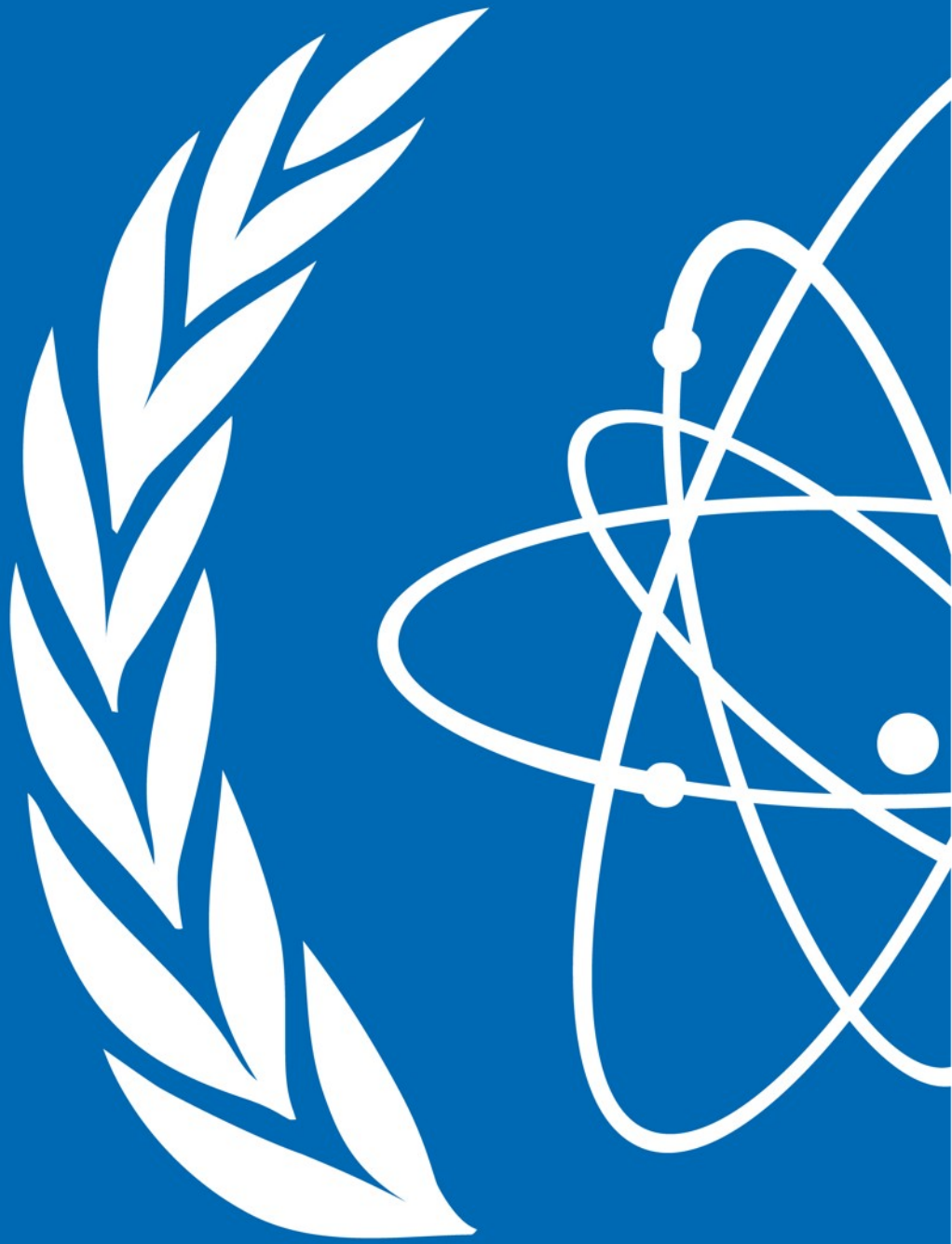
# Six Gen-IV Innovative Conceptual Reactor Designs

*Vladimir Kriventsev,*
*Nicole Virgili, Panashe Ndlalambi*

*Fast Reactor Technology Development Team*
*Nuclear Power Technology Development Section*
Division of Nuclear Power
Department of Nuclear Energy
International Atomic Energy Agency

IAEA Interregional Workshop on Aspects of Modelling and Simulation in Gen-IV Type SMR Developments, *03-07 November 2025, Moscow*





https://www.iaea.org/topics/fast-reactors

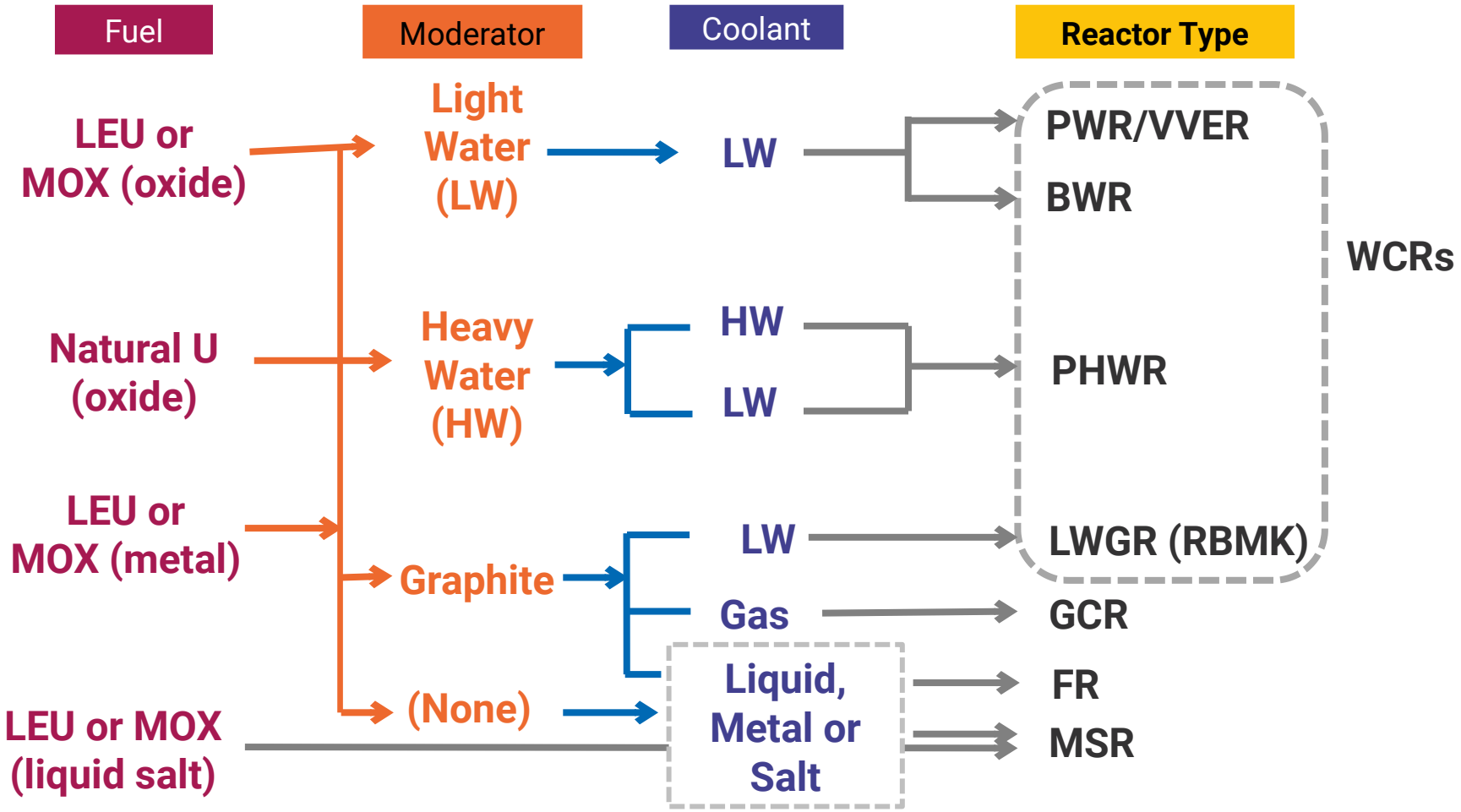
# Outline

- Innovative Nuclear Reactors and Six Gen-IV Concepts by GIF
  - Reactor Classification and Innovative Nuclear Energy Systems
  - Gen-IV Systems and IAEA Terminology
  - Limitations of Water cooled Reactors?
  - Six Gen-IV Conceptual Designs
    - *Super-Critical Water cooled Reactor (SCWR)*
    - *Very High Temperature Reactor (VHTR)*
    - *Gas cooled Fast Reactor (GFR)*
    - *Sodium cooled Fast Reactor (SFR)*
    - *Lead and LBE cooled Fast Reactor (LFR)*
    - *Molten Salt cooled Reactor (MSR)*
  - Other options: Thorium Fuel Cycle
  - IAEA Advanced Reactors Information System (ARIS)

# Outline

- Innovative Nuclear Reactors and Six Gen-IV Concepts by GIF
  - Reactor Classification and Innovative Nuclear Energy Systems
  - Gen-IV Systems and IAEA Terminology
  - Limitations of Water cooled Reactors?
  - Six Gen-IV Conceptual Designs
    - *Super-Critical Water cooled Reactor (SCWR)*
    - *Very High Temperature Reactor (VHTR)*
    - *Gas cooled Fast Reactor (GFR)*
    - *Sodium cooled Fast Reactor (SFR)*
    - *Lead and LBE cooled Fast Reactor (LFR)*
    - *Molten Salt cooled Reactor (MSR)*
  - Other options: Thorium Fuel Cycle
  - IAEA Advanced Reactors Information System (ARIS)

# Nuclear Power Reactor Classifications




MOX: mixed-oxide containing any combination of U, Pu and Th

# Innovative Reactors (Gen-IV)

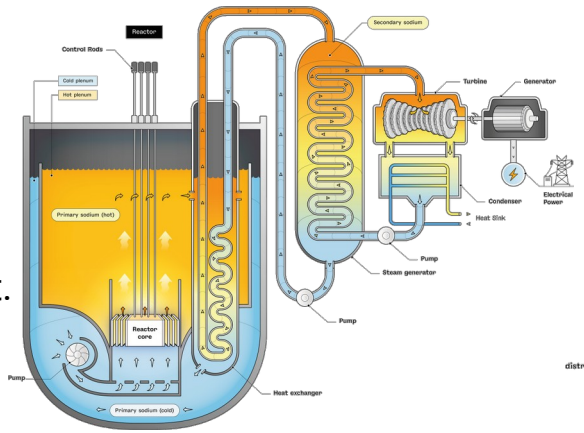
GEN IV International Forum
Expertise | Collaboration | Excellence

**Innovative Reactor**:

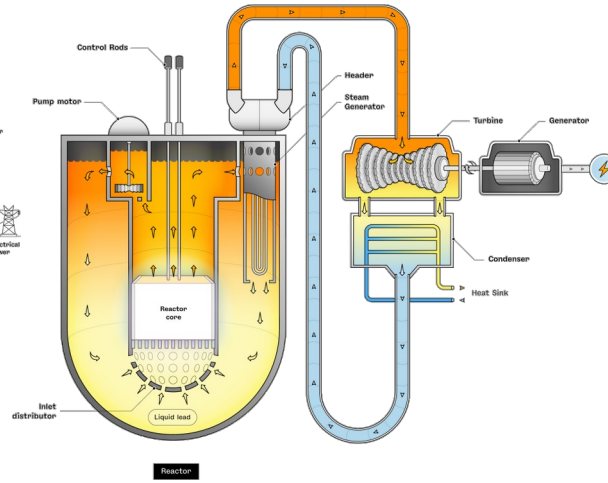
Advanced design which incorporates conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial R&D, feasibility tests, and possibly a prototype or demonstration reactor are required prior to deployment.

- **Early Prototypes and Demonstration Plants Gen-I**
- **Current Fleet Gen-II/III**
- **Advanced Nuclear Reactors**
  - *Evolutionary designs*
    Gen-III and Gen-III+
  - *Innovative designs*
    Gen-IV
  - SMRs can be either *evolutionary* or *innovative*
  - *Innovative SMR*
    *Advanced Modular Reactor (AMR)*

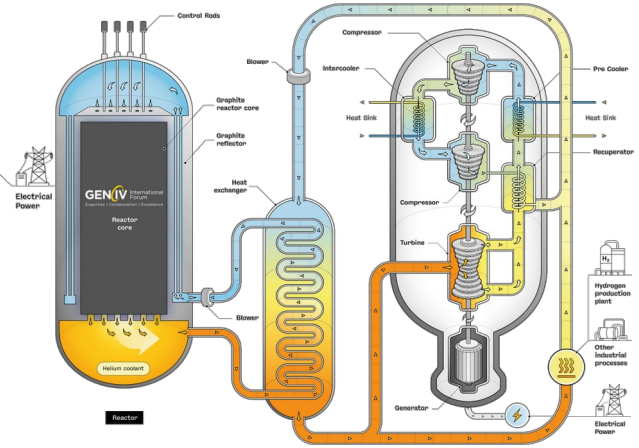
Sodium cooled Fast Reactor (SFR)

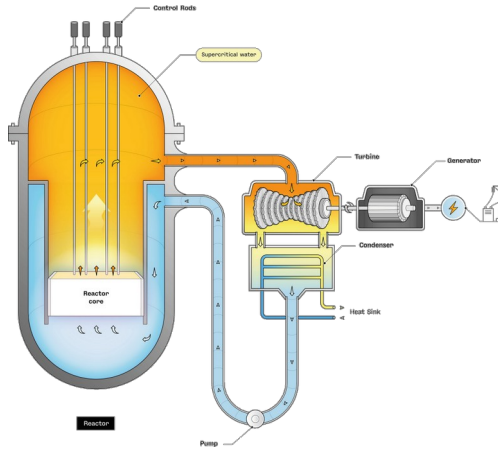



Lead cooled Fast Reactor (LFR)

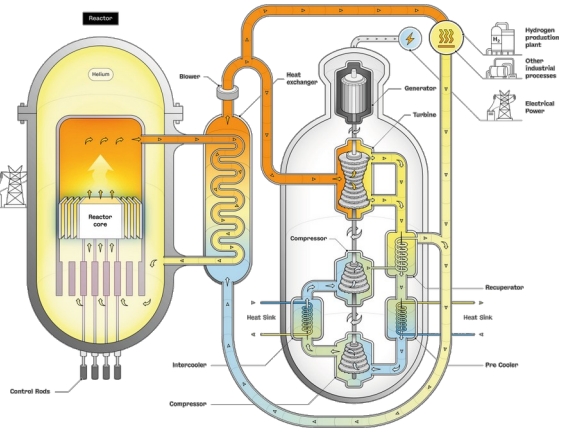



Very-High-Temperature Reactor (VHTR)

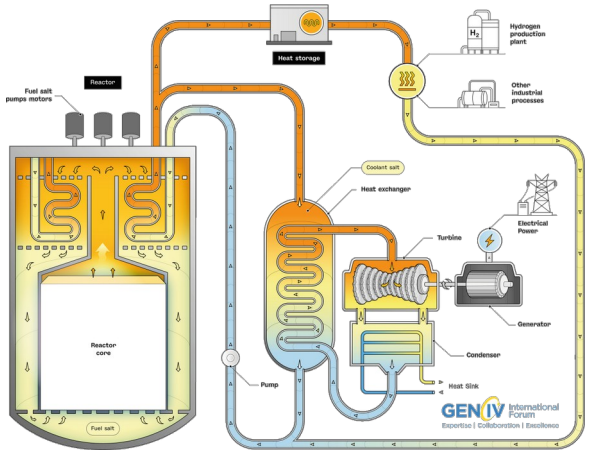



Supercritical Water cooled Reactor (SCWR)




Gas cooled Fast Reactor (GFR)



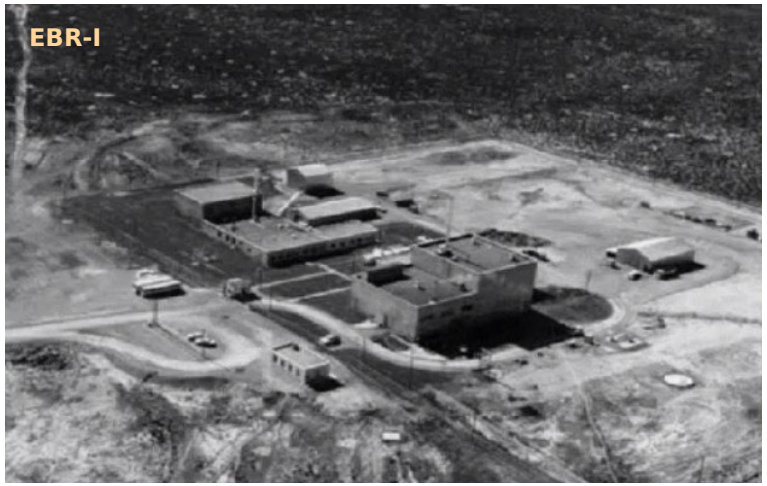

Molten Salt Reactor (MSR)

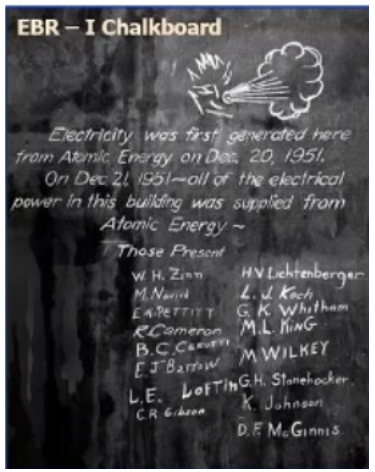
Source: GIF homepage (www.gen-4.org)

# Experimental Breeder Reactor (EBR-I)


## First Electricity Generated from Nuclear Reactor

- First ever liquid metal cooled fast reactor built by Argonne National Laboratory (ANL) – West (now Idaho National Laboratory (INL))
- The primary purpose of EBR-I is to demonstrate breeding of fissile material
- Coolant: NaK Eutectic Alloy, Fuel: Metallic Uranium
- On 20 December, 1951, EBR-I generated first usable electricity to power four light bulbs
- Later, EBR-I continued to supply 200 kW to power its own building
- Reactor operated for 12 years before its final shutdown in 1953





Source: https://www.ne.anl.gov/About/reactors/frt.shtml

# Outline

- Innovative Nuclear Reactors and Six Gen-IV Concepts by GIF
  - Reactor Classification and Innovative Nuclear Energy Systems
  - Gen-IV Systems and IAEA Terminology
  - Limitations of Water cooled Reactors?
  - Six Gen-IV Conceptual Designs
    - *Super-Critical Water cooled Reactor (SCWR)*
    - *Very High Temperature Reactor (VHTR)*
    - *Gas cooled Fast Reactor (GFR)*
    - *Sodium cooled Fast Reactor (SFR)*
    - *Lead and LBE cooled Fast Reactor (LFR)*
    - *Molten Salt cooled Reactor (MSR)*
  - Other options: Thorium Fuel Cycle
  - IAEA Advanced Reactors Information System (ARIS)

# GIF: Gen-IV Nuclear Energy Systems Goals

## Generation IV nuclear energy systems will…

| | |
|---|---|
| **Sustainability-1** | Provide long-term availability of systems and effective fuel utilization |
| **Sustainability-2** | Minimise the volume and the half-life of nuclear waste |
| **Economics-1** | Present a clear life-cycle cost advantage over other energy sources |
| **Economics-2** | Have a comparable level of financial risk vs. other energy projects |
| **Safety and Reliability-1** | Be operated safely and reliably |
| **Safety and Reliability-2** | Have a very low likelihood and degree of reactor core damage |
| **Safety and Reliability-3** | Eliminate the need for offsite emergency response |
| **Proliferation Resistance and Physical Protection** | Limit proliferation by being the least desirable route for diversion or theft of weapons-usable materials |

Source: GIF homepage (www.gen-4.org)

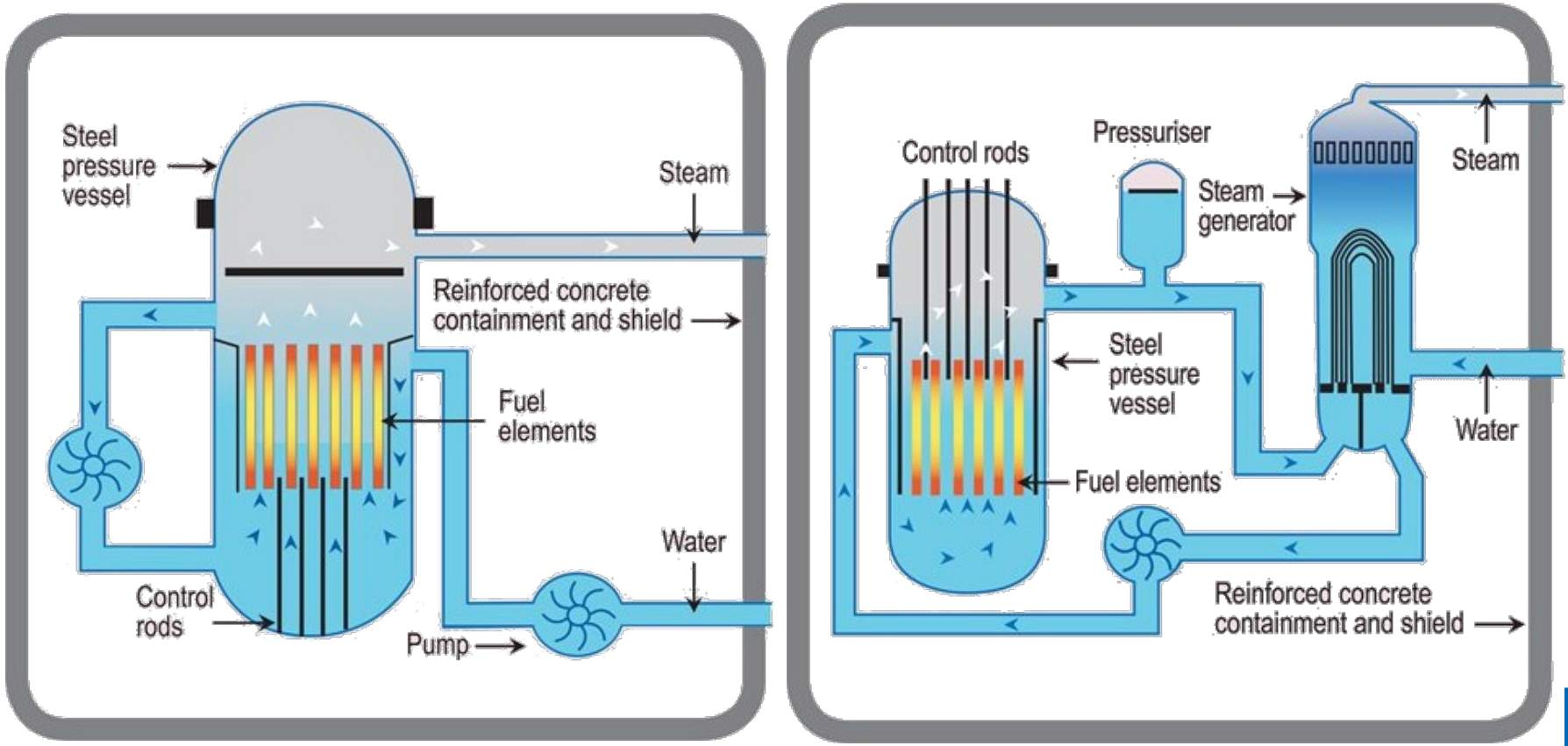
# Outline

- Innovative Nuclear Reactors and Six Gen-IV Concepts by GIF
  - Reactor Classification and Innovative Nuclear Energy Systems
  - Gen-IV Systems and IAEA Terminology
  - Limitations of Water cooled Reactors?
  - Six Gen-IV Conceptual Designs
    - *Super-Critical Water cooled Reactor (SCWR)*
    - *Very High Temperature Reactor (VHTR)*
    - *Gas cooled Fast Reactor (GFR)*
    - *Sodium cooled Fast Reactor (SFR)*
    - *Lead and LBE cooled Fast Reactor (LFR)*
    - *Molten Salt cooled Reactor (MSR)*
  - Other options: Thorium Fuel Cycle
  - IAEA Advanced Reactors Information System (ARIS)

# Water Cooled Reactors: Why are we unsatisfied?

| | WCR |
|---|---|
| coolant | $H_2O/D_2O$ |
| outlet T, C | 288-329 |
| efficiency, % | 35 |
| max P, MPa | 7-17 |
| spectrum | thermal |

- *Mature Technology*
- *Low T => Low Efficiency*
- *High Pressure => safety issues*
- *Only thermal spectrum => not sustainable*

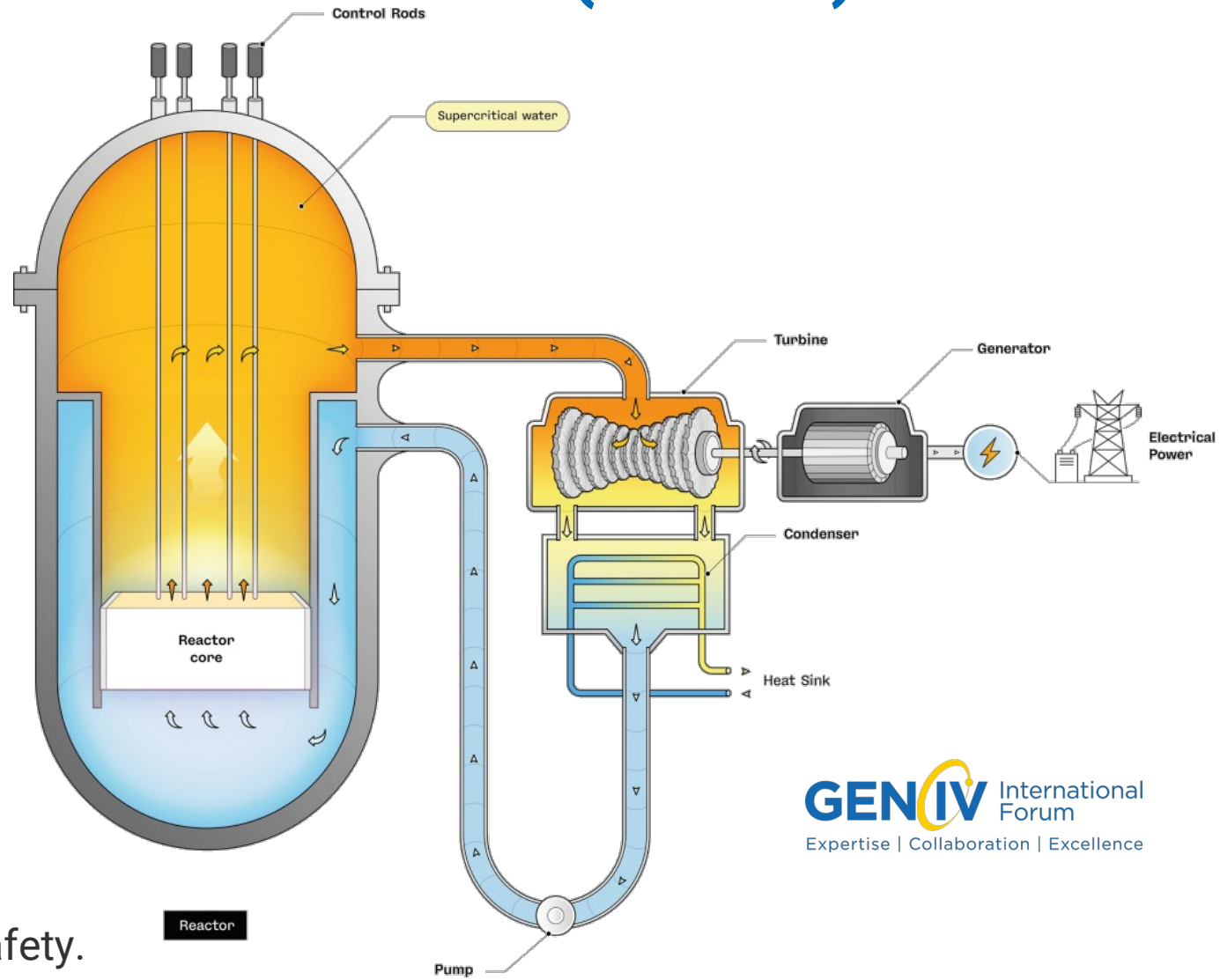


# Outline

- Innovative Nuclear Reactors and Six Gen-IV Concepts by GIF
  - Reactor Classification and Innovative Nuclear Energy Systems
  - Gen-IV Systems and IAEA Terminology
  - Limitations of Water cooled Reactors?
  - Six Gen-IV Conceptual Designs
    - *Super-Critical Water cooled Reactor (SCWR)*
    - *Very High Temperature Reactor (VHTR)*
    - *Gas cooled Fast Reactor (GFR)*
    - *Sodium cooled Fast Reactor (SFR)*
    - *Lead and LBE cooled Fast Reactor (LFR)*
    - *Molten Salt cooled Reactor (MSR)*
  - Other options: Thorium Fuel Cycle
  - IAEA Advanced Reactors Information System (ARIS)

# Super-Critical Water cooled Reactors (SCWR)

| | WCR | SCWR |
|---|---|---|
| coolant | $H_2O$ | $H_2O$ |
| outlet T, C | 288-329 | 500 |
| efficiency, % | 35 | 45 |
| max P, MPa | 17 | 25 |
| spectrum | thermal | thermal/fast |



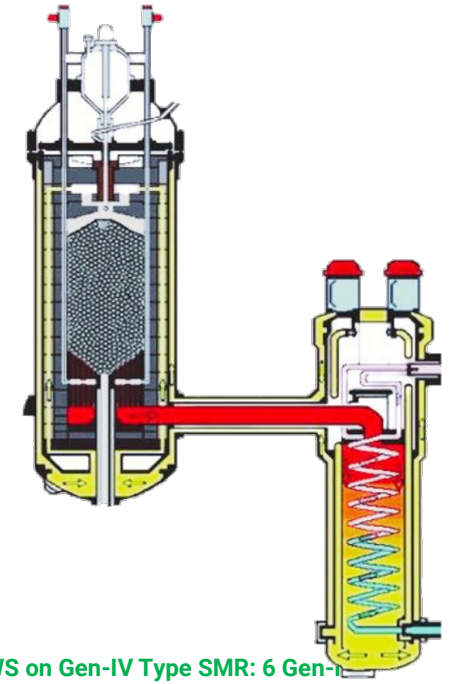

- Use water above critical point (22.12MPa and 647.14 K) as coolant.
- The high outlet temperature increases efficiency
- Potential for fast neutron spectrum in some designs.
- High Pressure -> increased costs for ensuring safety.
- Known technology for gas and coal plants but no experience in nuclear reactors.

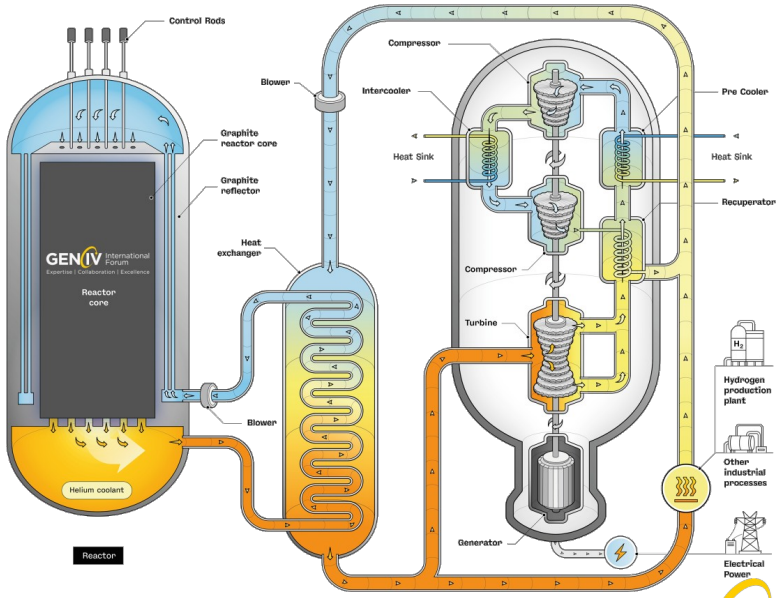
GEN IV International Forum
Expertise | Collaboration | Excellence

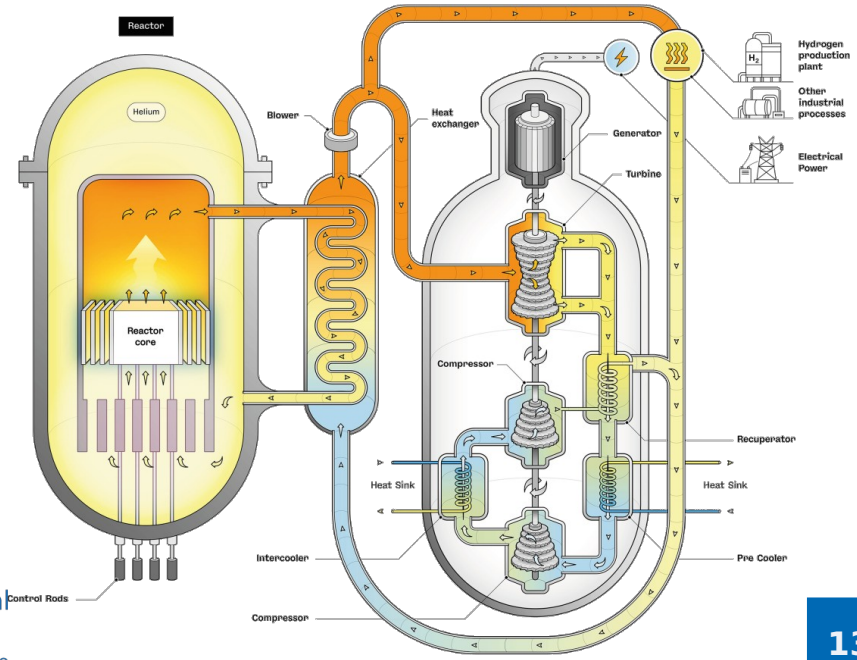
# Gas cooled Reactors (HTGR - VHTR, GFR)

| | WCR | SCWR | HTGR | GFR |
|---|---|---|---|---|
| coolant | $H_2O$ | $H_2O$ | He | He |
| outlet T, C | 288-329 | 500 | 750 | 750 |
| efficiency, % | 35 | 45 | 50 | 50 |
| max P, MPa | 17 | 25 | 7 | 7 |
| spectrum | thermal | thermal/fast | thermal | fast |

- The high temperatures and direct cycle increase efficiency
- The high temperature enables non-electric industrial applications
- Extended experience in gas and coal power plants but limited experience in nuclear
- GFR design allows for fast spectrum
- *Low Voiding Reactivity*





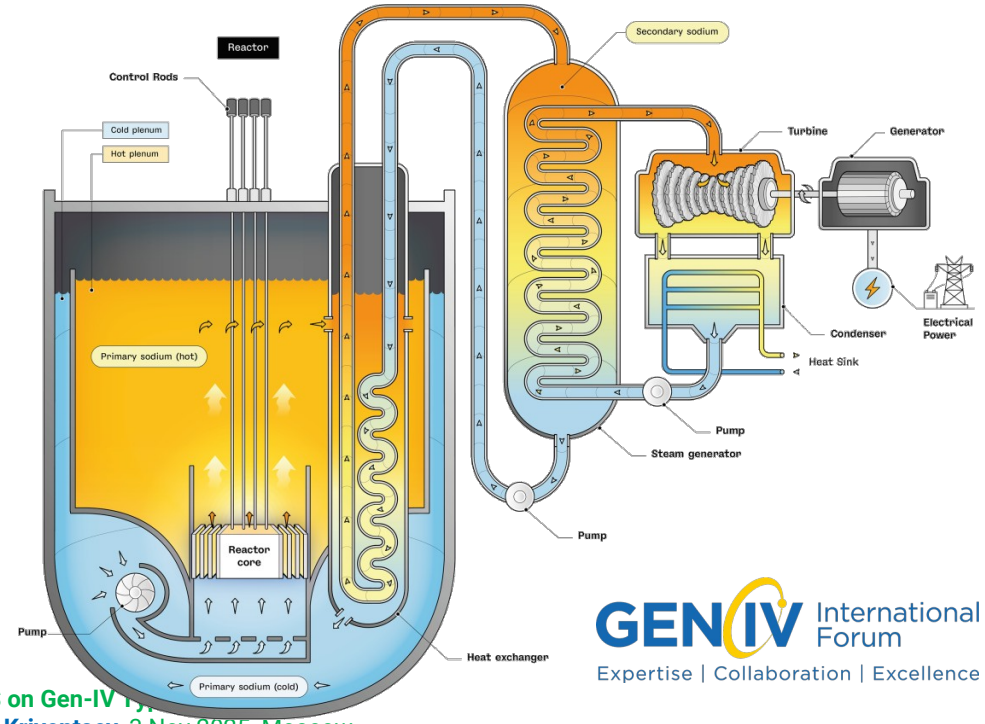



GEN IV International Forum
Expertise | Collaboration | Excellence

# Sodium cooled Fast Reactors

| | WCR | SCWR | HTGR | GFR | SFR |
|---|---|---|---|---|---|
| coolant | $H_2O$ | $H_2O$ | He | He | Na |
| outlet T, C | 288-329 | 500 | 750 | 750 | 550 |
| efficiency, % | 35 | 45 | 50 | 50 | 45 |
| max P, MPa | 17 | 25 | 7 | 7 | ~0.2 |
| spectrum | thermal | thermal/fast | thermal | fast | fast |

EBR-I 1951

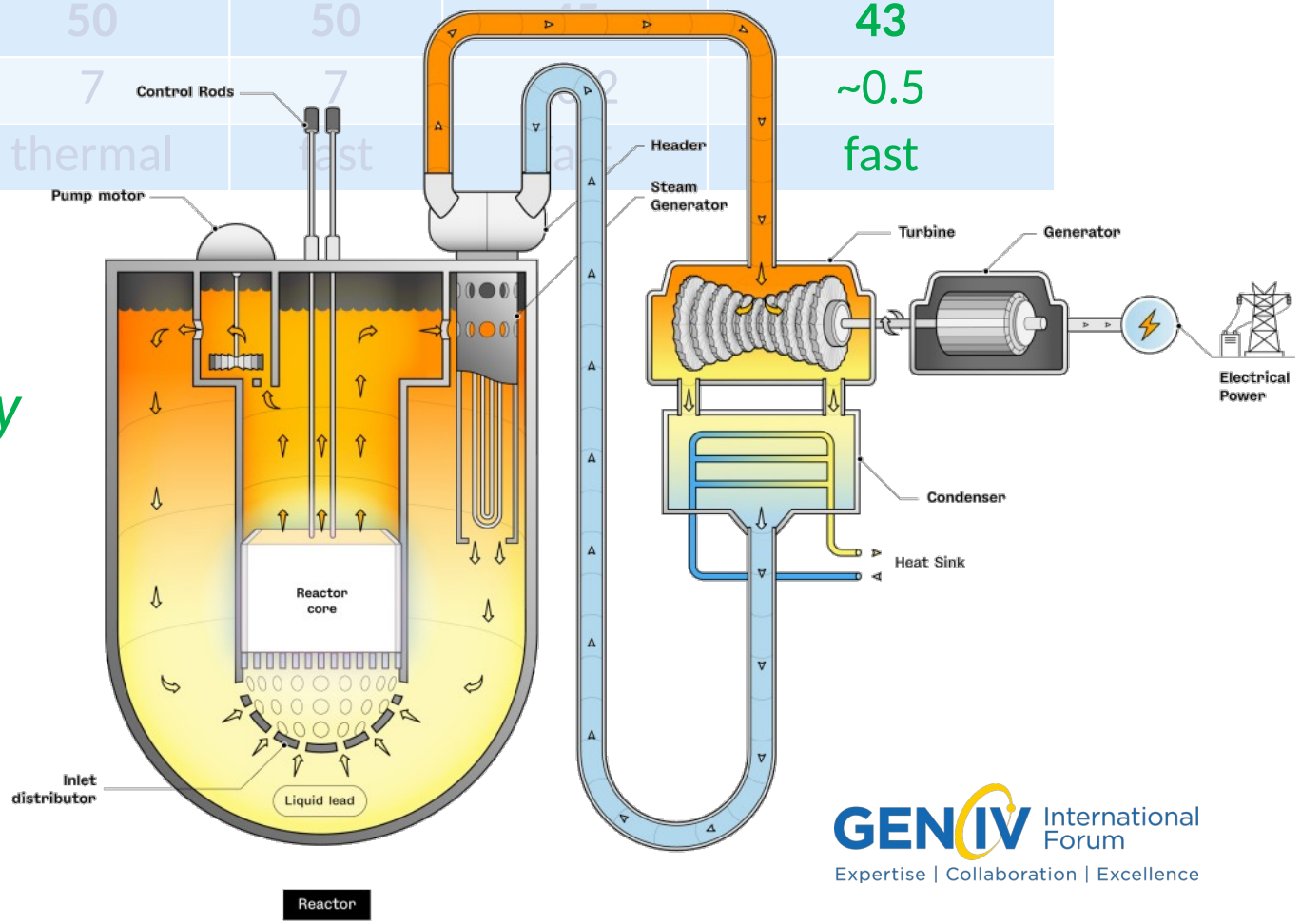

- *Hight coolant T => High Efficiency*
- *Low Pressure*
- *Mature Technology*
- *Fast spectrum*
- *Sodium violently reacts with water and air*

GEN IV International Forum
Expertise | Collaboration | Excellence

# Heavy Liquid Metal cooled Fast Reactors

| | WCR | SCWR | HTGR | GFR | SFR | LFR |
|---|---|---|---|---|---|---|
| coolant | $H_2O$ | $H_2O$ | He | He | Na | Pb/LBE |
| outlet T, C | 288-329 | 500 | 750 | 750 | 550 | 500 |
| efficiency, % | 35 | 45 | 50 | 50 | | 43 |
| max P, MPa | 17 | 25 | 7 | 7 | | ~0.5 |
| spectrum | thermal | thermal/fast | thermal | fast | | fast |

- *No intermediate circuit*
- *Hight coolant T => High Efficiency*
- *Low Pressure*
- *Fast spectrum*
- *New Technology*
- *Compatibility of Materials*
- *Pb/LBE $O_2$ Control*

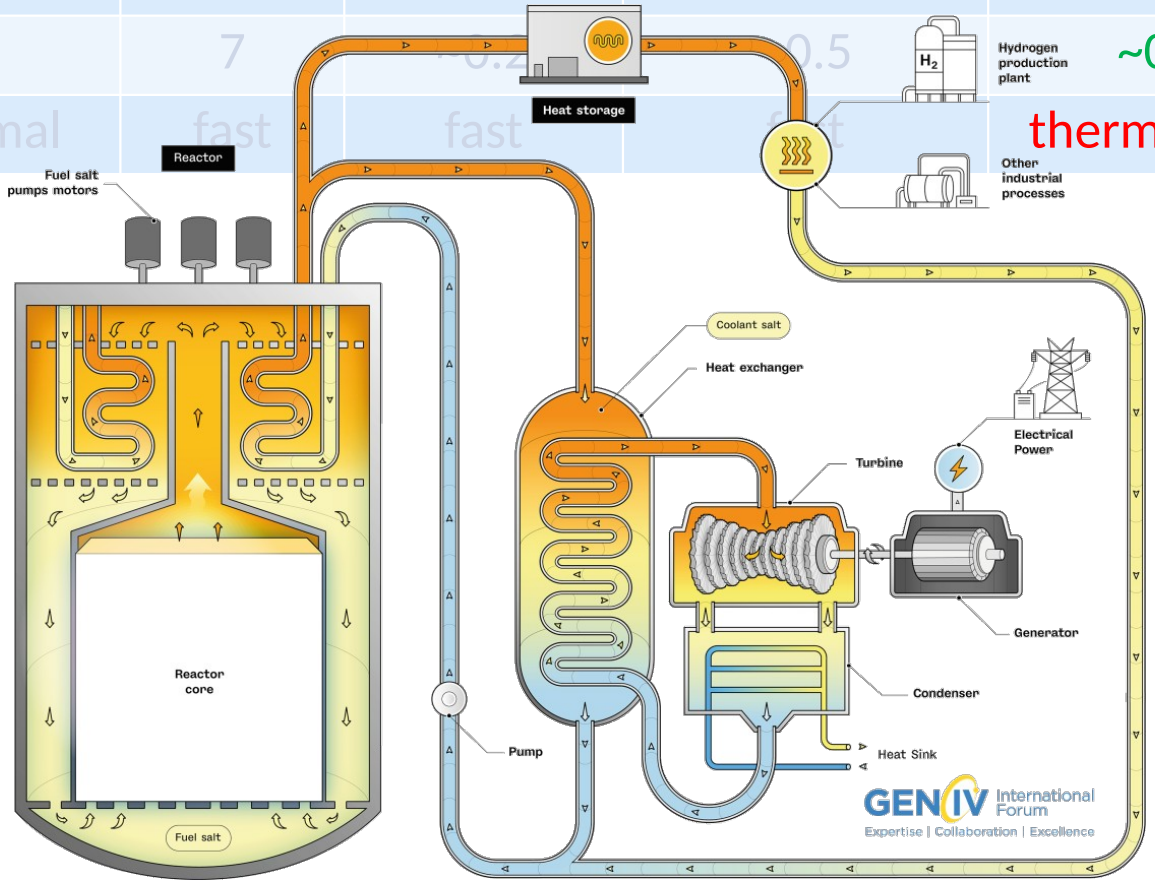



GEN IV International Forum
Expertise | Collaboration | Excellence

# Molten Salt Reactors

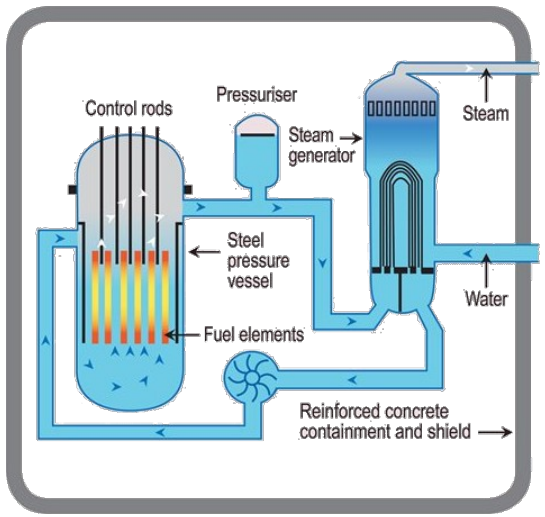
| | WCR | SCWR | HTGR | GFR | SFR | LFR | MSR |
|---|---|---|---|---|---|---|---|
| coolant | $H_2O$ | $H_2O$ | He | He | Na | Pb/LBE | Fluoride/Chloride |
| outlet T, C | 288-329 | 500 | 750 | 750 | 550 | 500 | 800 |
| efficiency, % | 35 | 45 | 50 | 50 | 45 | 43 | 48 |
| max P, MPa | 17 | 25 | 7 | 7 | ~0.2 | ~0.5 | ~0.2 |
| spectrum | thermal | thermal/fast | thermal | fast | fast | fast | thermal/fast |

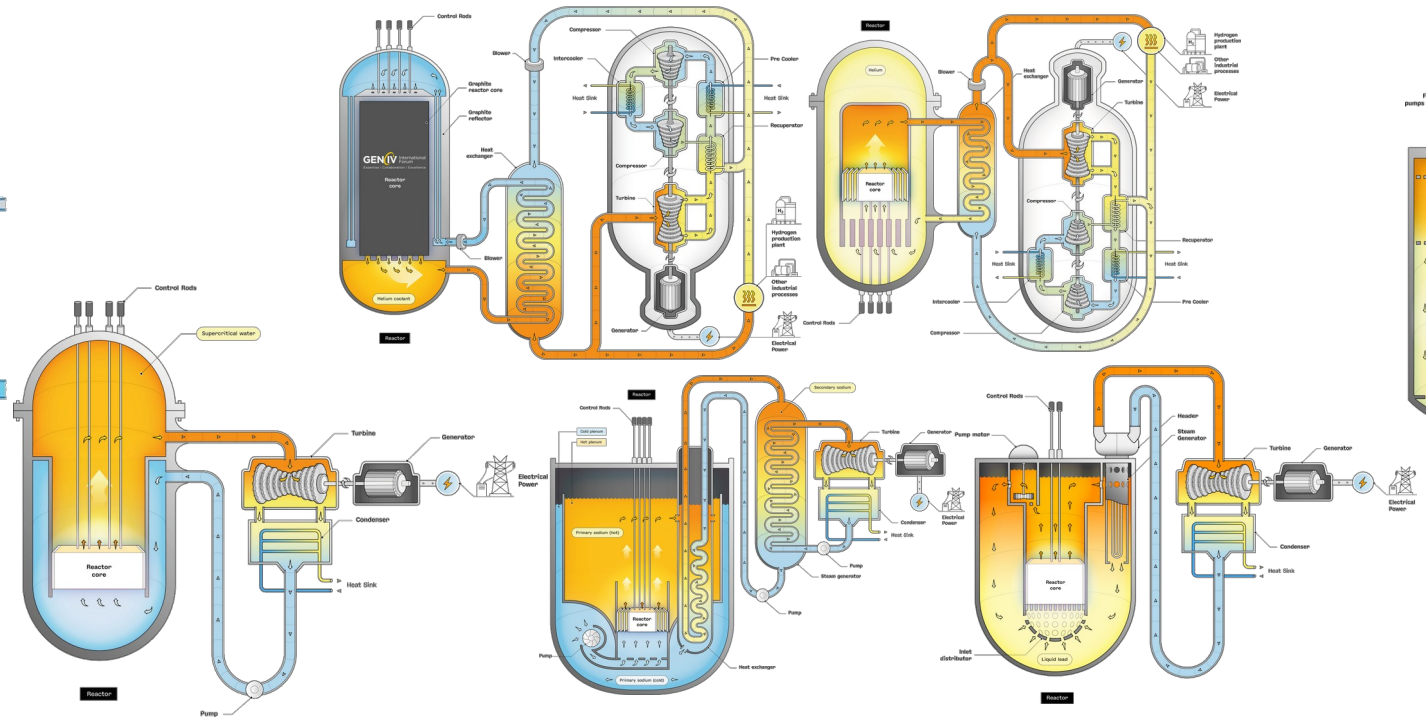
- *Hight coolant T => High Efficiency*
- *Low Pressure*
- *Very safe (negative temperature reactivity)*
- *Online Waste/Fuel Management*
- *Thermal/Fast spectrum*
- *New Technology*
- *Compatibility of Materials*

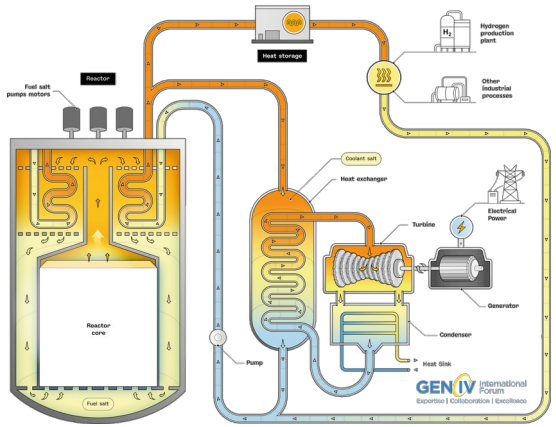


# Comparing Innovative Reactor Concepts

| | WCR | SCWR | HTGR | GFR | SFR | LFR | MSR |
|---|---|---|---|---|---|---|---|
| coolant | $H_2O$ | $H_2O$ | He | He | Na | Pb/LBE | Fluoride/Chloride |
| outlet T, C | 288-329 | 500 | 750 | 750 | 550 | 500 | 800 |
| efficiency, % | 35 | 45 | 50 | 50 | 45 | 43 | 48 |
| max P, MPa | 17 | 25 | 7 | 7 | ~0.2 | ~0.5 | ~0.2 |
| spectrum | thermal | thermal/fast | thermal | fast | fast | fast | thermal/fast |





# Innovative Reactors: Coolant Properties & More

| | WCR | SCWR | HTGR | GFR | SFR | LFR | MSR |
|---|---|---|---|---|---|---|---|
| coolant | $H_2O$ | $H_2O$ | He | He | Na | Pb/LBE | Fluoride/Chloride |
| outlet T, C | 329 | 500 | 750 | 750 | 550 | 500 | 800 |
| efficiency, % | 35 | 45 | 50 | 50 | 45 | 43 | 48 |
| max P, MPa | 17 | 25 | 7 | 7 | 0.2 | 0.5 | 0.2 |
| n. spectrum | thermal | thermal/fast | thermal | fast | fast | fast | thermal/fast |
| , kg/m$^3$ | 700 | 800/90 | 0.12/8.5 | | 830 | 10000 | 3200 |
| , kJ/kg/K | 5.7 | 5/4 | 5.2/5.2 | | 1.3 | 0.15 | 1.4 |
| , MJ/m$^3$/K | 4 | 0.35 | 6x10$^{-4}$/0.4 | | 1 | 1.5 | 4.5 |
| k, W/m/K | 0.6 | 0.1 - 0.4 | 0.15/0.24 | | 70 | 18 | 0.01 |
| boiling T, C | 350 | | | | 880 | 1700 | 1700 |
| melting T, C | | | | | 98 | 327/125 | ~500 |
| CMI[1] | ok | ok | good | good | ok | ? | ? |
| enrichment, % | <5 | <5/<20 | <5 | <20 | <20 | <20 | <5/<20 |

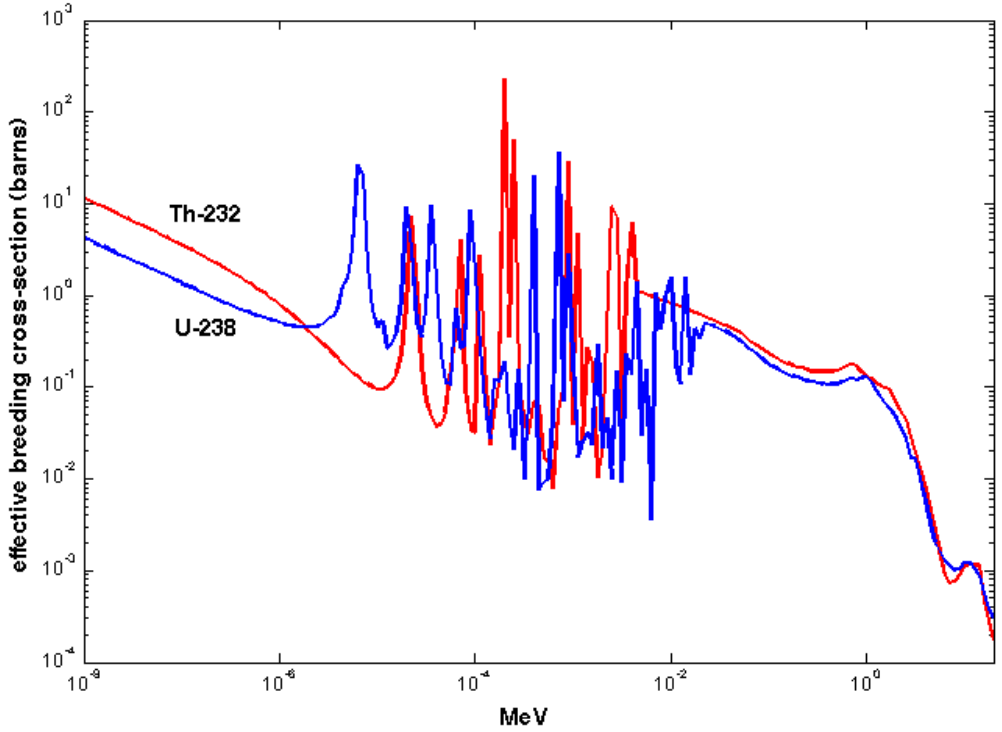
1) CMI: Coolant – structural Materials Interaction

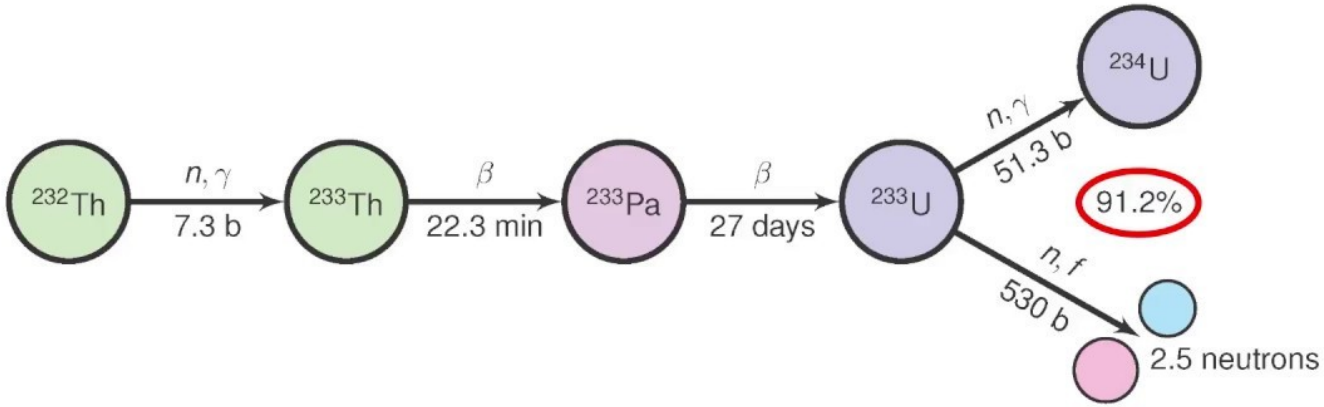
# Outline

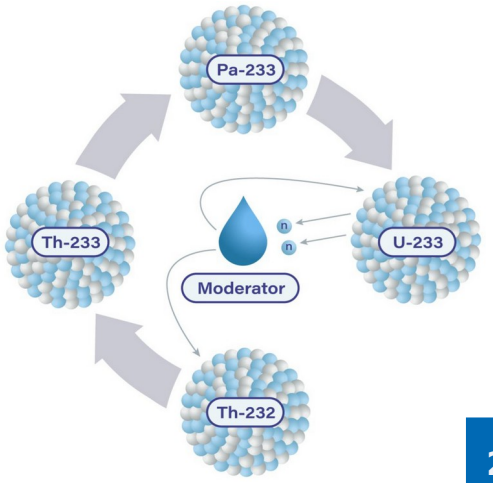
- Innovative Nuclear Reactors and Six Gen-IV Concepts by GIF
  - Reactor Classification and Innovative Nuclear Energy Systems
  - Gen-IV Systems and IAEA Terminology
  - Limitations of Water cooled Reactors?
  - Six Gen-IV Conceptual Designs
    - *Super-Critical Water cooled Reactor (SCWR)*
    - *Very High Temperature Reactor (VHTR)*
    - *Gas cooled Fast Reactor (GFR)*
    - *Sodium cooled Fast Reactor (SFR)*
    - *Lead and LBE cooled Fast Reactor (LFR)*
    - *Molten Salt cooled Reactor (MSR)*
  - Other options: Thorium Fuel Cycle
  - IAEA Advanced Reactors Information System (ARIS)

# Thorium Fuel Cycle

## $^{232}$Th >> $^{233}$U: Th Cycle can operate in thermal spectrum




Absorption of neutrons by $^{232}$Th initiates the series of transformations leading to the production of fissile $^{233}$U that is by far the best 'fissile' isotope for thermal neutron spectrum and can be used for breeding in both thermal and fast reactors.

See IAEA e-Learning Module on Thorium-Cycle-Based Reactors

# Outline

- Innovative Nuclear Reactors and Six Gen-IV Concepts by GIF
  - Reactor Classification and Innovative Nuclear Energy Systems
  - Gen-IV Systems and IAEA Terminology
  - Limitations of Water cooled Reactors?
  - Six Gen-IV Conceptual Designs
    - *Super-Critical Water cooled Reactor (SCWR)*
    - *Very High Temperature Reactor (VHTR)*
    - *Gas cooled Fast Reactor (GFR)*
    - *Sodium cooled Fast Reactor (SFR)*
    - *Lead and LBE cooled Fast Reactor (LFR)*
    - *Molten Salt cooled Reactor (MSR)*
  - Other options: Thorium Fuel Cycle
  - IAEA Advanced Reactors Information System (ARIS)

# Advanced Reactors Information System (ARIS)

| Designs in ARIS | Design Organizations | Countries |
|---|---|---|
| 127 | > 75 | ~25 |

Web accessible database and a tool for Member States at various stages of nuclear power development, offering standardized, impartial data on reactor designs, including evolutionary and innovative concepts, to support informed reactor technology assessments

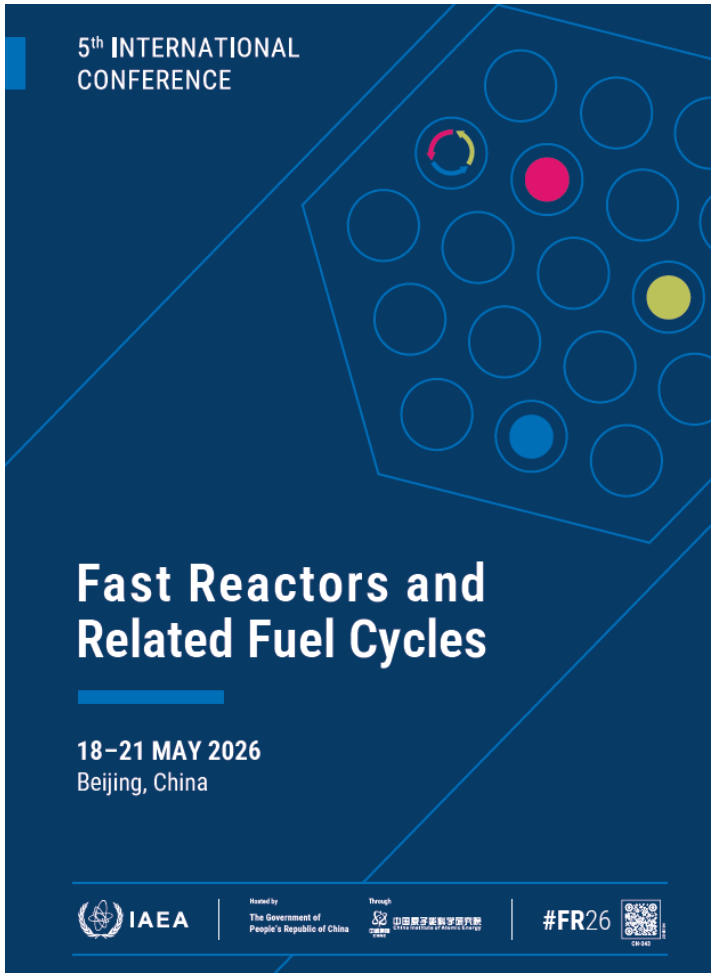

Access online: Advanced Reactor Information System | Aris

# IAEA Conferences on Fast Reactors and Related Fuel Cycles


FR22

DG Grossi opens FR22


Mr Bhaduri,
**FR22** General Chair




## FR26 in Beijing

- Hosted by CIAE
- 18 - 21 May 2026

IAEA

*Atoms for peace and Development…*

# Thank You!

email:
**FR@IAEA.ORG**