IAEA
International Atomic Energy Agency

"Atoms for Peace and Development"

3rd Joint ICTP-IAEA Workshop on Physics and Technology of Innovative Nuclear Energy Systems

12 – 16 December 2022, Trieste, Italy

Overview of Innovative Reactor Designs

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FastRTeam

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

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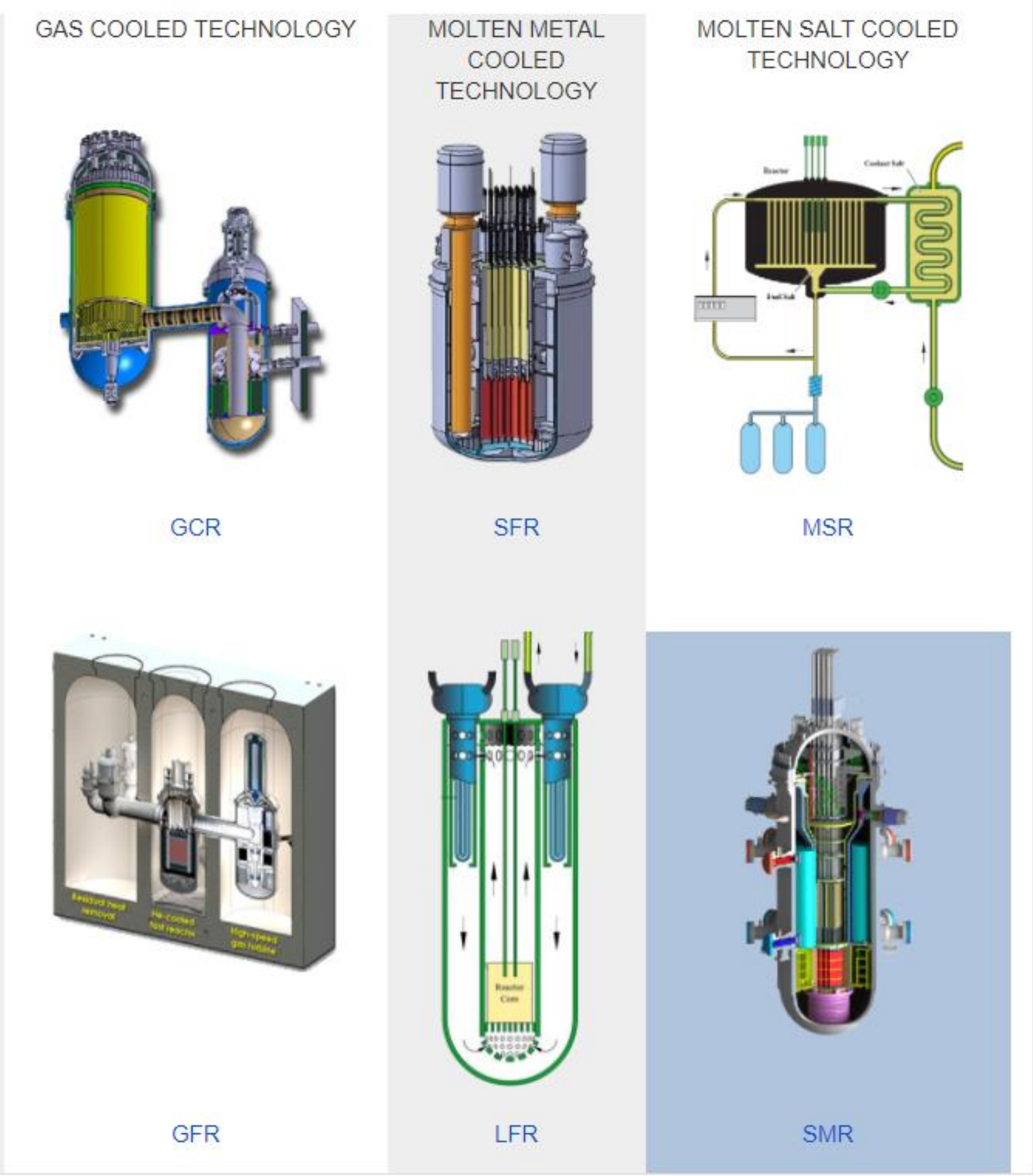
Outline

- Reactor Classification and Innovative Fast Neutron Systems
- GIF Systems and IAEA Terminology
- Comparison of Coolant Physical Properties
- Six GIF Gen-IV reactor concepts and other innovative systems
  - *Sodium cooled Fast Reactor (SFR)*
  - *Lead and LBE cooled Fast Reactor (LFR)*
  - *Gas cooled Fast Reactor (GFR)*
  - *Very High Temperature Reactor (VHTR)*
  - *Super Critical Water cooled Reactor (SCWR)*
  - *Molten Salt cooled Reactor (MSR)*
- Fast Reactors: World Status

IAEA and GIF Terminology

- **Early Prototypes and Demonstration Plants Gen I**
- **Current Fleet Gen II-III**
- **Advanced Nuclear Reactors**
  - *Evolutionary designs* Gen III and III+
  - *Innovative designs* Gen IV
  - SMRs can be either *evolutionary* or *innovative*
- **ARIS:** IAEA Advanced Reactors Information System: https://aris.iaea.org/



Generation IV Goals

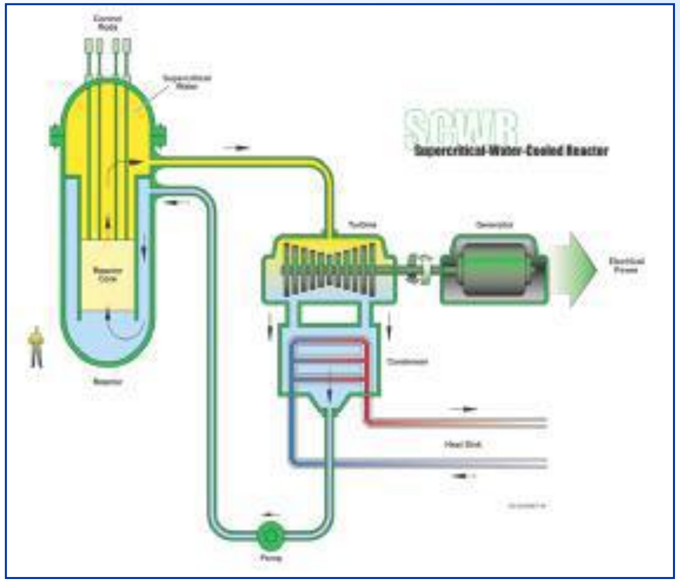
www.gen-4.org

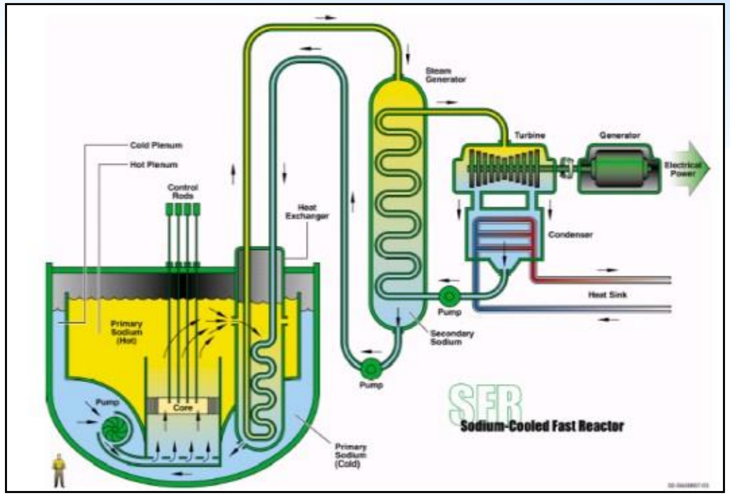
Sustainability	Gen-IV nuclear energy systems (NES) will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production.
	Gen-IV NES will minimise and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
Economics	Gen-IV NES will have a clear life-cycle cost advantage over other energy sources.
	Gen-IV NES will have a level of financial risk comparable to other energy projects.
Safety and Reliability	Gen-IV NES operations will excel in safety and reliability.
	Gen-IV NES will have a very low likelihood and degree of reactor core damage.
	Gen-IV NES will eliminate the need for offsite emergency response.
Proliferation Resistance and Physical Protection	Gen-IV NES 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.

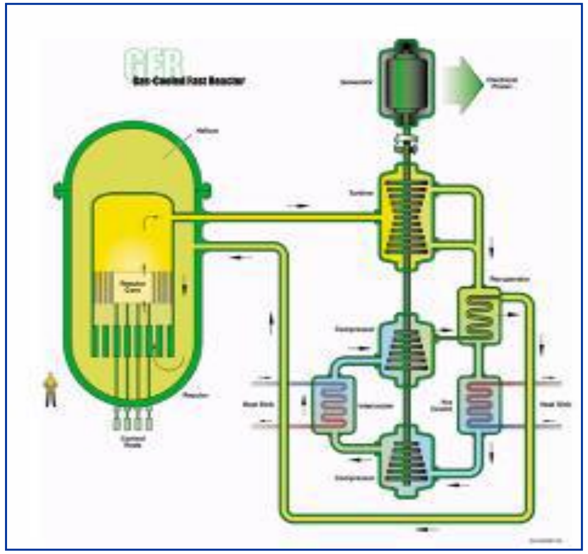
General Reactor Classification

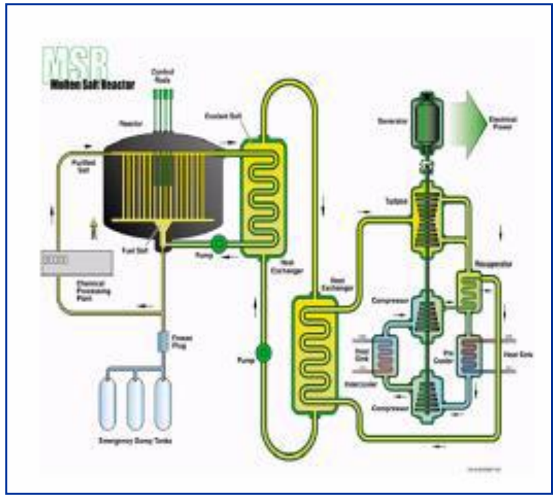
- Moderator
  - Water / Heavy Water
  - Graphite
  - None (fast neutron systems)
- Coolant
  - Water/Heavy Water
  - Liquid Metal
    - Sodium / Lead / Lead-Bismuth Eutectic (LBE)
  - Gas
    - Air / CO_2 / Helium
  - Molten Salt
- Fuel
  - UO2
  - MOX (UO_2 + PuO_2)
  - Metallic
  - U/Pu nitride
  - Molten Salt
- Purpose
  - Electricity/Non-Electric Application
- Power
  - Low/Middle/High

GEN-IV Reactors (GIF)









Six GIF Technology Systems

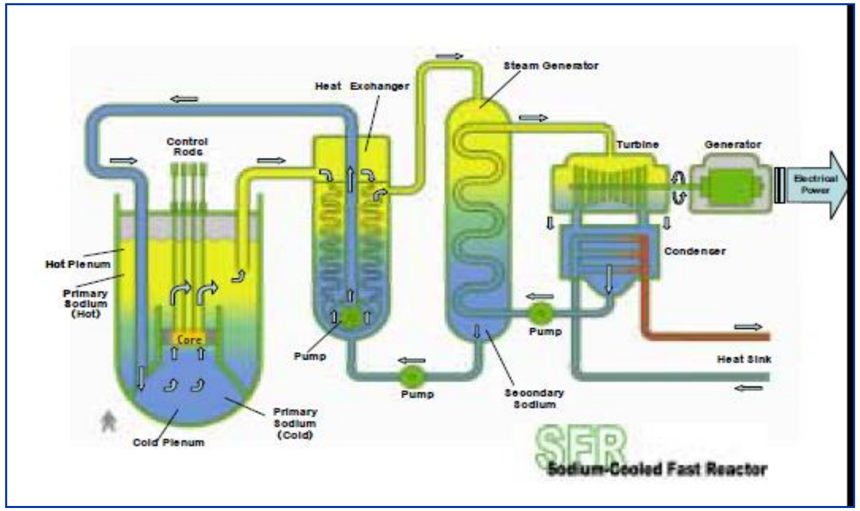
www.gen-4.org

System	Neutron spectrum	Coolant	Outlet Temperature °C	Fuel cycle	Power (MWe)
VHTR (Very-high-temperature reactor)	Thermal	Helium	900-1000	Open	250-300
SFR (Sodium-cooled fast reactor)	Fast	Sodium	500-550	Closed	50-150 300-1500 600-1500
SCWR (Supercritical-water-cooled reactor)	Thermal/fast	Water	510-625	Open/closed	300-700 1000-1500
GFR (Gas-cooled fast reactor)	Fast	Helium	850	Closed	1 200
LFR (Lead-cooled fast reactor)	Fast	Lead	480-570	Closed	20-180 300-1200 600-1000
MSR (Molten salt reactor)	Thermal/fast	Fluoride salts	700-800	Closed	1000

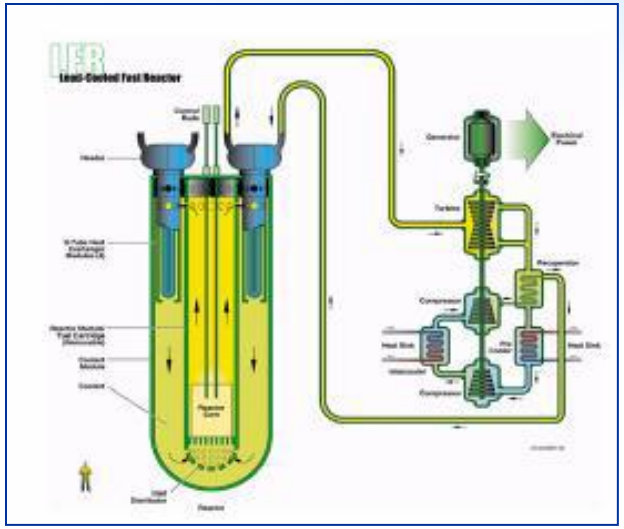
Six Generation-IV Reactor systems

GIF website: www.gen-4.org

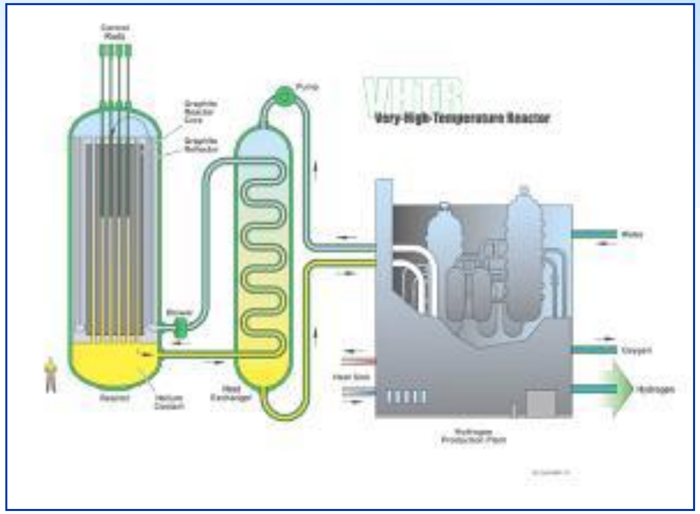
Sodium cooled Fast Reactor (SFR)

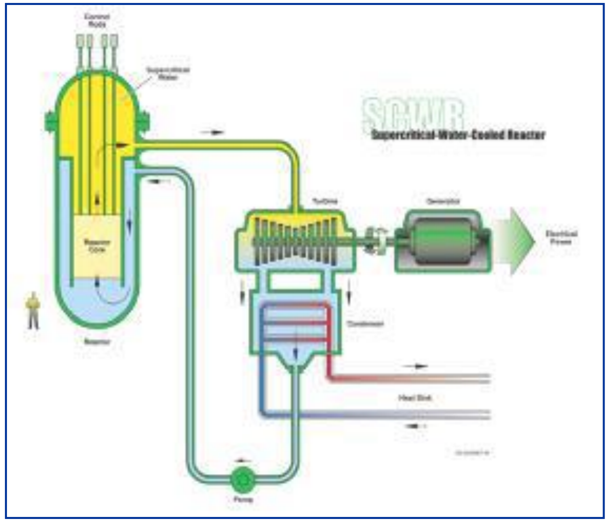


Lead cooled Fast Reactor (LFR)

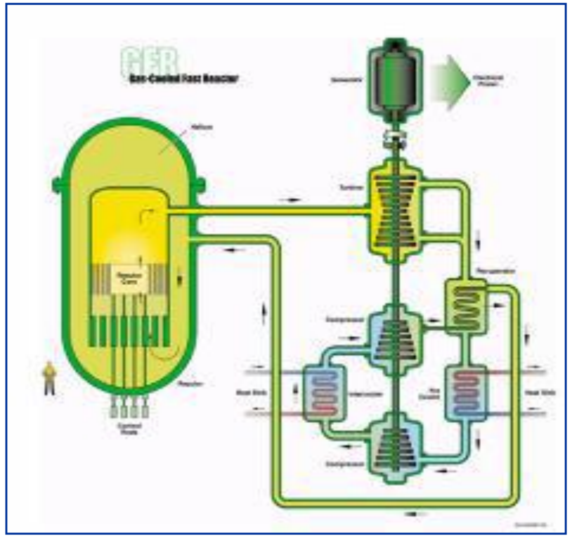


Very-High-Temperature Reactor (VHTR)

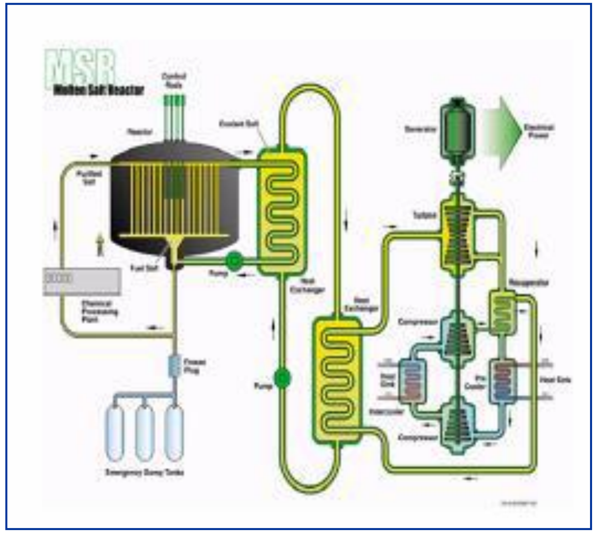




Supercritical Water cooled Reactor (SCWR)



Gas cooled Fast Reactor (GFR)



Molten Salt Reactor (MSR)

Coolants: *key physical properties* (1/3)

- Melting temperature: impact on the reactor's cold shutdown temperature for fuel handling
- Boiling point and liquid phase temperature range
- Thermal characteristics: Cp, λ, Prandtl number
- Thermal stability: decomposition close to high temperature, safety margin
- Density: impact on power pumping required, internal dynamic pressures, seismic behavior
- Interaction with structural materials: Dissolution (solubility of metal elements), corrosion, embrittlement and potential mass transfer
- Chemical reactivity with surrounding fluids (air, water, organic products, etc) and impact on operating safety

Coolants: *key physical properties* (2/3)

- Interaction with primary coolant when used as different intermediate coolant: corrosion, contamination.
- Interaction with ECS coolants (water, SC CO2, etc) when used as different intermediate coolant: corrosion, contamination
- Transparency/opacity: special in-service inspection methods
- Vapor pressure: impact on aerosols production and deposition
- Ability to "block" the Tritium produced in the primary system (Tritium is the only radioactive contaminant capable to cross metal walls)
- Capability to be purified and meet quality standards

Coolants: *key physical properties* (3/3)

- Potential structures wetting: impact on fluid-material interactions, instrumentation, quality of ultra-sound transmission, maintenance
- Toxicity: need to confine the coolant during handling and repair
- Possibility of processing during dismantling, including specific systems like cold trapping
- Production of wastes and their processing during operation and dismantling
- Availability in nature
- Cost

Fast Reactor Coolants: Neutronic Considerations

- Neutrons interact with the atoms of the coolant
- The strength of the overall effect is governed by the probability of a particular interaction (absorption or scattering) and the number density of the coolant atoms
- Absorption removes neutrons from the system
- Scattering causes the neutrons to “bleed” energy thus slowing them down (moderation)
- Both of these mechanisms add negative reactivity
- If the coolant is removed (lost or “voided”), the loss of negative reactivity is equivalent to an insertion of positive reactivity:

Void Reactivity effect

Coolant Thermal-Physical Properties

		H_2O	Na	Pb	LBE	He	LiF-BeF_2-ThF_4-UF_4
Atomic Weight		18	23	207	208	4	
Melting Point	°C	0	97.8	327.4	123.5		~500
Boiling Point	°C	100/ 350	892	1737	1670	-267	~1700
Density	kg/m3	1000	832	10460	10080	0.178 8.491	~3200
Vol. Heat Capacity	MJ/m3/K	4.18	1.05	1.53	1.47	0.00093 0.044	~4.5
Specific Heat Capacity	J/kg/K	4180 5682	1264	147	146	5200	~1400
Thermal Conductivity	W/m/K	0.6	70	18	15	0.152 0.238	~0.01
Kinematic Viscosity	$m^2/s \times 10^6$	1 0.12	0.28	0.11	0.13	0.15 0.71	~2.3

cold 20 °C
water at 17Mpa
hot water 300 °C
hot LM, 500 °C,
hot He 850 °C, 20 MPa

Sodium Cooled Fast Reactor (SFR)

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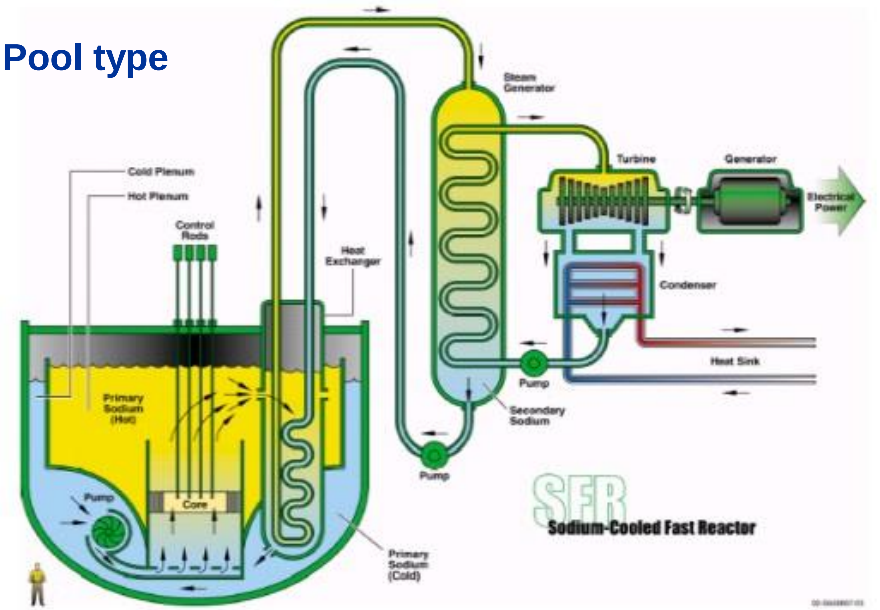
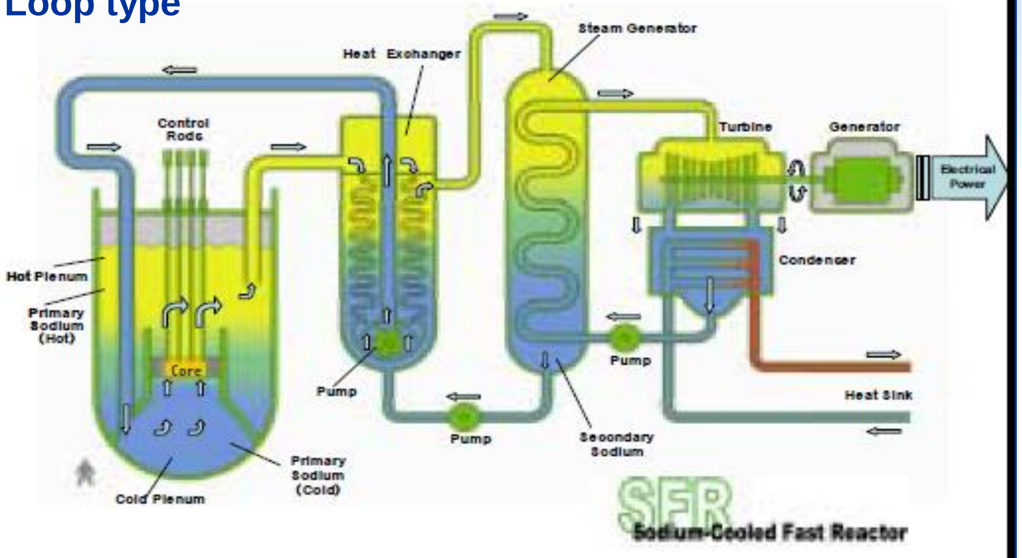
GIF website: www.gen-4.org

Pool type



Loop type



- ✓ Relatively low melting point; relative high boiling point: 97.8° .. 881.5° C at 1 bar
- ✓ Low density and viscosity
- ✓ Very high thermal conductivity and good heat capacity
- ✓ Excellent electrical conductivity
- ✓ Low activation and no alpha emitters
- ✓ Cheap and largely available
- ✓ Perfectly compatible with steels

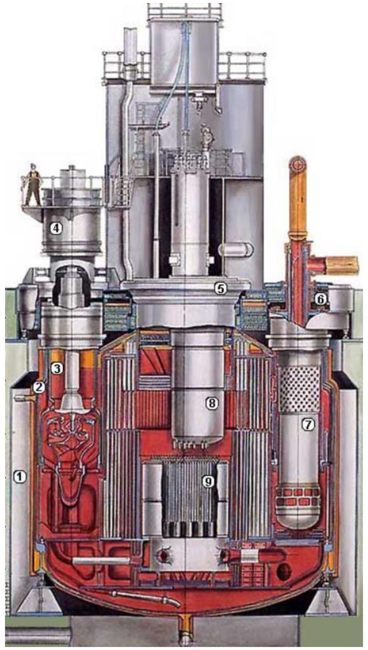
- — Aggressive chemical **reaction with water**
- — Reaction with **air**: self-ignited **sodium fires**
- — Void reactivity effect
- — Not transparent: Need special equipment for control and inspections

SFR: Sodium Cooled Fast Reactor (History)

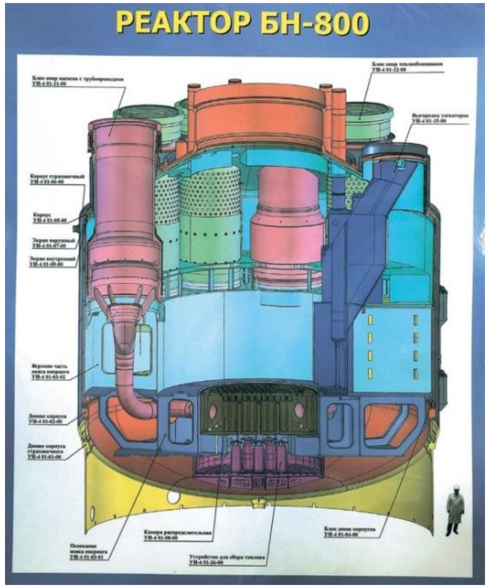
France		
Rapsodie	25-40 MW(th)	1967 - 1982
Phenix	250 MW(e)	1973 - 2009
Superphenix	1240 MW(e)	1985 - 1998
Germany		
KNK-1/2	60 MW(th)	1977 - 1991
SNR-300	327 Mw(e)	Construction started in 1972 but abandoned in 1991
Russia/Kazahstan		
BOR-60	12 MW(e)	1968 -
BN-350	135 MW(e)	1964 - 1973
BN-600	625 MW(e)	1980 -
BN-800	880 MW(e)	2015 -
BN-1200	1200 MW(e)	design
MBIR	60 MW(e)	construction
Japan		
Joyo	150 (th)	1971 -
Monju	260 MW(e)	1995 - 1995

U.S.A.		
EBR-I (Na-K)	200 kW(e)	1951 - 1964
Fermi-1	69 Mw(e)	1956 - 1972
EBR-II	20 MW(e)	1965 - 1994
FFTF	400 MW(th)	1982-1992
VTR	300 Mw(th)	design
India		
FBTR	30-40 MW(th)	1985 -
PFBR	500 MW(e)	commissioning, 2021?
FBR 1&2	600 MW(e)	design
MFBR	1000 MW(e)	concept
China		
CEFR	20 MW(e)	2011 -
CFR600	600 MW(e)	construction (2 units)
CFR1000	600 MW(e)	Design
UK		
PFR	250 MW(e)	1975 - 1994

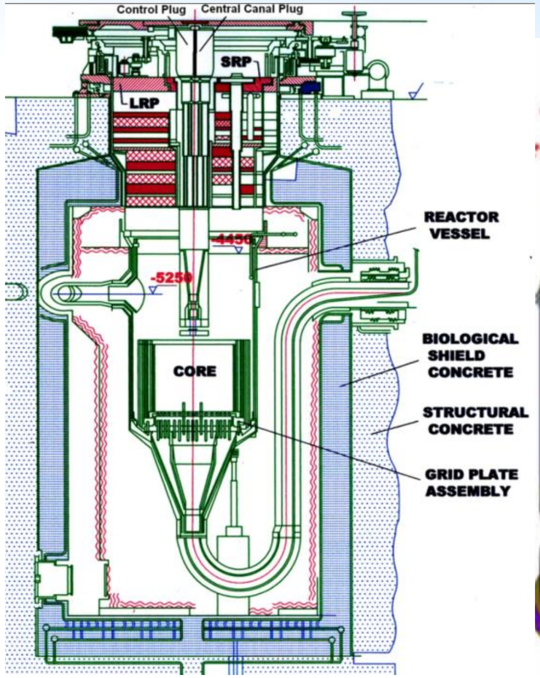
SFR: Sodium Cooled Fast Reactor (In Operation)



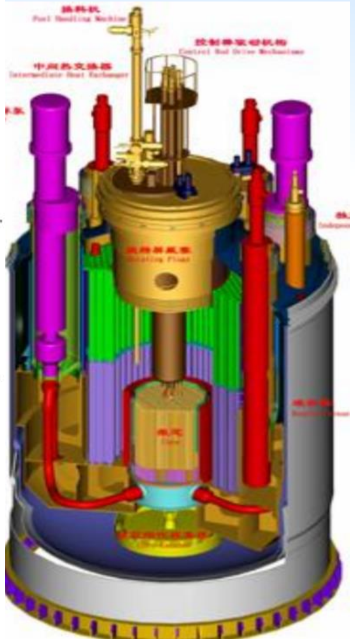
BN-600
Russia, 1980



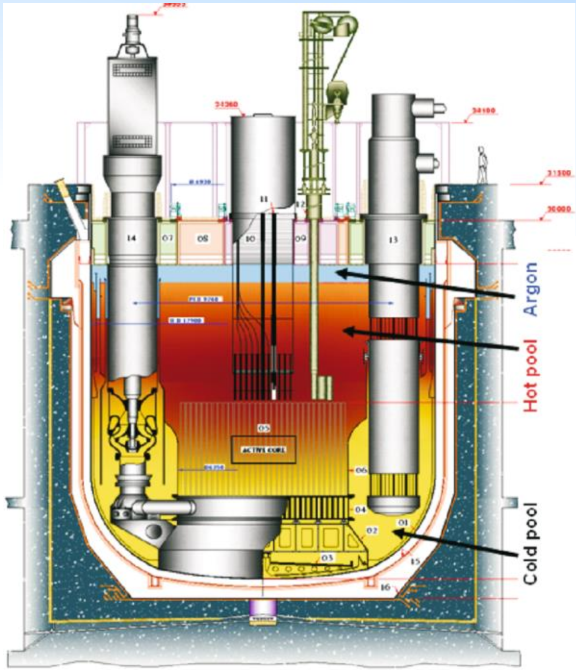
BN-800
Russia, 2015



FBTR, 30-40 MW(th)
India, 1985



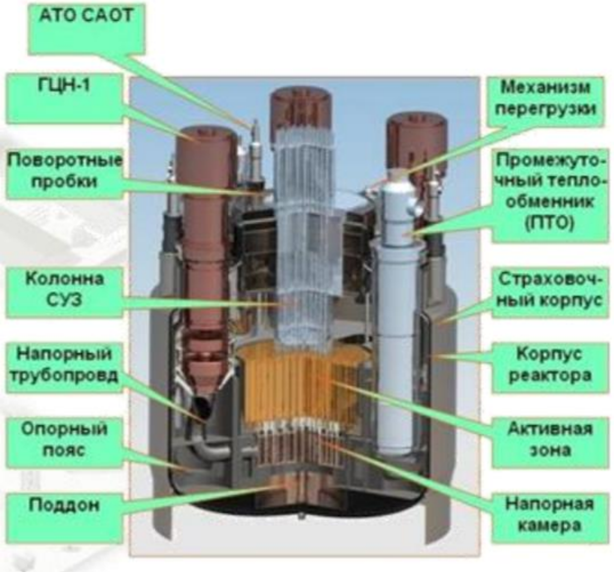
CEFR, 20 MW(e)
China, 2011



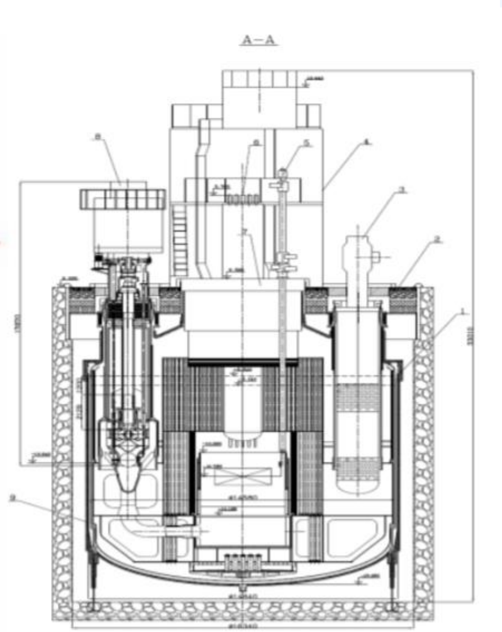
PFBR, 500 MW(e)
India, 2023?

3D-экскурсия по Белоярской АЭС

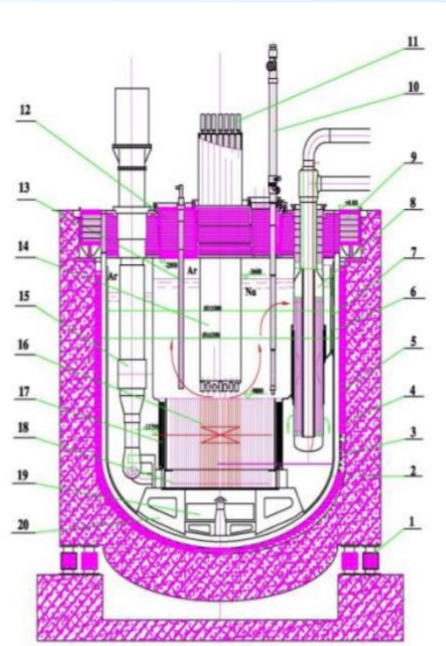
SFR: New Innovative Designs (Gen-IV?)



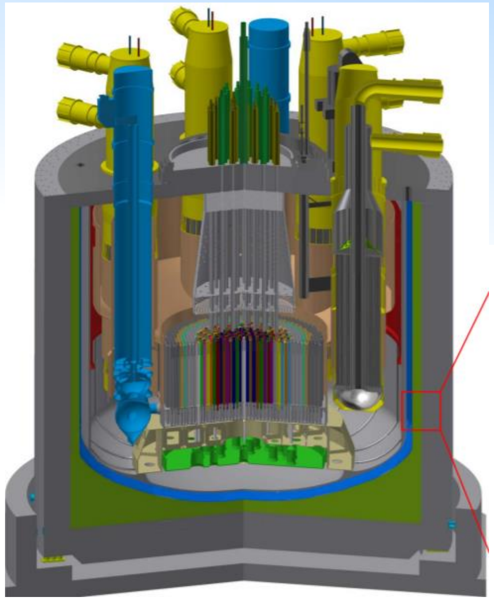
BN-1200
Russia



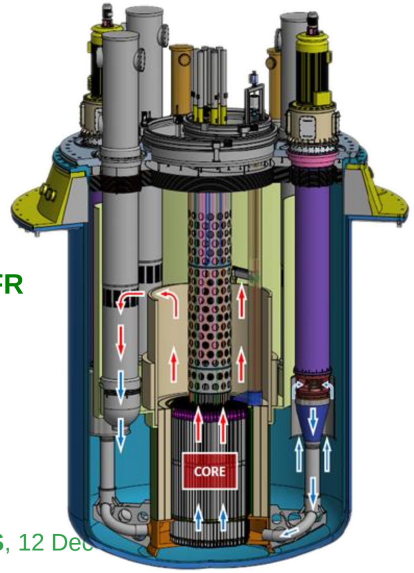
CFR600
China



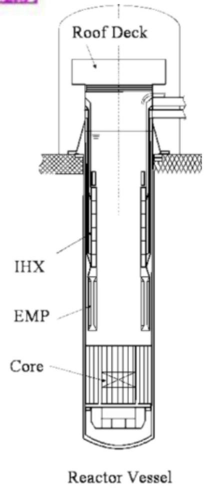
CFR1000
China



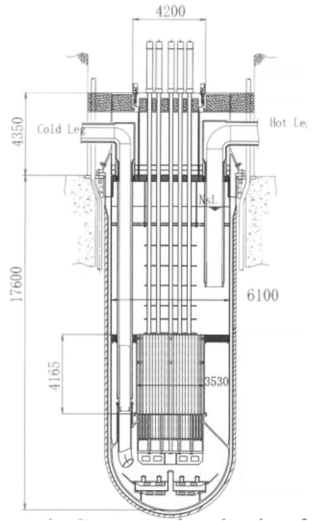
ESFR, 1500 MW(e)
EU



150 MW(e) PGSFR
Rep. of Korea



50 MW(e) SMFR
Japan



300 MW(e) SFR
Japan

SFR: Existing Fleet > Evolutionary > Innovative

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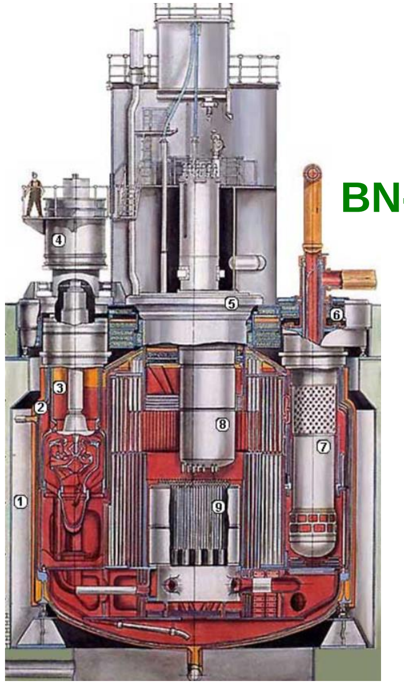
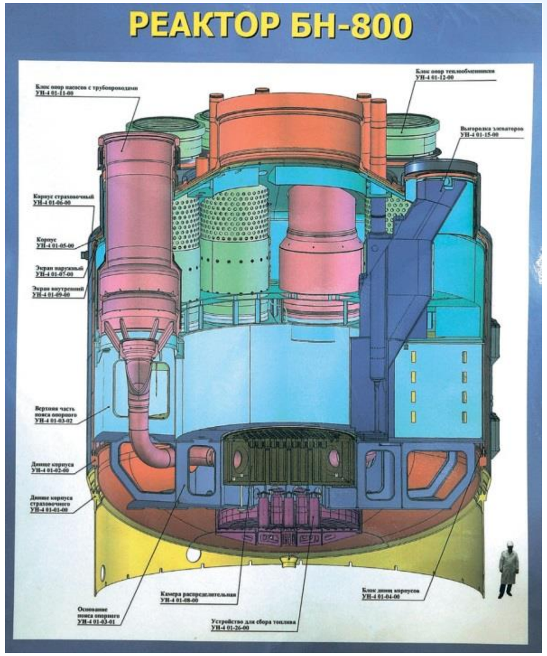


BN-600 >>> BN-800



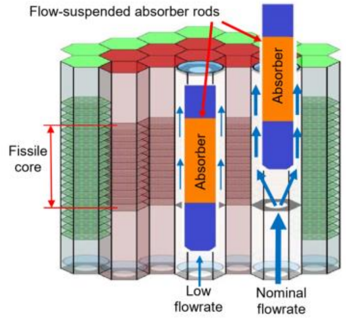
BN-800 >>> BN-1200

Similar:

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

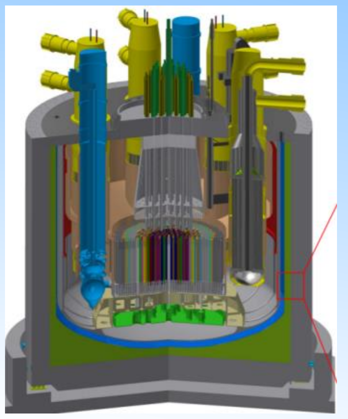
New:

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



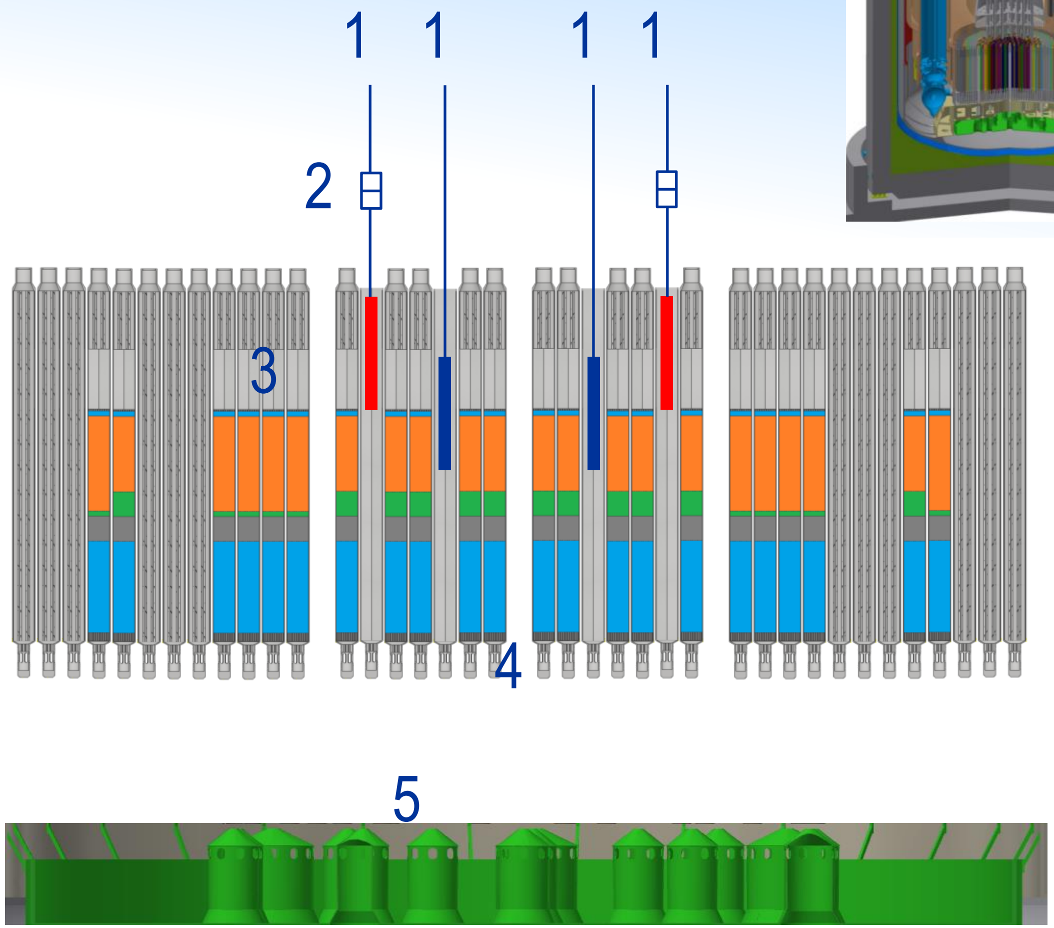
- Proven technologies based on BN-600/800 experience
- Safety: accidents that require public evacuation are practically eliminated
  - Additional passive high temperature actuated control rods system
- Fuel: uranium-plutonium nitride
- Lower power density
- Passive DHR systems
- Competitive with other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

Control of reactivity: example of ESFR (EU Gen-IV SFR)



In case of accident:

1. Scram activation by one of the signals or by operator
2. Curie-point devices on safety control rod drivelines for passive scram at temperature increase
3. Sodium plenum to avoid power run-away
4. Corium discharge tubes to avoid re-criticality in the core
5. Core catcher designed to guarantee subcriticality of corium



Courtesy of K. Mikityuk, PSI,
lecture at Joint IAEA-ICTP Workshop on Physics and Technology of Innovative Nuclear Energy Systems, 2018, Italy

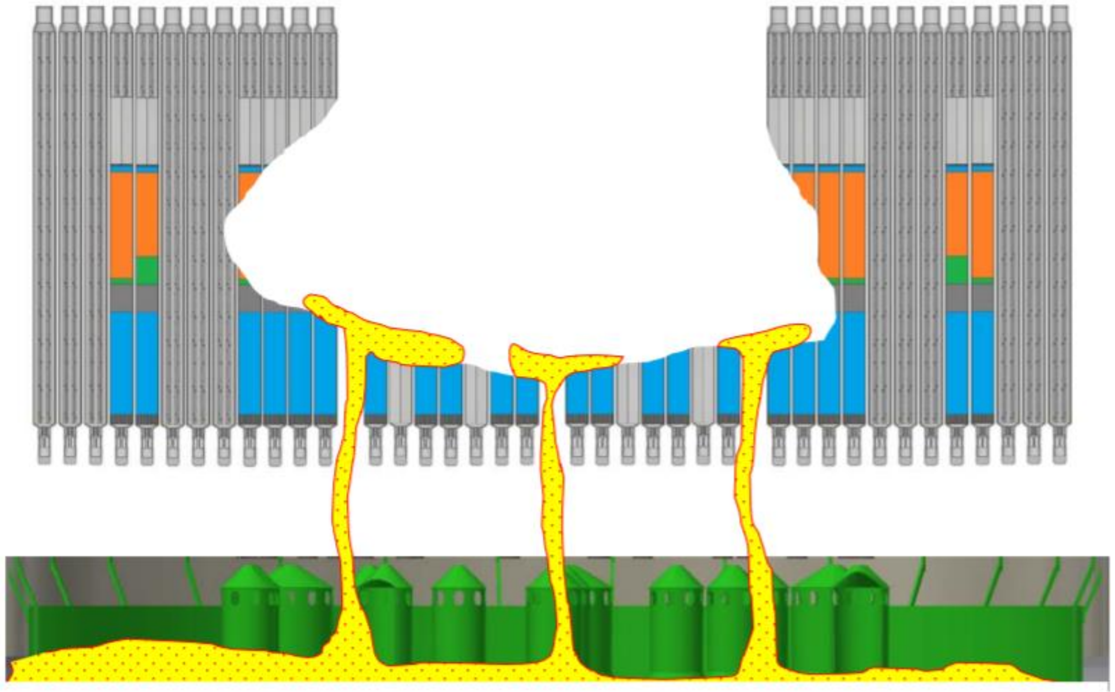
Corium Discharge in ESFR (EU Gen-IV SFR)

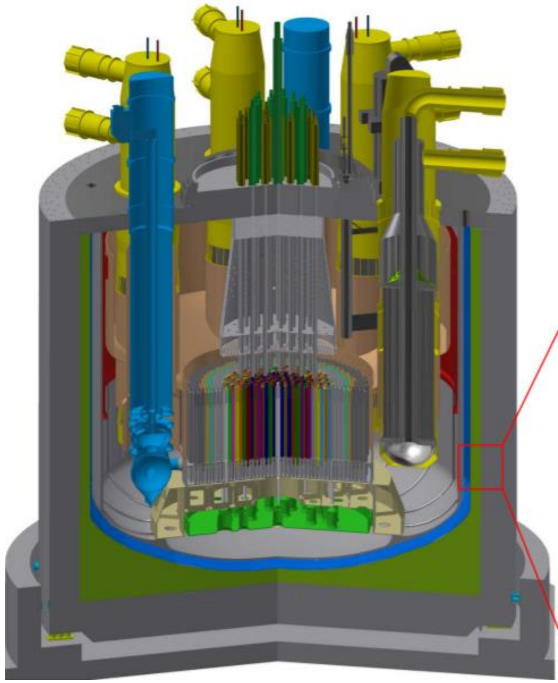
New core design: path for corium

Courtesy of K. Mikityuk, PSI,
53rd Meeting of the IAEA Technical Working Group on Fast Reactors, 2021

In case of very low probability core meltdown event, the corium discharge channel helps

— To avoid re-criticality
— To promote transfer of the corium to the core catcher
— To efficiently remove decay heat

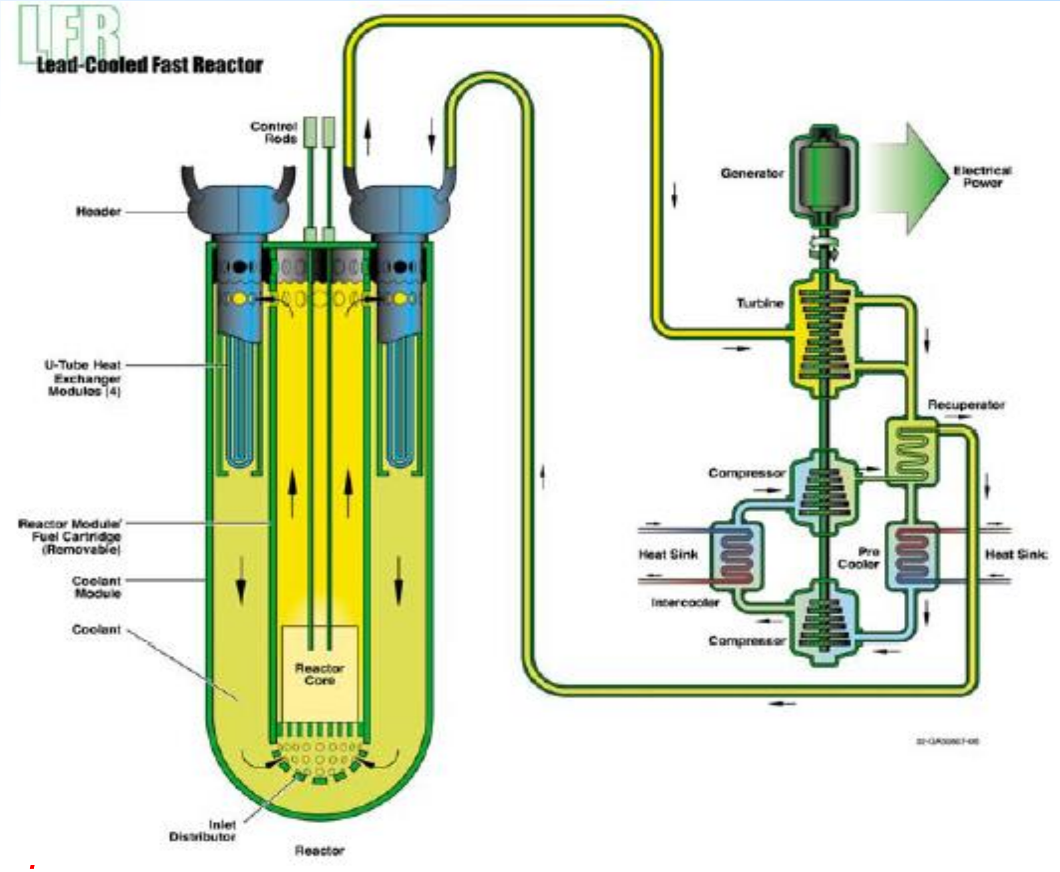




Lead/LBE Properties: *advantages and challenges*

- High boiling point (1749/1670 °C at 1 bar)
- Very low vapor pressure
- High thermal capacity
- Good heat transfer properties
- Chemically inert, in particular with water and air (allows elimination of intermediate circuit)
- Effective gamma-rays shielding
- Cheap and largely available (lead but not bismuth)

- **Material compatibility: erosion, corrosion**
  - *Low coolant velocity*
  - *Requires strict oxygen control*
  - *New steels, Coatings*
- **High density** (*also an advantage due to reduced risk of re-criticality in case of core melting*)
- Not transparent : Need special equipment for control and inspections
- Very limited **operational experience** (submarines)



Lead/LBE cooled Fast Reactors

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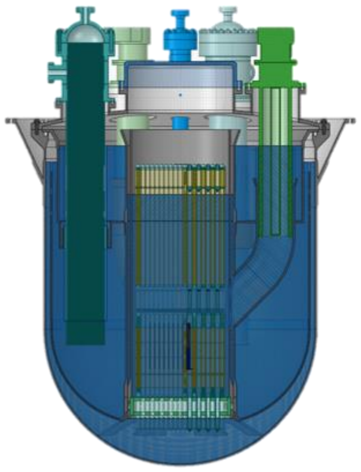
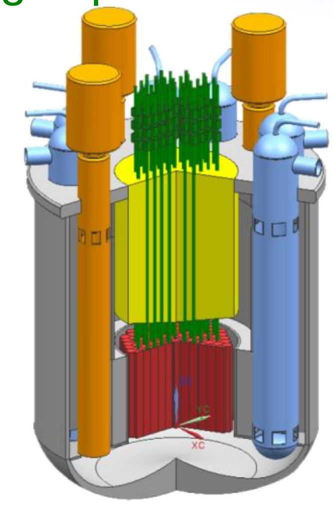
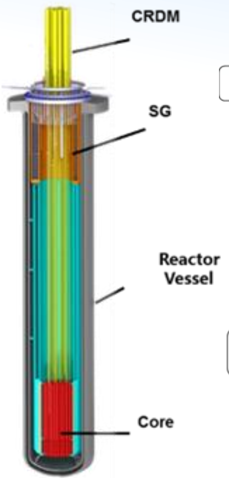
Reactor designs presented at TM on Fast SMRs in Milan in 2019



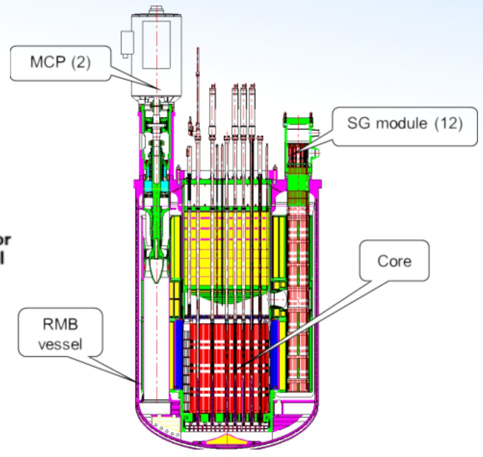
ALFRED
125-250 MW(e)
EU



CLFR-300
China

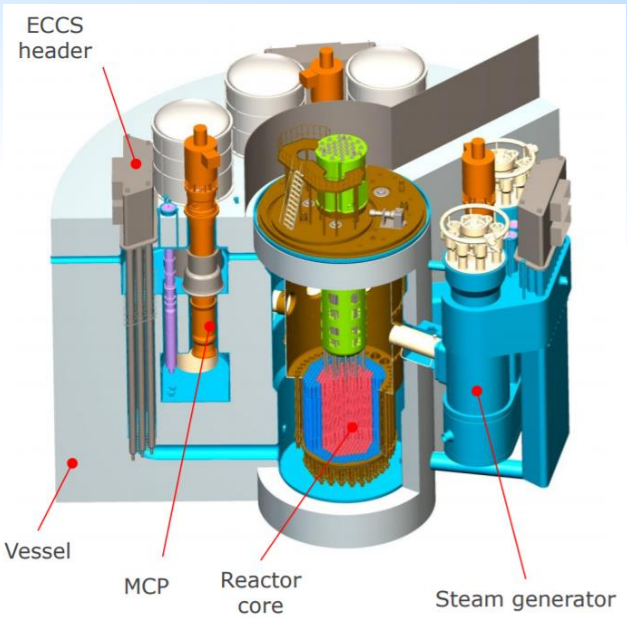


14 MW(e) CLEAR-M10d
China

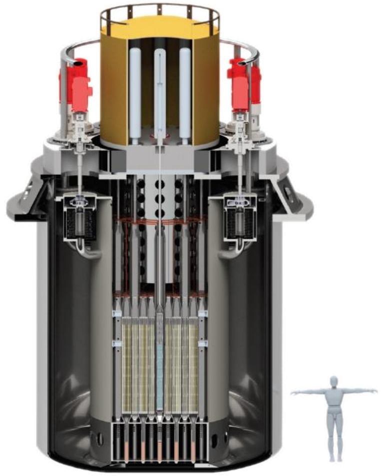


СВБР-100 (LBE)
Russia

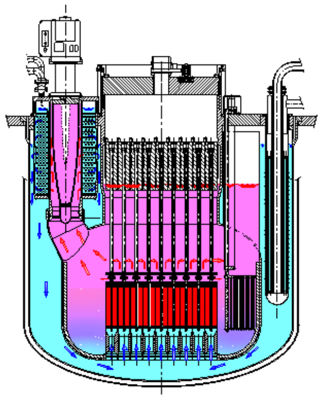
BREST-OD-300
Russia



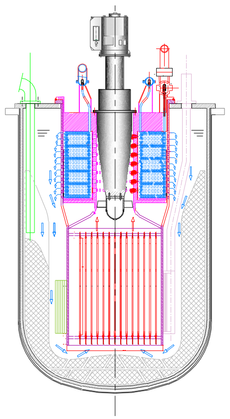
3-10 MW(e) SEALER
Sweden



55 MW(e) SEALER-UK
Sweden

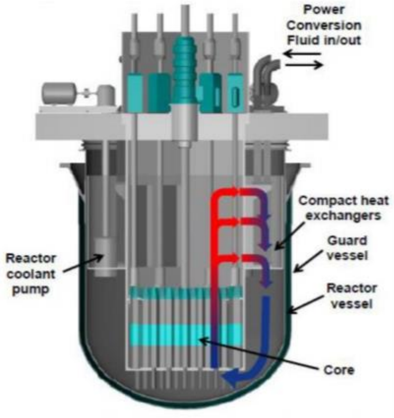


LFR-AS-200 MW(e)
Luxembourg



Transportable LFR-TL-5 MW(e)
Luxembourg

MYRRHA (LBE)
70MW(th) Belgium

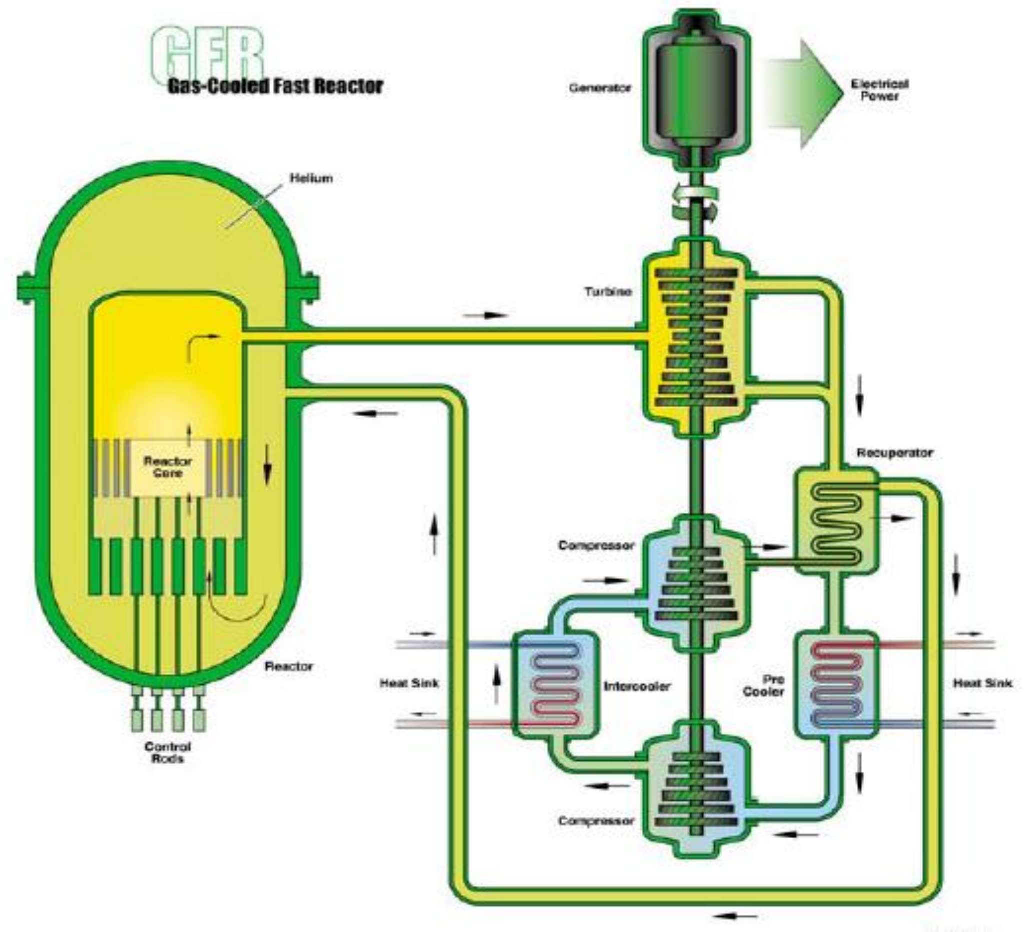


Westinghouse LFR

550MW(e) USA

Gas (He) Properties: *advantages*

- Completely transparent to neutron (very hard neutron spectrum)
- Low reactivity insertion due to voiding of the coolant
- Chemically inert
- Single phase behavior
- Optical transparency
- Electrically non-conducting
- Possibility to adopt direct gas turbine cycle
- Very high temperature applications



~850°C, 5-20 MPa

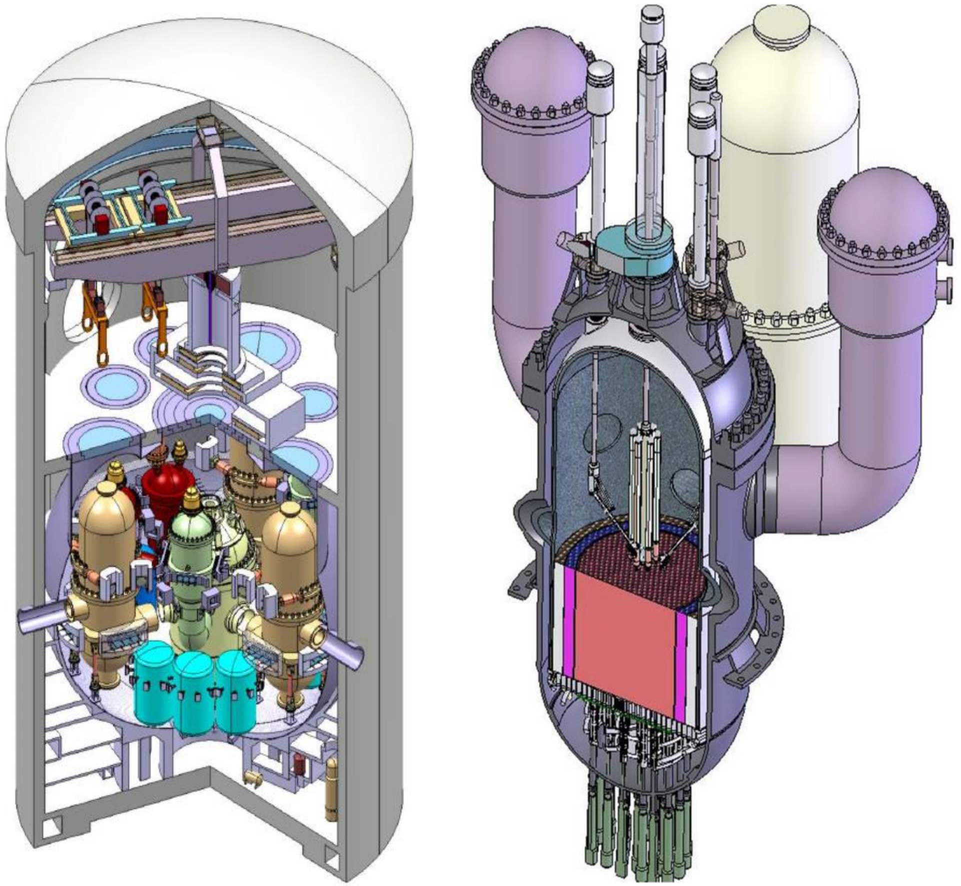
Gas (He) Properties: *four main disadvantages*

- **Low density creating requirement for pressurization**
  - ✓ *Likelihood and severity of a LOCA*
- **Inability to adopt a pool configuration**
  - ✓ *Core remains uncovered in case of breached primary circuit*
- **Non-condensable**
  - ✓ *Pressure loading the containment building in case of LOCA*
- **Low-thermal inertia**
  - ✓ *The reactor core heat up rapidly if forced cooling is lost*

No operational experience

Fast Reactors Programmes in Europe

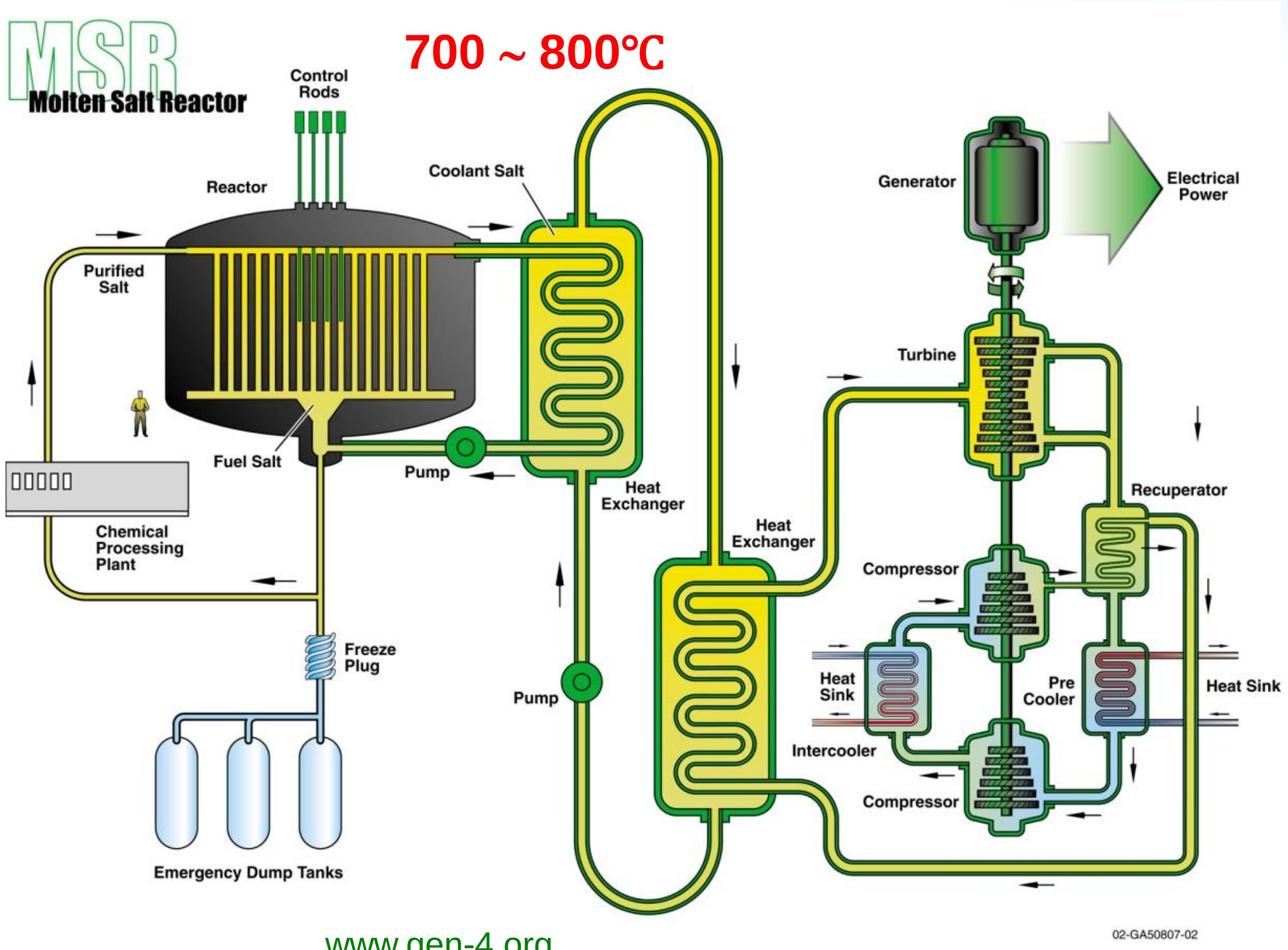
ESNII - The European Sustainable Nuclear Industrial Initiative



GFR - ALLEGRO

- 2400 MW(th) power output
- Advantages of chemically inert coolant, no risk of coolant boiling, high temperature operation
- Disadvantage of the small coolant thermal inertial

GEN-IV Molten Salt Reactor (MSR)



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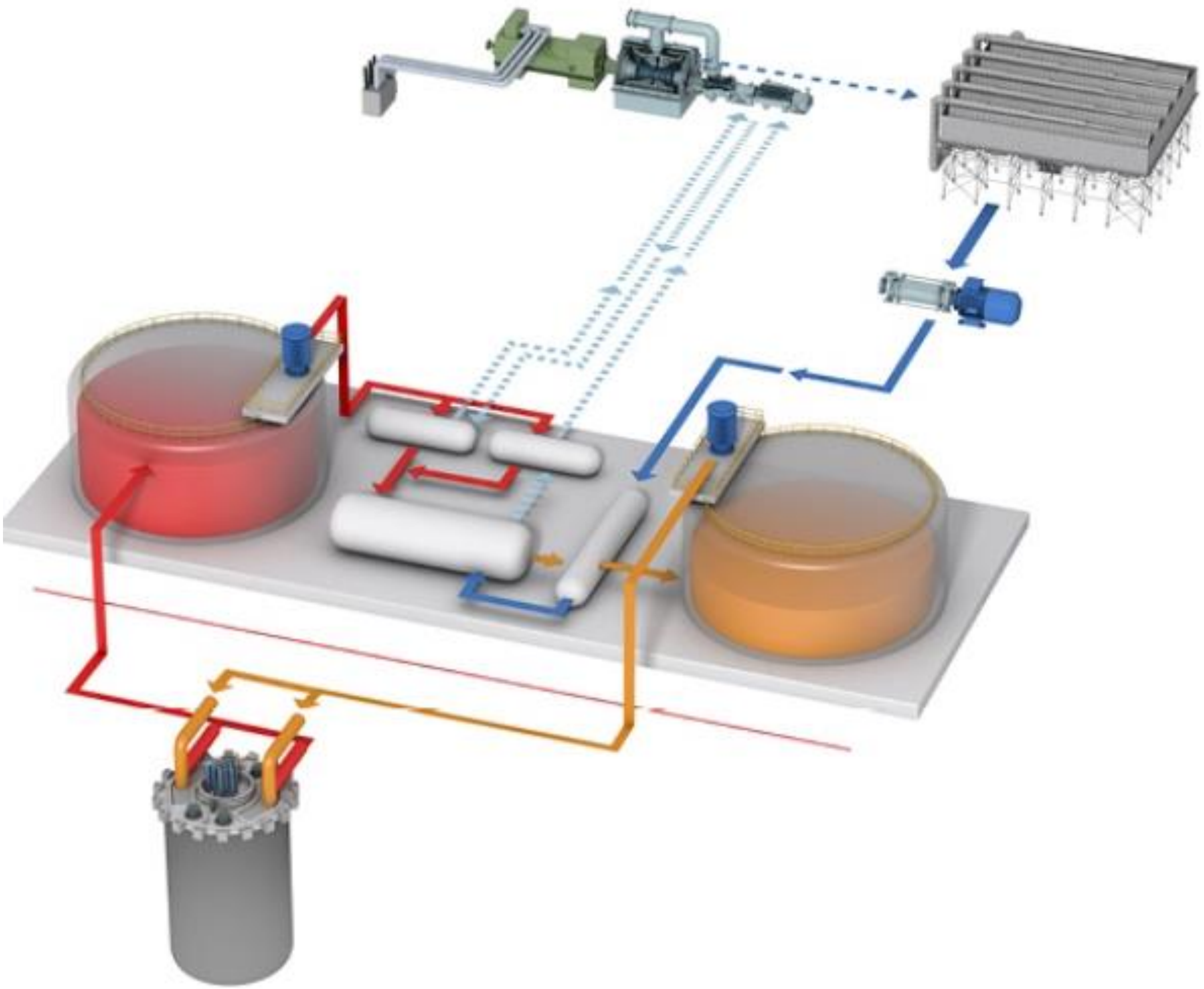
- **High temperature system**
  - High temperature enables non-electric applications
- **On-line waste management**
- **Design Options**
  - Solid fuel with molten salt coolant
  - Fuel dissolved in molten salt coolant (MSFR)

Different reactor concepts using molten salt are discussed in GIF

- ***Molten Salt Fuelled Reactors (the circulating salt is the fuel + coolant)***
  - *MSR MOU Signatories France EU and Switzerland work on Th-U MSFR (Molten Salt Fast Reactor). Switzerland joined MOU in 2015.*
  - *Russian Federation works on MOSART (Molten Salt Actinide Recycler & Transmuter) with and without Th-U support. RF joined the MOU in 2013*
  - *China, Japan and South Korea work on Th-U TMSR with graphite moderator*
- ***Molten Salt Cooled Reactors (solid fuelled)***
  - *USA and China work on FHR (fluoride-salt-cooled high-temperature reactor) concepts and are Observers to the PSSC*
  - *Australia works with China on materials development for MSR and FHR Australia is joining the MOU in 2016*

NATRIUM: SFR with Molten Salt Storage System



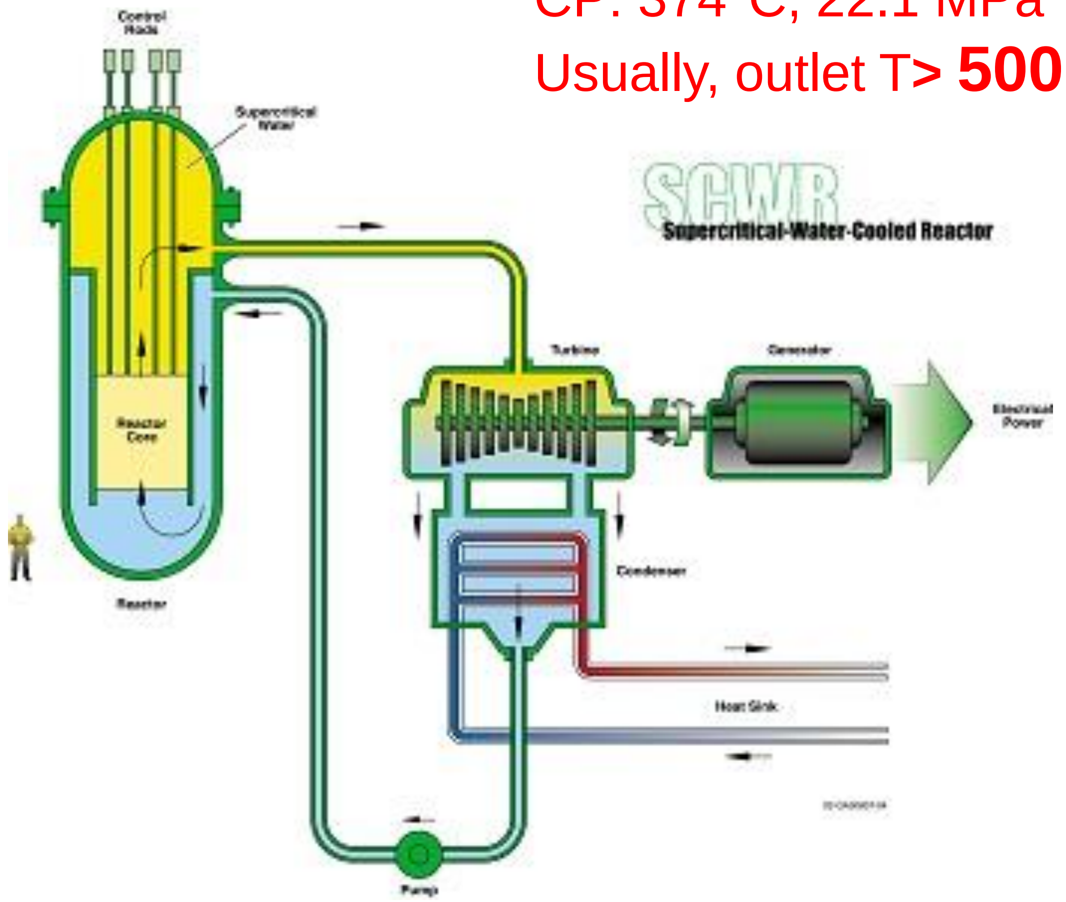
Announced by Terrapower

- 345 MW(e) SFR combined with
- 1GW(th) Energy molten salt-based storage system
- Pick power can reach 500-600 MW(e)
- Can be used for non-electrical applications
- Can work with renewables

GEN-IV Supercritical-Water-Cooled Reactor (SCWR)

CP: 374°C, 22.1 MPa

Usually, outlet T**> 500°C**



- Advantages
  - Either thermal or a fast-neutron spectrum
  - High thermal efficiency 44%
  - No steam generator, single loop
  - Higher steam enthalpy allows to smaller turbine size

- Challenges
  - High pressure
  - Passive safety systems to be demonstrated
  - Heat transfer near critical point

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From Gen-III to Gen-IV: GIF View

Concept	PWR	SCWR	(V)HTR	GFR	SFR	LFR	MSR
Specific design*	EPR	HPLWR	HTR-PM	GCFR	ESFR	ALFRED	MSFR
Thermal power (MW)	4300	2300	458	2400	3600	300	3000
Efficiency (%)	37	~44	~45	~45	~42	~42	~43
Primary coolant	H_2O	H_2O	He	He	Na	Pb	$LiF\text{-}ThF_4\text{-}(Pu\text{-}MA)F_3$
Inlet/outlet temp. (C)	296 327	280 500	250 750	400 780	395 545	400 480	600 800
Pressure (MPa)	~16	~25	~7	~7	~0.2	~0.5	~0.2
Moderator	H_2O	H_2O	C	None	None	None	None
Neutron spectrum	Thermal	Thermal	Thermal	Fast	Fast	Fast	Fast
Breeding gain	<< 0	<< 0	<< 0	~ 0	~ 0	~ 0	~ 0
Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]
G1: Sustainability	Poor	↔	?	↑	↑	↑	↑
G2: Safety & reliability	Good	↓	↑	↓	↓↑	↓↑	?
G3: Economics	Good	↑	↑	?	↓	?	?

Courtesy of K. Mikityuk, PSI,
lecture at Joint IAEA-ICTP Workshop on Physics and Technology of Innovative Nuclear Energy Systems, 2018, Italy

Challenges for Innovative fast reactors

- At present, there is a wide convergence on the choice of sodium as coolant, with oxide, metal (e.g. for high conversion ratio) or nitride fuel.
- However, it seems important to explore/develop a viable backup option, such as lead (or lead-bismuth) coolant with oxide or nitride fuel, or gas coolant with carbide fuel.
- In this context, an innovative sodium-cooled prototype and a demo/experimental plant for exploring a backup option should/could be the focus of international initiatives.
- Other internationally recognized major challenges are:
  - ✓ The very limited availability of fast spectrum irradiation facilities, in particular to test and qualify advanced materials, fuels and targets (currently only operating are BOR-60 in Russia and FBTR in India; soon MBIR in Russia and maybe VTR in the US);
  - ✓ The industrial demonstration of a fully closed fuel cycle with fast reactors, including the multi-recycling of the fuel as well as the (homogenous or heterogeneous) partitioning and transmutation of minor actinides (Am, Cm and Np).

Fast Reactors in Operation, and under Construction and Decommissioning

IAEA

Country		Type	coolant	Purpose	Power (th/e) MW	Year (Op.)	Status
Russia	BOR-60	SFR	sodium	experimental	**60/10**	1969	operating
	BN-600	SFR	sodium	prototype	**1470/600**	1980	operating
	BN-800	SFR	sodium	industrial	**2100/880**	2015	operating
	MBIR	SFR	sodium	experimental	**150/50**	~2028	construction
	BREST-OD-300	LFR	lead	Gen-IV, demonstrator	**700/300**	~2026	construction
China	CEFR	SFR	sodium	prototype	**80/20**	2011	operating
	CFR600 x2	SFR	sodium	prototype	**1500/600**	~2025	construction (2 units)
India	FBTR	SFR	sodium	experimental	**40/-**	1985	operating
	PFBR	SFR	sodium	demonstrator	**1250/500**	?2022	comissioning
Japan	MONJU	SFR	sodium	prototype	**714/280**	1994	decomissioning
	JOYO	SFR	sodium	experimental	**140/--**	1978	license renew

Fast Reactors under Developing and Design

Country	Name	Type	coolant	Purpose	Power (th/e), MW	Status
Russia	**BN-1200**	SFR	sodium	Gen-IV, industrial	2900/1220	design
	SVBR-100	LFR	LBE	prototype	280/100	design
	MOSART	MSR	molten salt	prototype	2400/	concept
China	**CFR1000**	SFR	sodium	Gen-IV, industrial	2512/1000	design
	CLFR-300	LFR	LBE/lead	demonstrator	740/300	concept
	CLEAR-M10a	LFR	LBE	experimental	10/1-3	concept
	CLEAR-I	LFR	LBE	experimental	10/-	design
	CLEAR-M10d	LFR	lead	demonstrator	25/10	concept
EU	ALFRED	LFR	lead	Gen-IV, prototype	300/120	design
	ALLEGRO	GFR	helium	Gen-IV, demonstrator	75/-	design
	MSFR	MSR	molten salt (LiF-AFn)	Gen-IV, prototype	3000/	concept
Belgium	MYRRHA	LFR ADS	LBE	experimental	100/-	design
France	ASTRID	SFR	sodium	demonstrator	1500/600	suspended
Italy	newcleo LFR-AS-30/200	LFR	lead	experimental/prototype	/30 or /200	concept
R. of Korea	KALIMER-600	SFR	sodium	GEN-IV, prototype	1523/600	design
	PGSFR	SFR	sodium	GEN-IV, demonstrator	400/150	suspended
Sweden	**SEALER-55**	LFR	lead	demonstrator	140/55	design
UK	**Westinghouse LFR**	LFR	lead	demonstrator	950/450	design
USA	**Westinghouse LFR**	LFR	lead	demonstrator	950/450	design
	NATRIUM	SFR	sodium	demonstrator	1000/345-500	design
	VTR	SFR	sodium	experimental	300/-	design
	SSTAR	LFR	lead	experimental	45/20	supended
	MCFR	MSR	chloride salt	experimental	1800/800	design
	EM2	GFR	helium	demonstrator	500/265	concept
	KP-FHR	MSR	fluoride salt	demonstrator	310/140	concept
	PRISM	SFR	sodium	demonstrator	840/311	concept
	LLC ARC-100	SFR	sodium	demonstrator	260/110	concept

IAEA
International Atomic Energy Agency

Atoms for peace and Development…

Thank You!

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