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EPFL

The Future of Nuclear Fission Power Generation

**ICES Biennial Workshop VIII,
Geneva, October 01, 2026**

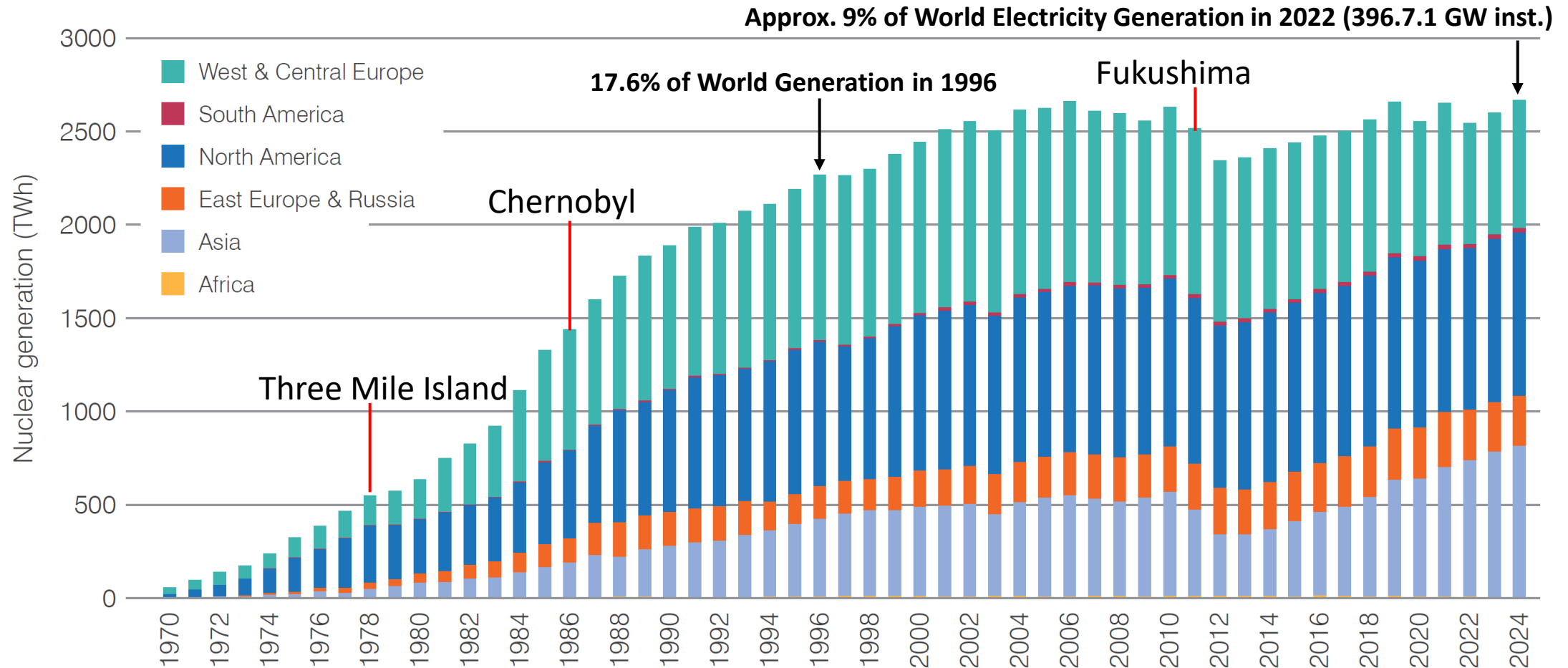
Andreas Pautz, École Polytechnique Fédérale de Lausanne
(EPFL) and Paul Scherrer Institut (PSI)
Geneva, 01 October 2026



Content

- Nuclear Power Utilization: Context
- From Large to Small Reactors
- Design and Safety Features of LWR-SMR
- Generation-IV Reactors: HTR and MSR

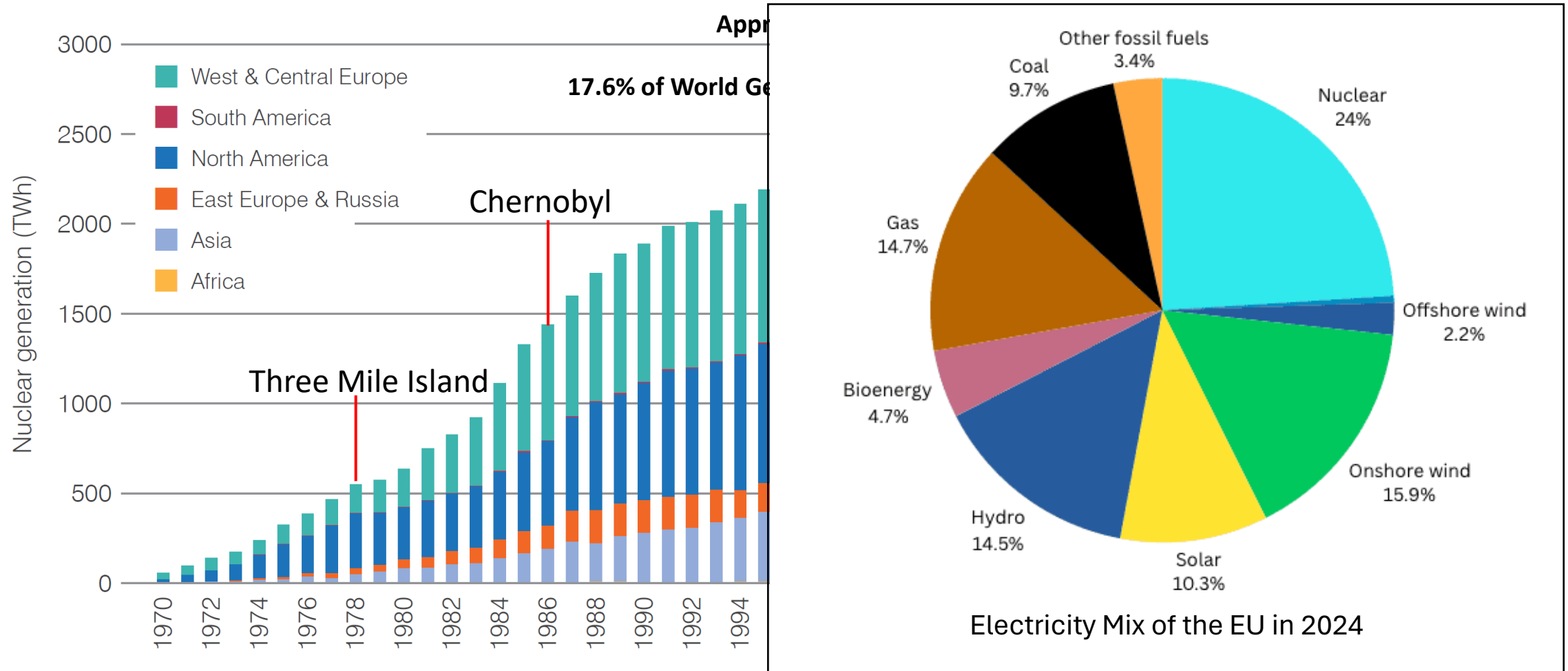
Global Development of Nuclear Generation Capacities



Source: World Nuclear Association and IAEA Power Reactor Information Service (PRIS)

There are currently 420 plants in operation worldwide (+21 waiting for restart in Japan), 80 plants under construction in 15 countries, and 123 in advanced project planning in 19 countries. 220 have been decommissioned.

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Dec 2023 - Cop28

Ziel: Tripling of Nuclear Energy until 2050



25 Countries: **USA**, Armenia, Bulgaria, **Canada**, Croatia, Czech Republic, Finland, **France**, Ghana, Hungary, Jamaica, **Japan**, **South Korea**, Moldavia, Mongolia, Morocco, Netherlands, Poland, Romania, Slovakia, Slovenia, Sweden, Ukraine, United Arab Emirates, **United Kingdom**.

July 2023 – EU NUCLEAR ALLIANCE

Goal:

- Development of integrated nuclear industry.
- 150 GW nuclear in EU electricity mix by 2050



Nuclear power officially labelled as 'strategic' for EU's decarbonisation

The Council of EU member states and the European Parliament agreed on Tuesday (6 February) to label nuclear power as a strategic technology for the EU's decarbonisation, following months of intense negotiations in Brussels over the Net-Zero Industry Act (NZIA).

Feb 2024

Belgium ushers in new era of nuclear energy with millions in funding

Tuesday, 14 July 2026

By Anas El Baye



A drone view of the Doel nuclear power plant in Doel, Beveren, on Tuesday 24 November 2020. Credit: Belga / Dirk Waem.

Nearly a quarter of a century after deciding to phase out nuclear power, Belgium's recent U-turn took another step after it announced almost €11 million in funding for nuclear research on Monday.

Cop28 Agreement of Nuclear Energy until 2050



Participants include: USA, Armenia, Bulgaria, Canada, Czech Republic, Finland, France, Ghana, Hungary, India, Japan, South Korea, Moldova, Mongolia, Morocco, Poland, Romania, Slovakia, Slovenia, United Arab Emirates, United Kingdom.



Nuclear power official

The Council of EU member states (February) to label nuclear power as sustainable following months of intense debate (NZIA).

Feb 2024

Italy's Senate approves a return to nuclear power

Thursday, 24 September 2026

Prime Minister Giorgia Meloni's bill paving the way for a return to nuclear power in Italy after four decades was passed in the Senate by 81 votes to 51, with seven abstentions.



(Image: Ministry of Energy)

Gilberto Pichetto Fratin, Minister of the Environment and Energy Security, said: "Today, Italy is taking a step toward the future: the approval of the government's mandate for new, sustainable nuclear power completes a process begun three years ago, aimed at exploring the potential of this new, clean, and sustainable technology."

Baseload Electricity for AI-Data and Computing Centers

Three Mile Island to be restarted to power Microsoft data centers

By David Szondy
September 22, 2024

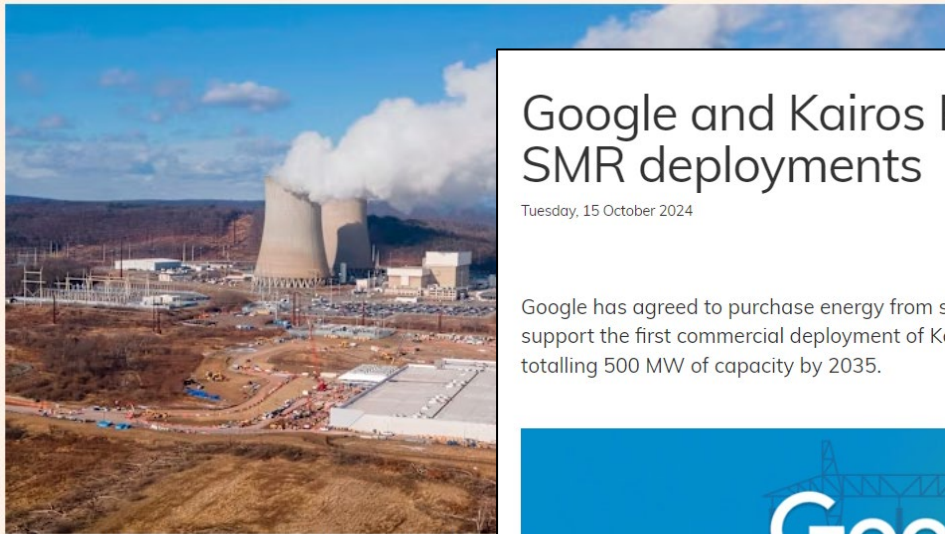


The Three Mile Island nuclear power station (CC BY-SA 4.0) Constellation Energy

In a remarkable topical twofer, not only is Microsoft turning to nuclear power to run its data centers, it's commissioned the restarting of the infamous Three Mile Island station – the site of the worst commercial nuclear accident in US history.

Amazon, Google and Meta support tripling of nuclear capacity by 2050

Tech groups join call for new power stations to meet growing energy demands and combat climate change



An Amazon Web Services data centre, foreground, under construction in Pennsylvania in January 2024 © Ted Shaffrey/AP

Malcolm Moore, Jamie Smyth and Amanda Chu in H

Published MAR 12 2025

Google and Kairos Power team up for SMR deployments

Tuesday, 15 October 2024

Google has agreed to purchase energy from small modular reactors under a deal that will support the first commercial deployment of Kairos Power's reactor by 2030 and a fleet totalling 500 MW of capacity by 2035.



Baseload Electricity for AI-Data and Computing Centers

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The Three Mile Island nuclear power station (CC BY-SA 4.0) Constellation Energy

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Amazon, Google and nuclear capacity by 2026

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An Amazon Web Services data centre, foreground, under construction in Pennsylvania in January 2024 © Ted Shaffner

Malcolm Moore, Jamie Smyth and Amanda C

Published MAR 12 2025

Criticality for fourth US microreactor to meet 4 July deadline

Tuesday, 7 July 2026

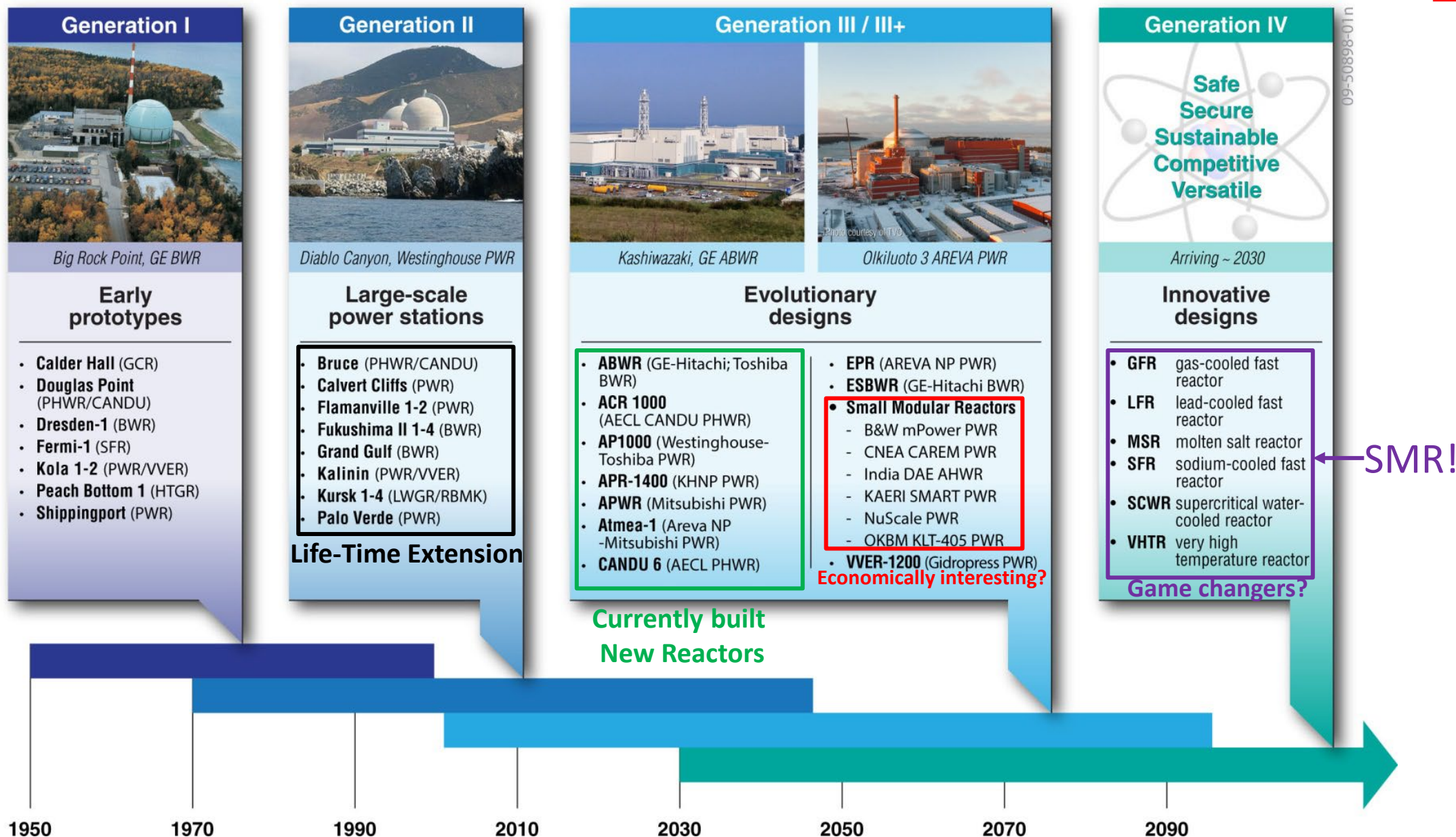
Aalo Atomics announced that its Critical Test Reactor at the Idaho National Laboratory successfully achieved initial criticality in the early hours of Saturday morning, becoming the fourth microreactor under US Department of Energy authorisation to achieve the milestone by 4 July 2026.



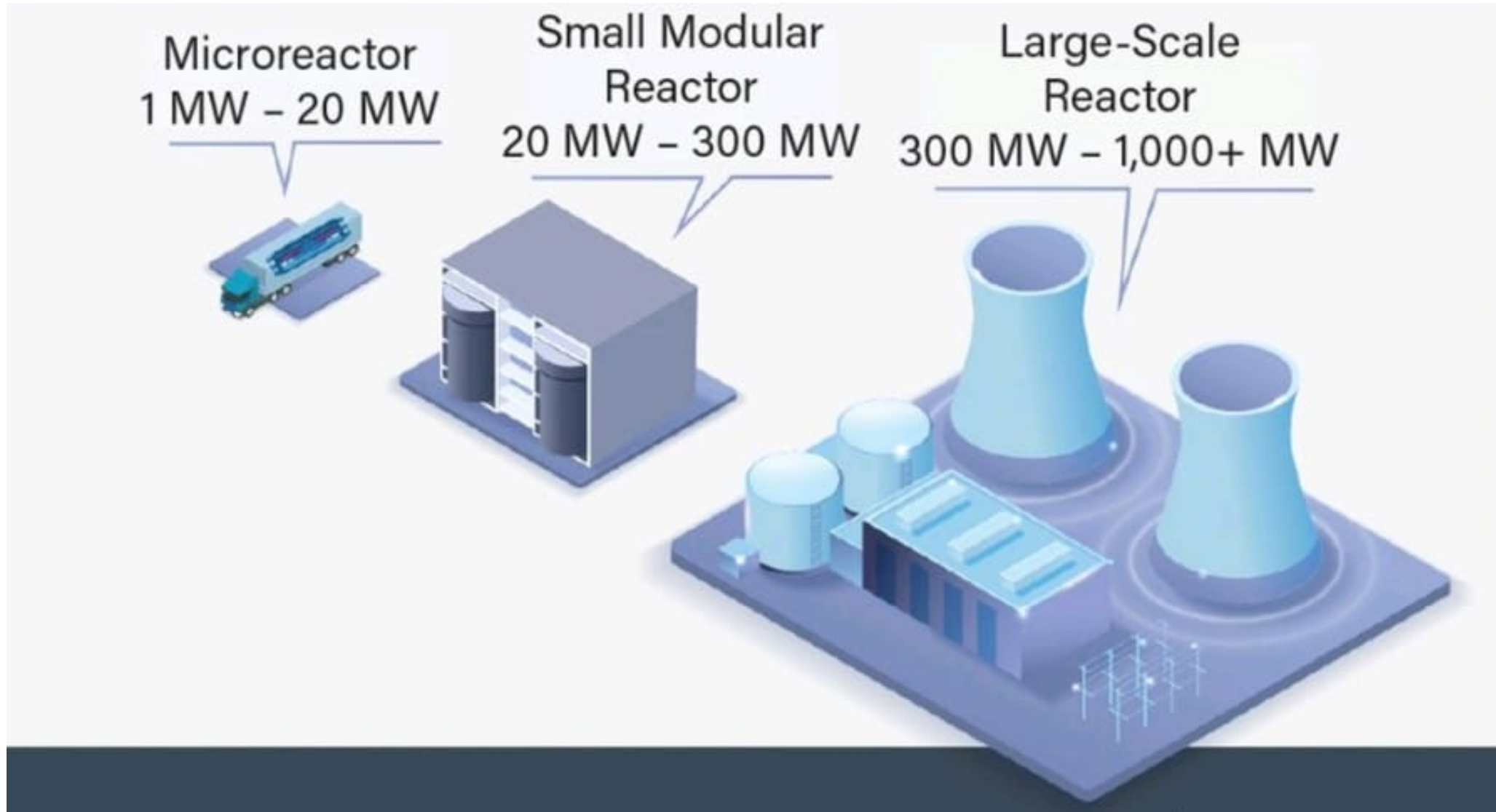
Image: Aalo Atomics

Austin, Texas-based Aalo was named in August last year by the Department of Energy (DOE) as one of 11 advanced reactor projects initially selected for support through its Nuclear Reactor Pilot Program, which aimed to see at least three of them achieve criticality by 4 July this year. The Reactor Pilot Program leverages DOE authorisation to expeditiously certify and construct first-of-a-kind advanced reactor designs for demonstration. The initiative is part of the Reforming Nuclear Reactor Testing at the Department of Energy executive order signed by President Donald Trump in May 2025.

The Four Generations of Nuclear Power Plants

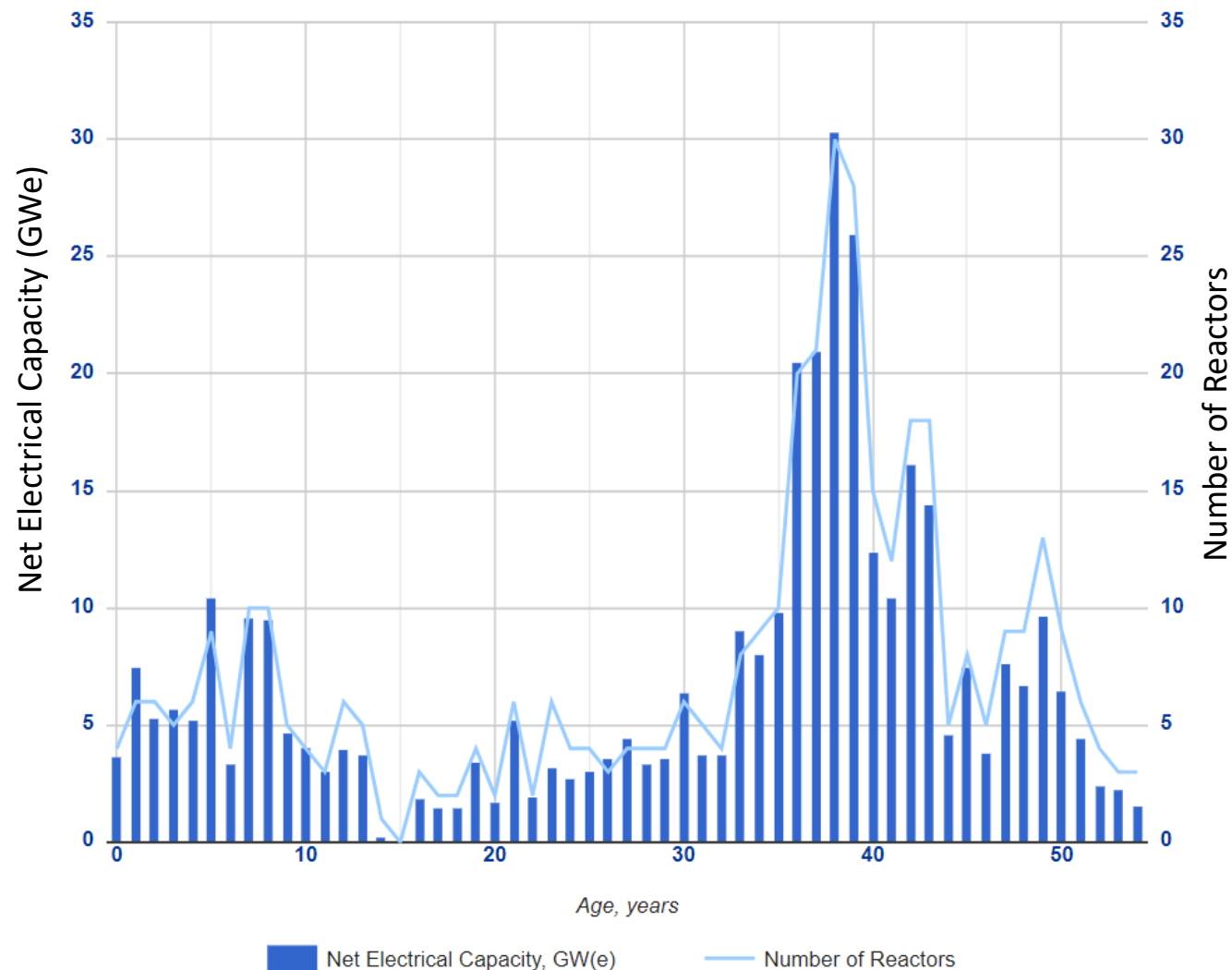


New Developments in Reactor Design



Long-Term Operation of Nuclear Power Plants

- The **average age** of the global nuclear power plant fleet is **31.6 years**
- Of this capacity, **15 %** (74 NPPs) will reach their 60-year operating life by 2040, **61 %** (255 NPPs) by 2050
- **Long-term operation (LTO)** is therefore being considered in several countries, especially in the USA with its ageing fleet
- By 2023, **25** US NPP units have received their extended operating license (**up to 80 years**), **three** are under review by the NRC and **30** are in preparation
- The NRC does not rule out the possibility of a **100-year service life (!)**

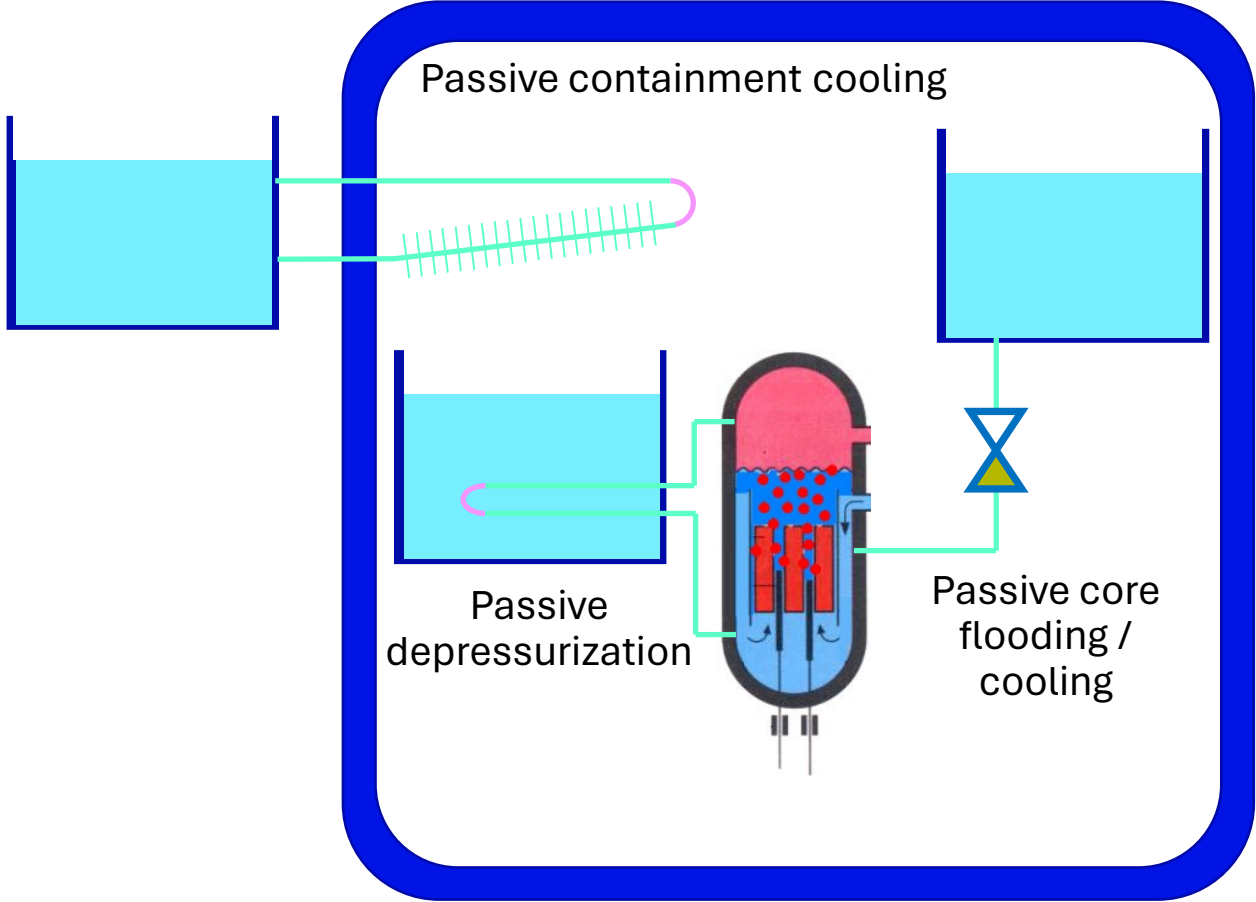


New Builds of Generation-III Reactors

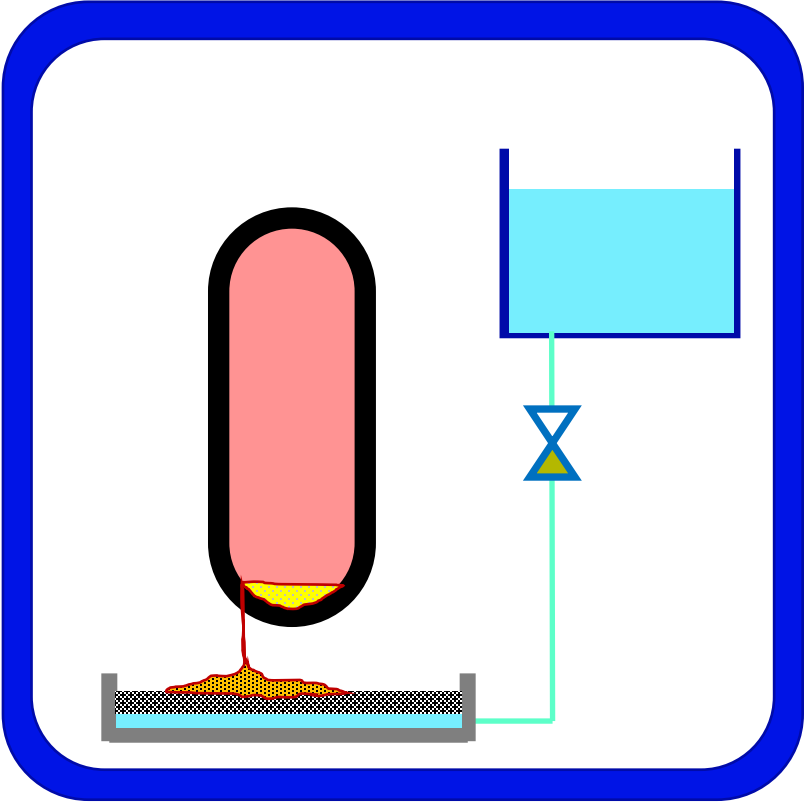
The vast majority of new Generation-III plants are based on proven large ($> 1000 \text{ MW}_{\text{el}}$) light water reactor technology and implement the “lessons learnt” from the three major severe accidents:

- Massive use of both active and passive safety systems, severe accidents as design-basis accidents
- Core Damage Frequency $< 10^{-6}/\text{year}$ (factor of 10-100 better than current plants)
- **"Practical elimination" of accident sequences** that lead to an early release of radioactivity ($< 10^{-7}/\text{year}$), with up to **one week grace period until human intervention necessary**
- As of today, **51 operating reactors qualify as Generation-III-reactors, 60 Generation-III reactors** are under construction (thereof 33 in China alone)
- The average building time for the completed 45 reactors is **7.5 years**, however some reactors have taken up to **16 years** to complete (Finland, EPR), the fastest less than **4 years** (38 -44 months, ABWR, Japan)

Core Melt Management and Passive Heat Removal: common elements of Gen-III



GEN III+



Core Catcher

Melt cooling by passive core catcher
flooding from in-containment pool

Safety Systems of Generation-III Reactors: EPR

Internal Containment:

- Steel shell
- Leak-proof up to 6.5 bar
- Exclusion of H₂-Explosion

External Containment: Air Plane Crash Protection

Wet Fuel Storage:
protected against air plane crash

Active/Passive Safety systems:
bunkered against external hazards, designed throughout 4-times (2v4) redundant with several diversified levels of safety systems

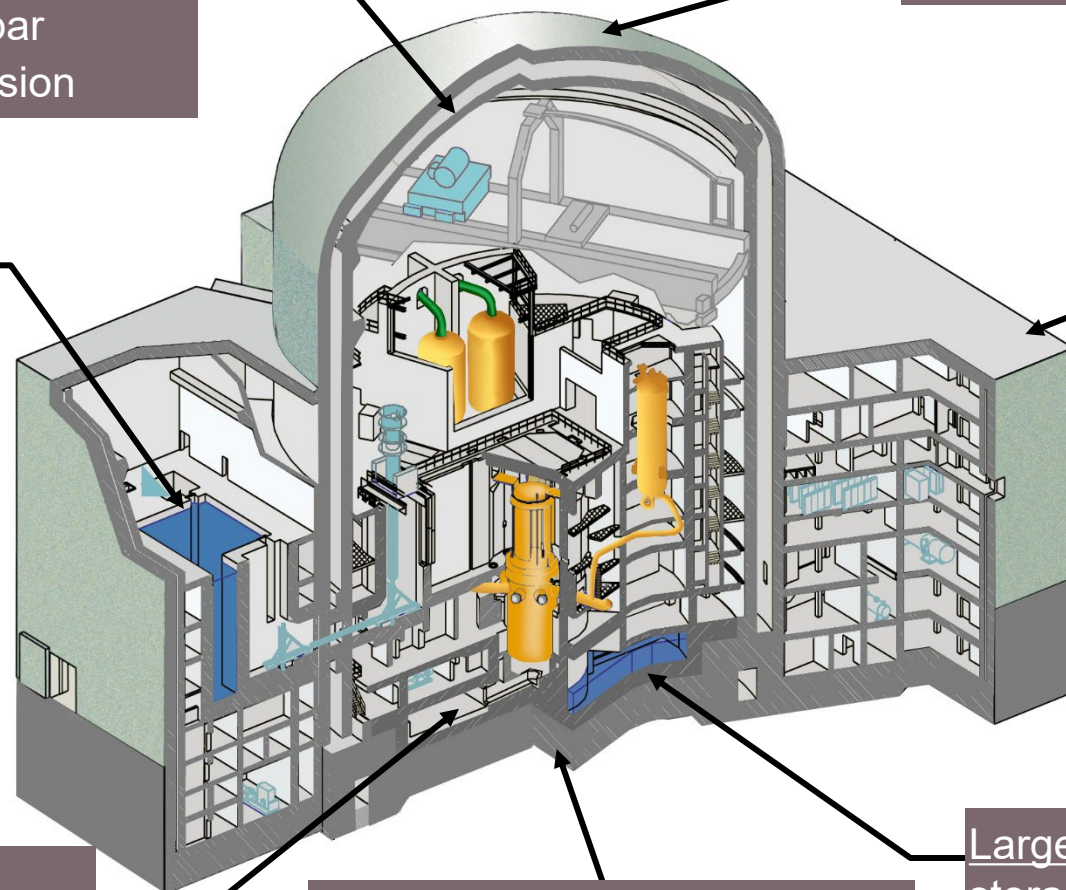
Probability of a core melt accident $<10^{-6}$ /Jahr

Probability of an early release $<10^{-7}$ /Jahr

Core Catcher:
Safe containment of molten core

Earthquake-proof: designed against 100'000-year earthquake

Large protected in-containment water storage for coping with severe accidents



Internationally Operating Generation-III Power Plant Vendors



EPR (Framatome) in Olkiluoto (FI), 1600 MW
7'500 \$/kW installed, construction time 16y, LCOE ~120 \$/MWh

«Economic» Reactor Project:
Construction Costs / Time:
5000-8000 \$/ kW installed,
built in 6-8 years:
LCOE: 60-100 \$/MWh



AP-1000 (Westinghouse) in Vogtle (USA), 2 x 1200 MW
9'000 \$/kW installed, construction time 10y, LCOE >150 \$/MWh



VVER-1200 (Rosatom) in Tianwan (China), 2 x 1250 MW
5'000 \$/kW installed, construction time 5.5y, LCOE <70 \$/MWh



APR-1400 (KEPCO) in Barakah (UAE), 4 x 1400 MW
5'000-8'000 \$/kW installed, construction time 5-8 y, LCOE <100 \$/MWh

Large NPPs - challenges

- Large, complex, inefficient construction sites
- High capital costs and longer amortization times (less attractive for private companies)

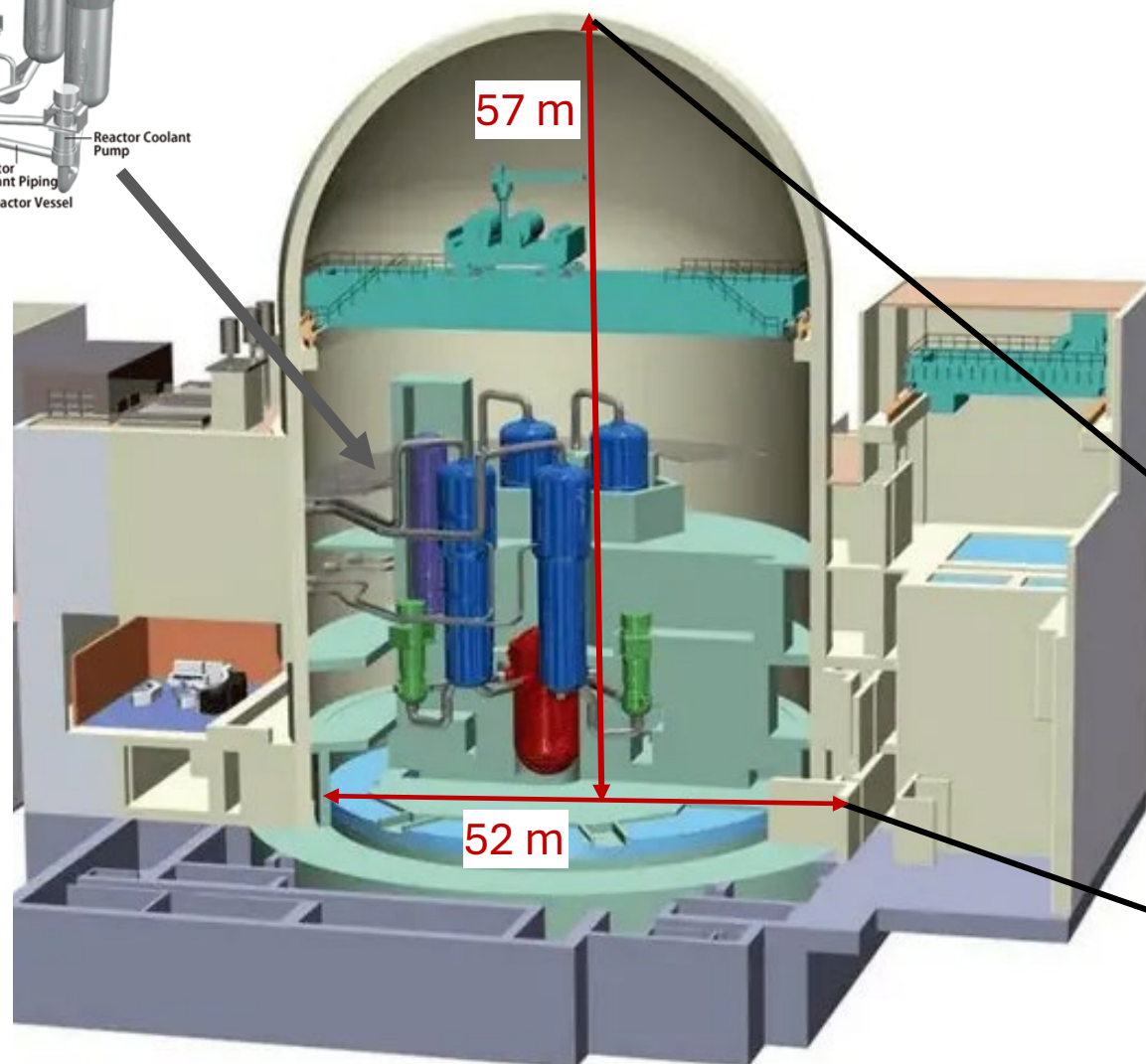
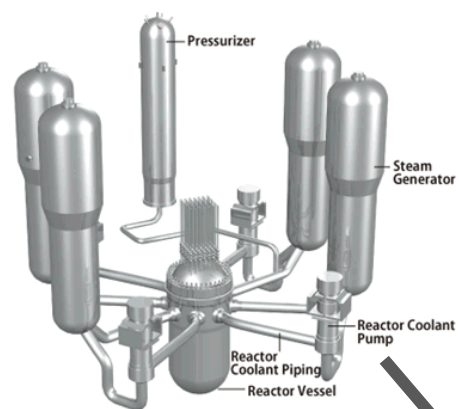


The Answer: Small Modular Light Water Reactors (LWR-SMR)?

- **Power up to ~300 MW_e**
- Smaller / less monolithic units and therefore **reduced CAPEX**
- Modules are factory-built and factory-tested before installation on site
- **Significantly shorter construction** times for individual modules (goal: 2 - 4 years)
- **Higher flexibility** to better integrate with renewables
- Transportable by truck, train, boat or plane
- Compact design allows the possibility for **underground construction**
- Passive safety: „**Walk-away**“ **safe** and therefore significant **reduction of emergency planning zone** (EPZ), which is limited to plant site perimeter (no evacuation zone required):
 - NuScale licensed 500 meter perimeter, 1 km for GE-Hitachi BWRX-300)

Beispiel: Large Light Water Reactor (PWR)...

...vs. SMR (PWR)

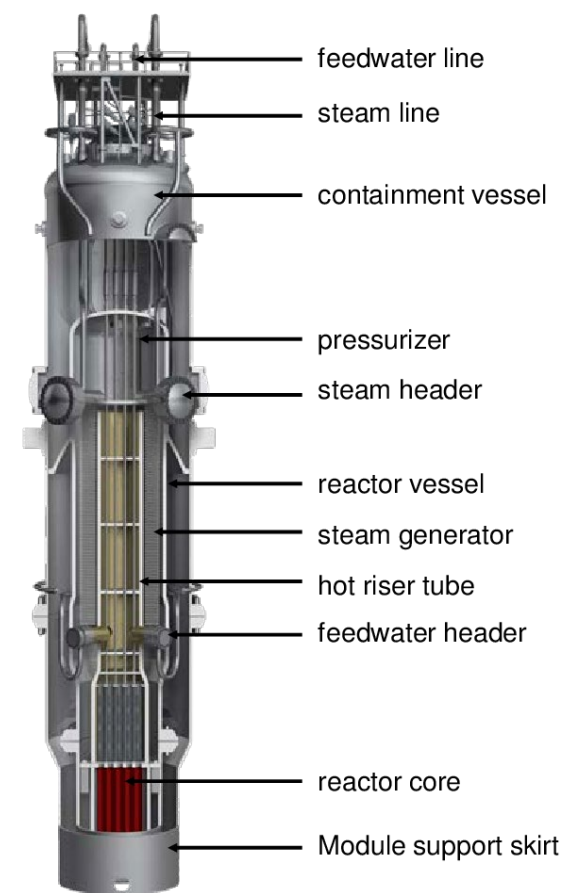


77 MW_e

23 m

4.5m

NuScale combined
containment vessel &
reactor primary circuit



SMRs already on the market or available by early 2030s



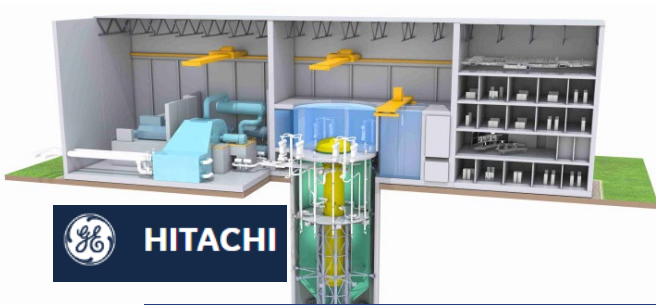
RITM-200 (Russia)
several in operation



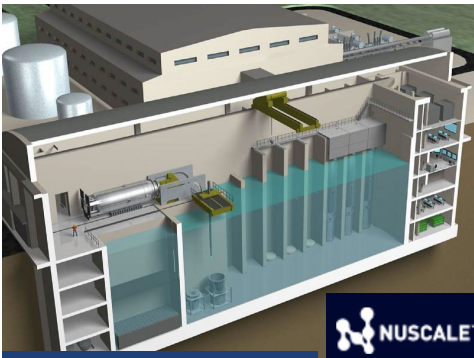
ACP 100,
Commissioning
In 2026



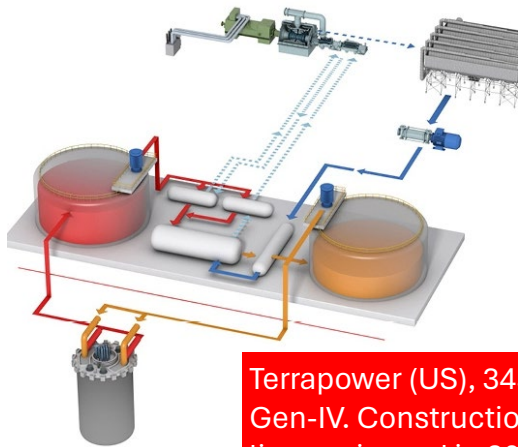
2xHTR-PM
in operation (China)



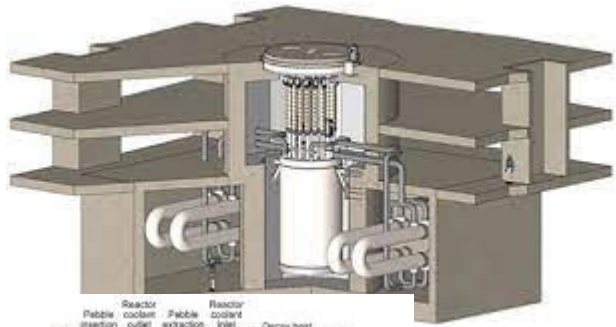
BWRX-300 (GE/Hitachi)
4 units in Ontario Power, from 2028
Construction license issued in 2024



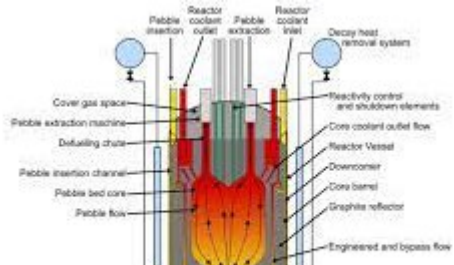
NuSCALE (6 x 77 MW)
Licensed in USA



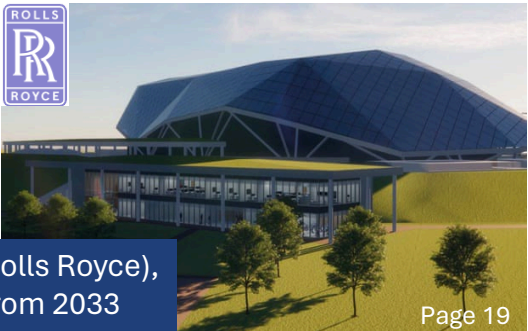
Terrapower (US), 345 MW
Gen-IV. Construction
license issued in 2024



Kairos (US). Construction
licensed received in March
2024 (Tennessee).
Completion in 2028



UK SMR (Rolls Royce),
443 MW, from 2033

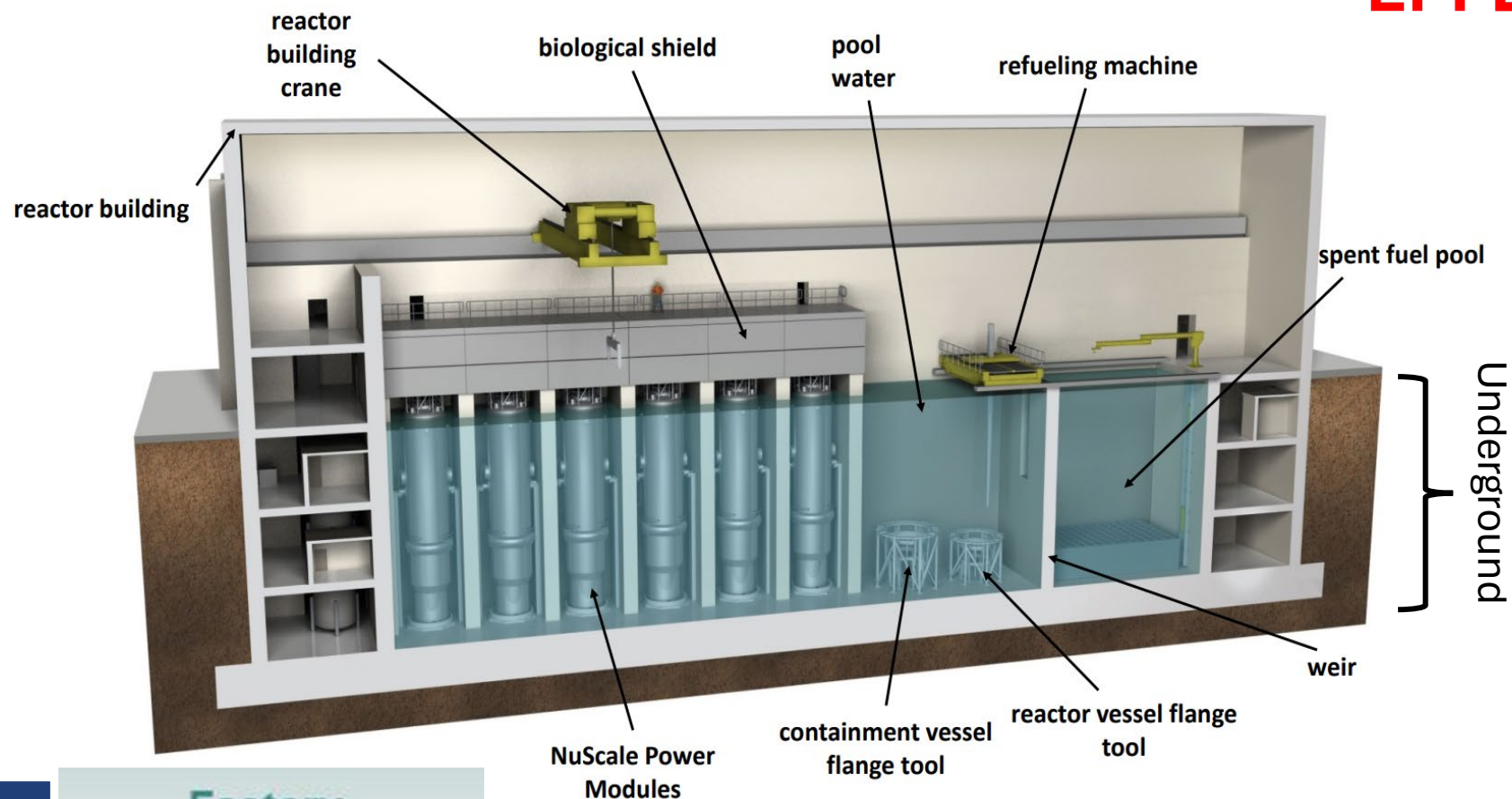
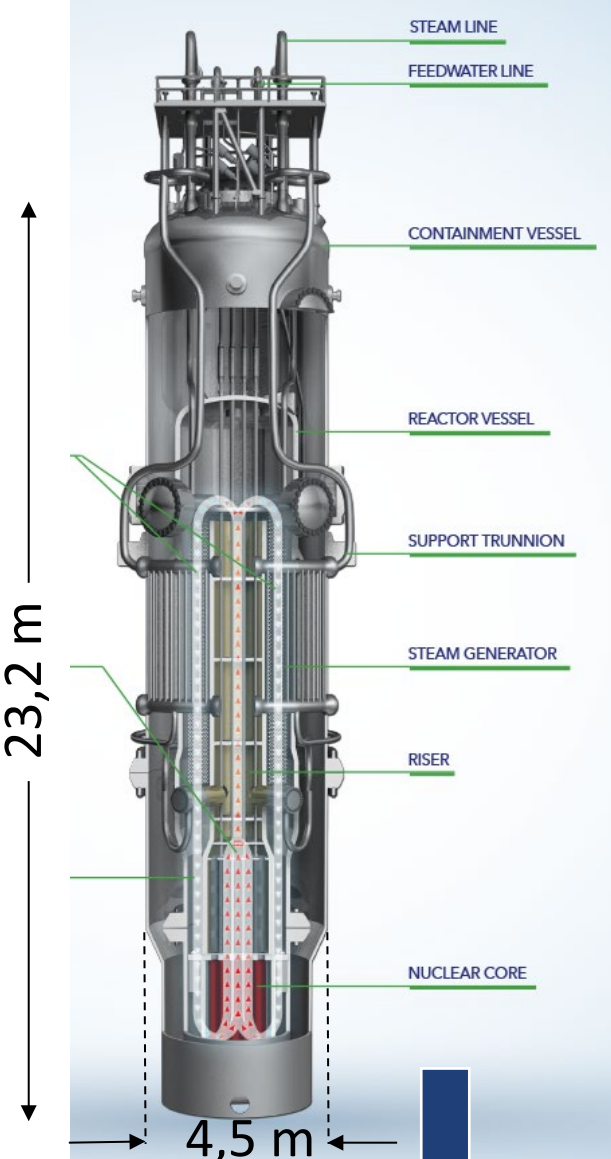


NUWARD (EdF/Technicatome)
170 MW, from 2035



X-energy (USA)
DOW, construction
planned for 2026

NuScale: The First Licenced SMR Design in the USA



Factory Manufacturing

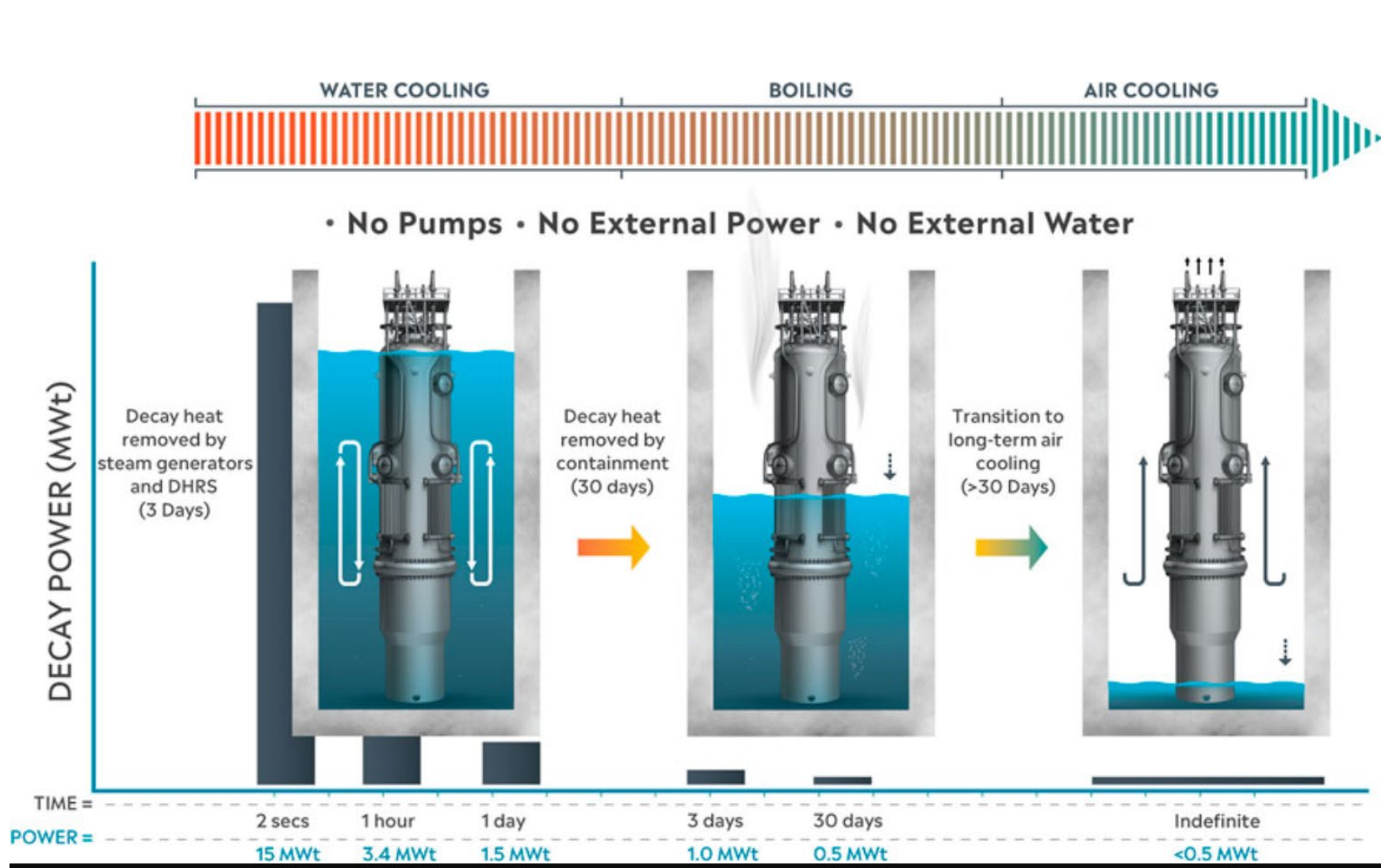


Each Module is refueled underwater while the remainder of the plant produces power

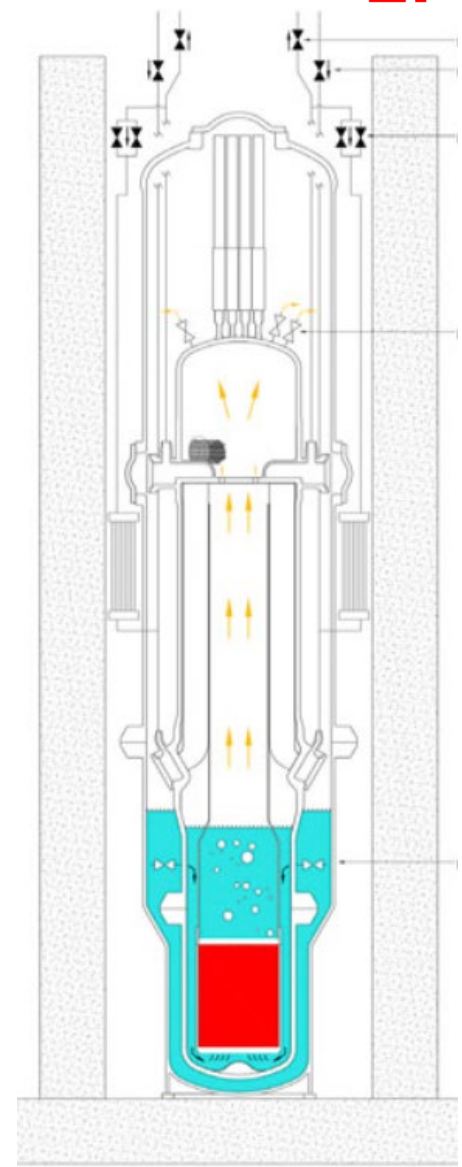
- Refueled once every 24 months
- Capable of 48-month fuel cycle
- 10 Day Refueling Target



Passive Safety Systems: «Walk-Away Safety»

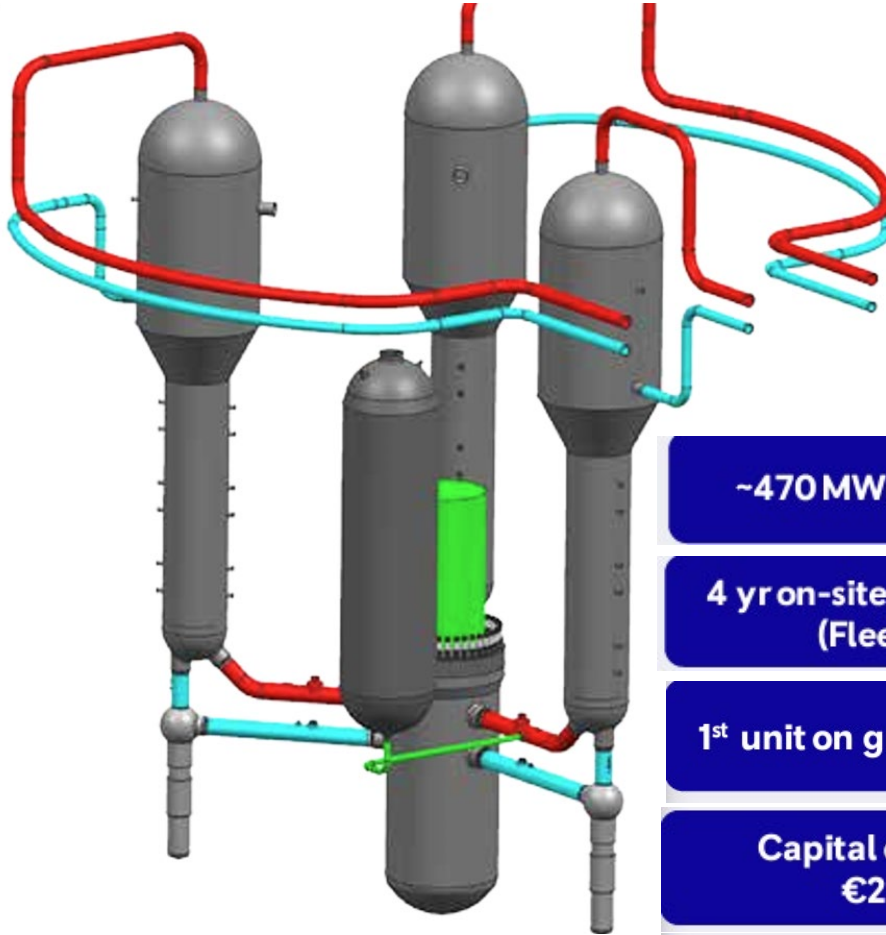


Decay Heat Removal after Reactor Shutdown (Long-Term Station Blackout Scenario)



Reactor Core remains Covered at all Times

Rolls-Royce (UK)



~470 MWe net output

4 yr on-site Construction
(Fleet unit)

1st unit on grid early 2030s

Capital cost under
€2.3bn*

LCOE range €39-€56 per
MWh**

* 2021 economics, fleet unit; £1:€1.1406 (5yr average), costs based on UK labour rates

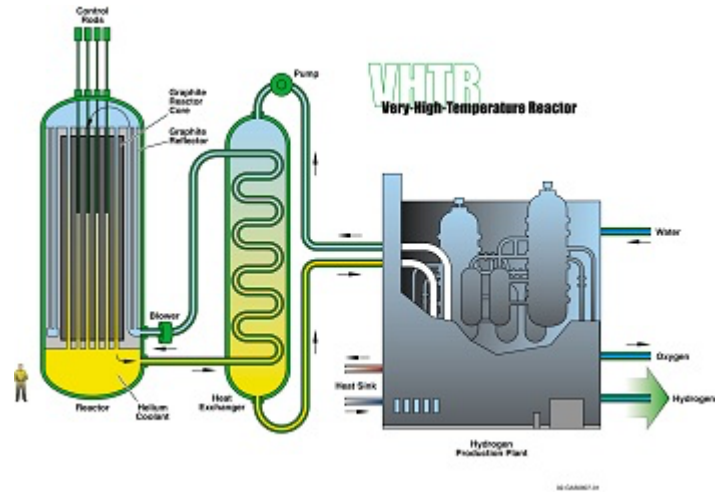
** 2021 economics, 2 unit plant, range dependent on financing mechanism

AP300 (Westinghouse, US)

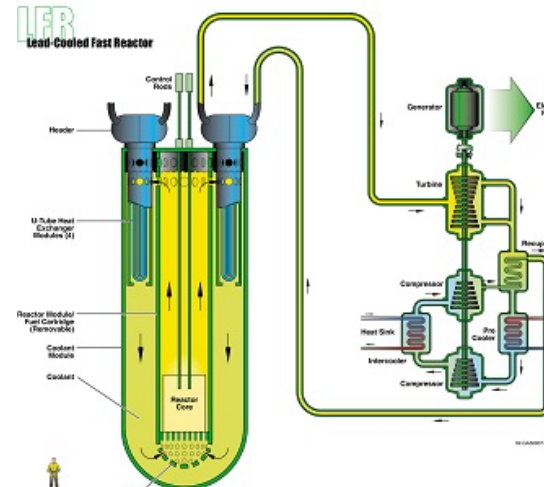


The Generation-IV Reactor Concepts

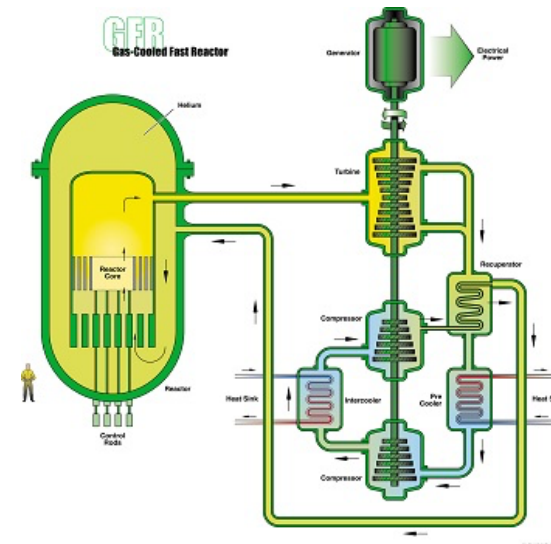
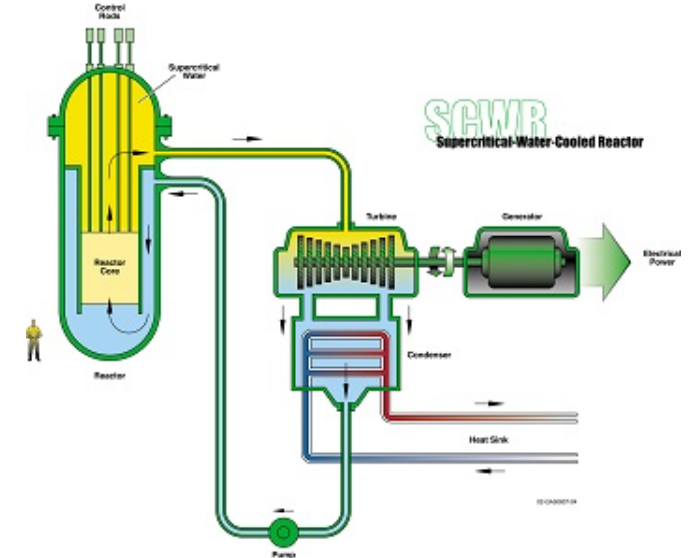
High Temperature Reactor (HTR)



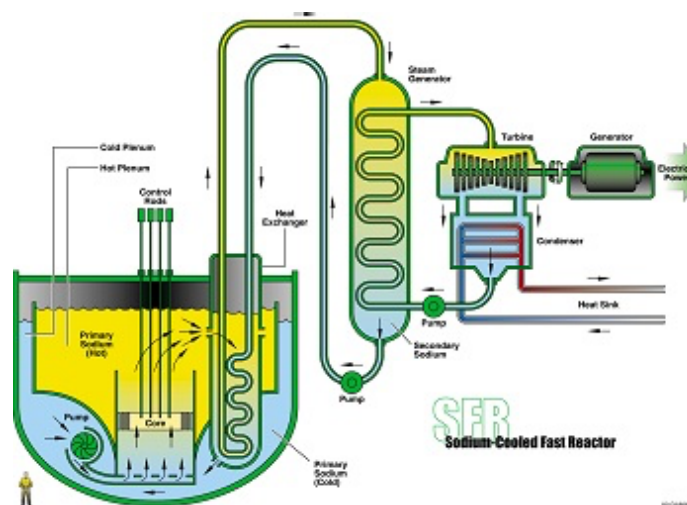
Lead Cooled Fast Reactor (LFR)



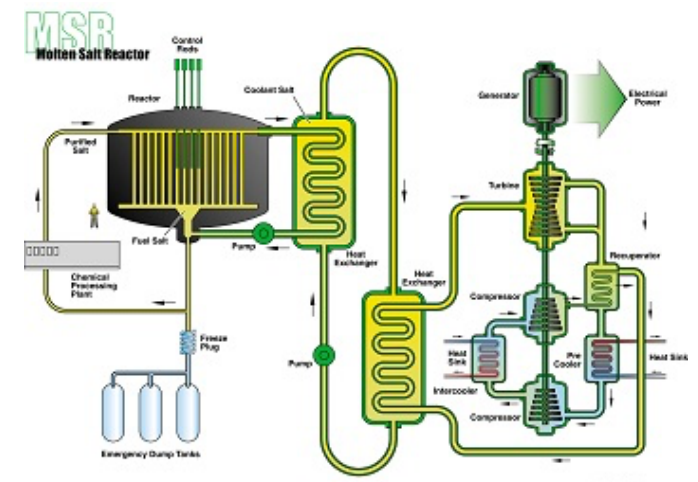
Supercritical LWR (SCWR)



Gas-Cooled Fast Reactor (GFR)



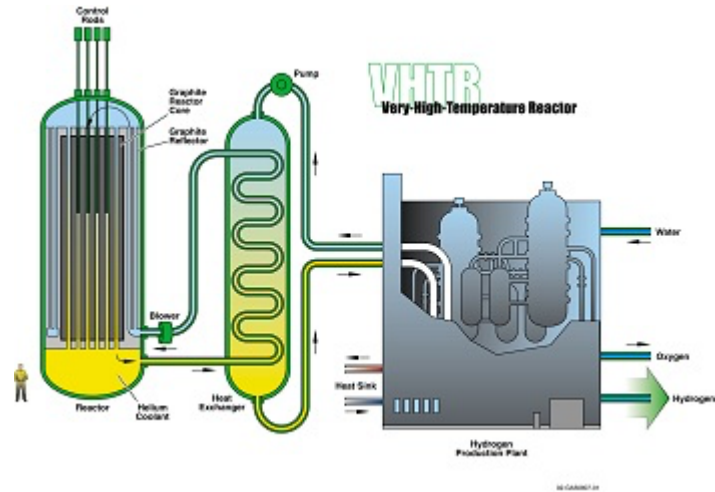
Sodium-Cooled Fast Reactor (SFR)



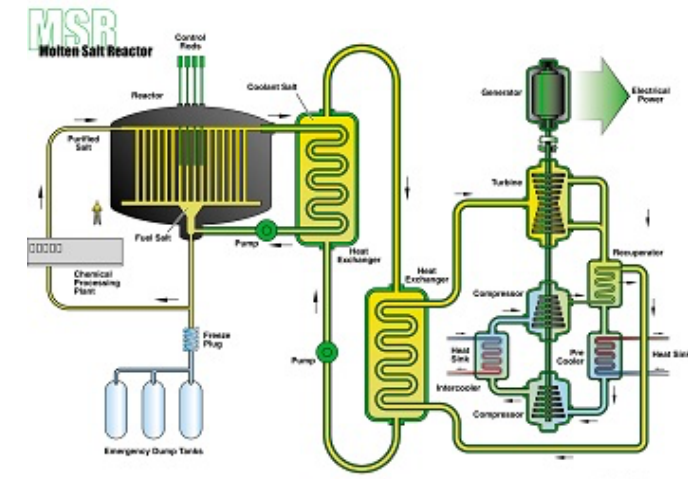
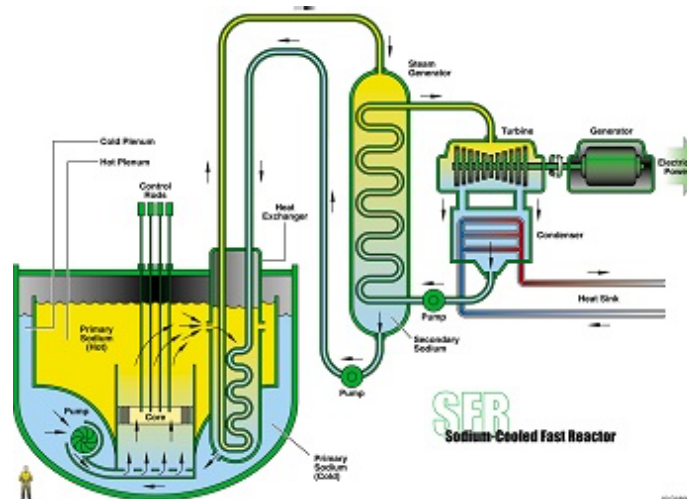
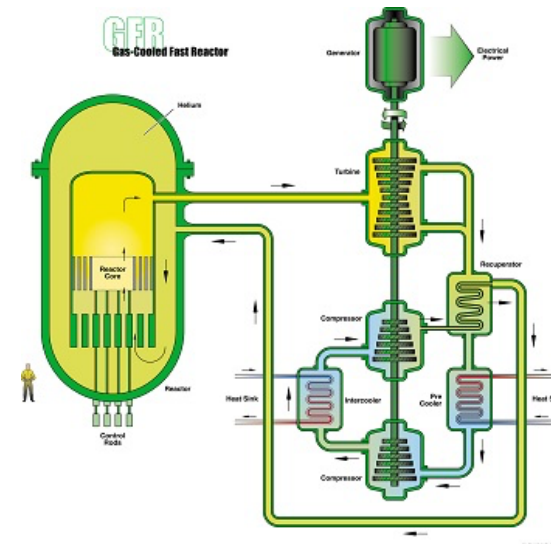
Molten Salt Reactor (MSR)

The Generation-IV Reactor Concepts

High Temperature Reactor (HTR)



- Improved Economic Performance
- Safety Level equal/better compared to Generation-III
- Sustainability: Circular Fuel Economy and Waste Minimization
- Proliferation Resistance and Physical Protection



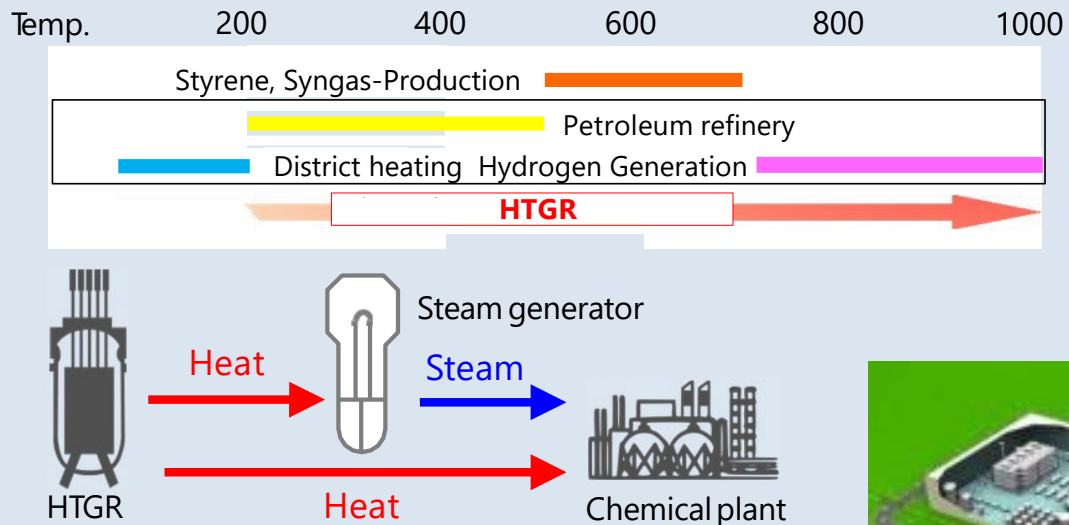
Gas-Cooled Fast Reactor (GFR)

Sodium-Cooled Fast Reactor (SFR)

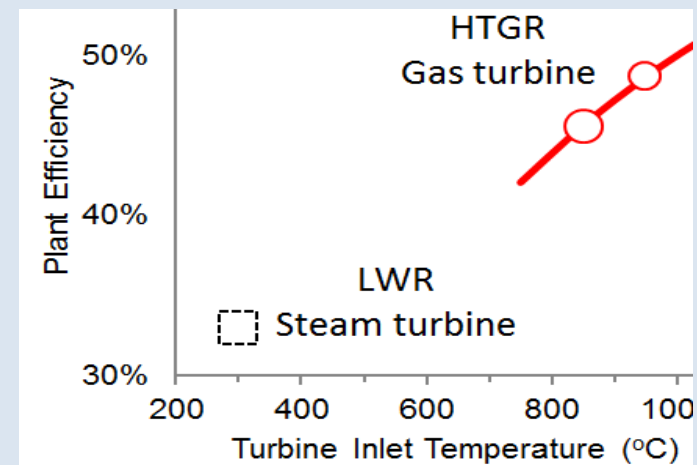
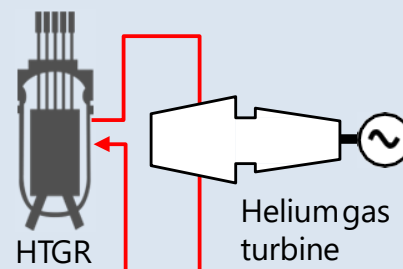
Molten Salt Reactor (MSR)

Applications for Combined Heat & Electricity (Hybrid) Generation

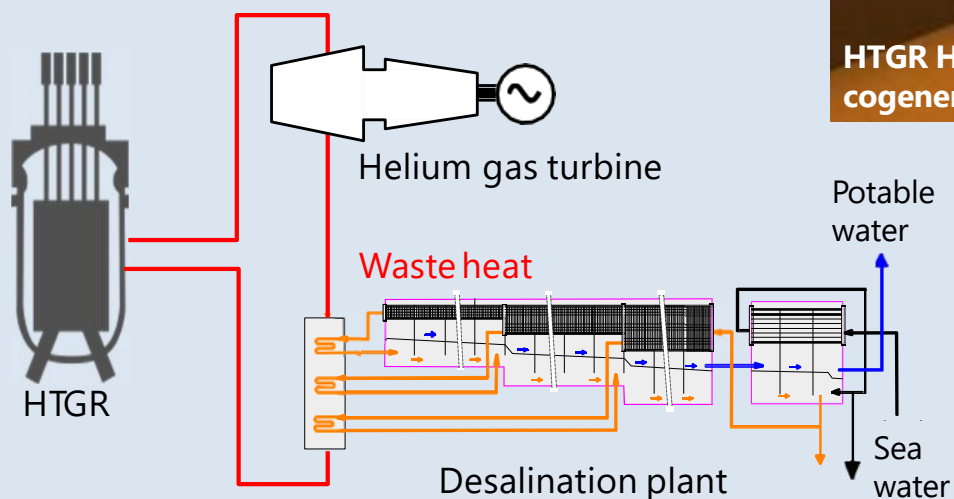
Industrial use of nuclear heat



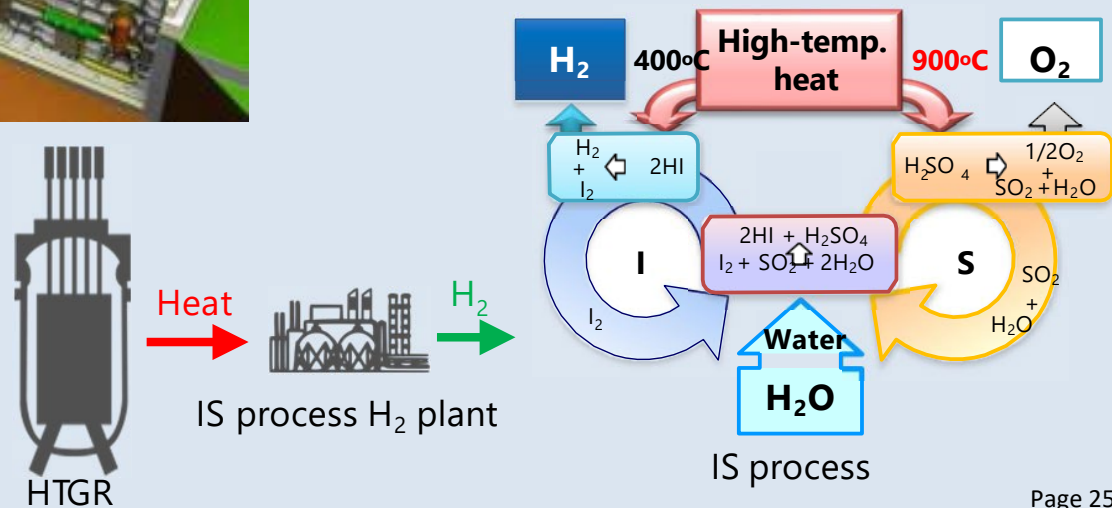
High Efficient Gas Turbine Power Generation



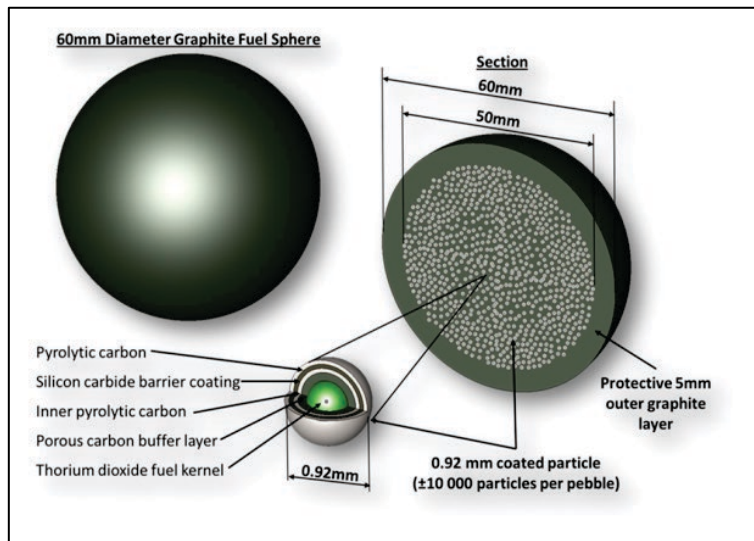
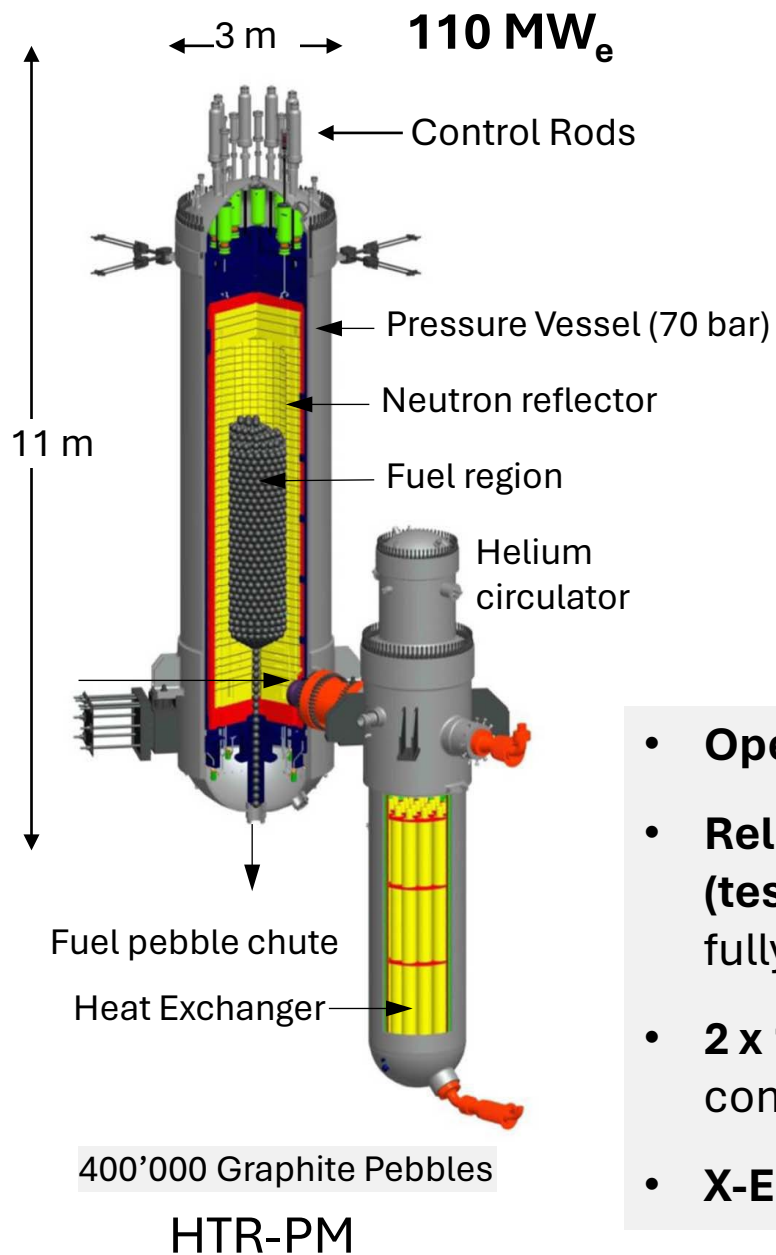
Desalination using waste heat



Carbon-free H₂ production

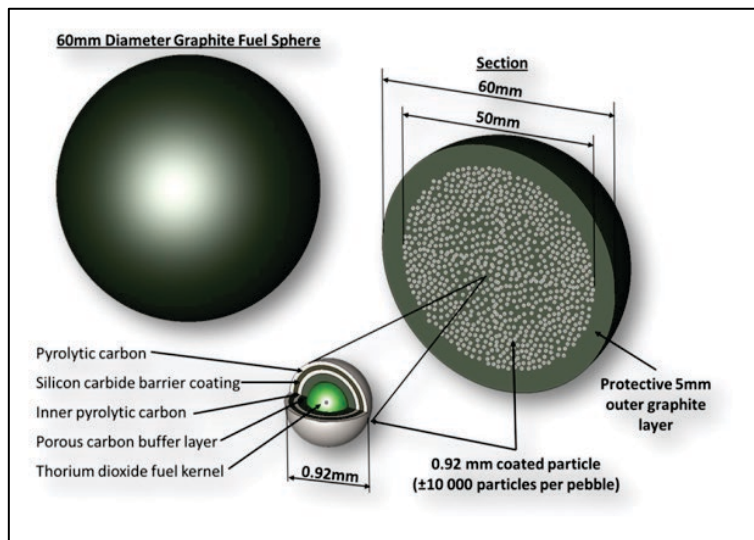


GEN-IV: High Temperature Reactor (HTR)



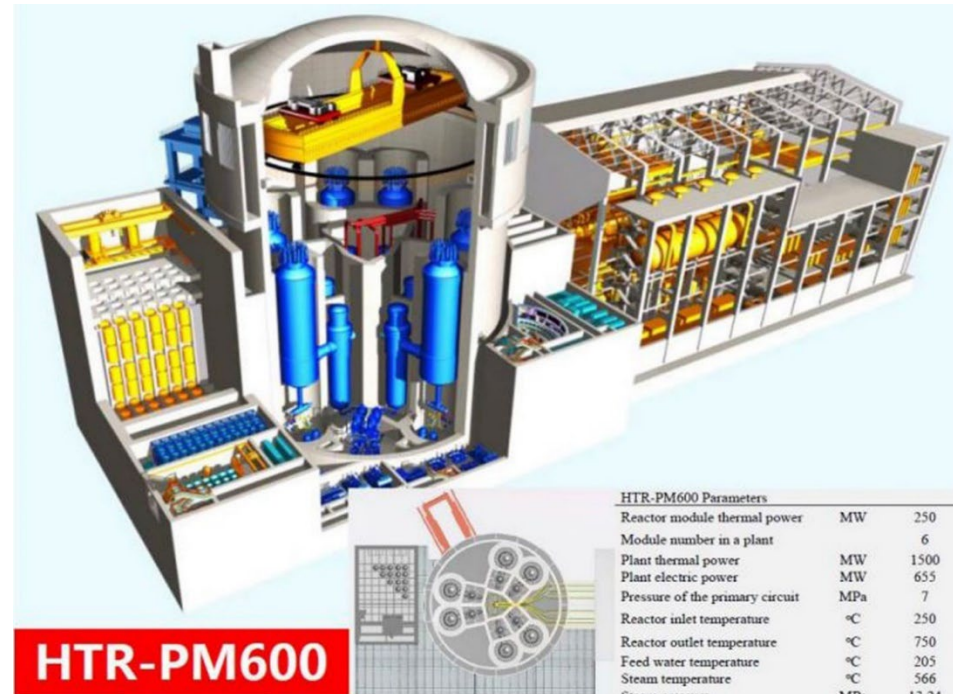
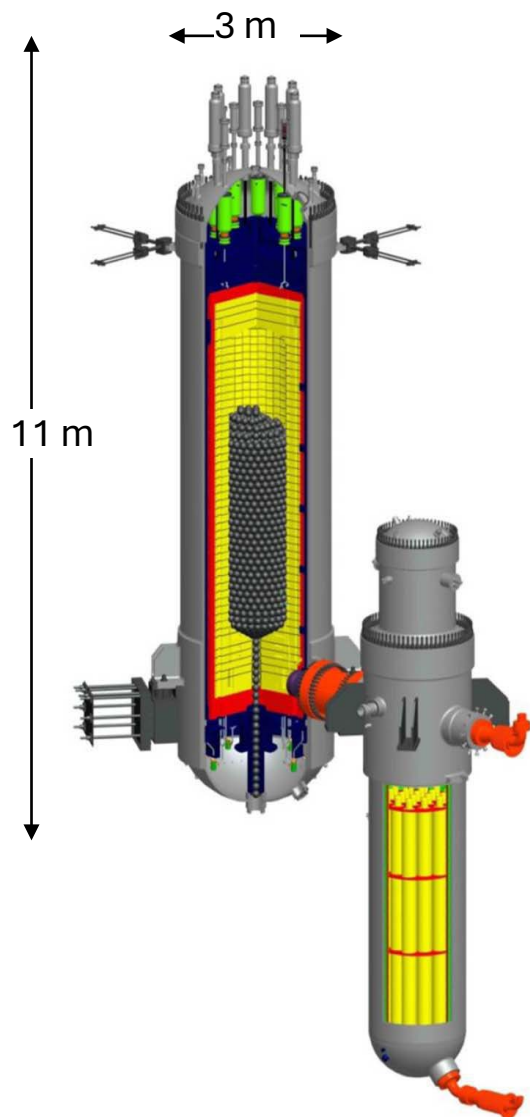
- **Operating temperature up to 900 °C, thermal efficiency up to 48% (!)**
- **Release of radioactivity ruled out by design thanks to accident-tolerant fuel (tested in Germany, Japan, the U.S., and China), „Walk-Away Safe“ „Safe“ thanks to fully passive residual heat removal (demonstrated in tests)**
- **2 x 110 MW_{el} plants in operation in China since 2021** and 6 x 110 MW_{el} plants under construction
- **X-Energy and Kairos** (both U.S.) plan to complete demonstrators by 2030

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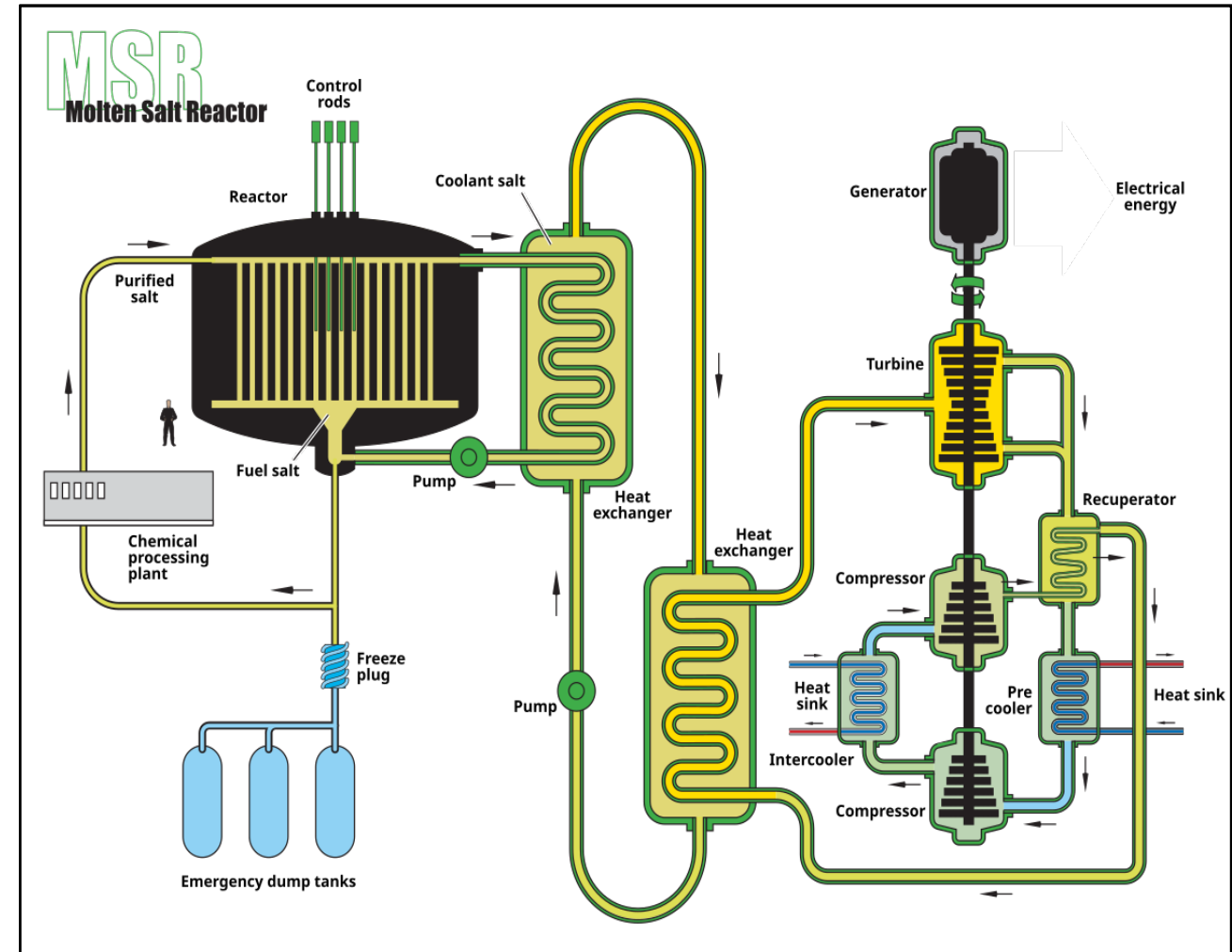
«Transmutation Maschine» Molten Salt Reactor

Advantages of MSR Concepts

- The system operates at **atmospheric pressure and high temperatures (>500 °C)**
- **Continuous removal** of hazardous radioactive substances is possible during operation
- **Excellent controllability** (50% P_N in <10 s) on the GW scale (!)
- **Significantly simplified fuel fabrication**
- The reactor can “burn” highly radioactive waste
- Thorium can be used as an alternative to uranium

Remaining Challenges:

- **Corrosion resistance** of structural materials
- **Chemical control** (solubility, precipitation)
- Possible “freezing” of the fuel
- **Complex flow fields and reactor noise**
- **First Criticality of TMSR-LF1 (2 MW_{th}) in China in October 2023**
- **No operational experience in Europe => test facility at PSI (!)**



Design of a molten salt reactor according to the Generation IV Int. Forum

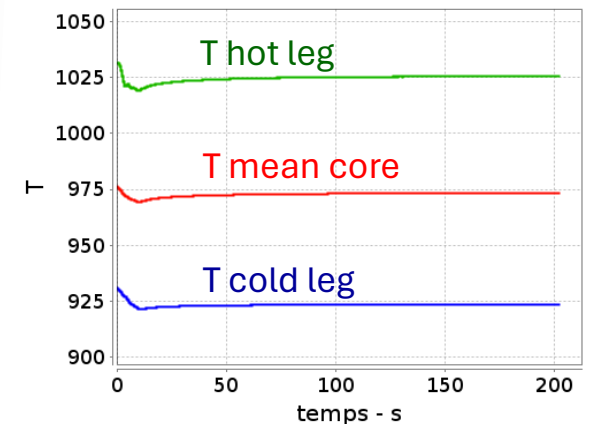
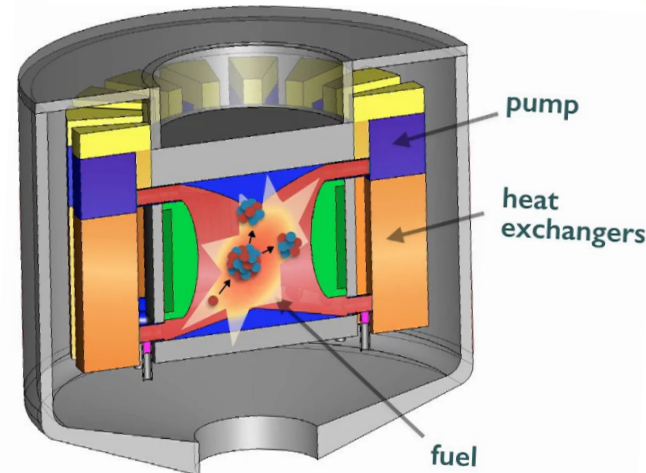
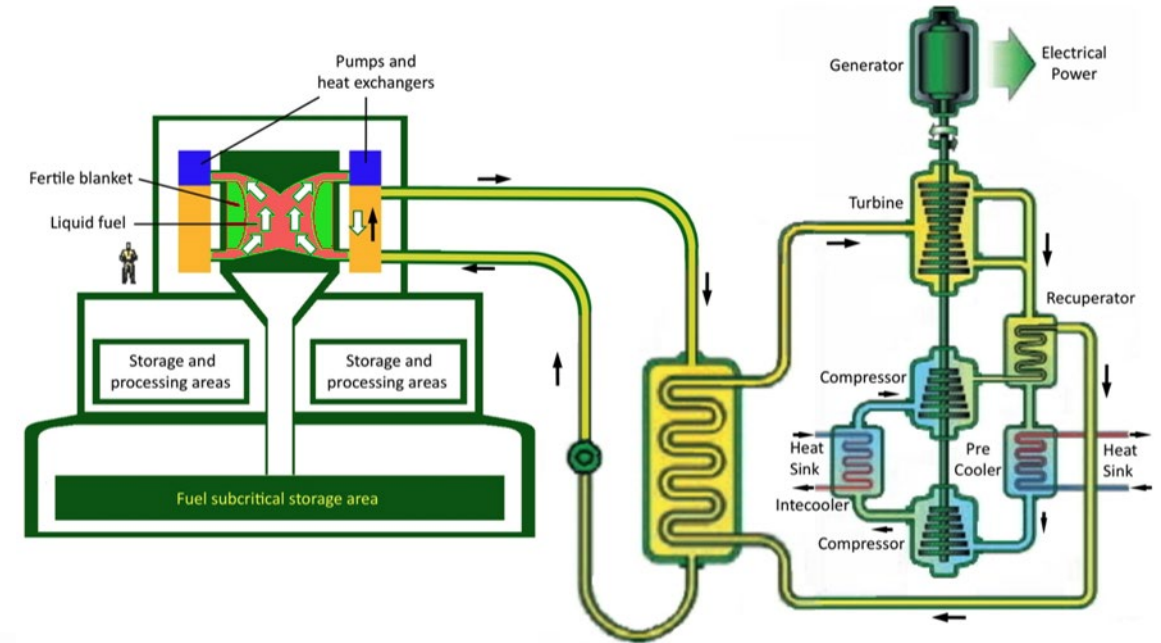
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«Transmutation Maschine» Molten Salt Reactor

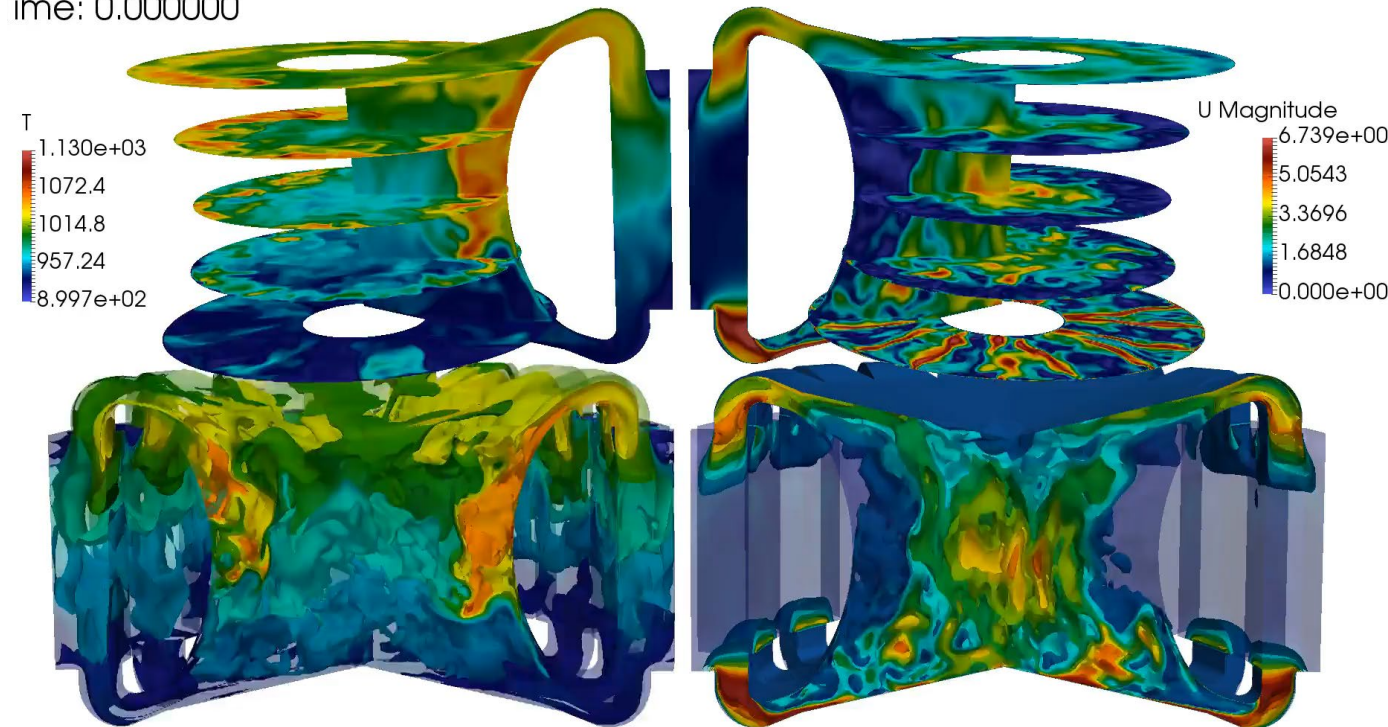
Advantages of MSR Concepts

- The system operates at **atmospheric pressure and high temperatures ($>500\text{ °C}$)**
- **Continuous removal** of hazardous radioactive substances is possible during operation
- **Excellent controllability ($50\% P_N$ in $<10\text{ s}$)** on the GW scale (!)
- **Significantly simplified fuel fabrication**
- The reactor can “burn” highly radioactive waste
- Thorium can be used as an alternative to uranium

Remaining Challenges:

- **Corrosion resistance** of structural materials
- **Chemical control** (solubility, precipitation)
- Possible “freezing” of the fuel
- **Complex flow fields and reactor noise**
- **First Criticality of TMSR-LF1 (2 MW_{th}) in China in October 2023**
- **No operational experience in Europe => test facility at PSI (!)**

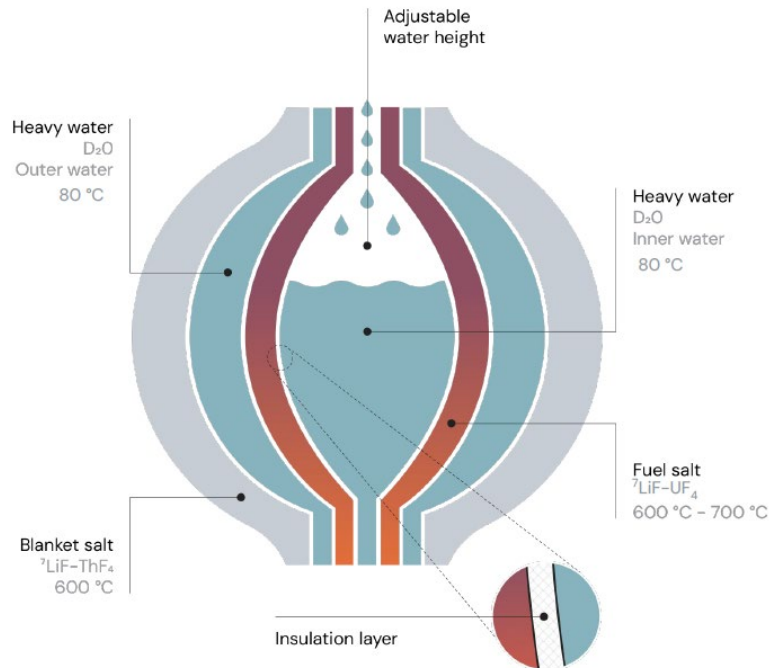
Time: 0.000000



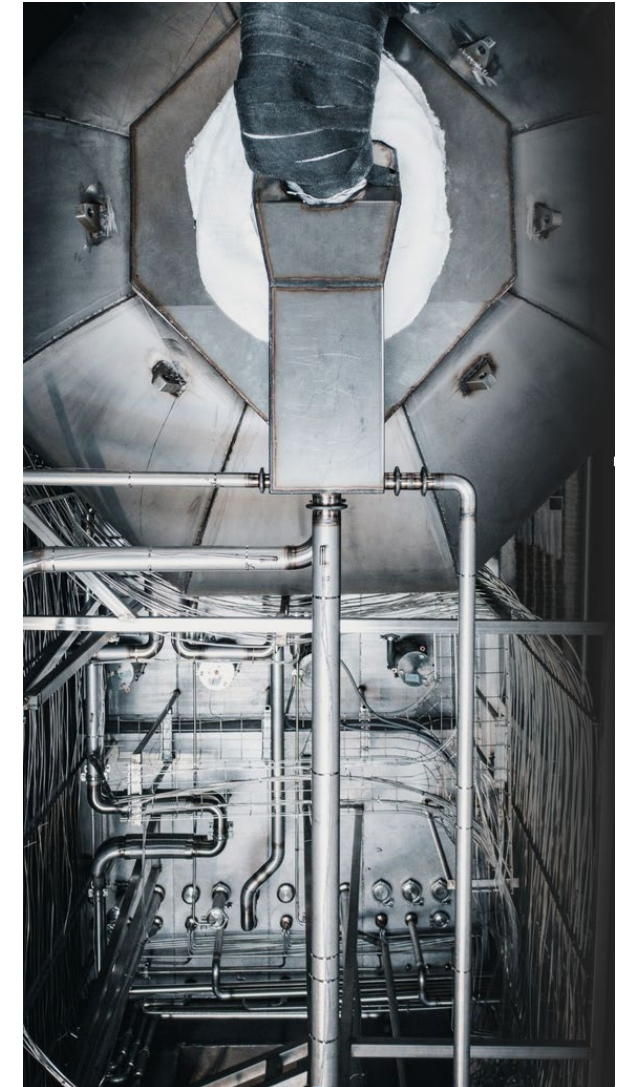
Molten Salt Experiment at 1 MW_{th} at PSI

Key design data:

- Fuel Salt: F-Li-LEU (4.95% enriched), ~ 500 l,
- Blanket Salt: F-Li-Th, ~ 3000 l
- Moderator: D₂O, ~ 3000 l
- Walls: SS-316, Zircalloy,



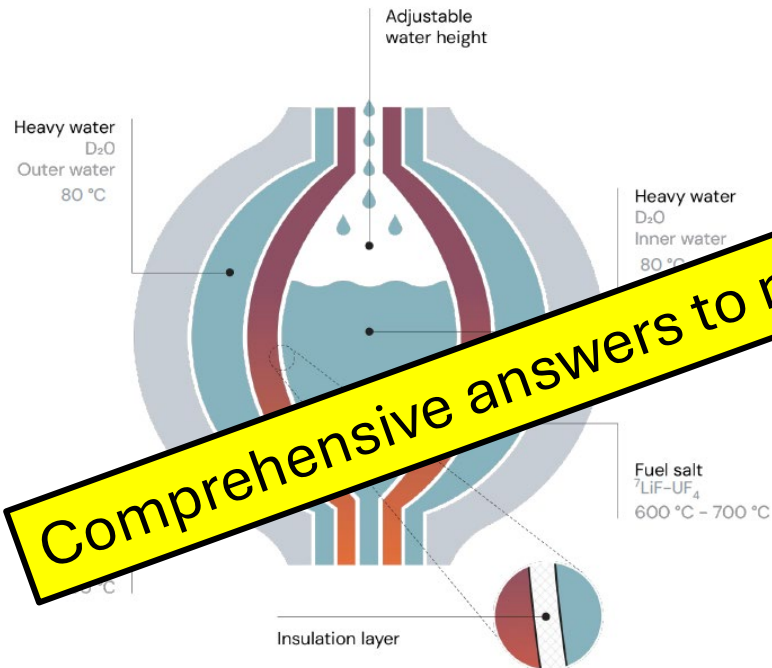
Cross section illustrative view of MSE core



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Cross section illustrative view of MSE core



Nuclear Energy, quo vadis?

- Most Generation-II nuclear power plants will apply for **lifetime extensions** and run for 60 years or more
- **Large Generation III nuclear power plants** will continue to be built, especially in emerging countries, but also gradually in Central/Eastern Europe (EU taxonomy!) and the USA.
- **SMRs will start to penetrate the market from 2030**. OECD studies estimate that SMRs will account for 10-30% of total nuclear capacity by 2060
- **Generation IV** reactors are being developed in parallel and may be commercially available in the early 2030s. They enable efficient cogeneration technologies and **sustainable fuel utilization**
- According to the majority of global energy system studies, nuclear power generation will account for **10 to 20% of total global power generation** by 2050

Thank you very much for your attention!

