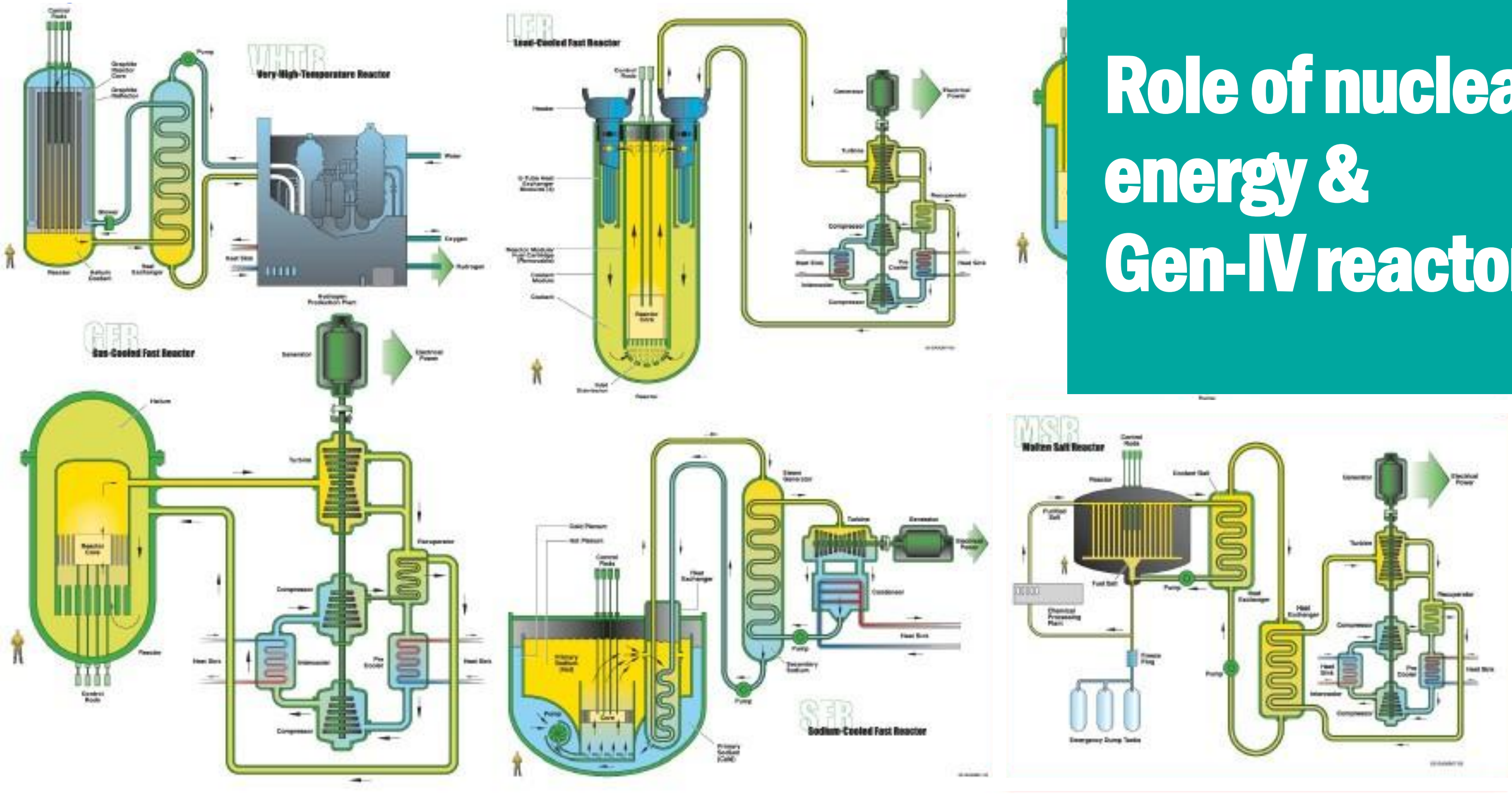
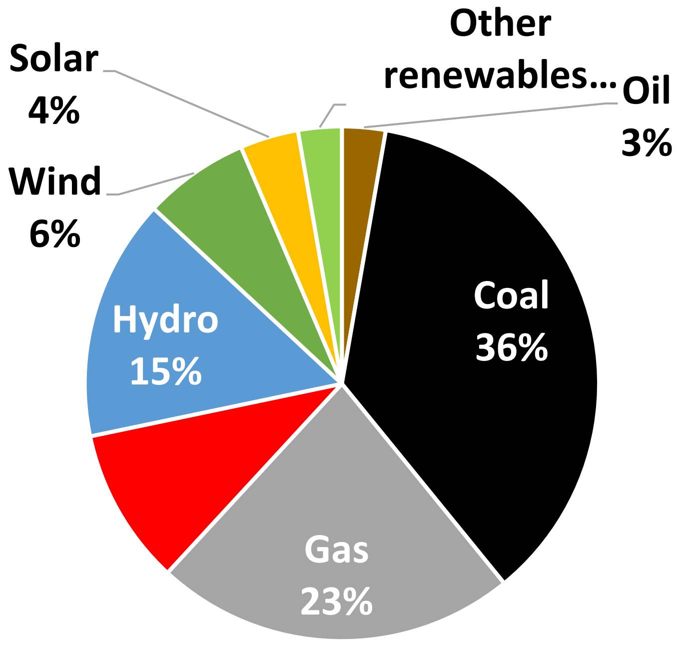
Role of nuclear energy & Gen-IV reactors



Role of nuclear in today's energy mix and current situation

Today's worldwide energy mix – Electricity production



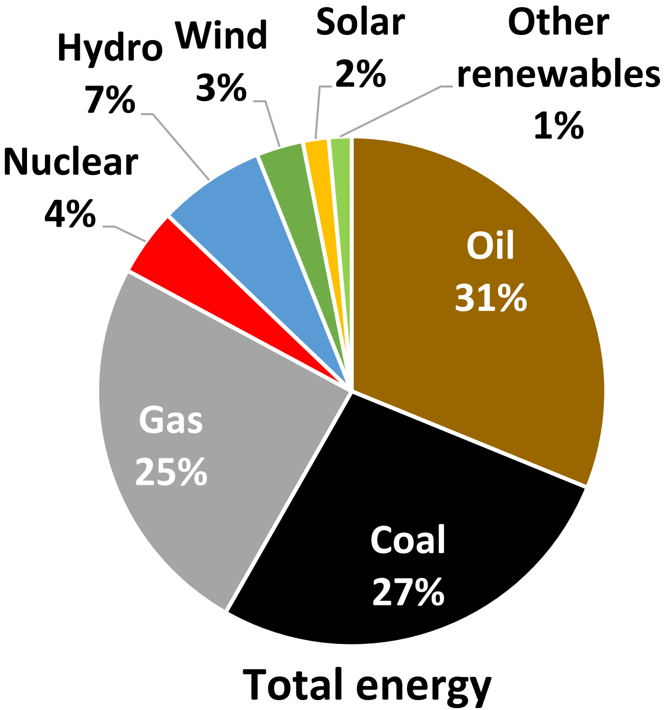
Electricity only

- Nuclear ~10% of world's electricity generation.
- Today's high-carbon/low-carbon split:
  - Total fossil fuel ~62%
  - Low-carbon sources ~38%
- 2000's high-carbon/low-carbon split:
  - Total fossil fuel ~65%
  - Low-carbon sources ~35%

Note: derived from ourworldindata.org (data of 2021 from BP Statistical Review of World Energy)

EPFL

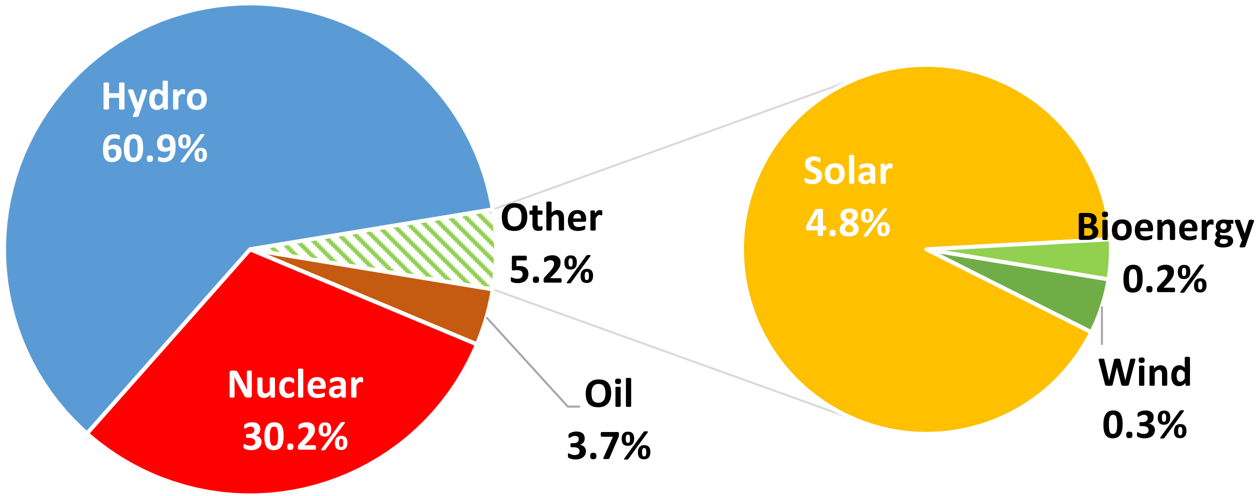
Today's worldwide energy mix – Total energy consumption



- Nuclear ~4% of world's energy consumption.
- Today's high-carbon/low-carbon split:
  - Total fossil fuel ~83%
  - Low-carbon sources ~17%
- 2000's high-carbon/low-carbon split:
  - Total fossil fuel ~86%
  - Low-carbon sources ~14%

Note: derived from ourworldindata.org (data of 2021 from BP Statistical Review of World Energy)

National Context: Electricity generation in Switzerland



What about total energy consumption?

- Nuclear ~15.5%
- Oil ~34.5%
- Gas ~12%
- Hydro ~32%,
- Solar ~2.5%
- Others ~3.5%

Note: derived from ourworldindata.org (data of 2021 from BP Statistical Review of World Energy)

National Context: NPPs in Switzerland

NPP	Type	Shut down	50 yrs	60 yrs	Net Elect. Power
Beznau I	PWR	(?)	2019	2029 (?)	365 [MWe]
Beznau II	PWR		2021	2031	365 [MWe]
Mühleberg	BWR	2019	-	-	373 [MWe]
Gösgen	PWR		2029	2039	1010 [MWe]
Leibstadt	BWR		2034	2044	1220 [MWe]

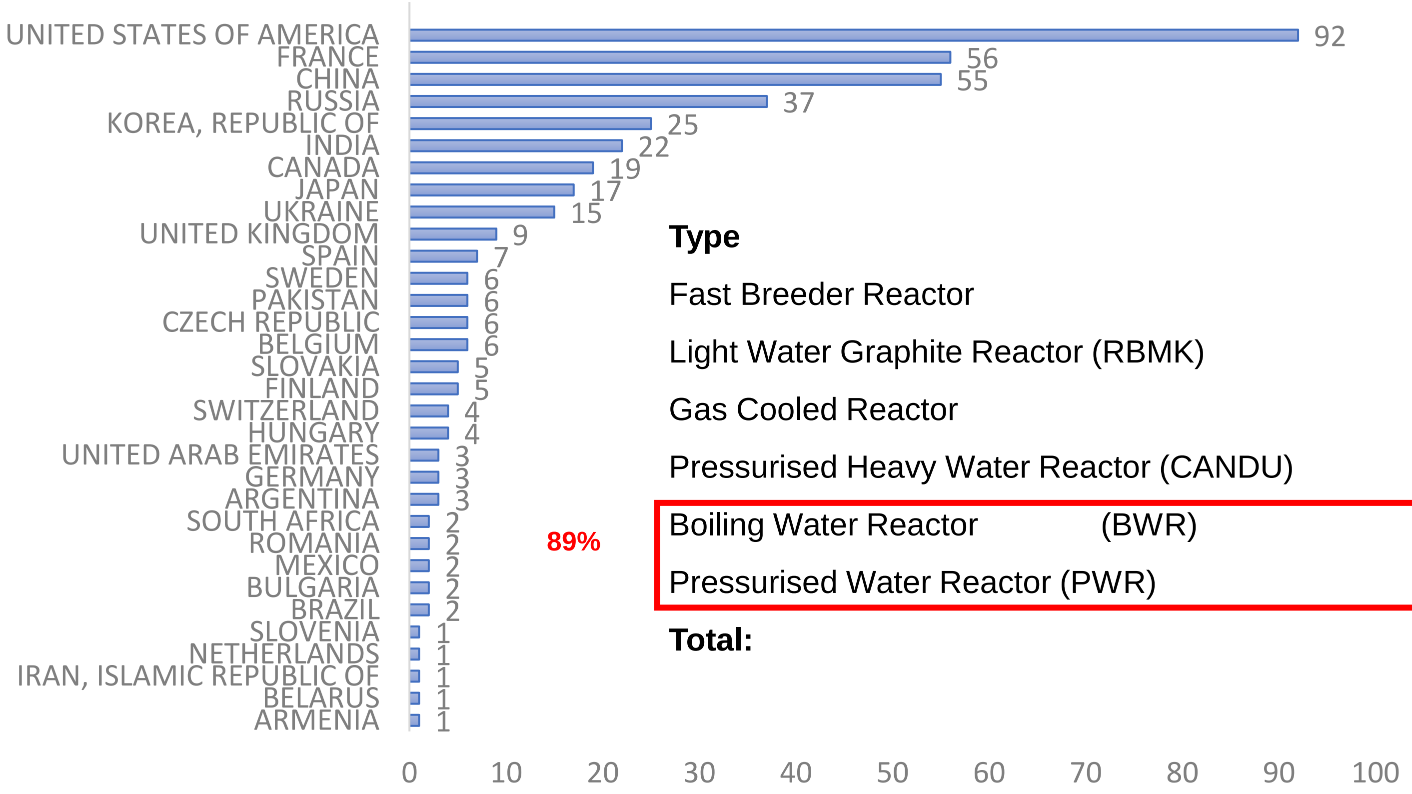
General energy context today

- Continuous growth in energy demand worldwide due to rising living standards (though population growth may eventually stabilize and decrease).
- Continued reliance on fossil fuels poses significant risks, including climate change, air pollution, and the depletion of resources.

- "Renewables" energies are crucial, but have not yet reached the capacity to fully meet medium-term energy needs…
- …***thus, nuclear is increasingly recognized as part of the solution***
  - Fusion considered a long-term solution; timeline and feasibility still under research.
  - Fission has potential for increased use, ***but advancements are needed to address safety concerns, waste management, and regulatory issues.***

- Economic viability, environmental impact, and socio-political factors play critical roles in shaping energy policy and technology adoption.

Nuclear reactors in operation worldwide (data from IAEA)



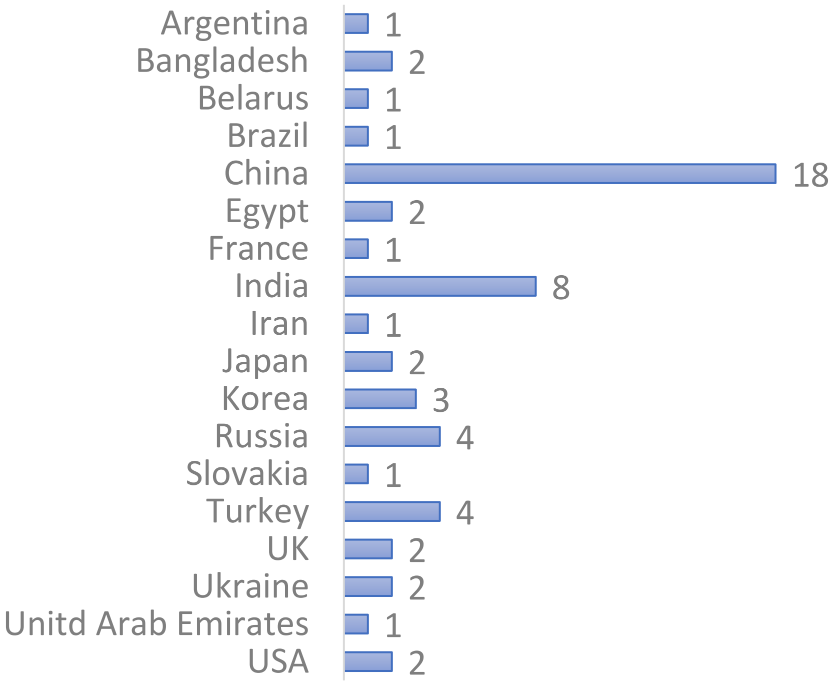
89%

Type	#Units	MWe
Fast Breeder Reactor	3	1 400
Light Water Graphite Reactor (RBMK)	11	7 433
Gas Cooled Reactor	9	4 885
Pressurised Heavy Water Reactor (CANDU)	47	24 314
Boiling Water Reactor (BWR)	49	49 565
Pressurised Water Reactor (PWR)	304	291 157
Total:	**423**	**378 754**

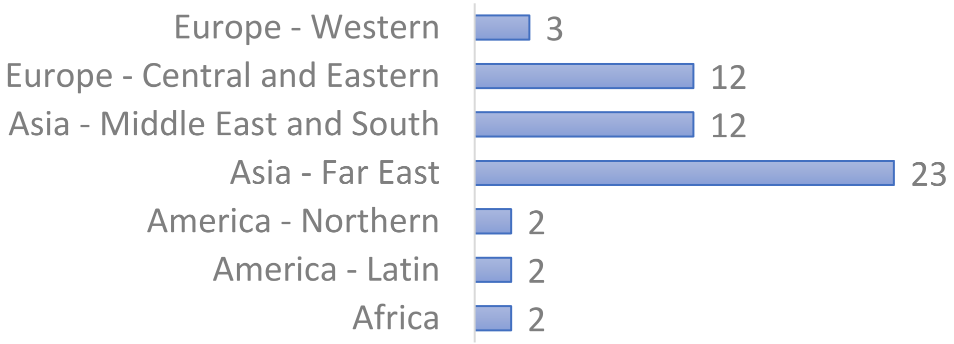
Note: around 120 commercial reactors have been shutdown, of which less than 15 have been fully dismantled

NPP worldwide under construction (updated 2023)

By country

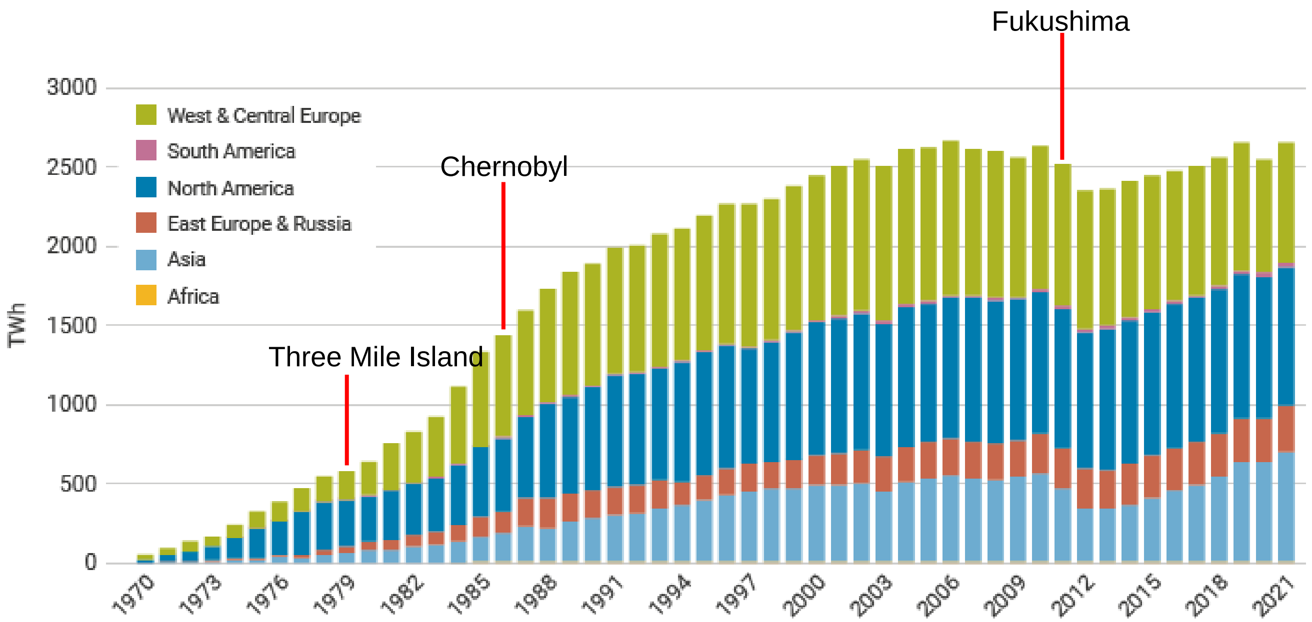


By region



Note: data from IAEA PRIS, updated 2023

Nuclear Power Plants Worldwide



Note: data from World Nuclear Association, IAEA PRIS

Historic Development of NPPs: The beginnings

1932

J. Chadwick discovers neutron

1938

1938: Otto Hahn, Lise Meitner and Fritz Strassmann discover nuclear fission.

1942

1942: Chicago Pile-1 is the first nuclear reactor (lead by E. Fermi)

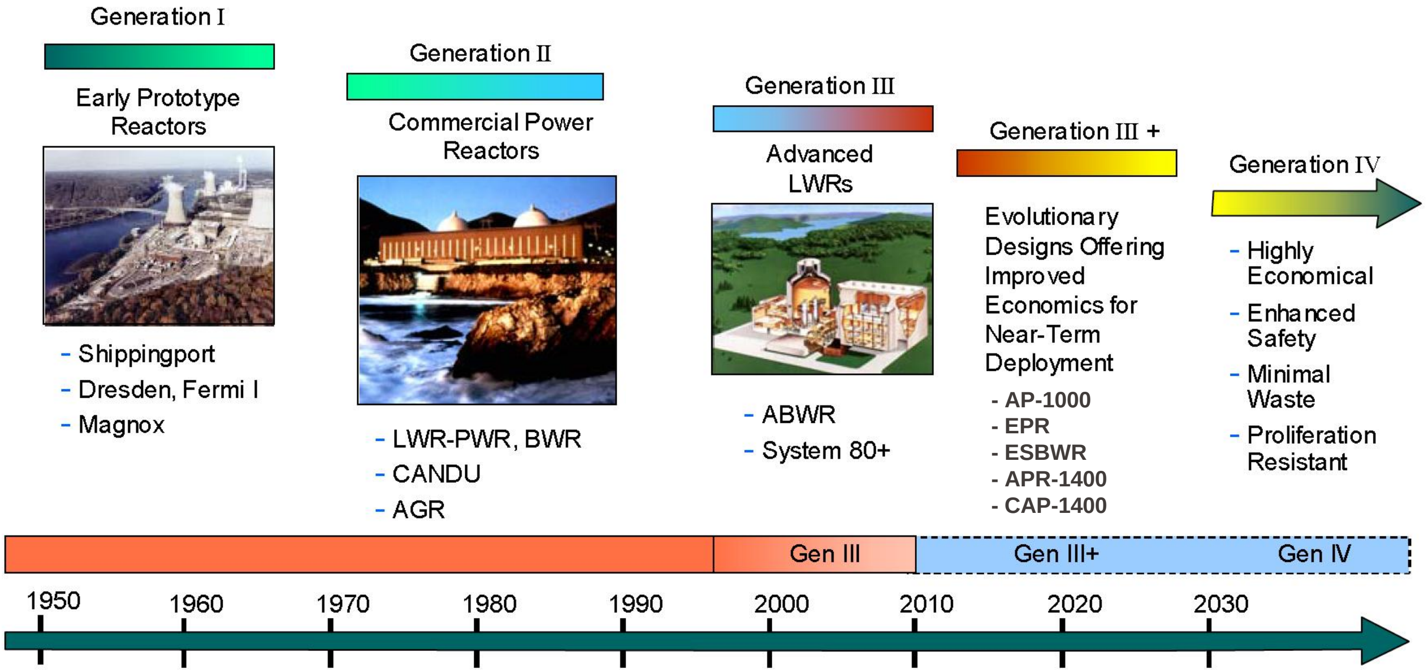
1951

1951: The Experimental Breeder Reactor I (EBR-I) is the world's first nuclear power reactor to generate electricity (developed by ANL and operated in Idaho, USA)

1956

1956: Calder Hall, gas-cooled Magnox at Sellafield (UK), 50 MW (later 200 MW) is the first commercial Nuclear Power Plant (NPP)

Historic Development of NPPs: Generation I-IV

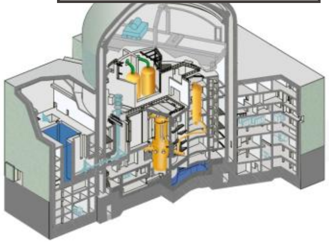


Safety features in modern reactors (Gen3 and Gen3+)

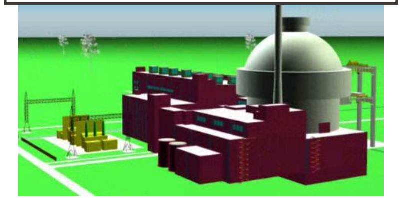
Gen3 and Gen3+ Plant Types

APR-1400 (Korea)

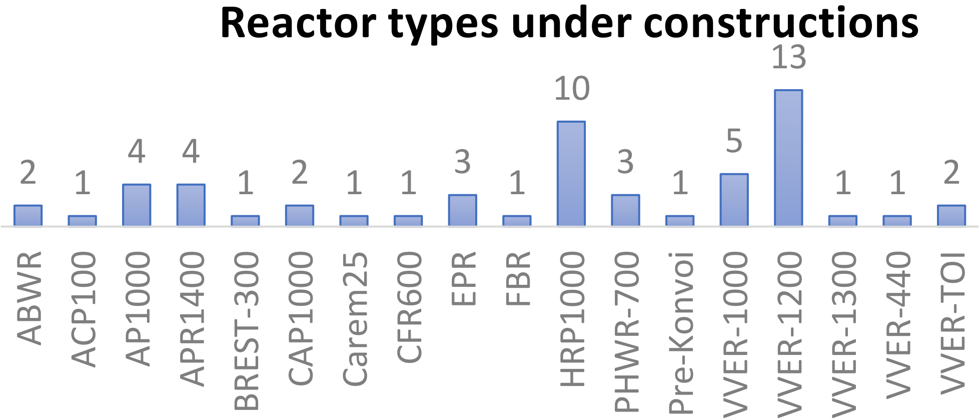
EPR (France)



WWER-1000/W-466B



AP-1000 (USA)



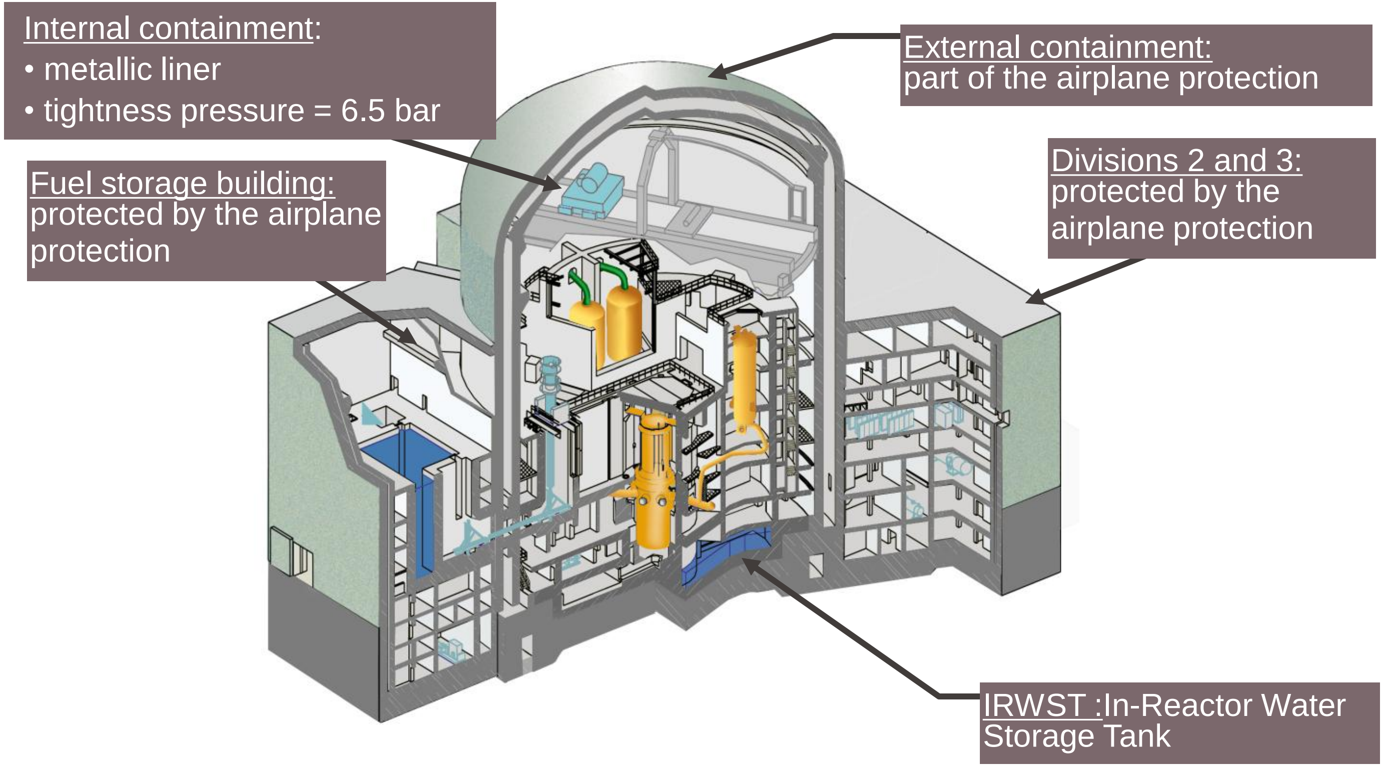
Note: data from IAEA PRIS, updated 2023

Two different approaches to improving safety

- **Evolutionary Approach (e.g. EPR)**: use operational feedback from existing power plants
  - Active Safety Systems with high Redundancy and Diversity
  - Long-term power supply even under most adverse conditions
  - Core melt scenarios are part of Design Basis Accidents

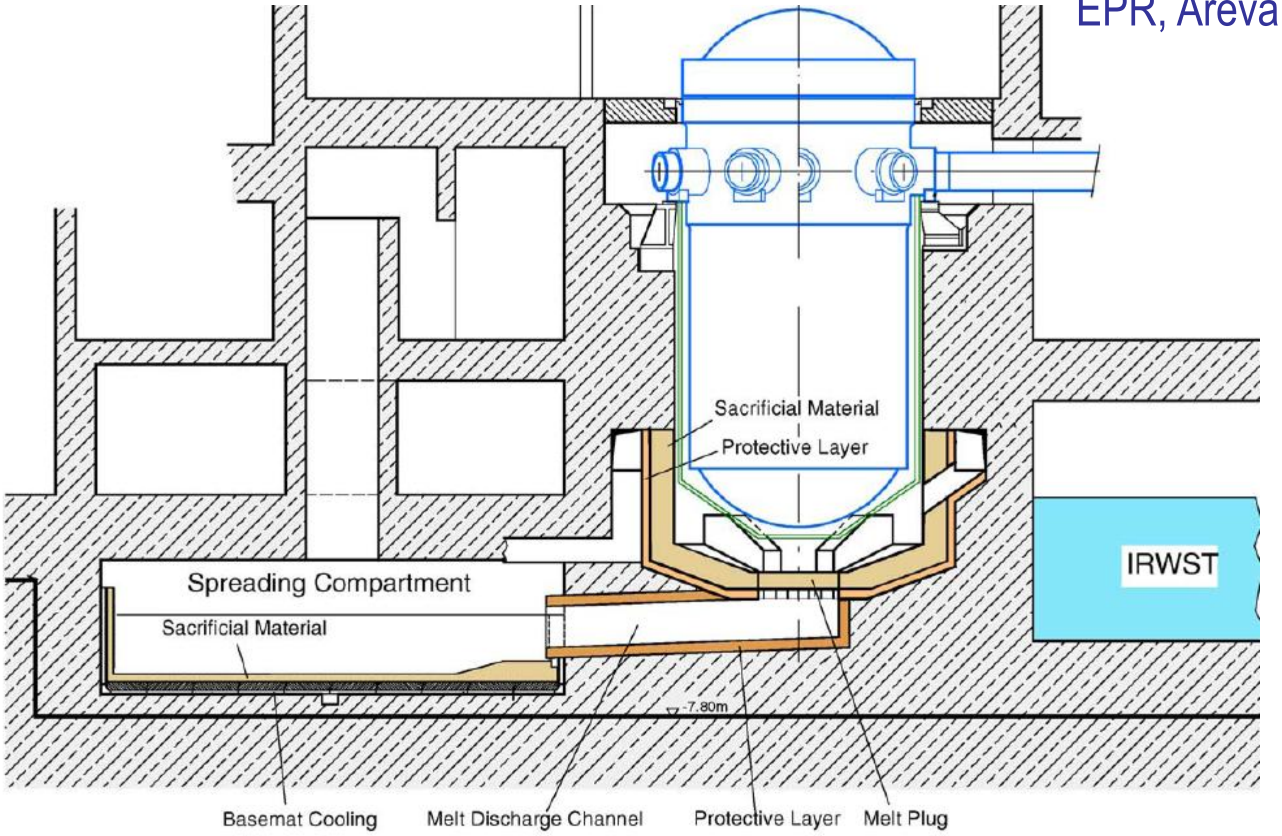
- **Passive Safety Systems (e.g. AP1000)**: reduced reliance on active components and power supplies
  - Deployment of passive systems driven by physical principles (gravitation and natural convection)
  - Passive systems extend time margins for initiating severe accident measures
  - Improved protection against internal and external hazards

EPR - Protection against Internal and External Hazards



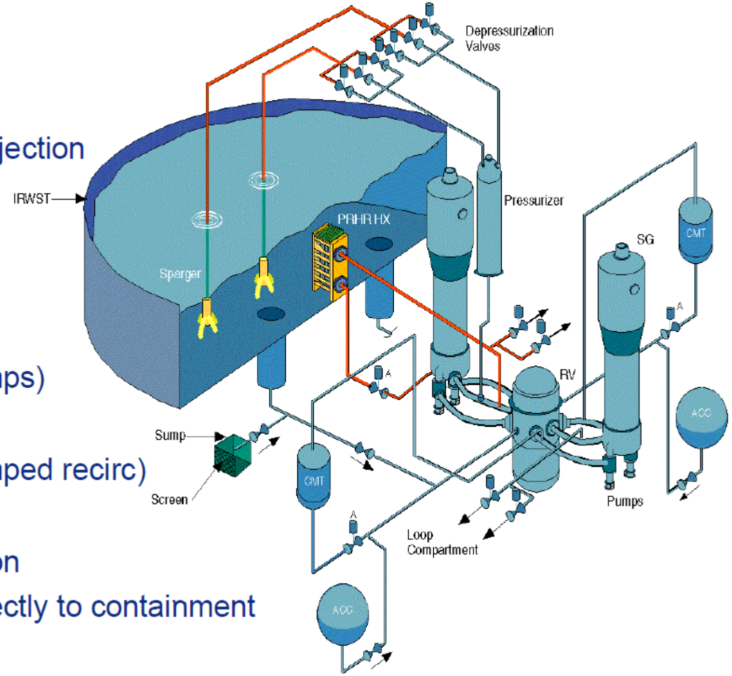
EPR - Core Catcher

EPR, Areva NP



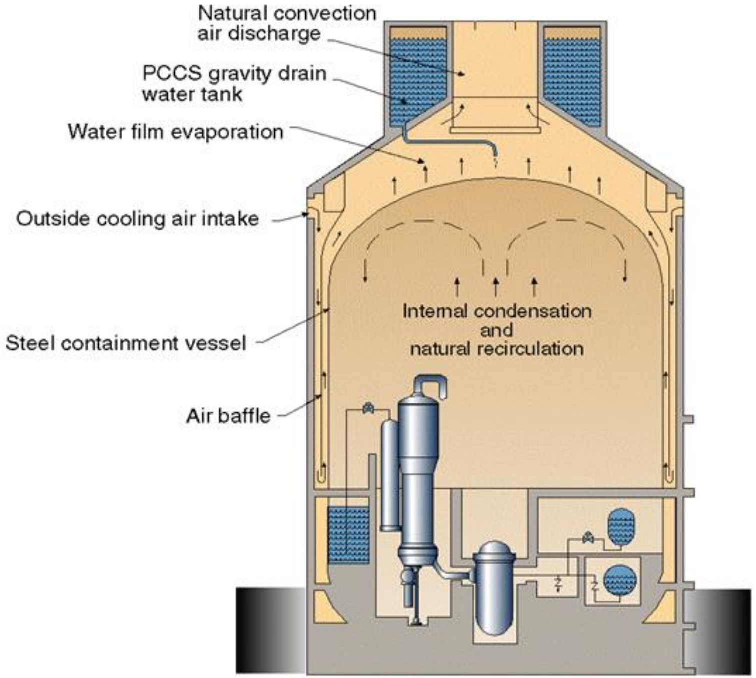
AP1000 Passive Core Cooling System

- **PRHR Heat Exchanger**
  - Natural circulation heat removal
- **Passive Safety Injection**
  - Core Makeup Tanks (CMT)
    - Full RCS pressure, natural circ. injection
    - Replace HHSI pumps
  - Accumulators
    - Similar to current plants
  - IRWST Injection
    - Low pressure (replaces LHSI pumps)
  - Containment Recirculation
    - Gravity recirculation replaces pumped recirc)
  - Automatic RCS Depressurization
    - Staged, controlled depressurization
    - Stages 1-3 to IRWST, stage 4 directly to containment



AP-1000: Passive Containment Cooling System (PCCS)

- Steel containment vessel acts as heat exchanger / is cooled by convective airflow
- PCCS limits heat and pressure rise below design criteria (150 °C, 4 bar)
- Air cooling can be supplemented by water evaporation (source: water tank on top)



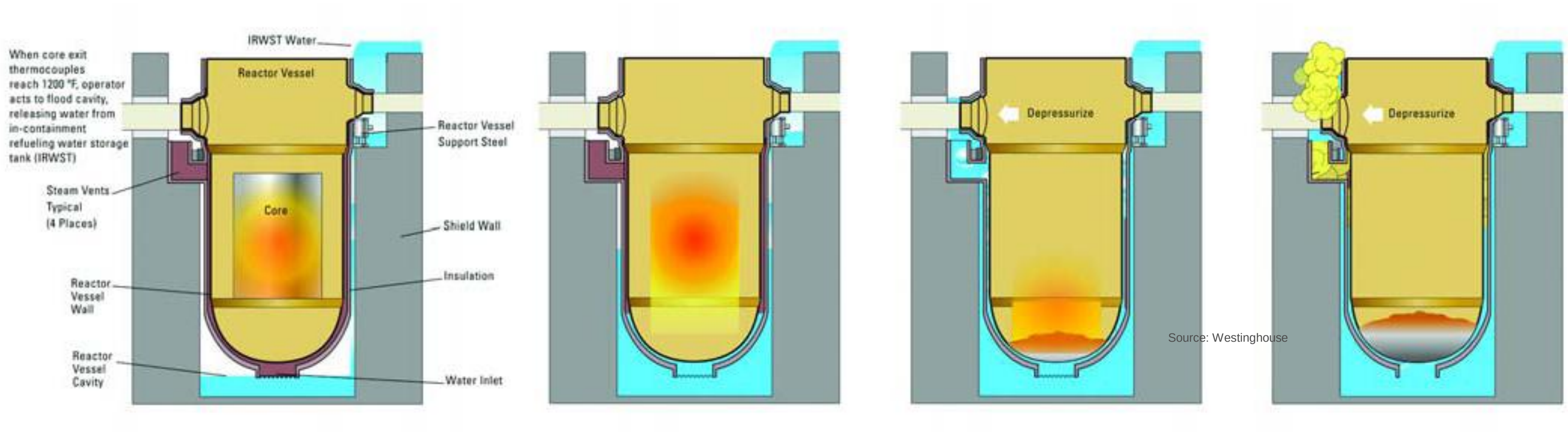
Source: Westinghouse

AP-1000: Severe Accident Measures

1) In-Vessel-Retention (IVR) of core melt by Ex-Vessel Cooling

- Core temperature > 650°C: the cavity is flooded with IRWST-water
- Convective flow of water/steam mixture between insulation and RPV

2) Passive autokatalytic Recombiners and Igniter to prevent hydrogen explosions

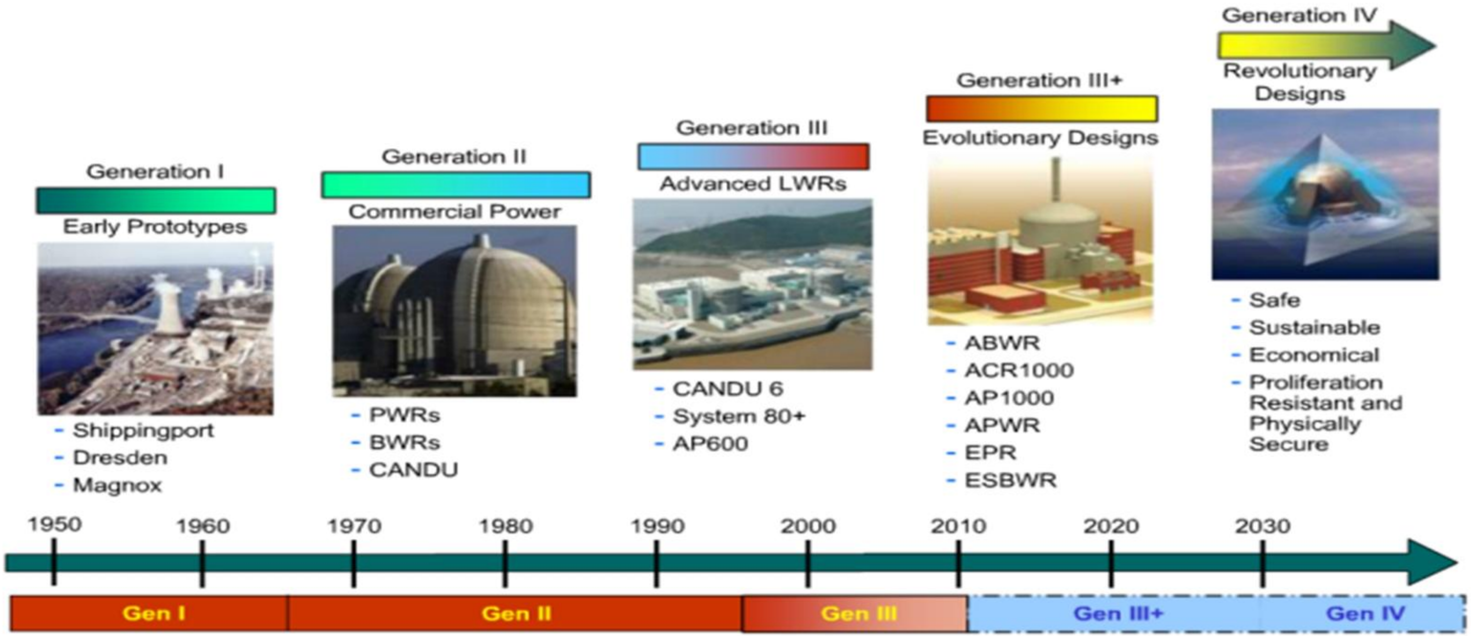


Source: Westinghouse

Generation IV Nuclear Reactors

Gen IV: noble idea & political signal for cooperation

- The reactor classification was primarily introduced around year 2000 to define the next generation of reactors.



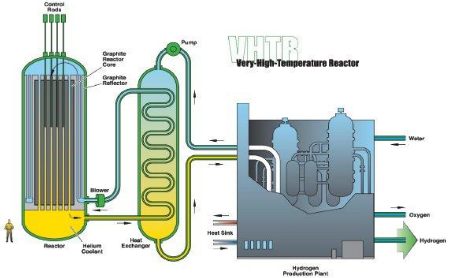
Generation IV – Foreseen features

The features of Gen IV reactors have been proposed and published in Gen IV technology roadmap:

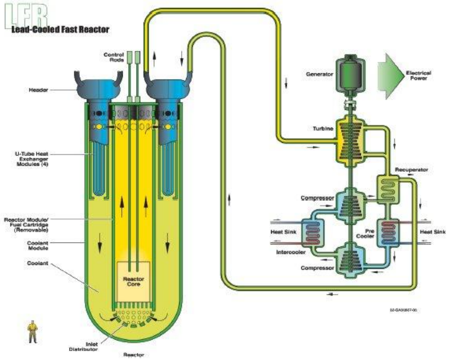
- **Sustainability**: effective resources utilization for long-term availability, reduction of nuclear waste
  - Large R&D effort needed for technologies of reprocessing, isotope separation, fabrication, etc.
- **Economics**: clear lifetime cost and financial risk comparable to other systems (fossil fuels)C
  - Capital costs, as also time of licensing/construction need to be reduced strongly
- **Safety and reliability**: very low core damage frequency and no need of offsite emergency response
  - Greater degree of public confidence needed (clear & transparent safety approach)
- **Proliferation resistance and physical safety**: More inherent “safeguards”, greater resistance or protection against terrorist attacks

Generation-IV Reactor Concepts

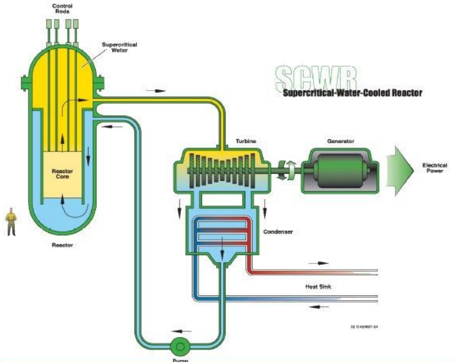
High Temperature Reactor

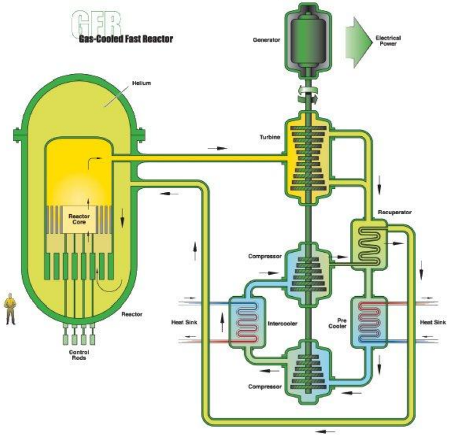


Lead-Cooled Fast Reactor

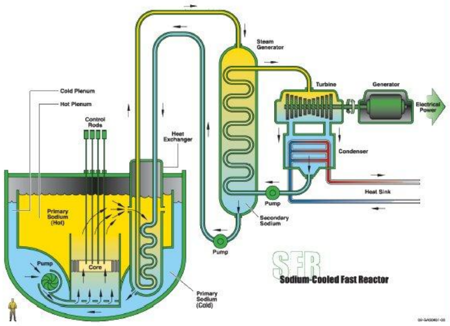


Supercritical LWR

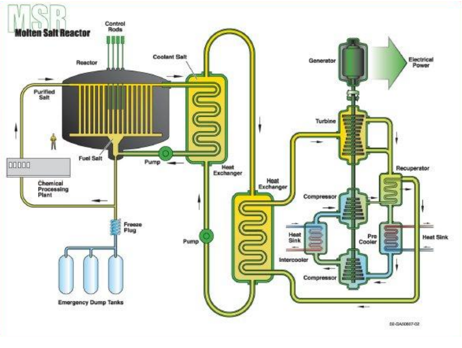




Gas-cooled Fast Reactor



Sodium Cooled Fast Reactor

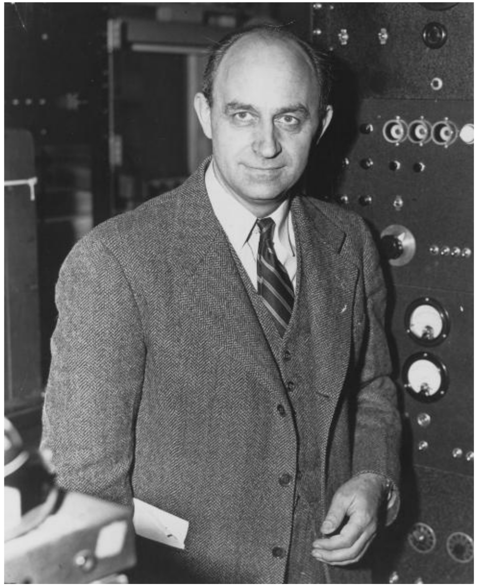


Molten Salt Reactor

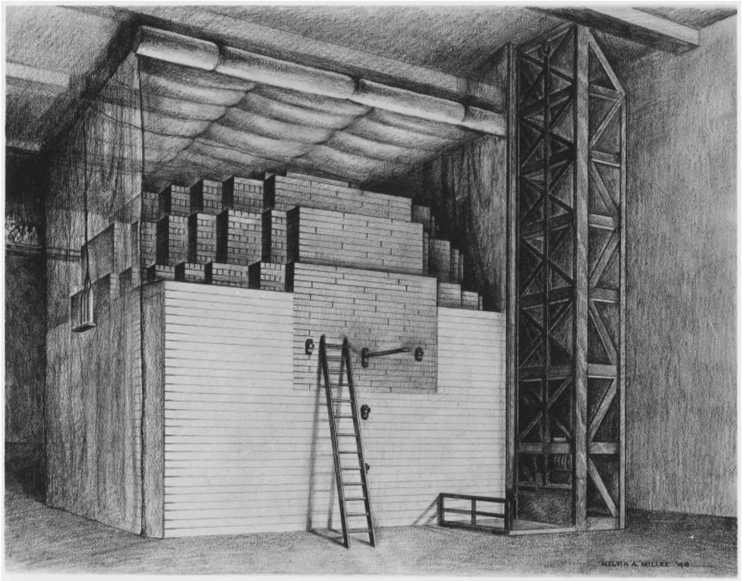
Fast Reactors: SFRs and LFRs

First chain reaction was obtained in a thermal reactor

- December 2, 1942: at the University of Chicago, a team of physicists led by Enrico Fermi initiated the first self-sustaining chain reaction in the first man-made nuclear reactor called "Chicago Pile-1".



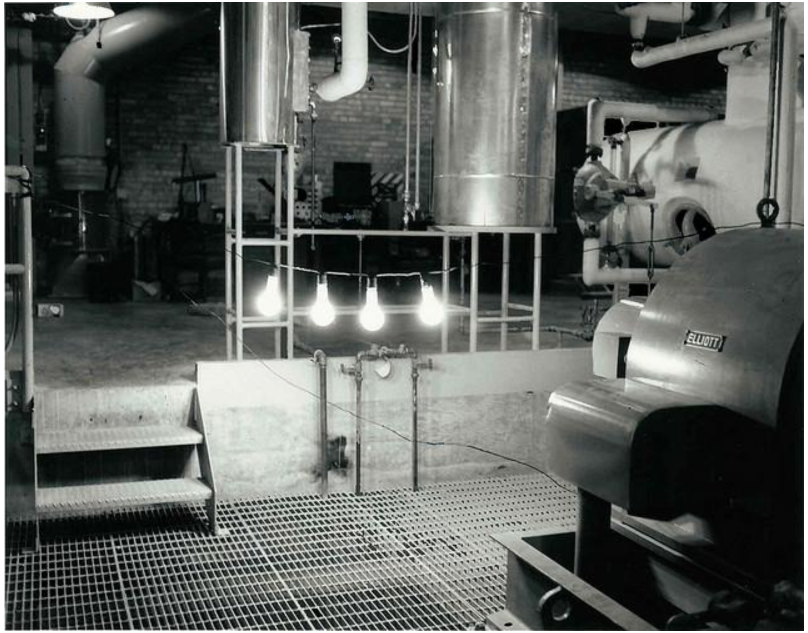
E. Fermi (1901-1954)



Sketch of Pile-1. Courtesy of ANL.

First "nuclear" electricity obtained in a fast reactor

- 1949: The EBR-I – Experimental Breeder Reactor I – was designed at Argonne National Laboratory. In 1951 the world's first electricity was generated from nuclear fission in the fast-spectrum breeder reactor with **plutonium fuel cooled by a liquid sodium**.



First "nuclear" electricity : four 200-watt light bulbs. Courtesy of ANL.

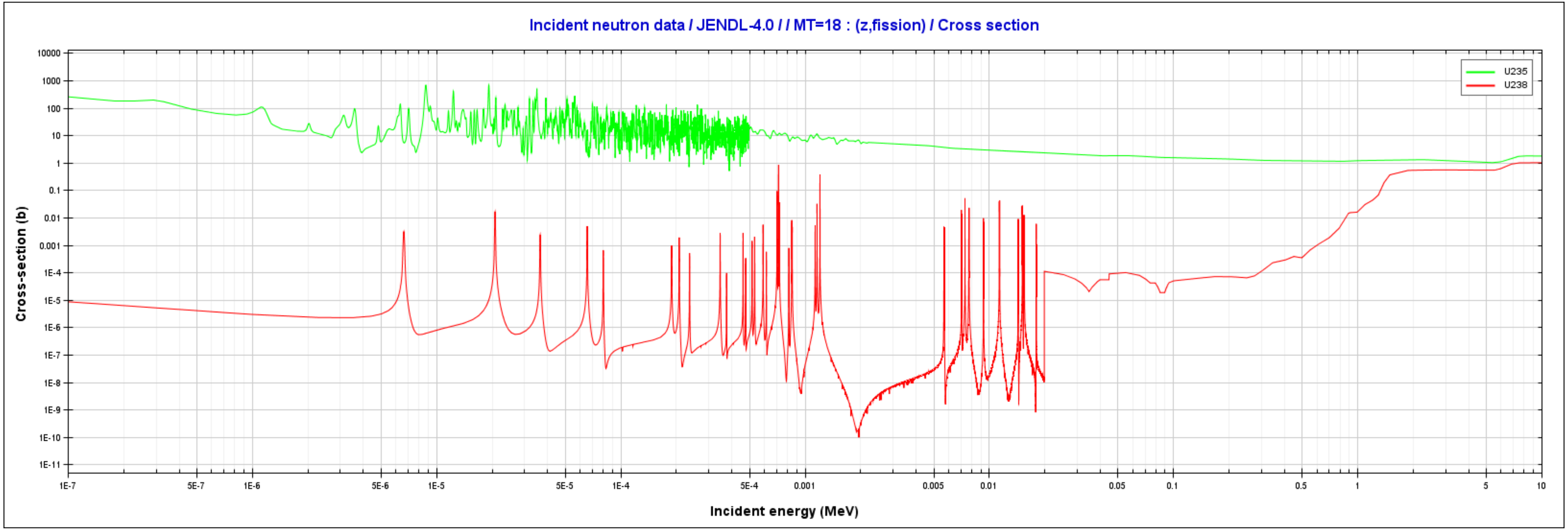
Why fast reactor?

- Natural uranium contains only 0.7% of fissile isotope U^{235}. The rest 99.3% is non-fissile U^{238}.

- The resources of U^{238} are estimated as 35 million tones. Only the U^{238} mass from the depleted uranium stocks in the world was estimated to be more than 1 million tons.

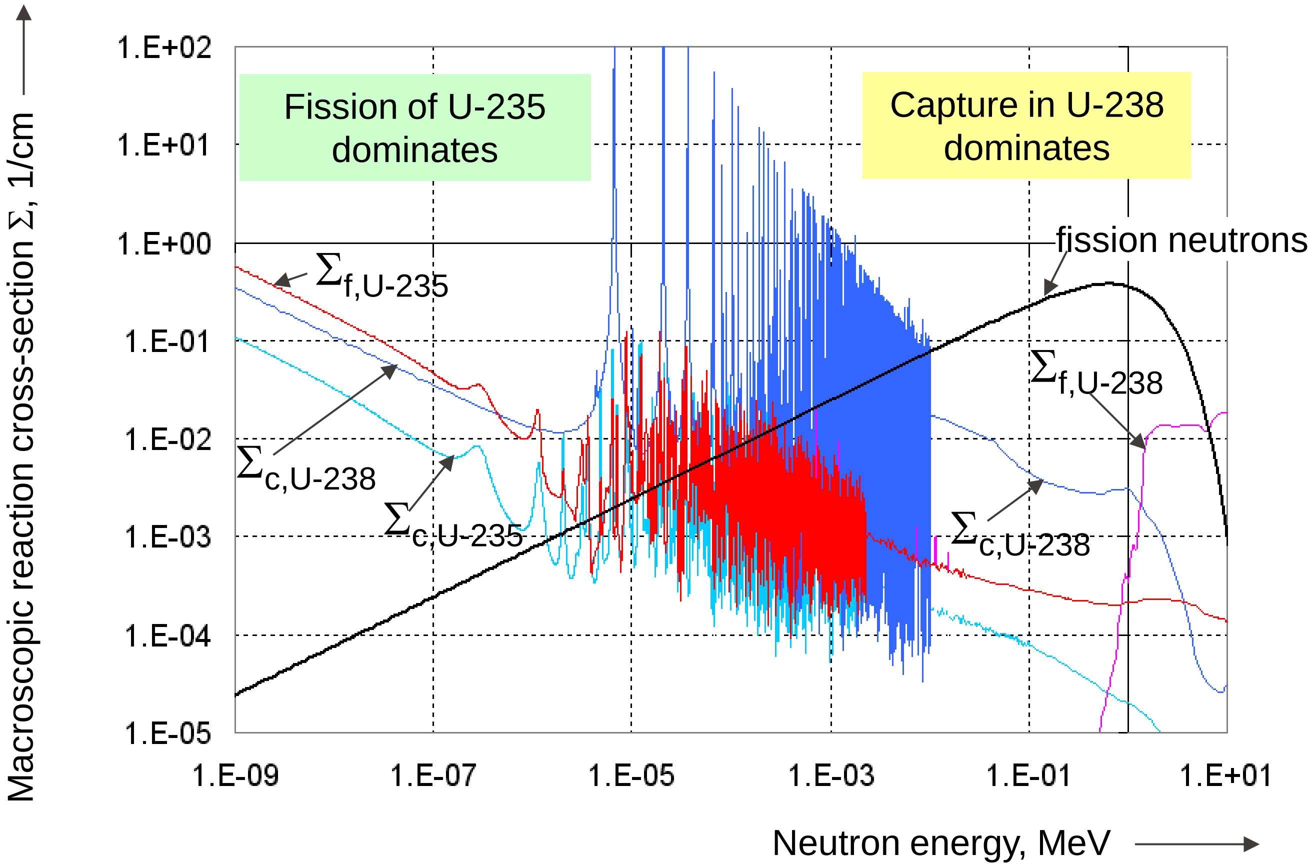
- We will obtain an almost infinite, sustainable energy source for millennia, if we find the way how to “burn” this large amount of non-fissile U^{238}.

Why fast reactor?



Fast reactor, how?

Macroscopic reaction cross sections in natural uranium (U235 at 0.72 w%)



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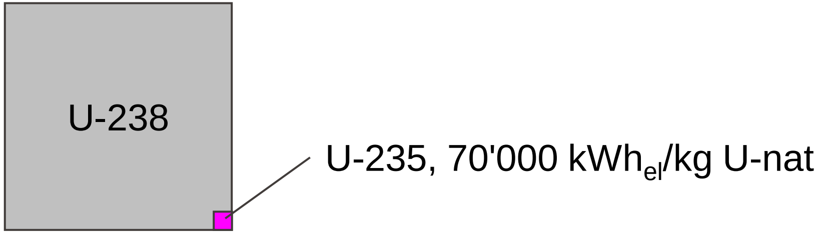
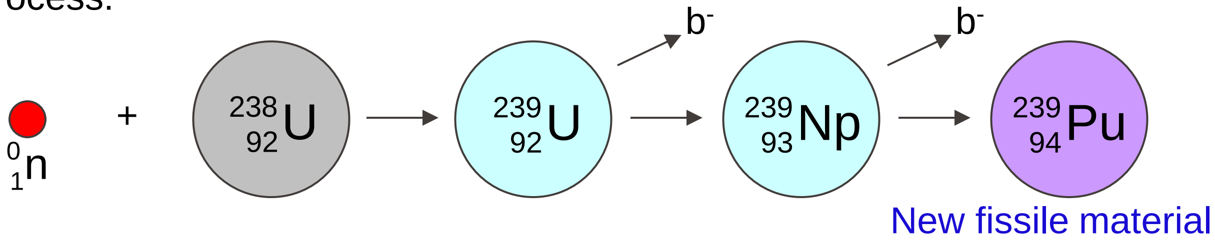
- We will obtain an almost infinite, sustainable energy source for millennia, if we find the way how to “burn” this large amount of non-fissile U^{238}.
- **A fast-spectrum nuclear reactor is a device that can make it possible via conversion of U^{238} to fissile Pu^{239}**
- Also, in fast spectrum one can burn fissile higher actinides, decreasing the decay time of nuclear waste

Breeding

Natural uranium:



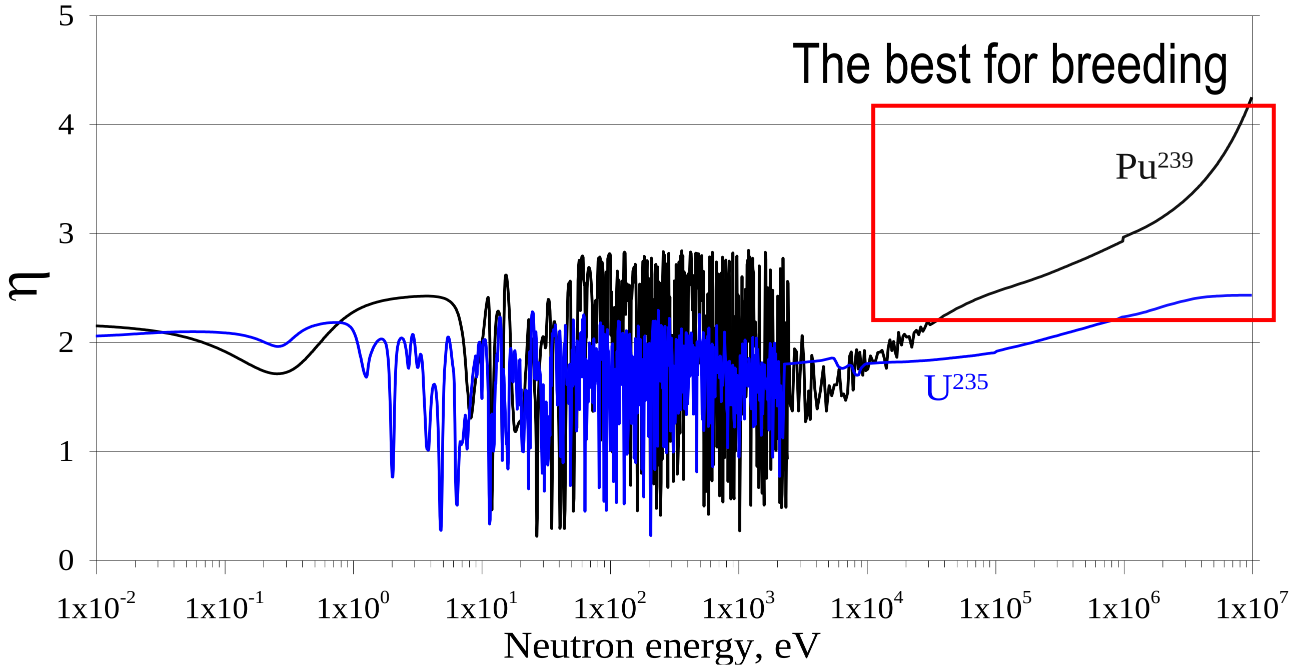
Conversion process:



More fission neutrons are needed beyond those required for sustaining chain reactions!

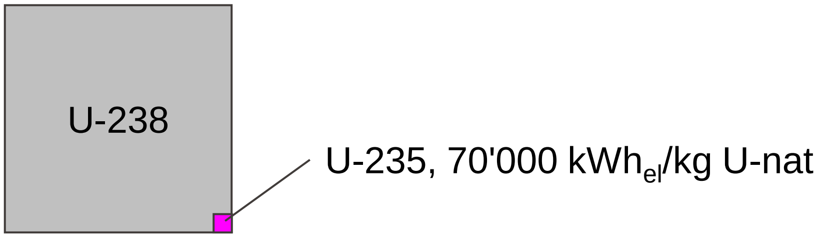
Breeding: Pu-239 in fast neutron spectrum

- Average number of fission neutrons emitted per neutron absorbed as a function of absorbed neutron's energy for U-235 and Pu-239 fissile isotopes

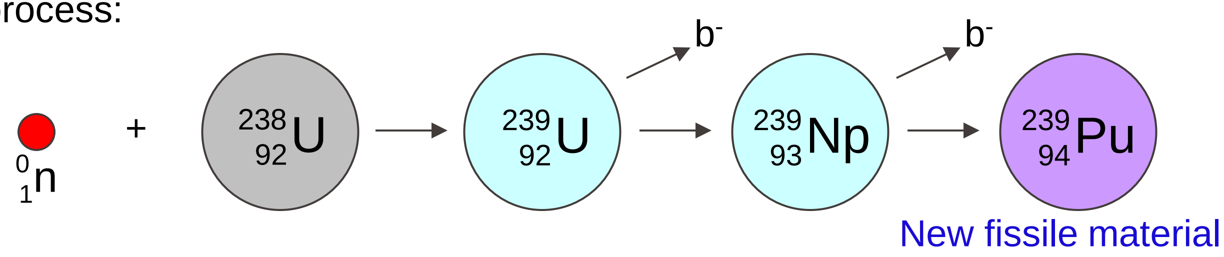


Breeding

Natural uranium:



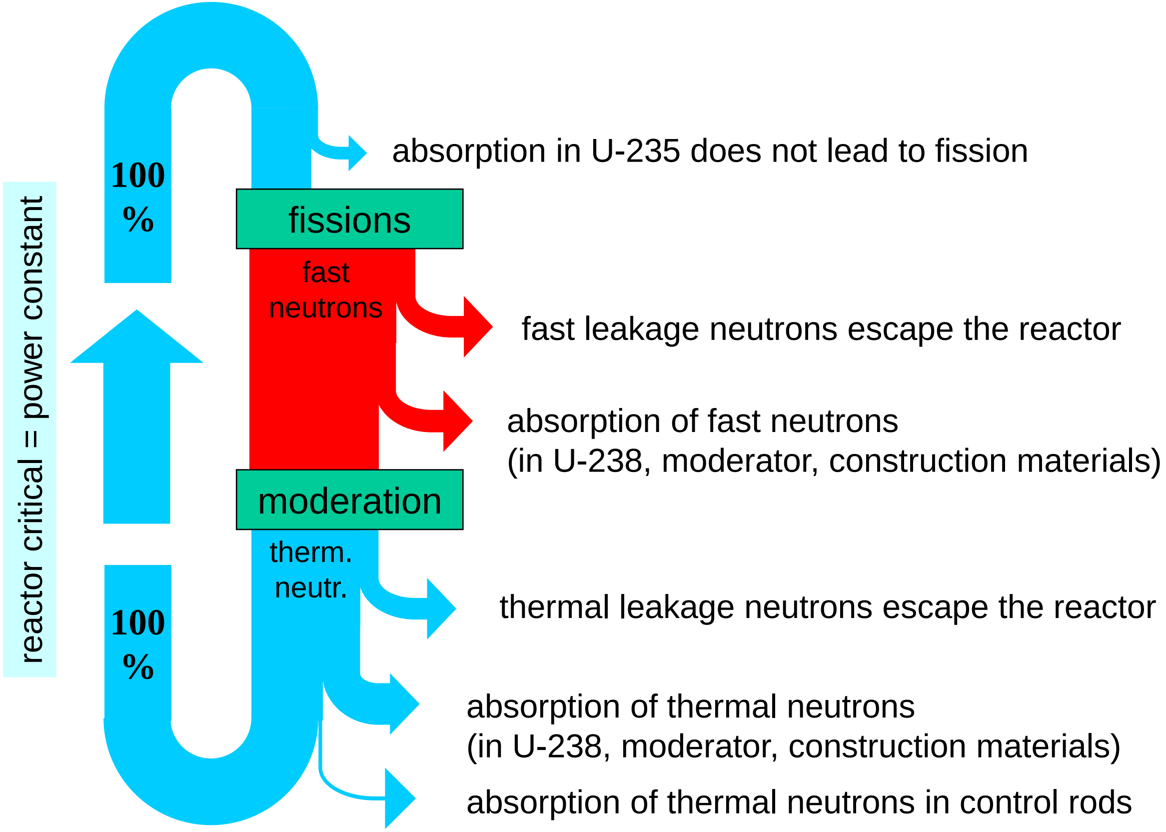
Conversion process:



More fission neutrons are needed beyond those required for sustaining chain reactions!

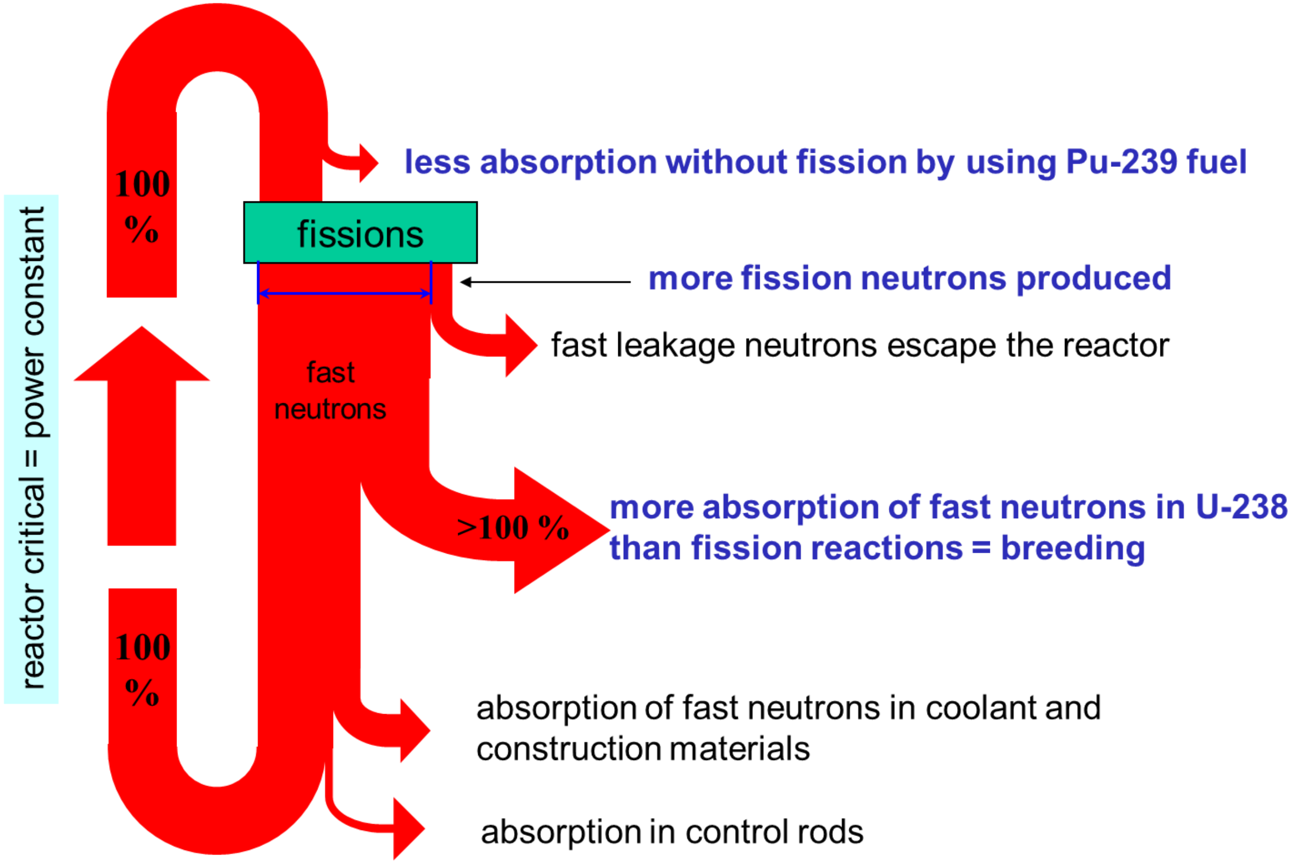
- Use Pu-239 as fissile material → more new neutrons per fission

Chain reaction in thermal reactor



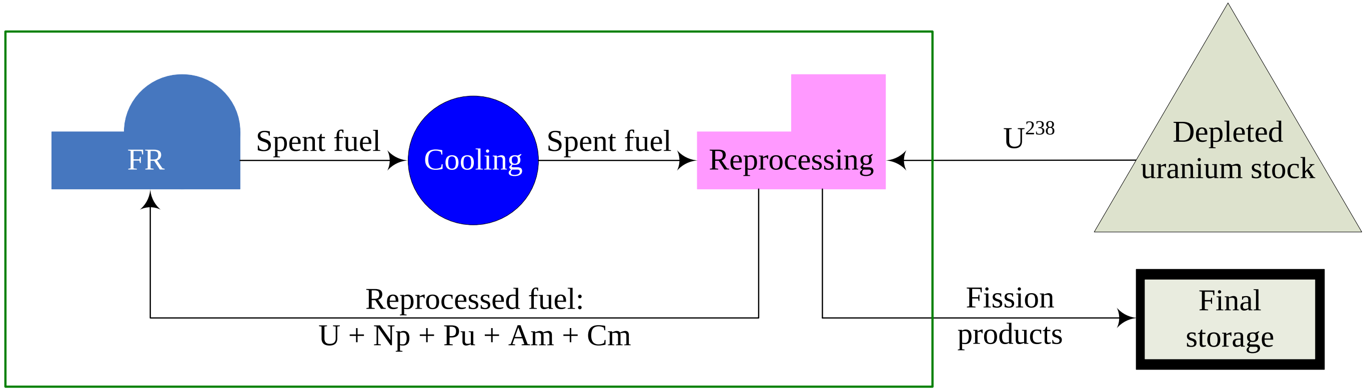
⇒ Side product: conversion of U-238 into Pu-239 by neutron capture

Chain reaction in fast reactor



Sustainability: Iso-breeder in a closed fuel cycle

- All GIF fast-spectrum systems can operate in an equilibrium closed fuel cycle with BR=1 (amount of fissile produced = amount of fissile consumed)
  - Input: Uranium-238
  - Output: Fission products + Losses



Assuming efficient reprocessing and final disposal technologies, fast-spectrum nuclear reactors are a sustainable energy source

Main issues of fast reactors

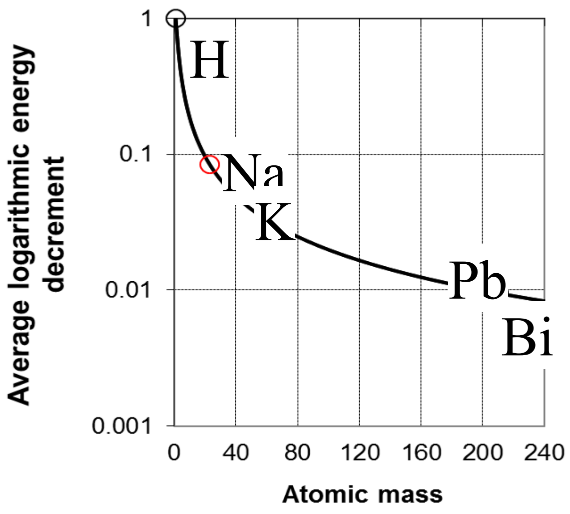
- **Positive void feedback** is a consequence of the low moderation
  - coolant does not contribute to maintaining chain reaction and mainly acts as neutron absorber
  - loss of coolant = less absorption → positive feedback of voiding

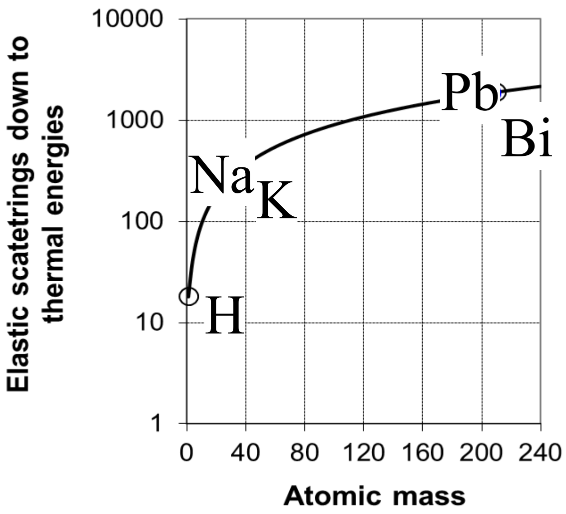
Other particular issues:

- Low share of delayed neutrons because of the use of plutonium fuel (β = 0.212 %)
  - Prompt super-criticality is reached at smaller positive reactivity perturbation ($\rho > \beta$)
- Less moderation → less resonance absorption → small fuel temperature feedback
- Material compatibility/corrosion/erosion issues → more development needed
- Reprocessing is a complex and “dirty” process (radiotoxicity)

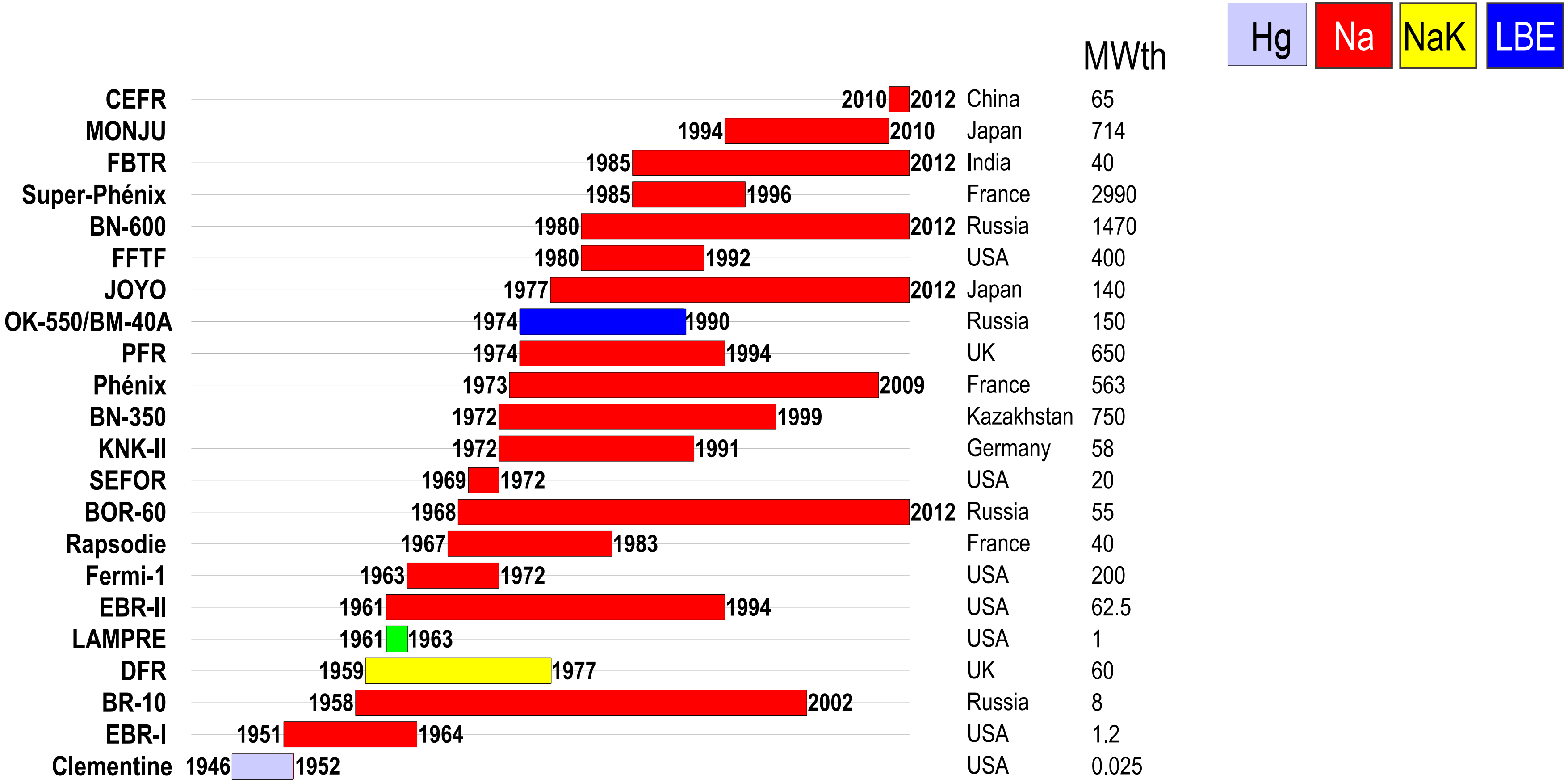
Which coolants for fast reactors?

- Need elements with higher atomic weights because they have low energy loss per scattering event
- Helium has been considered in the past (low density, low scattering XS) but not currently.
- Main options are liquid (molten) metals: sodium, potassium, lead, bismuth





Fast reactors: 1946 – 2012



Fast reactors: October 2017

Current FNRs

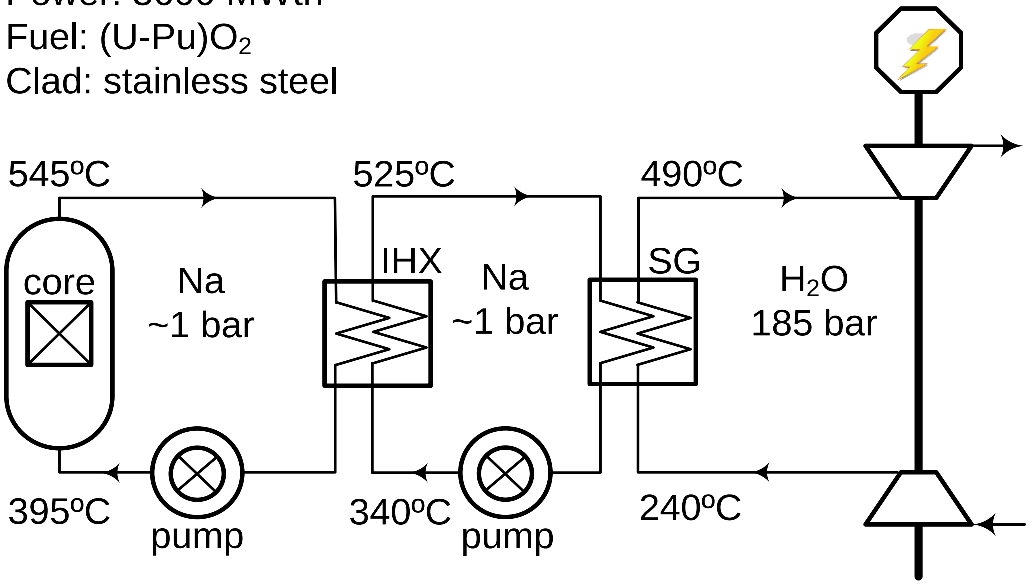
Reactor	Type, coolant	Power thermal/elec	Fuel (future)	Country	Notes
BOR-60	Experimental, loop, sodium	55/10	oxide	Russia	1969-2020
BN-600	Demonstration, pool, sodium	1470/600	oxide	Russia	1980-
BN-800	Experimental, pool, sodium	2100/864	oxide	Russia	2014-
FBTR	Experimental, pool, sodium	40/-	oxide & carbide (metal)	India	1985-2030
PFBR	Demonstration, pool, sodium	1250/500	oxide (metal)	India	(2018?)
CEFR	Experimental, pool, sodium	65/20	oxide	China	2010-
Joyo	Experimental, loop, sodium	140/-	oxide	Japan	1978-2007, maybe restart 2021
Monju	Prototype, loop, sodium	714/280	oxide	Japan	1994-96, 2010, shutdown

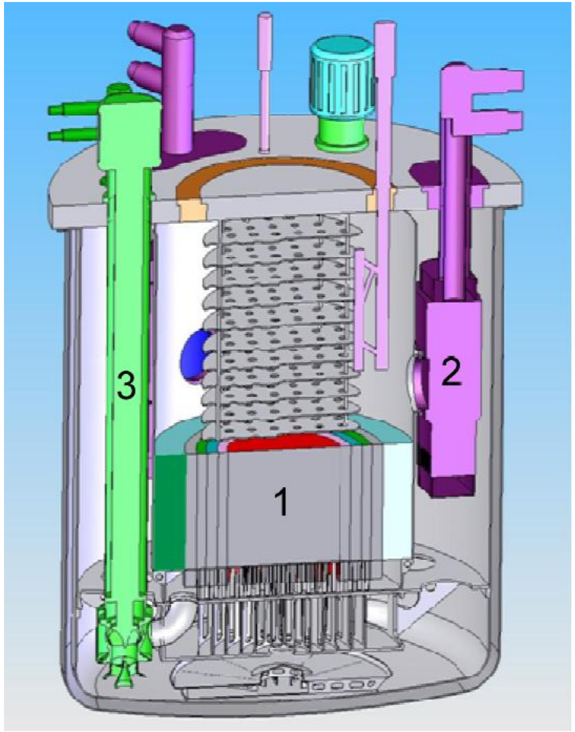
FNR designs for near- to mid-term deployment – active development

Reactor	Type, coolant	Power thermal/elec	Fuel (future)	Country	Notes
PRISM	Demonstration, pool, sodium	840/311	metal	USA	From 2020s
ARC-100	Prototype, pool, sodium	260/100	metal	USA	Working with GEH
Astrid	Demonstration, pool, sodium	1500/600	oxide	France, with Japan	About 2030
Allegro	Experimental, loop?, gas	50-100 MWt	oxide	France	About 2025
MYRRHA	Experimental, Pb-Bi	57/-	oxide?	Belgium, with China	Early 2020s
ALFRED	Prototype, lead	300/120	oxide	Romania, with Italy & EU	From 2025
BN-1200	Commercial, pool, sodium	2800/1220	oxide, nitride	Russia	From mid-2020s
BREST-300	Demonstration, loop, lead	700/300	nitride	Russia	From 2020
SVBR-100	Demonstration, pool, Pb-Bi	280/100	oxide (variety)	Russia	From 2019
MBIR	Experimental, loop, sodium (Pb-Bi, gas)	100-150 MWt	oxide	Russia	From 2020
CDFR-1000	Demonstration, pool, sodium	/1000	oxide	China	From 2023
CDFBR-1200	Commercial, pool, sodium	/1200	metal	China	From 2028
PGSFR	Prototype, pool, sodium	/150	metal	South Korea	From 2028
JSFR	Demonstration, loop, sodium	/500	oxide	Japan	From 2025?
TWR	Prototype, sodium	/600	metal	China, with USA	From 2023?

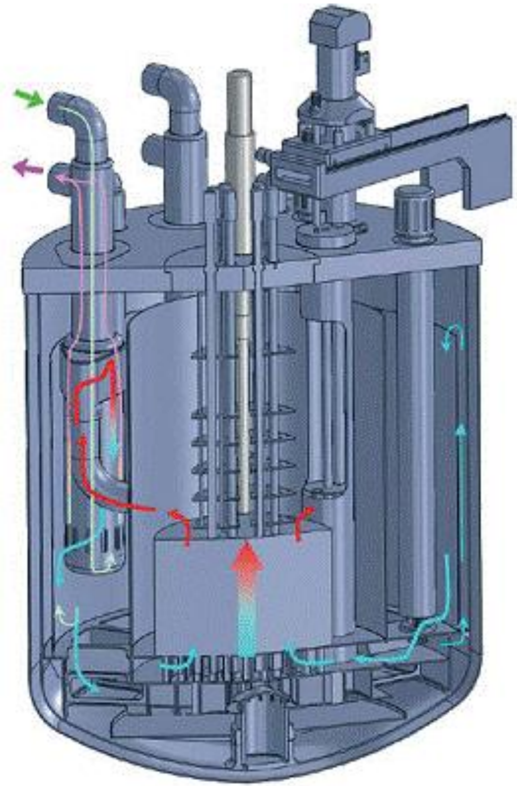
Sodium-cooled fast reactor (SFR)

Power: 3600 MWth
Fuel: $(U\text{-}Pu)O_2$
Clad: stainless steel





Sodium-cooled fast reactor (SFR): Advantages



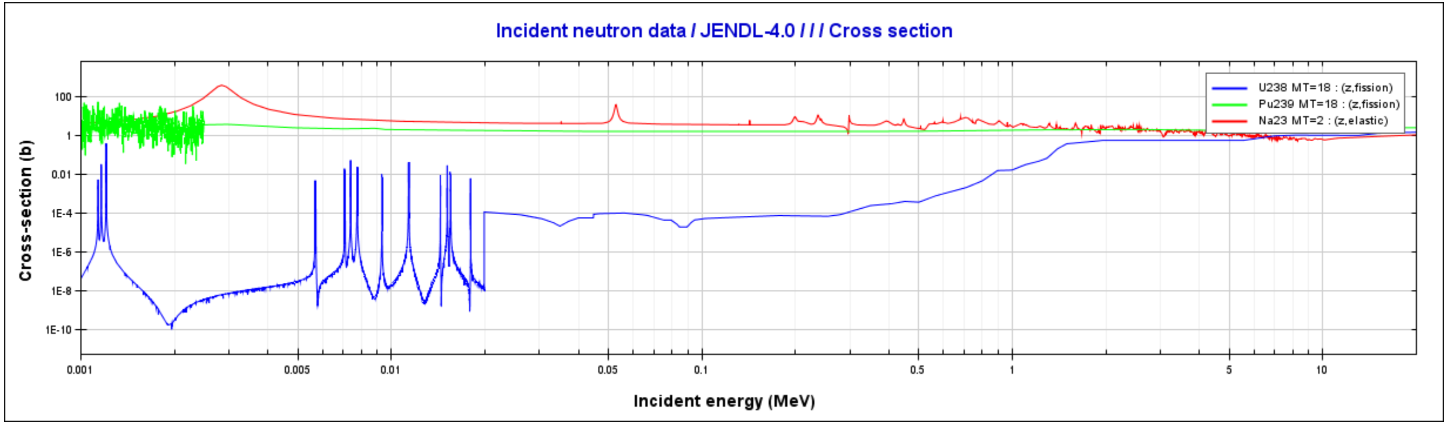
- Sodium excellent thermal conductivity and high heat capacity allow for very efficient cooling and high natural circulation within the core.
- The large margin to boiling means that no pressurization is required.
- 300+ reactor-years of operational experience with SFR.

- Safety design features help prevent Loss of Coolant Accident
  - Vessel non pressurized, no piping below core level
  - Main vessel surrounded by safety vessel
    - Gap sufficiently large to permit periodic robotic inspection
    - Gap sufficiently narrow to keep the sodium level near to nominal in case of RPV breach
  - Space between main and safety vessel and above sodium level filled with inert gas

RPV inspection robot (Superphenix)

Specific SFR disadvantages

- Sodium is chemically active when contacting water or air...
  - Special measures like an intermediate circuit are required to exclude the contact of the primary sodium with water.
  - A specific sodium-fire protection system should be included in the plant design.
- Sodium has a non-neglibile scattering cross section...
  - Sodium removal from the core results in a shift of a neutron spectrum that increases core reactivity and power (positive reactivity void effect).
  - An accident in which sodium boiling occurs can result in a quick power excursion.



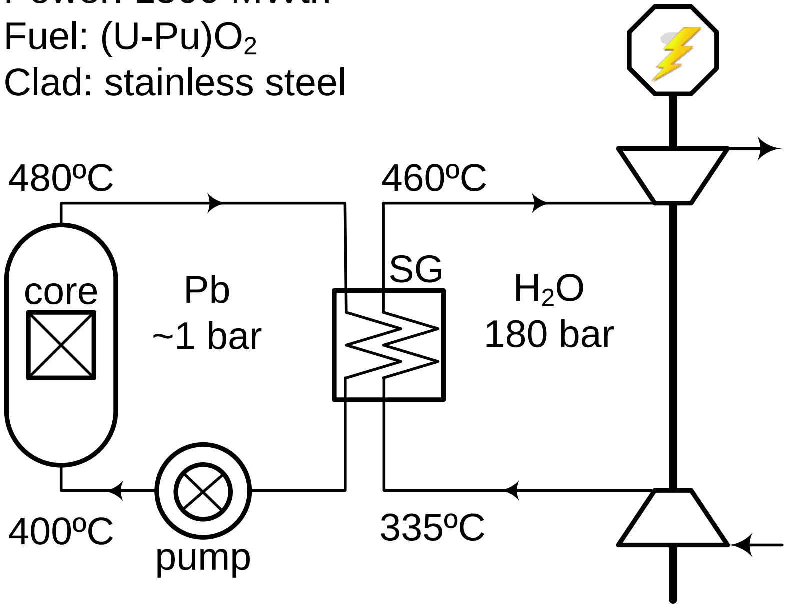
TerraPower Natrium^{TM} reactor

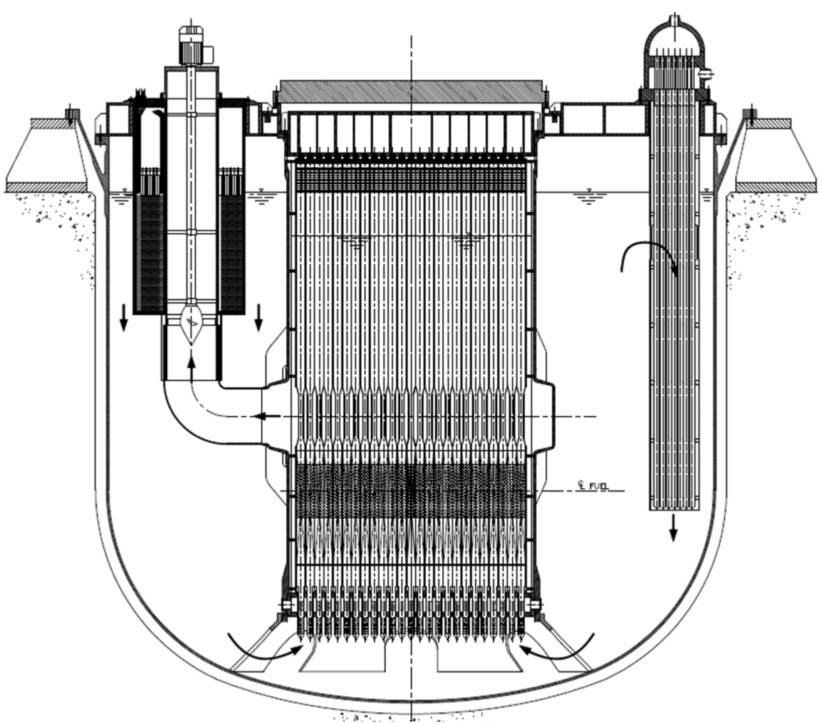
- 345MWe SFRr with gigawatt-hour-scale molten-salt based thermal storage:
  - It can boost the system's output to 500MWe of power for more than 5 hr when needed.
- Application to NRC for building a demonstration plant

https://www.terrapower.com/resources/

Lead-cooled fast reactor (LFR)

Power: 1500 MWth
Fuel: (U-Pu)O_2
Clad: stainless steel





Lead Fast Reactor (LFR): Advantages

- Lead is very heavy thus thermal inertia of the system is very high.
  - All transients are smooth and slow.

- Lead has a high thermal conductivity and expansion coefficients
  - The core can be efficiently cooled at low velocities.
  - Natural circulation level is high.

- Lead is passive with air and water

- Lead boils at a very high temperature (1740º C)...
  - Lead boiling has low-probability. No pressurization is required.

Specific LFR Disadvantages

- Lead is very heavy
  - Erosion of structural materials in lead flow is significant.
  - Seismic stability of reactor becomes an important safety issue.

- Lead can dissolve components of stainless steel
  - At high T structural materials (such as iron or nickel) are slowly dissolving in lead flow.

- Lead has a positive void reactivity effect
  - Partial removal of lead from the core (e.g. due to gas injection) can lead to power excursion.

- Lead freezes at a high temperature (327º C).
  - Lead freezing is a safety issue.
  - Lead/Bismuth Eutectic (LBE) can be used to reduce the melting point (123º C)

Notes on Lead Bismuth Systems

- Drawback of PbBi (LBE) systems over pure Lead
- Production of highly radiotoxic Po-210 (T1/2 = 138 d)

protons + Bi generate Po isotopes up to Po-209

Po-209 + n $\rightarrow$ Po-210

Bi-209 + n $\rightarrow$ Bi-210

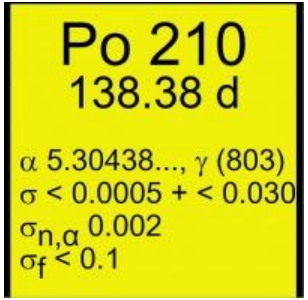
Bi-210 $\rightarrow$ Po-210 + β^-

(in ADS: all four lines above)

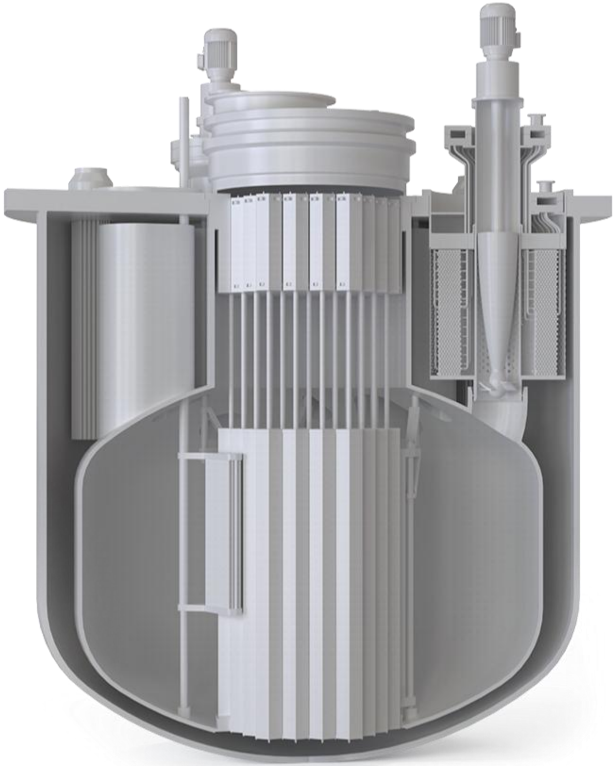
(in all fast LBE systems: the last two lines)

$\rightarrow$ pure Pb systems are interesting

Technology challenge: higher melting point



Developments in LFRs



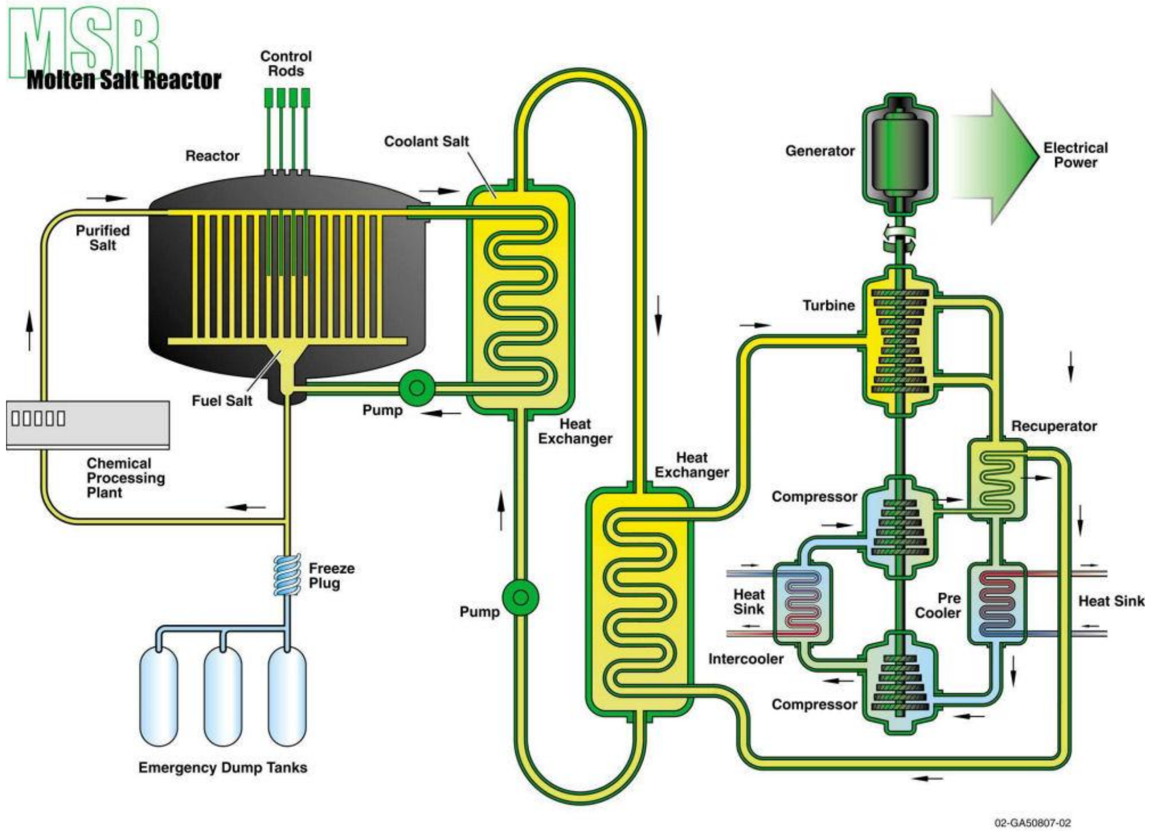
https://www.newcleo.com

- BREST is a Russian LFR:
  - Two designs, BREST-300 (300 MWe) and the BREST-1200 (1200 MWe).
  - Construction started in 2021 for BREST-300
- TRANSMUTEX – company in Switzerland – is developing a lead-cooled system that should generate energy by transmuting nuclear waste
- *newcleo* is developing the concept of an ultra-compact and transportable 200MWe LFR

Alternative GenIV Concepts: MSR and HTRs

Molten Salt Reactors (MSR)

- Coolant: fluor salts, without significant pressure (e.g. LiF-BeF_2-ZrF_2-UF_4)
- Moderator: graphite (only in thermal version)
- Fuel: U, Pu, or Thorium dissolved in the salts
- Coolant temperature at the outlet of the core: 850°C



MSR: Advantages

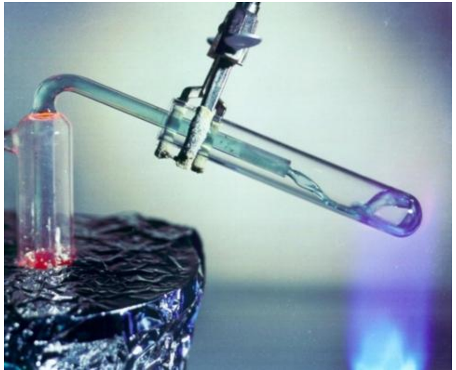
- No core melt accidents by design, reactor can be shutdown safely by dumping the molten salt into emergency dump tanks

- **Very flexible neutron economy**, can used both for Breeding and Transmutation/waste burning

- Fission products can be **removed on-line** during operation => Mitigation of radiological consequences if leakage occurs, also reduces the decay heat production

- Suitable for Uranium/Thorium fuel cycle

- Low amount of waste



Molten Salt Reactors: Historical Overview

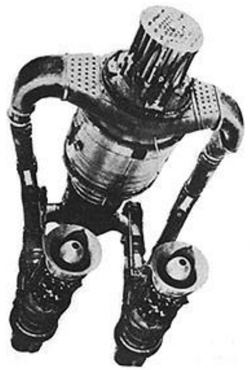
1950s • **Aircraft Reactor Experiment (ARE)***

1960s • **Molten Salt Reactor Experiment (MSRE)***

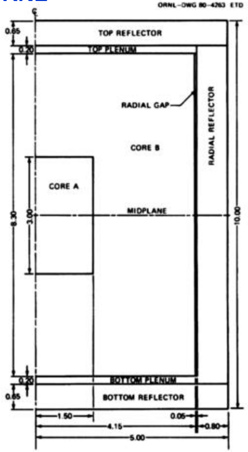
1970s • **Molten Salt Breeder Reactor (MSBR)***

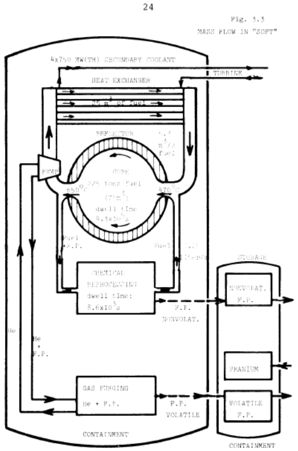
1970s • **EIR (PSI) study (report nr. 411, 1975)**
fast spectrum, chlorides

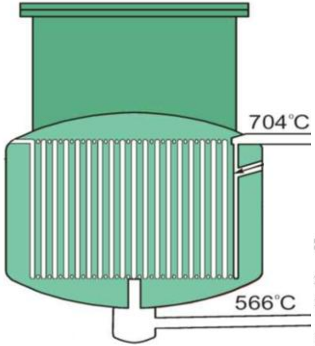
1980s • **Denatured Molten Salt Reactor (DMSR)***

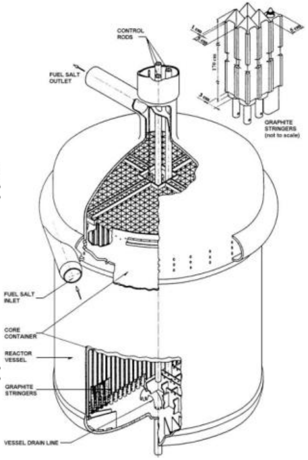


* ORNL









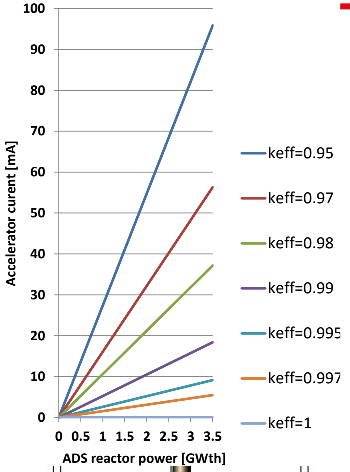
Molten Salt Reactors: Historical Overview

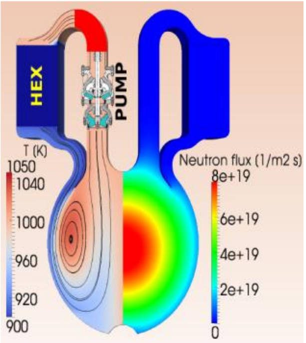
1990s • Accelerator-driven transmutation of Nuclear Waste - ATW (LANL)

2000s • Generation IV, Amster, Sphinx, …

2010s • MSFR, MOSART,… *fast spectrum, fluorides*

Future • Th-U or U-Pu breeding, TRU transmutation (as *start-up fuel*) ..?





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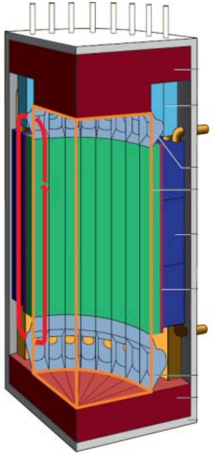

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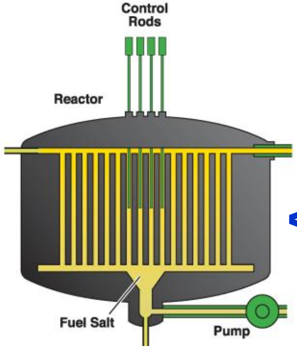

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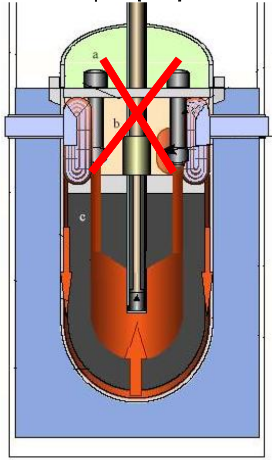


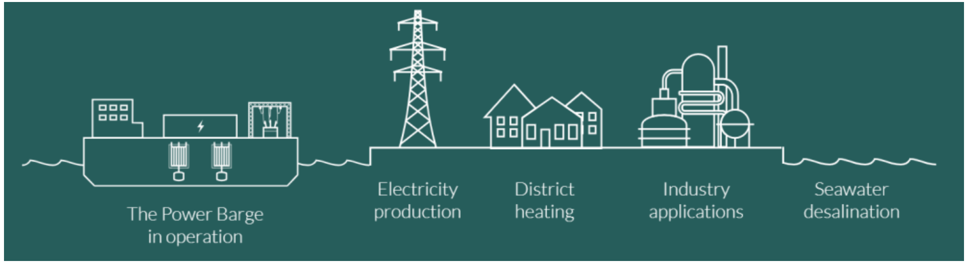
MSR: Disadvantages & Challenges

- Corrosion and material challenges:
  - Fluorine salts are highly corrosive with limited solubility for fission products.
  - Structural materials face corrosion and irradiation embrittlement
- Operational and safety concerns:
  - Melting temperature of the salts exceeds 500 °C, complicating handling and maintenance.
  - High radiation exposure of components affects durability and safety - limited graphite lifespan due to irradiation.
  - Thermal fluid dynamics of molten salt flow are complex, affecting stability and control.
- Reprocessing and waste management:
  - Complex reprocessing techniques required
  - Challenges in handling and treating fuel salts, such as on-line refueling and managing gaseous and volatile fission products
- Limited operating experience from reactors in the 1960s restricts empirical knowledge base.
- Potential ease of separating fissile materials like 233Pa or 233U poses significant proliferation risks.

Developments in MSRs

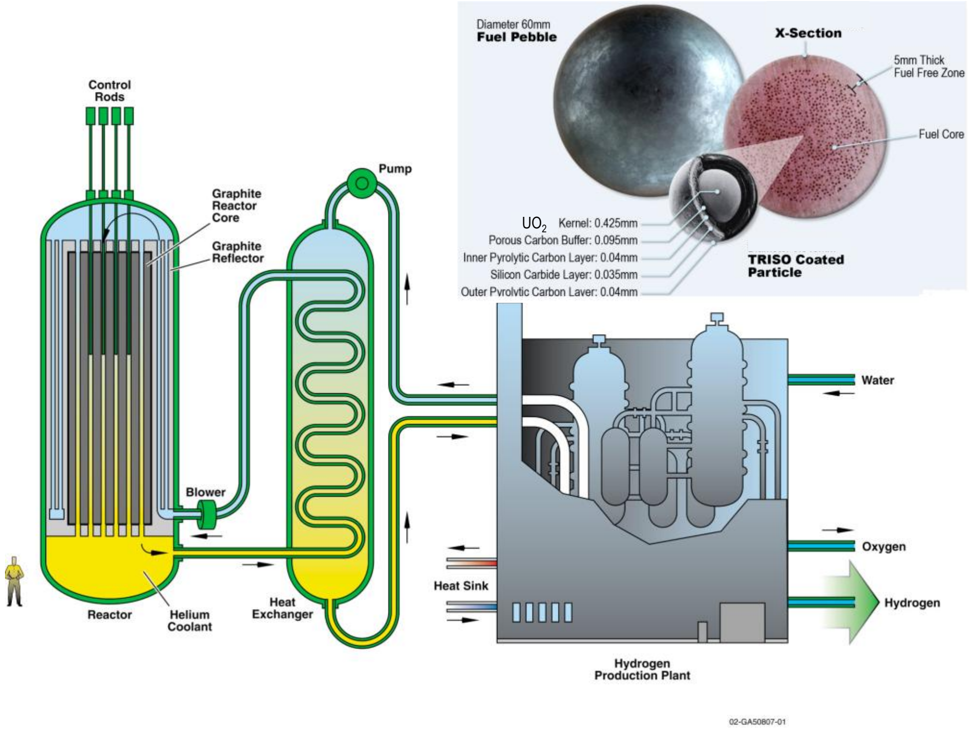
- Copenhagen Atomics (Denmark) - https://www.copenhagenatomics.com/technology/
  - Thorium cycle, thermal breeder reactor (based on U-233)
  - Small modular reactor
  - 100 MWth, 560 °C outer temperature
  - Fuel is $F_7LiThPu$
  - Moderator is unpressurized heavy water

- Seaborg Technologies
  - Compact Molten Salt Reactor
  - Power Barge concept



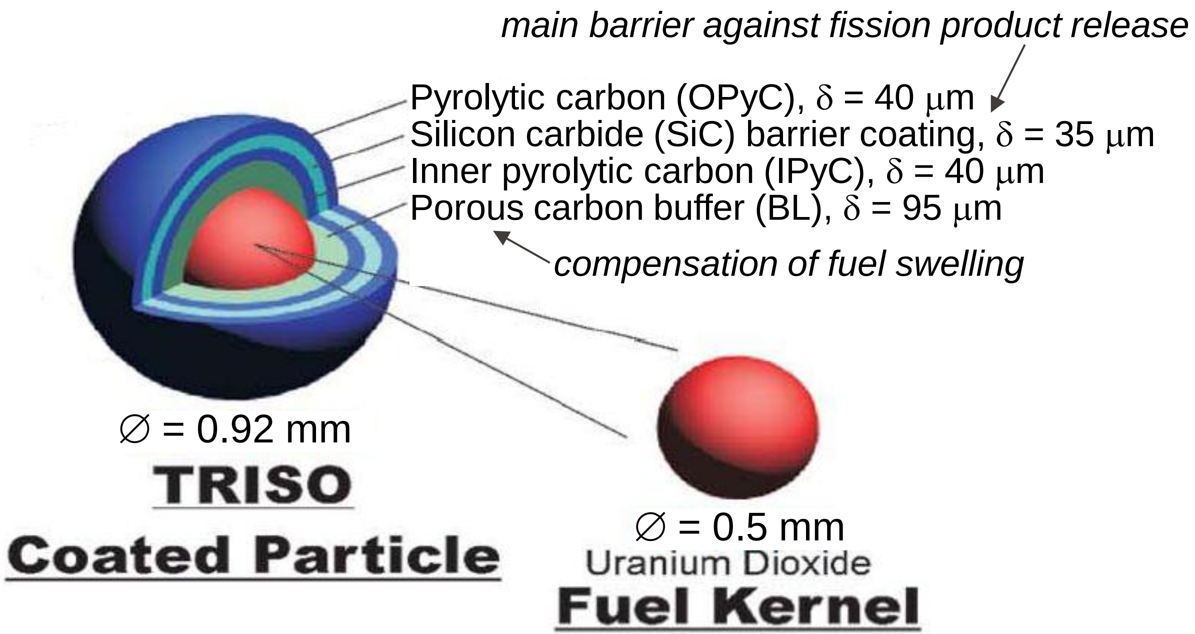
https://www.seaborg.com/the-reactor

Generation-IV: High Temperature Reactor (HTR)



- Power: 300 to 600 MWth
- Coolant: Helium, under pressure (40 – 90 bar)
- Moderator: Graphite
- Coolant temperature at the outlet of the core: 850°C to 1000°C (or more)
- Fuel: Uranium low enriched (8 to 15%); pebbles or compacts

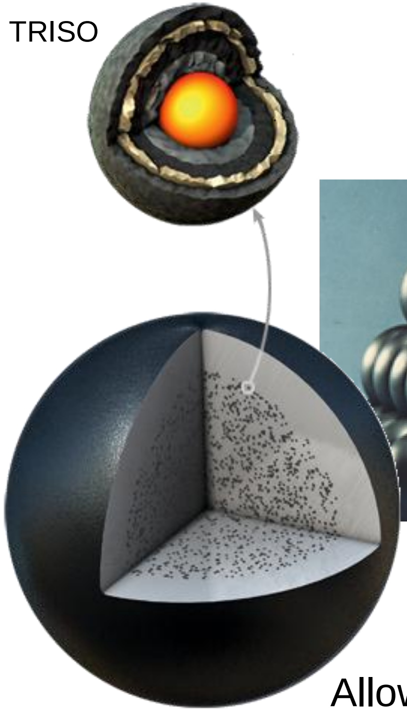
HTR fuel – TRISO particles



Two fuel concepts using coated particles

Spherical fuel elements

TRISO



Allow continuous refueling

→ no excess reactivity needed

→ wear while moving through reactor, dust production

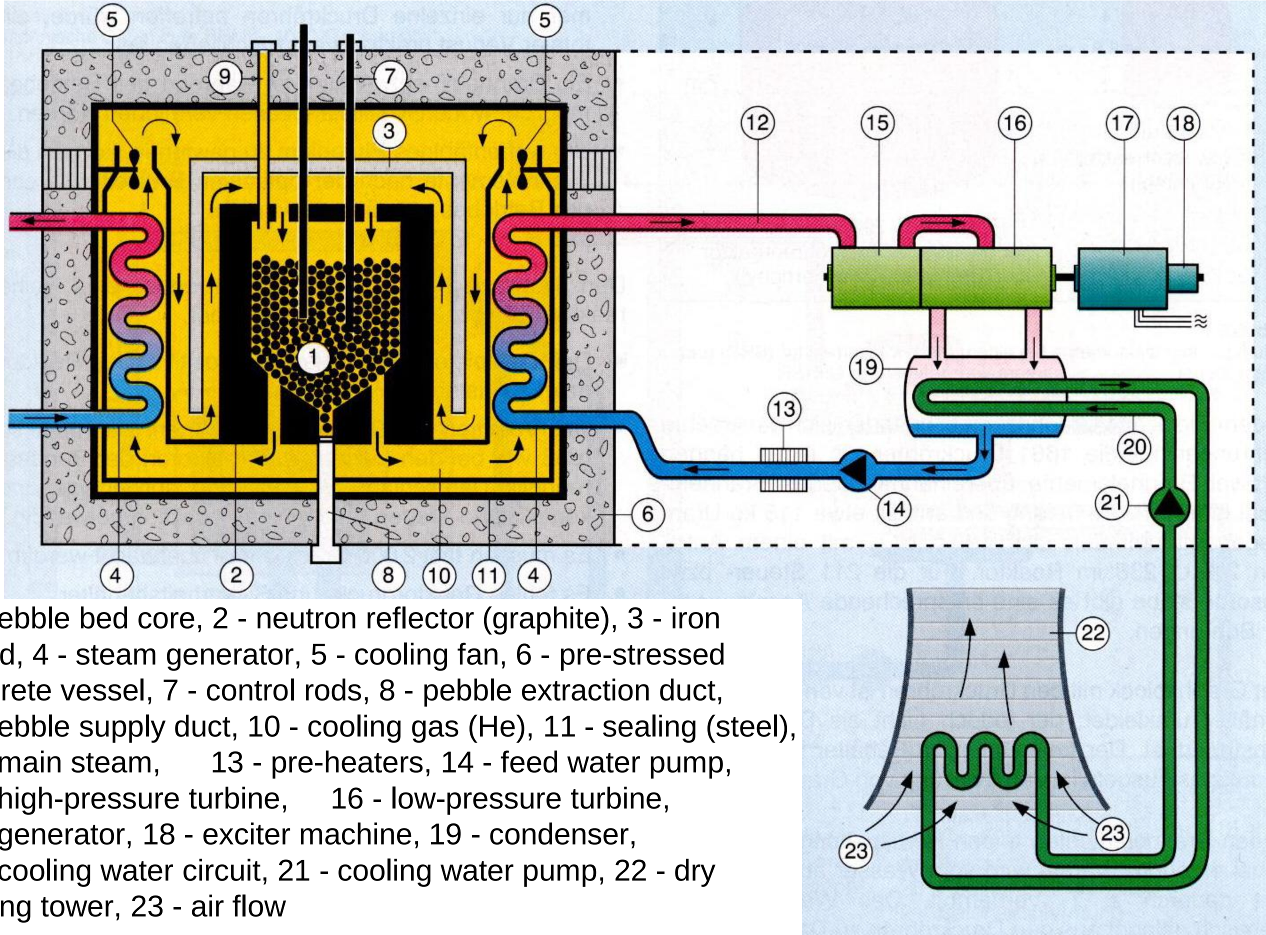
Prismatic fuel elements

Only periodic refueling

→ excess reactivity needed

→ no wear during reactor operation

Scheme of a Gas-cooled HTR (Pebble Bed Reactor)

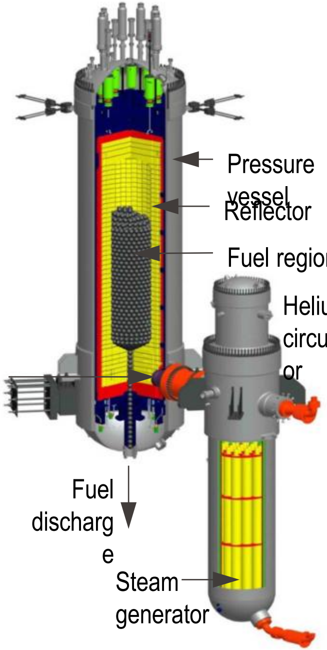


1 - pebble bed core, 2 - neutron reflector (graphite), 3 - iron shield, 4 - steam generator, 5 - cooling fan, 6 - pre-stressed concrete vessel, 7 - control rods, 8 - pebble extraction duct, 9 - pebble supply duct, 10 - cooling gas (He), 11 - sealing (steel), 12 - main steam, 13 - pre-heaters, 14 - feed water pump, 15 - high-pressure turbine, 16 - low-pressure turbine, 17 - generator, 18 - exciter machine, 19 - condenser, 20 - cooling water circuit, 21 - cooling water pump, 22 - dry cooling tower, 23 - air flow

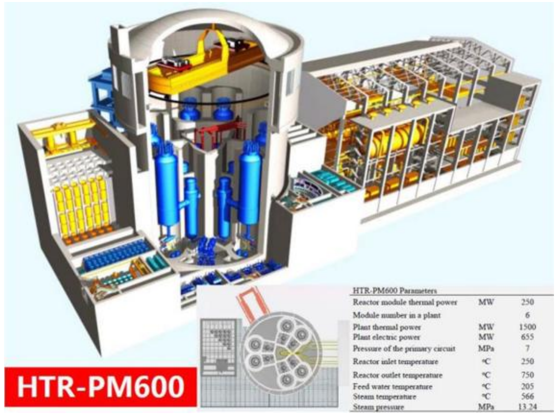
High-temperature gas cooled reactor prototype plants and projects

Reactor Type		Power	Operation
Pebble bed reactors			
AVR Germany	**FZ Jülich**	46 MWth/15 MWel	1966–1988
THTR-300 Germany	**Hamm-Uentrop**	750 MWth/296 MWel	1985–1989
HTR-10 China	**Uni Tsinghua**	10 MWth	Since 2000
HTR-PM China		2x250 MWth/210 Mwel	since Dec, 2021
Prismatic core			
Peach Bottom 1 US		40 MWel	1966–1974
Fort St Vrain US		842 MWth/330 MWel	1976–1988
HTTR Japan		30 MWth	Since 1998
GT-MHR US/Russia		600 MWth/293 MWel	Point Design

Generation-IV: HTR-PM (China)



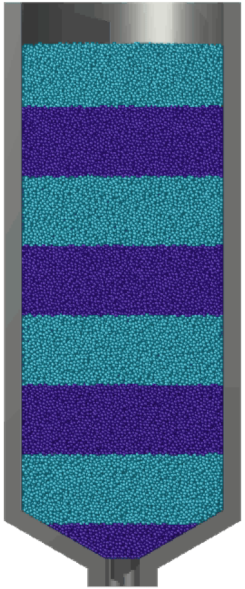
Single-Module HTR-PM: Courtesy of Tsinghua University



HTR-PM600 Parameters

Reactor module thermal power	MW	250
Module number in a plant		6
Plant thermal power	MW	1500
Plant electric power	MW	655
Pressure of the primary circuit	MPa	7
Reactor inlet temperature	°C	250
Reactor outlet temperature	°C	750
Feed water temperature	°C	205
Steam temperature	°C	566
Steam pressure	MPa	13.24

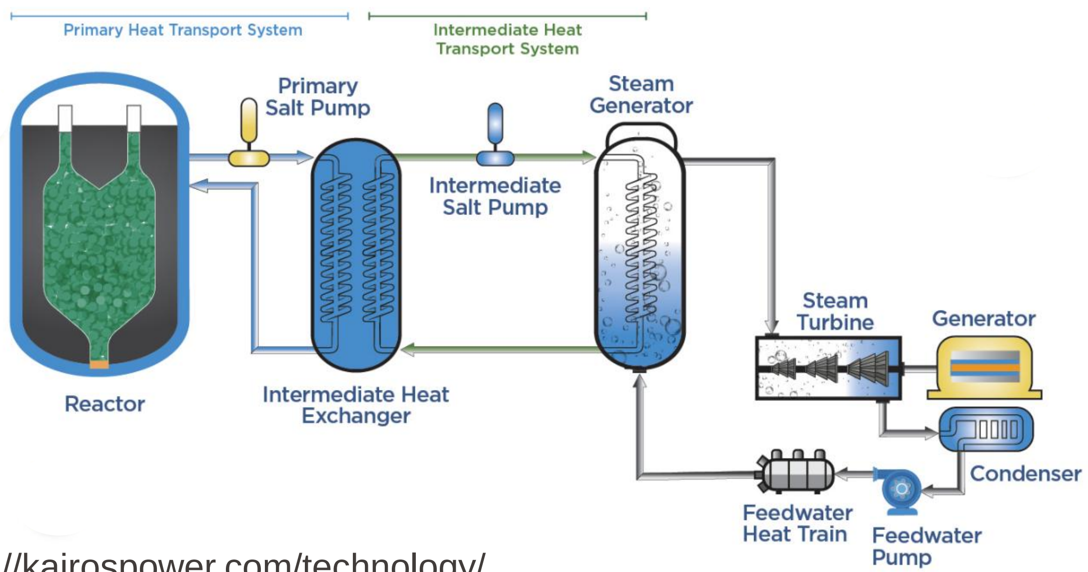
- Power density ~ 3.3 MW/m^3 (factor of 30 lower than in PWR)
- High thermal inertia
- Core Outlet temperature: 750 °C, plant thermal efficiency: 44%
- There is no need in core emergency cooling system since decay heat is removed by natural mechanisms in case of accidents



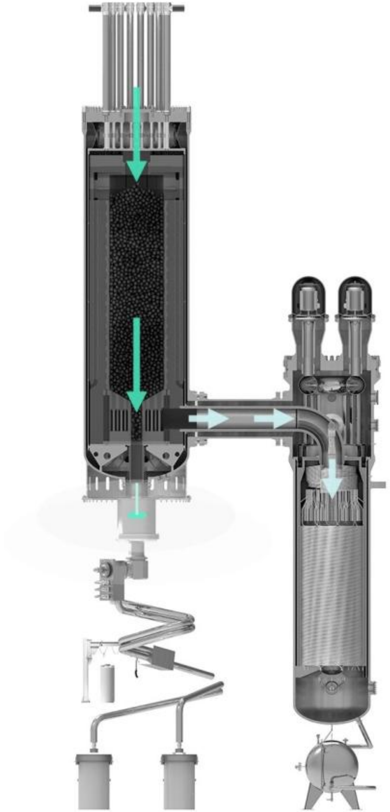
Simulation Pebble Flow
Rycroft, Debhi (PSI)

Kairos Power and X-Energy HTRs

- Kairos Power develops a version of HTR called FHR that combines TRISO fuel with low-pressure fluoride salt as coolant.
  - 140 MWe, 585°C steam, 650°C outlet core temperature
- X-Energy is developing a small modular HTR, the Xe-100
  - 80 Mwe, 750°C outer He T at 6MPa, 565°C Steam T



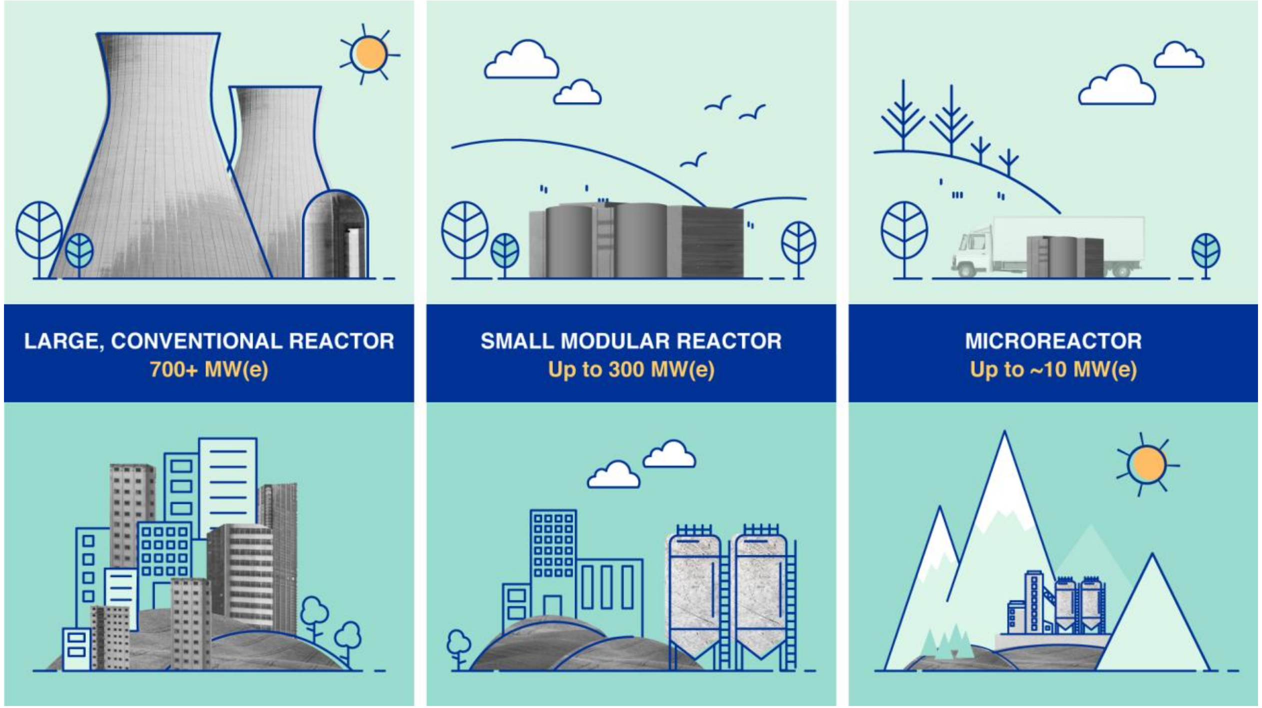
https://kairospower.com/technology/



https://x-energy.com/reactors/xe-100

Current trends: Small Modular Reactors and Micro-Reactors

Small Modular and Micro Reactors



https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

Small Modular Reactors

- A fraction of the size of conventional reactors (small); systems and components are factory-assembled and transported for onsite installation (modular).
- Most often intended for PWR, but recent designs include Generation IV concepts

- Promised advantages:
  - Smaller footprint – Units can be added to a site as necessary
  - Cost-effective as prefabricated units would reduce cost and construction time
  - Simplified designs with focus on passive safety systems and low operational pressure.
  - Less frequent refueling - operational periods of 3 to 7 years,

- However, there are uncertainties about actual costs and overall advantages on traditional NPPs:
  - NuScale initial agreement to build reactors in Idaho by 2030 was cancelled in 2023 due to a cost increase from $3.6 billion to $9.3 billion for a 460 MWe plant.

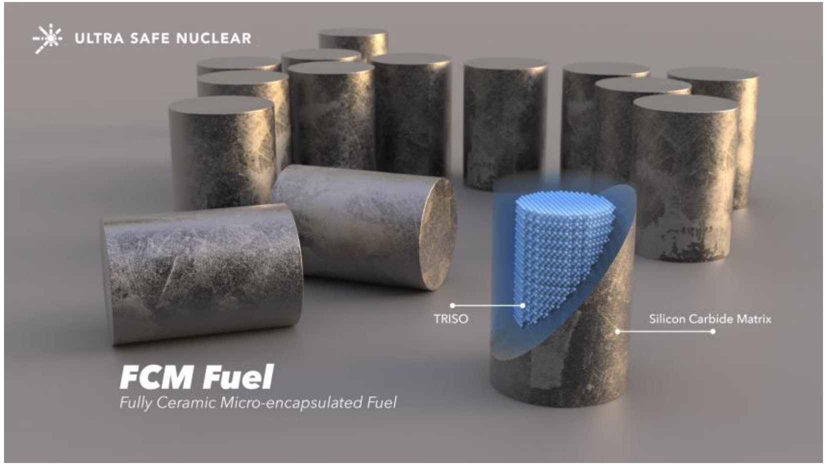
Micro-reactors: e-Vinci from Westinghouse

- Designed to operate for 8 years without refueling using 19.75% enriched TRISO fuel.
- Factory-assembled and transported in shipping containers – suitable for remote locations.
- Requires minimal onsite staff and capable of supplying district heating and high-grade heat.
- Passive Safety Systems:
  - Heat pipes provide self-regulating heat transport, no need for traditional coolant systems.
  - Passive Heat Removal System (PHS) by natural convection and radiation.

https://www.westinghousenuclear.com/energy-systems/evinci-microreactor/

Micro-reactors: MMR from Ultra Safe Nuclear

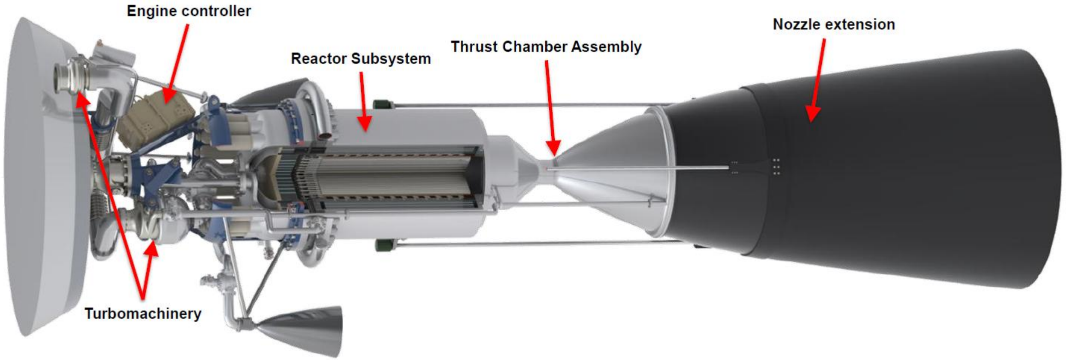
- Micro Modular Reactor (MMR) is being licensed in Canada and the U.S.A. and is described as "the first fission battery. Demonstration units are scheduled for first nuclear power in 2026.
- The idea is that multiple MMR units (3-15 MWe) can be linked together.
- MMR would be suitable for remote communities and large industrial sites: it uses no water and has no need for an electrical grid or infrastructure support. MMR is compatible with the harshest climates from arctic to desert to tropical.
- MMR uses a particular form of TRISO called the Fully Ceramic Micro-encapsulated (FCM) fuel



https://www.usnc.com/mmr/

The last frontier: Nuclear Thermal Propulsion (NTP)

- A fission-based rocket engine that heats a low molecular weight fluid like liquid hydrogen propellant using a nuclear reactor. The superheated hydrogen expands through a nozzle, producing thrust.
- Quite extensive past experience with KIWI program … NASA & DARPA's DRACO program aims to demonstrate NTP in space by 2027.
- Advantages:
  - 2× higher efficiency than chemical rockets, enabling faster travel.
  - Shorter mission durations to Mars and beyond, reducing crew exposure to space hazards.
- Challenges:
  - High-temperature materials needed to withstand reactor conditions.
  - Safe handling of nuclear materials during launch and operation & Regulatory approvals.



https://www1.grc.nasa.gov/