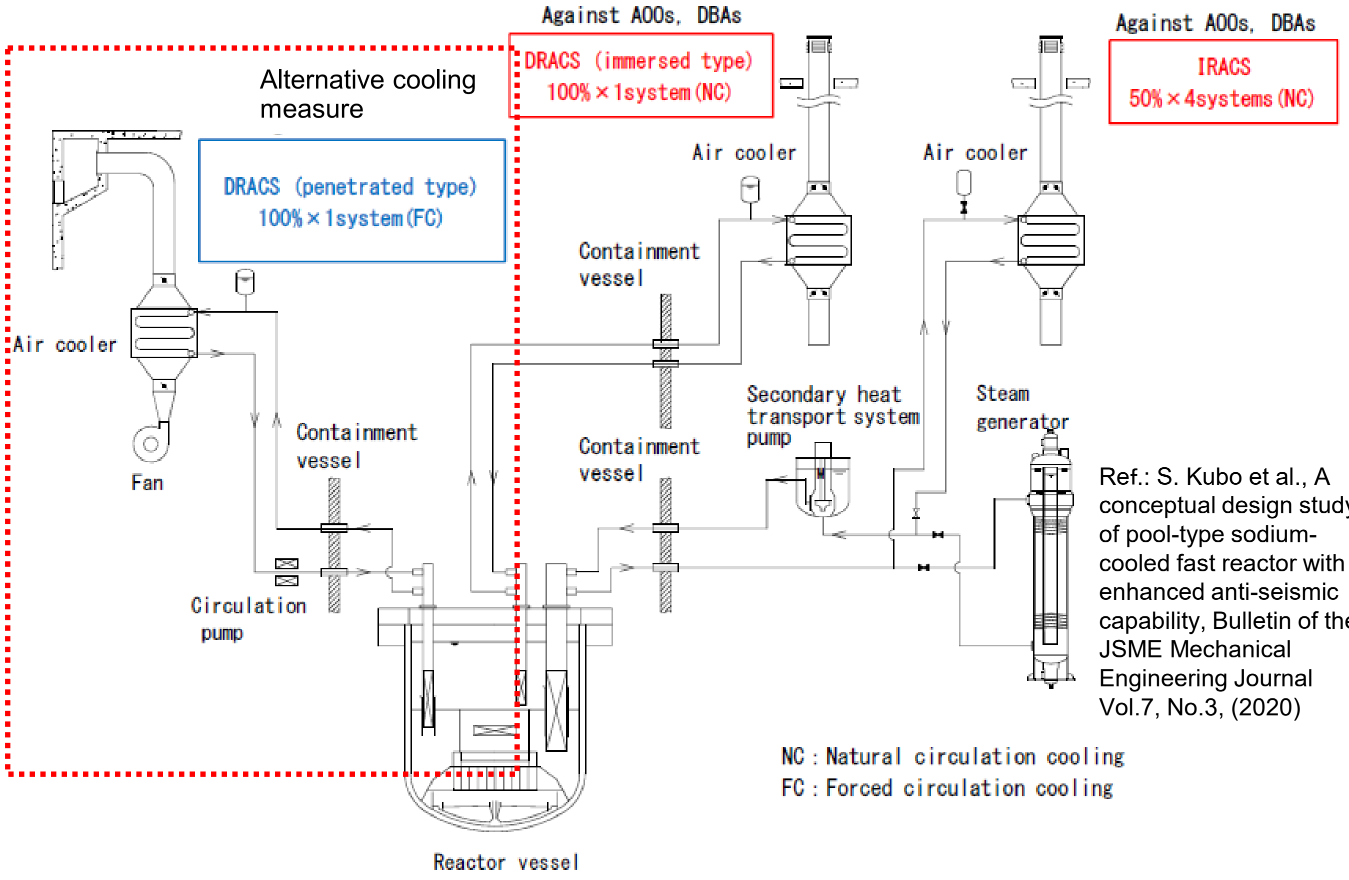
NC: Natural circulation cooling
FC: Forced circulation cooling
IRACS: Intermediate Reactor Auxiliary Cooling System
IHX: Intermediate Heat Exchanger
DRACS: Direct Reactor Auxiliary Cooling System
DHX: Heat Exchanger of DRACS

Ref.: S. Kubo et al., A conceptual design study of pool-type sodium-cooled fast reactor with enhanced anti-seismic capability, Bulletin of the JSME Mechanical Engineering Journal Vol.7, No.3, (2020)

Safety design of DHRS for DECs

DRACS (penetrated type)

- Provided as an alternative cooling measure in accordance with SDC/SDG.
- Has a capability of NC in primary cooling system
- Has a capability of FC in secondary cooling system and the air-cooling system from a viewpoint of diversity.
- Independent from DHRSs to cope with AOOs and DBAs.
- Has a shutter to prevent bypass flow from hot pool to cold pool during normal operation.
- The shutter opens in the case of operating.



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Configuration of DHRS

NC: Natural circulation cooling, FC: Forced circulation cooling, IRACS: Intermediate Reactor Auxiliary Cooling System, DRACS: Direct Reactor Auxiliary Cooling System, DHRS: Decay Heat Removal System

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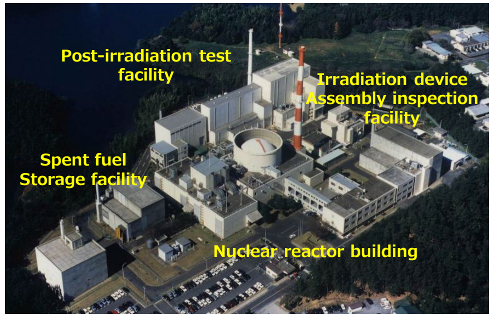
Development of Fast Reactor Cycle Technology at JAEA

Features of the fast reactor cycle	○Dozens of times more **effective use of uranium resources** than the light-water reactor ○**Reduction of the amount of radioactive waste and significant shortening of the period of attenuation of radioactivity**
Major research and development	○Research and development of **technologies necessary for practical application of the fast reactor** ○**Technology development aiming at establishment of a fuel cycle** ○Initiatives to **resume operation of the experimental fast reactor "JOYO"**

[Purpose]

- Confirmation of core characteristics and plant performance
- Irradiation test of fuels and materials
- Basic infrastructure research (RI production, etc.) utilizing the large amount of fast neutrons

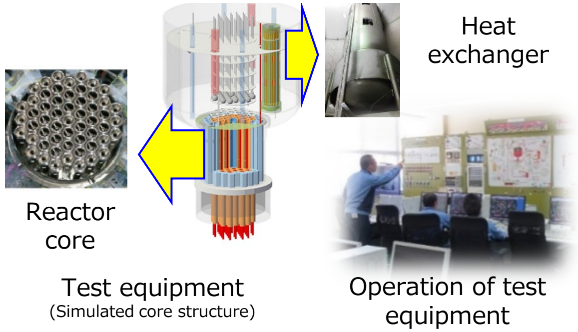
■ Thermal output	100MW (air-cooled)
■ Coolant	Liquid sodium



Experimental fast reactor "JOYO"

Developing simulation technology used in the design of fast reactors, Making rule for safety assurance, conducting safety tests, and construction of new research facilities are underway.

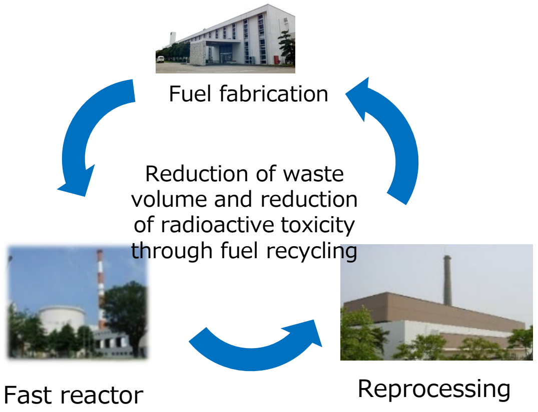
Examples of research and development



- Confirm that the heat exchanger can stably cool the reactor core even in the loss of power

Research and development for practical application of the fast reactor

Technology development using research facilities in Oarai and Tokai is proceeding to reduce the amount of radioactive waste



Technology development aiming at establishment of a fuel cycle

Experimental fast reactor “Joyo”

Current status

- Joyo has been under NRA review with the new regulatory requirements since 2017.
- NRA approval for restart in July 2023.
- Scheduled to restart in 2026 after seismic reinforcement.

Role of Joyo

- Demonstrated basic sodium-cooled FR technologies.
- Irradiation testing of fuels and materials, and validation of innovative technologies for the development of future reactors.
- Basic research using high fast neutron flux.
- Various Irradiation uses. (e.g., Production of medical RI such as Ac-225)

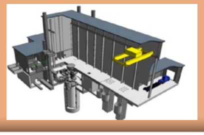
Thermal power	100MW
Fuel	MOX fuel
Coolant	Sodium
First Criticality	1977

Located in Oarai, Ibaraki Pref.

Potential role of "Joyo" as a versatile research platform

For the energy security and innovation to realize a "carbon net zero" society

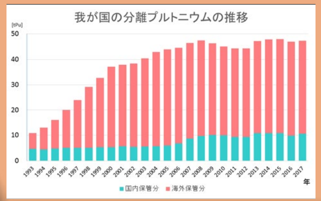
- ■SMR, next generation reactor development NEXIP
- ■support for private sector's innovation
- ■ Advanced fuels & materials development, safety improvement
- ■collaboration with US and France



VTR

For a world free from the threat of nuclear proliferation and terrorism

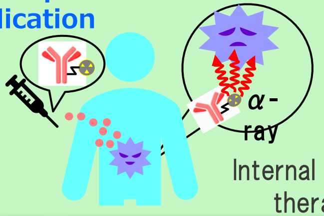
- ■Utilization of separated Pu
- ■Development of Pu burner reactor



Use of separated Pu

Production of medical and industrial isotopes

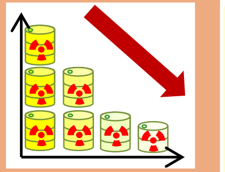
- ■Production of isotopes for medical purpose
- ■Isotopes for industrial application

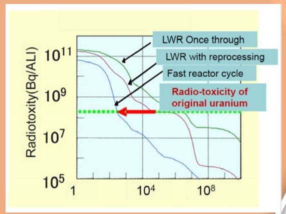


Internal cancer therapy

Experimental fast reactor "Joyo"

- ■ Minor actinide transmutation
- ■ Transmutation of LLFP





Reduction of Radiological hazard of waste

Sustainable use of nuclear energy

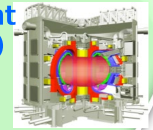
- ■Collaboration with universities
- ■ Acceptance of foreign engineers

Training

Internship for foreign researchers

Human resources development

- ■Basic research, multipurpose use
- ■International collaboration
- ■Fusion reactor development (R&D of first wall materials)



Pursuit of nuclear potential

Concluding remarks

- Many countries have been developing next-generation innovative reactors, such as advanced LWRs including SMRs, fast reactors, high-temperature gas-cooled reactors.
- R&D on innovative reactors is one of the most attractive areas in nuclear energy deployment.
- Sodium-cooled fast reactors (SFRs) are recognized to be the most mature technology in the Generation-IV systems.
- Japan starts the conceptual design of the next SFR for technology demonstration from 2024 for its operation start in 2040s.
- Student involvement and engagement are necessary for realization of the next-generation innovative reactors.