Progress in Technology of Innovative Reactors

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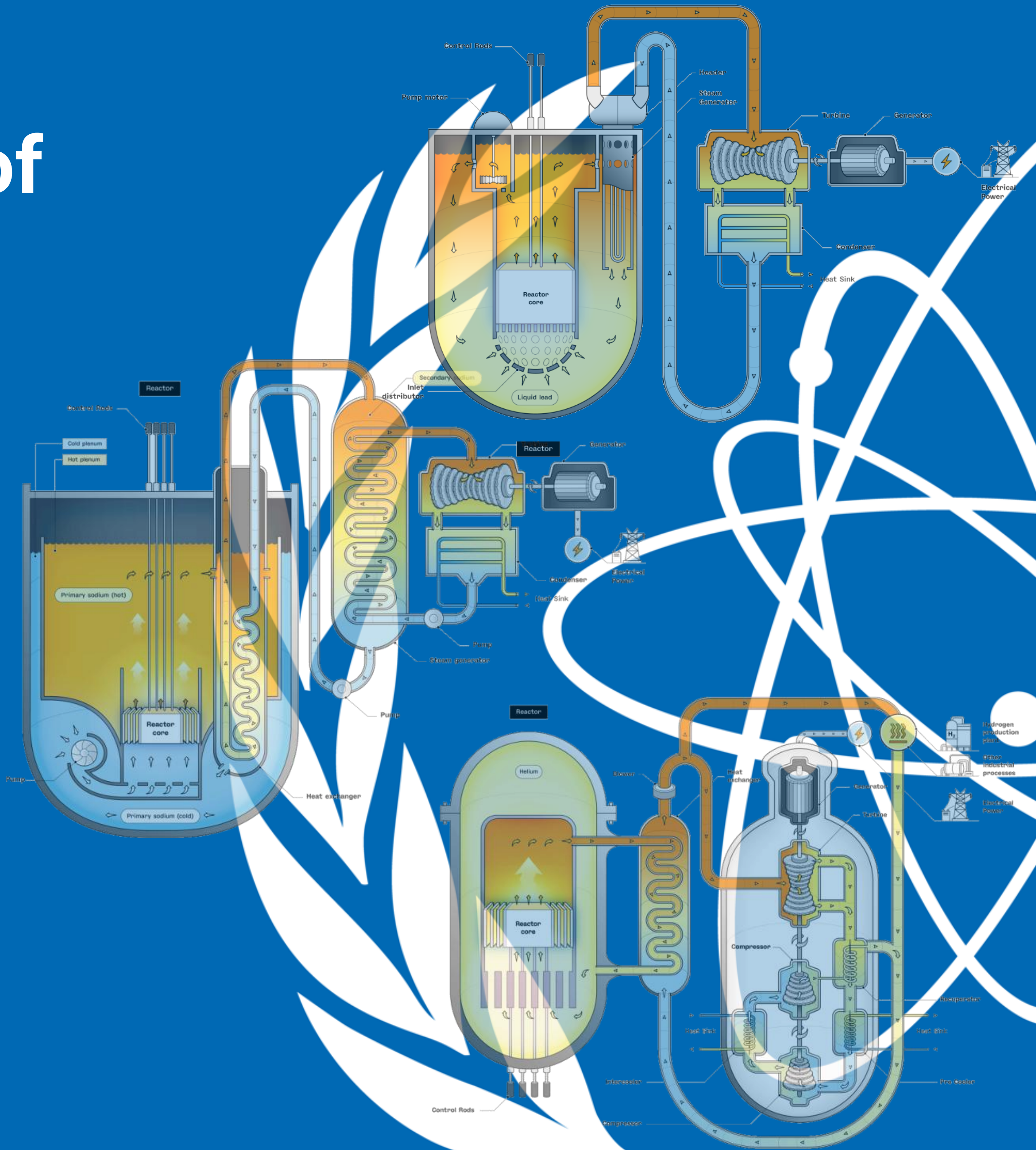
https://nucleus.iaea.org/sites/fr



Innovative Nuclear Reactors and Gen-IV Concepts

- Fission Basics
- A bit of History
  - Nuclear Reactor Terminology
  - Classification
  - WCR: Water Cooled Reactors
- Innovative Nuclear Reactors
  - SWCR: Super Critical Water Cooled Reactor
  - HTGR: High Temperature Gas cooled Reactor
  - GFR: Gas cooled Fast Reactor
  - SFR: Sodium cooled Fast Reactor
  - LFR: Lead (and LBE) cooled Fast Reactor
  - MSR: Molten Salt Cooled Reactor
  - SMR: Small Modular Reactor

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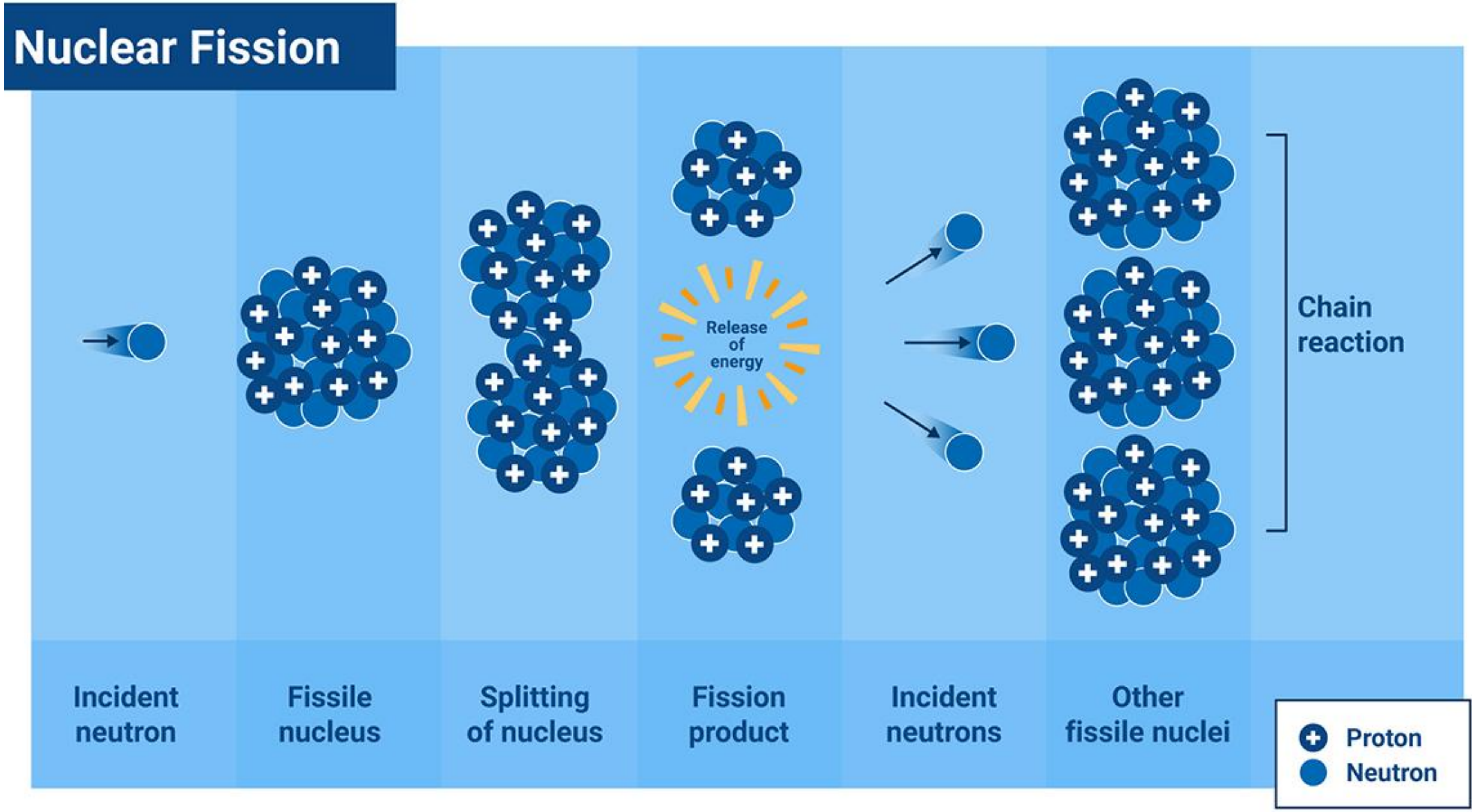
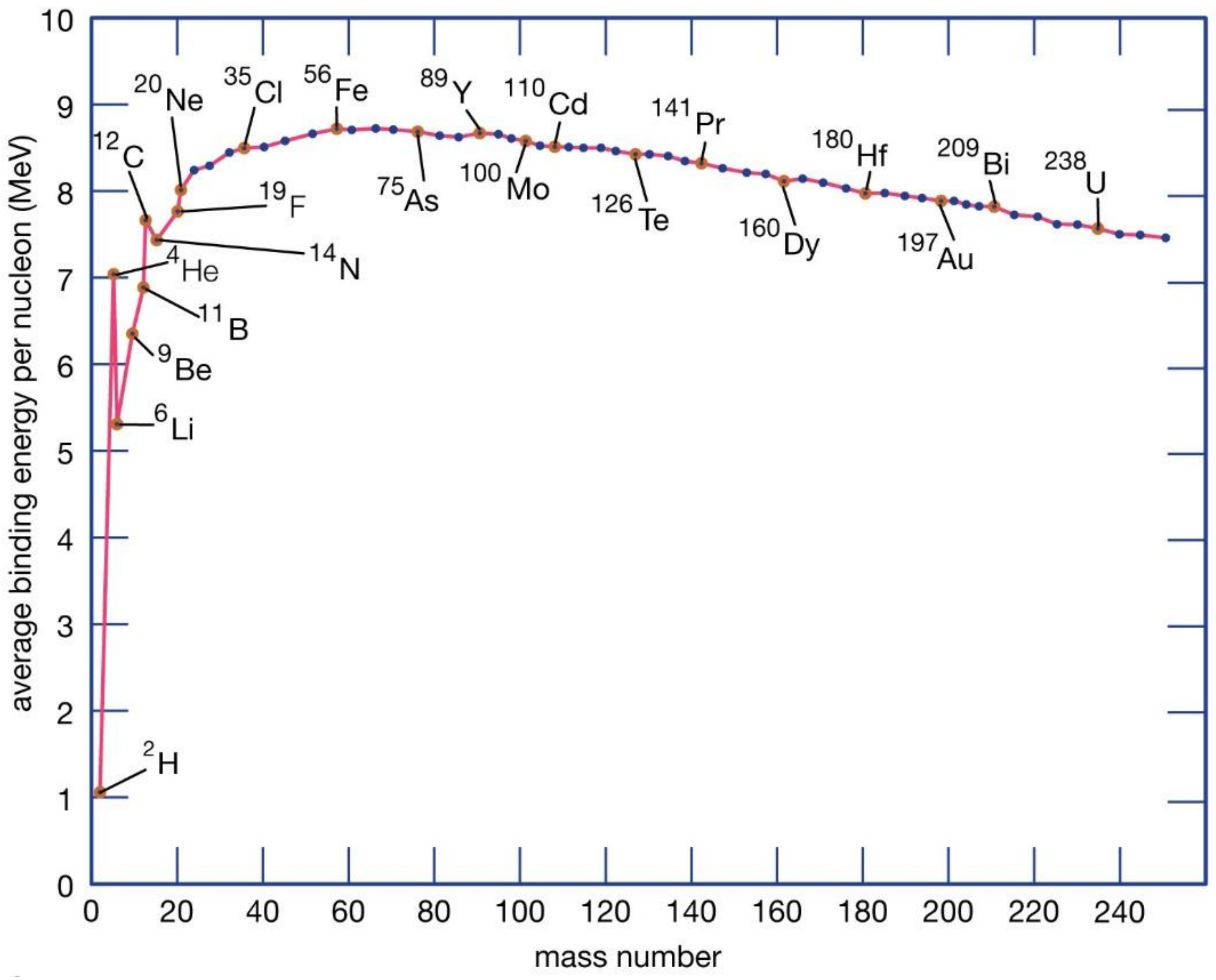
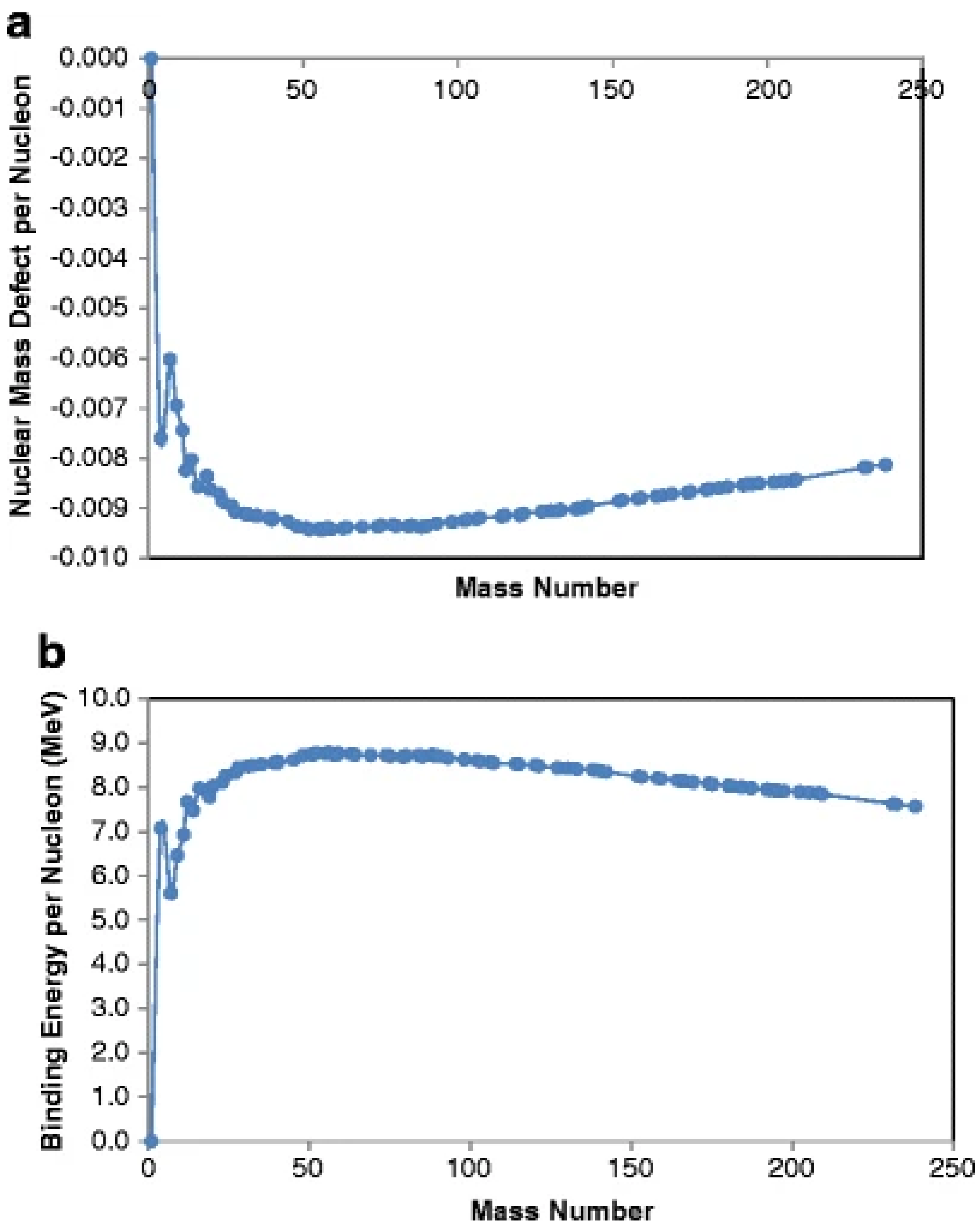
Basic Nuclear Fission Concepts

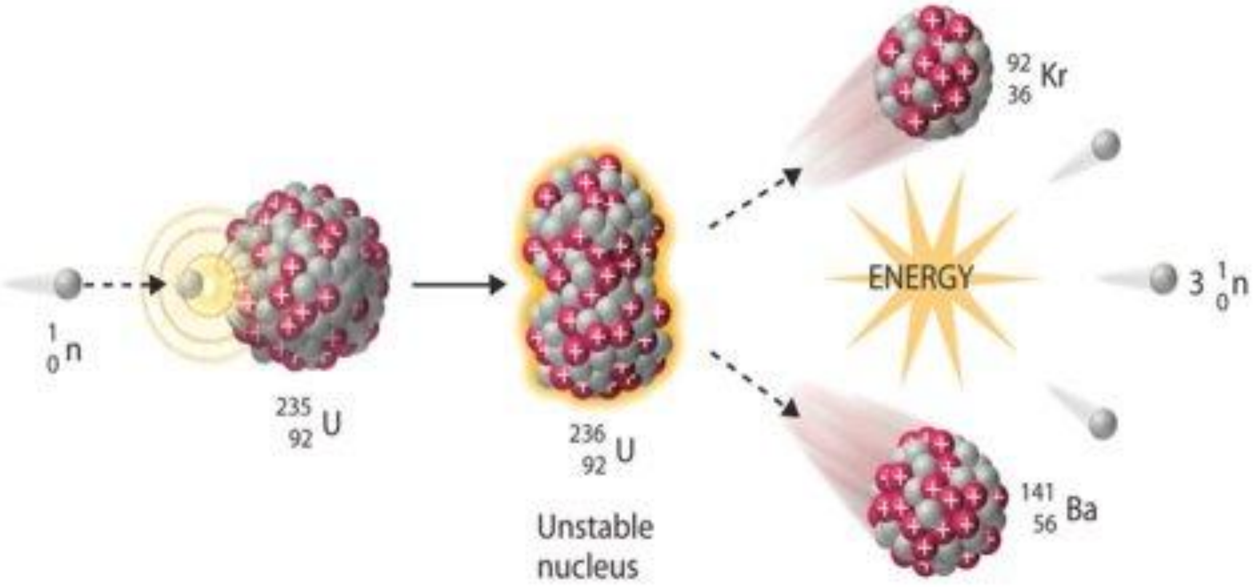


Binding Energy and Mass Defect





Fission Reaction Energy



Otto Hahn and
Lise Meitner
1913

$$^{235}_{92}U \quad + \; n \quad \rightarrow \quad ^{92}_{36}Kr \; + \; ^{141}_{56}Ba + \; 3n \qquad + \Delta mc^2$$

$$\Delta m = 235.044 + 1.009 - (140.914 + 91.926 + \; 3 \times 1.009) = 0.186amu$$

$$1u = 931.5 \; MeV$$

$$E = \Delta mc^2 = 0.1927 * 931.5 = 173.3MeV$$

Photons (in the form of gamma rays) are also produced in addition to released energy.
Therefore, average energy of fission reaction U-235 is about *203 MeV*

Neutron Induced Nuclear Fission in Heavy Nuclei

$^{235}_{92}U$ $^{239}_{94}Pu$

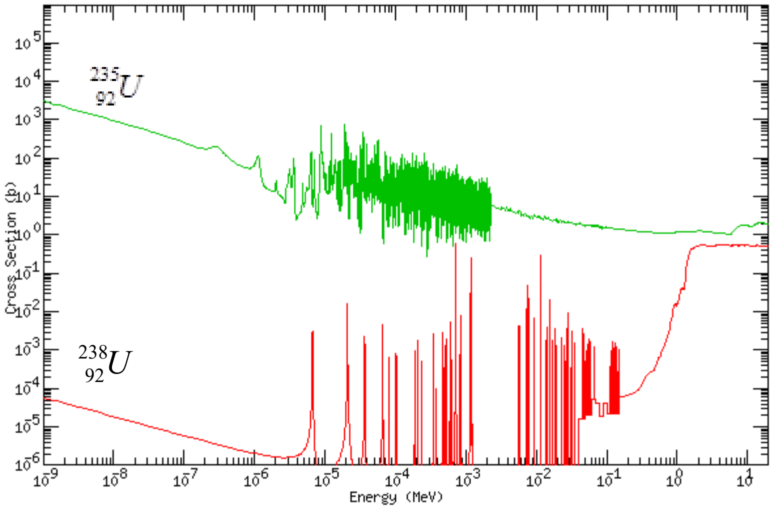
Fissile:

Nuclides that can be induced to fission with high probability by **thermal neutrons** are referred to as ***fissile***

$^{238}_{92}U$ $^{240}_{94}Pu$

Fissionable:

Fissile Nuclides and those that fission when induced by **fast neutrons** are referred to as ***fissionable***



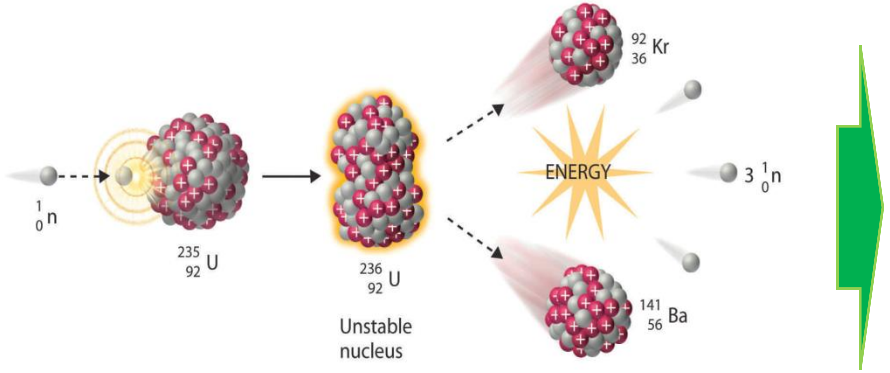
Microscopic cross sections
(probability of neutrons inducing fission)

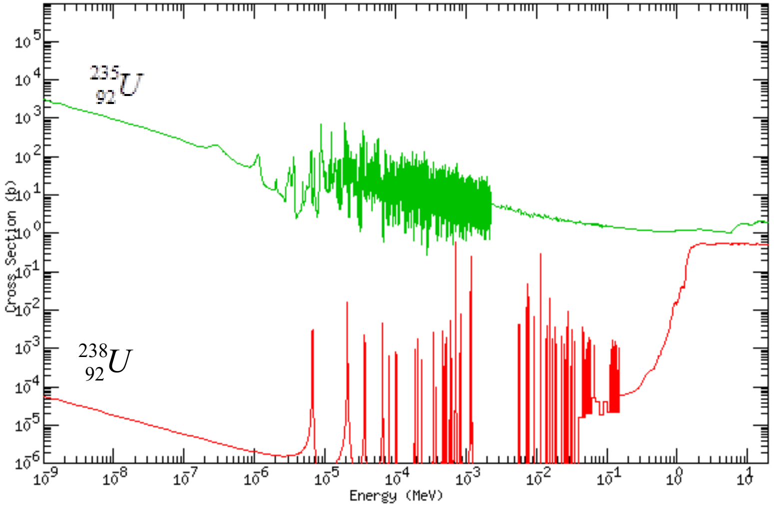
Fertile

Nuclides from which fissile material is generated by neutron absorption and subsequent nuclei conversions

$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \xrightarrow{\beta^-} {}^{239}_{93}Np \xrightarrow{\beta^-} {}^{239}_{94}Pu$$

Neutron Induced Nuclear Fission in Heavy Nuclei





Neutrons created after fission are fast neutrons (high energy)

Microscopic cross sections
(probability of neutrons inducing fission)

Thermal fission requires slow 'thermal' neutrons (0.025 eV, 2km/s) → needs moderator (light nuclei) required to slow fast neutrons

Fast fission requires fast neutrons (1 MeV, 14000km/s)→ moderator must be excluded

Thermal Nuclear Reactors

Fast Nuclear Reactors

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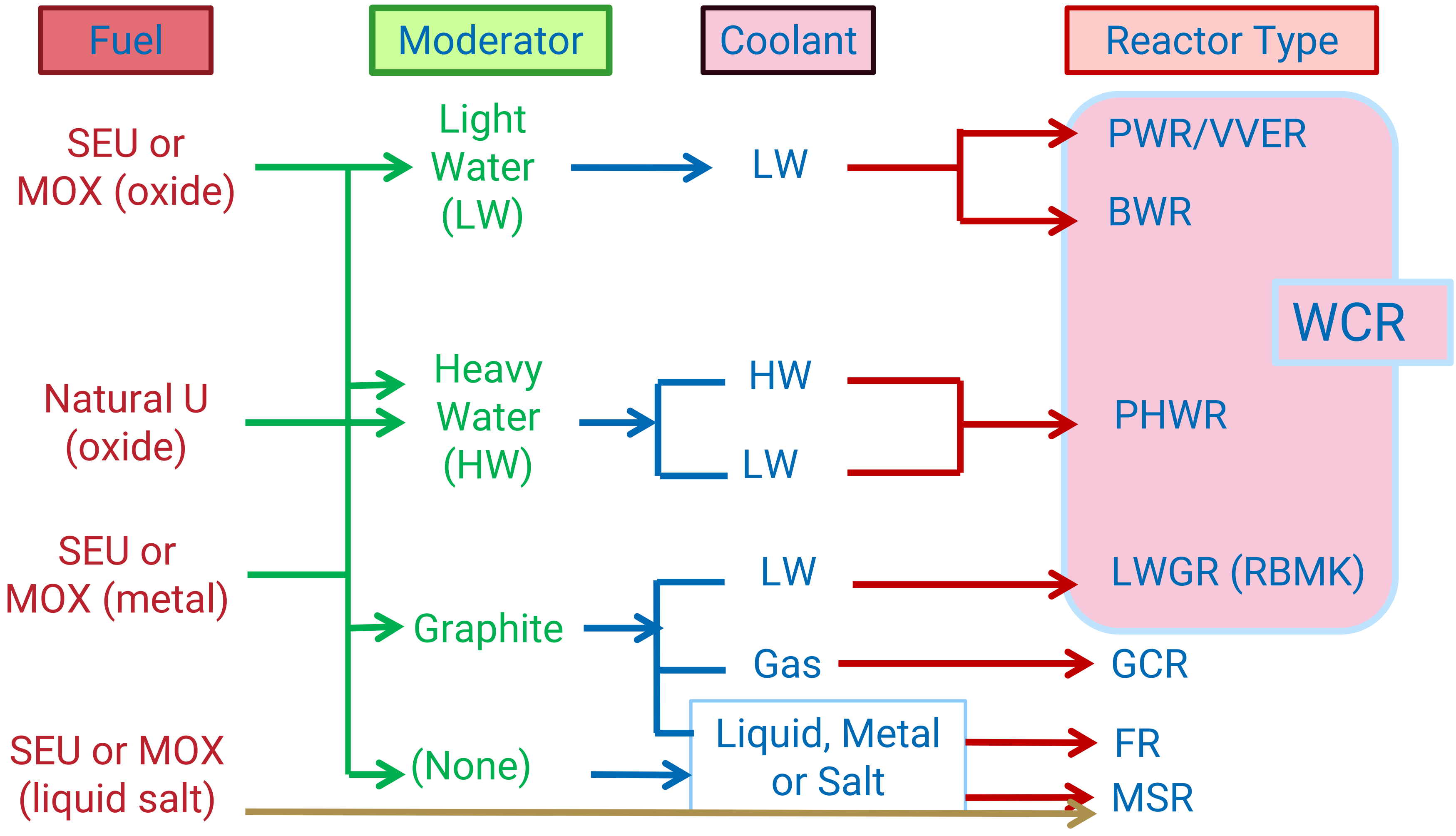
Classification of Nuclear Fission Reactors

- Moderator
  - Water / Heavy Water
  - Graphite
  - None (fast neutron systems)
- Coolant
  - Water/Heavy Water
  - Liquid Metal
    - Sodium/Lead/Lead-Bismuth Eutectic (LBE)
  - Gas
    - Air
    - CO_2
    - He
  - Molten Salt
    - Fluoride
    - Chloride

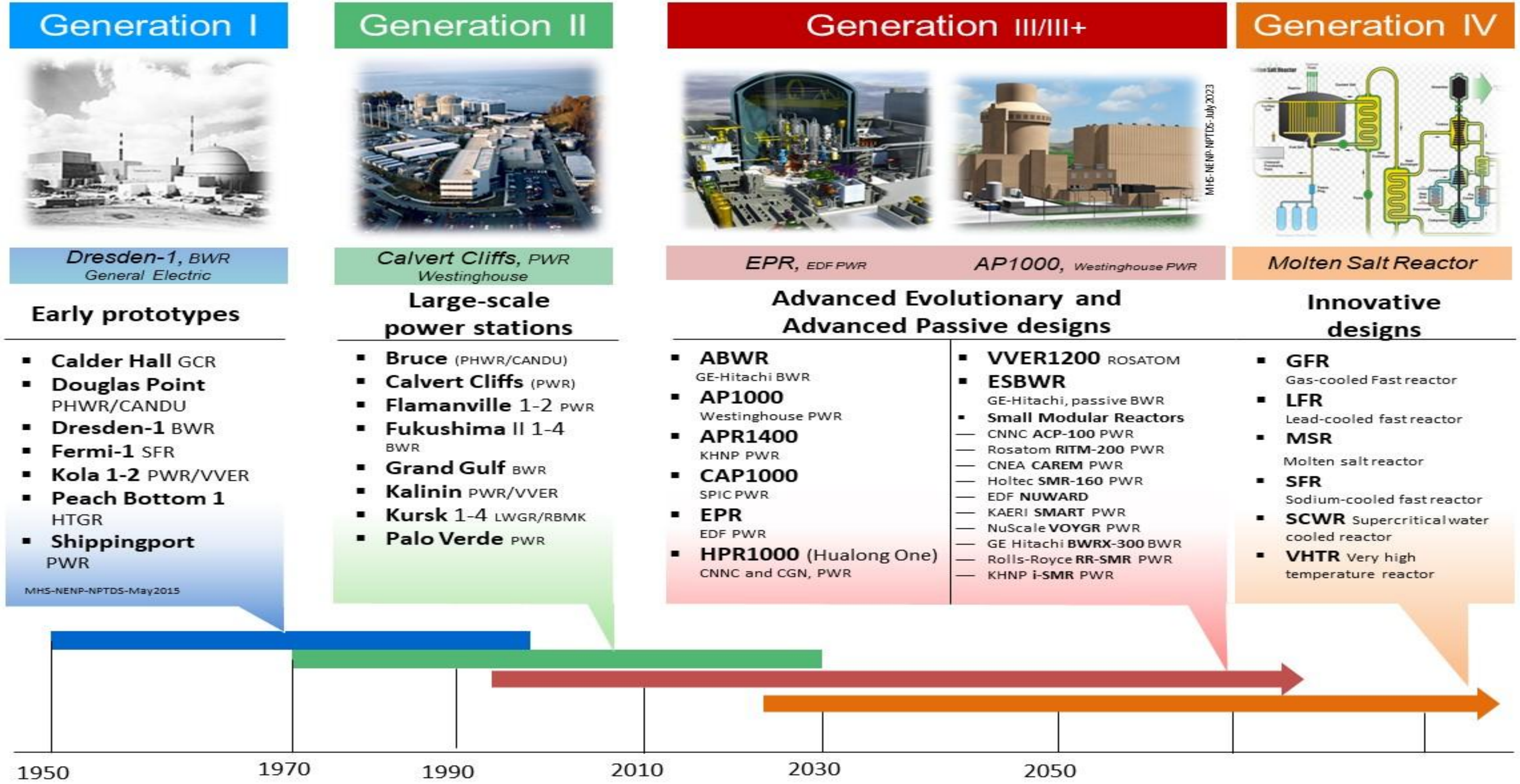
- Fuel
  - UO2
  - MOX (UO_2 + PuO_2)
  - Metallic
  - U/Pu Nitride
  - U/Pu Carbide
  - Molten Salt
- Purpose
  - Electricity Generation
  - Non-Electric Application
    - District Heating
    - Water Desalination
    - Industrial Purposes
    - H_2 Production
- Power
  - Low/Middle/High

Nuclear Power Reactor Classifications



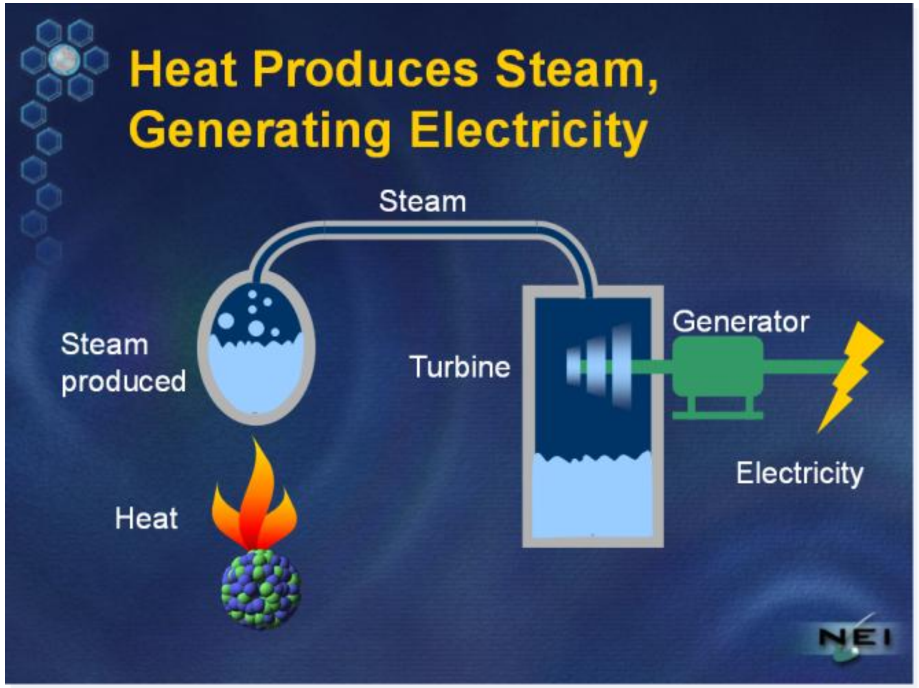
MOX is a mixed-oxide containing any combination of U, Pu and Th.

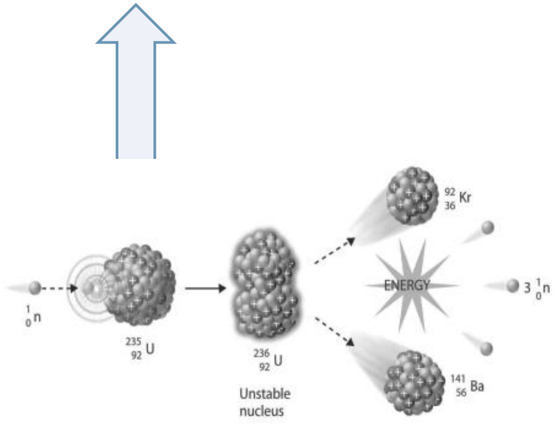
Evolution of Nuclear Power Reactor Technology



Major Features of WCRs

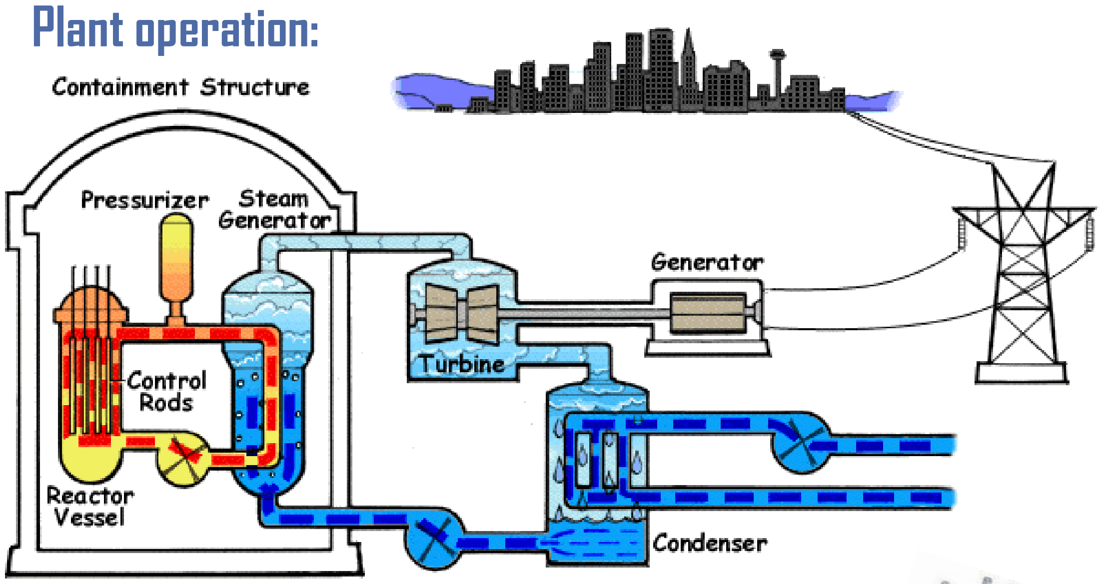
- Water Cooled & Moderated
  - Water used to remove heat from nuclear fission in the fuel
    - Long history using water; first steam engine developed by Egyptian mathematician in Alexandria
  - Neutrons are slowed down, which improves controllability of fission chain reaction
- If High Pressures
  - Achieve high energy content
  - Require pressure vessel, and containment





Fission in fuel

PWR Technology

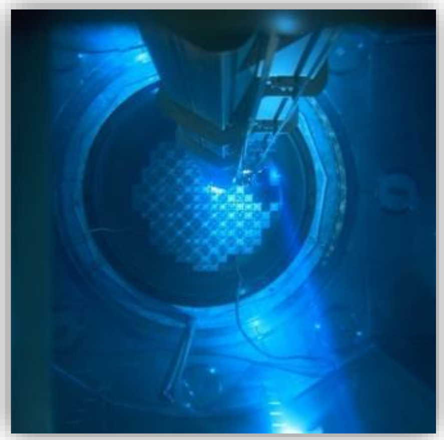


- **Most common** thermal reactor technology
- Moderator: **light water**
  Important safety feature: increase in temperature causes water to "expand" reducing probability of neutron thermalization which reduces new fissions thus reducing reactivity (called negative temperature coefficient of reactivity)
- Coolant: **light water**
  Primary loop: coolant is under ~ 15.5MPa (water remains liquid despite high temperature)

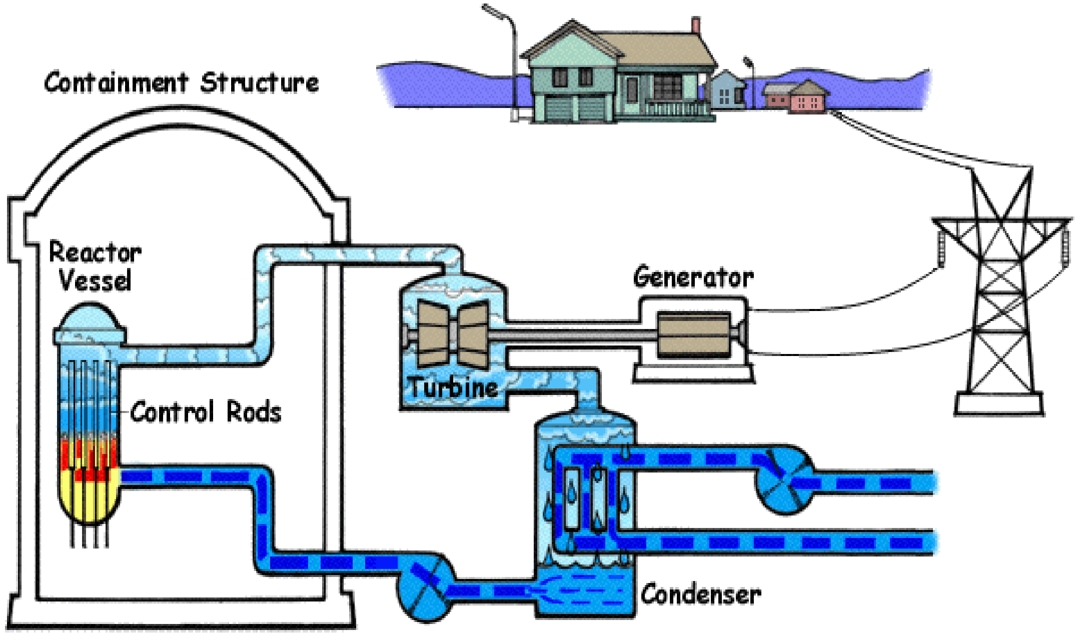
Fuel pellet (enriched UO_2)

Fuel assembly

Reactor core



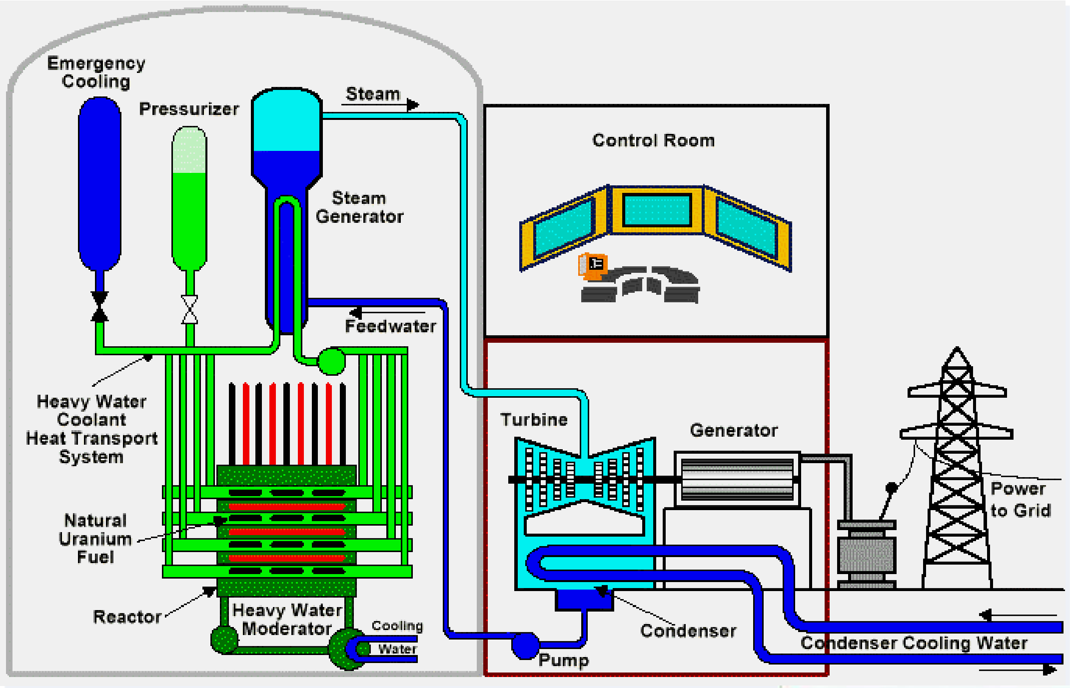
BWR Technology



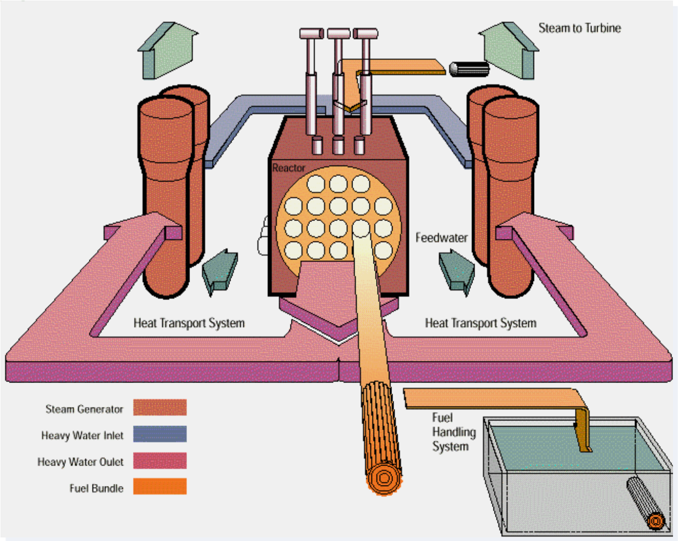
Fuel assembly & Cruciform control rods

- Second most common power reactor type
- Water: coolant & moderator
- Fission generates heat that causes cooling water to boil producing steam
- Steam from the reactor drives the turbines directly: direct-cycle
- Cooling water is at low pressure, ~ 7.6 MPa (it boils in the core at ~ 285℃)

Pressurized Heavy Water Reactor (PHWR)



- Better neutron economy
- On-line refuelling



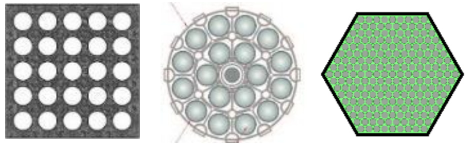
- Moderator: heavy water (D_2O)→
- Fuel: natural uranium (no enrichment)
- Pressure-tube design: pressure tubes within the calandria (380 – 480 tubes assembles a reactor)

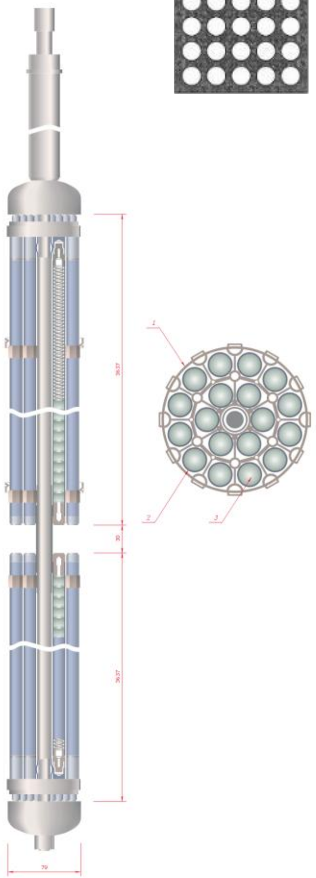
The CANDU Bruce Nuclear Generating Station is the largest nuclear power plant in the world by net operating capacity

Qinshan Phase III units 1 & 2, located in Zhejiang China (30.436 N 120.958 E): Two CANDU 6 reactors, designed by Atomic Energy of Canada Limited (AECL), owned and operated by the Third Qinshan Nuclear Power Company Limited

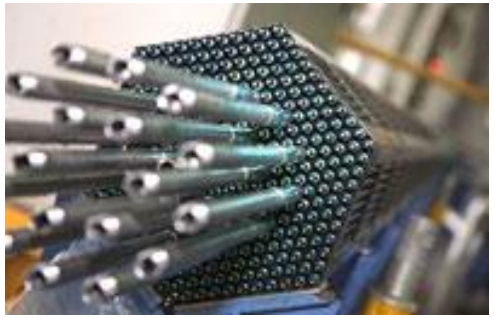
…also known as CANDU

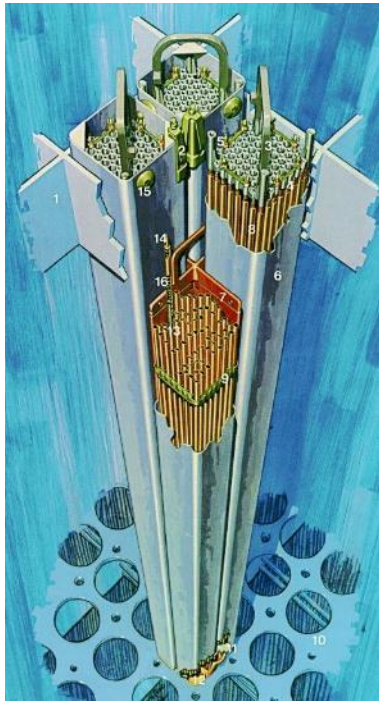
WCR Fuel Assemblies (Rod Bundles)





PWR





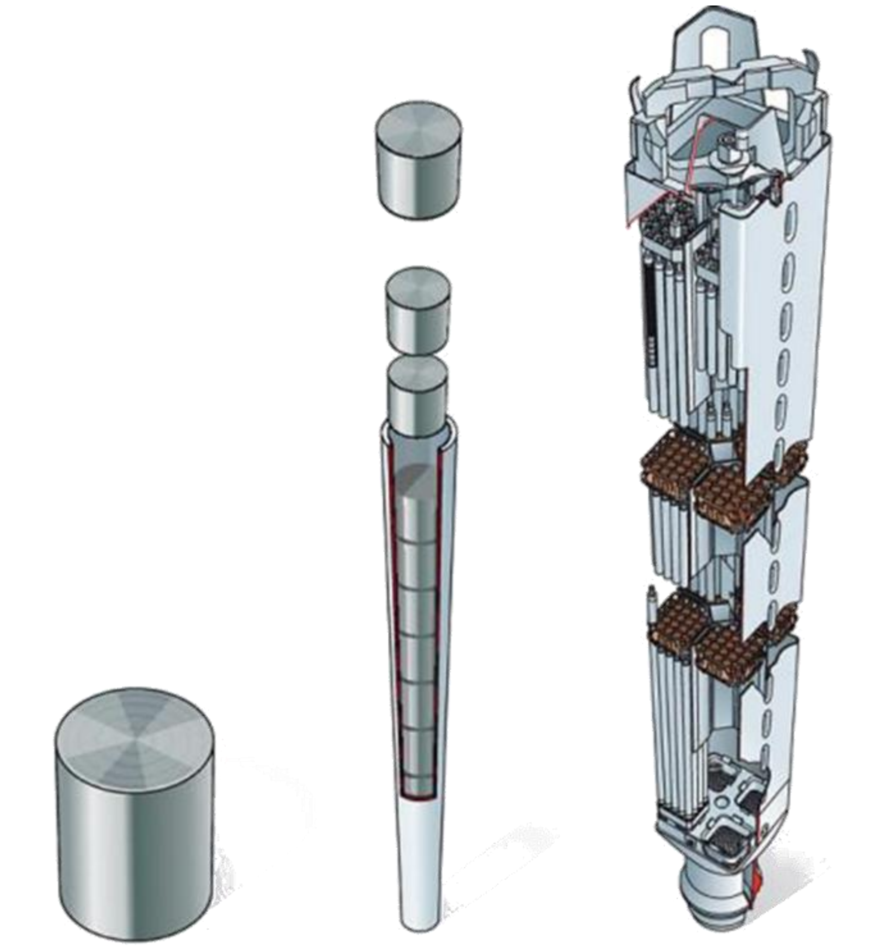
RBMK

VVER

CANDU

BWR

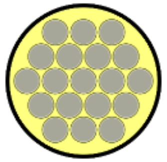
Fuel Assembly Types



Fuel pellet of uranium dioxide

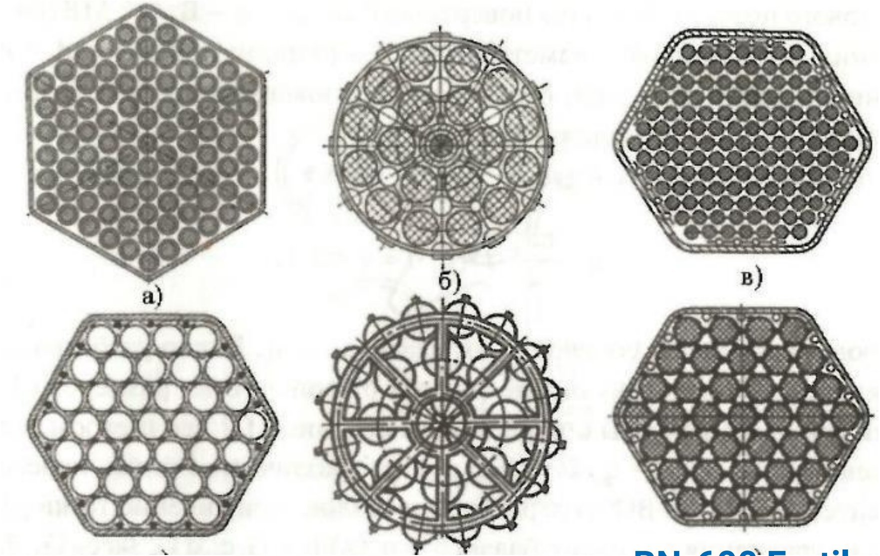
Fuel rod

Fuel assembly (length about 4 metres)



Control Rod S/A

VVER-1000 | RBMK-1000 | BN-600 Fissile



BOR-60 | CANDU | BN-600 Fertile

Different Scales!

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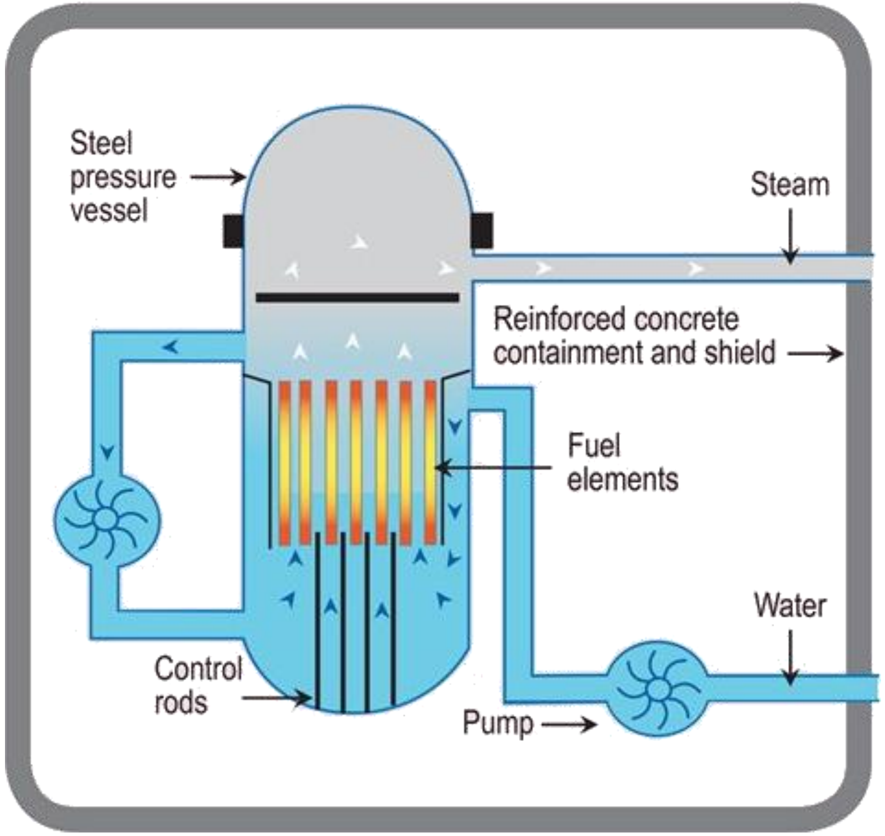
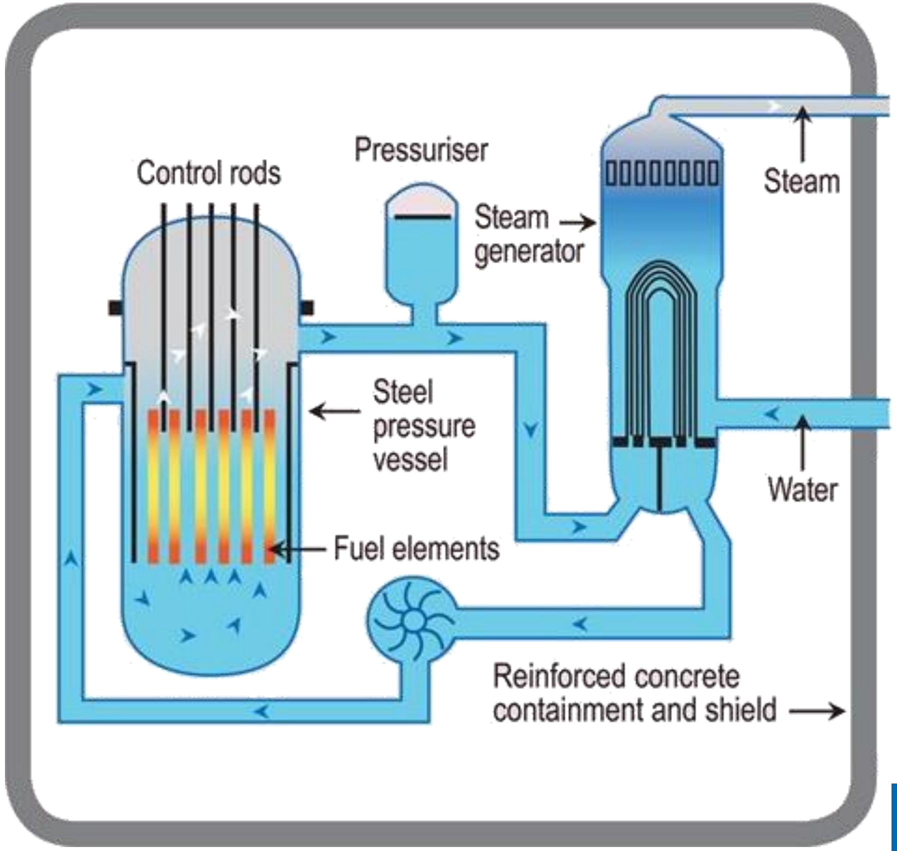
Water Cooled Reactors: Why are we unsatisfied?

	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*





Innovative Reactors (Gen-IV)

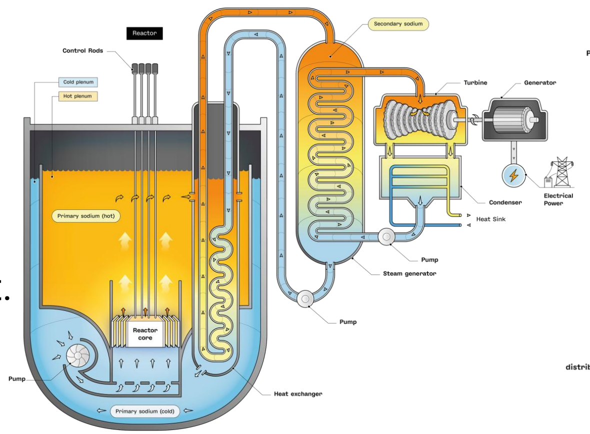
GEN IV International Forum
Expertise | Collaboration | Excellence

Innovative Reactor:

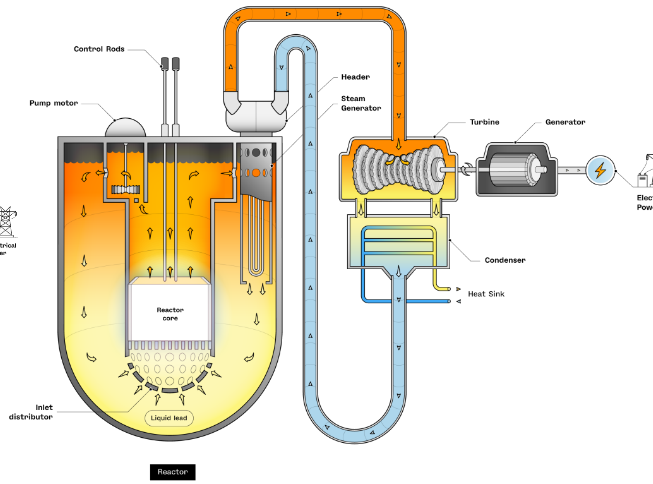
Advanced design which incorporates conceptual changes in design approaches or system configuration in comparison with existing practice. Substantial R&D, feasibility tests, and possibly a prototype or demonstration reactor are required prior to deployment.

- **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)

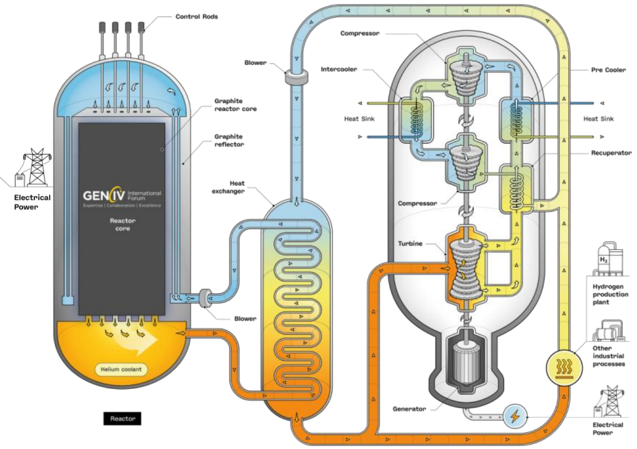
Sodium cooled Fast Reactor (SFR)

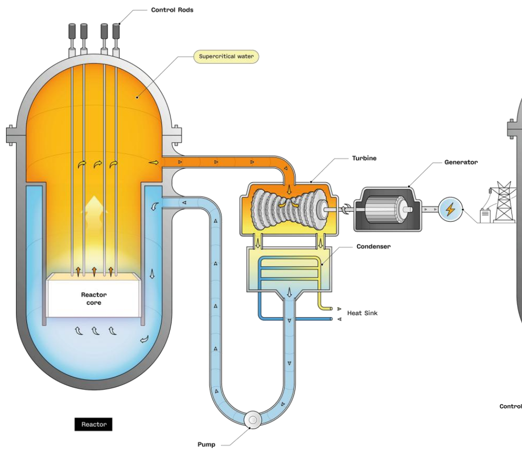


Lead cooled Fast Reactor (LFR)

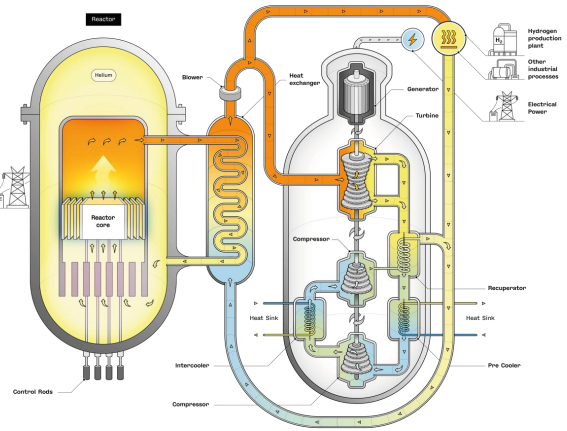


Very-High-Temperature Reactor (VHTR)

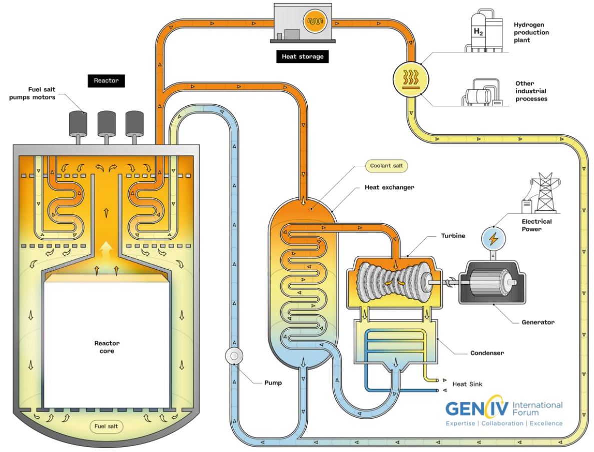




Supercritical Water cooled Reactor (SCWR)



Gas cooled Fast Reactor (GFR)



Molten Salt Reactor (MSR)

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

GIF: Goals for Gen-IV Nuclear Energy Systems

IAEA

Sustainability-1	Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production.
Sustainability-2	Generation IV nuclear energy systems will minimise and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
Economics-1	Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.
Economics-2	Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.
Safety and Reliability-1	Generation IV nuclear energy systems operations will excel in safety and reliability.
Safety and Reliability-2	Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.
Safety and Reliability-3	Generation IV nuclear energy systems will eliminate the need for offsite emergency response.
Proliferation Resistance and Physical Protection	Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

See at: www.gen-4.org

Thermal vs. Fast Neutron Reactors: Sustainability?

Two main Isotopes in Natural Uranium:

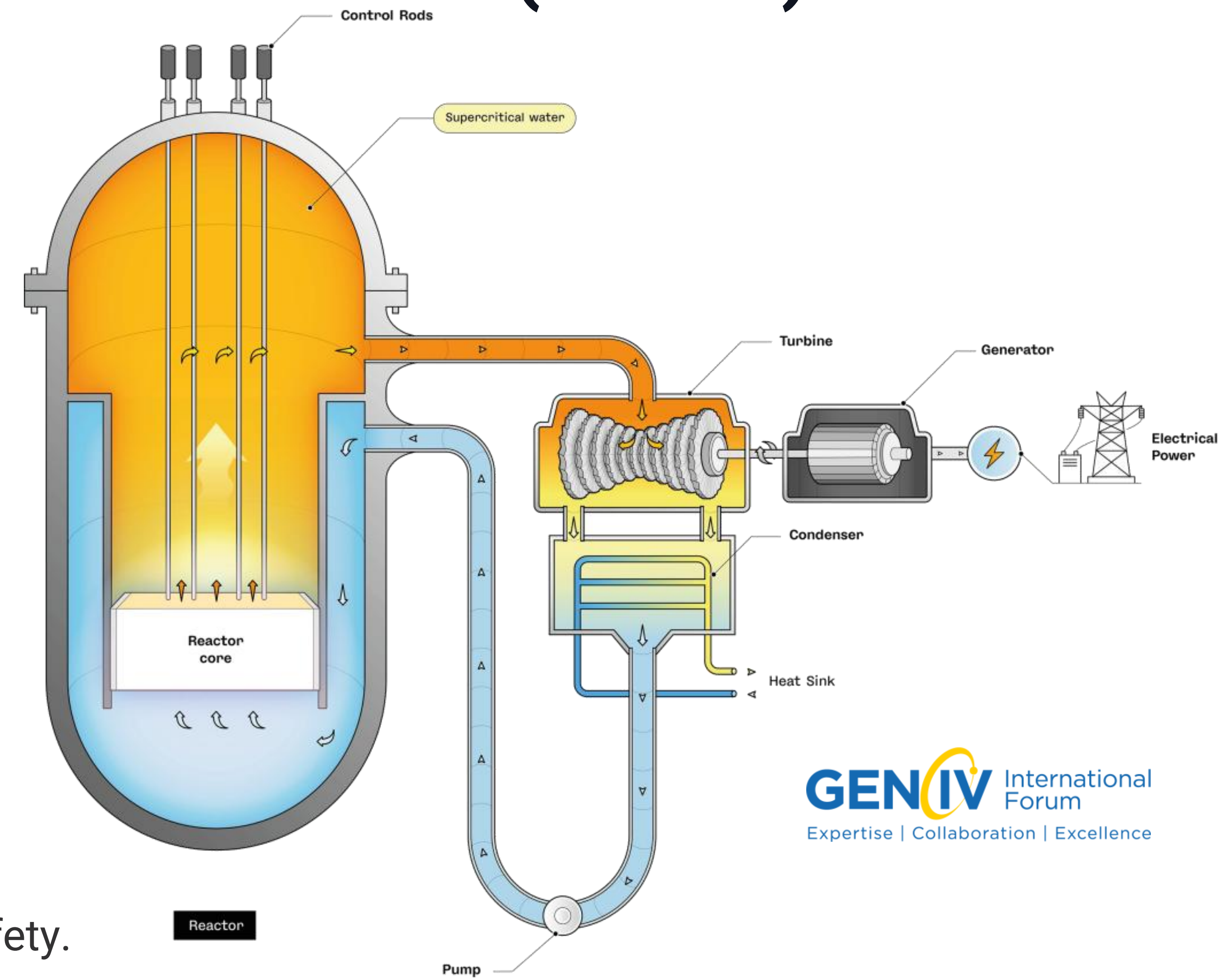
fissile ^{235}U 0.7%

fertile ^{238}U 99.3%

	Thermal Reactor	Fast Reactor
fuel efficiency (sustainability-1)	less 1% of natural U used	can utilize 60 times more U
waste production (sustainability-2)	significant amounts of long-lived radioactive waste	potentially less waste; burnup of long-lived isotopes is possible
enrichment	<3-5%	15-100% (20% ref.)
proliferation issues	easier	more problems as it require closing the fuel cycle
coolant	H_2O	water is not possible
neutron flux density (material damage)	10^{13} - 10^{14} n/cm²/s	10^{14} - 10^{15} n/cm²/s
compatibility of structural materials	long experience	needs qualifications
technology readiness	mature technology	pong experience with Na coolant but not with others
Safety	Well-established but…	to be proven

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

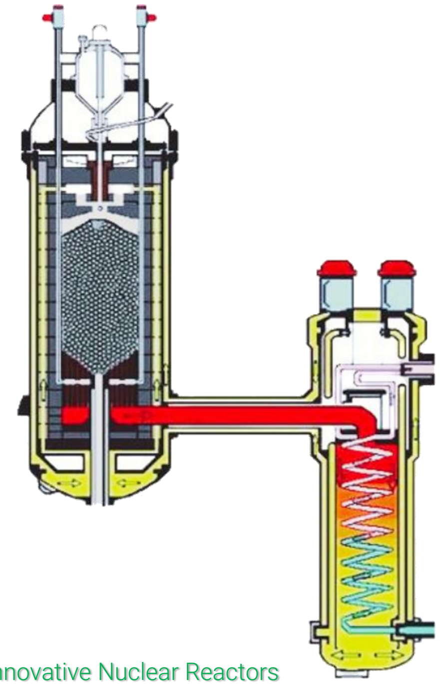


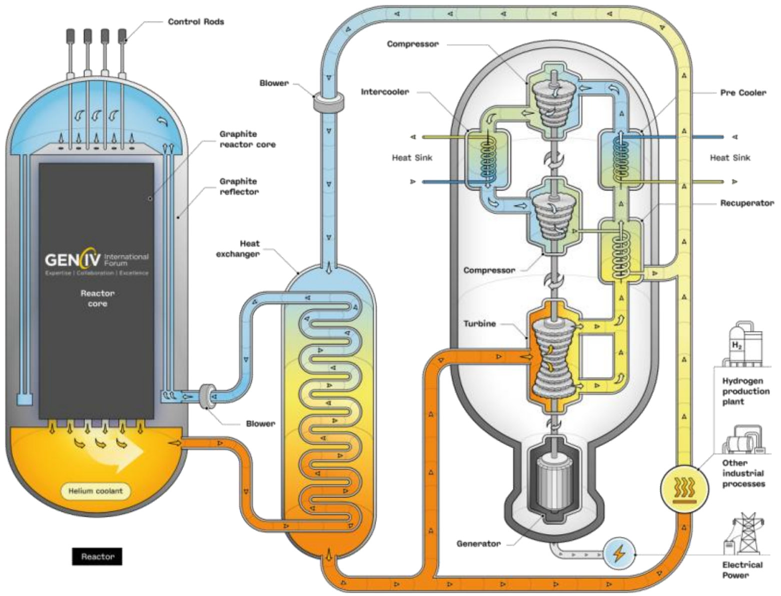
- Use water above critical point (22.12MPa and 647.14 K) as coolant.
- The high outlet temperature increases efficiency
- Potential for fast neutron spectrum in some designs.
- High Pressure -> increased costs for ensuring safety.
- Known technology for gas and coal plants but no experience in nuclear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

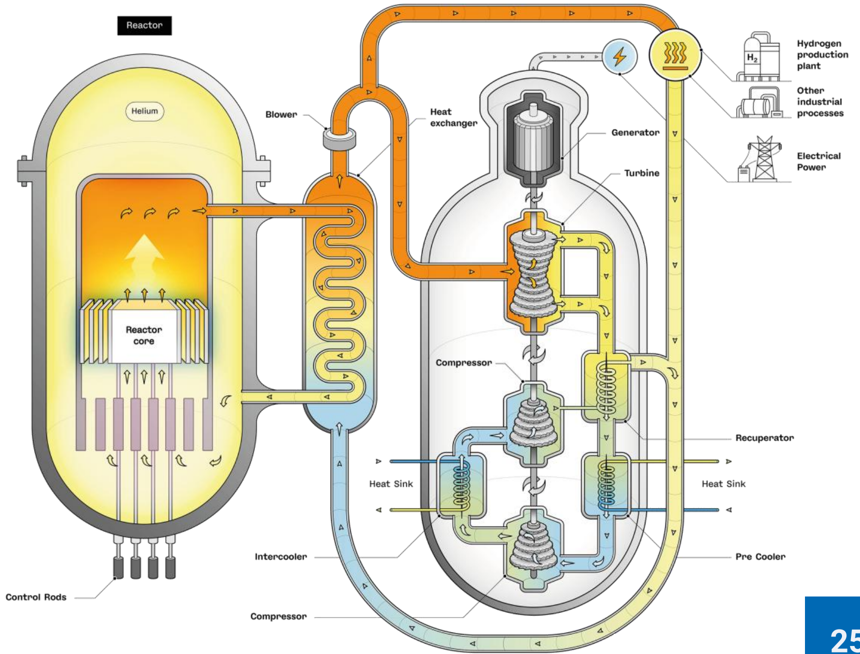
Gas cooled Reactors (HTGR - VHTR, GFR)

	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*



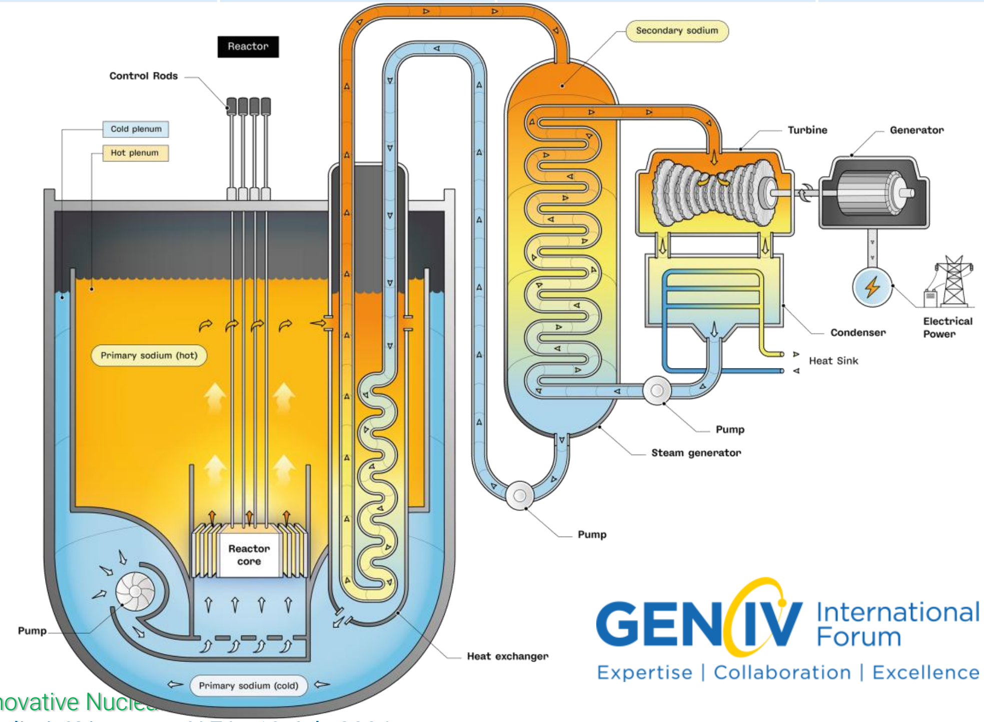




Sodium cooled Fast Reactors

	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



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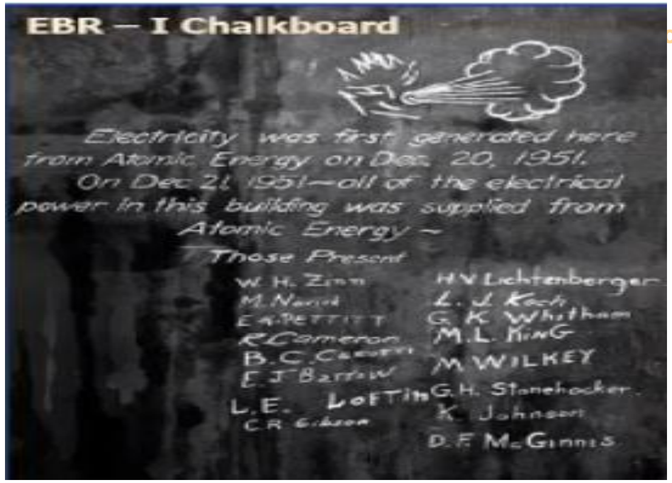
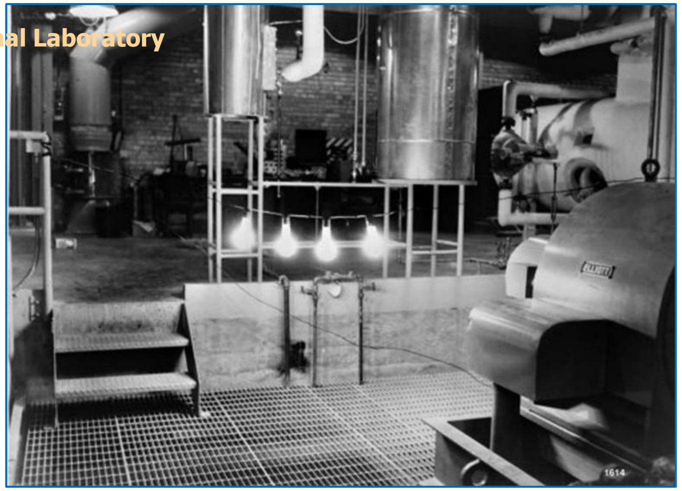
- *Hight coolant T => High Efficiency*
- *Low Pressure*
- *Mature Technology*
- *Fast spectrum*
- *Sodium violently reacts with water and air*

Experimental Breeder Reactor (EBR-I)
(First Ever 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





Fast Reactors in Operation & under Commissioning

IAEA

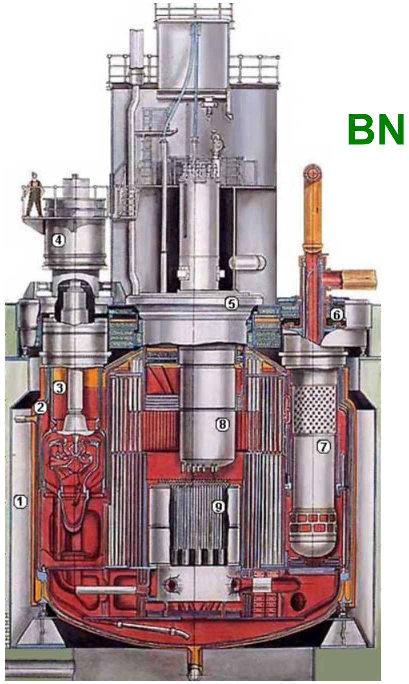
BN-600,
Russia, 1980

CEFR, 20 MW(e)
China, 2011

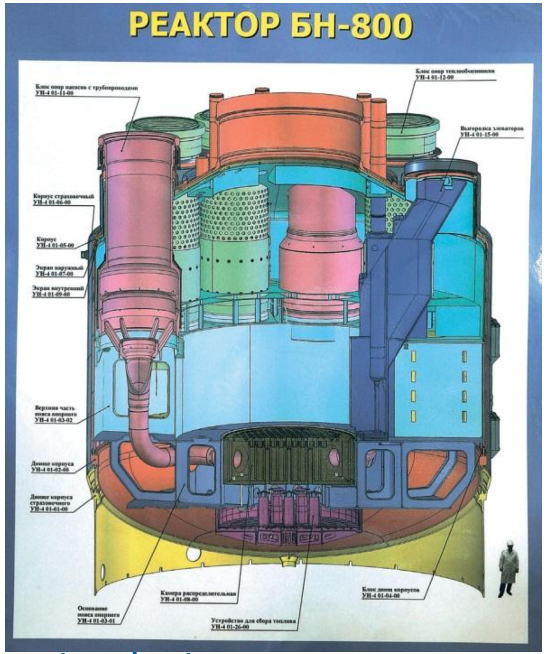
BN-800
Russia, 2015

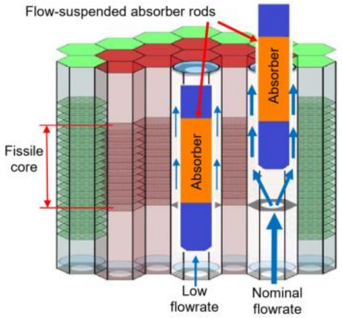
PFBR, 500 MW(e)
India, 2026

SFR: Existing Fleet > Evolutionary > Innovative



BN-600 >>> BN-800





Similar:

- sodium circuits design
- Basic safety systems
- I&C systems including
  - reactor monitoring systems

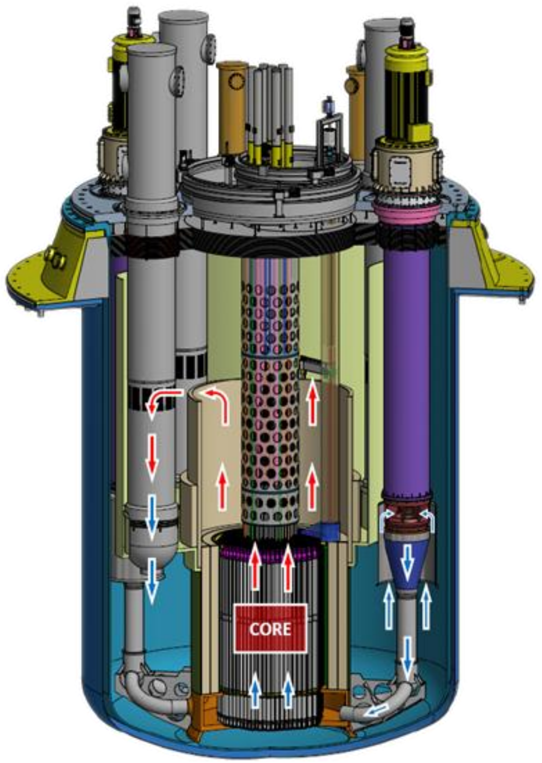
New:

- safety systems
  - including passive: hydraulically suspended control rods
- numerous other improvements

BN-800 >>> BN-1200

- Proven technologies based on BN-600/800 experience
- Safety: accidents that require public evacuation are practically eliminated
  - Additional passive high temperature actuated control rods system
- Fuel: uranium-plutonium nitride
- Lower power density
- Passive DHR systems
- Competitive with other advanced nuclear power plants and with power plants using fossil fuel

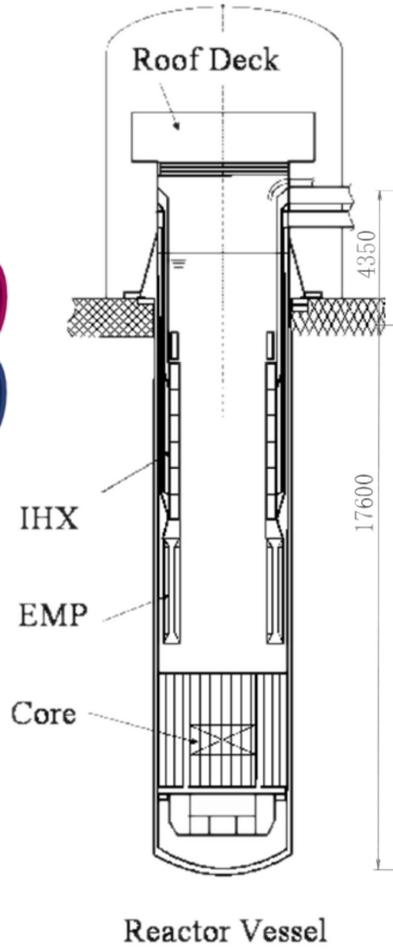
Sodium cooled Fast SMRs



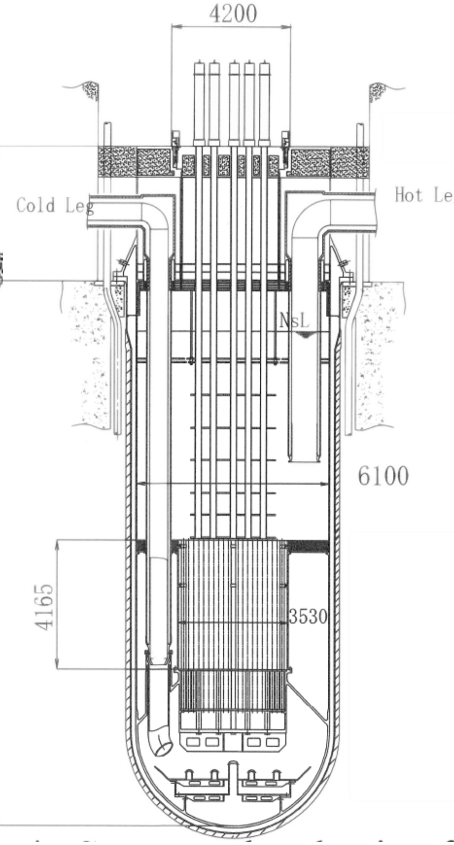
150 MW(e) PGSFR
Rep. of Korea

400 MW(th) HEXANA
France

180MW(th) + 110 MW(e)
OTRERA
France

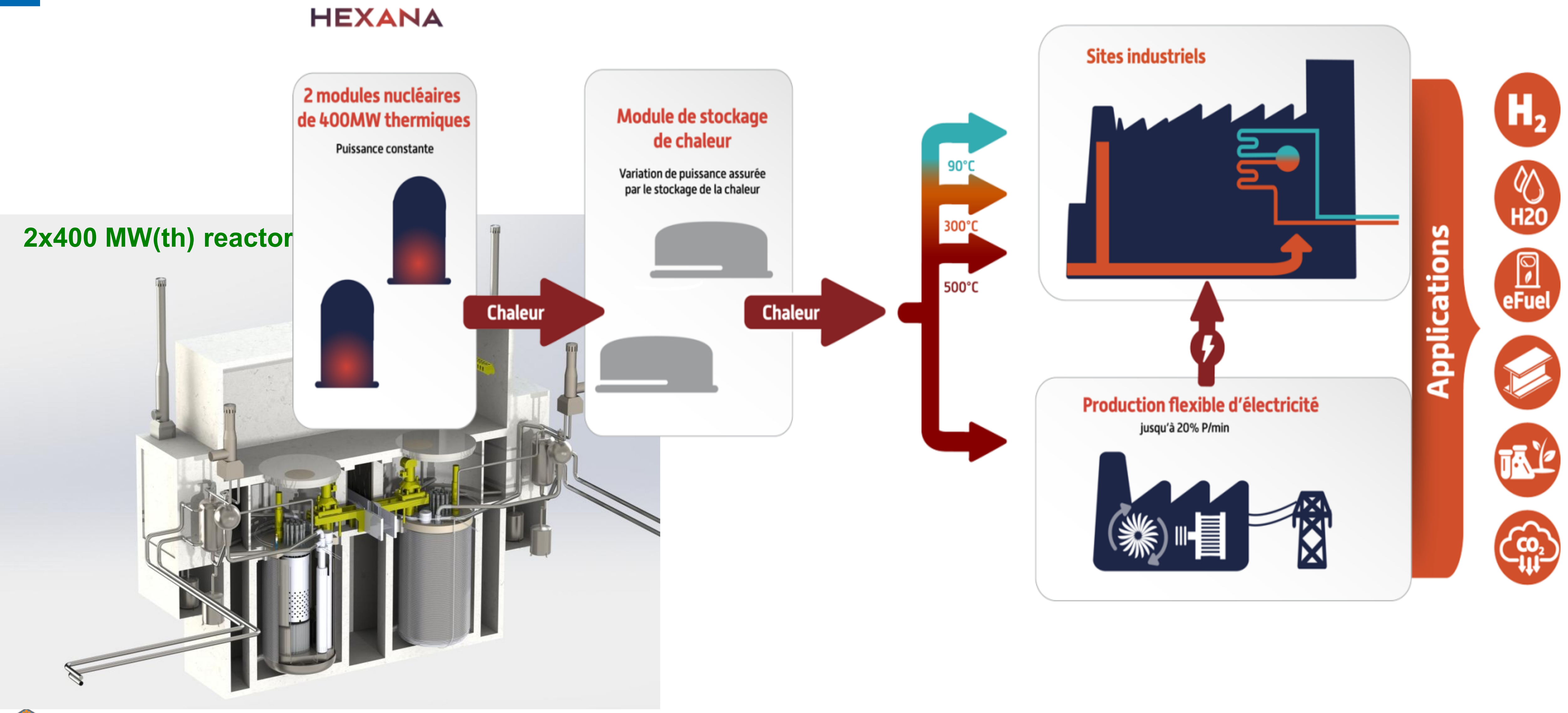


50 MW(e) SMFR
Japan



300 MW(e) SFR
Japan

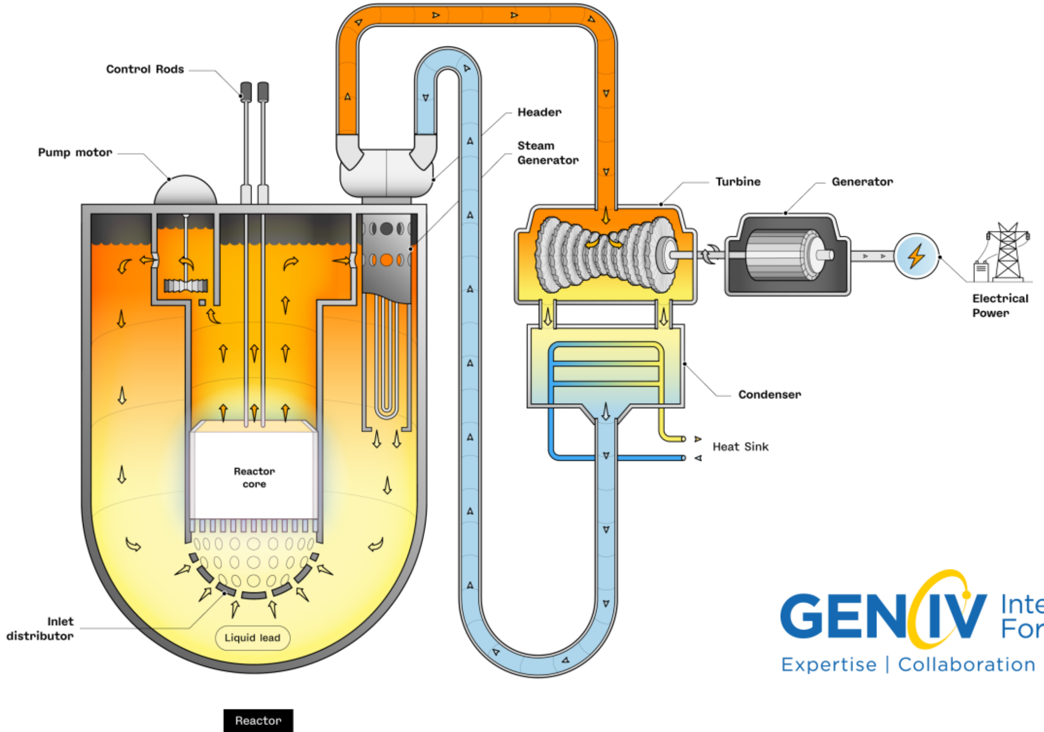
HEXANA: Multi-Purpose SFR



Heavy Liquid Metal cooled Fast Reactors

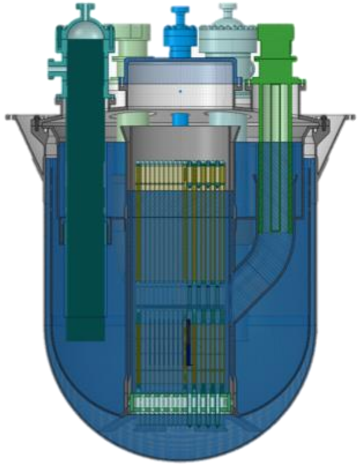
	WCR	SCWR	HTGR	GFR	SFR	LFR
coolant	H_2O	H_2O	He	He	Na	Pb/LBE
outlet T, C	288-329	500	750	750	550	500
efficiency, %	35	45	50	50	45	43
max P, MPa	17	25	7	7	~0.2	~0.5
spectrum	thermal	thermal/**fast**	thermal	fast	fast	fast

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

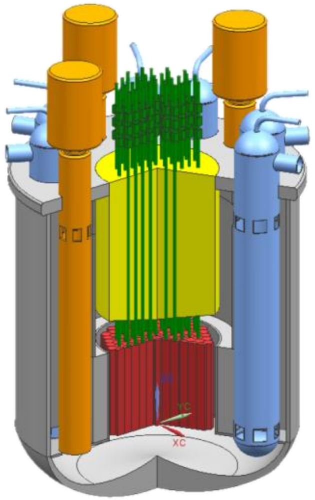


GEN IV International Forum
Expertise | Collaboration | Excellence

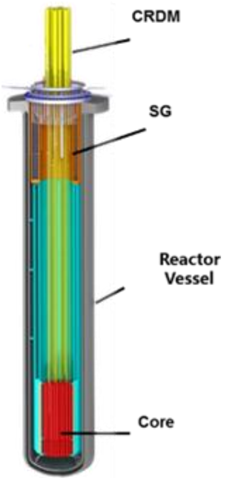
Heavy Liquid Metal cooled Fast Reactors



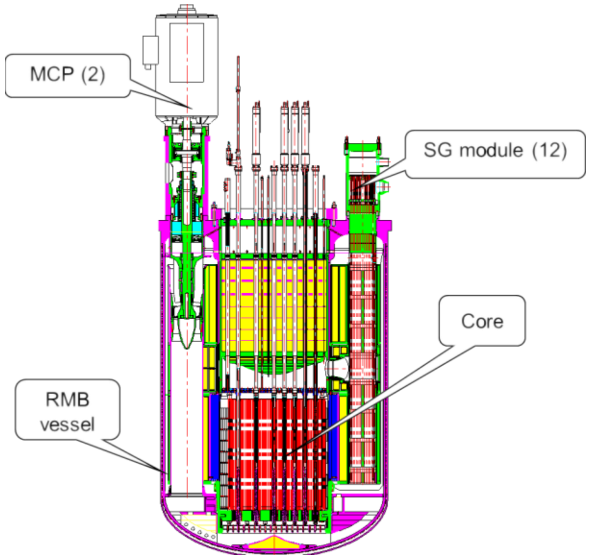
ALFRED
125-250 MW(e)
EU



CLFR-300
China



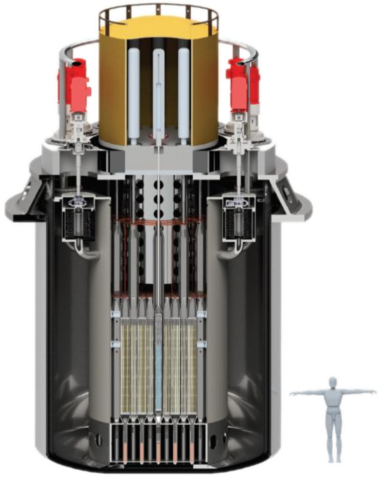
14 MW(e) CLEAR-M10d
China



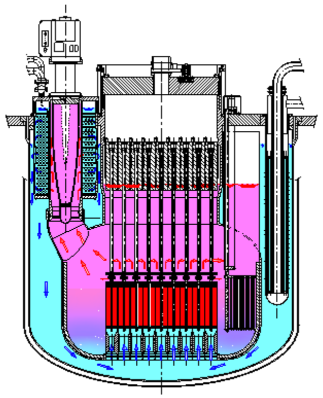
СВБР-100 (LBE)
Russia

BREST-OD-300
Russia

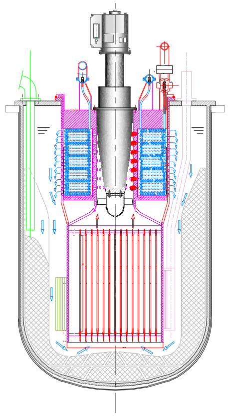
3-10 MW(e) SEALER
Sweden



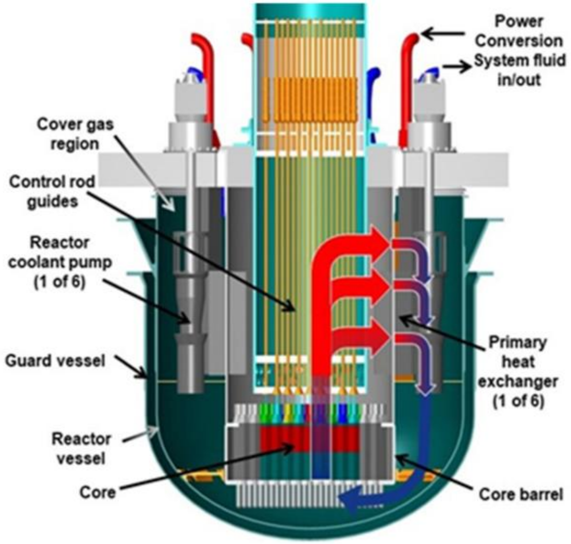
55 MW(e) SEALER
Sweden



LFR-AS-200 MW(e)
newcleo, Italy



Transportable LFR-TL-5 MW(e)
newcleo, Italy



Westinghouse LFR 450 MW(e)
WEC, USA

See recently upgraded ARIS database: aris.iaea.org

中国原子能科学研究院
中核集团 CNNC
CHINA INSTITUTE OF ATOMIC ENERGY
IAEA

Conceptual design of CiFR1000

CiFR1000 is composed of several fast reactors and one fuel regeneration facility in same plant site. Fuel regeneration facility integrate pyro-processing and metal fuel fabrication line for fuel reprocessing and regeneration.

Parameter	Value
1) Coolant type	Na-Na-H_2O
2) Thermal power	2800MWt
3) Electric power	1200MWe
4) Thermal efficiency	>40%
5) Primary loops	4
6) Secondary loops	4
7) Fuel type	Metal Fuel
8) Cladding material	FMC630
9) Breeding ratio	>1.2
10)Maximum fuel burnup	180000MWd/tHM
11) Refueling cycle	>12 months
12) Availability	> 90%
13) Safe Shutdown Earthquake (SSE)	0.3g
14) CDF	$<1\times10^{-6}$
15) LERF	$<1\times10^{-7}$
16) Design life	60 years
17) Construction cycle	60 months

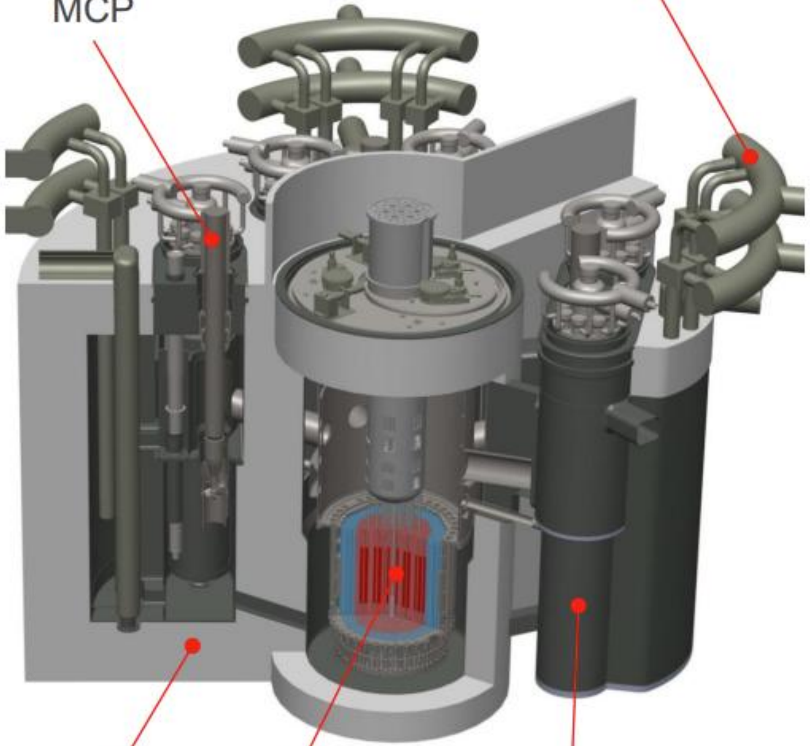
As presented by Mr YANG HongYi at TWG-FR Meeting in June 2025

BREST 300

IAEA

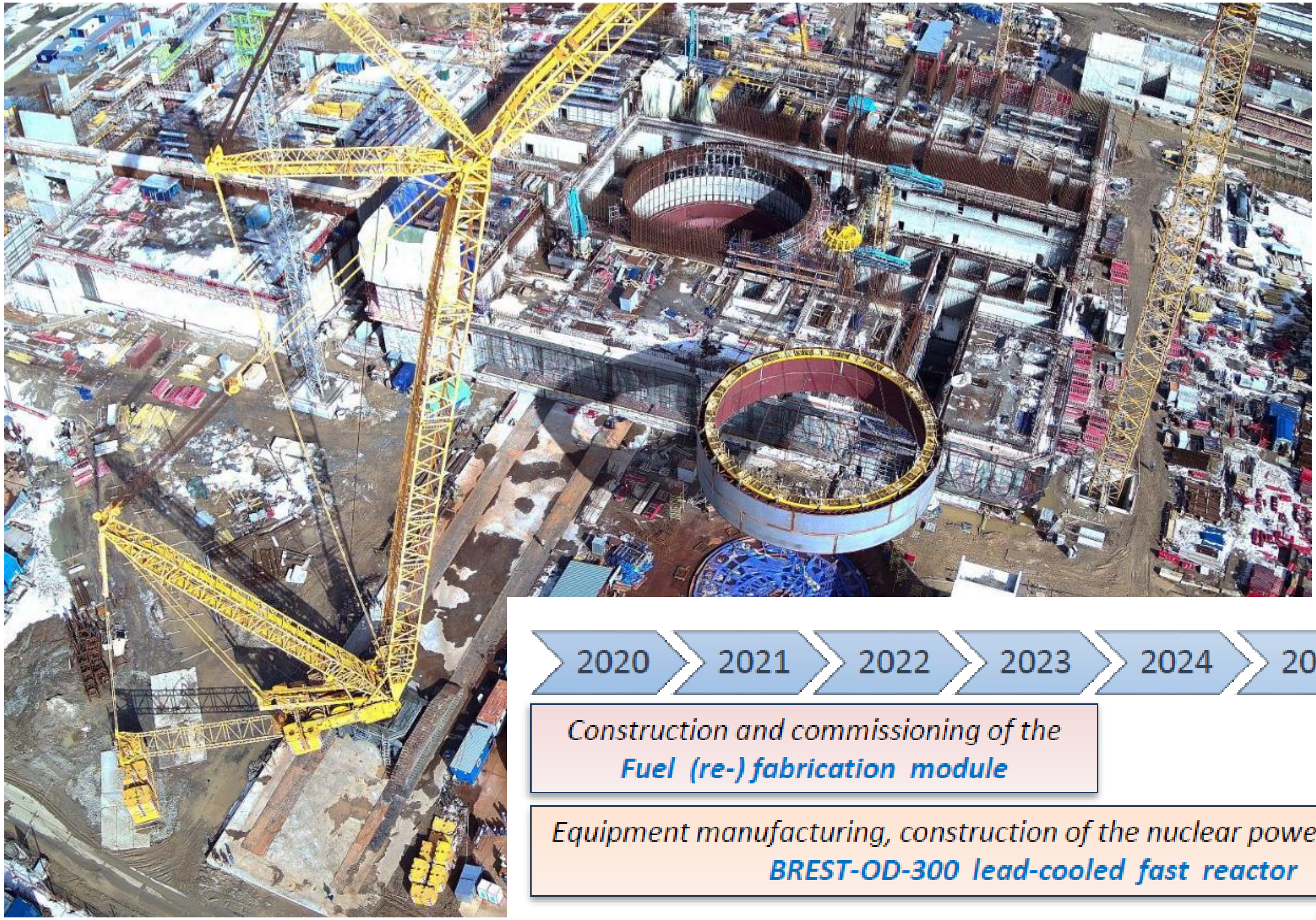
POCATOM

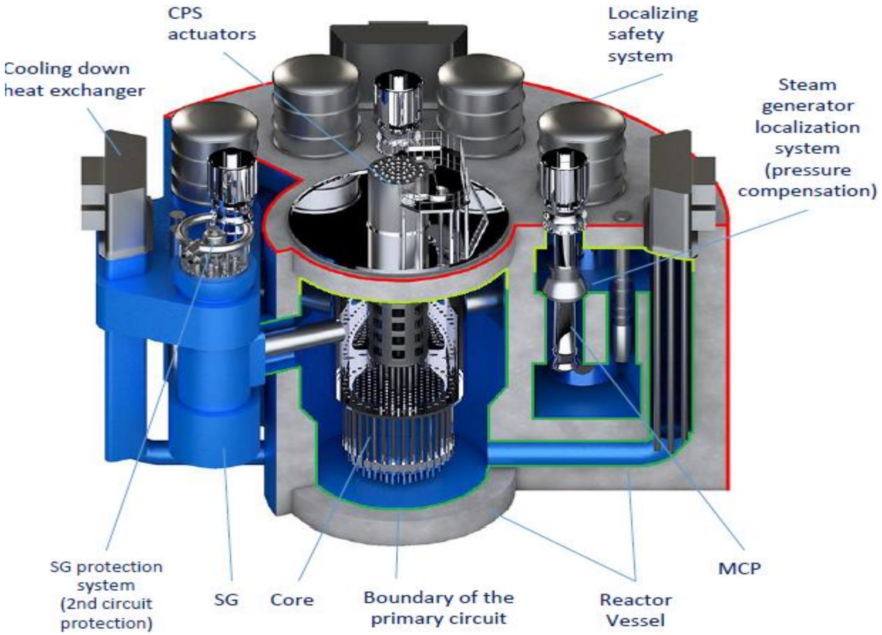
The BREST: key components and technical characteristics



Thermal power, MW	700
Electric power, MW	300
Steam production rate, no less than, t/hour	1480
Coolant of the first contour	Lead
Gas pressure above the lead level: - exceed, MPa - maximal, MPa	 0,003-0,008 0,02
Average temperature of the lead coolant on the active zone entry/ exit, °C	420/540
Average temperature of the lead coolant on the steam generator entry/ exit, °C	340/505
Loop number	4
FA number in the active zone	169
Active zone height, mm	1100
Fuel load, t	20,6
Fuel campaign, years	5
Burn-up of unloaded fuel (maximum/ average), % HM.	9,0/5,5

BREST-OD-300 (April 2024)





2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

Construction and commissioning of the ***Fuel (re-) fabrication module***

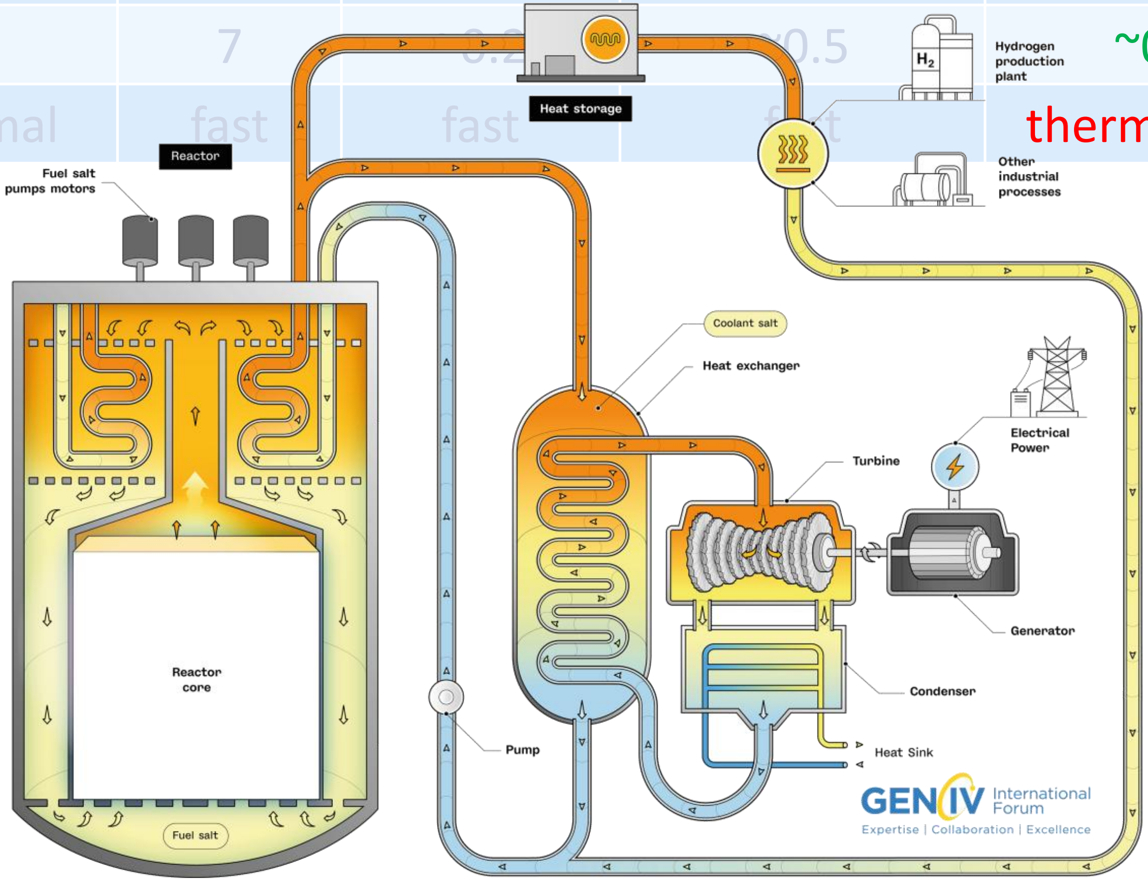
Equipment manufacturing, construction of the nuclear power plant with the ***BREST-OD-300 lead-cooled fast reactor***

Construction and commissioning of the ***Reprocessing module***

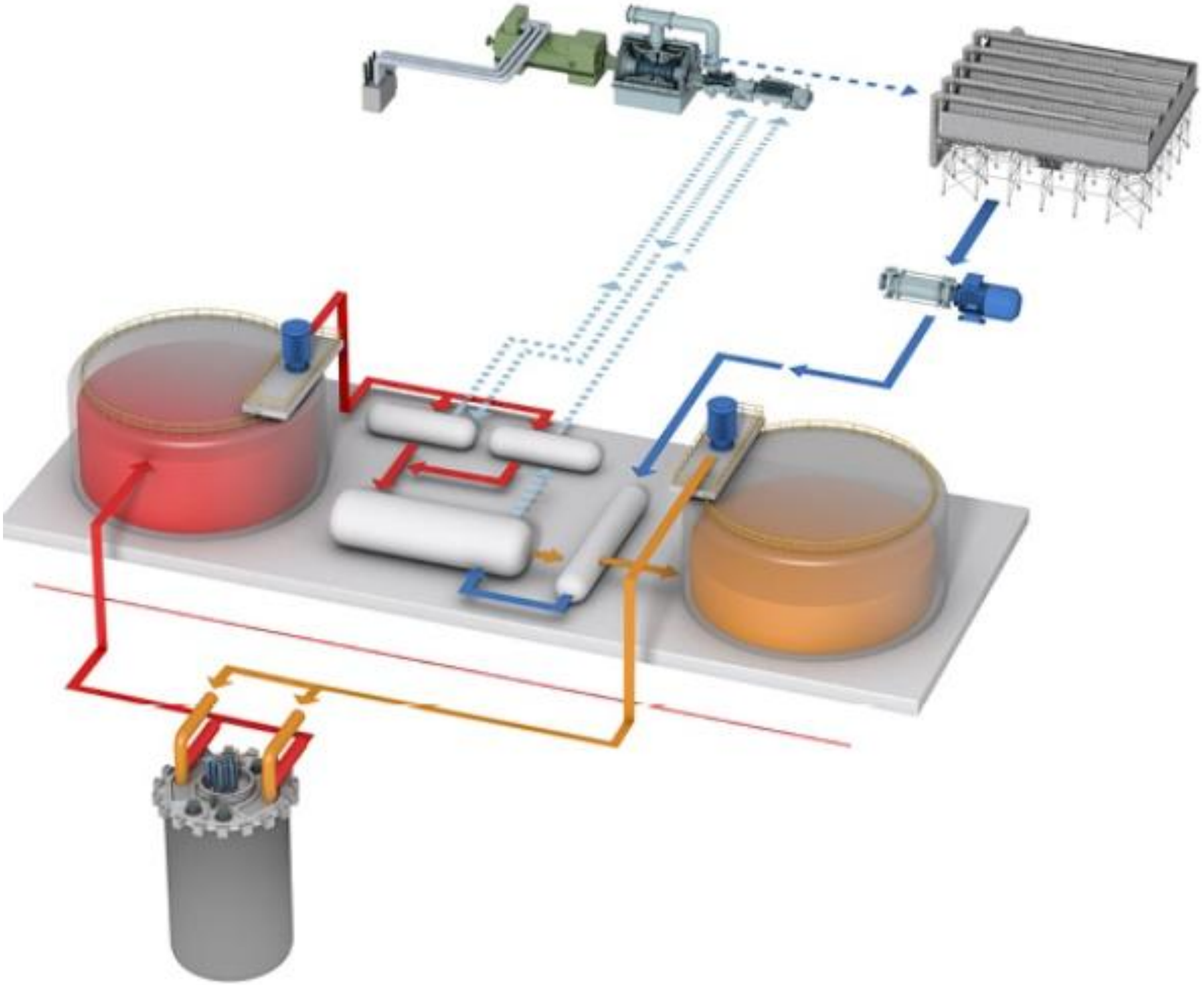
Molten Salt Reactors

	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*



NATRIUM: SFR with Molten Salt Storage System

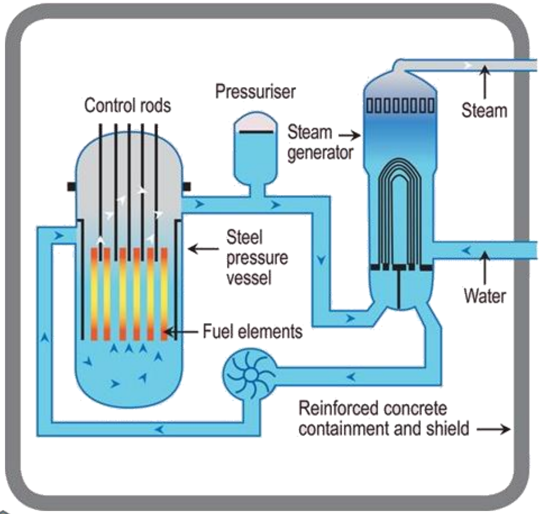


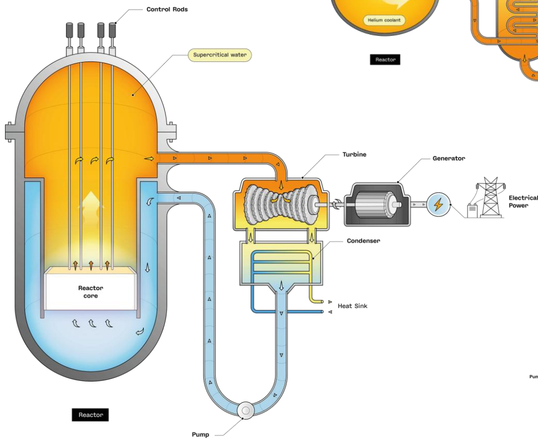
Designed by Terrapower

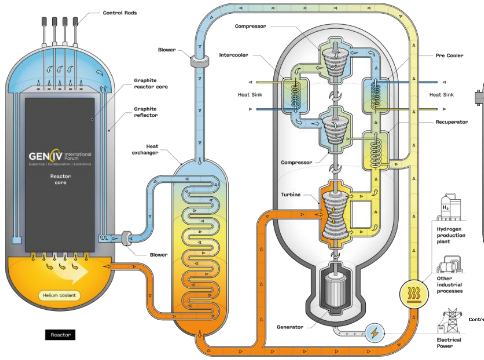
- 345 MW(e) SFR combined with
- 1GW(th) Energy molten salt-based storage system
- Pick power can boost to 500 MW(e)
- Can be used for non-electrical applications
- Can work with renewables

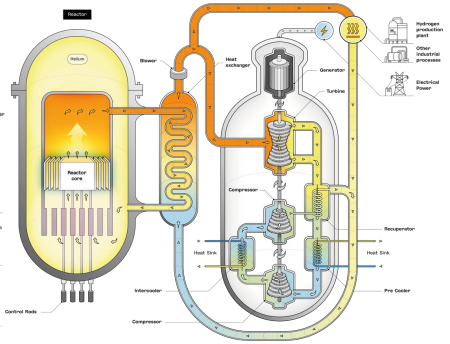
Comparing Innovative Reactor Concepts

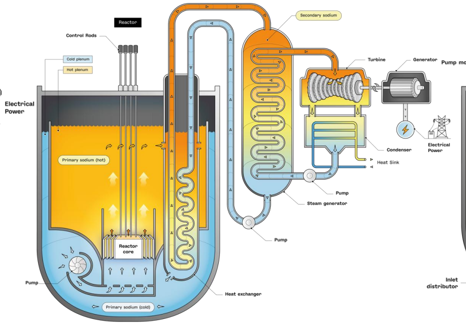
	WCR	SCWR	HTGR	GFR	SFR	LFR	MSR
coolant	H_2O	H_2O	He	He	Na	Pb/LBE	Fluoride/Chloride
outlet T, C	288-329	500	750	750	550	500	800
efficiency, %	35	45	50	50	45	43	48
max P, MPa	17	25	7	7	~0.2	~0.5	~0.2
spectrum	thermal	thermal/fast	thermal	fast	fast	fast	thermal/fast

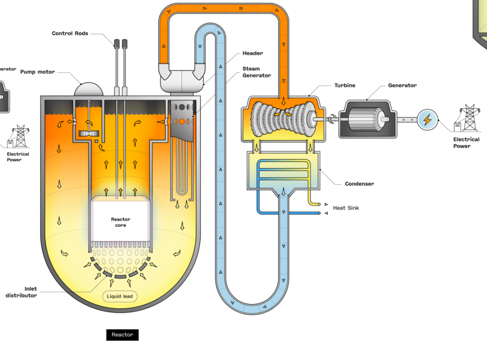


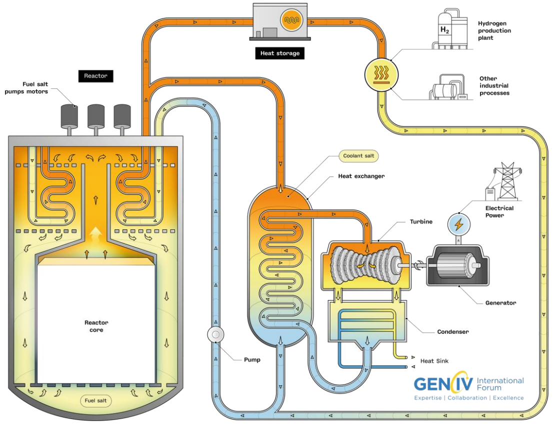












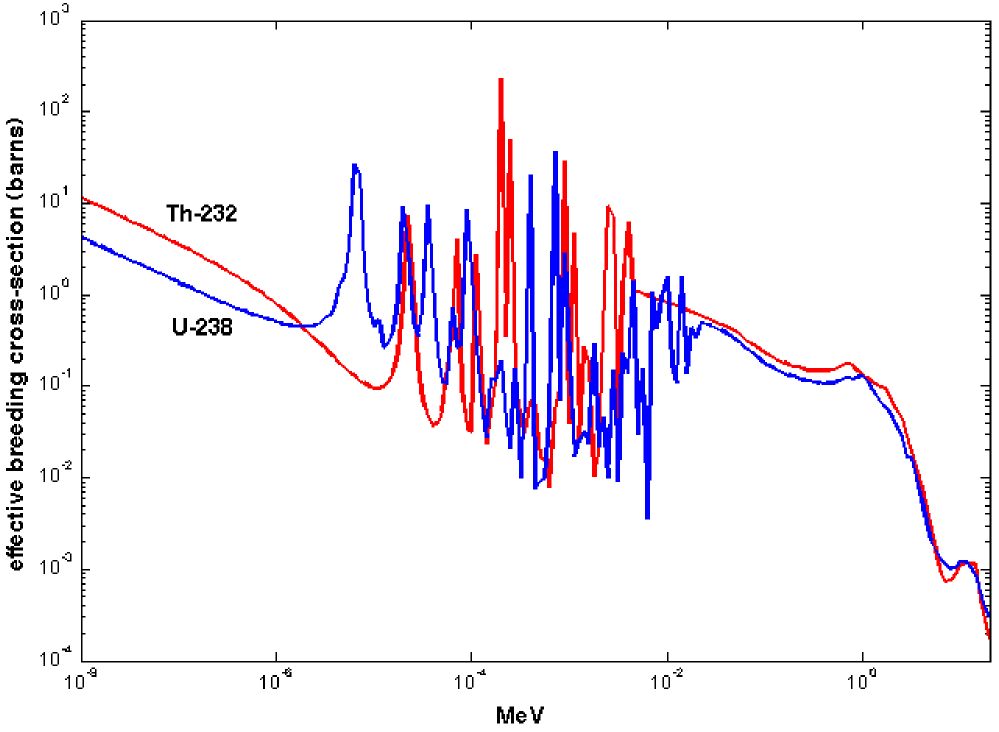
Innovative Reactors: Coolant Properties & More

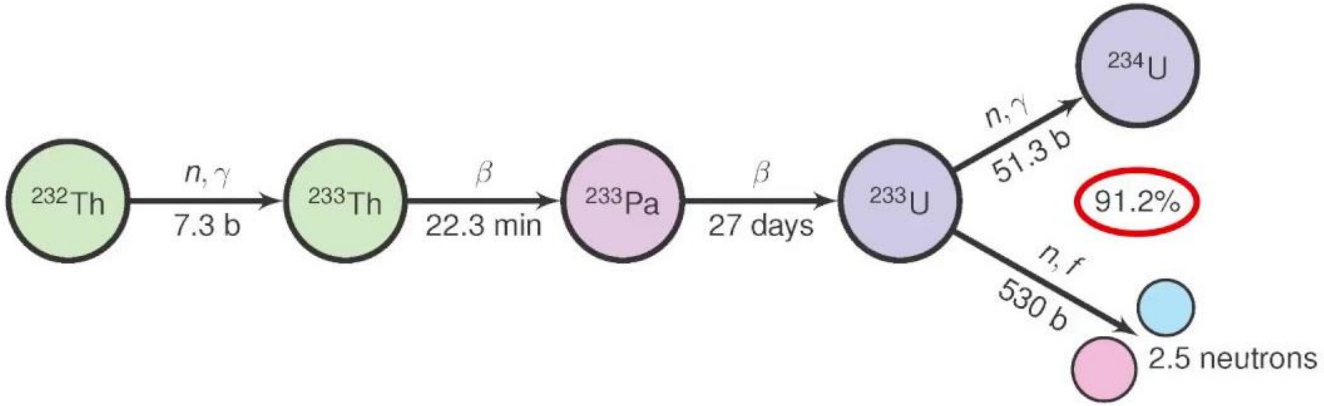
	WCR	SCWR	HTGR	GFR	SFR	LFR	MSR
coolant	H_2O	H_2O	He	He	Na	Pb/LBE	Fluoride/Chloride
outlet T, C	329	500	750	750	550	500	800
efficiency, %	35	45	50	50	45	43	48
max P, MPa	17	25	7	7	0.2	0.5	0.2
n. spectrum	thermal	thermal/fast	thermal	fast	fast	fast	thermal/fast
ρ, kg/m³	700	800/90	0.12/8.5		830	10000	3200
C_P, kJ/kg/K	5.7	5/4	5.2/5.2		1.3	0.15	1.4
ρC_P, MJ/m³/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

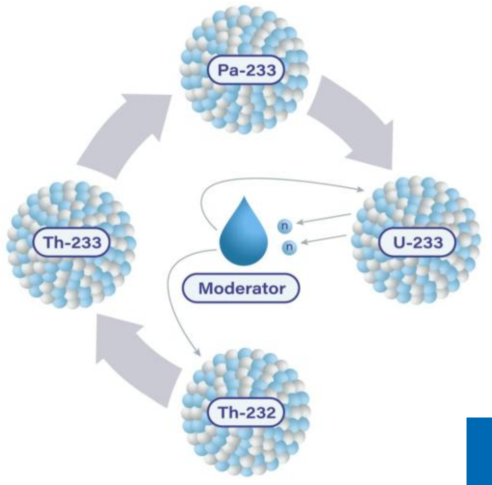
1) CMI: Coolant – structural Materials Interaction

Thorium Fuel Cycle

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





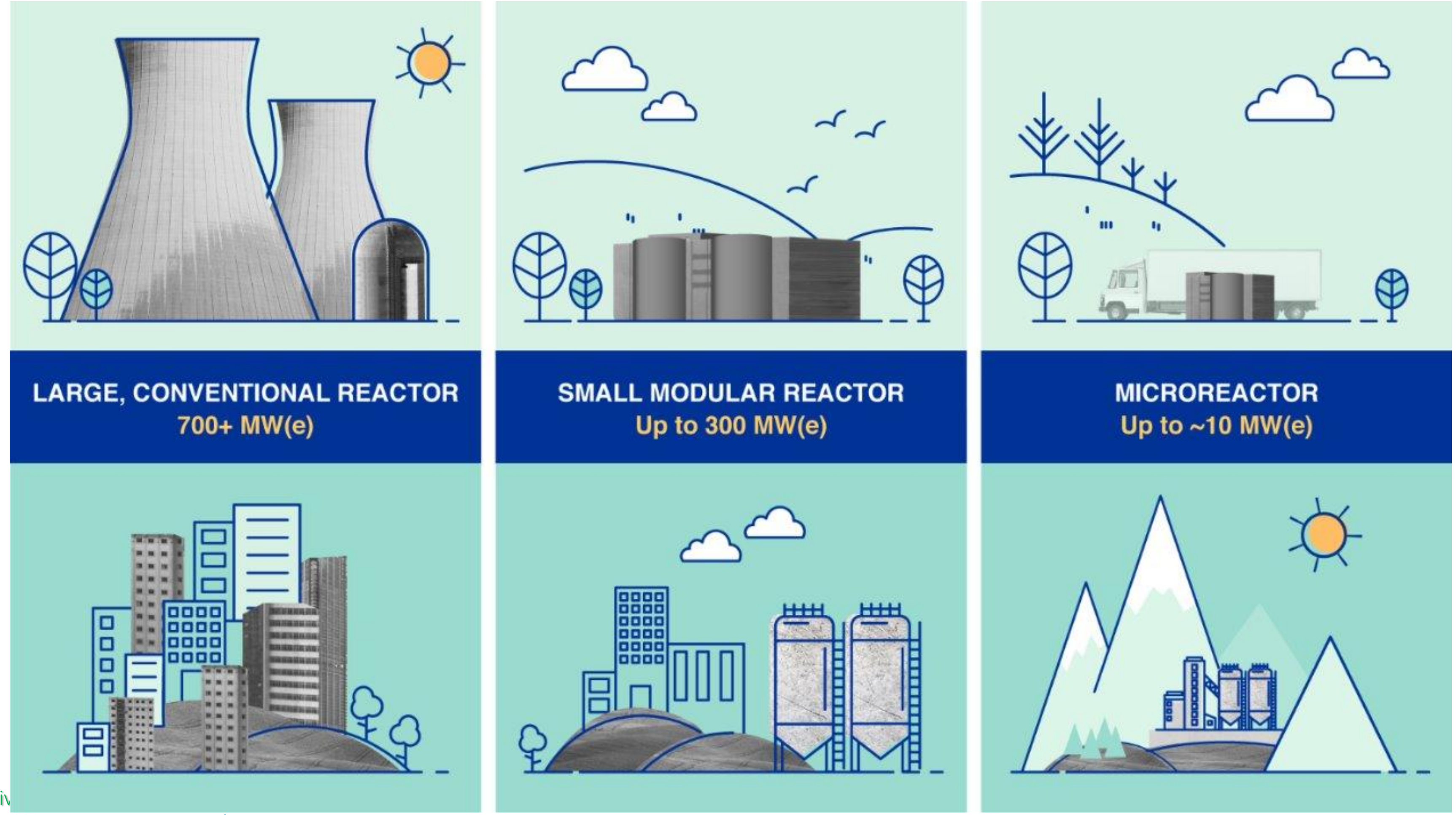


Absorption of neutrons by ^{232}Th initiates the series of transformations leading to the production of fissile ^{233}U that is by far the best ‘fissile’ isotope for thermal neutron spectrum and can be used for breeding in both thermal and fast reactors.

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

Small Modular Reactors

Advanced Reactors that produce typically **up to 300 MWe**, built in factories and transported as **Modules** to sites for installation as demand arises.



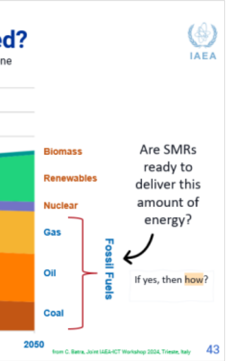
Small: in size, compared to traditional reactors.

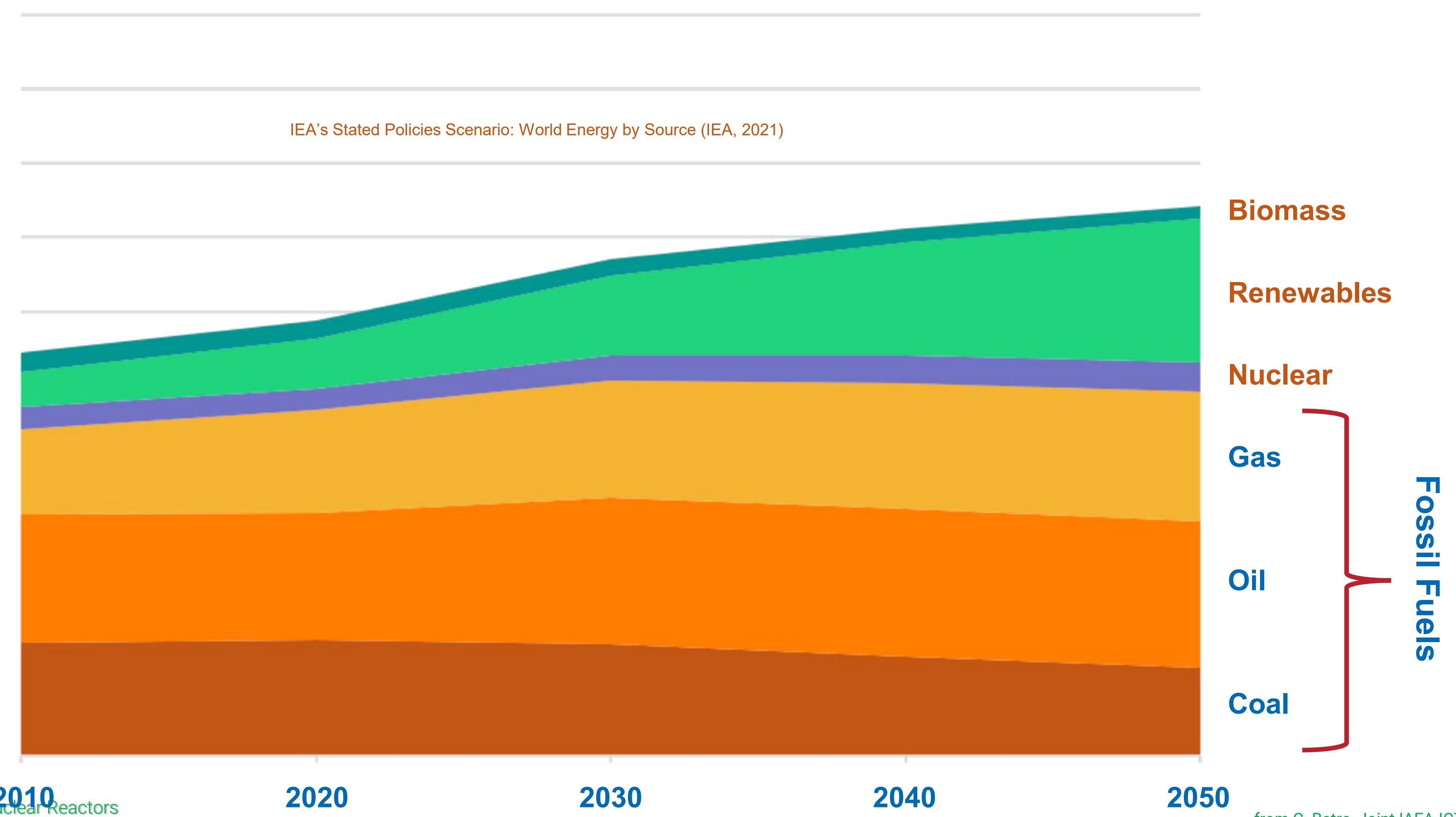
Modular: factory-manufactured, installed onsite.

Reactor: energy generation via nuclear fission.

How much clean energy do we need?

Now, this question is different from the previous one



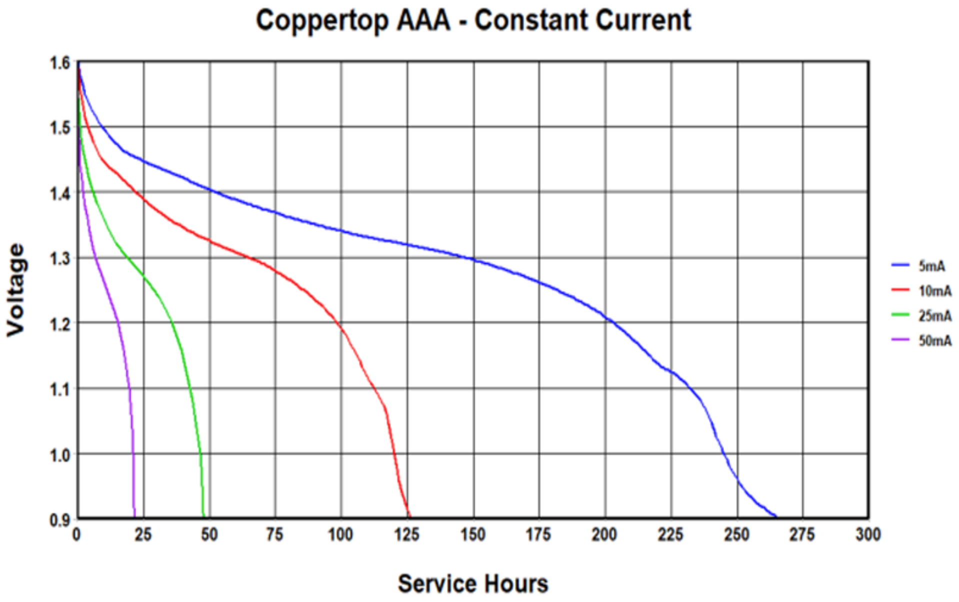


Are SMRs ready to deliver this amount of energy?

If yes, then how?

Understanding Product: AAA Batteries

Nominal voltage	1.5 V
Impedance	156 m-ohm @ 1 kHz
Typical weight	11 g (0.4 oz)
Typical volume	3.5 cm³ (0.2 in³)



- Nominal Voltage: 1.5 V
- Battery capacity: 1200 mAh
- Energy capcity: $1.5 \times 1200 = 1800$ mWh = 1.8 Wh
- Cost of 1 battery < $1
- Cost per kWh = 1/1.8 ~ $550 /kWh!!

https://batteryspecialties.com/batteries/Duracell/MN2400BK/MN2400BK-CS1190

- But we still use it. Why?
  - *It is a product designed for the right market. If we look only at the cost as a metric, we will never use a AAA battery*

Deployment and Development Status in Brief (1/3)

In operation

Floating NPP "Akademik Lomonosov"

- *Russian Federation*
- *2 units of KLT-40S (PWR), 35 MW(e) per unit*
- *Commercial operation started May 2020, first fuel cycle completed*

HTR-PM

- *China*
- *2 units of high temperature gas cooled reactor pebbled-bed module, 200 MW(e) generated from single Turbine Island*
- *Operation started in 2023*

Under construction

ACP100

- *China*
- *Integral PWR, 125 MW(e)*
- *Operation expected in 2026*

BREST-OD-300

- *Russian Federation*
- *Lead-cooled fast reactor, 300 MW(e)*
- *Operation expected in 2026*

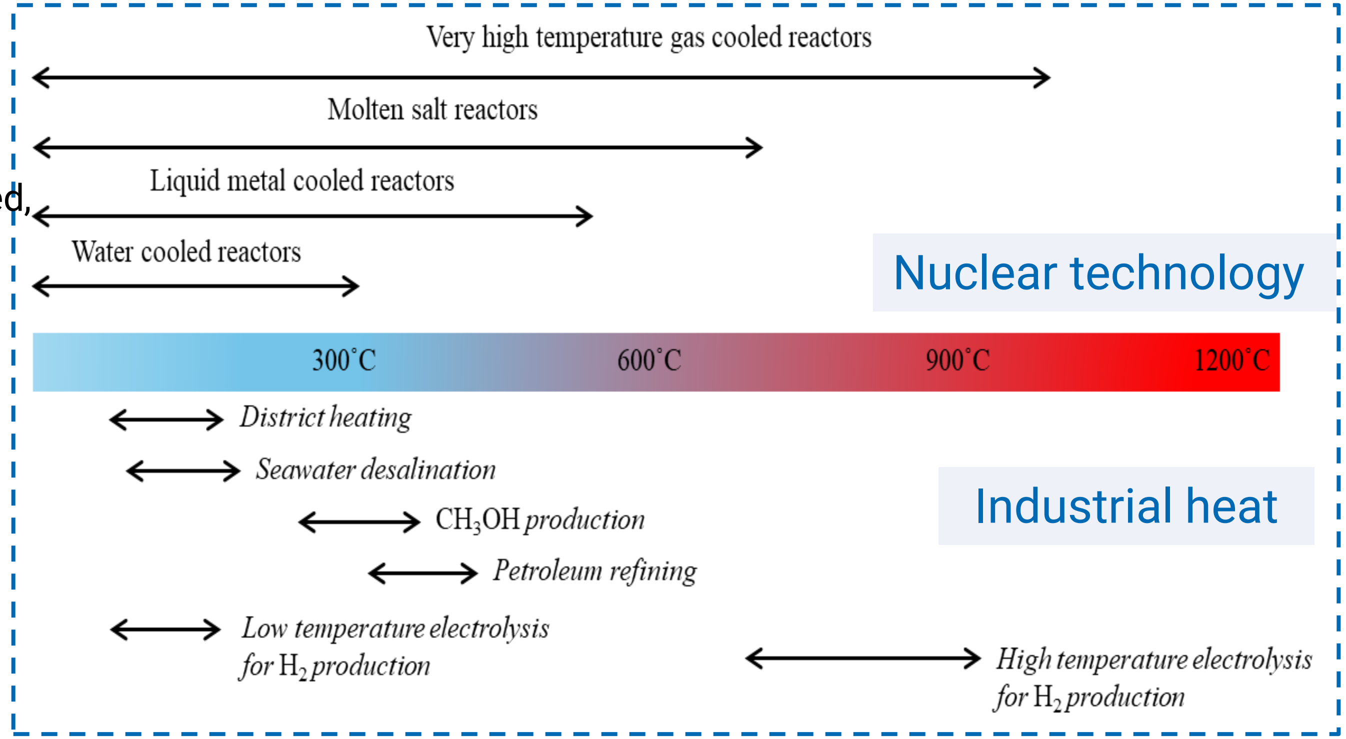
CAREM

- *Argentina*
- *Integral PWR, 32 MW(e)*

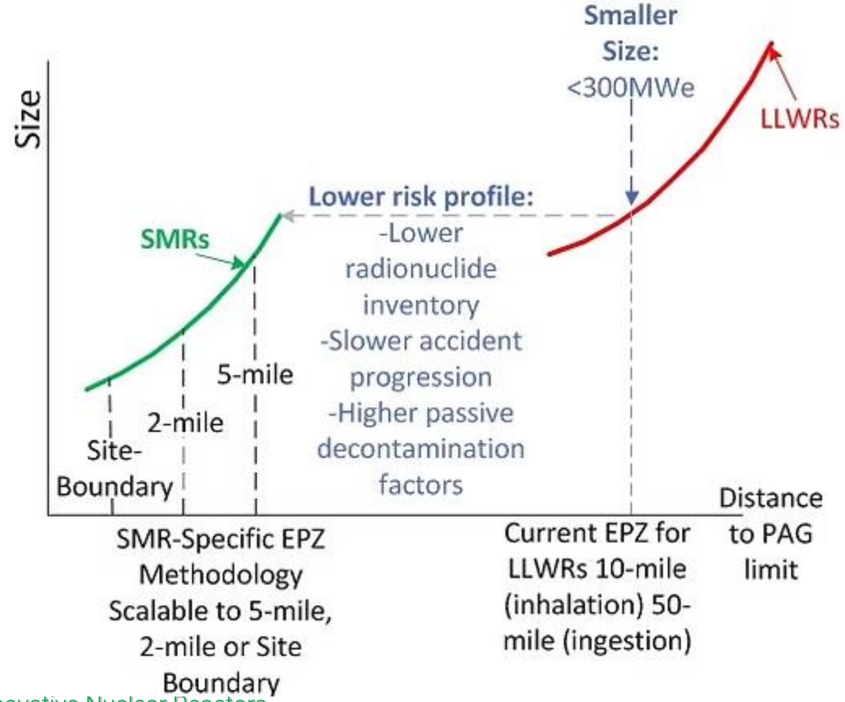
Non-Electric Applications

The nature of the industrial heat market is highly fragmented, and therefore suitable for SMRs

50% of the users for industrial processes require less then 10 MWth
40% require 10 -50 MWth
99% included in the 1 to 300 MWth range



Small emergency preparedness zone (EPZ) Provides to locate SMRs close to end-users



Interest in non-el applications

Country	Organization	Applications
China	Bauwu	Hydrogen for steel production
Italy	Federacciai	Steel production
Japan	Nippon Steel	Hydrogen for steel production
Jordan	Jordan Atomic Energy Commission	Desalination
Korea	Nuclear Heat Utilization Council	Process heat, Hydrogen for steel production
Poland	Synthos Chemical Group	Hydrogen production
USA	Dow Chemicals	Process heat

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]

Atoms for Peace and Development…

Thank You!

email: FR@IAEA.ORG