PSI Center for Nuclear Engineering and Sciences

Small Modular Reactors: A Paradigm Shift in Nuclear Technology?

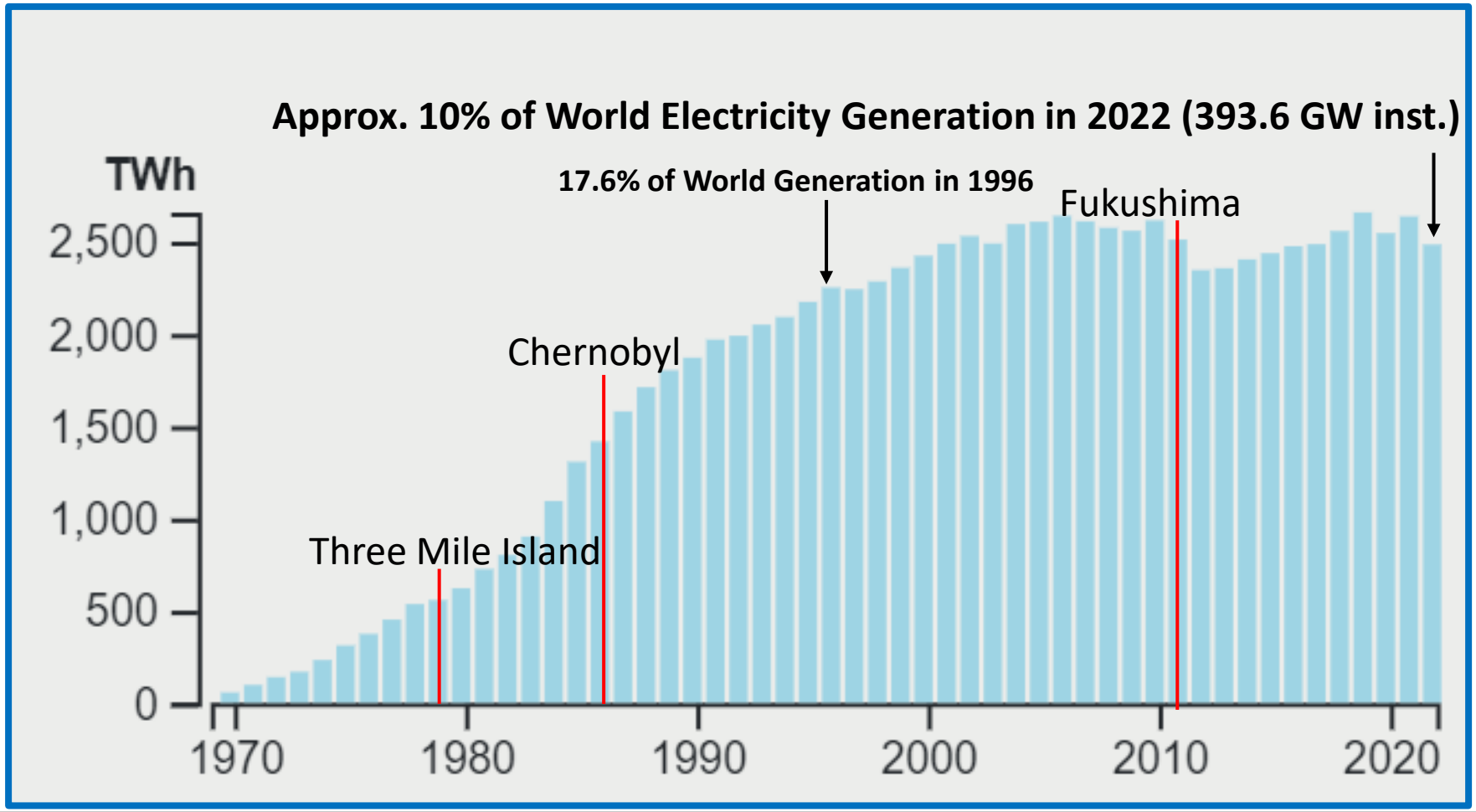
ESSRI: *Energy for Sustainable Science at Research Infrastructures*

Andreas Pautz, Head of Nuclear Energy and Safety Division,
Paul Scherrer Institut (PSI)
Madrid, 26 September 2024

Content

- Nuclear Power Utilization: Context
- From Large to Small Reactors
- Design and Safety Features of LWR-SMR
- Near-Term SMR and Microreactors

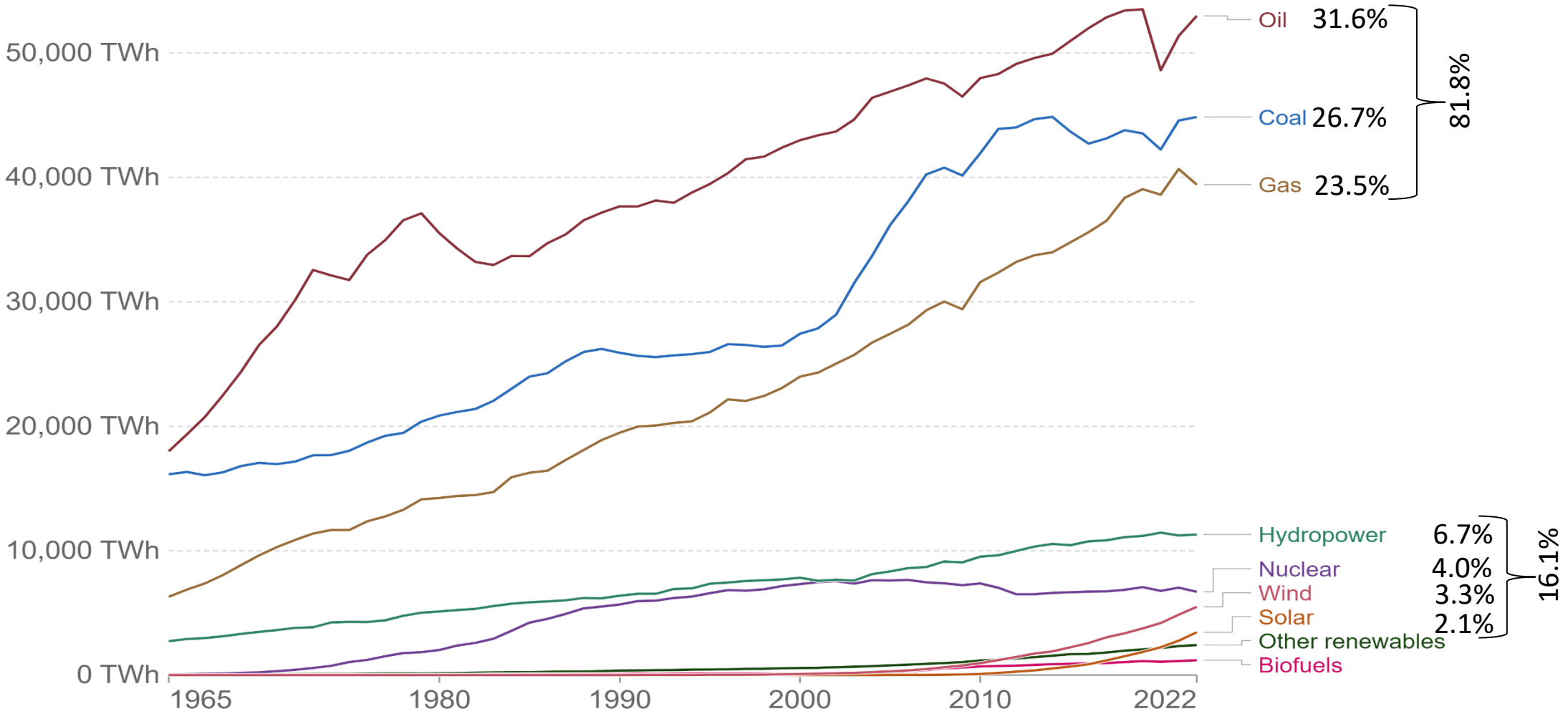
Global Development of Nuclear Generation Capacities



There are currently 415 plants in operation worldwide (+25 waiting for restart in Japan), 60 plants under construction in 17 countries, and 91 in advanced project planning in 15 countries. 189 have been decommissioned.

Quelle: https://www.nuklearforum.ch/de/nuclearplanetfr

World Primary Energy Generation by Source



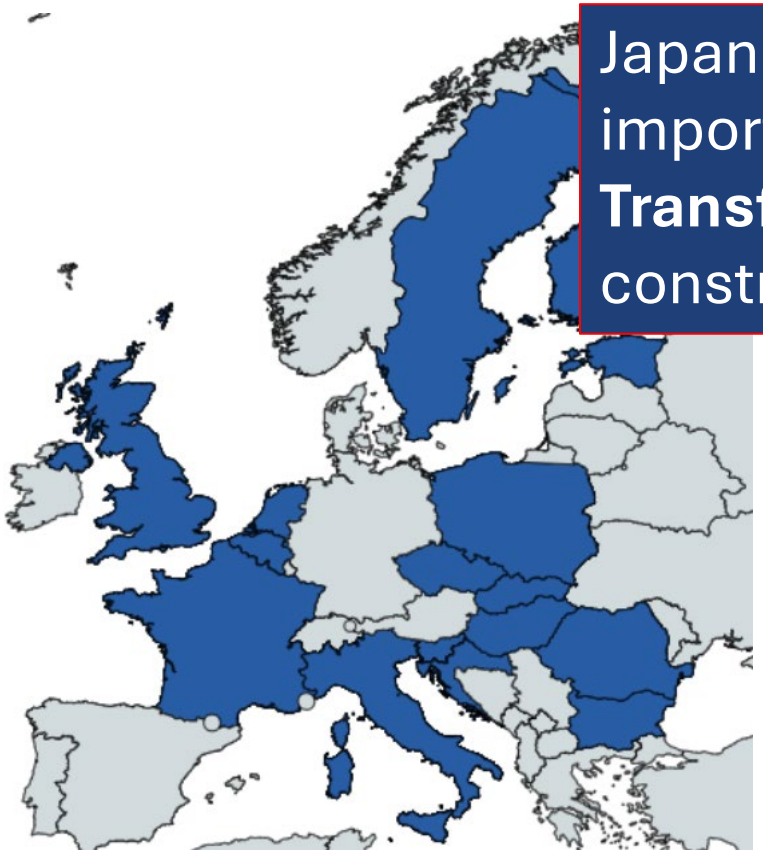
Source: Energy Institute Statistical Review of World Energy (2023)

OurWorldInData.org/energy • CC BY

Developments in recent years

2022: Nuclear energy in EU Taxonomy

Japan - December 2022: Nuclear decleared as important part of government plan for „**Green Transformation**“. Restart of shutdown NPPs and construction of new NPPs planned



July 2023 – EU NUCLEAR ALLIANCE
Goal:

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

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

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INDUSTRIAL
SMRs
on launched
strial Alliance for Small Modular Reactors (SMRs).
~ 3000 European companies

European Industrial Alliance on SMRs

22 March 2024
Brussels

European Commission

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

Baseload Electricity for AI-Data and Computing Centers

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Three Mile Island to be restarted to power Microsoft data centers

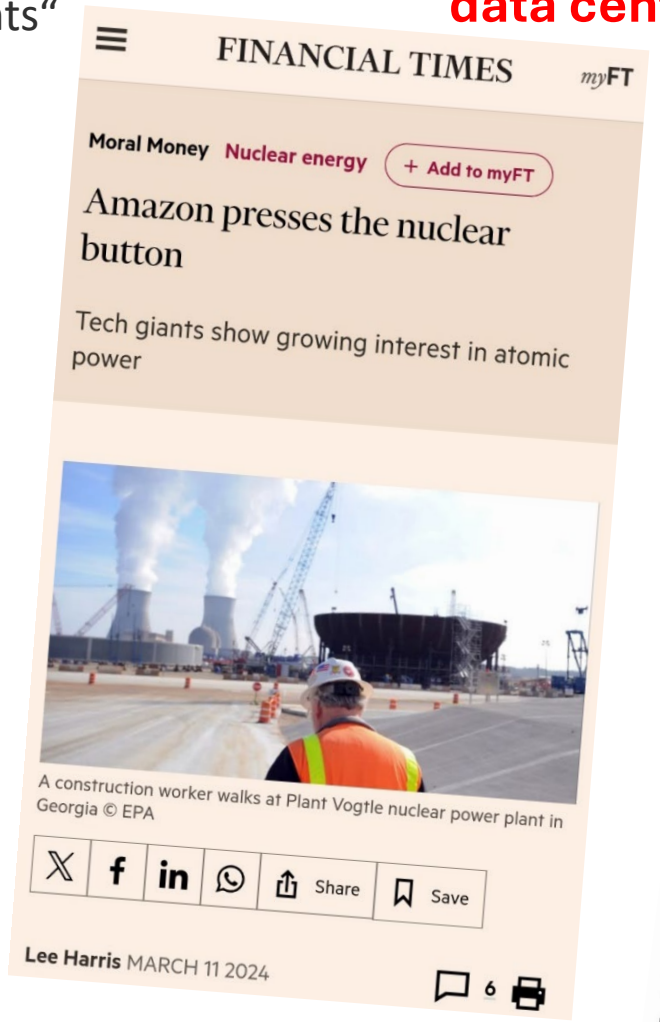
By David Szondy
September 22, 2024

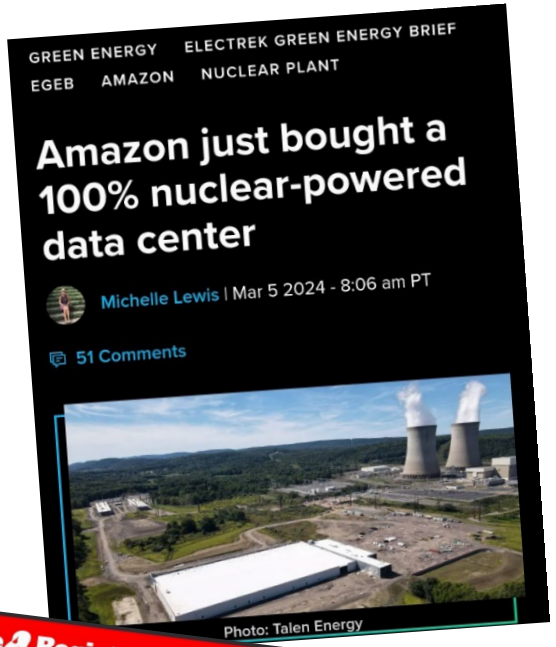
The Three Mile Island nuclear power station (CC BY-SA 4.0) Constellation Energy

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.

...acities to be
...nts"

Nuclear-powered data centers





...acenters: > 100 MW Power
...oday 11 MW, 25 MW in the future

The Four Generations of Nuclear Power Plants

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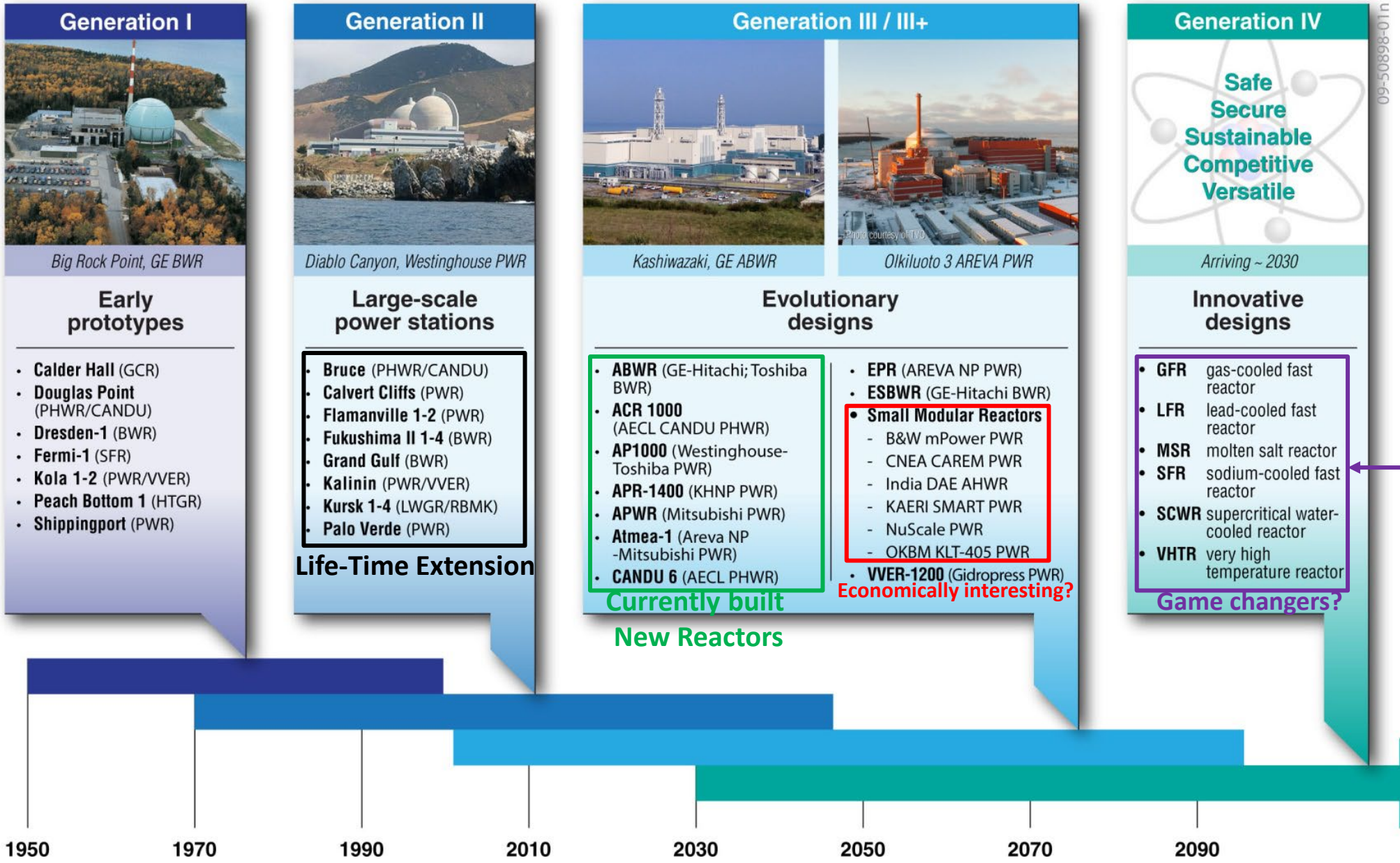
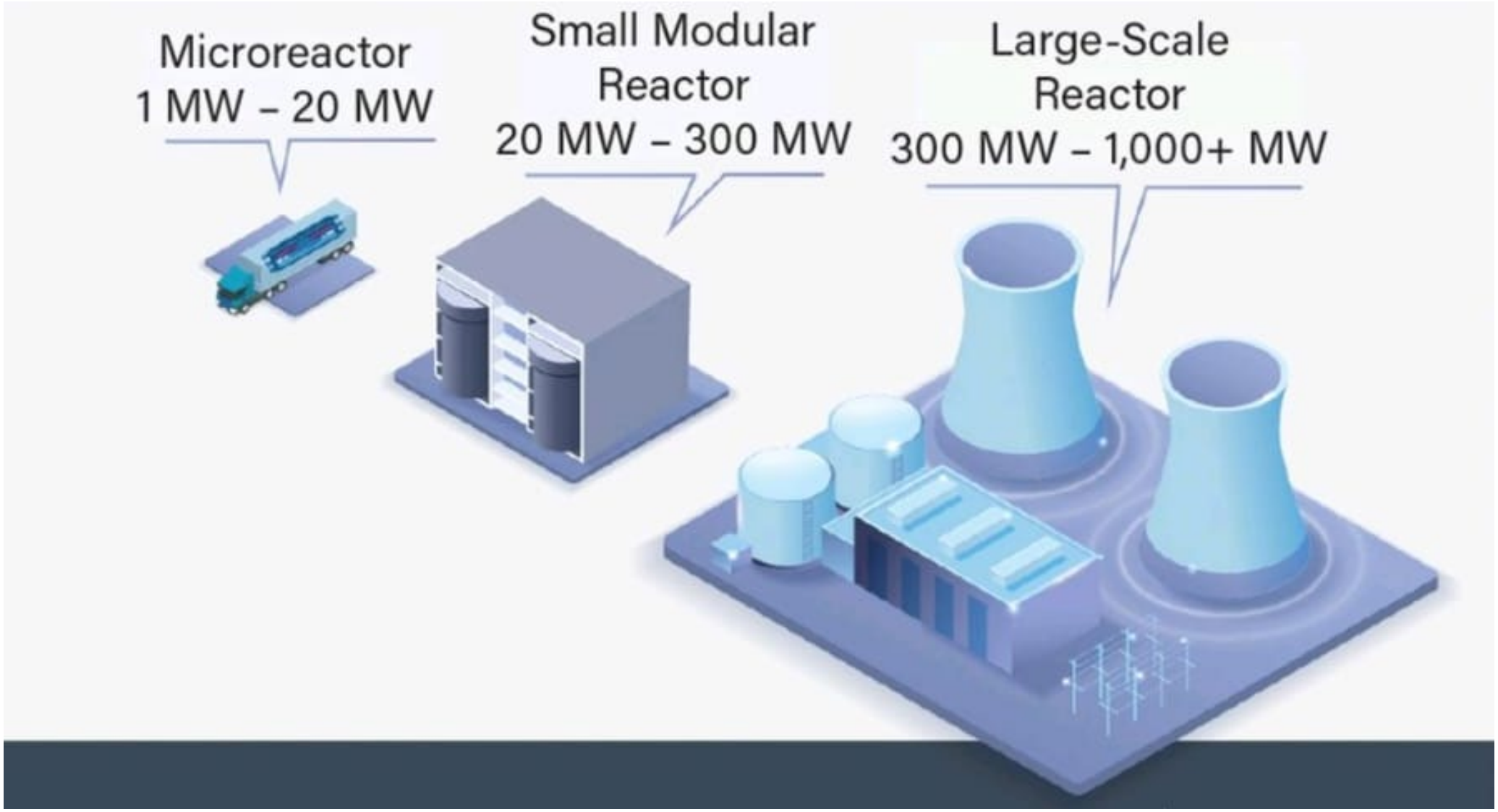


New Developments in Reactor Design



New Builds of Generation-III Reactors

The vast majority of new Generation-III plants are b
MW_{el}) light water reactor technology and implemer
the three major severe accidents:

- Massive use of both active and passive safety systems, s
accidents
- **Core Damage Frequency < 10^{-6}/year (factor of 10-100 l**

- **"Practical elimination" of accident sequences** that
radioactivity (<10^{-7}/year), with up to **one week grace p**
necessary

- As of today, **38 operating reactors qualify as Generation-III-reactors**, **51 Generation-III reactors** are under construction (thereof 24 in China alone)

- The average building time for the completed 38 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)

Safety Systems of Generation-III Reactors: EPR

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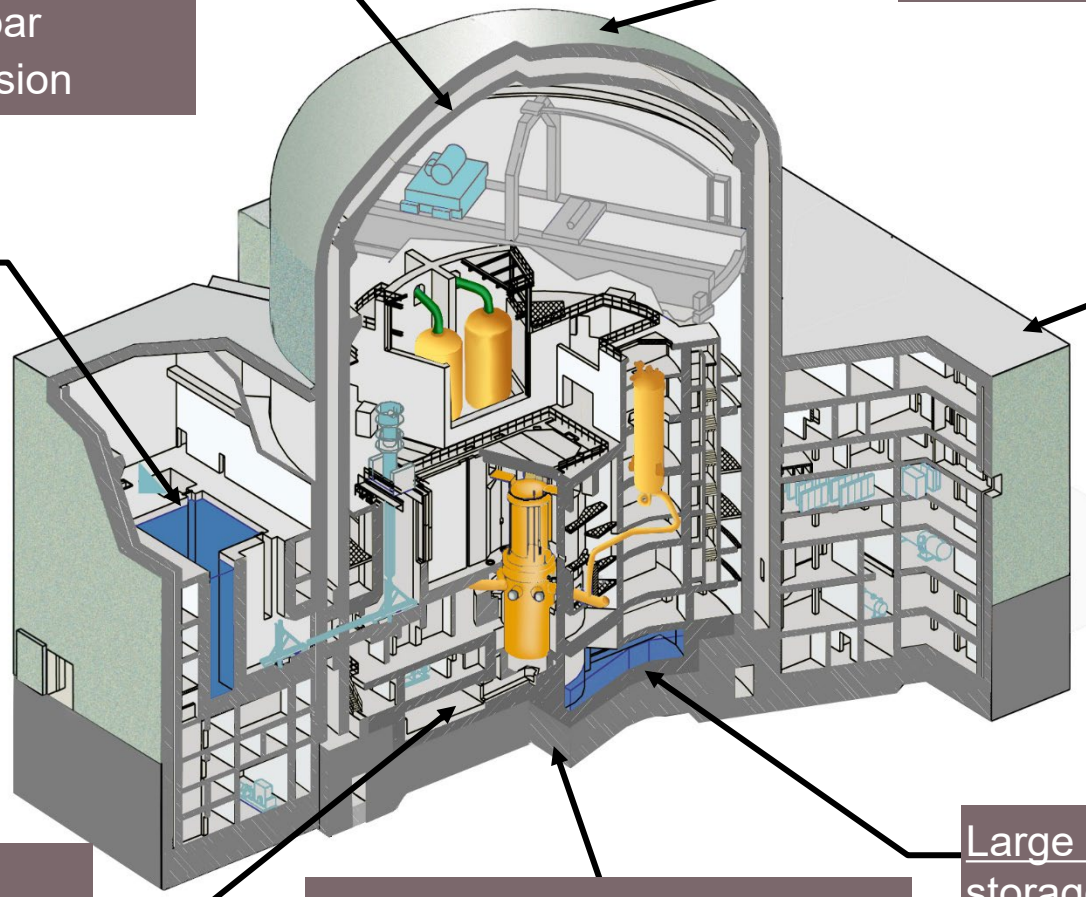
Internal Containment:
- Steel shell
- Leak-proof up to 6.5 bar
- Exclusion of H_2-Explosion

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

From Generation-II to Generation-III: Evolution of Safety Technology

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1970
Generation-II

2020
Generation-III

Internationally Operating Generation-III Power Plant Vendors

EPR (Framatome) in Olkiluoto (FI), 1600 MW

«Economic» Reactor Project:
Construction Costs / Time:
4000-5000 $/ kW installed,
built in 5-7 years:
LCOE: 60-100 $/MWh

AP-1000 (Westinghouse) in Vogtle (USA), 2 x 1200 MW

VVER-1200 (Rosatom) in Tianwan (China), 2 x 1250 MW

APR-1400 (KEPCO) in Barakah (UAE), 4 x 1400 MW

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)?

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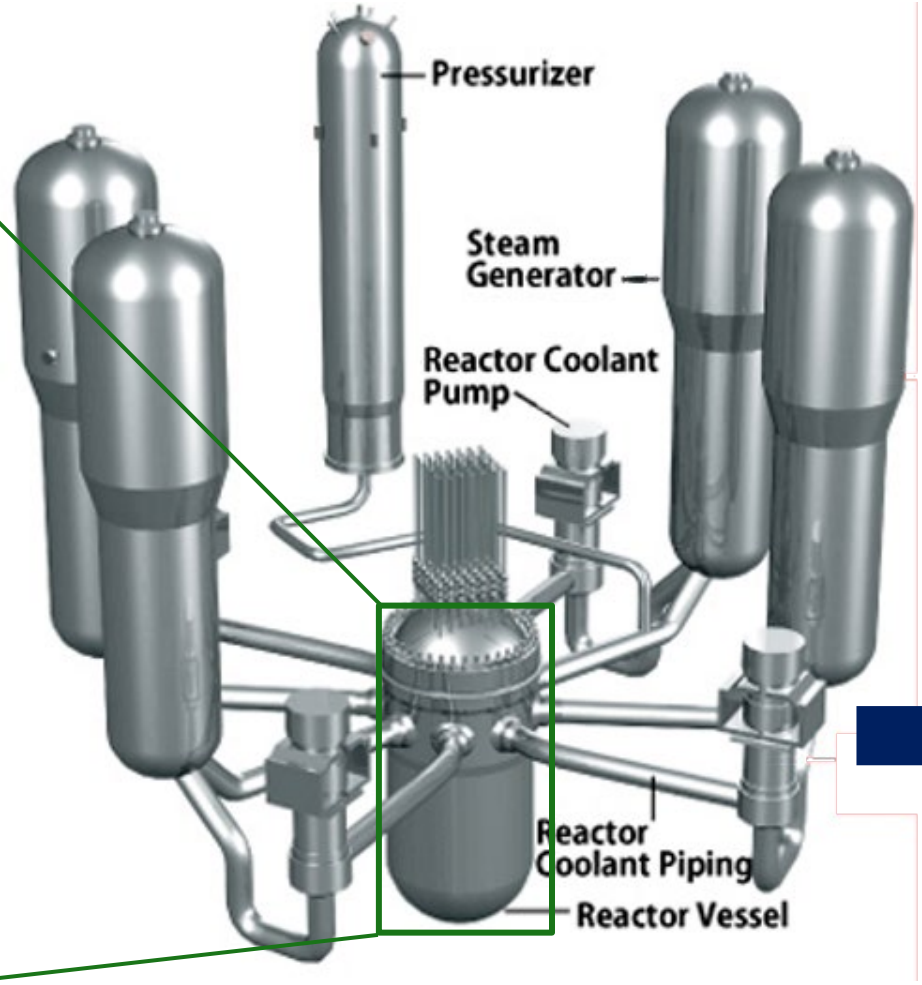
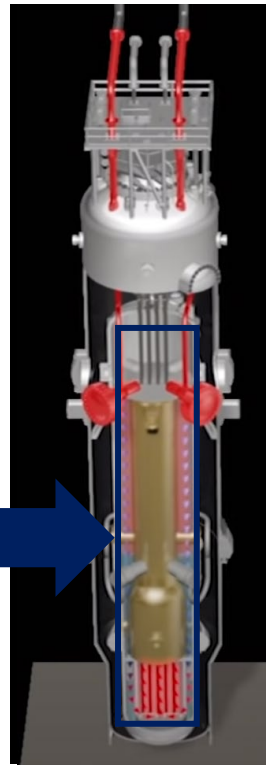
- Power up to ~300 MWe
- Smaller / less monolithic units and therefore reduced CAPEX
- Modules are factory-built and factory-tested before installation on site
- Significant shorter construction times for individual modules (goal: 2 – 4 years)
- Higher flexibility to better integrate with renewables
- Transportable by truck, train, boat or plane
- Applications include heat to isolated sites not connected to the electric grid
- 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)

Large LWR vs. LWR-SMR: Comparison in Size

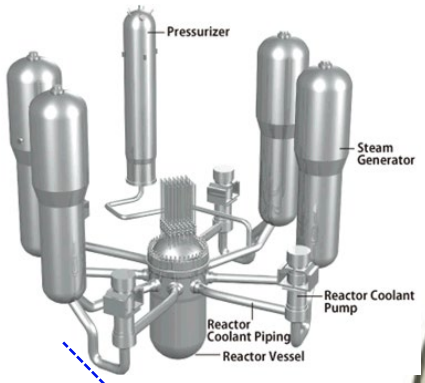
- Entire class of accidents eliminated by design (e.g. LBLOCAs)
- Fabricated in factory and transported to plant site

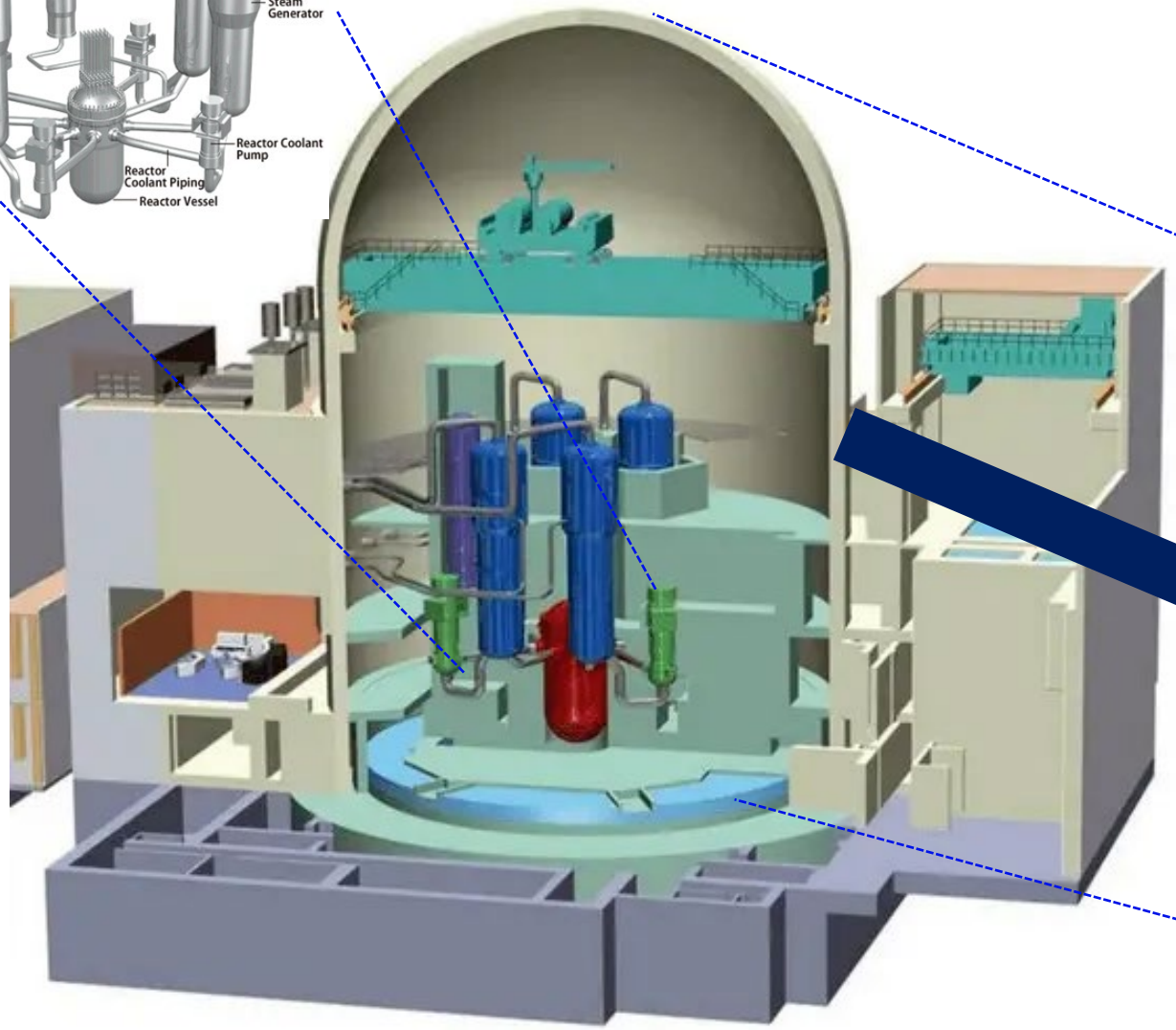
~ 11 m

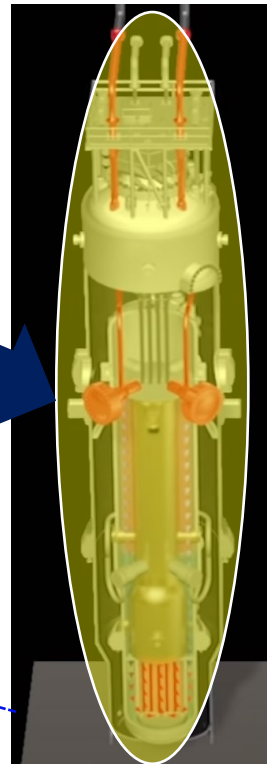




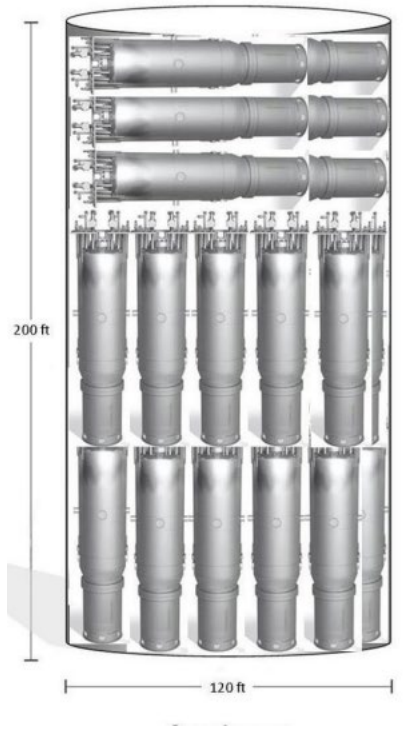
Large LWR vs. LWR-SMR: Comparison in Size





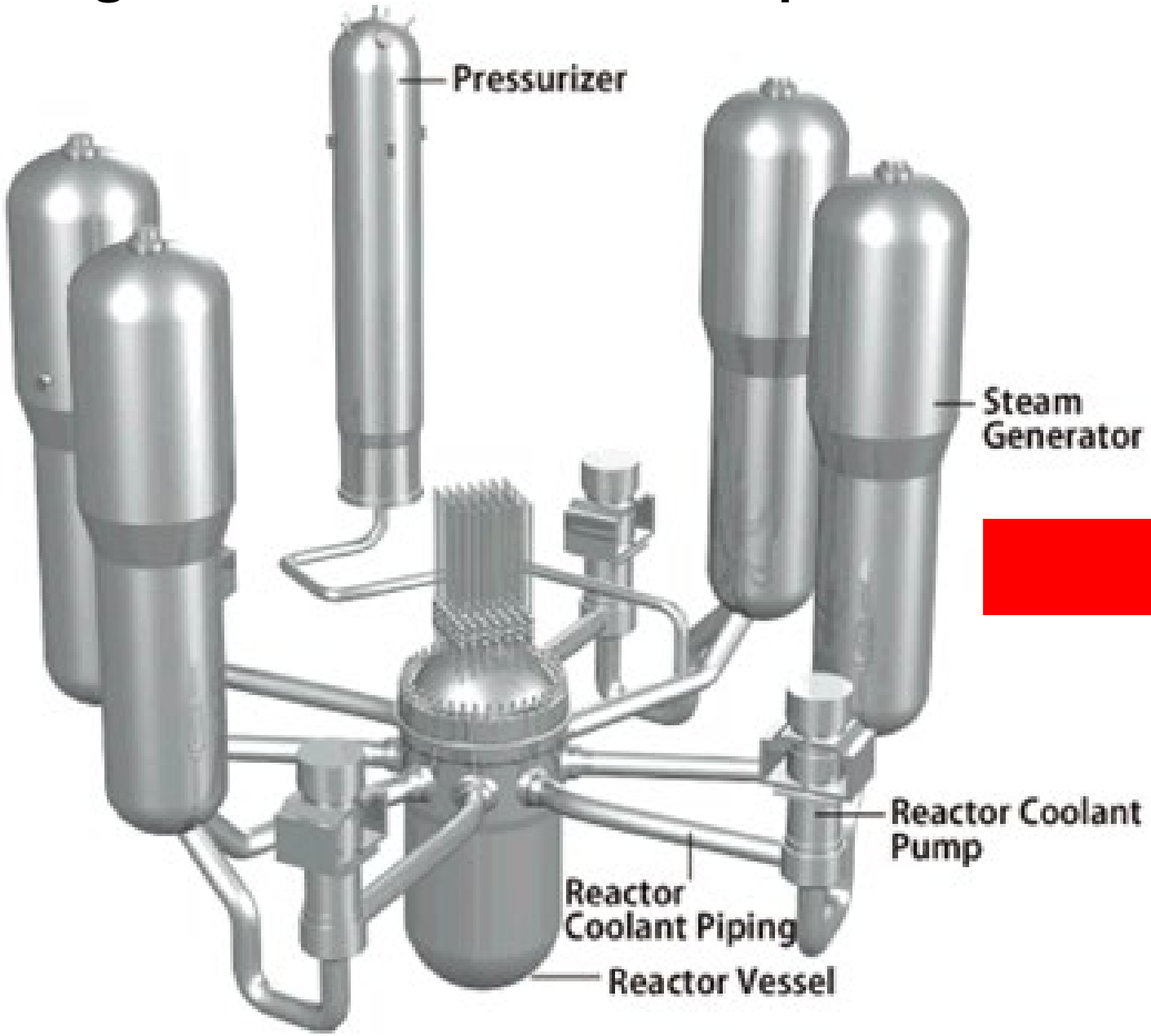


126 NuScale Power Modules



NuScale's combined containment vessel and reactor system

Large LWR vs. LWR-SMR: Comparison in Size



SMRs already on the market or available by 2030

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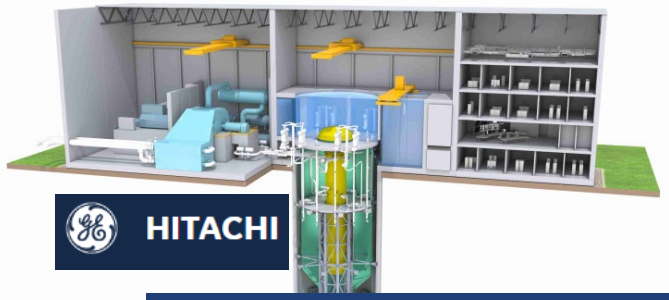
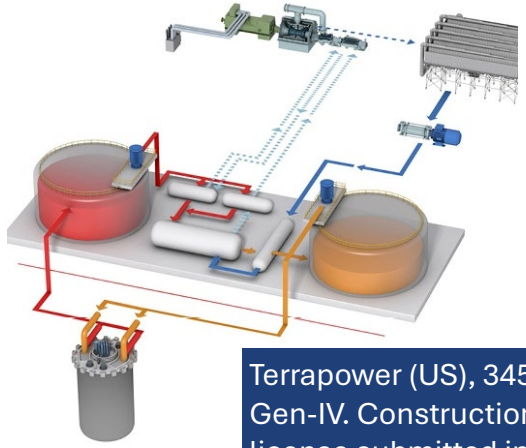
RITM-200 (Russia)
several in operation

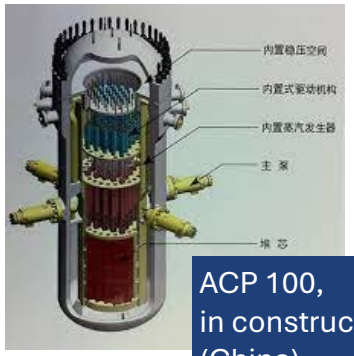


BWRX-300 (GE/Hitachi)
4 units in Ontario Power, from 2028
Construction license expected in 2024



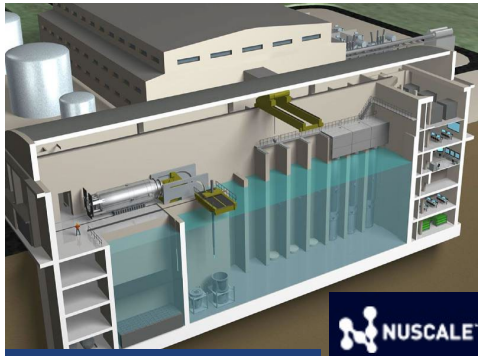
Terrapower (US), 345 MW
Gen-IV. Construction
license submitted in 2024

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

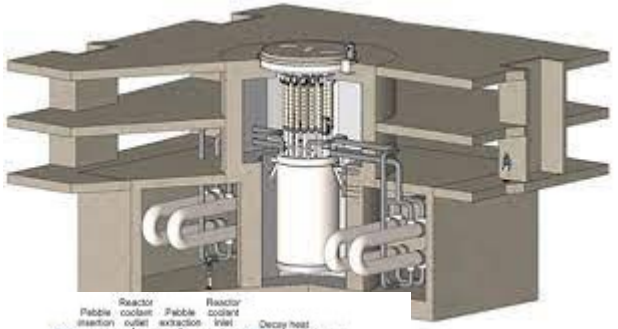


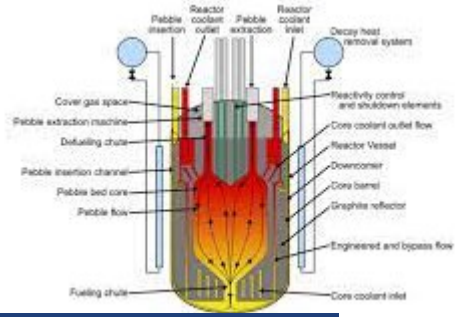
ACP 100,
in construction
(China)

2xHTR-PM
in operation (China)



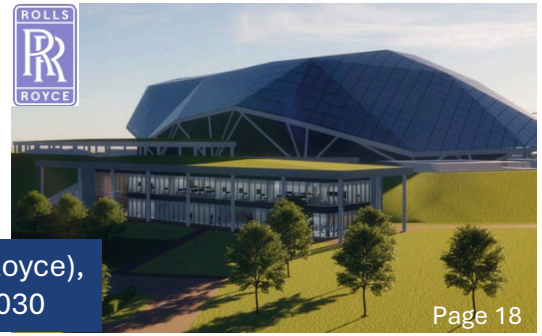
NuSCALE (6 x 77 MW)
Licensed in USA





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

NUWARD (EdF/Technicatome)
170 MW, from 2030



UK SMR (Rolls Royce),
443 MW, from 2030

Russia: 8 in operation (LWR), several planned (LWR/SFR)
China: 2 in operation (HTGR), 3 in construction (1 LWR), 2 SFR)
Canada: 4 ordered**, Argentina:** 1 in construction
USA: 1 in construction (Kairos), several planned

NuScale: The First Licenced SMR Design in the USA

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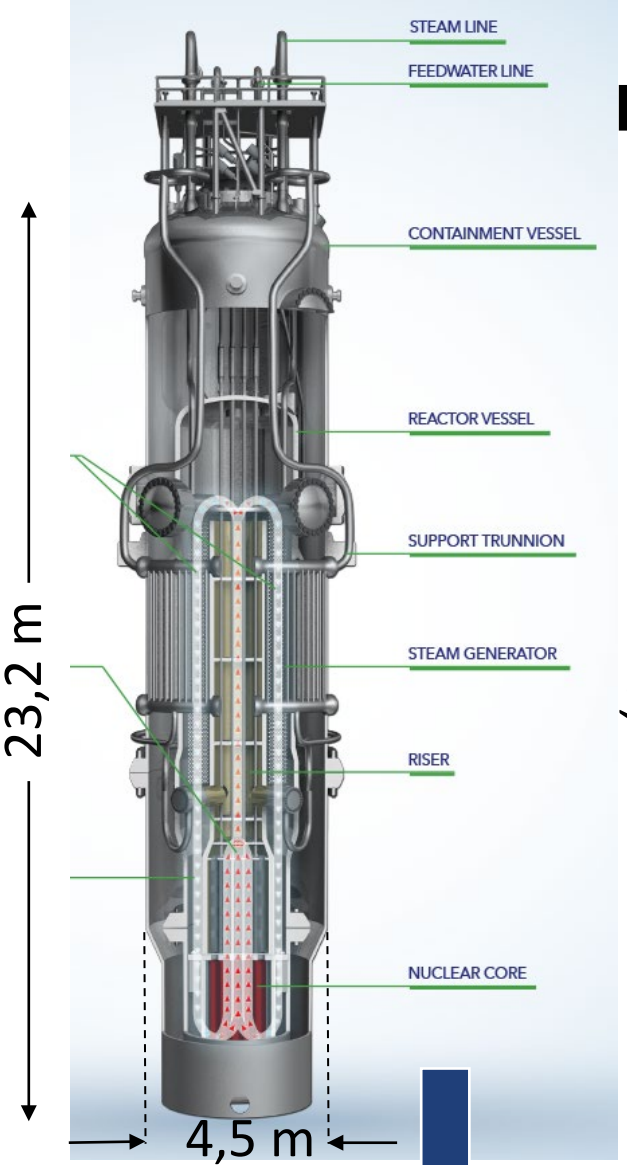
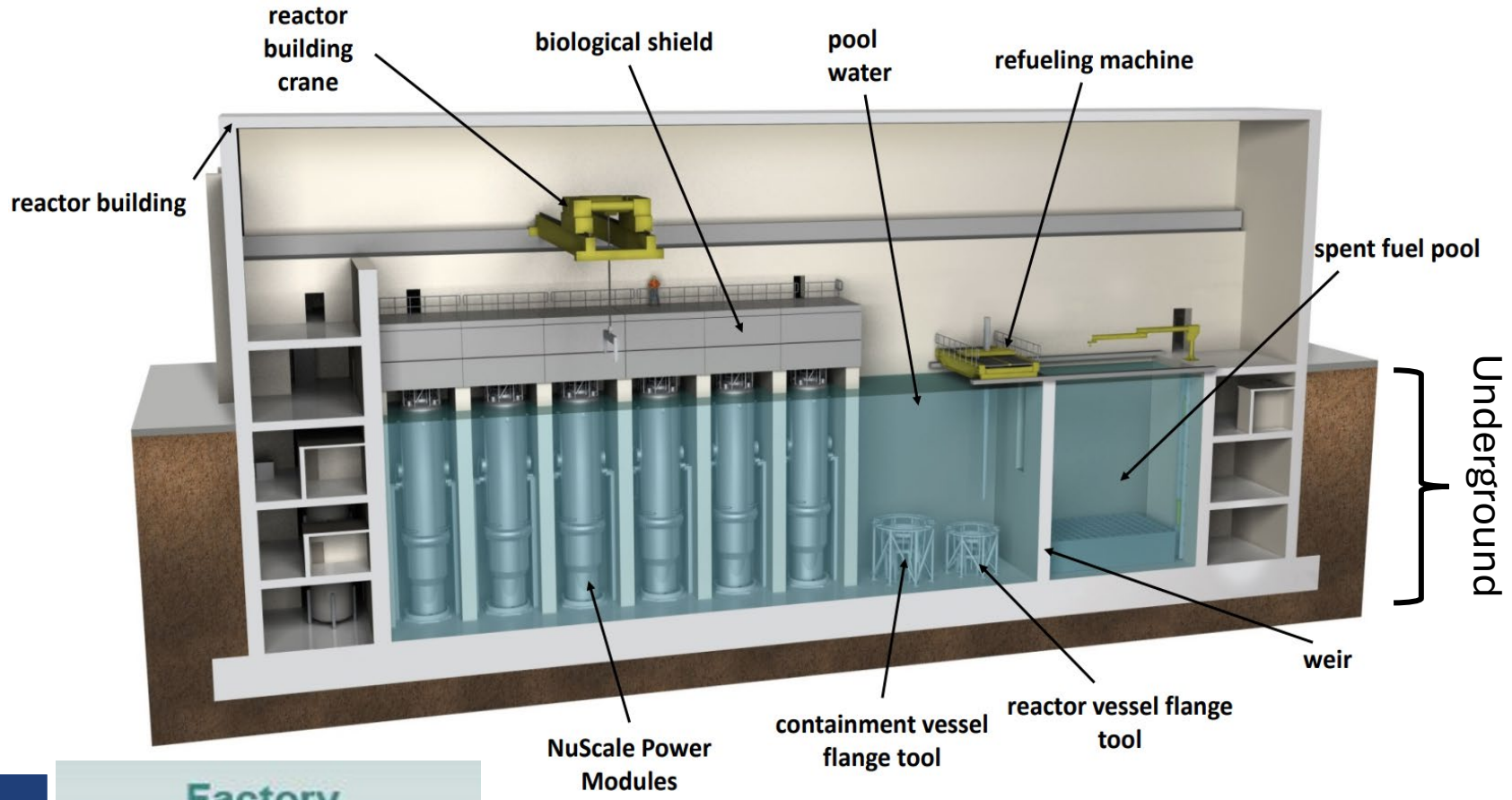
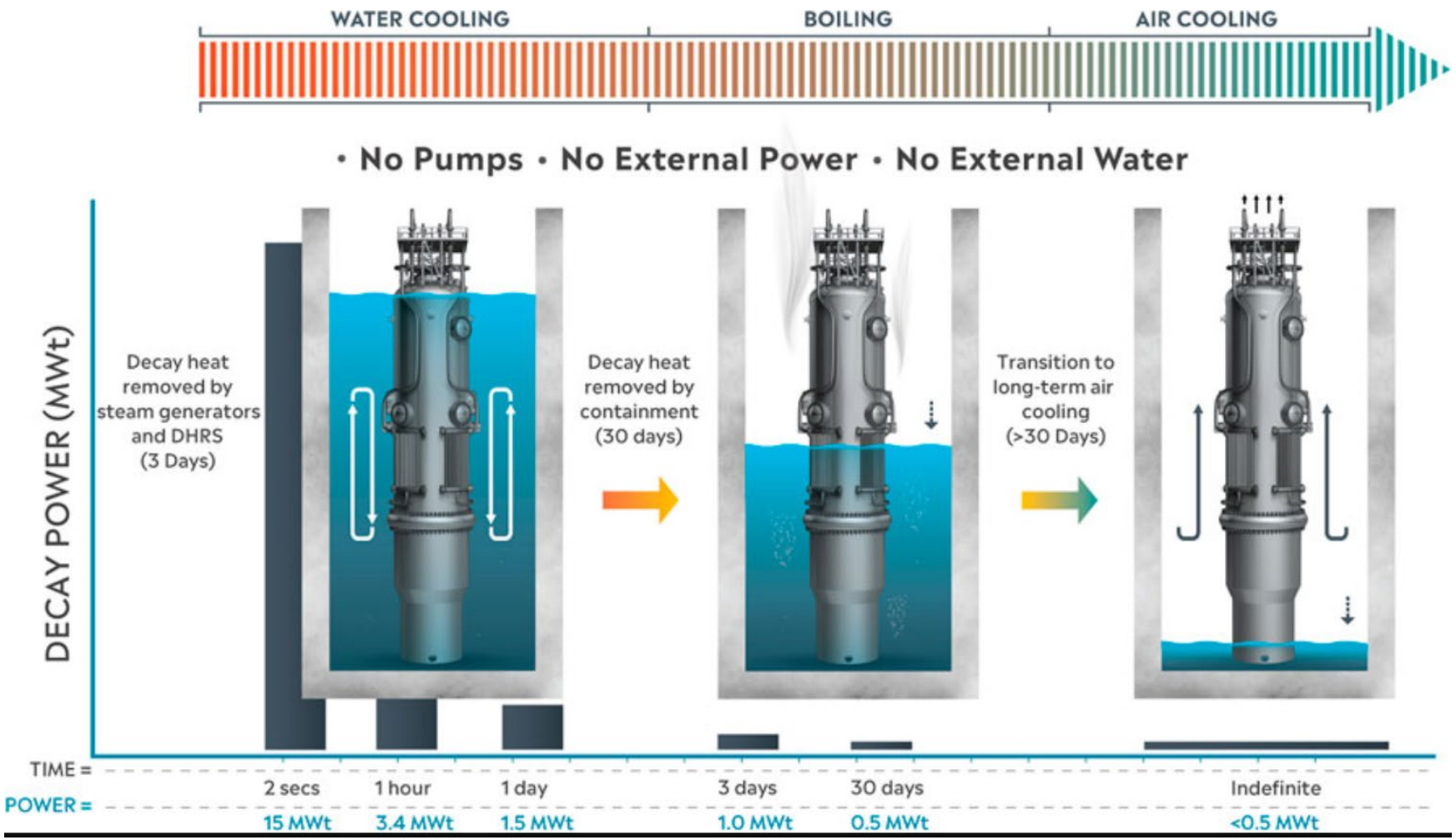




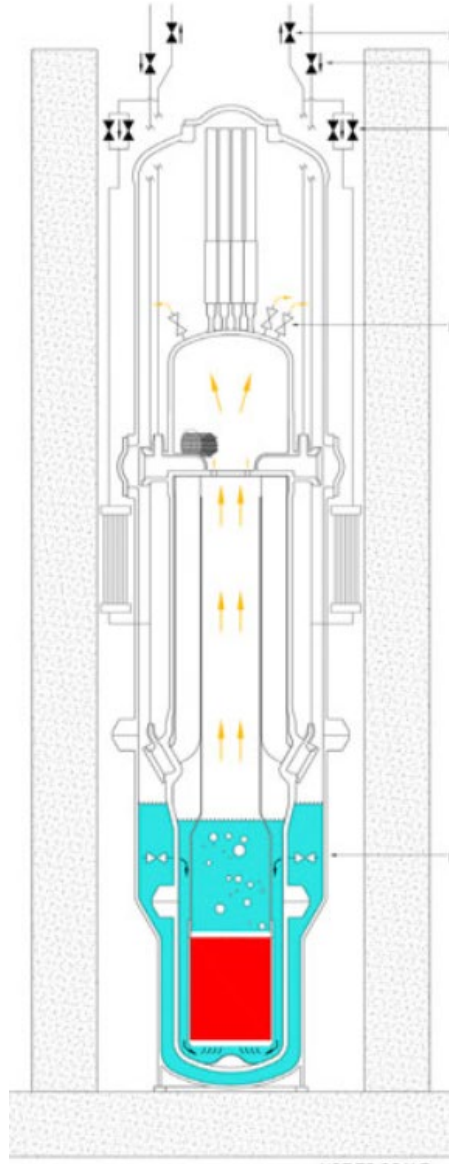
Each Module is refueled underwater while the remainder of the plant produces power

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

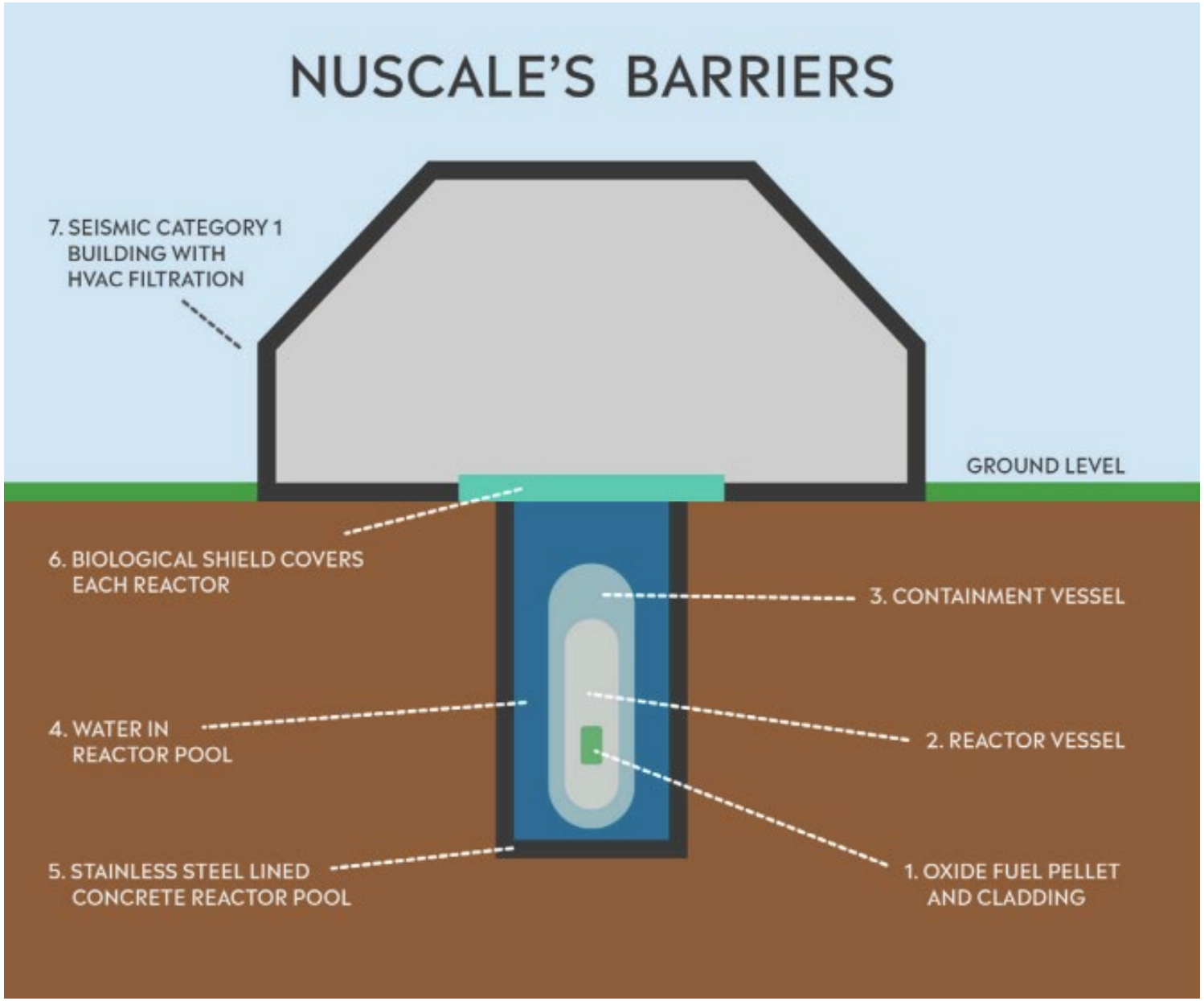
Passive Safety Systems: «Walk-Away Safety»

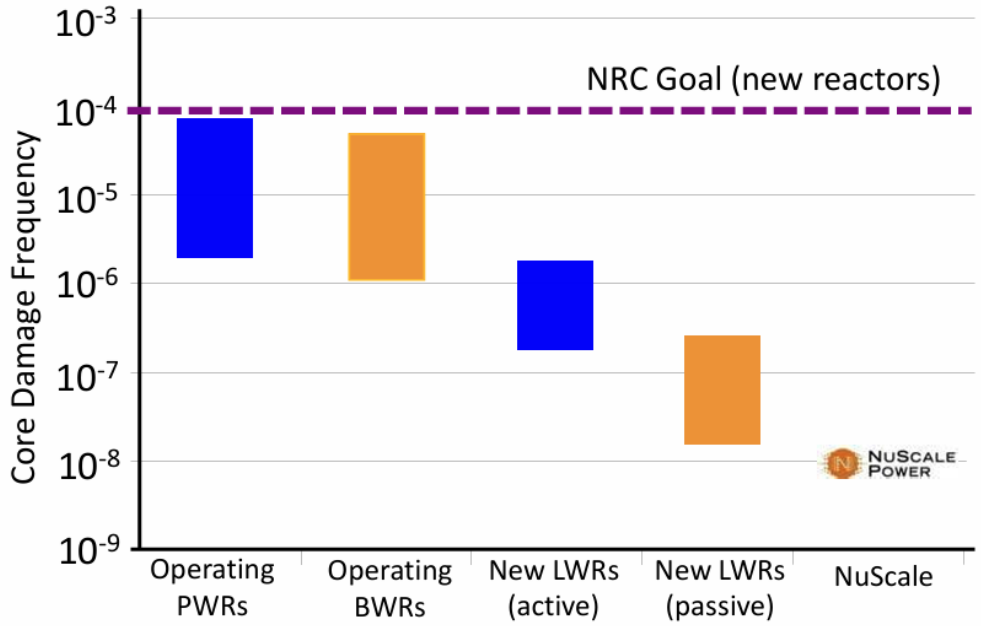


Decay Heat Removal after Reactor Shutdown (Long-Term Station Blackout Scenario)



Reactor Core remains Covered at all Times





Emergency planning zone (PEZ) limited to the site boundary (no evacuation required, even in case of severe accidents)

NUWARD (France)

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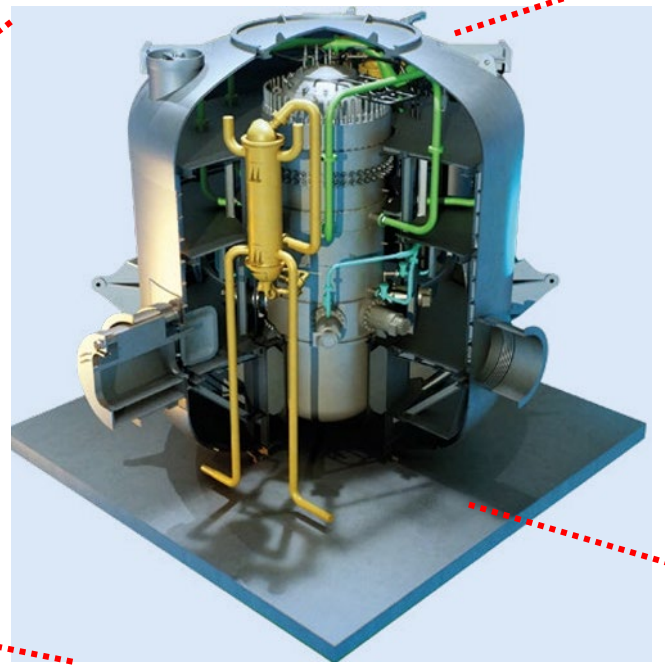
Flexible operation between 20% to 100% of rated power

Containment



RPV

General characteristics

- 2 reactors of 540 MWth
- 2 containment structures submerged in water
- 1 Nuclear Island semi-buried (25 m) protected against aircraft crash
- 2 generation units of 170 MWe

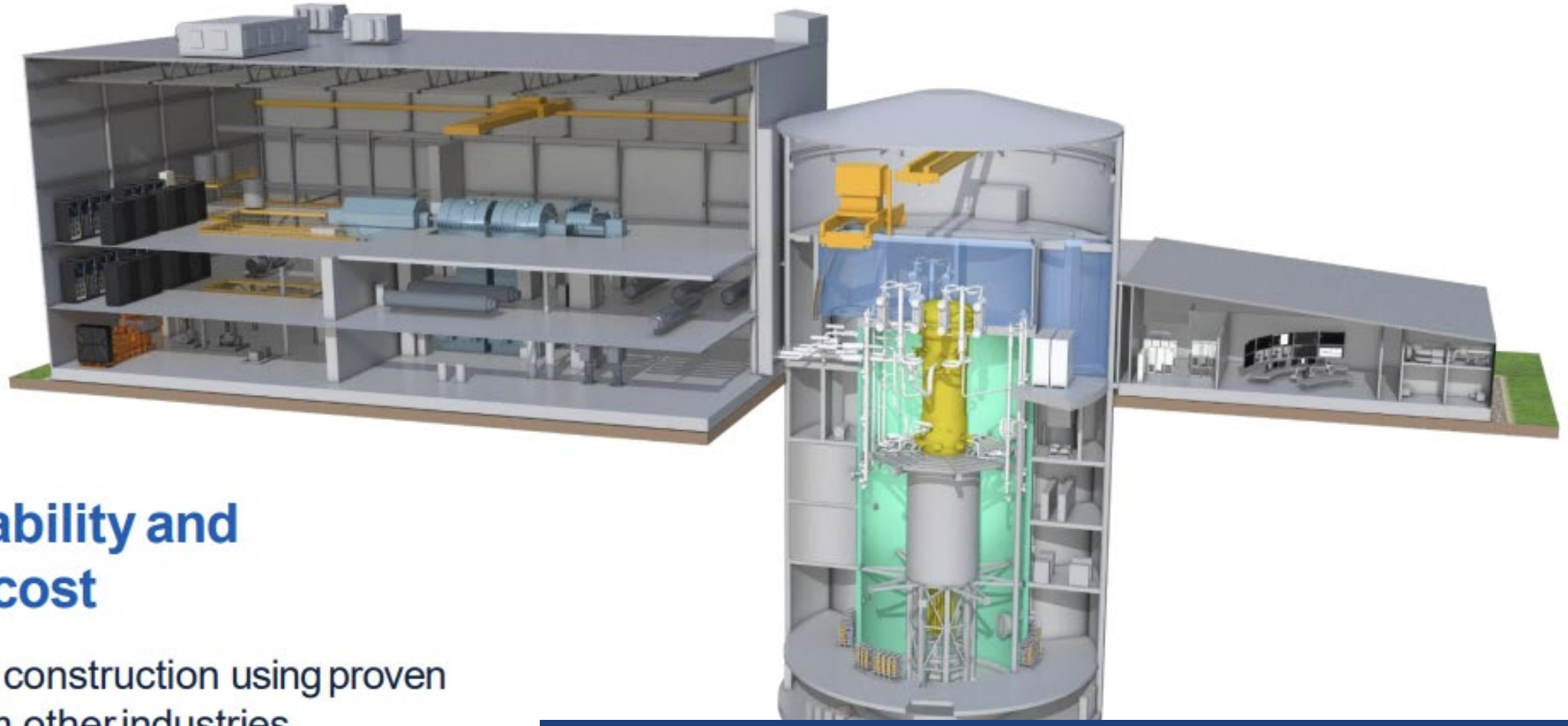
STRATEGIC SUPPORT FROM FRENCH GOV.

2020: EUR 50 M (French Recovery Plan) for Conceptual Design

2022: EUR 500 M ("France 2030" plan)

2026: Start of licensing procedure, first concrete by 2030

GE-Hitachi BWRX-300

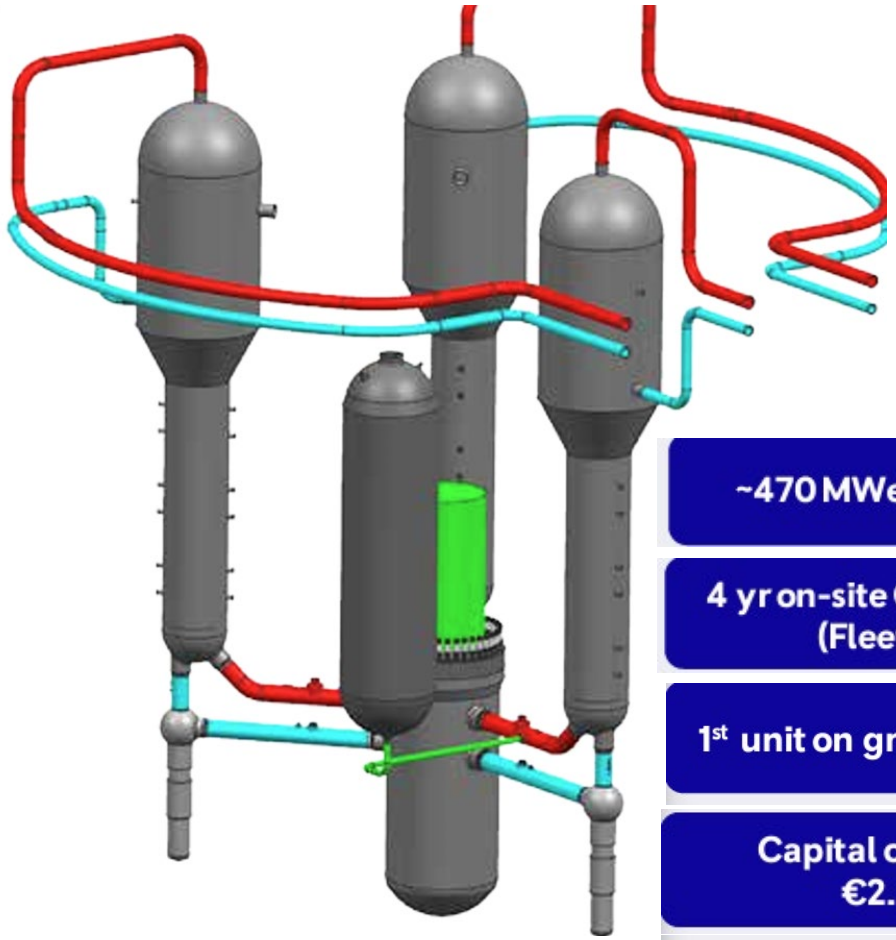


Constructability and Design-to-cost

- Underground construction using proven methods from other industries
- Maximum use of catalogue items
- “Off the shelf” turbine/generator

Canada has already ordered 4 units.
Site preparation started.
Expecting construction license by end of 2024
Capital cost at 700 Mio. $, 2250 $/kWh, O&M cost<16 $/MWh,
Claimed LCOE at ~40 $/MWh

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

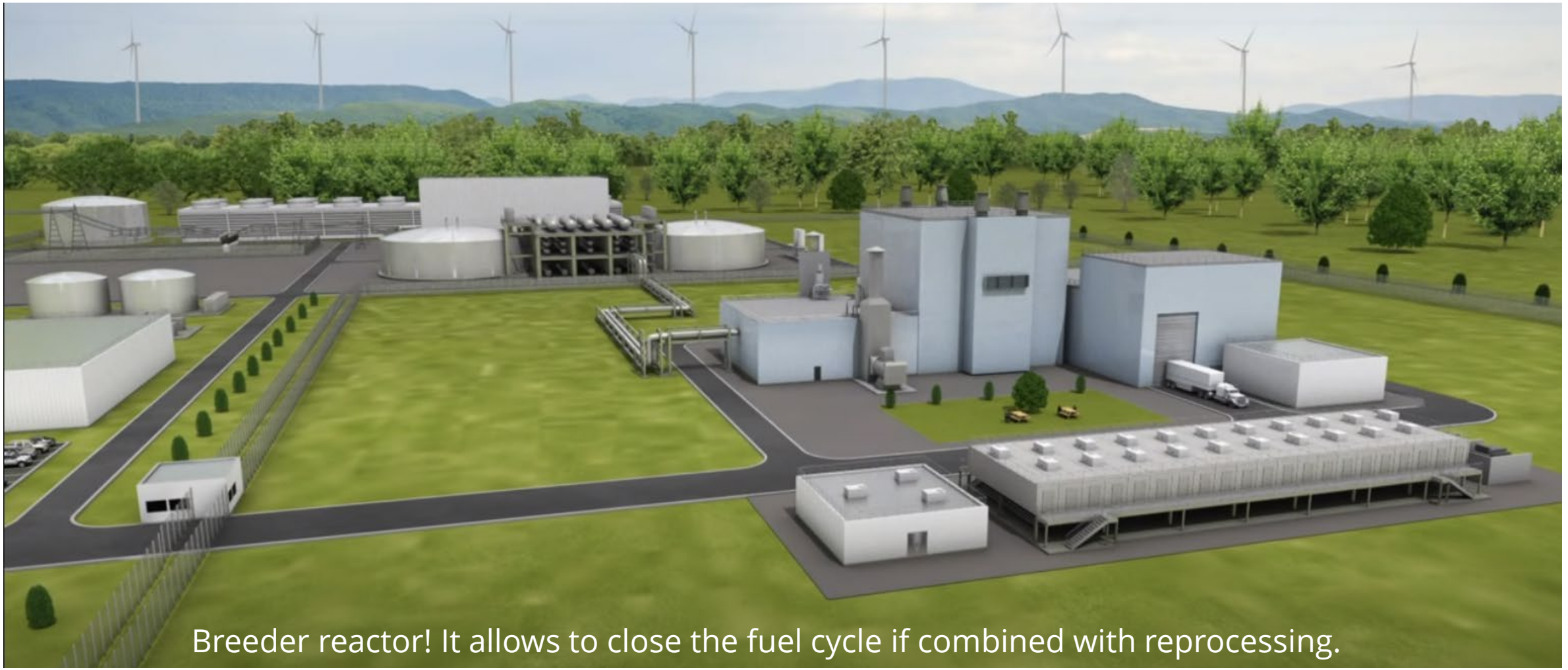
AP300 (Westinghouse, US)

Gen IV / Sodium-cooled SMR

- Gen-IV-Reaktor (sodium-cooled) SMR
- With integrated storage (molten salt)

Construction license submitted in March 2024 (Wyoming)

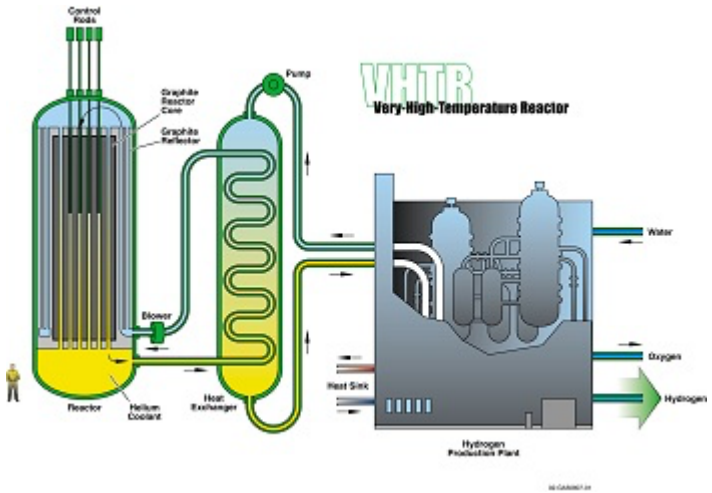
TERRAPOWER – 345 MWe
1 GWh Energy Storage



Breeder reactor! It allows to close the fuel cycle if combined with reprocessing.

The Generation-IV Reactor Concepts

High Temperature Reactor (HTR)

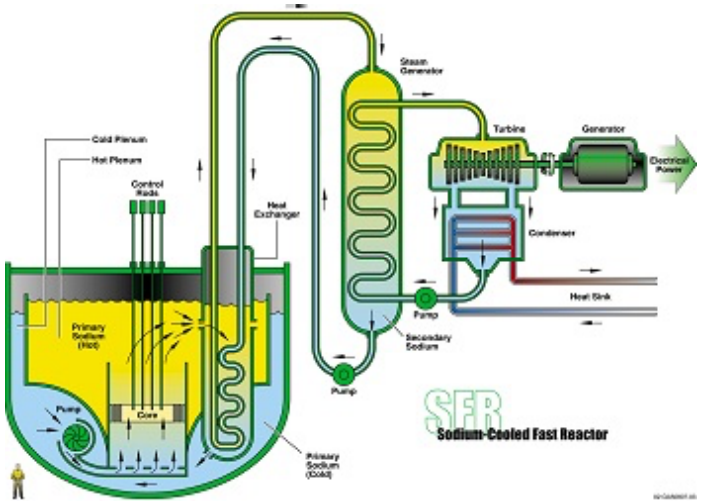


Lead Cooled Fast Reactor (LFR)

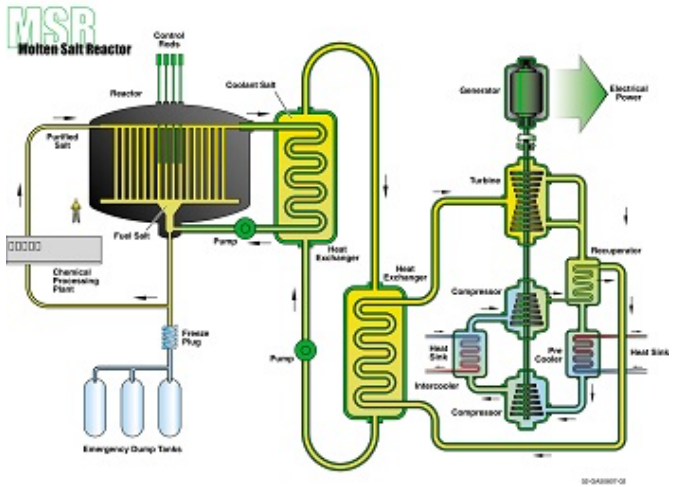
Supercritcal LWR (SCWR)

Gas-Cooled Fast Reactor (GFR)

Sodium-Cooled Fast Reactor (SFR)



Molten Salt Reactor (MSR)



Not only for electricity production

Remote mining operations

Industrial process heat

District heating

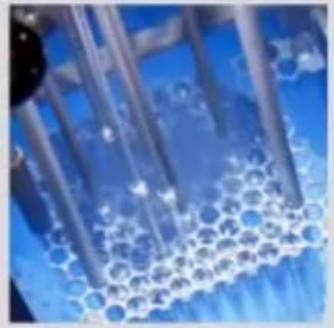
Remote communities

Hydrogen Generation

Marine Shipping

Critical Infrastructure Installations

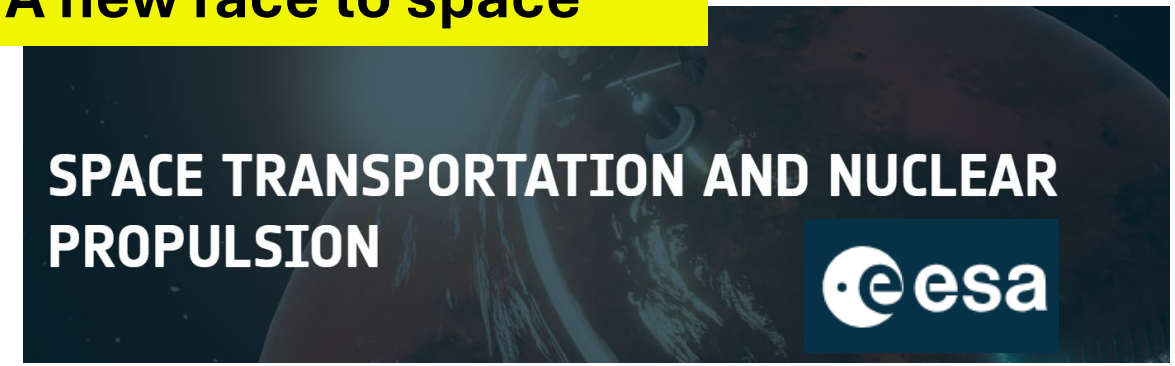
Disaster relief



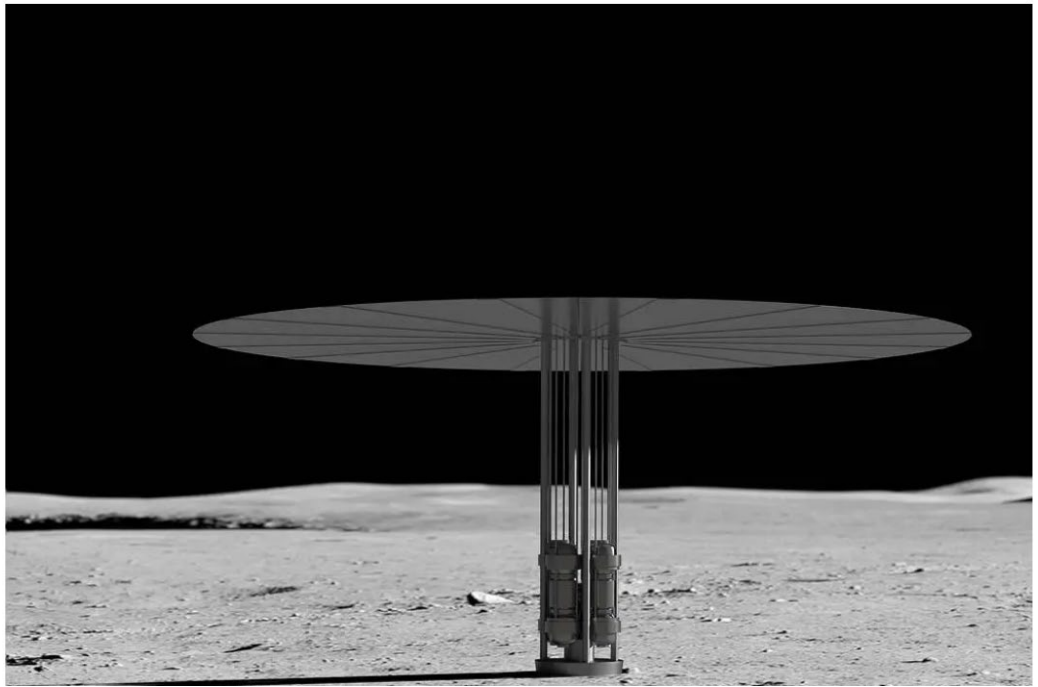
Research Reactors

Pilot plant - Production of hydrogen from 1.25 MW of Nine Mile Point NPP (NY, USA)

A new race to space



NASA Announces Artemis Concept Awards for Nuclear Power on Moon



Russia and China planning nuclear power plant on Moon by 2035

The joint project between the two countries could be a step towards establishing future lunar settlements.

March 6, 2024

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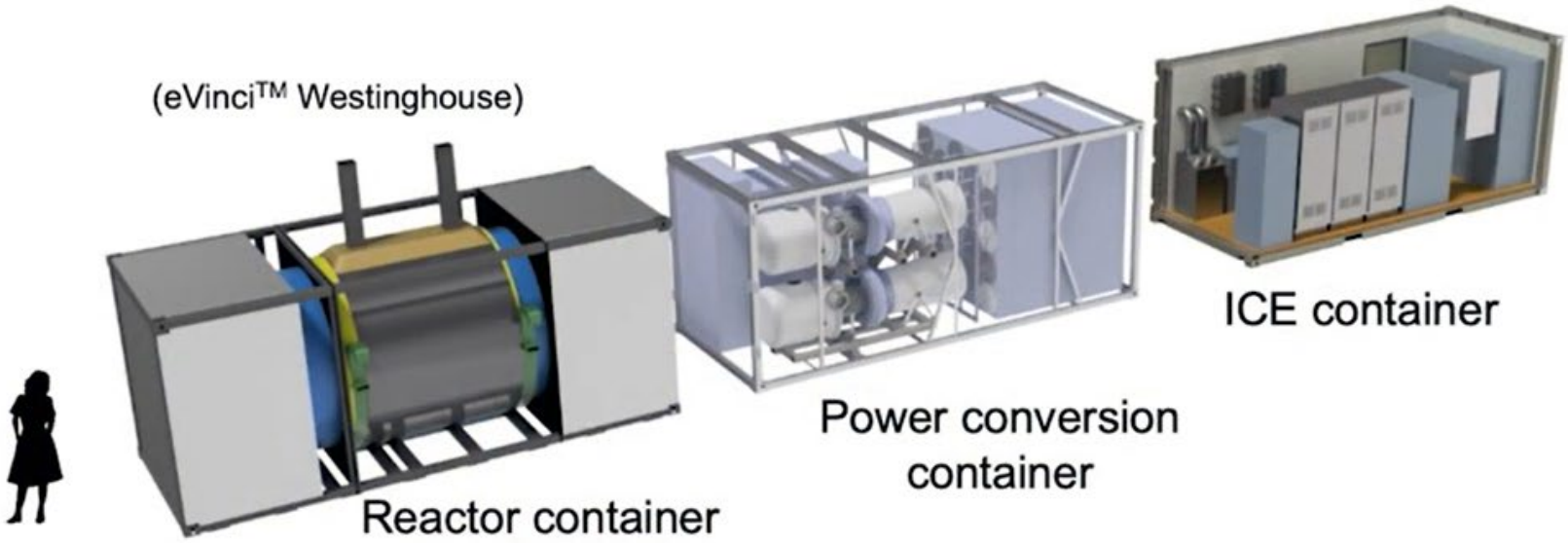
Microreactors – up to ~ 10 MWe



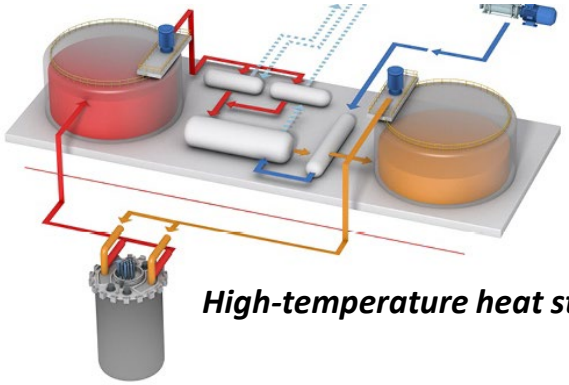
PLAYERS (USA)

- **MARVEL (INL, in construction)**
- **Westinghouse (INL, 2026)**
- **BWRT (INL, 2025)**
- **Kairos (ORNL, 2026; in constr.)**
- **X-Energy**
- **Ultra Safe Nucl. Corp.**
- **OKLO**
- **HOLOS (in licensing phase)**

- ❑ Plug-and-Play connection (< 1 month)
- ❑ Reduced space needed (~15 m^2), small site (< 2000 m^2)
- ❑ Refueling once every 10 years
- ❑ No water needed for cooling (heat pipes)
- ❑ As part of grid, microgrid or independent from grid
- ❑ Build in factory, and transported on site with ISO container
- ❑ For desalination, hydrogen production, and other industries
- ❑ Offiste refueling every 10 years
- ❑ No on-site storage of radioactive material

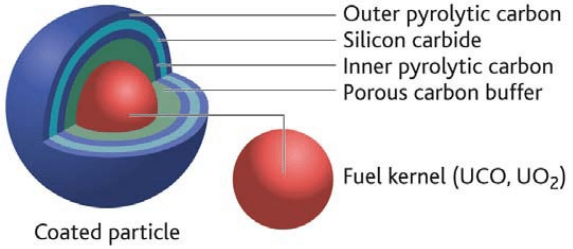
Microreactors – cogeneration applications

PSI



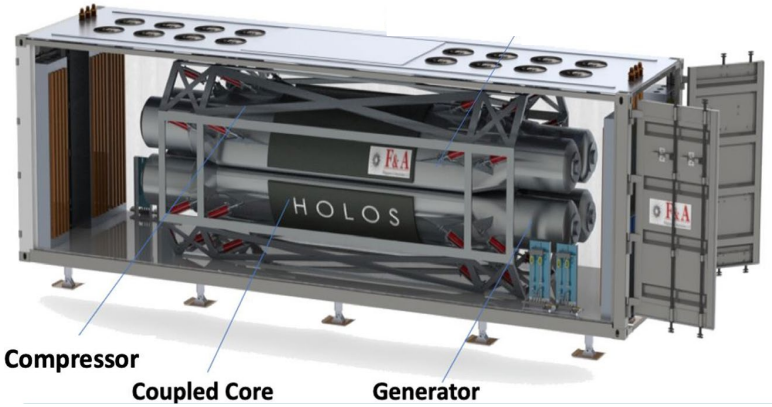
High-temperature heat storage

Reactor available from 2028 onwards
30 + 24 MCHF for reactor + fuel
Openness for PPP on vendor's side
LCOE: ~3.6 ct./kWh



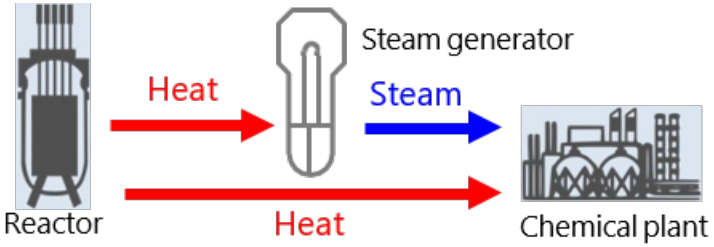
Ultimately safe by reactor and TRISO fuel design ("walk-away safe")

CO_2-neutral concrete production



Nuclear microreactor with 30 MW_{th}/14 Mw_{el}, up to 12 years non-stop operation, outlet temperature 900 °C (!)

Potential for radioisotope generation



High quality steam / process heat for wide range of applications (District heating, synfuels, petroleum refining etc.)

Conclusion

- Small Modular Reactors (LWR) will approach commercialization in this decade
- Rated reactor power between 20 to 300 MW_{el} will be available, given the large number of experienced vendors
- Severe Accident with Core Melt are practically excluded by design
- SMR have the potential to beat large LWR in LCOE, but this needs to be proven
- Microreactors (power below 20 MW_{el}) may likewise enter the market in the late 2020s

Small Modular Reactors: are they available today?

PSI