Nuclear Innovation

Generation-IV Reactor Systems

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Sustainability of Energy Supply: Environmental Burden

- Construction foot print

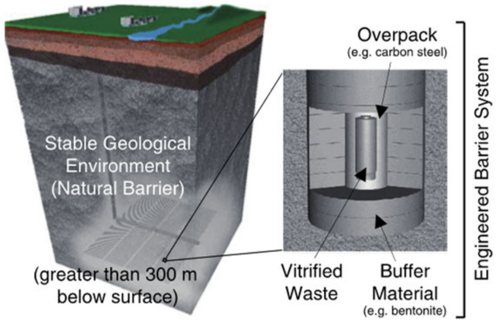
*1

Light Water Reactor (LWR) site
- 1.0 GWe
- 0.6 km^2 (example)

*2

Mega Solar site
- 0.1 GWe
- 2.2 km^2 (example)

- Waste



Nuclear
- Radioactive waste
- Geological disposal of High Level Waste (HLW)

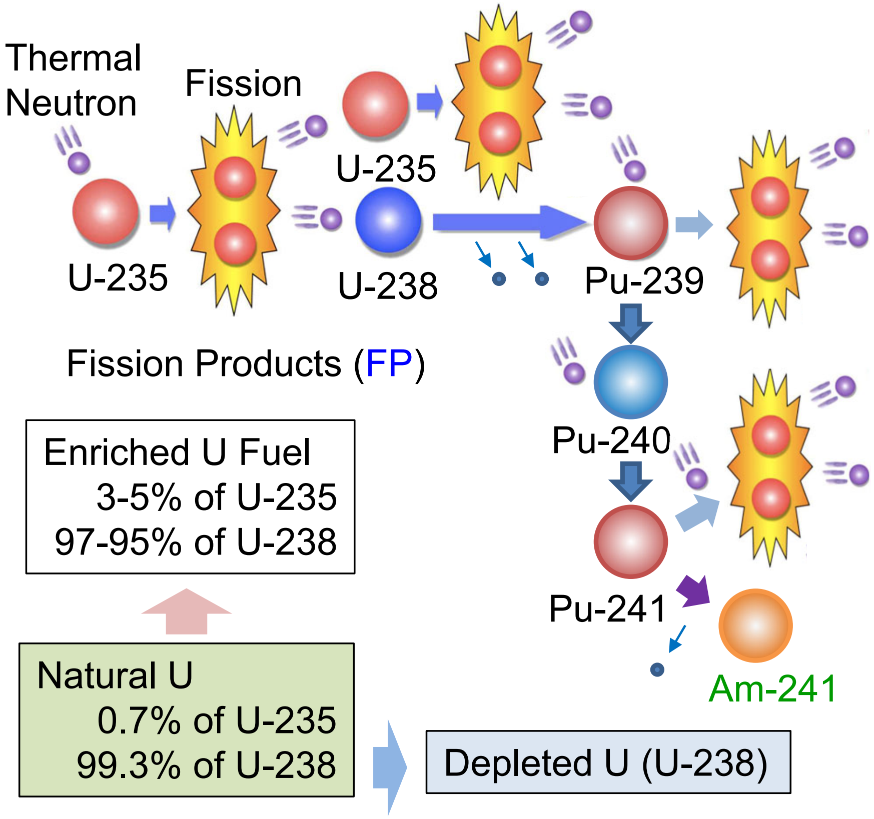
*3

Thermal Power Plant
- Large amount of waste
- Green House Gas

*1; Image by Kurt K. from Pixabay, *2: by skeeze, *3 : by Rebecca Human

Sustainability: Waste Management of Nuclear

● Nuclear Reactions in LWR Cycle

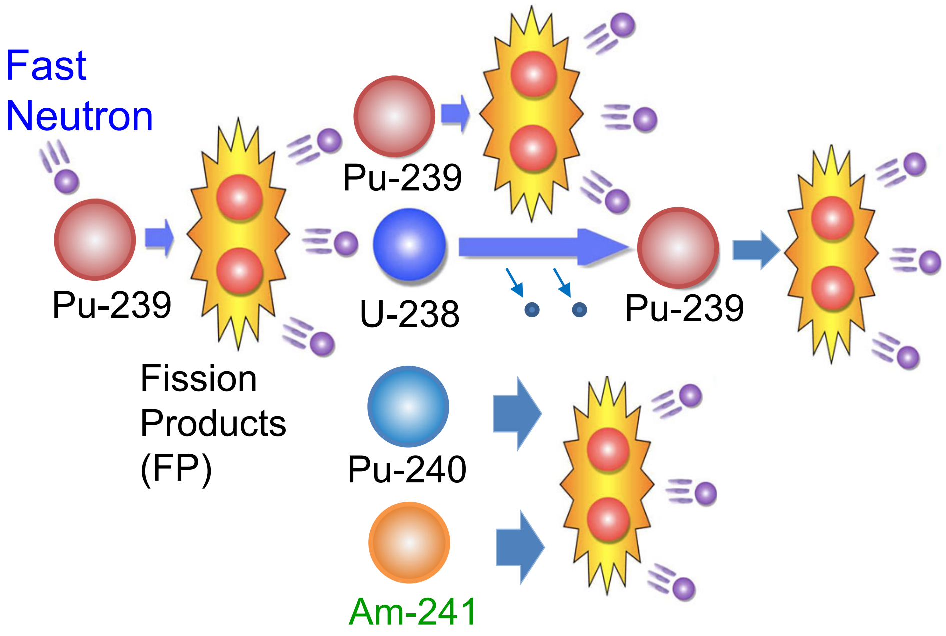


Enriched U Fuel
3-5% of U-235
97-95% of U-238

Natural U
0.7% of U-235
99.3% of U-238

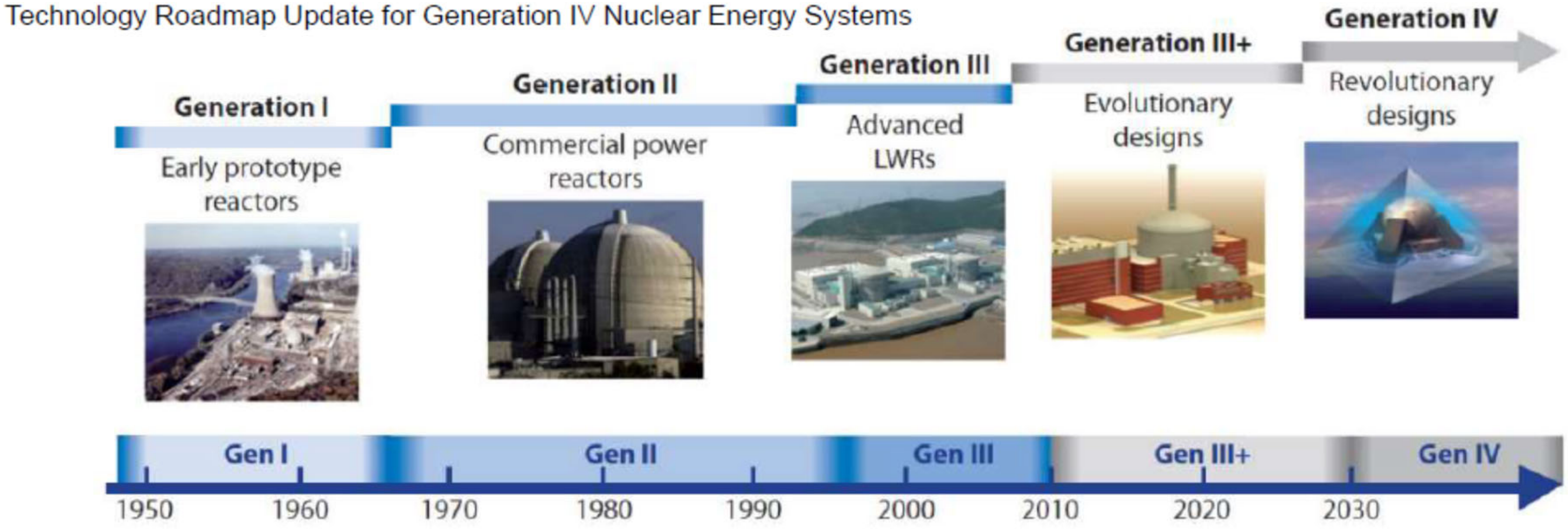
Depleted U (U-238)

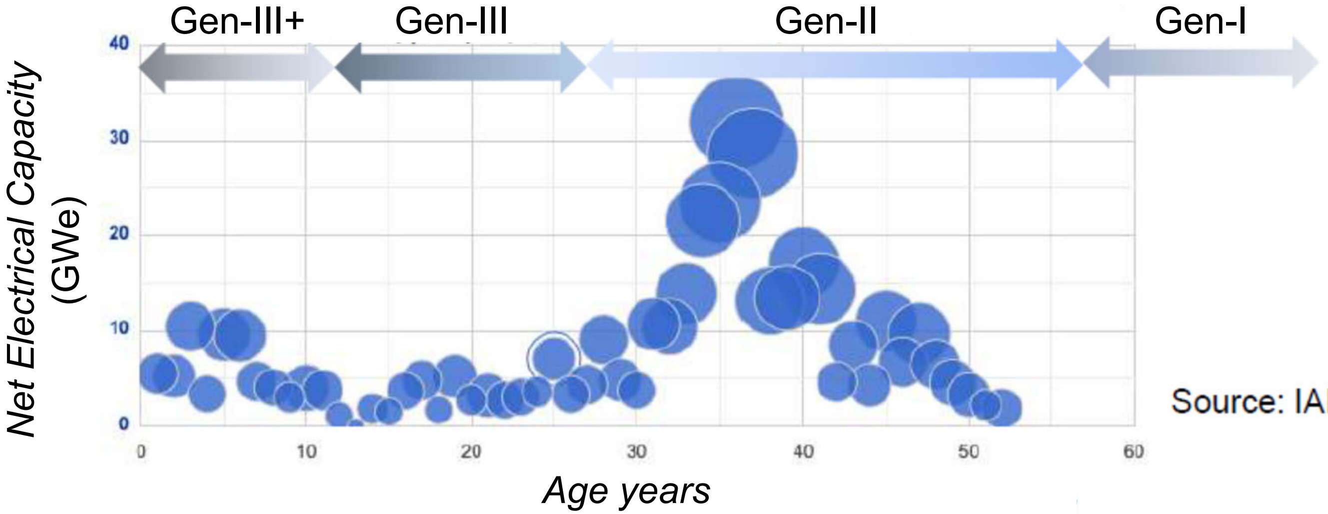
● by Fast neutron reactors



Pu and U mixed Fuel (MOX)
- Pu ~ 20%
- Depleted U (U-238)
- Minor Actinides (MA) 0 ~3%

Generation IV Nuclear Energy is Now required





Source: IAEA, PRIS

- Size reflects the Number of Reactors

Generation IV International Forum (GIF)

☐ USA proposed a bold initiative in 2000

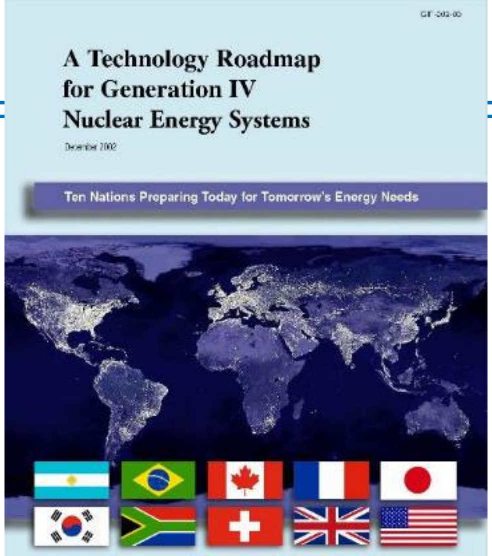
- The vision was to leapfrog LWR technology and collaborate with international partners to share R&D on advanced nuclear systems
- 9 Countries and EU joined USA in developing the initiative

☐ Gen IV concept defined via technology goals and legal framework

- Technology Roadmap released in 2002
  - Nearly 100 reactor designs evaluated and down selected to 6 most promising concepts
- First signatures collected on Framework Agreement in 2005; first research projects defined in 2006

GIF Goals

- Sustainability
  - Long term fuel supply
  - Minimize waste and long term stewardship burden
- Safety & Reliability
  - Very low likelihood and degree of core damage
  - Eliminate need for offsite emergency response
- Economics
  - Life cycle cost advantage over other energy sources
  - Financial risk comparable to other energy projects
- Proliferation Resistance & Physical Protection
  - Unattractive materials diversion pathway
  - Enhanced physical protection against terrorism



A Technology Roadmap for Generation IV Nuclear Energy Systems

Ten Nations Preparing Today for Tomorrow's Energy Needs

Gen-IV Nuclear Reactor Systems and Major Specifications

System	Neutron Spectrum	Coolant	Outlet temp. (Degree C)	Fuel cycle
Sodium-cooled Fast Reactor (SFR)	Fast	Sodium	500-550	Closed
Lead-cooled Fast Reactor (LFR)	Fast	Lead	480-570	Closed
Gas-cooled Fast Reactor (GFR)	Fast	Helium	850	Closed
Molten Salt Reactor (MSR)	Thermal/ Fast	Fluoride/Chloride salts	700-800	Open/ Closed
Supercritical Water-cooled Reactor (SCWR)	Thermal/ Fast	Water	510-625	Open/ Closed
Very High Temperature Reactor (VHTR)	Thermal	Helium	900-1000	Open

Examples of SMRs / Non-light water Reactors

Organizations	Project or Reactor	Coolant	Characteristics
NuScale Power	VOYGR	Light Water	PWR base, Multi units in a pool
GE-Hitachi	BWRX-300	Light Water	BWR base
ROSATOM	Akademik Lomonosov	Light Water	PWR base, Floating power unit
CEA, EDF,…	NUWARD	Light Water	PWR base
MSIT	SMART	Light Water	PWR base
Oklo	AURORA	Heat Pipe	Fast Reactor
TerraPower	NATRIUM	Sodium	Fast Reactor
ARC Clean Energy	ARC-100	Sodium	Fast Reactor
Westinghouse	Demo. LFR	Lead	Fast Reactor
X-energy	Xe-100	Helium	High Temperature gas cooled Reactor (HTGR)
USNC	MMR	Helium	HTGR
U-Battery	U-Battery	Helium	HTGR
Terrestrial Energy	IMSR	Fluoride Salt	Molten Salt Reactor (MSR), Thermal Reactor
TerraPower	MCFR	Chloride Salt	MSR, Fast Reactor

Nuclear Energy Policy Direction in Japan (December 2022)

1. All-out Efforts for Restarting NPPs

- Voluntary Improvements on Safety, Coexistence with Local Communities

2. Maximum use of Existing Reactors

- Develop a Framework for NPP Operation Period, under the premise of safety

3. Develop/Construct of Next-gen Advanced NPPs

- Target on rebuilding the site which has been decided DCM (decommissioning),
- Improve in NPP Business Env and HRD, Promote Intl' R&D (incl. SMR)

4. Accelerate Back-end Process

- Promote Fuel Cycle, Steady & Efficient DCM, Efforts for Final Disposal

5. Maintain/Strengthen Supply-chain

- Reinforce JPN Supply-chain, by Support to Industry for join in Intl' Projects

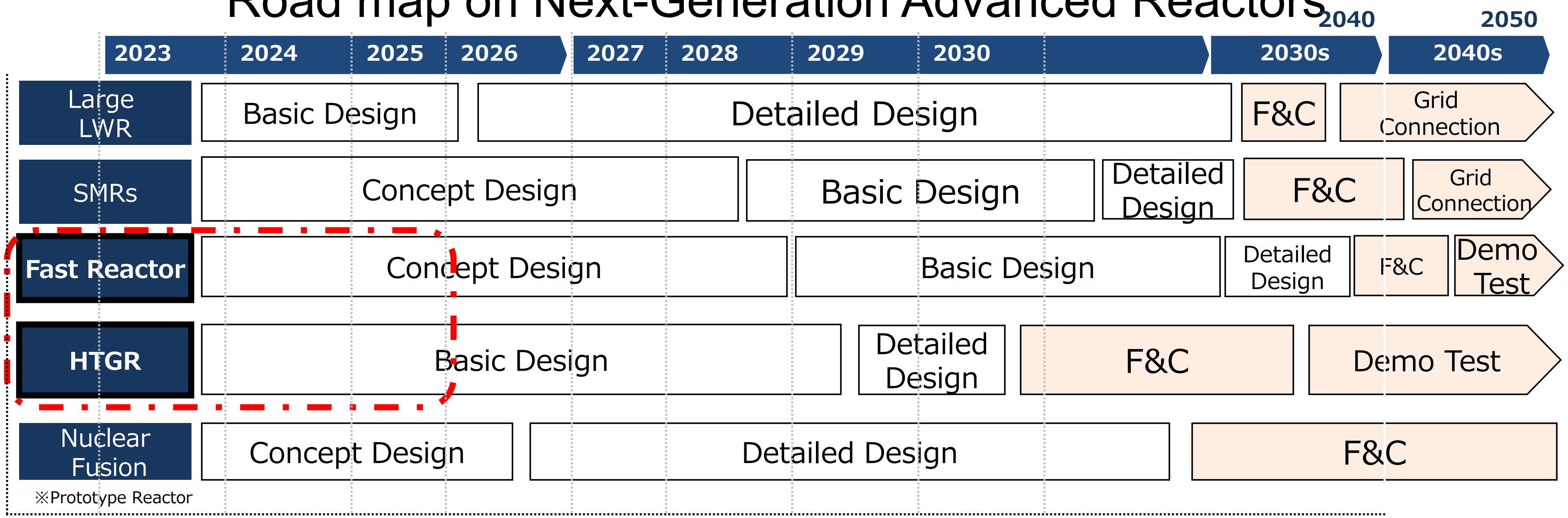
6. Contribute to Solve Common Intl' Issues

- Cooperation among like-minded countries, Ensuring Nuclear Safety in Ukraine

Development of Next-generation Advanced NPPs

- ❑ In order to accelerate GX(Green Transformation) , GoJ has announced to establish budget proposal GX bond (provisional translation)
- ❑ The amount of bonds is 20 trillion yen in the next 10years (2023-2034)

Road map on Next-Generation Advanced Reactors



※F&C, Fabrication & Construction

- **Fast Reactor Demonstration and Development Project**
  【$357mil for 3years(2023-2025)】
- **High-Temperature Gas-cooled Reactor Demonstration and Development Project**
  【$335mil for 3years(2023-2025)】

Development of Sodium-cooled Fast Reactors as Nuclear Innovation

Requirements for next-generation innovative reactors

Stable and reliable power supply

- As a carbon-free power source, contribute to stable, sustainable power supply across the nation.
- Innovations of safety for the public trust.
- Innovate processes of 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 for limited natural resources
- Enable natural resource recycling of energy through technological innovation (Reprocessing)

Flexibility

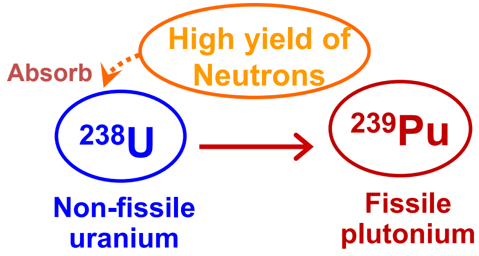
- Support variable renewables by adjusting power output
- Produce hydrogen, achieve various heat application, and store heat when electricity demand is low
- Be flexible in site locations by reducing the sizes of emergency planning zones
- National welfare through medical RI production

Further enhancement of safety

- Develop and promote technologies for safer nuclear power by reflecting lessons learned from TEPCO's Fukushima Daiichi nuclear power plant (1F) accident.

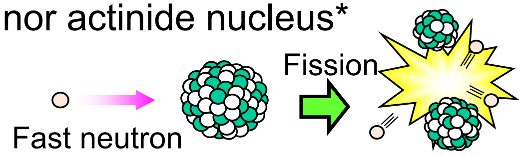
Features of a Sodium-cooled Fast Reactor (SFR)

Fast neutron



Produce new fuel

Minor actinide nucleus*

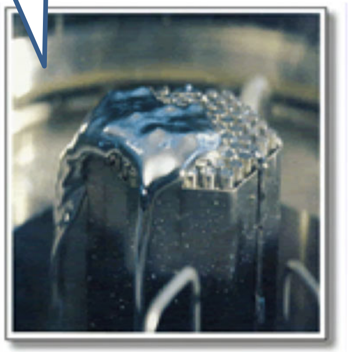


Reduce the toxicity of radioactive waste

- Fast neutrons have higher energy to make nuclear reactions and various applications.

Liquid sodium

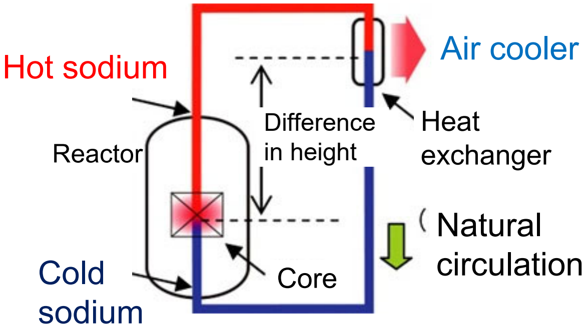
Sodium flowing through a fuel assembly model



- Sodium does not moderate neutron speed at collision so much (compared with water).
- Boiling point is 883 degree C, lower by 300 C than operation temperature (~550 C) at low pressure (➔Higher thermal efficiency and easy to keep the liquid level)

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.

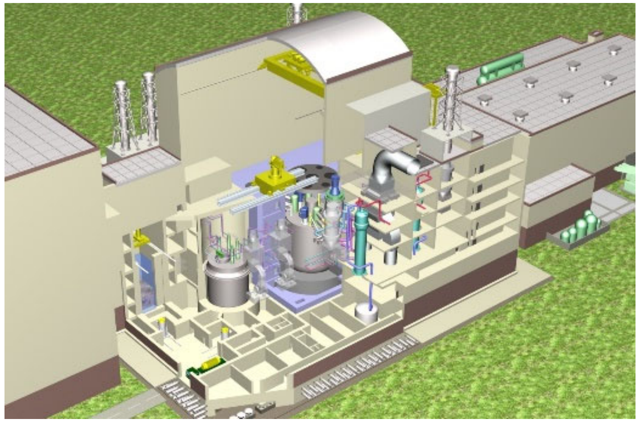


- Sodium is easily circulated naturally by convection driven by temperature difference, allowing natural cooling of the reactor even if the power source is lost.

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

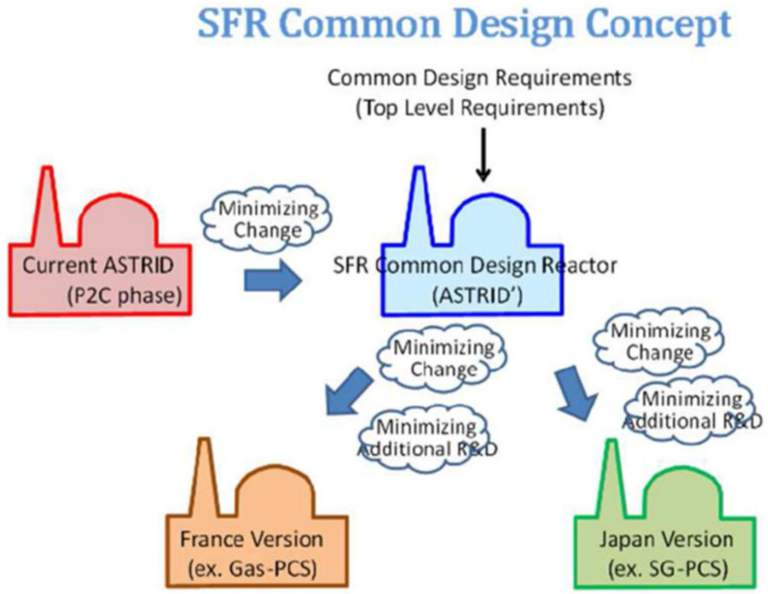
Design study of pool type Fast Reactors

- Japanese pool type reactor design with 3D seismic isolation system.
  - Electric output: 650MWe
  - Core: MOX fuel, using FAIDUS subassembly as a mitigation measure of severe accidents, i.e., discharge of core melt in early phase of accident
  - 3D seismic isolation system (a 1/2 scaled mockup of 3D isolation system was fabricated and Experiments in progress.)
  - Feasibility of safety, economical competitiveness, and seismic design has been confirmed.



Schematic of Japanese pool type reactor

- France-Japan common design: target of effective R&D cooperation

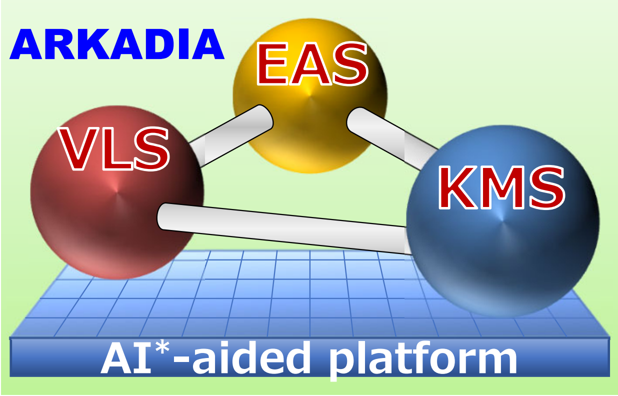


- Electric output: 650MWe
- Core fuel: MOX fuel, CFV core

1/2 scaled mockup of 3D seismic isolation system

ARKADIA as a Digital Triplet for Reactor Design

- ☐ Support evaluation of various innovative reactor concepts represented by a sodium-cooled fast reactor
- ☐ Optimize plant lifecycle of an advanced reactor automatically by using state-of-the-art simulation technologies and knowledge



*Artificial Intelligence

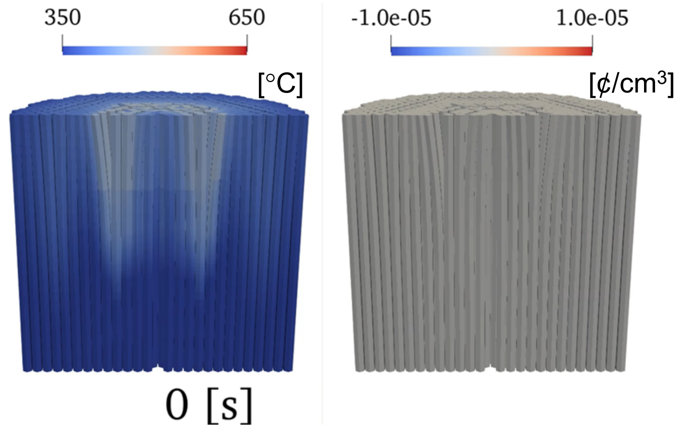
- ☐ Virtual Plant covering its life cycle
- ☐ Knowledgebase of Experiment, Simulation, Design, Maintenance...
- ☐ Design optimization with AI

- ❖ VLS: Virtual plant Life System,
- ❖ KMS: Knowledge Management System,
- ❖ EAS: Enhanced and AI-aided design optimization System

ARKADIA-Design

optimizes core design, plant structure design, and maintenance program

Example coupled simulation by VLS (Neutronics, thermal hydraulics, structure)

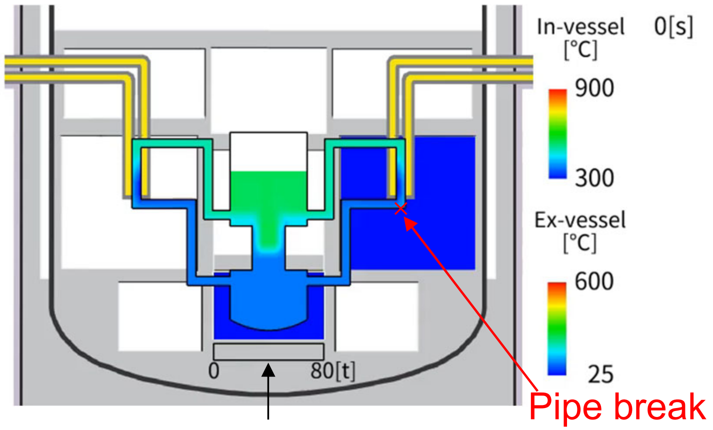


Temperature Deformation Reactivity

ARKADIA-Safety

provides design satisfying requirements of safety and economics from SA* simulation

Example SA simulation by VLS (loss of rector level)



Leaked debris

* Severe Accident

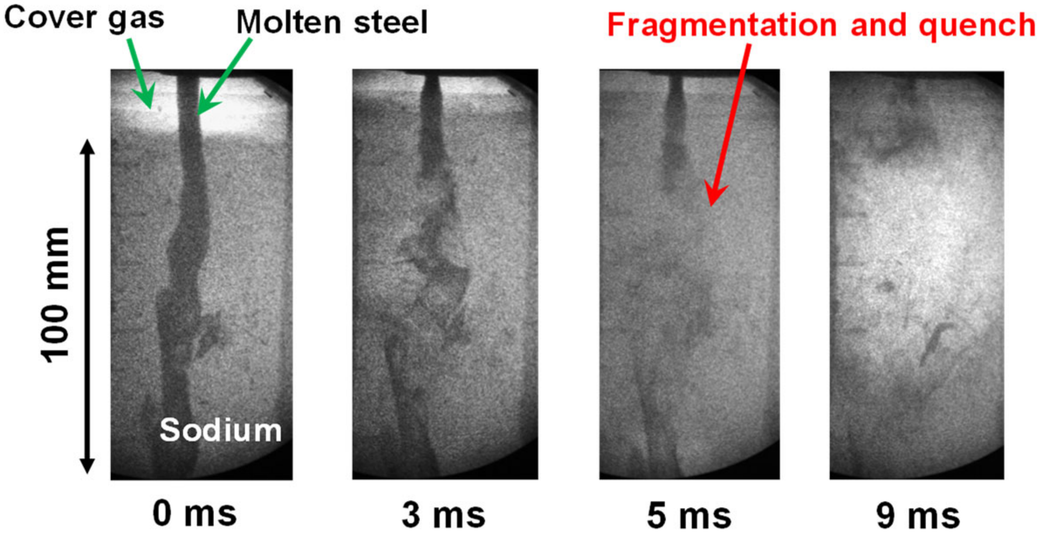
Components of VLS for Design and Safety Evaluations

Sodium experiments on Safety Issues

➢ *In-vessel retention of Core melt Accident*

MELT facility:

Utilized for experimental studies to clarify the molten-core material behavior during severe accidents of SFR

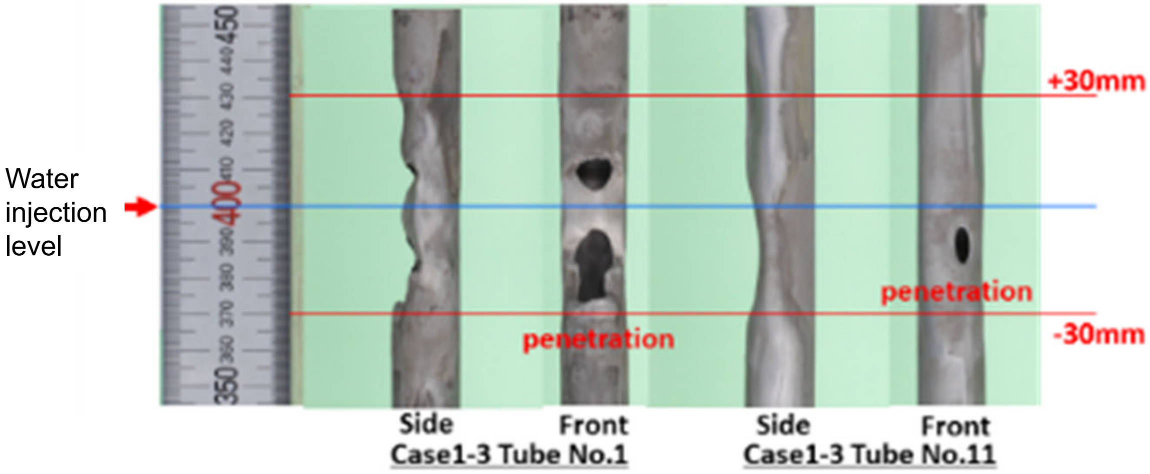


X-ray images of melt behavior in sodium

➢ *Sodium Water Rection*

SWAT-3R Facility:

Sodium-water reaction (SWAT-3R) test simulating high temperature and pressure steam-water jets into sodium in SG

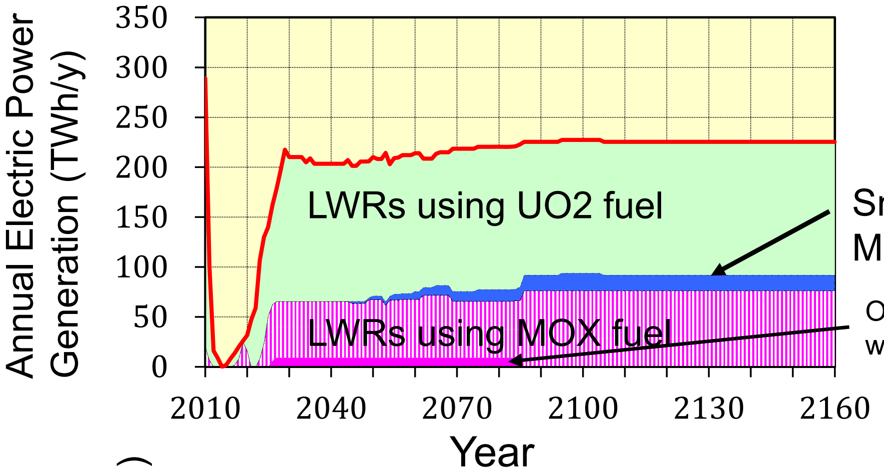


Example of Test: Penetrating failure tubes

Case Study of SMR SFR operations in Japan for Pu & Waste Management

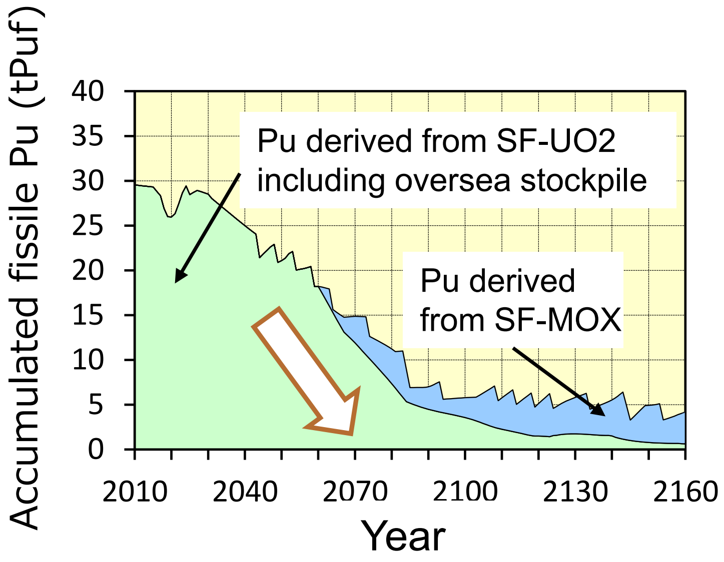
Assumption:
Small-sized SFRs are introduced one by one from 2045 up to 9 units

- 300MWe, Conversion rate:0.8 uses degraded Pu recovered from SF-MOX of LWRs

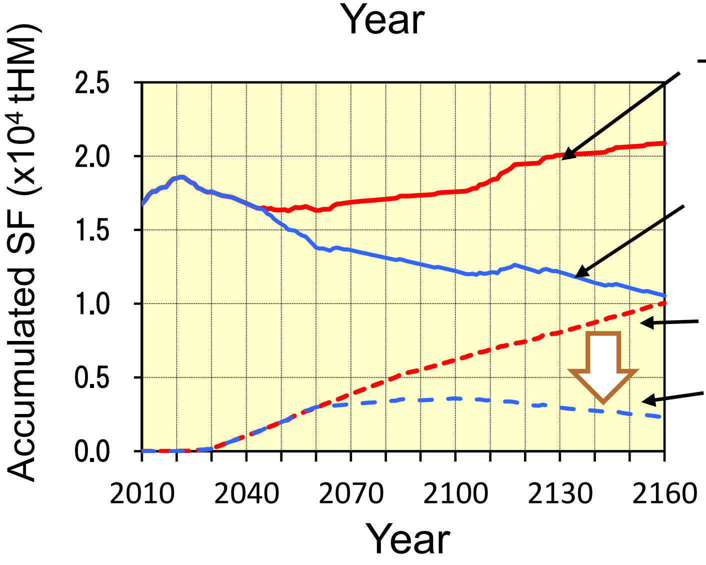


Small Fast Reactors using MOX fuels: max. 9 units

Ohma power plant (ABWR) with full MOX core



【History of Separated Pu Accumulation】



Total spent fuels w/o FR

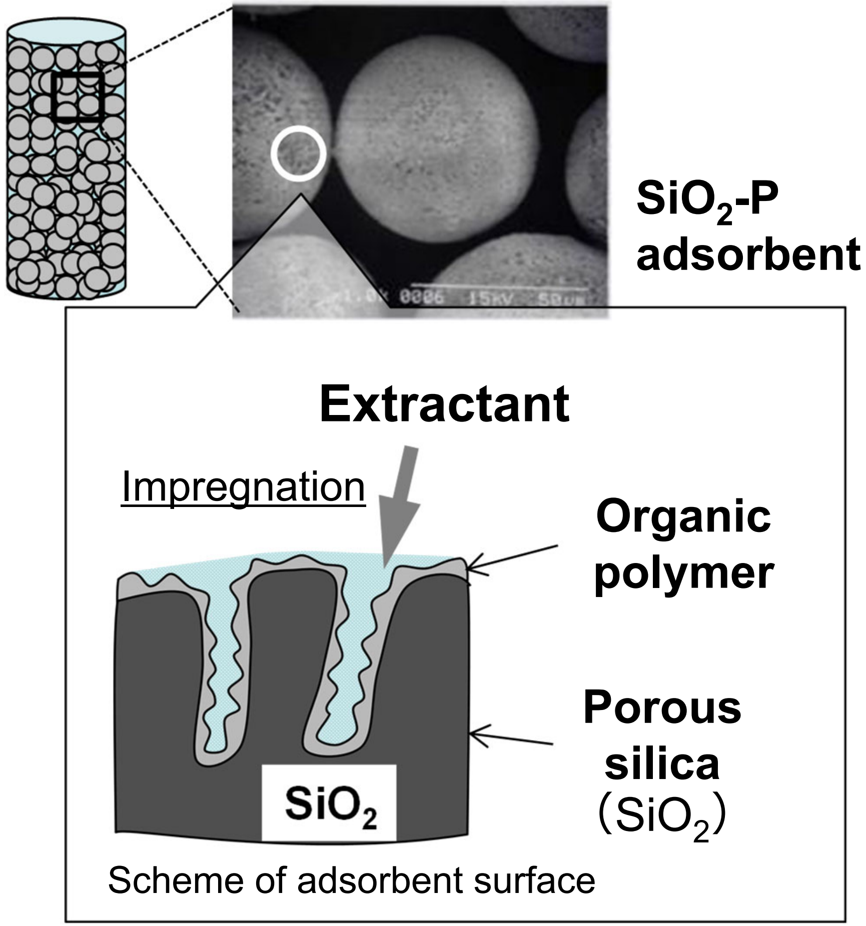
Total spent fuels with FR introduction

Spent MOX fuel w/o FR

Spent MOX fuel with FR introduction

【History of Accumulated Spent Fuels amount】

Minor Actinides (MA) Separation Technology Developments



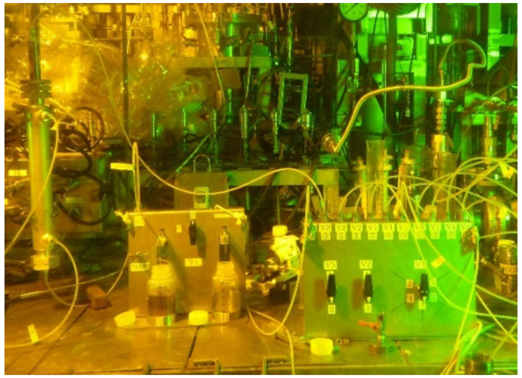
Particle size： 50 – 100 µm, Pore size：500-600nm

Basic structure of SiO_2-P adsorbent

- MA separation technology from high level liquid waste (HLLW) using extraction chromatography.
- Adsorbent: porous silica coated with polymer and impregnated extractants.

⇨ Compact equipment and waste reduction of organic solvent

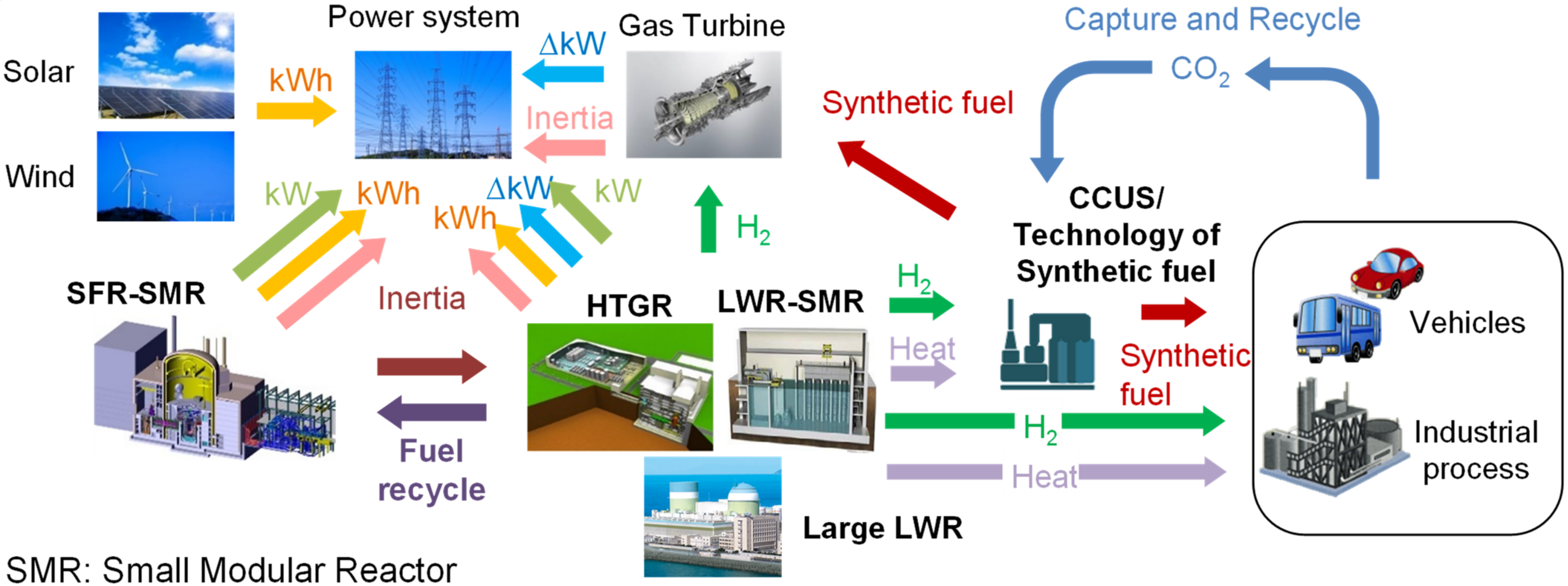
About 2g of MA (Am and Cm) was successfully separated from HLLW using this technology.



Extraction chromatography setup in hot cell

MA solution recovered from HLLW

Nuclear and Renewable Hybrid Energy System



SMR: Small Modular Reactor

kWh：Power Generation ΔkW：Power Generation Adjustability kW：Supply capacity

■ Development Goals
- Energy supply security & reliability
- Carbon neutrality
- Safe and sustainable nuclear energy

1) Modeling & Simulation
   - ✓ National electricity grids resilience
2) Platform for Demonstration
   - ✓ IoT (digital twin) to monitor, forecast and optimize production

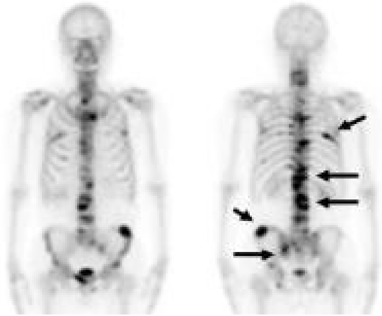
Contribution to non-energy fields: RI production

- 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.

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

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

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



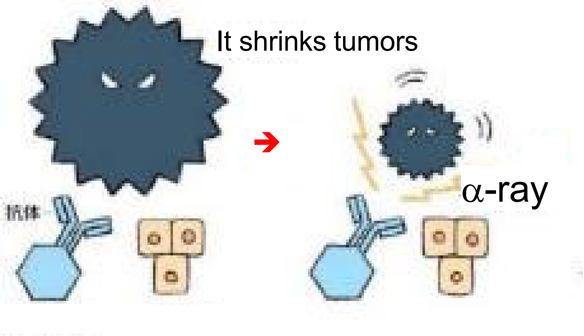
Mo-99

Used in nuclear medical 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

Education & Training: GIF activity

https://www.gen-4.org/gif/jcms/c_82831/webinars

Please web search by "GIF and Webinar"

GIF Webinar Guide

Webinars

In 2016, the GIF Education and Training Task Force began organising a webinar series which features speakers from around the world, explaining why GEN IV reactor systems are crucial for the sustainability of the nuclear fuel cycle. The webinar series was launched with a presentation by former GIF Chair John Kelly on "Atoms for Peace – the Next Generation" and includes monthly webinars. The Task Force was elevated to a Working Group in November 2019.

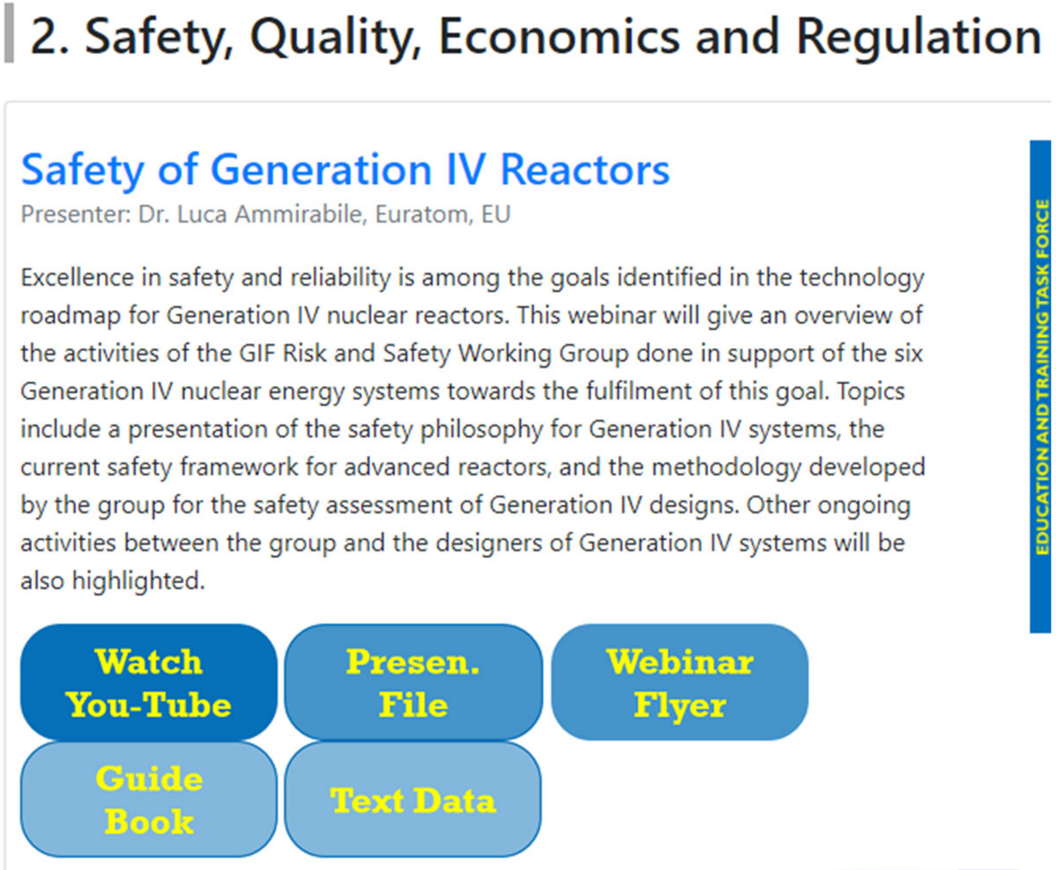
All webinars are also accessible on "YouTube" under the "GIF Education and Training Working Group".

By following the links below, you will access all past webinars:

2022 2021 2020 2019 2018 2017 2016 - or GIF Portal -

Webinar - (jaea.go.jp)

NEW 2023 SERIES (from 73 to 84)



2. Safety, Quality, Economics and Regulation

Safety of Generation IV Reactors

Presenter: Dr. Luca Ammirabile, Euratom, EU

Excellence in safety and reliability is among the goals identified in the technology roadmap for Generation IV nuclear reactors. This webinar will give an overview of the activities of the GIF Risk and Safety Working Group done in support of the six Generation IV nuclear energy systems towards the fulfilment of this goal. Topics include a presentation of the safety philosophy for Generation IV systems, the current safety framework for advanced reactors, and the methodology developed by the group for the safety assessment of Generation IV designs. Other ongoing activities between the group and the designers of Generation IV systems will be also highlighted.

Summary

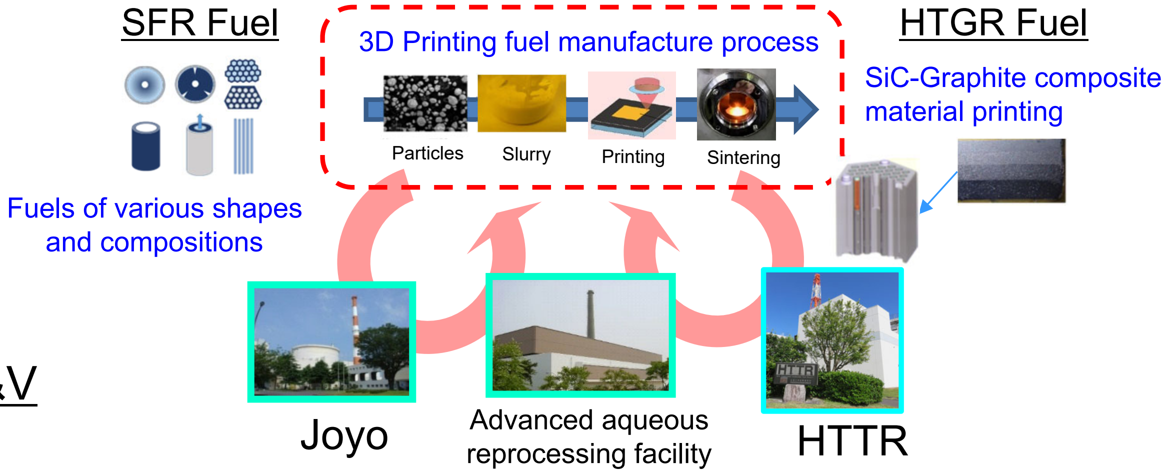
- ❑ Sustainability of Nuclear Energy Use
  - – Efficient use of Uranium
  - – Reduction of waste; Greenhouse Gas and volume/ toxicity of High Level radioactive Waste
- ❑ Potential of Generation IV Reactor Systems thanks to fast neutron and high temperature output (> 500 degree C)
- ❑ Innovations in Sodium cooled Fast Reactor (SFR) developments
  - – Designs on seismic isolation system, safety enhancement, by Digital Triplet
  - – Sodium experiments on Passive safety, In-vessel retention of Severe Accidents
  - – Reduction of HLW in Fuel cycle, 3D-printing for fuel production
  - – Hybrid energy system with Renewal Energies,
  - – Non-energy fields: RI production for medical use
- ❑ International Cooperation through GIF (Generation IV International Forum)
  - – Safety Design Criteria, Education & Training; GIF Webinar series

This presentation material includes some of the results of the “Technical development program on a commercialized FBR plant” and “Technical development program on a fast reactor international cooperation, etc.” and “Technical development program on a common base for fast reactors” entrusted to JAEA by the Ministry of Economy, Trade and Industry in Japan (METI).

3D Printing Ceramic Fuel Technology

■ Development Goals :

- Fuel cycle synergy for SFR and HTGR
- Enable advanced fuel features
- Enhance safety and economics



SFR Fuel

Fuels of various shapes and compositions

3D Printing fuel manufacture process

HTGR Fuel

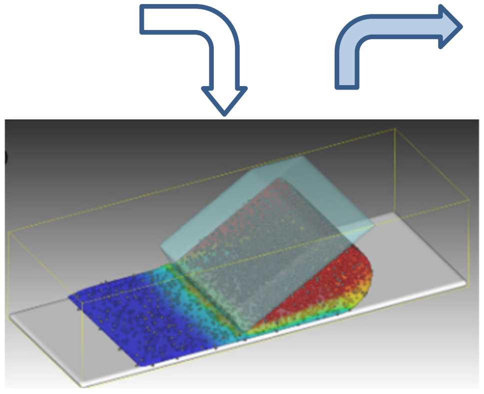
SiC-Graphite composite material printing

Research on 3D Printing CAE Simulation and V&V

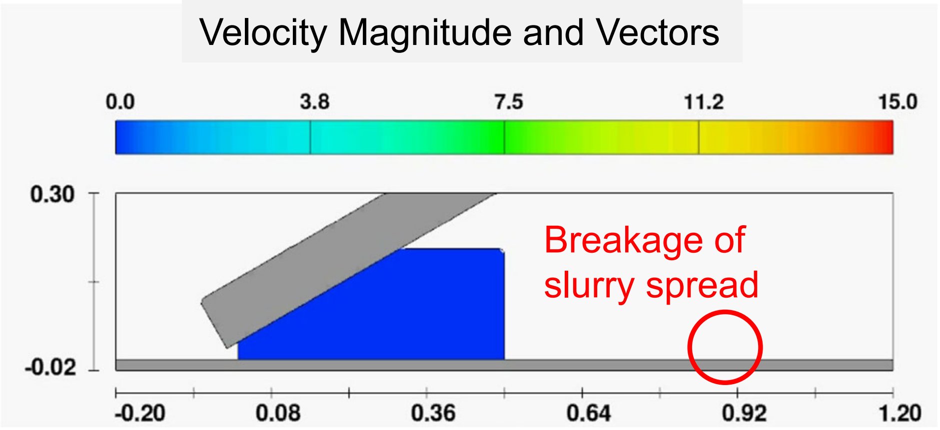
(Computer-Aided Engineering)

- ✓ Particles and slurry
  Complex behavior re-produced by CFD
- ✓ Stereolithography printing
- ✓ Spark plasma sintering
- ✓ Irradiation performance

CAE will greatly accelerate deployment of 3D printing fuels



Slurry Spreading Process



Velocity Magnitude and Vectors

Breakage of slurry spread