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Overview and Update of Sodium Fast Reactor Activities within the Generation IV International Forum

Dr. Yoshitaka Chikazawa

JAEA, Japan

25 September 2024

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Pacific Northwest NATIONAL LABORATORY

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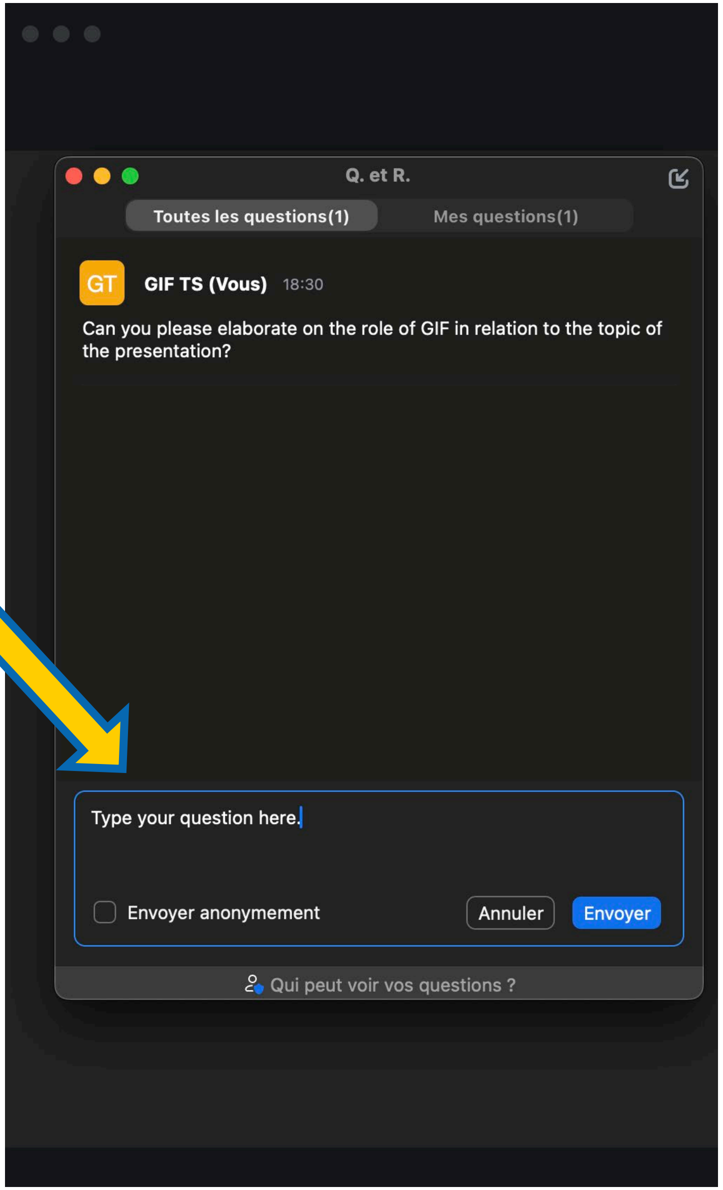

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Meet the Presenter

Dr. Yoshitaka Chikazawa completed his Ph. D. in Nuclear Engineering at the University of Tokyo in 2001.

Following his PhD graduation in 2001, he joined the Japan Nuclear Cycle Development Institute (JNC) which is the Japan Atomic Energy Agency (JAEA) where he worked for fast reactor system design.

He is currently the Deputy Director of the JAEA Fast Reactor Cycle System Project Management Office.

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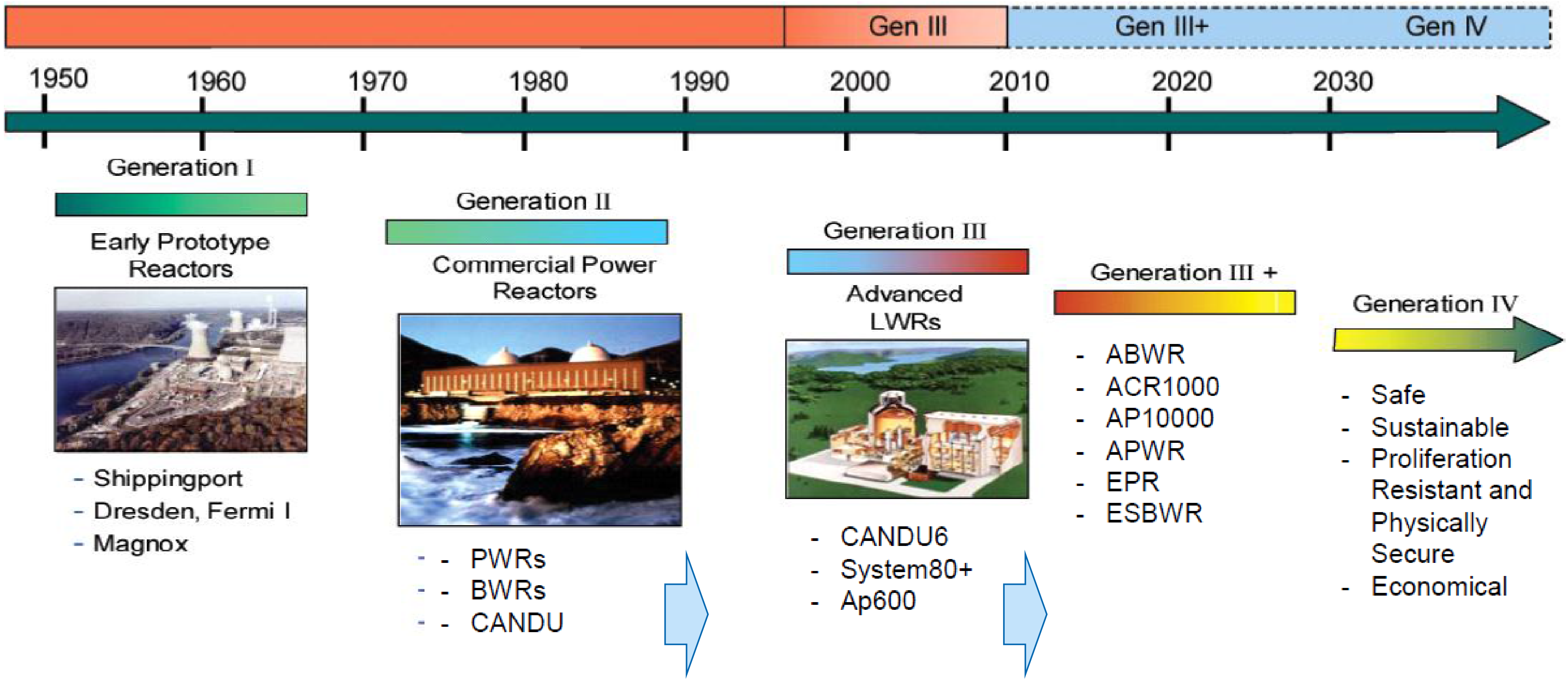
Categories of historical nuclear reactors

	Light Water	Heavy Water	Gas	Liquid Metal
Natural Uranium		CANDU	Magnox	Category #1
Enriched Uranium	BWR PWR Advanced LWR	Category #2	AGR VHTR	SRE Hallam
Recycle			GFR	SFR LFR

Category #3

Category #1: Reactor with natural uranium
Category #2: Reactor with enriched uranium (enhanced competitiveness)
Category #3: Reactor with fuel cycle for sustainability

Over view history of nuclear reactors

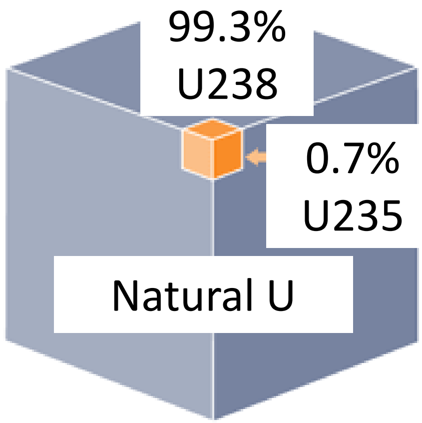


Enhanced economic competitiveness

Consideration of sustainability

Over view history of nuclear reactors

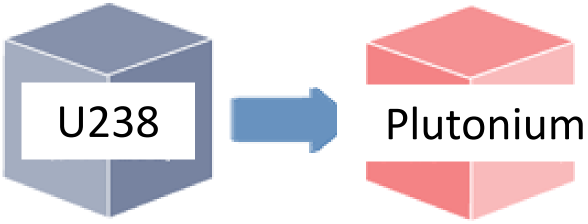
Reactor	Fuel	Coolant
Magnox	Natural Uranium	carbon dioxide
AGR	Enriched Uranium	carbon dioxide
CANDU	Natural Uranium	heavy water
LWR	Enriched Uranium	light water



Generation I – III including III+

Issue #1: 0.7% of natural uranium could be used as fuel.
Issue #2: Spent fuel includes Trans Uranium elements (*).

*:High number plutonium and minor actinides are difficult to burn in thermal reactors including LWR.



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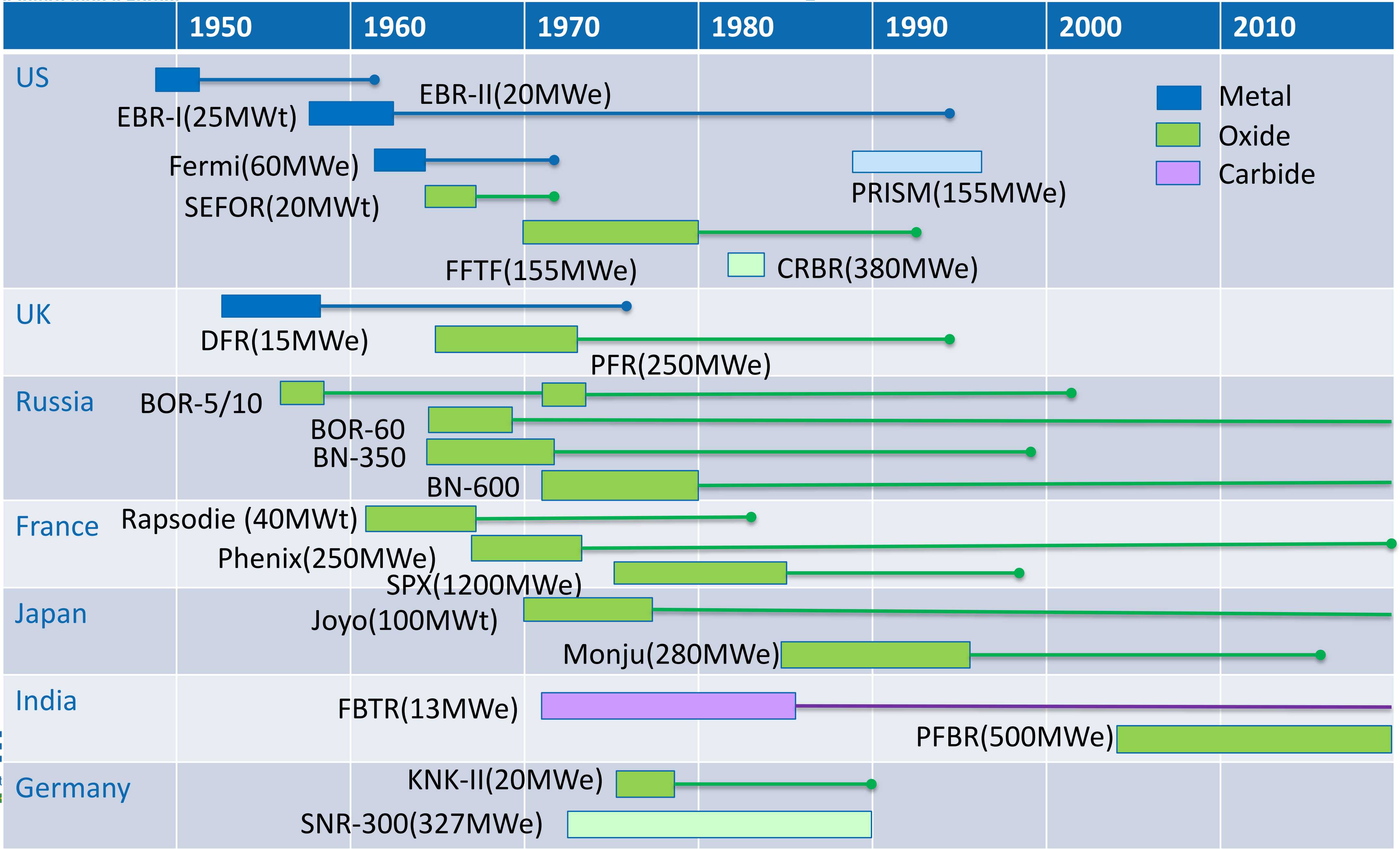
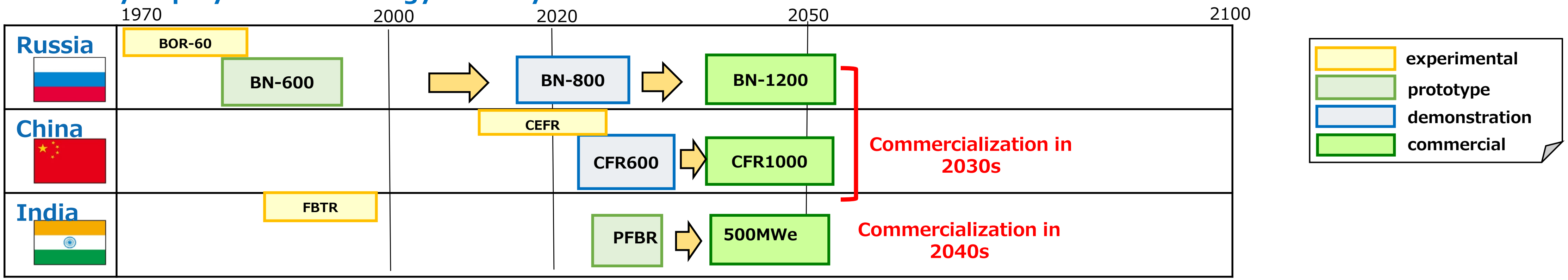
Solution #1: Sustainable nuclear fuel with recycling
Solution #2: Transmutation of plutonium and minor actinide

World fast reactor history

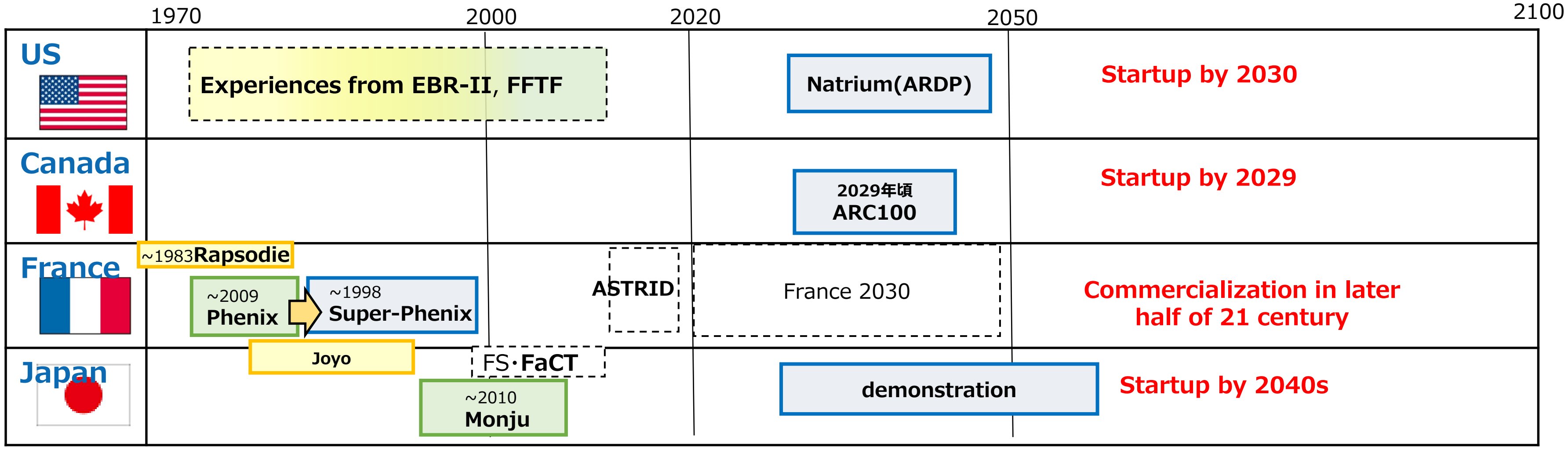


Overview of recent SFR projects

■ Early deployment for energy security



■ Multi-purpose / Plutonium utilization / MA transmutation



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Overview of recent SFR projects

Country	Organization	Project	Concept		remark
US	DOE	ARDP	Natrium (TerraPower)	345	Selected October 2020 Startup in 2030
		ARDP	inherent safety SMR (ARC)	100	Selected December 2020 Commercialization in 2030s
Canada	NB Power	SMR project	ARC-100 (ARC Clean Energy)	100	Startup in 2029
France	CEA	ASTRID project	ASTRID（CEA)	600	project was suspended in December 2019
Russia	ROSATOM	Two component system	BN-600（ROSATOM)	600	under operation
			BN-800（ROSATOM)	880	under operation
			BN-1200（ROSATOM)	1220	start construction in 2027 start up in 2030s
China	CIAE	863 project	CEFR（CIAE)	20	under operation
	CNNC	SFR pilot project	CFR600（CNNC)	600	Startup in 2025
			CFR1000（CNNC)	1000	Startup in 2030
India	BHAVINI	3 step nuclear development	PFBR（BHAVINI)	500	Startup in 2024
			CFBR（BHAVINI)	600	

: Government / national laboratory
: State government

Long-term nuclear recycling plans in France (March 2024)

- Decision to continue with France's treatment-recycling strategy for used nuclear fuel beyond 2040

  - sustainability/resilience programme extending the life of the La Hague and Melox recycling plants beyond 2040

  - studies for a new MOX fuel fabrication plant at the La Hague site

  - studies for a new used fuel processing plant, also at La Hague, by 2045-2050

1) Les Echos, “Nucléaire : Emmanuel Macron prolonge l'usine de La Hague jusqu’en 2100,” Feb. 27, 2024. https://www.lesechos.fr/industrie-services/energie-environnement/nucleaire-la-poursuite-du-retraitement-du-combustible-validee-jusquen-2100-2078926

2) Orano, “During their visit to Orano's La Hague site, Bruno Le Maire and Roland Lescure confirm treatment-recycling strategy beyond 2040,” Mar. 7, 2024. https://www.orano.group/en/news/news-group/2024/march/during-their-visit-to-orano-s-la-hague-site-bruno-le-maire-and-roland-lescure-confirm-treatment-recycling-strategy-beyond-2040

3) World Nuclear News, “France sets out long-term nuclear recycling plans,” Mar. 8, 2024. https://www.world-nuclear-news.org/Articles/France-confirms-long-term-recycling-plans

PFBR start fuel loading in March 2024

- The filling of the Main Vessel of PFBR of BHAVINI with about 1,150 tonnes of liquid Sodium has been completed in August 2023. All the indigenously manufactured Primary and Secondary sodium pumps have been put in service successfully and integrated commissioning of the plant is in an advanced.
- PFBR started to fuel loading in March 2024.
- PFBR(500MWe) is expected completion 2024.
- MOX fuel recycle by 2047
- FBTR-2 (Metal fuel experiment reactor) by 2040
- FBR-Metal by 2050

PFBR start fuel loading in March 2024 (references)

1) World Nuclear News, "India gives update on nuclear construction projects," Dec. 16, 2022. https://www.world-nuclear-news.org/Articles/India-gives-update-on-nuclear-construction-project

2) INDIAN DEFENCE NEWS, "ADVANCEMENT OF INDIA'S PROTOTYPE FAST BREEDER REACTOR PROGRAM," Dec. 31, 2023. https://www.indiandefensenews.in/2023/12/advancement-of-indias-prototype-fast.html

3) World Nuclear News, "Fuel loading begins at Indian fast breeder reactor," Mar. 4, 2024. https://www.world-nuclear-news.org/Articles/Fuel-loading-begins-at-Indian-fast-breeder-reactor

4) DAE , "Press Release No.5/2024," Mar. 4, 2024. https://cdnbbsr.s3waas.gov.in/s35b8e4fd39d9786228649a8a8bec4e008/uploads/2024/03/202403042034845222.pdf

5) International Panel on Fissile Materials, "India's Prototype Fast Breeder Reactor delayed again," Mar. 5, 2023. https://fissilematerials.org/blog/2023/03/indias_prototype_fast_bre_1.html

6) B. Venkatraman, "Fast Reactor Program in India," FR22, Apr. 19-22, 2022.

Construction of BN-1200 will begin in 2027

- BN-1200 sodium-cooled fast neutron reactor will begin in 2027 as unit 5 at Russia's Beloyarsk NPP.

- Construction will be completed by 2035

1) ria.ru, "В России планируют построить коммерческий энергоблок "АЭС будущего"," Jan. 17, 2024. https://ria.ru/20240117/energoblok-1921758818.html

2) International, "Russia's BN1200 to begin construction in 2027," Jan. 23, 2024. https://www.neimagazine.com/news/newsrussias-bn1200-to-begin-construction-in-2027-11456363

3) B.A. Vasilyev, et al., "Current status of BN-1200M reactor plant design," Nuclear Engineering and Design, Vol. 382, October 2021. https://doi.org/10.1016/j.nucengdes.2021.111384

4) Nuclear Engineering International, "Russia to build BN1200 by 2035," Jan. 17, 2022. https://www.neimagazine.com/news/newsrussia-to-build-bn1200-by-2035-9406431

TerraPower Submits Construction Permit Application in March 2024

- TerraPower selected five suppliers to support its Natrium Reactor Demonstration Project
  - GERB Vibration Control Systems Inc: Seismic isolation equipment
  - Thermal Engineering International (USA) Inc.: Sodium-Salt Heat Exchanger
  - Hayward Tyler, Inc.: Primary and Intermediate Sodium Pumps
  - Framatome US Government Solutions LLC: Ex-Vessel Fuel Handling Machine and Bottom Loading Transfer Cask
  - Teledyne Brown Engineering: In-Vessel Transfer Machine (IVTM)

- TerraPower Submits Construction Permit Application to the U.S. Nuclear Regulatory Commission for the Natrium Reactor Demonstration Project

- The Natrium technology is advanced nuclear design featuring a 345 MWe sodium-cooled fast reactor with a molten salt-based energy storage system. Non-nuclear construction will begin on the Natrium reactor demonstration project this summer

TerraPower (references)

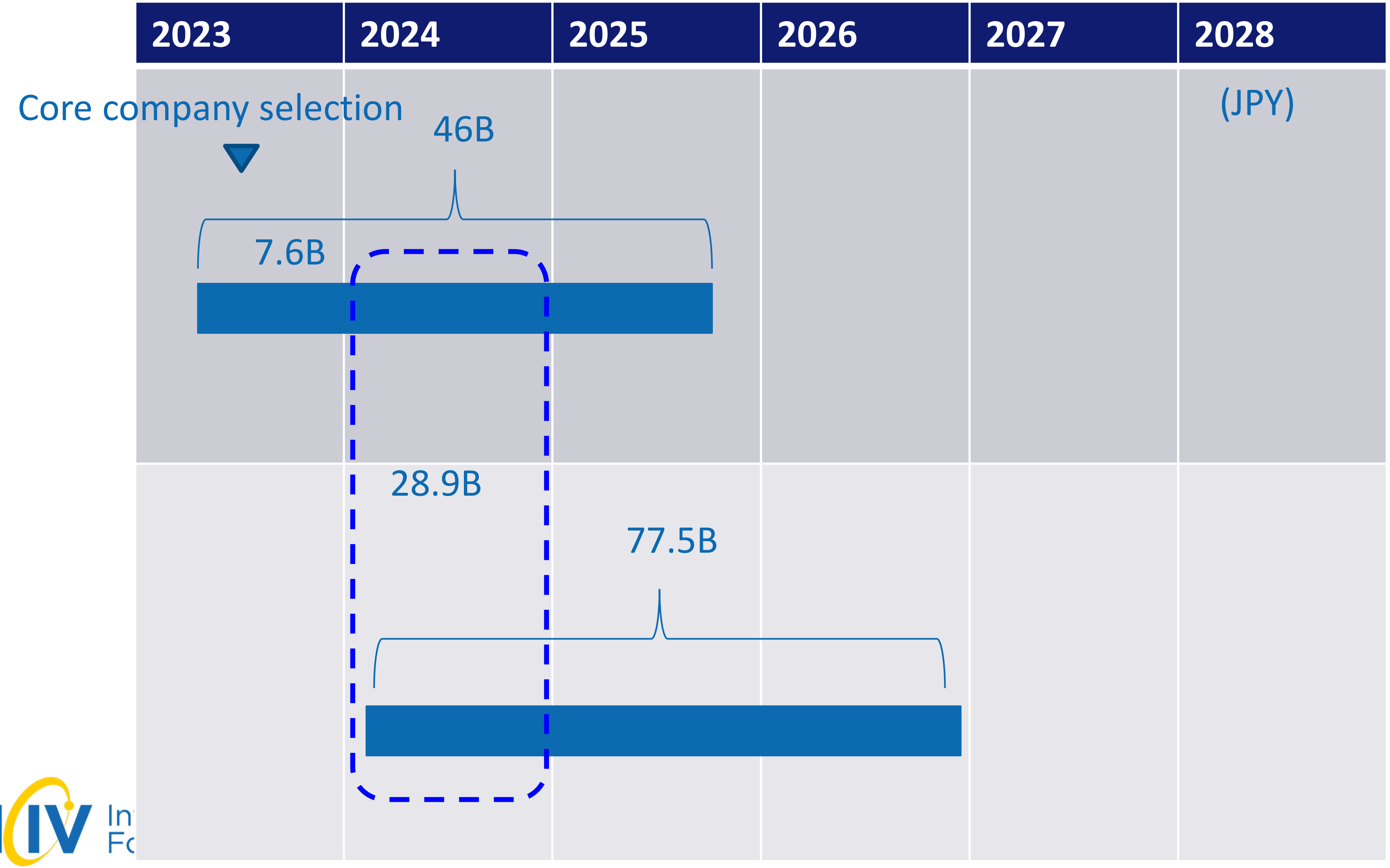
1) TerraPower, "TerraPower Submits Construction Permit Application to the U.S. Nuclear Regulatory Commission for the Natrium Reactor Demonstration Project," Mar. 29, 2024. https://www.terrapower.com/terrapower-submits-cpa-nrc/
2) World Nuclear News, "TerraPower submits application to build Natrium reactor," Apr. 2, 2024. https://www.world-nuclear-news.org/Articles/TerraPower-submits-application-to-build-Natrium-re
3) Forbes, "TerraPower: What We Know About Bill Gates's Nuclear Power Plant In Wyoming," Mar. 19, 2024. https://www.forbes.com/sites/antoniopequenoiv/2024/03/19/terrapower-what-we-know-about-bill-gatess-nuclear-power-plant-in-wyoming/
4) TerraPower, "TerraPower Awards Second Round of Contracts for Natrium Reactor Vendors," Feb. 7, 2024. https://www.terrapower.com/terrapower-awards-second-round-of-contracts-for-natrium-reactor-vendors/
5) Nuclear Engineering International, "TerraPower selects five suppliers for its natrium reactor project," Feb. 13, 2024. https://www.neimagazine.com/news/newsterrapower-selects-five-suppliers-for-its-natrium-reactor-project-11512368

Japanese Strategic Roadmap for Fast Reactor Development

- A "Strategic Roadmap" was decided in December 21, 2018 at Ministerial Council on Nuclear Energy to clarify the policy to support research and development of fast reactors.
  - ➢ Expect to start operation of a realistic scale reactor at an appropriate time in the mid-21st century.
  - ➢ The timing for full-scale use is expected to be sometime in the second half of the 21st century.

- Revision of the Strategic Roadmap in 2022
  - ➢ Sodium-cooled fast reactor was evaluated as the most promising for future development
  - ➢ Work Plan for Future Development
    - 2023 Summer: Selection of a core company (MHI was selected) and specifications for reactor concept (pool type SFR).
    - FY2024 - FY2028 : Conceptual design and R&D of demonstration reactor.
    - Around 2026: Study on specific fuel technologies.
    - Around 2028: Decision to move to basic design and licensing application for the demonstration reactor.

Japanese Budget for fast reactor demonstration



Sodium-cooled Fast Reactor System

Members

China (CIAE) *EURATOM (JRC)* *France (CEA)* *Japan (JAEA)*

Korea (KAERI) *RF (Rosatom)* *UK (DESNZ)* *US (USDOE)*

System Research Plan

System Research Plan Rev. 3.2 completed and approved by SSC on October 9, 2019: Development Targets and Design Requirements

4 SFR R&D Projects

- **System Integration and Assessment**
- **Advanced Fuel**
- **Component Design and Balance of Plant**
- **Safety and Operations**

5 SFR Design Concepts

- **Loop Option** (JSFR Design Track)
- **Pool Option** (KALIMER-600, ESFR, and BN1200 Design Tracks)
- **Small Modular Option** (AFR-100 Design Track)


Generation IV Nuclear Energy Systems
System Research Plan
for the Sodium-cooled Fast Reactor

Revision 3.2
9 October, 2019

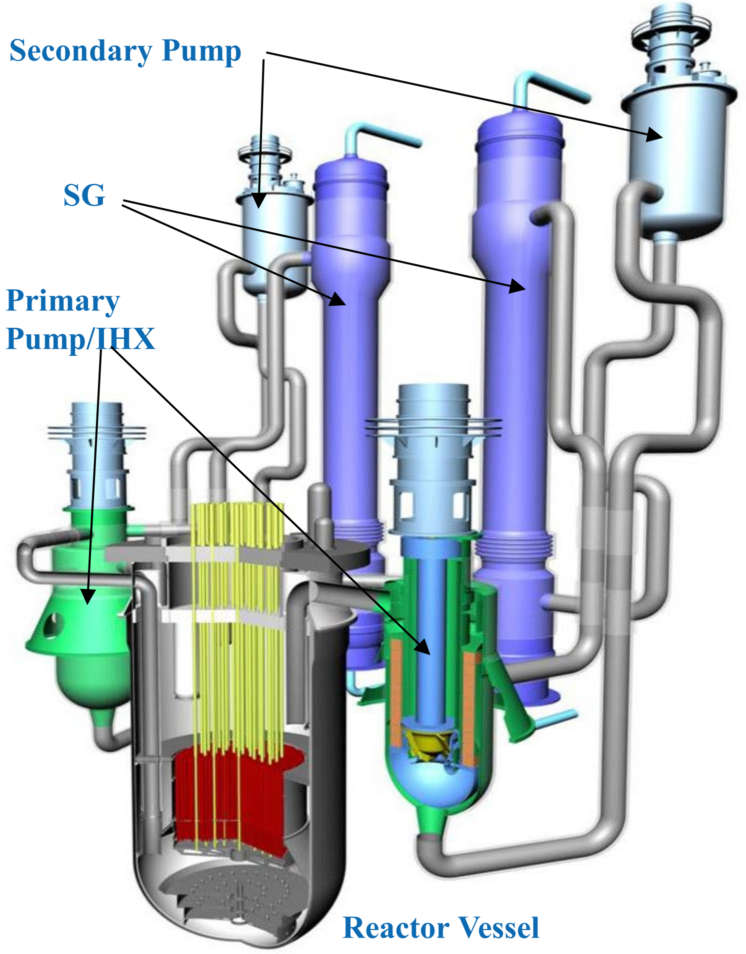
Preparing Today for Tomorrow's Energy Needs

Issued by the
Generation IV International Forum
SFR System Steering Committee

20

Japan Sodium Fast Reactor (JSFR) Design Track

Design Parameters	JSFR
Power Rating, MWe	1,500
Thermal Power, MWt	3,570
Plant Efficiency, %	42
Core Outlet Coolant Temperature, °C	550
Core Inlet Coolant Temperature, °C	395
Main Steam Temperature, °C	503
Main Steam Pressure, MPa	19.2
Cycle Length, years	1.5–2.2
Fuel Reload Batch, batches	4
Core Diameter, m	5.1
Core Height, m	1.0
Fuel Type	MOX (TRU bearing)
Cladding Material	ODS
Fuel Fissile Enrichment (Pu/HM), %	13.8
Average Burn-up, GWd/t	150
Breeding Ratio	1.0–1.2



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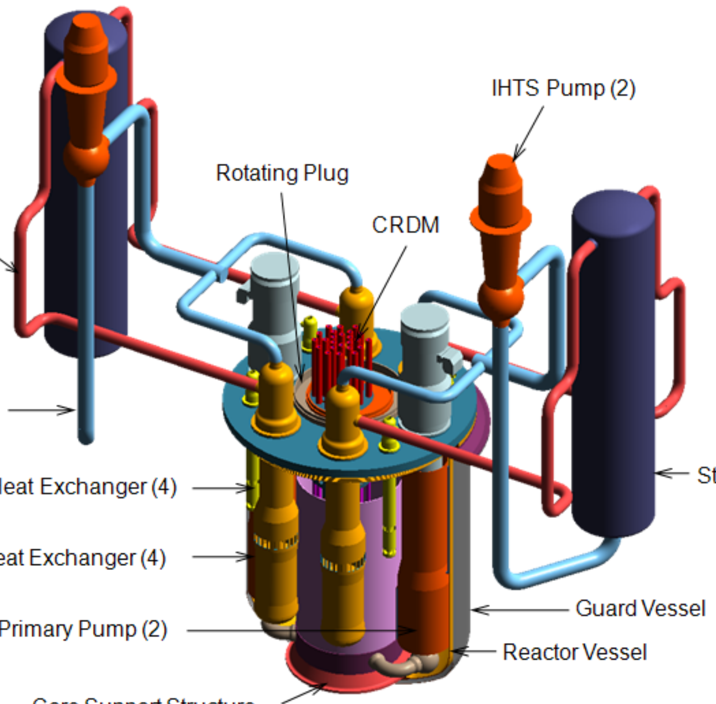
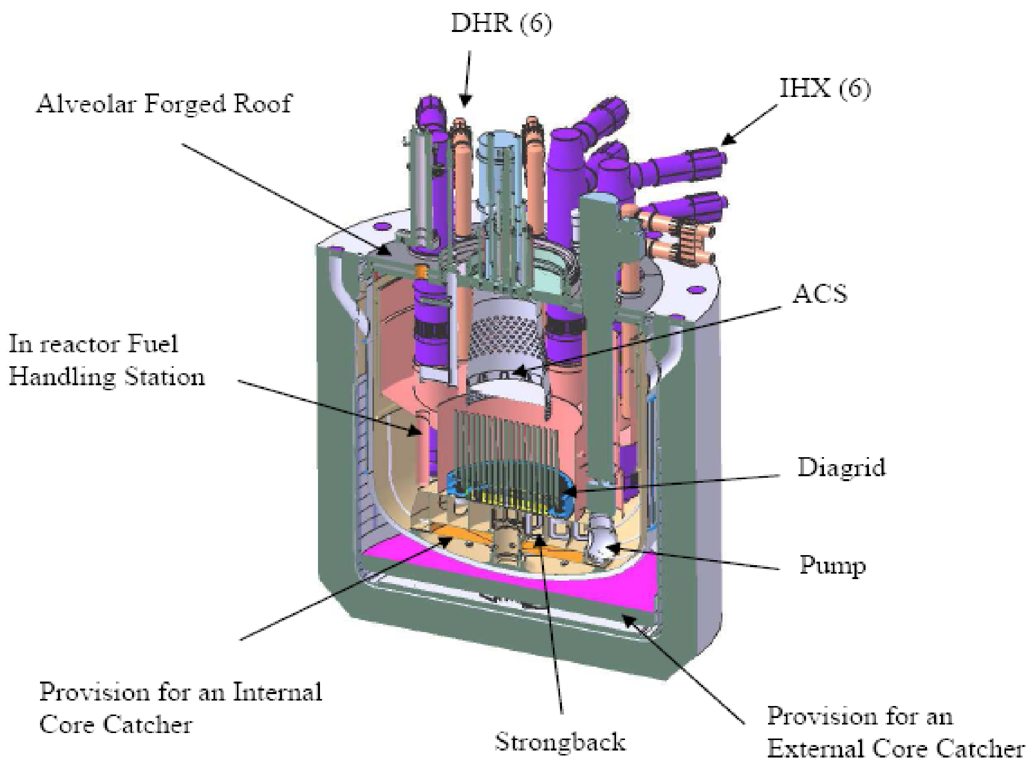
KALIMER-600 Design Track

Design Parameters	KALIMER
Power Rating, MWe	600
Thermal Power, MWt	1,500
Plant Efficiency, %	40
Core Outlet Coolant Temperature, °C	545
Core Inlet Coolant Temperature, °C	390
Main Steam Temperature, °C	503
Main Steam Pressure, MPa	16.5
Cycle Length, years	1.1
Fuel Reload Batch, batches	5
Core Diameter, m	4.2
Core Height, m	0.89
Fuel Type	Metal (U-TRU-10%Zr Alloy),
Cladding Material	HT9M
Fuel Fissile Enrichment (Pu/HM), %	25.2
Average Burn-up, GWd/t	139
Breeding Ratio	0.74



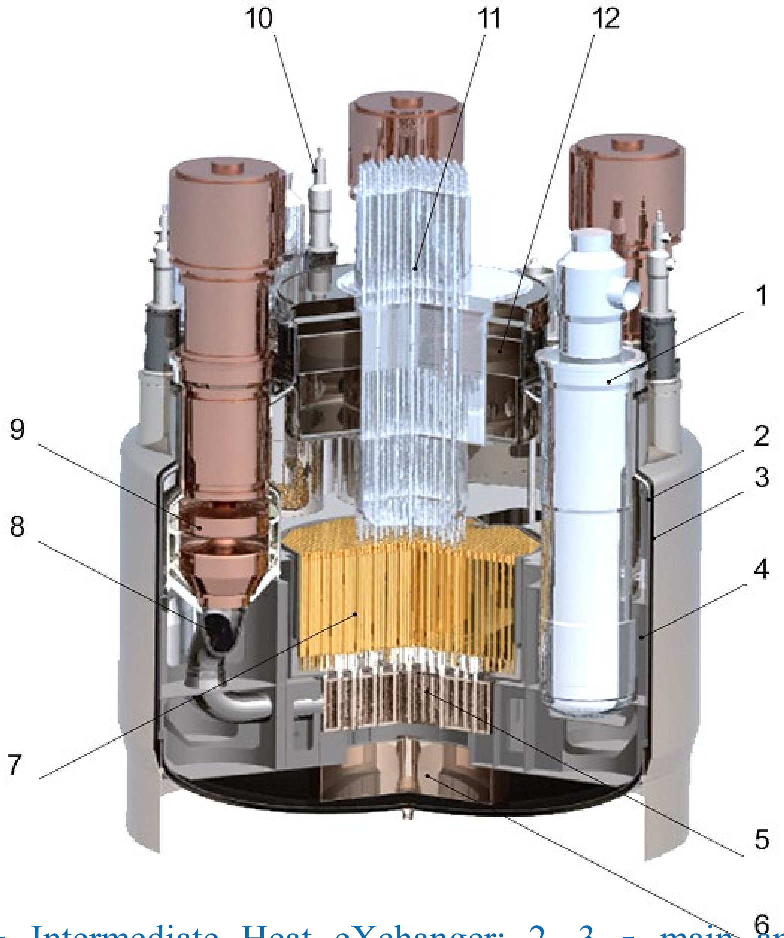
European Sodium Fast Reactor (ESFR) Design Track

Design Parameters	ESFR
Power Rating, MWe	1512
Thermal Power, MWt	3600
Plant Efficiency, %	42
Core Outlet Coolant Temperature, °C	545
Core Inlet Coolant Temperature, °C	395
Main Steam Temperature, °C	490
Main Steam Pressure, MPa	18.5
Cycle Length, years	1.35
Fuel Reload Batch, batches	5
Core Diameter, m	4.72
Core Height, m	1.0
Fuel Type	MOX
Cladding Material	ODS
Fuel Fissile Enrichment (Pu/HM), %	15.7
Average Burn-up, GWd/t	100
Breeding Ratio	1.0-1.2



BN-1200 Sodium-cooled Fast Reactor Design Track

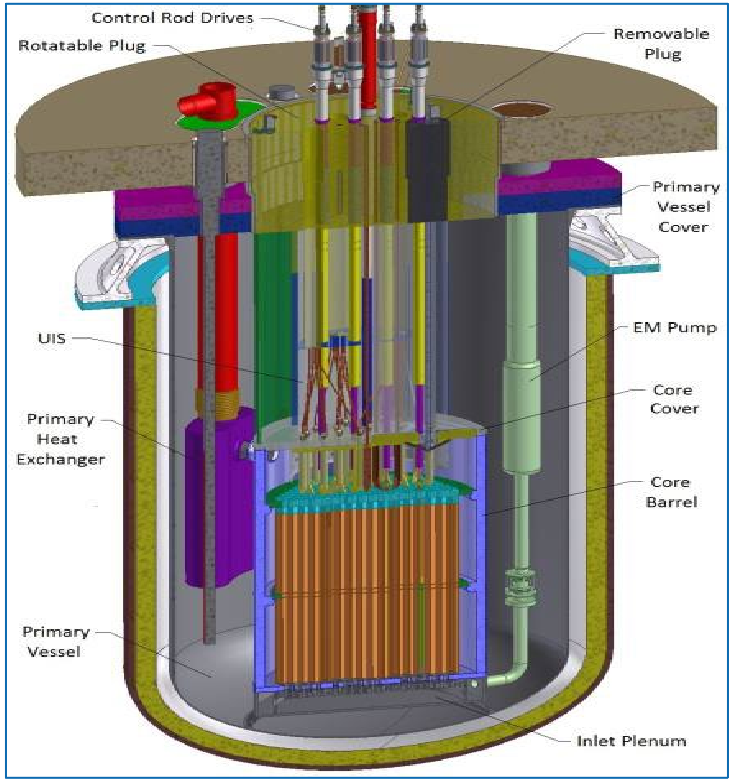
Design Parameters	BN-1200
Power Rating, MWe	1220
Thermal Power, MWt	2800
Plant Efficiency, %	43.5
Core Outlet Coolant Temperature, ºC	550
Core Inlet Coolant Temperature, ºC	410
Main Steam Temperature, ºC	510
Main Steam Pressure, MPa	17.0
Cycle Length, years	1.0
Fuel Reload Batch, batches	Up to 6
Core Diameter, m	4.18
Core Height, m	0.83/1.0
Fuel Type	MUPN/ MOX
Cladding Material	AAS/FMS/ODS
Fuel Fissile Enrichment (Pu/HM), %	Up to 20
Average Burn-up, GWd/t	Up to 100/125
Breeding Ratio	1.35/1.2



1 – Intermediate Heat eXchanger; 2, 3 – main and guard vessels respectively; 4 – supporting structure; 5 – inlet plenum; 6 – core catcher; 7 – core; 8 – pressure pipeline; 9 – Main Coolant Pump-1; 10 – Decay Heat eXchanger; 11 – Control Rod Driveline Mechanism; 12 – rotating plugs

Advanced Fast Reactor - 100 (AFR-100) Design Track

Design Parameters	AFR-100
Power Rating, MWe	100
Thermal Power, MWt	250
Plant Efficiency, %	40
Core Outlet Coolant Temperature, °C	550
Core Inlet Coolant Temperature, °C	395
Main Steam Temperature, °C	517[a]
Main Steam Pressure, MPa	20[a]
Cycle Length, years	30
Fuel Reload Batch, batches	1
Core Diameter, m	3.0
Core Height, m	1.1
Fuel Type	Metal (U-10%Zr Alloy),
Cladding Material	HT9
Fuel Fissile Enrichment (Pu/HM), %	13.5[b]
Average Burn-up, GWd/t	100
Breeding Ratio	0.8



System Integration & Assessment Project

Members

France (CEA)

US (USDOE)

Japan (JAEA)

Korea (KAERI)

EURATOM (JRC)

China (CIAE)

RF (Rosatom)

Project Objectives:

- Integration of the results of R&D Projects
- Performance of design and safety studies
- Assessment of the SFR System against the goals and criteria set out in the Gen IV Technology Roadmap

SIA PMB - Integral Fast Reactor by CIAE

CHINA INSTITUTE OF ATOMIC ENERGY

- China has completed experimental fast reactors, demonstration fast reactor units 1 and 2 are expected to be completed in 2023 and 2026, and is now developing integral fast reactor, and the first IFR will be applicated by 2035.
- Adoption of metal fuel fast reactor technology and integration of the fuel reprocessing with the reactors at the same site (area), which is both a fast reactor power plant and a nuclear energy system. Six sodium-cooled fast reactors, a fuel reprocessing subcomponent and other supporting subcomponents are built at one site (6+1 integrated design).

2021-2025 — ◻ Research on key technologies
- Complete standard preliminary design
- Complete technical and economic feasibility study

2026-2030 — ◻Engineering verification
- Complete all process validation
- Completion of equipment and engineering validation tests

2031-2035 — ◻Construction
- Complete the construction of the first IFR demonstration project

Overall Advancement Plan

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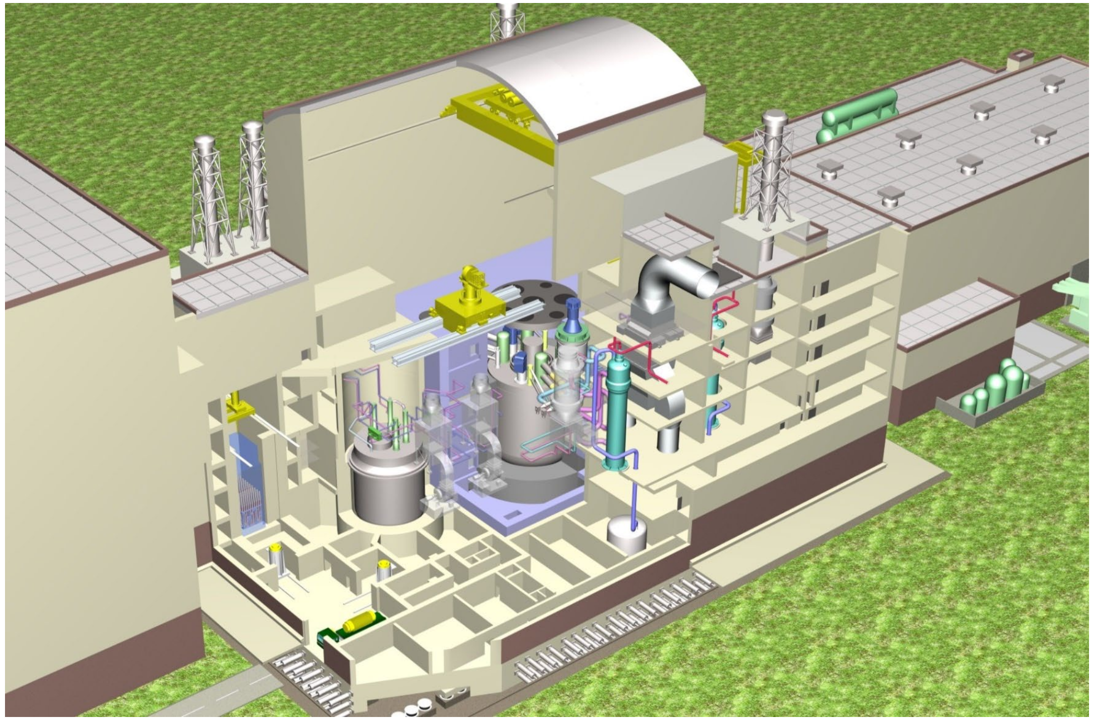
Japanese pool SFR with JSFR core

- In order to see feasibility of pool-type design in Japan, JAEA studies a pool concept with JSFR core.



Advanced Fuel Project

Members

France (CEA)

US (USDOE)

Japan (JAEA)

Korea (KAERI)

EURATOM (JRC)

China (CIAE)

RF (Rosatom)

UK (DESNZ) *(Pending)*

Project Objectives:

- Objective: development of MA-bearing high burnup fuel.
- R&D activities:
  - ✓ Fuel type: Oxide, Metal, Nitride, and Carbide.
  - ✓ Scope: Fuel Fabrication, Fuel Irradiation and Core Material Development.
- Work package
  - ✓ WP2.1 Non-MA-bearing Driver Fuel,
  - ✓ WP2.2 MA-bearing Transmutation Fuel
  - ✓ WP2.3 High-burnup Fuel

Metal fuel fabrication technology optimization and demonstration by DOE

- Historical injection casting is most likely near-term deployment strategy
- Recent studies have focused on EBR-II process technology gaps
- Unpublished data from used to quantify critical parameters
- Report to be released with detailed summary data

Example of EBR-II
“Molds and Dust”

Common work for AF

Advanced Fuel Project Plan 2017 – 2027 (1 September 2017)

During the second project phase there will be three major milestones and outputs (see Figure 1-1).

The existing experiences on SFR fuel and the results gained within this project arrangement will be culminated in a "Handbook on Sodium Fast Reactor Advanced Fuels".

The first version will be issued after four years and will include the comprehensive knowledge on preparation and synthesis, physical and chemical properties and irradiation behavior of oxide, metal, nitride and carbide fuel as well as on inert matrix fuel and advanced cladding/wrapper materials. Irradiation behavior will be comprised of general safety behavior as well as steady-state performance and transient performance. The handbook will then represent the current state of science and technology on SFR driver, transmutation and high-burnup fuels and advanced cladding/wrapper materials.

An updated version will be issued after eight years and a final report will be prepared at the end of the second SFR AF project phase, summarizing its results and drawing conclusions for the future.

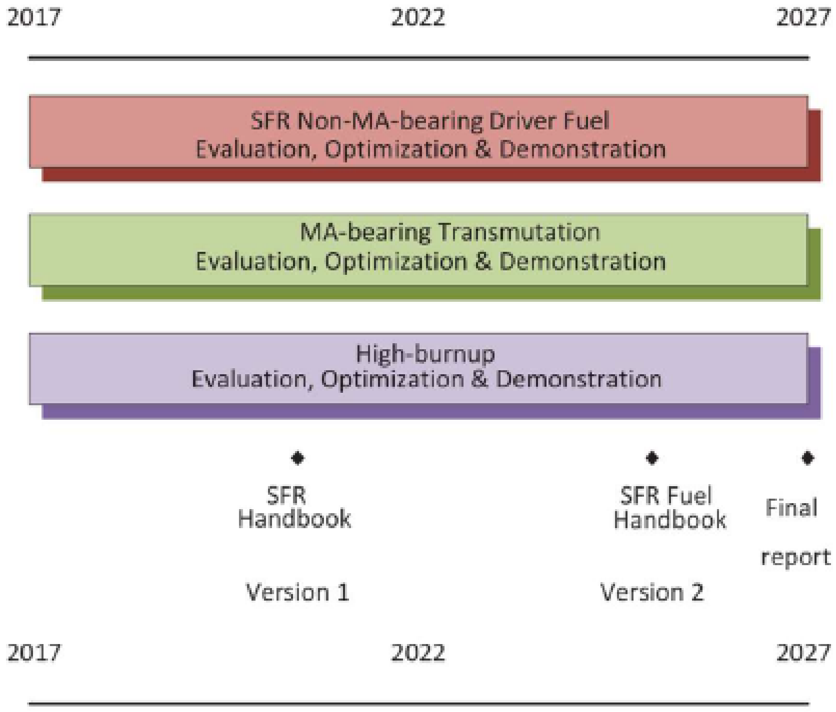


Figure 1-1: Research Items and Milestones of the Second SFR AF Research Period

Handbook of SFR Advanced Fuels - April 2022

- **Original handbook** was issues about **15 years ago**.
- The handbook was **periodically updated** since then.
- **The last version issued in 2022.**
- The PMB **will plan and start their work few years later** for updating the handbook by the end of 2027.

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Component Design and Balance of Plant Project

Members

France (CEA)

US (USDOE)

Japan (JAEA)

Korea (KAERI)

China (CIAE)

RF (Rosatom) *(Pending)*

UK (DESNZ)

Project Objectives:

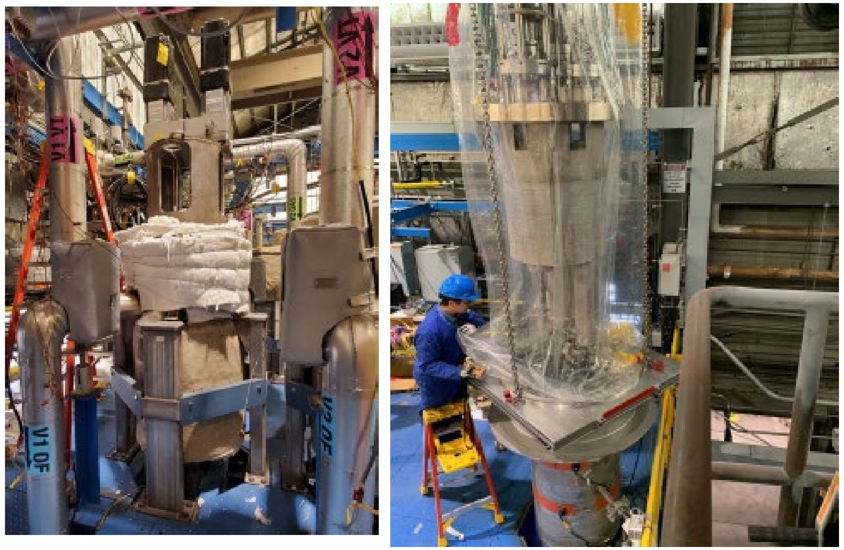
- The main objective is to enhance the performance and economic competitiveness of SFRs through:
  - ✓ development of advanced components and component-related technologies
  - ✓ research and development of advanced energy conversion approaches

CD&BOP PMB - Report on Third Year of Operations of Intermediat scale Testing Facility by ANL

Argonne NATIONAL LABORATORY

- Mechanisms Engineering Test Loop (METL): to test small or intermediate scale advanced liquid metal components and instrumentation in sodium (Gear Test Assembly for Compact Refueling Machine, Sodium Level sensor technology, Thermal-Hydraulic Experimental Test Article (THETA) and Flow Sensor Test Article (F-STAr)).
- The report on the 3rd year of operations of the Mechanism Engineering Test Facility is in progress – Due Dec 2023

Test vessels



Test articles

Common work on CD&BOP PMB – Decommissioning Information Sharing

- Objective: Information sharing of **decommissioning process of sodium facilities**.
- Work plan:
  - **Develop** an information sharing **template (Done).**
  - **Collect and share published information** by using the **template (continuing*)**.
    - ✓ Step1: Knowledge capture of past R&Ds for the decommissioning (from each country).
    - ✓ Step2: Specific experience on SFR plants relating with decommissioning (from each country).
  - Discuss **common recommendations** and **knowledge structure**.
    - ✓ **Facing problems and lessons leaned** on the decommissioning (common project deliverables).
    - ✓ **Recommendations on future R&Ds** on the decommissioning, including needed R&Ds (common project deliverables).
  - **Make an internal report** for the participants.

Current status

- Contributor: **members and negotiators** (FR, JP, KR, US, CH, RU, UK)
- Note: based on **published documents**.

* Continue to collect contributions in the fields of waste conditioning and cold trap treatment if there any.

Safety & Operation Project

Members

France (CEA)

US (USDOE)

Japan (JAEA)

Korea (KAERI)

EURATOM (JRC)

China (CIAE)

RF (Rosatom)

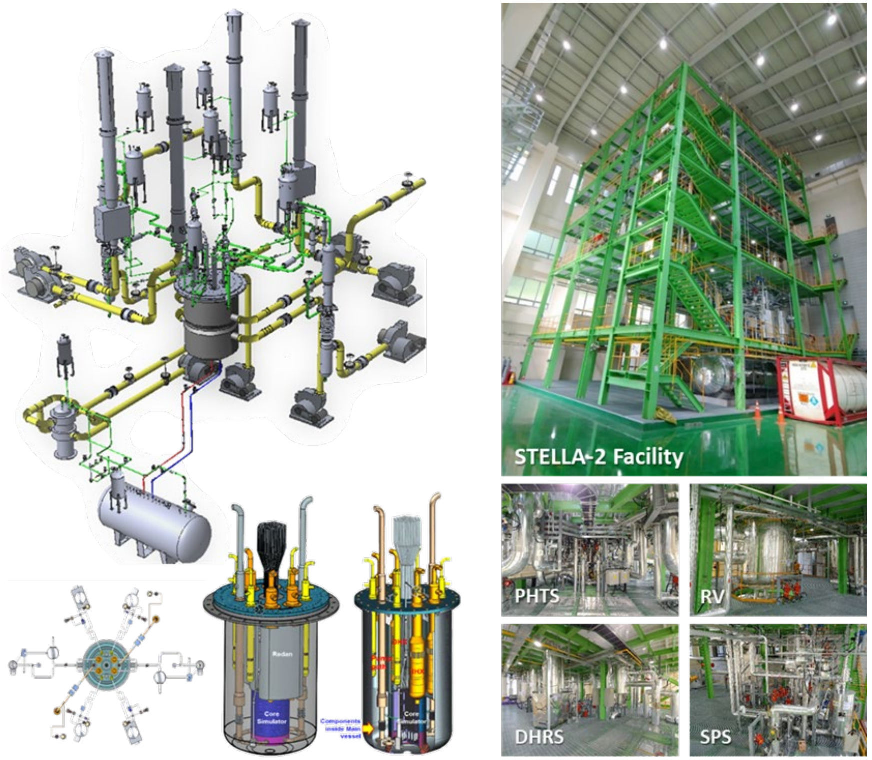
UK (DESNZ) *(Pending)*

Project Objectives

- Analyses and experiments that support safety approaches and validate specific safety features
- Development and validation of computational tools useful for such studies
- Acquisition of reactor operation technology, as determined largely from experience and testing in operating SFR plants

SO PMB - DHRS Cooling Capability Test Results and Analysis by KAERI

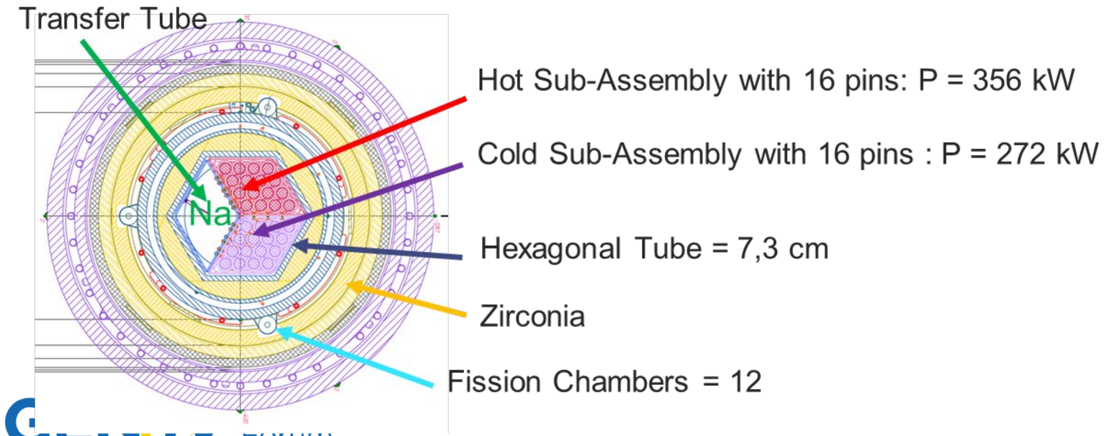
- Experiment to test the cooling capability of DHRS with various combination with 2 different type HXs, a helical-tube type (AHX) and finned-tube type (FHX)
- Comparison between the system code analysis and the experiment data on transient behavior

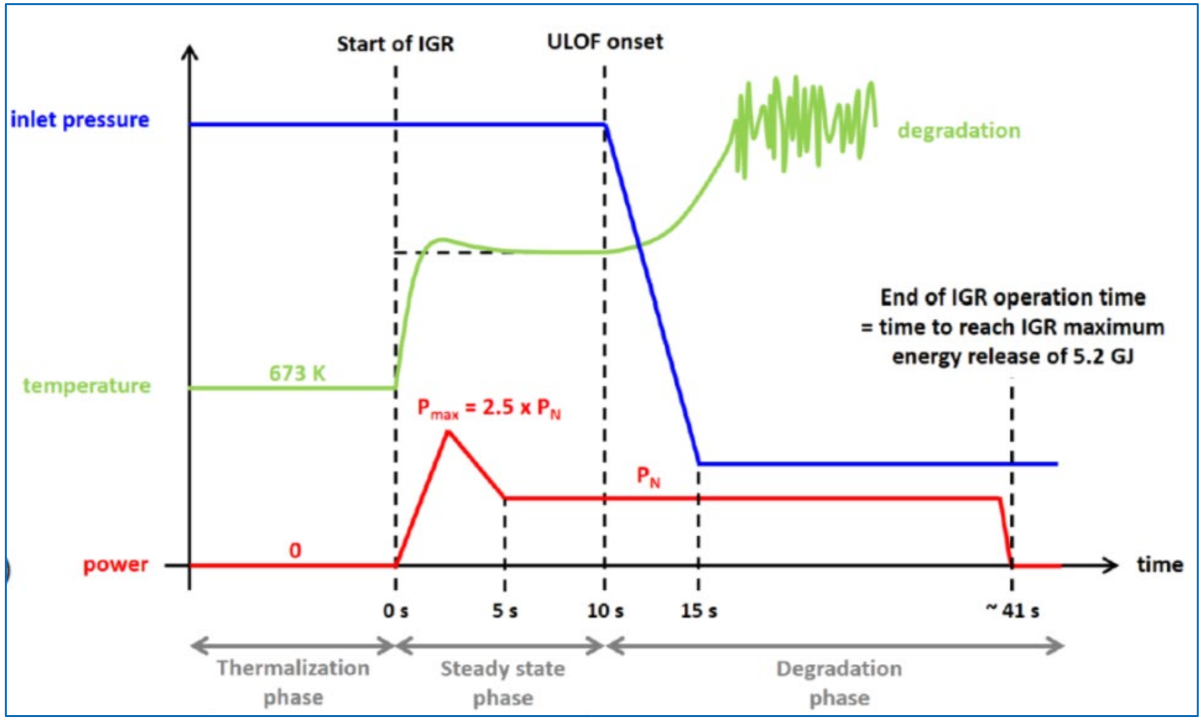


STELLA-2 Facility

SAIGA in-pile test preparation by CEA

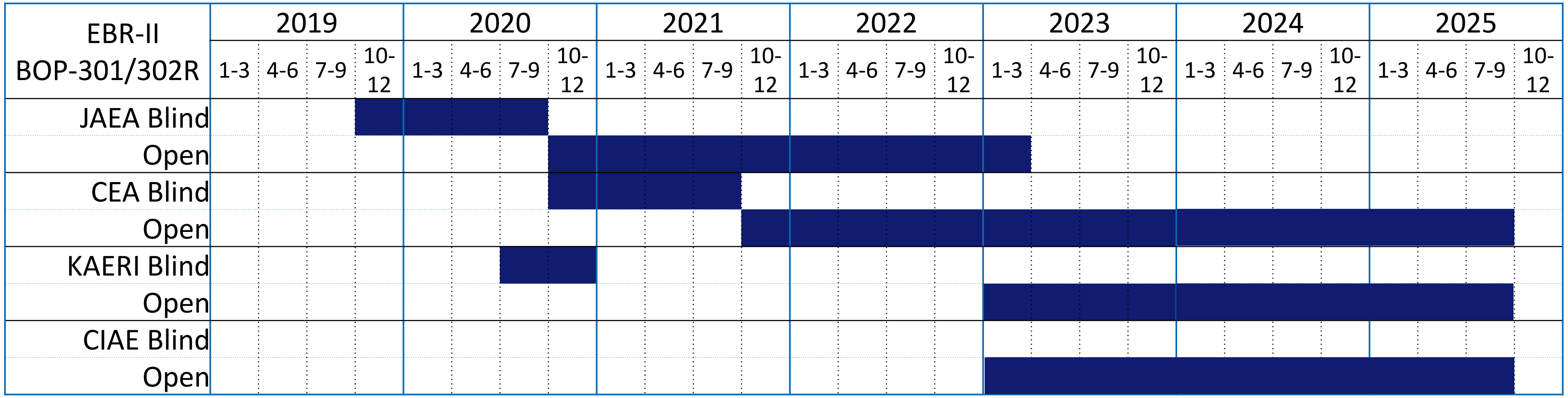
- Objective: investigate the efficiency of Corium Transfer Tube in SFR Core, considering conditions close to severe accident situation with an ULOF sequence
- Test under preparation in close cooperation with the National Nuclear Centre (Kazakhstan), to be performed by end of 2025 in the Impulsed Graphite Reactor (IGR)
- Test device & in-pile conditions :
  - 2 SA : fuel bundles in trapezoidal shaped tubes
  - 1 corium Transfer Tube





Common work on SO PMB– Common Benchmark Analysis (1/2)

EBR-II tests BOP-301 and BOP-302R (ANL)



- Contributors
  - ANL, JAEA, CEA, KAERI, CIAE
- Current status
  - JAEA: completed 1D calculation case, 1D+CFD coupling case and final report
  - CEA: completed 1D calculation case, refining calculation and drafting final report (and will consider 1D+CFD coupling case in 2024 - 2025
  - KAERI: completed 1D calculation case and 1D+neutronics case, and drafting final report
  - CIAE: completed 1D calculation case, conducting 1D+CFD coupling case and drafting final report in 2024 - 2025

Common work on SO PMB– Common Benchmark Analysis (2/2)

PHENIX dissymmetric test (CEA/Euratom)

Phenix Dissymmetric	2019				2020				2021				2022				2023				2024				2025			
	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12	1-3	4-6	7-9	10-12
JAEA Blind						■	■	■					■	■	■	■												
Open																	■	■	■	■	■	■	■	■	■	■	■	■
KAERI Blind																									■	■	■	■
Open																												
CIAE Blind																												
Open																												

- Contributors
  - CEA/EURATOM, JAEA, KAERI, CIAE
- Current status
  - JAEA: on schedule
  - KAERI: planning
  - CIAE: under consideration

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Upcoming Webinars

Date	Title	Presenter
02 October 2024	Prospects and Challenges of the GFR Technology	Petr Java, UJV, Czech Republic
26 November 2024	Overview and update of SCWR within GIF	Armando Naval, CNL, Canada
05 December 2024	Overview and Update of LFR Activities within GIF	Mariano Tatantino, ENEA, Italy

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https://tinyurl.com/PYG4Competition

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