Generation IV reactor design concepts: brief introduction

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Joint IAEA-ICTP Workshop on
Physics and Technology of Innovative Nuclear Energy Systems
20-24 August 2018, ICTP, Trieste, Italy

Outlook

Two lectures

- GIF: Gen IV reactor design concepts ~45 min
- Innovative nuclear energy systems: core design and neutronics ~60 min

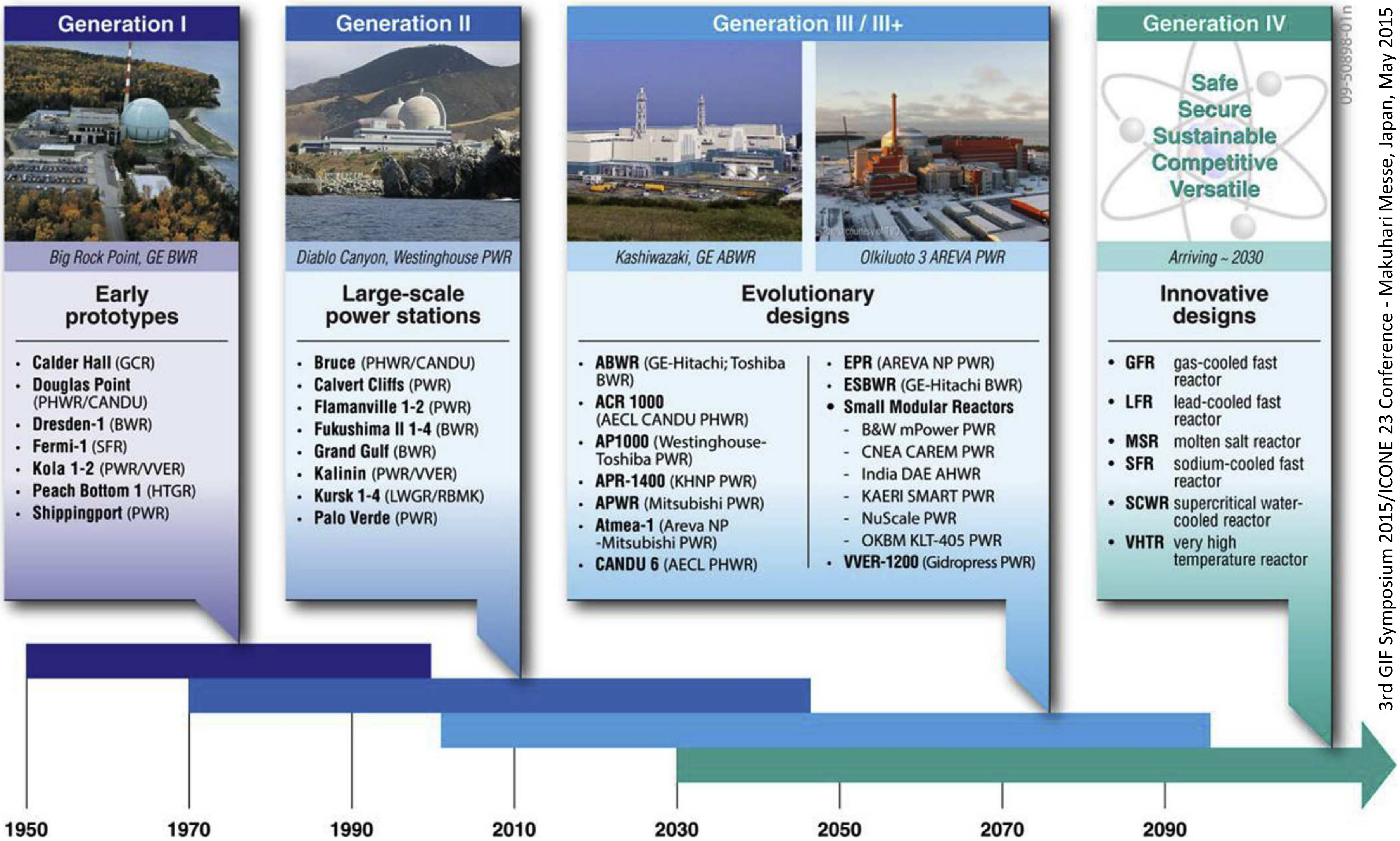
are combined in one as follows:

- — Introduction ~5 min
- — 6 GIF reactors ~90 min
- — Summary ~5 min
- — Q&A ~5 min

Other lectures at the school:

- Simulation of neutronics for advanced reactors: Monte-Carlo method ~45 min
- Safety of fast reactors: phenomenology and modeling aspects ~90 min

Nuclear reactors: from early prototypes to innovative designs



3rd GIF Symposium 2015/ICONE 23 Conference - Makuhari Messe, Japan, May 2015
https://www.gen-4.org/gif/jcms/c_9354/presentations

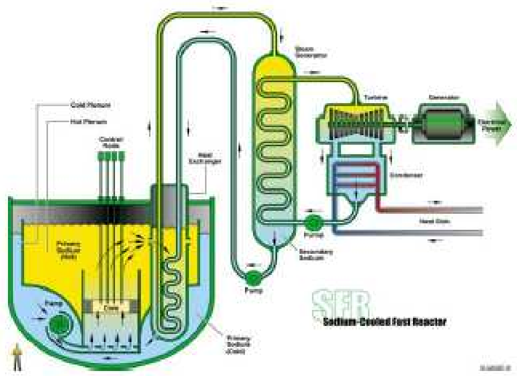
- The Generation IV International Forum (GIF) is a cooperative international endeavor organized to carry out the R&D needed to establish the feasibility and performance capabilities of the next generation nuclear energy systems.

- Argentina, Brazil, Canada, France, Japan, Korea, South Africa, the UK and the US signed the GIF Charter in July 2001, Switzerland in 2002, Euratom in 2003, China and Russia both in 2006, and Australia in 2016.

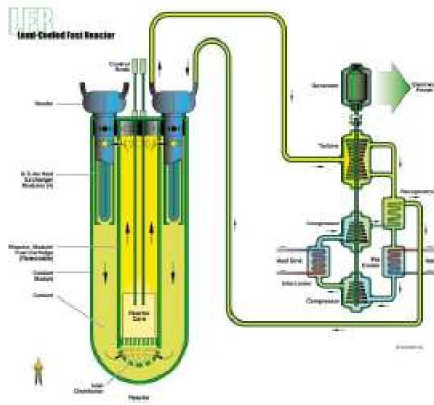
- Six nuclear energy systems were selected for further development:

	Fast	Thermal
Sodium-cooled fast reactor (SFR)	X	
Lead-cooled fast reactor (LFR)	X	
Gas-cooled fast reactor (GFR)	X	
Very-high-temperature reactor (VHTR)		X
Supercritical-water-cooled reactor (SCWR)	X	X
Molten salt reactor (MSR)	X	X

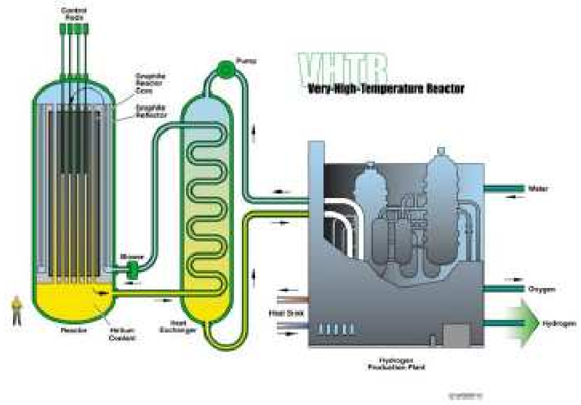
GEN IV International Forum℠



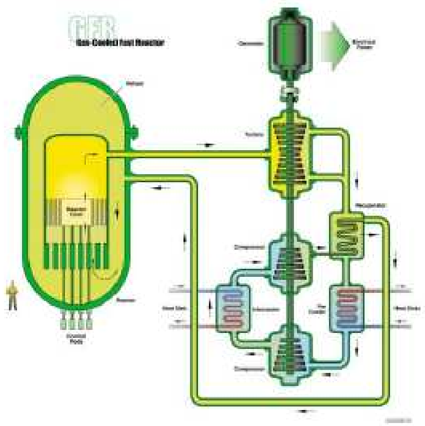
Sodium Fast Reactor



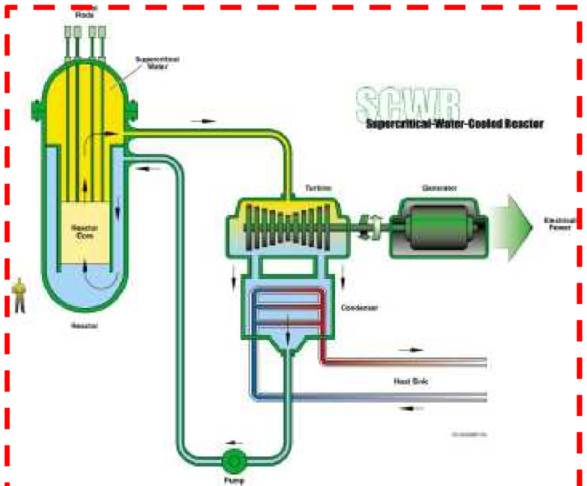
Lead Fast Reactor



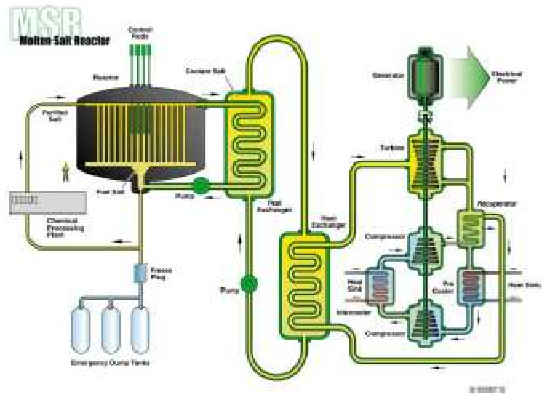
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

3rd GIF Symposium 2015/ICONE 23 Conference - Makuhari Messe, Japan, May 2015
https://www.gen-4.org/gif/jcms/c_9354/presentations

GEN IV International Forum

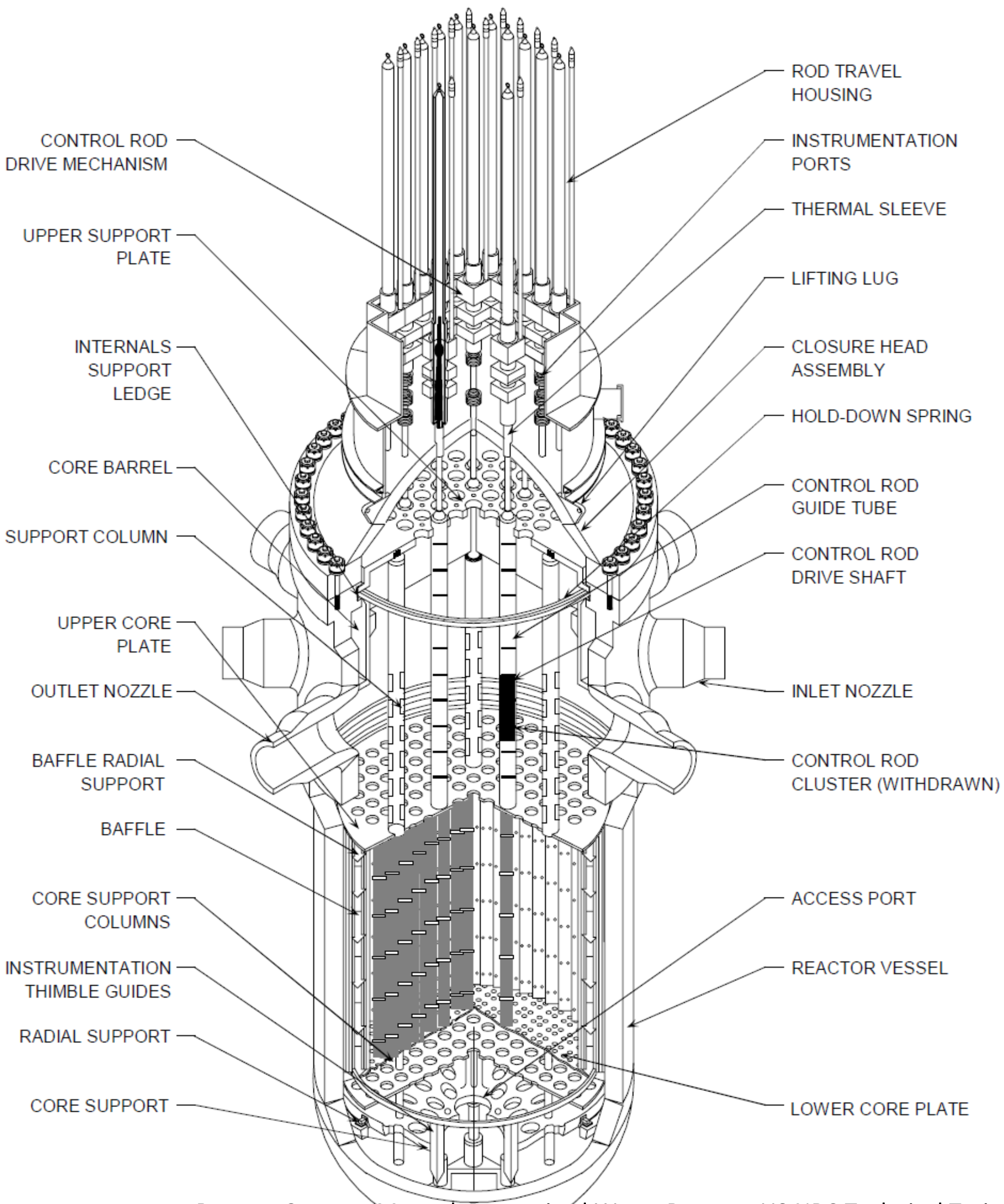
- **Goal 1: Sustainability**
  - Long term fuel supply
  - Minimize waste and long term stewardship burden
- **Goal 2: Safety & Reliability**
  - Very low likelihood and degree of core damage
  - Eliminate need for offsite emergency response
- **Goal 3: Economics**
  - Life cycle cost advantage over other energy sources
  - Financial risk comparable to other energy projects
- **Goal 4: Proliferation Resistance & Physical Protection**
  - Unattractive materials diversion pathway
  - Enhanced physical protection against terrorism

Template for presenting the Gen-IV reactor systems

- **General concept**
  - Image and main features
  - Fact sheet (advantages, challenges, designs under development, reactors under operation)

- **Specific example**
  - Main parameters, reactor, fuel, core, BoP
  - Problems from viewpoint of GIF goals

Pressurized Water Reactor: Generation-III concept to compare



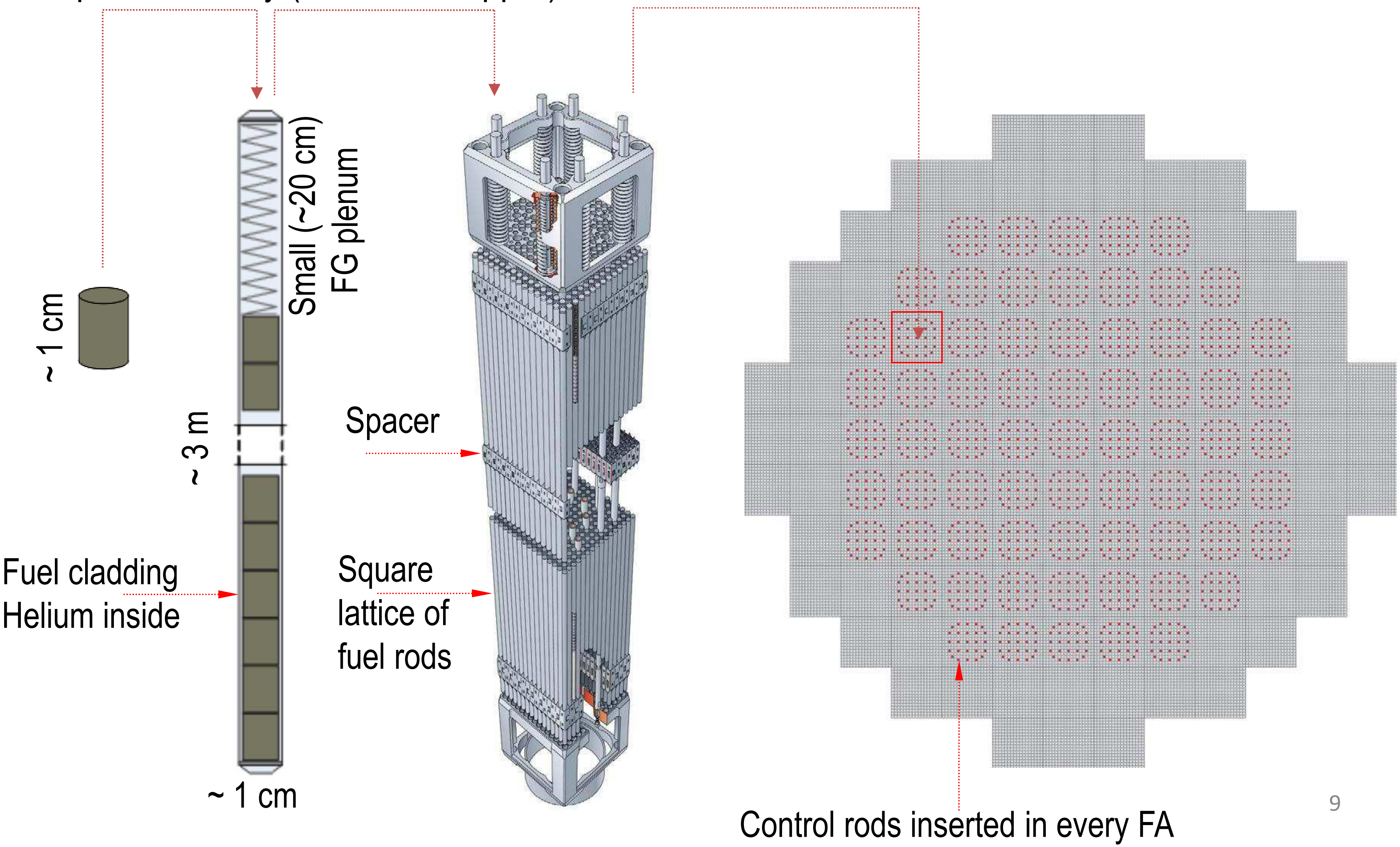
Concept	**PWR**
Specific design*	EPR
Thermal power (MW)	4300
Efficiency (%)	37
Primary coolant	H_2O
Pressure (MPa)	~16
Inlet/outlet temp. (C)	296 / 327
Moderator	H_2O
Neutron spectrum	Thermal
Breeding gain	<< 0
Reference	[1]
G1: Sustainability	Poor
G2: Safety & reliability	Good
G3: Economics	Good

*Specific designs chosen by lecturer

Reactor Concept Manual. Pressurized Water Reactor. US NRC Technical Training Center, https://www.nrc.gov/docs/ML1427/ML14274A090.pdf

Gen-III PWR fuel rod, fuel assembly and core

- Fuel: enriched uranium dioxide
- Cladding: Zry (zircaloy)
- Open assembly (no duct=wrapper) → cross flow between assemblies



Pressurized Water Reactor: fact sheet

- **Advantages**
  - Operational experience and established technologies (economics)
  - Light water as a coolant (transparent, easy to handle, boron control, ...)
  - ...
- **Challenges**
  - High coolant pressure (safety issues of depressurization)
  - Low breeding (sustainability)
  - ...
- **Designs under development**
  - EPR
  - ...
- **Reactors under operation**
  - As of January 2018, 292 operable reactors (275 GWe)

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

From Gen-III to Gen-IV: improvements to reach the goal(s)

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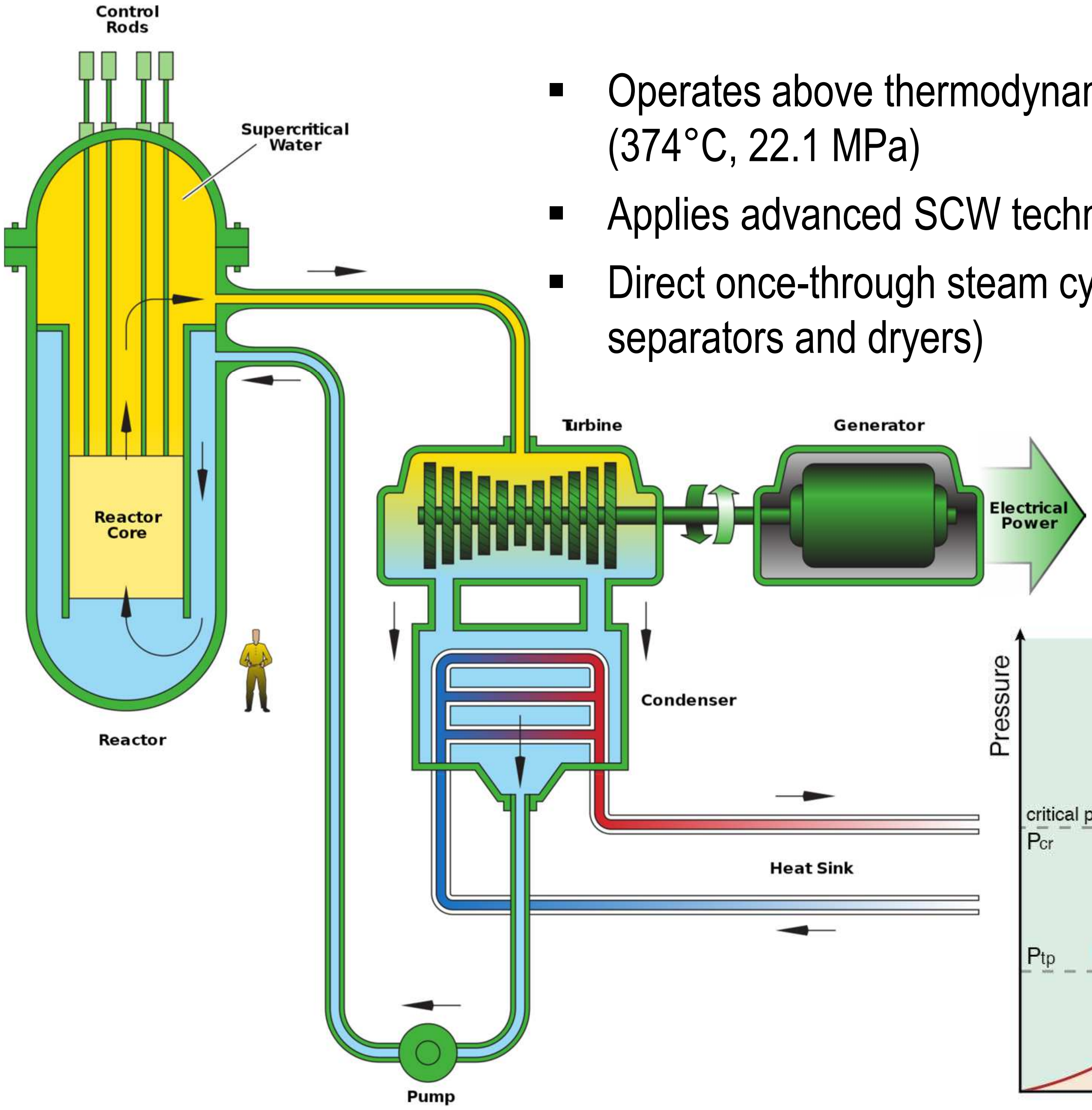
*Specific designs chosen by lecturer

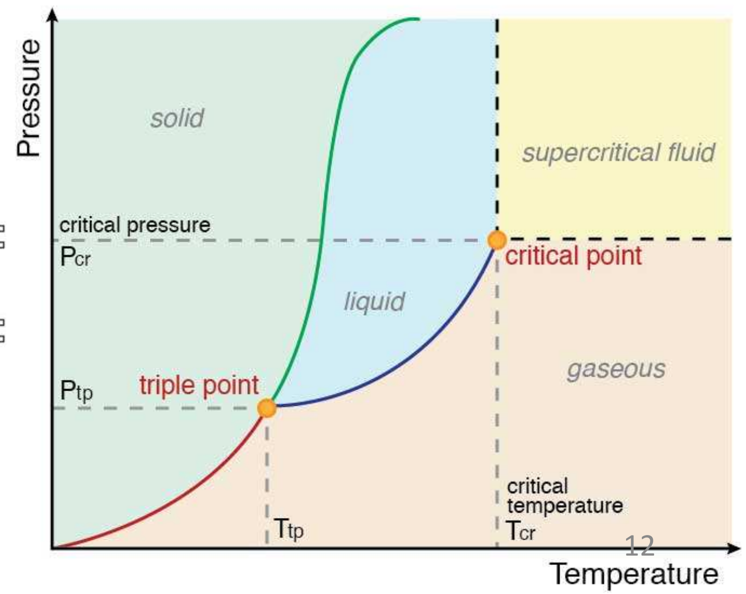
- How to increase efficiency (improve G3)?

→ Increase the water pressure and temperature

Supercritical-Water-cooled Reactor: concept

- Operates above thermodynamic critical point of water (374°C, 22.1 MPa)
- Applies advanced SCW technology used in coal plants
- Direct once-through steam cycle (no SG, steam separators and dryers)





Supercritical-Water-cooled Reactor: fact sheet

SCWR
(V)HTR
GFR
SFR
LFR
MSR

- **Advantages**
  - Based on Gen-III+ reactor technology
  - Merges it with advanced SCW technology used in coal plants
  - Higher efficiency than Gen-III+
  - Both thermal and fast spectrum possible

- **Challenges**
  - Materials, water chemistry, and radiolysis
  - Thermal hydraulics to fill gaps in SCW heat transfer and critical flow databases
  - Safety demonstration (positive void effect for fast spectrum option)
  - Fuel qualification

- **Designs under development**
  - HPLWR (EU), ...

- **Reactors under operation**
  - None

HPLWR (EU): High Performance LWR

Concept	**PWR**		**SCWR**	
Specific design*	EPR		HPLWR	
Thermal power (MW)	4300		2300	
Efficiency (%)	37		**~44**	
Primary coolant	H_2O		**H_2O**	
Inlet/outlet temp. (ºC)	296	327	280	**500**
Pressure (MPa)	~16		**~25**	
Moderator	H_2O		H_2O	
Neutron spectrum	Thermal		Thermal	
Breeding gain	<< 0		**<< 0**	
Reference	[1]		[2]	
G1: Sustainability	Poor		↔	
G2: Safety & reliability	Good		↓	
G3: Economics	Good		↑	

ΔT increased from 31ºC (PWR) to 220ºC (HPLWR) – issue for peak cladding temperature (target 630ºC).

Possible solution:
→ Heating in three steps

*Specific designs chosen by lecturer

HPLWR (EU): water circulation paths [2]

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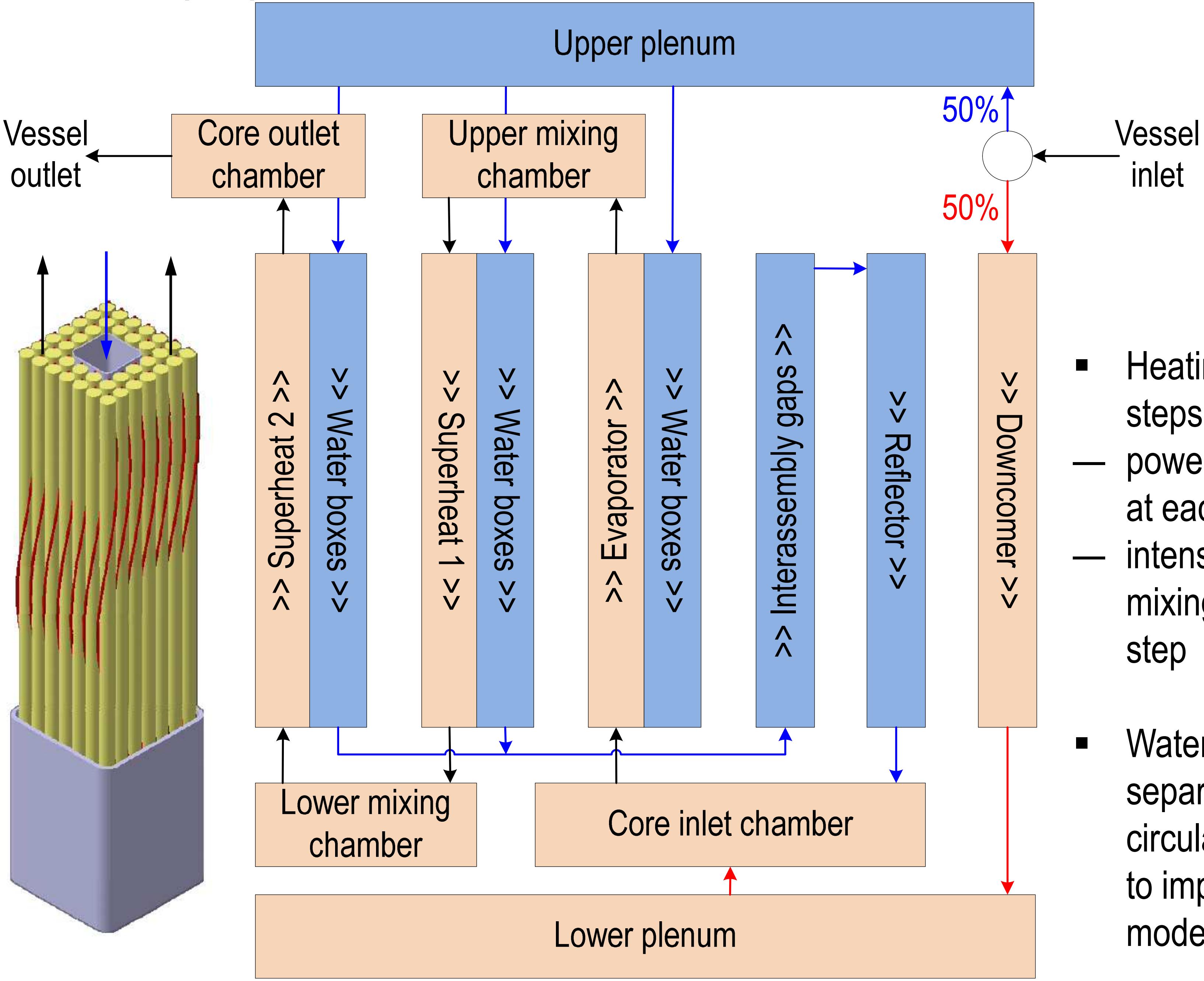
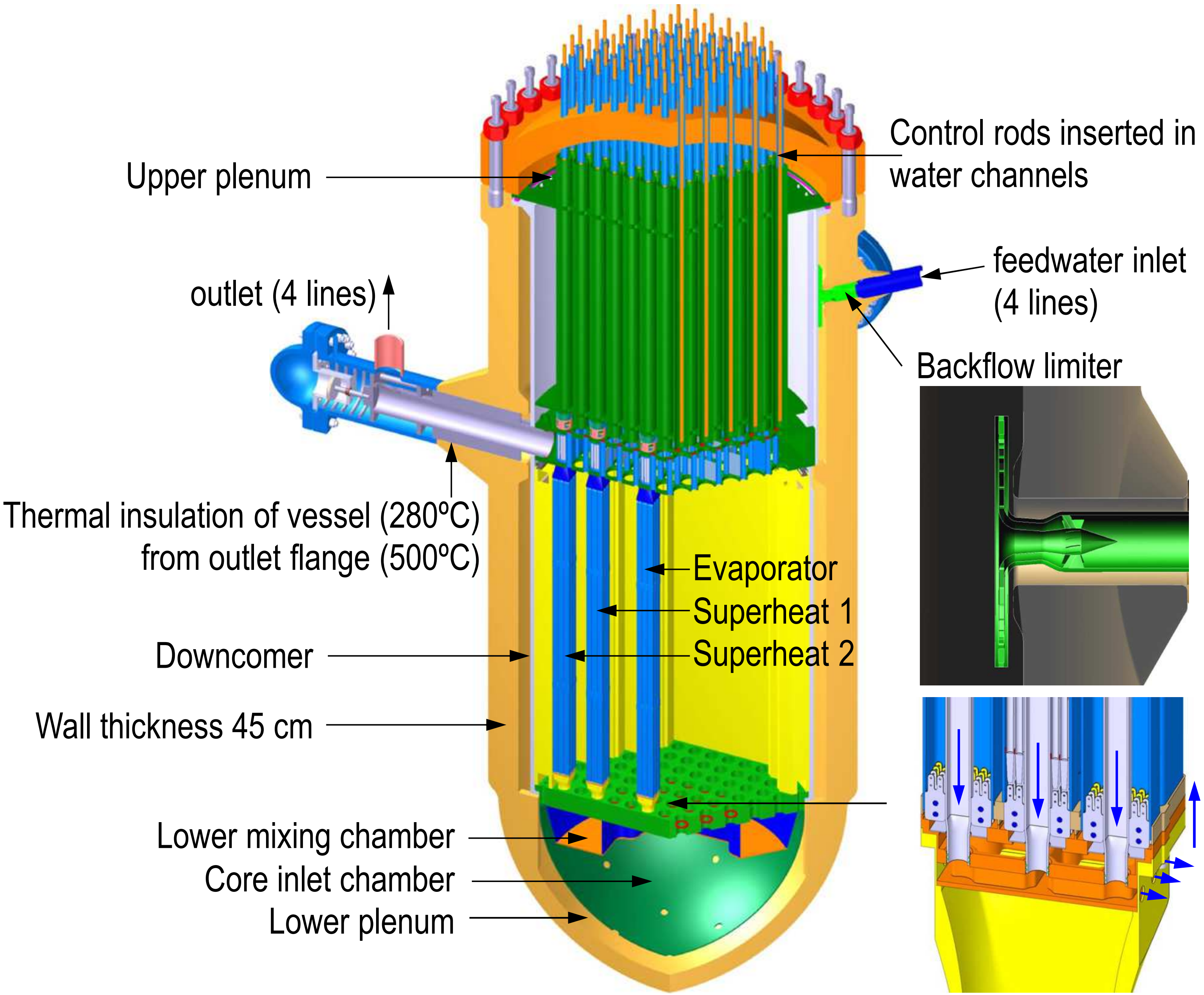


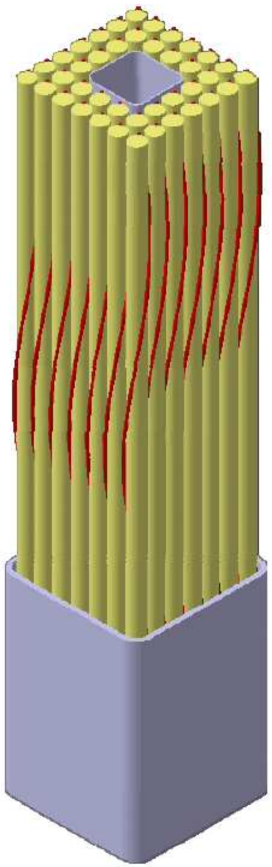
- Heating in three steps:
  - power reducing at each step
  - intensive coolant mixing after each step
- Water boxes with separate circulation circuit to improve moderation

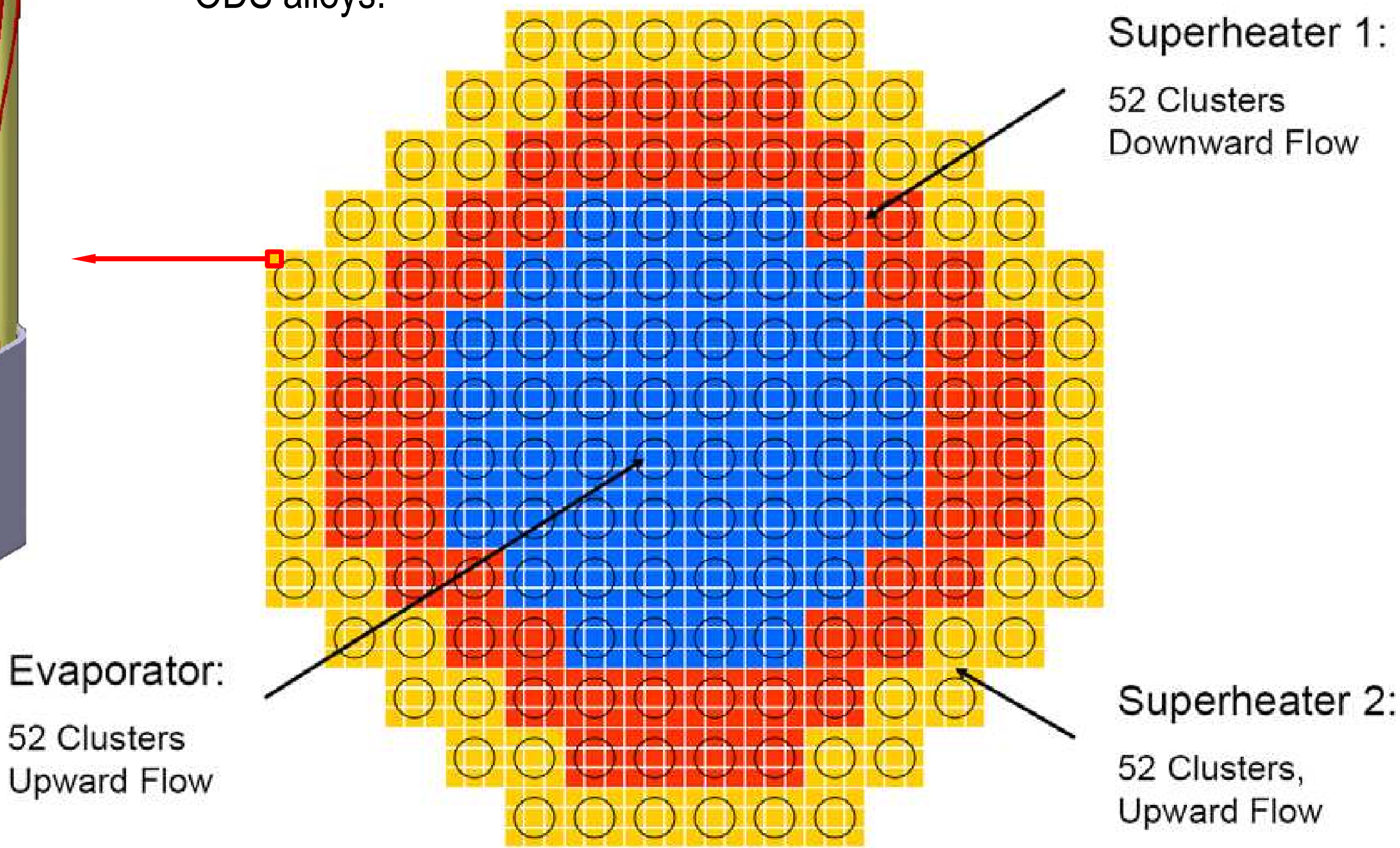
HPLWR (EU): reactor vessel internals design [2]



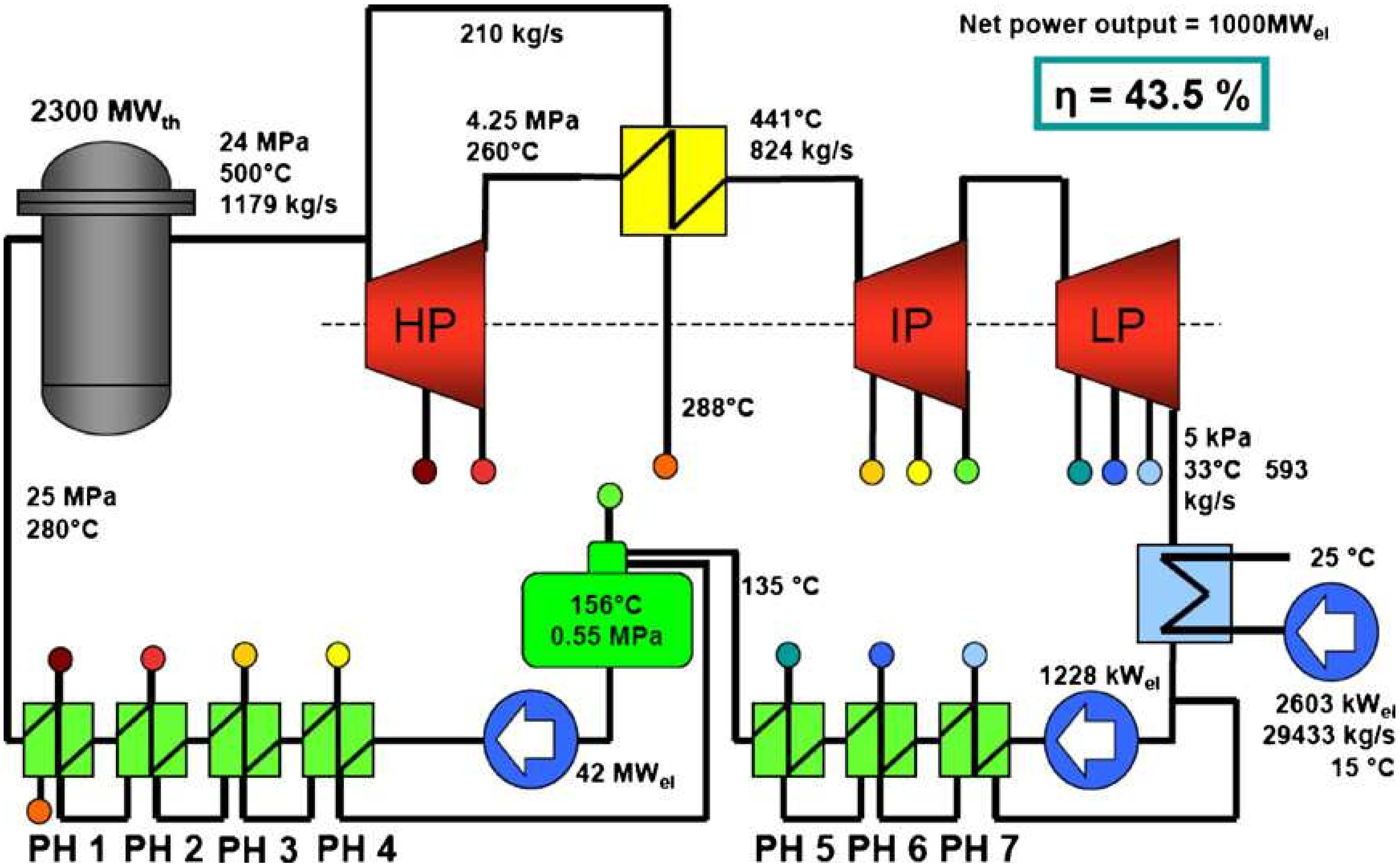
HPLWR (EU): core design [2]

Candidate cladding alloys under examination (corrosion issues):
— ferritic–martensitic steels;
— stainless steels;
— nickel-base alloys;
— ODS alloys.





HPLWR (EU): BoP concept



From Gen-III to Gen-IV: improvements to reach the goal(s)

SCWR
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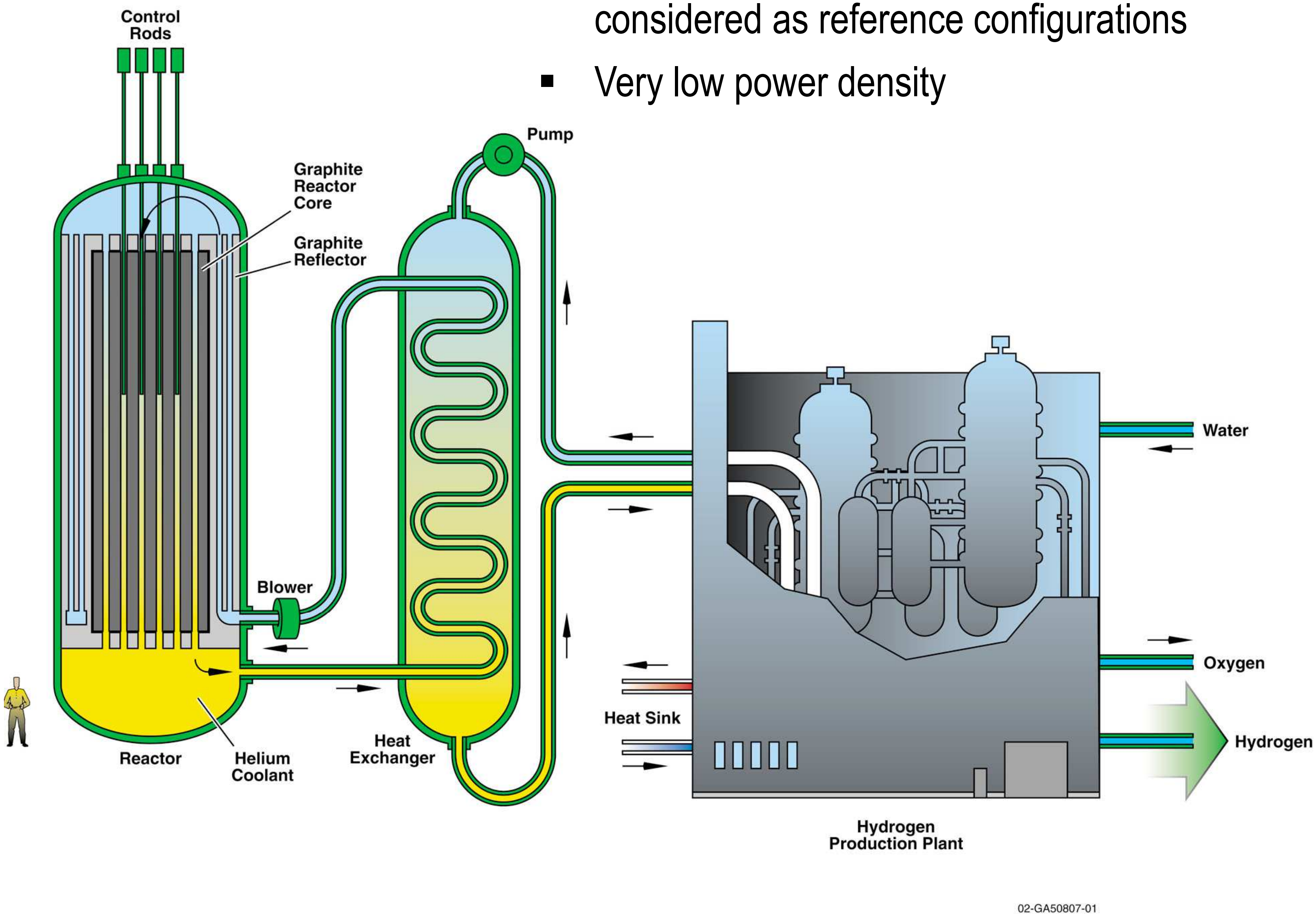
Pressure (MPa)	~16		**~25**	
Moderator	H_2O		H_2O	
Neutron spectrum	Thermal		Thermal	
Breeding gain	<< 0		**<< 0**	
Reference	[1]		[2]	
G1: Sustainability	Poor		↔	
G2: Safety & reliability	Good		↓	
G3: Economics	Good		↑	

- How to keep high efficiency (improve G3) but at the same time avoid problems related to water at high pressure and temperature (improve G2)?

→ Use inert gas instead of water

Very-High-Temperature Reactor: concept

- Both graphite prismatic and pebble bed are considered as reference configurations
- Very low power density



Very-High-Temperature Reactor: fact sheet

- **Advantages**
  - High temperature enables non-electric applications
  - "Walk-away" safe
  - Inert gas coolant
  - High efficiency

- **Challenges**
  - Reach temperature of ~1000ºC (for hydrogen production)
  - Coupling with process heat applications
  - Graphite as a waste

- **Designs under development**
  - Chinese HTR-PM
  - ...

- **Reactors under operation**
  - Japanese HTTR

HTR-PM (China)

Concept	PWR		SCWR		(V)HTR	
Specific design*	EPR		HPLWR		HTR-PM	
Thermal power (MW)	4300		2300		458	
Efficiency (%)	37		~44		~45	
Primary coolant	H_2O		H_2O		He	
Inlet/outlet temp. (C)	296	327	280	500	250	750
Pressure (MPa)	~16		~25		~7	
Moderator	H_2O		H_2O		C	
Neutron spectrum	Thermal		Thermal		Thermal	
Breeding gain	<< 0		<< 0		<< 0	
Reference	[1]		[2]		[3]	
G1: Sustainability	Poor		↔		?	
G2: Safety & reliability	Good		↓		↑	
G3: Economics	Good		↑		↑	

← Large amount of activated graphite produced (radwaste)

SCWR
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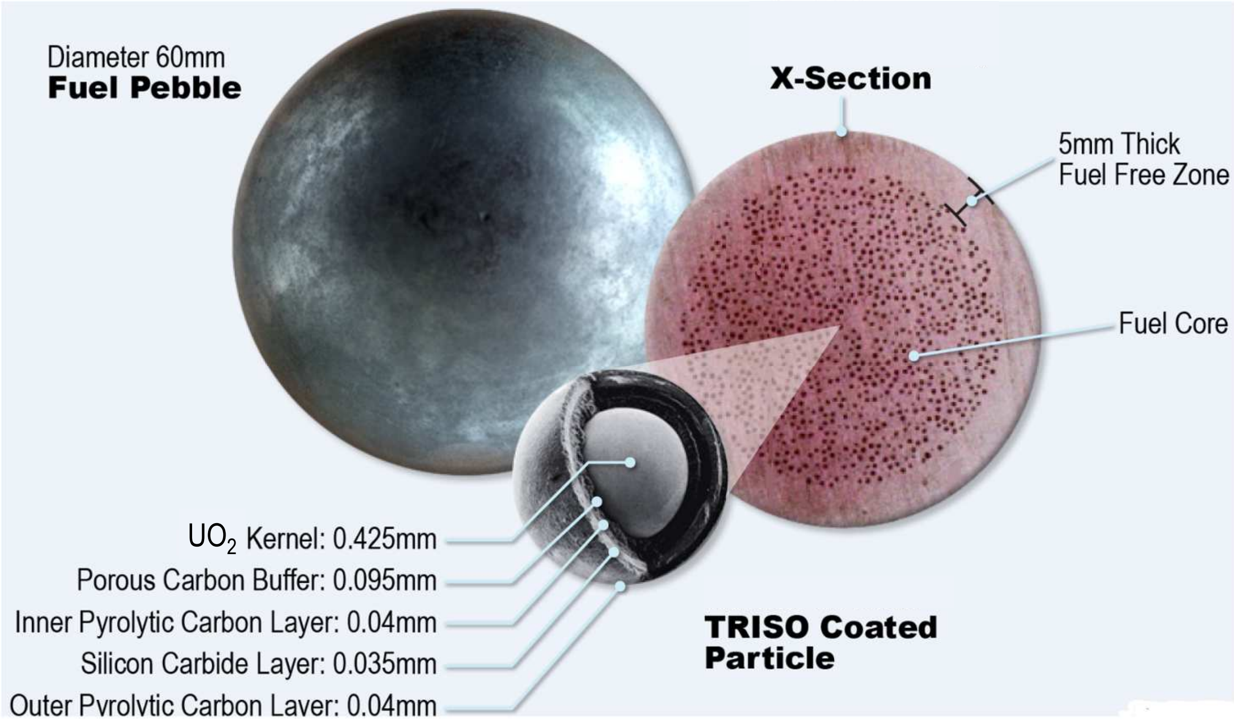
*Specific designs chosen by lecturer

HTR-PM (China): fuel

SCWR
(V)HTR
GFR
SFR
LFR
MSR



https://www.x-energy.com/copy-of-xe-100-reactor

Fuel	UO_2
Number of pebbles in the core	420’000
Heavy metal per pebble	~7 g
Number of coated particles in each pebble	~ 11’660
Fuel loading scheme	Multi-pass (six times)
Average discharge burnup	90 MWd/kgU

HTR-PM (China) [3]: reactor

SCWR
(V)HTR
GFR
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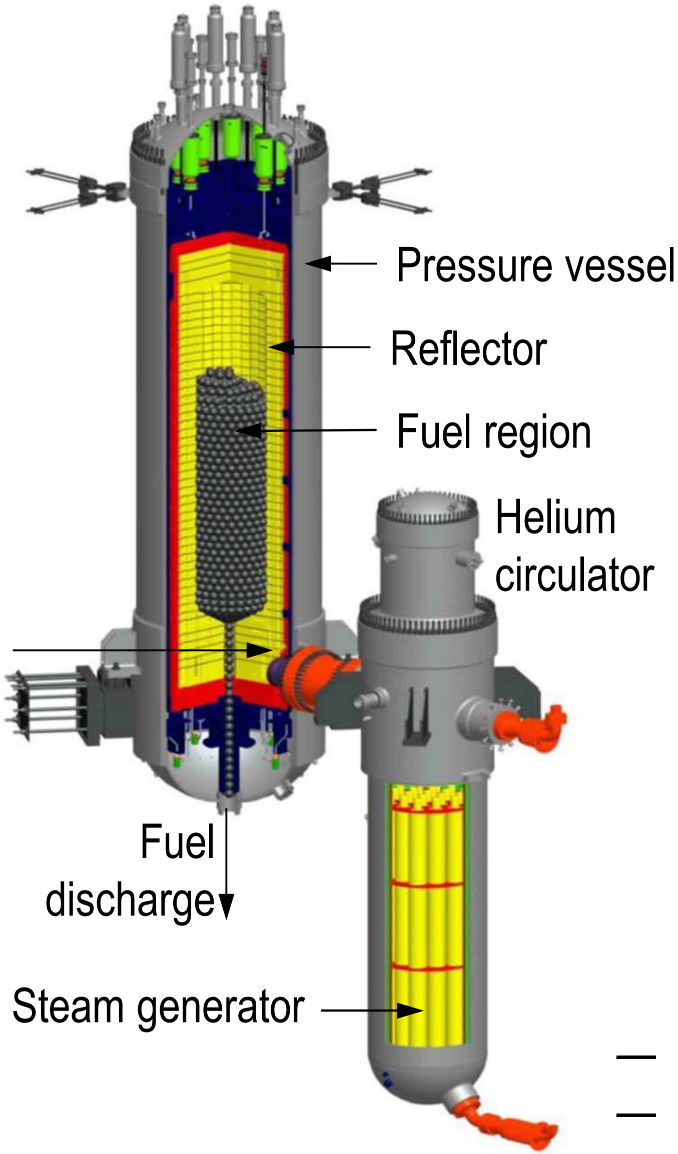
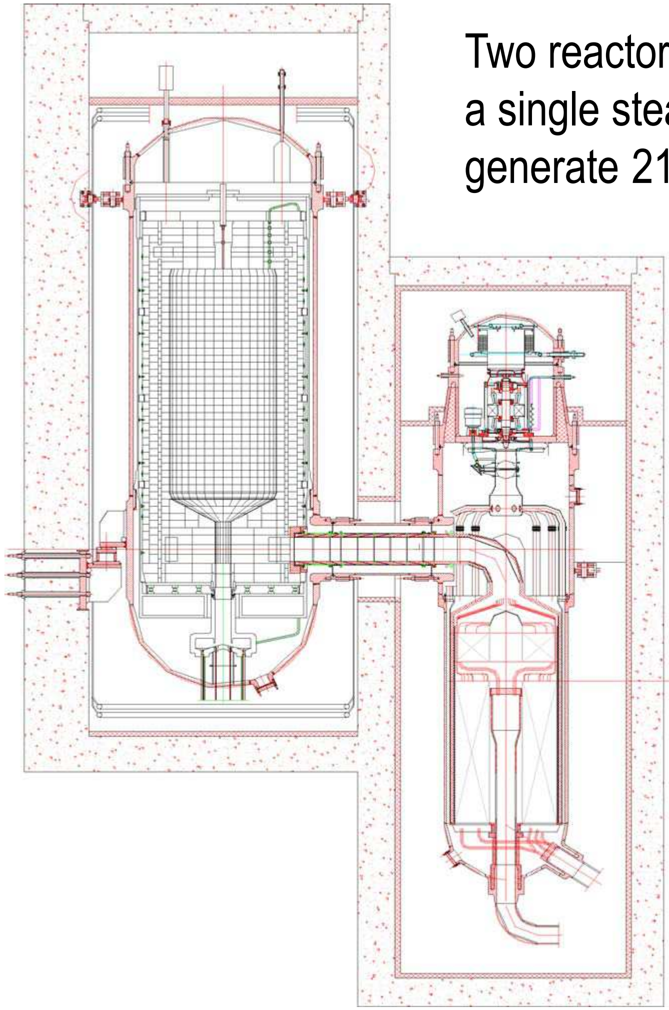
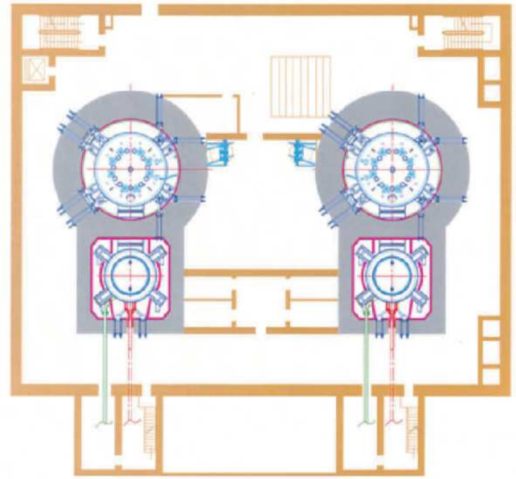


Courtesy of Tsinghua University



Two reactors are connected to a single steam turbine to generate 210 MW of electricity



- Power density ~ 3.3 MW/m^3 (factor of 30 lower than in PWR)
- High thermal inertia
- There is no need in core emergency cooling system since decay heat is removed by natural mechanisms in case of accidents

From Gen-III to Gen-IV: improvements to reach the goal(s)

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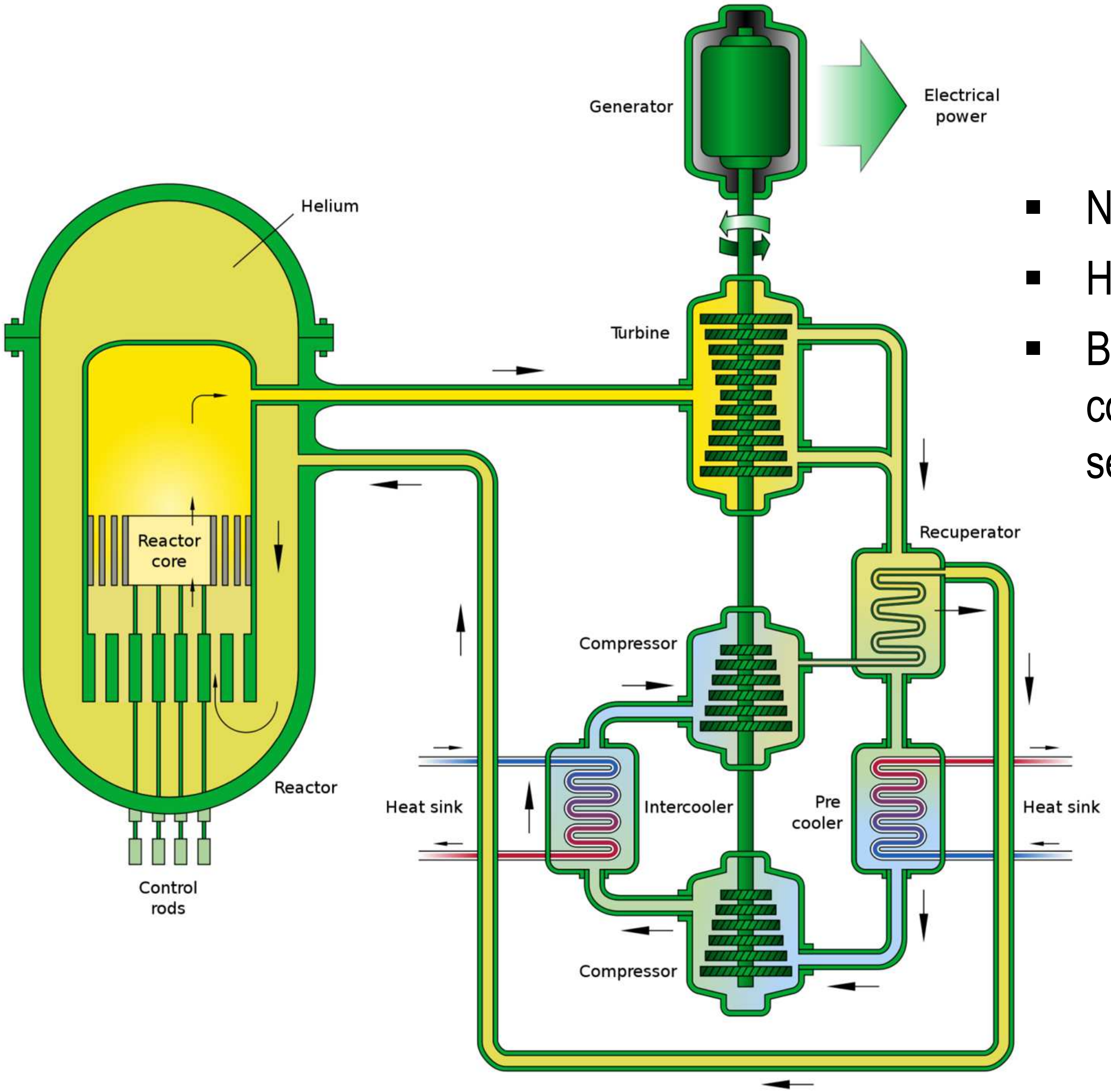
Pressure (MPa)	~16		~25		~7	
Moderator	H_2O		H_2O		C	
Neutron spectrum	Thermal		Thermal		Thermal	
Breeding gain	<< 0		<< 0		<< 0	
Reference	[1]		[2]		[3]	
G1: Sustainability	Poor		↔		?	
G2: Safety & reliability	Good		↓		↑	
G3: Economics	Good		↑		↑	

- The weakness of SCWR and (V)HTR is low breeding gain and difficulty to reach G1. How to reach G1 and in particular improved fuel utilization?

→ Change the design to obtain the fast neutron spectrum

Gas-cooled Fast Reactor: concept



- No moderator
- Helium coolant
- Both direct and indirect cycle considered (indirect cycle selected)

Gas-cooled Fast Reactor: fact sheet

SCWR
(V)HTR
GFR
SFR
LFR
MSR

- **Advantages**
  - Potential for new fissile breeding due to fast neutron spectrum
  - Transparent and inert coolant
  - High efficiency
- **Challenges**
  - Safety demonstration and in particular decay heat removal in case of loss of flow and depressurization accidents
  - High-temperature materials and fuel qualification
- **Designs under development**
  - ALLEGRO 75 MWth
  - GCFR 2400 MWth
- **Reactors under operation**
  - None

GCFR (EU): main parameters

SCWR
(V)HTR
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Concept	**PWR**		**SCWR**		**(V)HTR**		**GFR**	
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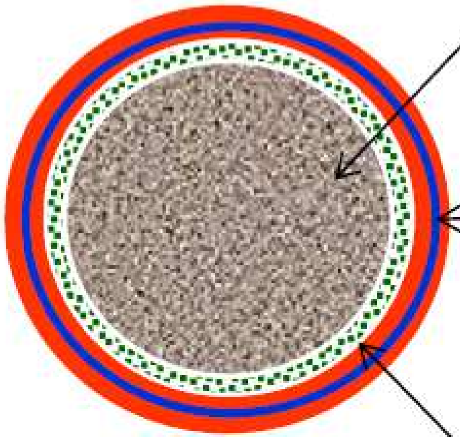
Primary coolant	H_2O		**H_2O**		He		He	
Inlet/outlet temp. (C)	296	327	280	**500**	250	750	400	780
Pressure (MPa)	~16		**~25**		~7		**~7**	
Moderator	H_2O		H_2O		C		**None**	
Neutron spectrum	Thermal		Thermal		Thermal		Fast	
Breeding gain	<< 0		**<< 0**		**<< 0**		**~ 0**	
Reference	[1]		[2]		[3]		[4]	
G1: Sustainability	Poor		↔		?		↑	
G2: Safety & reliability	Good		↓		↑		↓	
G3: Economics	Good		↑		↑		?	

← Depressurization accidents (GFR pressure ~7)

← Low thermal inertia (GFR moderator None)

*Specific designs chosen by lecturer

GCFR-2400 (EU): fuel



(U-Pu)C fuel pellet

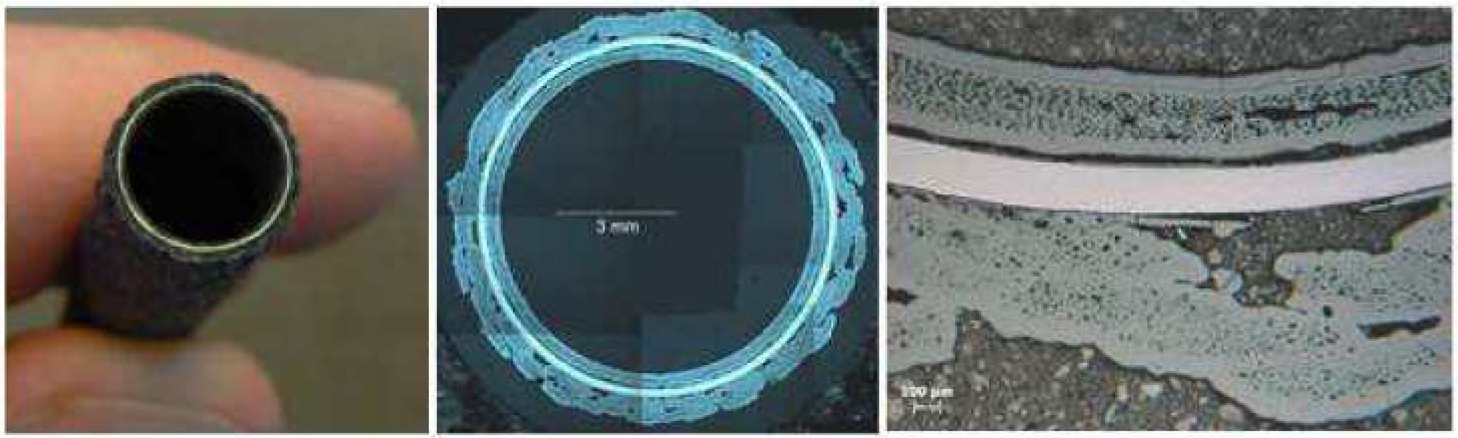
Sandwich cladding Ø~9 mm:

- inner SiC/SiC layer
- middle metalic liner
- outer SiC/SiC layer

Buffer bond:

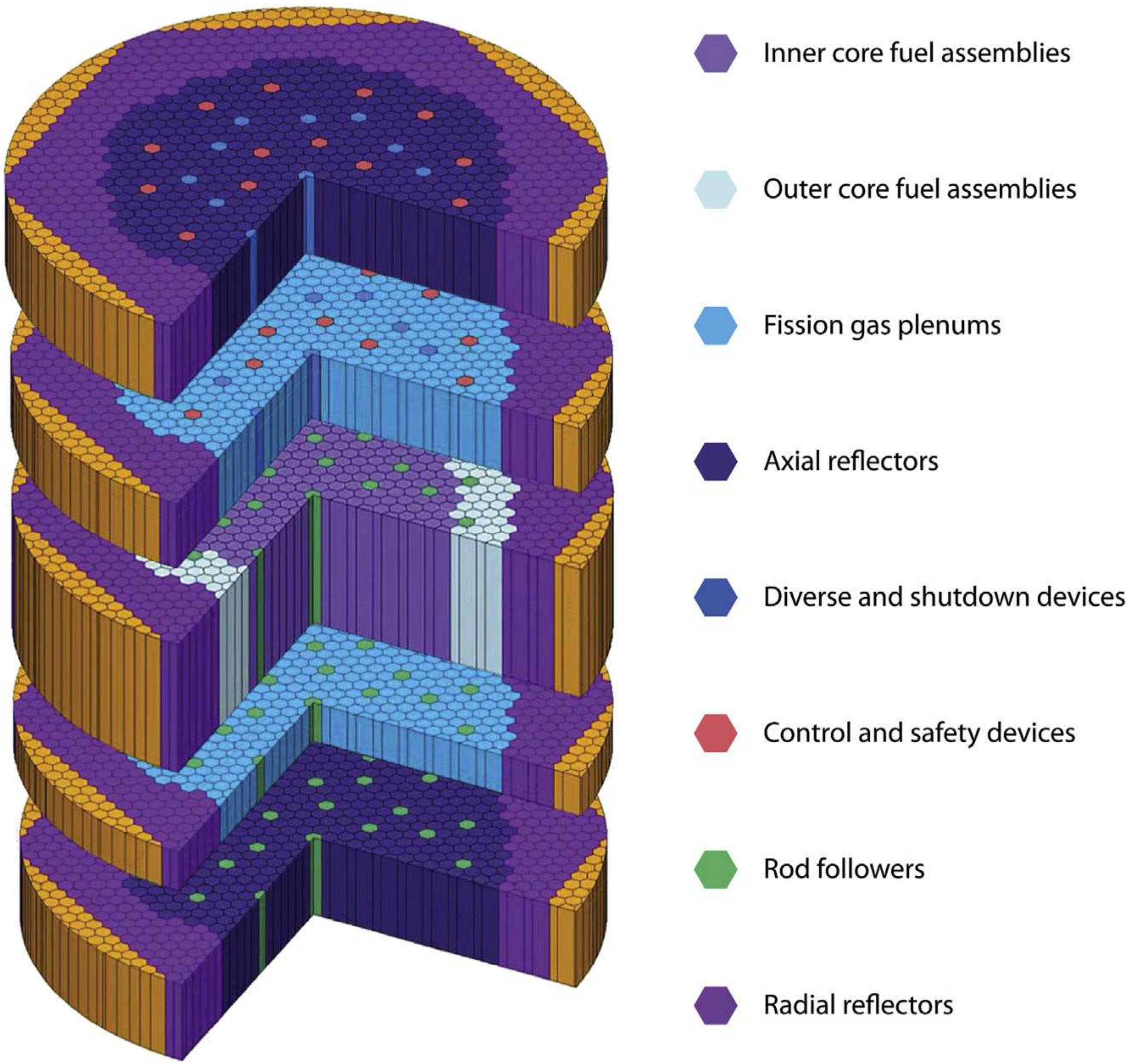
- high-porosity C-based braid

CEA manufactured "Sandwich" cladding

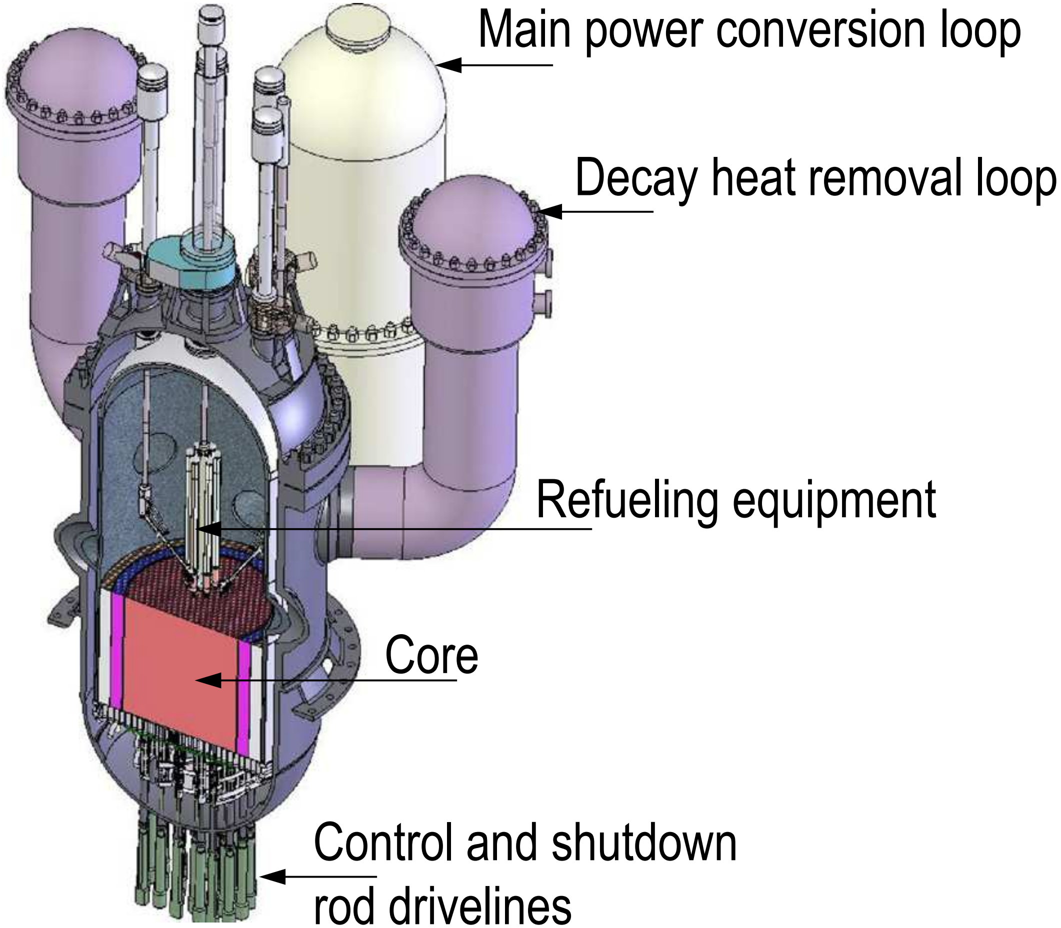


M. Zabiégo, et al. "Overview of CEA's R&D on GFR fuel element design: from challenges to solutions", FR'13 conference proceedings

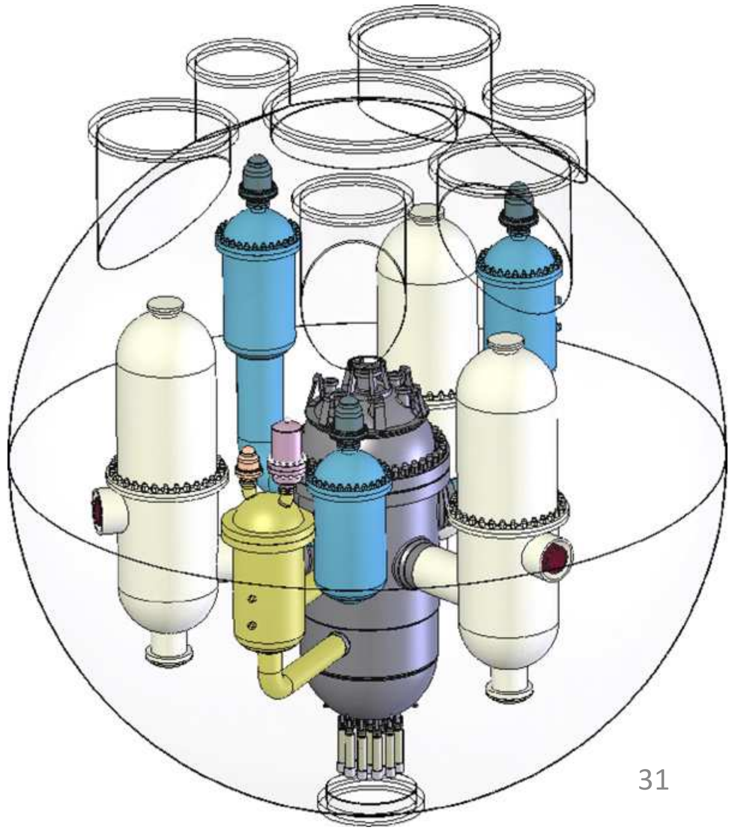
GCFR-2400 (EU): core



GCFR-2400 (EU): reactor



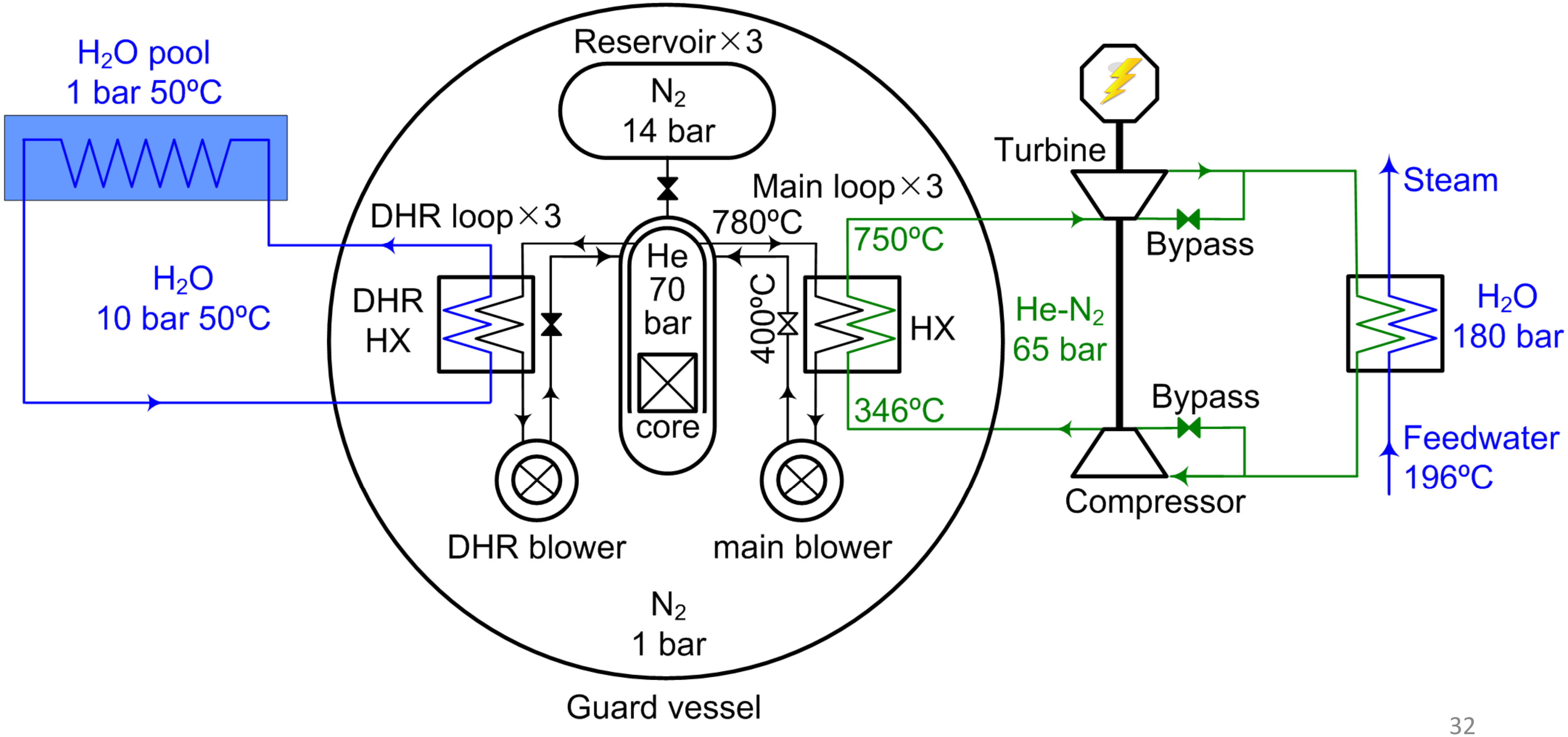
Spherical guard vessel



GCFR (EU): BoP concept

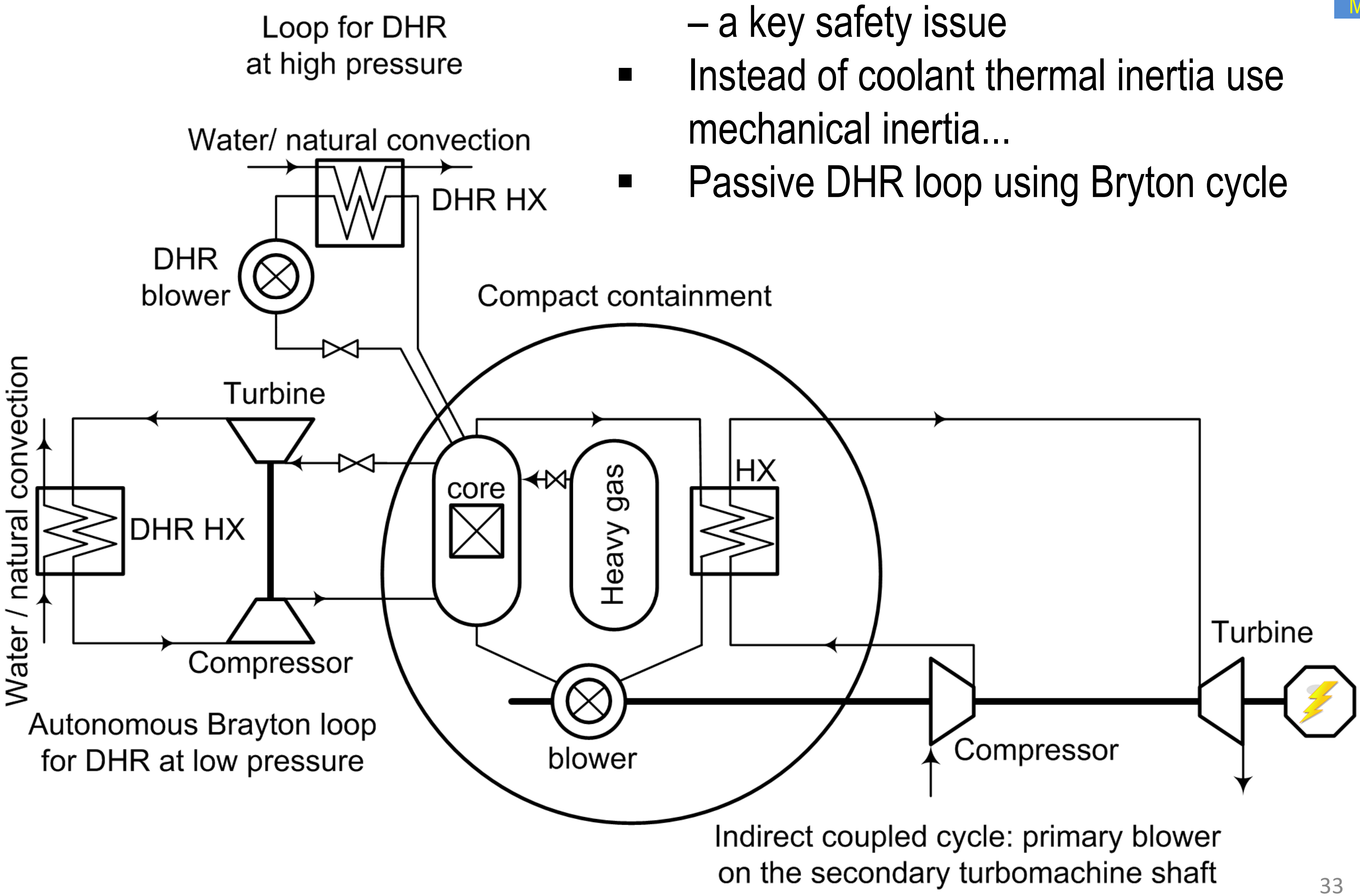
Power: 2400 MWth
Fuel: (U-Pu)C
Clad: SiC-SiC$_f$

- Guard vessel for backup pressure
- Heavy gas injection in accidents with depressurization
- DHR loops with forced convection



GCFR (EU): How to improve safety?

- DHR under depressurized conditions – a key safety issue
- Instead of coolant thermal inertia use mechanical inertia...
- Passive DHR loop using Bryton cycle



From Gen-III to Gen-IV: improvements to reach the goal(s)

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Pressure (MPa)	~16		**~25**		~7		**~7**	
Moderator	H_2O		H_2O		C		**None**	
Neutron spectrum	Thermal		Thermal		Thermal		Fast	
Breeding gain	<< 0		**<< 0**		**<< 0**		**~ 0**	
Reference	[1]		[2]		[3]		[4]	
G1: Sustainability	Poor		↔		?		↑	
G2: Safety & reliability	Good		↓		↑		↓	
G3: Economics	Good		↑		↑		?	

- The weakness of GFR is low thermal inertia of the core requiring special safety measures against core meltdown in case of depressurization events. How to improve G2?

→ Use liquid metal instead of gas

Sodium-cooled Fast Reactor: concept

SCWR
(V)HTR
GFR
SFR
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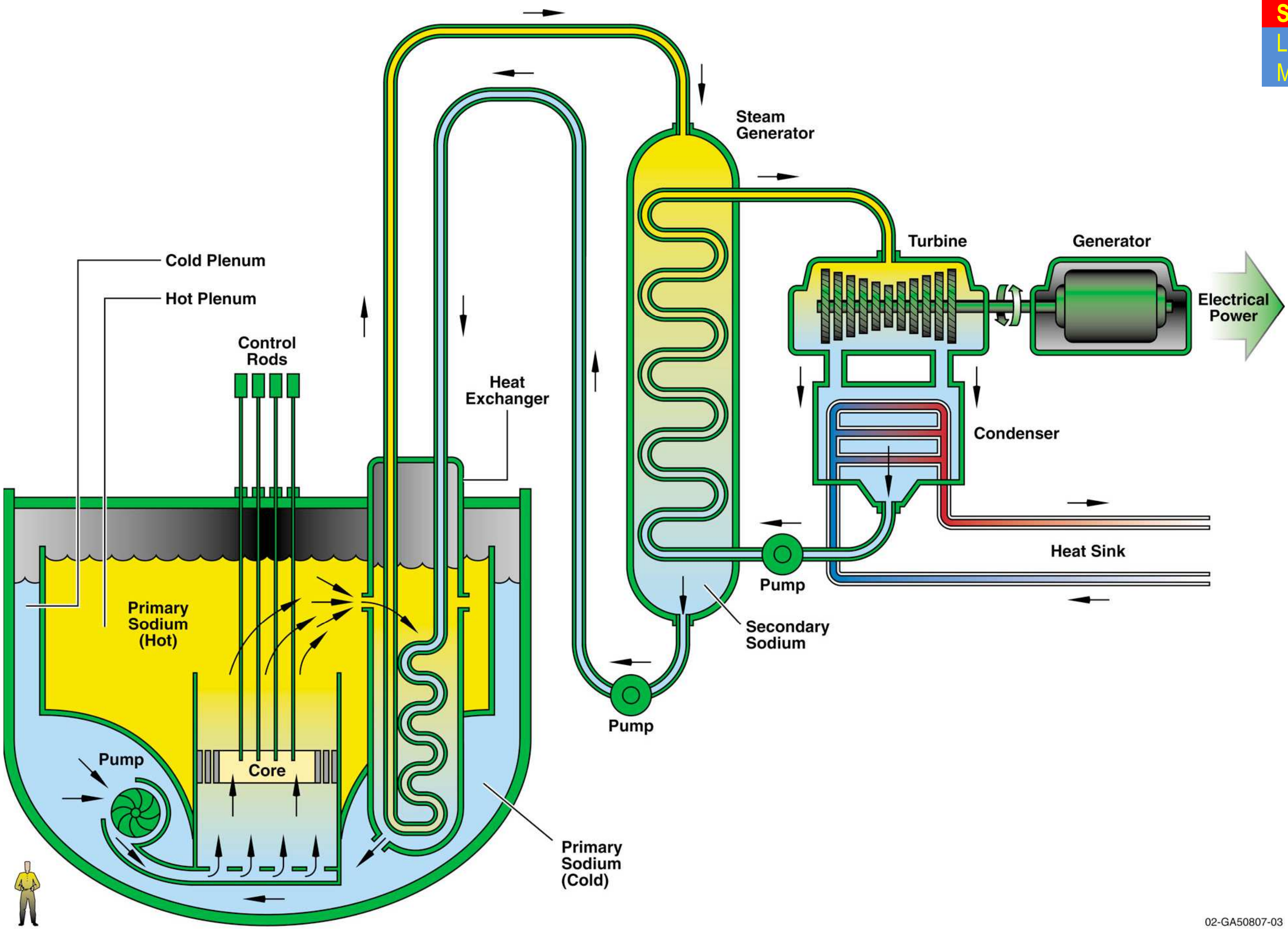
MSR



Sodium-cooled Fast Reactor: fact sheet

SCWR
(V)HTR
GFR
SFR
LFR
MSR

- **Advantages**
  - Potential for new fissile breeding due to fast neutron spectrum
  - Excellent thermal conductivity of sodium → VERY efficient cooling
  - Large margin to boiling → no pressurization required
  - Significant operational experience (300+ reactor-years)

- **Challenges**
  - Chemically active in contact with water or air → intermediate circuit needed
  - Significant scattering cross section → spectrum hardening when removed → positive reactivity effect → special safety measures needed

- **Designs under development**
  - PFBR (India), BN-1200 (Russia), ASTRID (France), ESFR (EU), ...

- **Reactors under operation**
  - BOR-60, BN-600, BN-800 (all Russia)
  - CEFR (China)

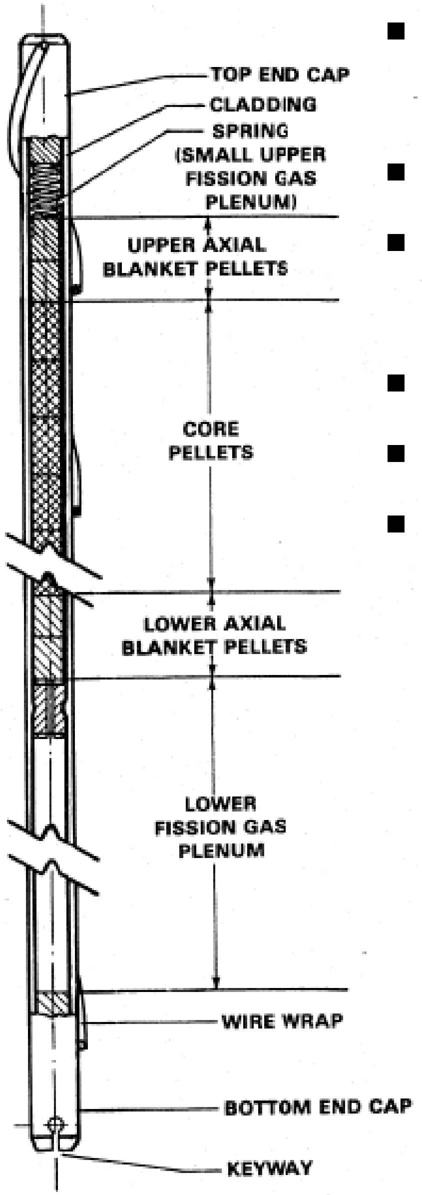
ESFR (EU): main parameters

SCWR
(V)HTR
GFR
SFR
LFR
MSR

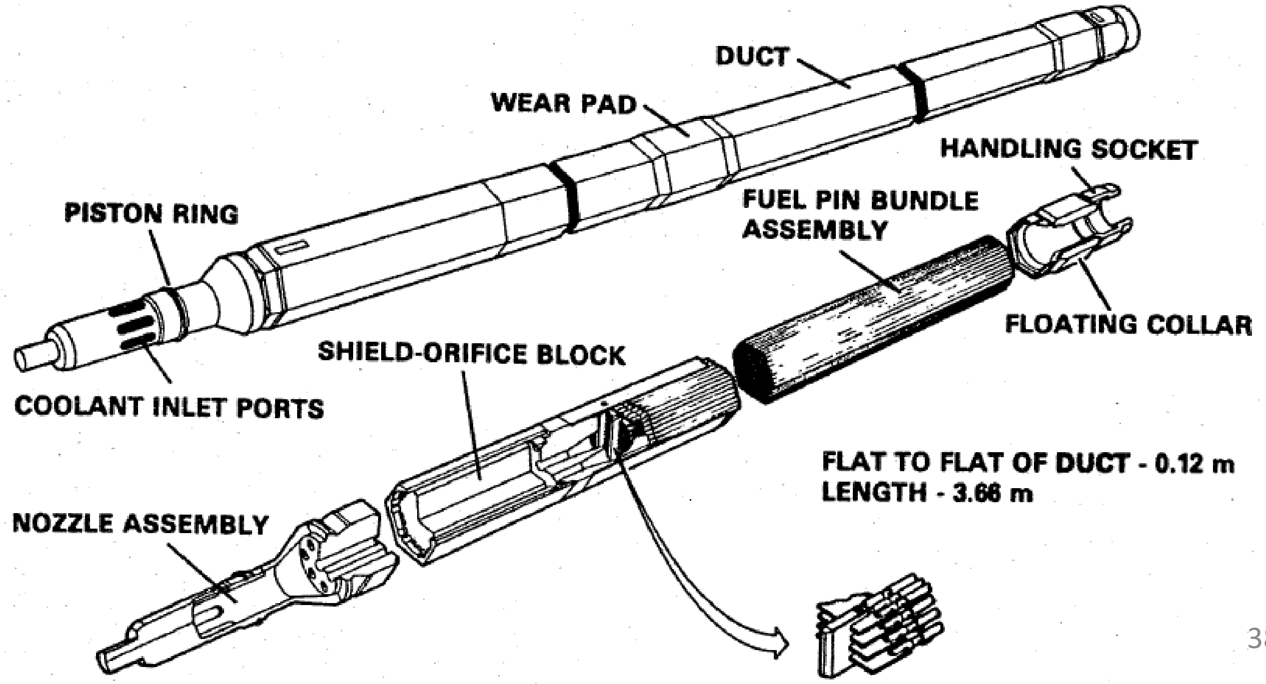
Concept	**PWR**		**SCWR**		**(V)HTR**		**GFR**		**SFR**	
Specific design*	EPR		HPLWR		HTR-PM		GCFR		ESFR	
Thermal power (MW)	4300		2300		458		2400		3600	
Efficiency (%)	37		**~44**		**~45**		**~45**		**~42**	
Primary coolant	H_2O		**H_2O**		He		He		**Na**	
Inlet/outlet temp. (C)	296	327	280	**500**	250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

Exothermic sodium-water and sodium-air reaction (→ Na)

SFR fuel rod and fuel subassembly

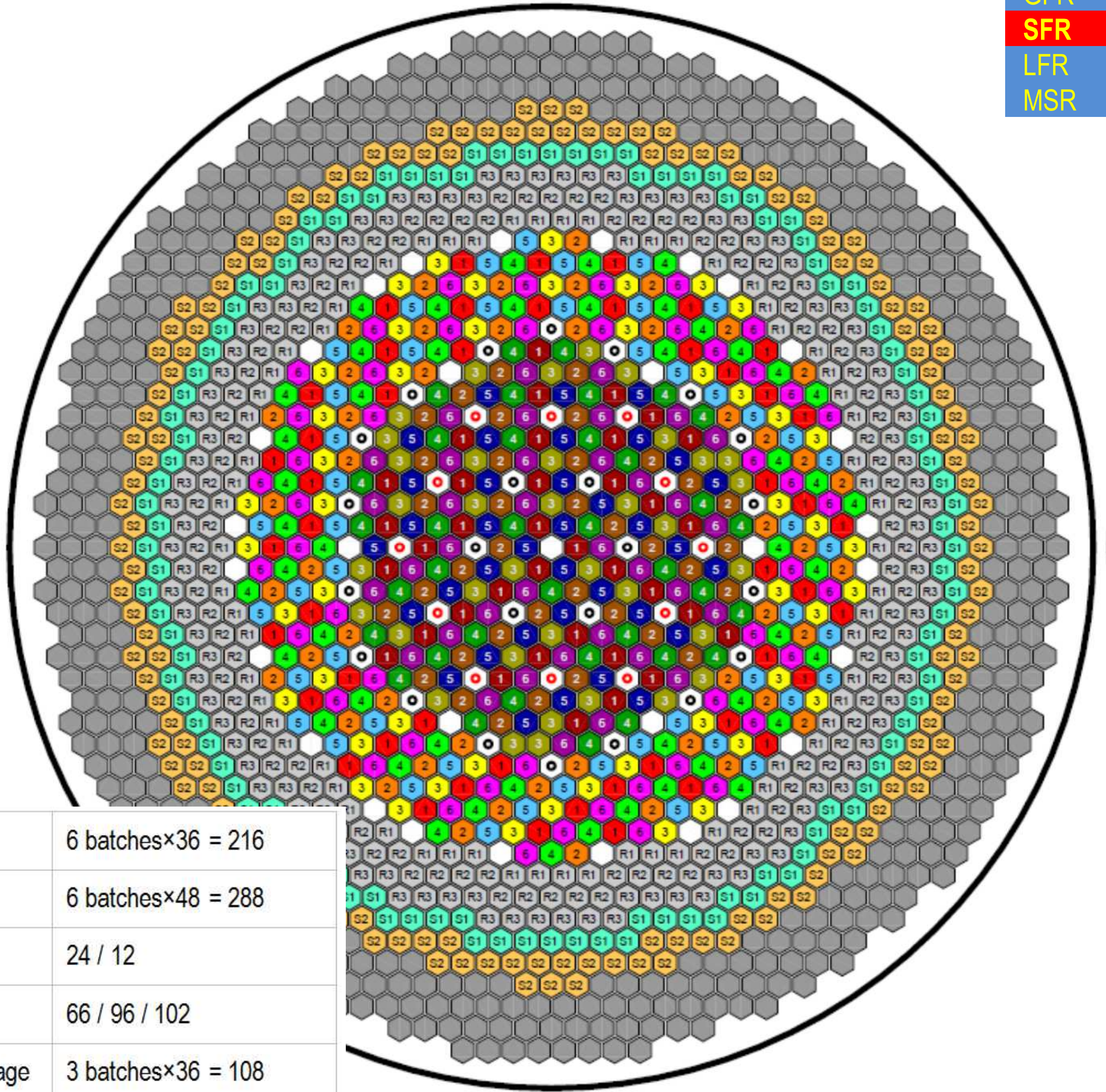


- Fuel and cladding are: mixed uranium and plutonium dioxides (MOX) and stainless steel
- Hexagonal lattice of rods fixed with helicoil wire spacers
- Closed assembly (duct=wrapper) → no cross flows between assemblies but interassembly flow
- Absorbers are inserted in the dedicated assemblies.
- Fuel stack height ~ 1 m; He inside
- Large (~1 m) FG plenum below



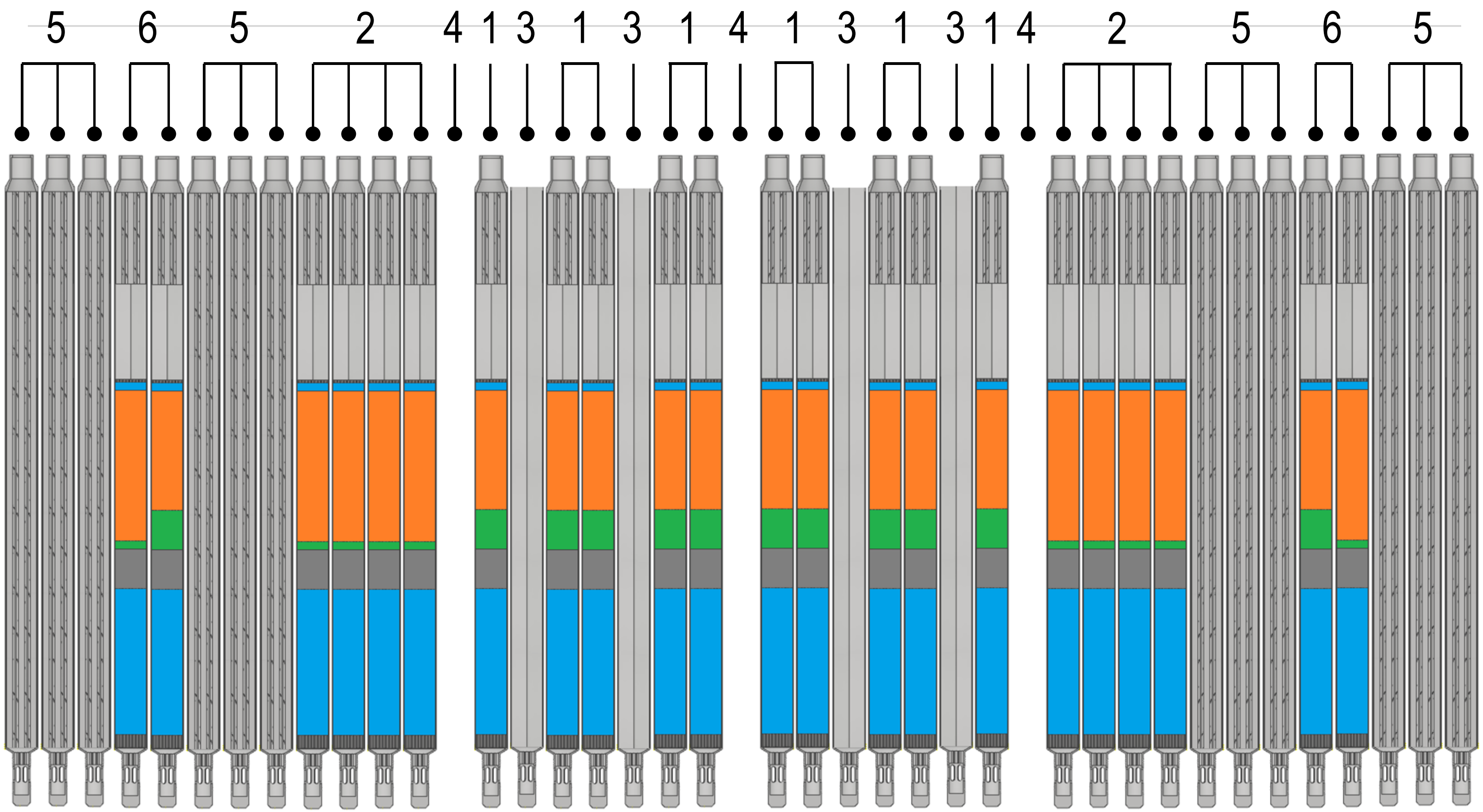
ESFR (EU): radial core layout

- Perfectly symmetric
- 6 batches = 6-year fuel cycle
- Mixed scheme (no reshuffling)
- Internal storage for 50% of core loading
- Corium discharge tubes
- All DSD rods equipped with passively-activated Curie-point locks

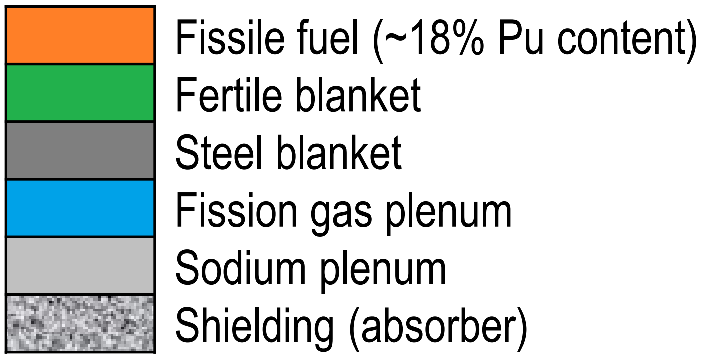


1 2 3 4 5 6	Inner fuel	6 batches×36 = 216
1 2 3 4 5 6	Outer fuel	6 batches×48 = 288
○ ○	CSD / DSD	24 / 12
R1 R2 R3	1st / 2nd /3rd reflector ring	66 / 96 / 102
S1	Spent Inner / Outer fuel storage	3 batches×36 = 108
S2	Spent Inner / Outer fuel storage	3 batches×48 = 144
	Corium discharge tubes	31

ESFR (EU): axial core layout

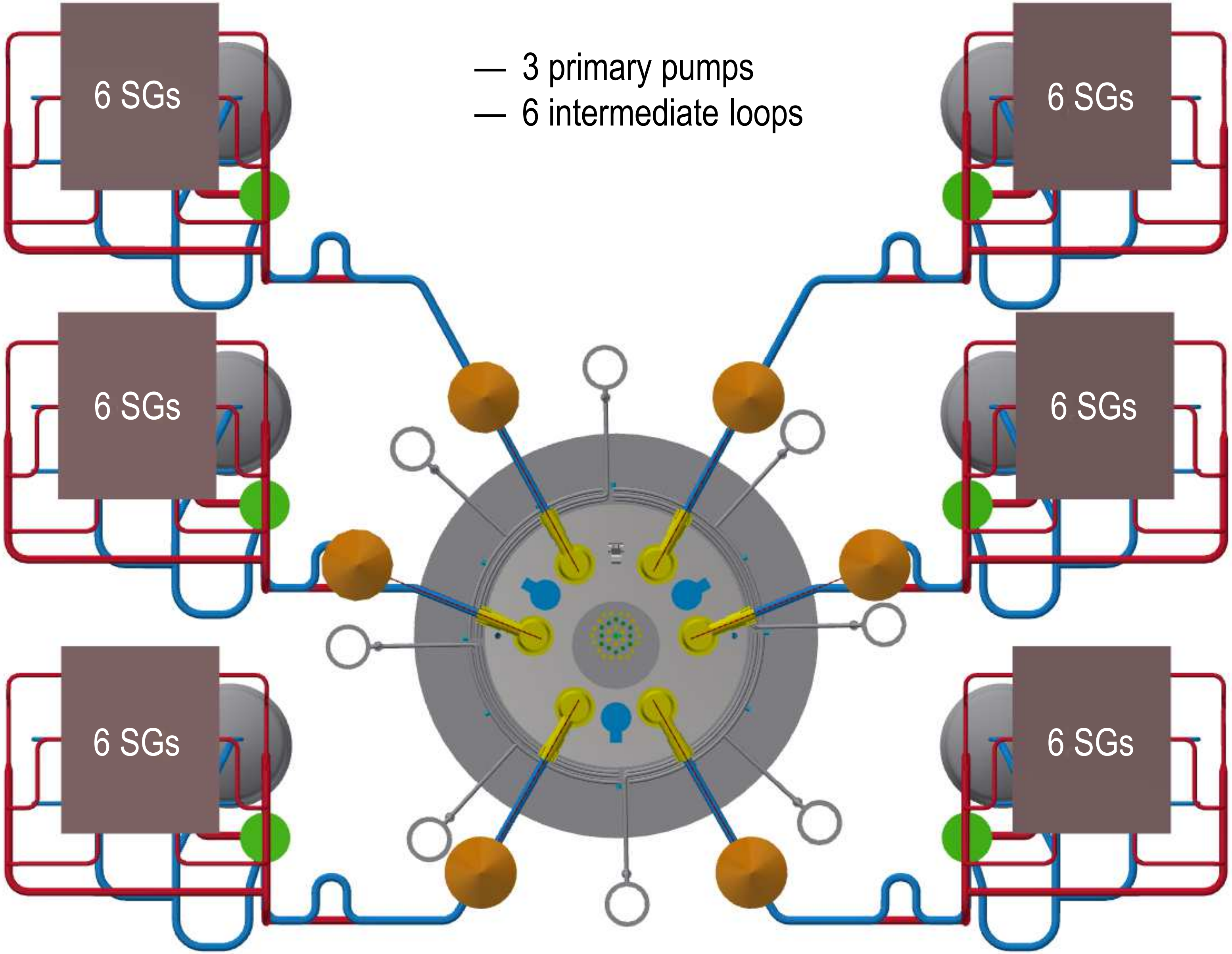


1 – Inner zone SA
2 – Outer zone SA
3 – Control assembly
4 – Corium discharge path
5 – Shielding SA
6 – Internal spent fuel storage

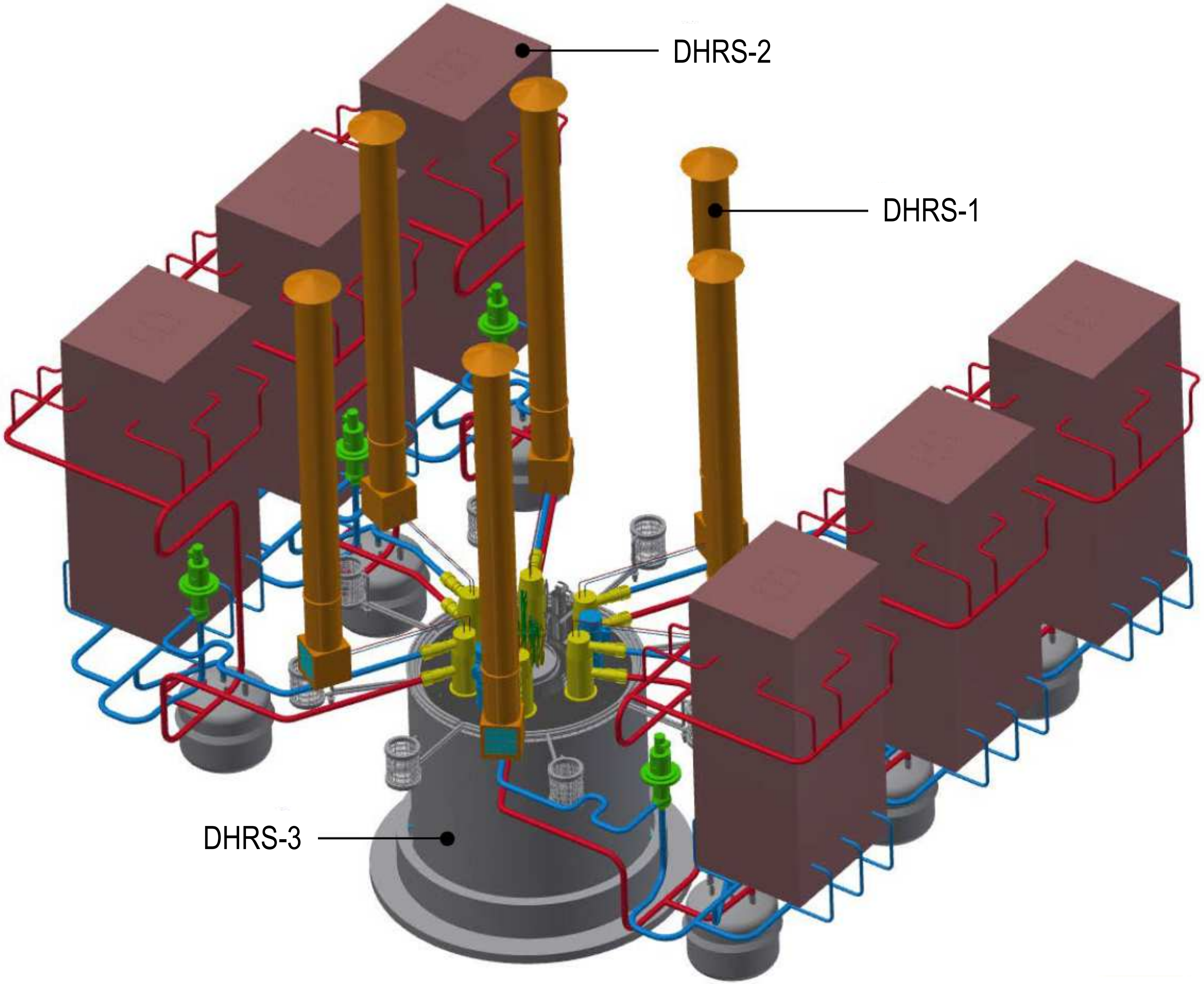


ESFR (EU): global view from above

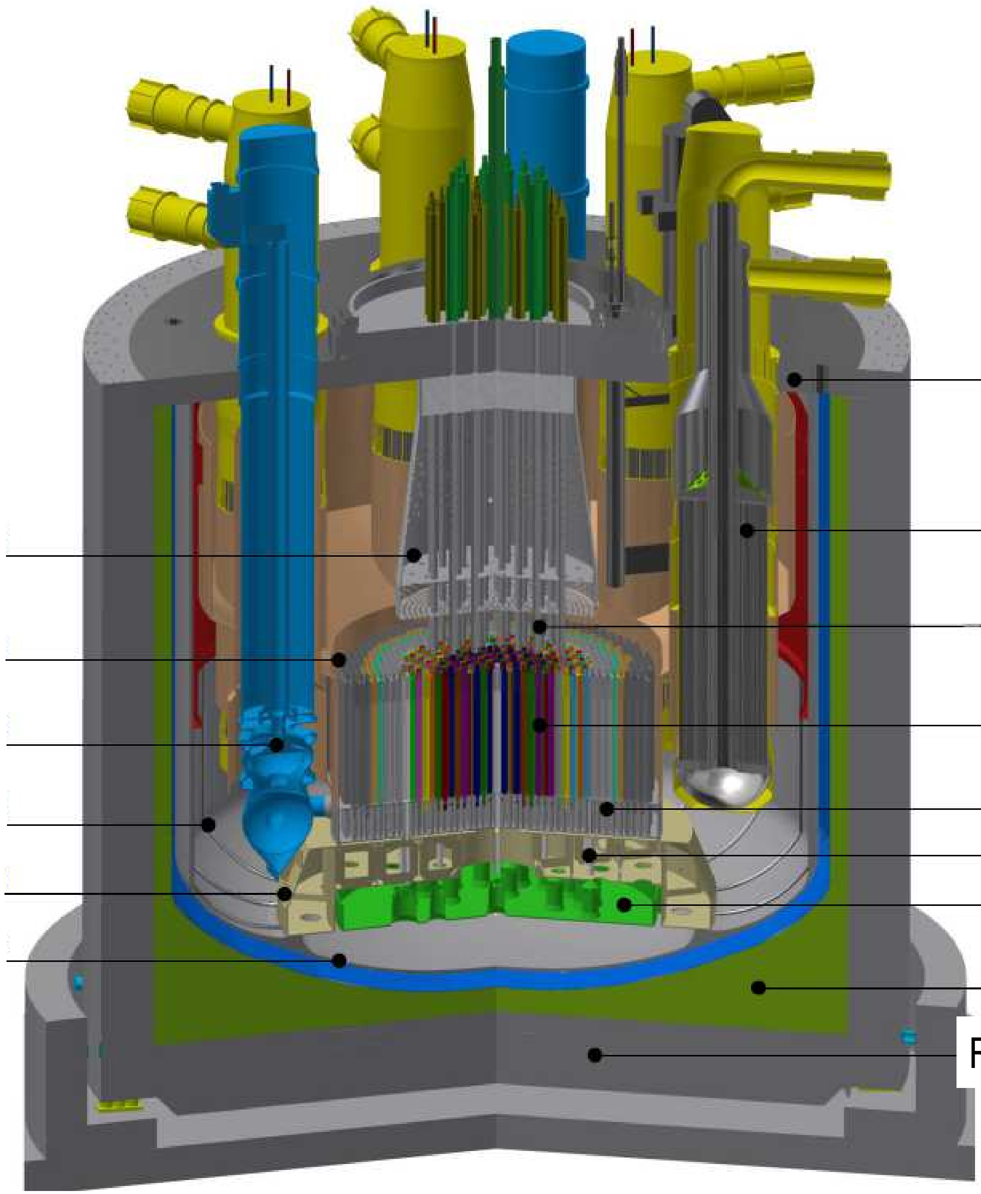
- 3 primary pumps
- 6 intermediate loops



ESFR (EU): global view



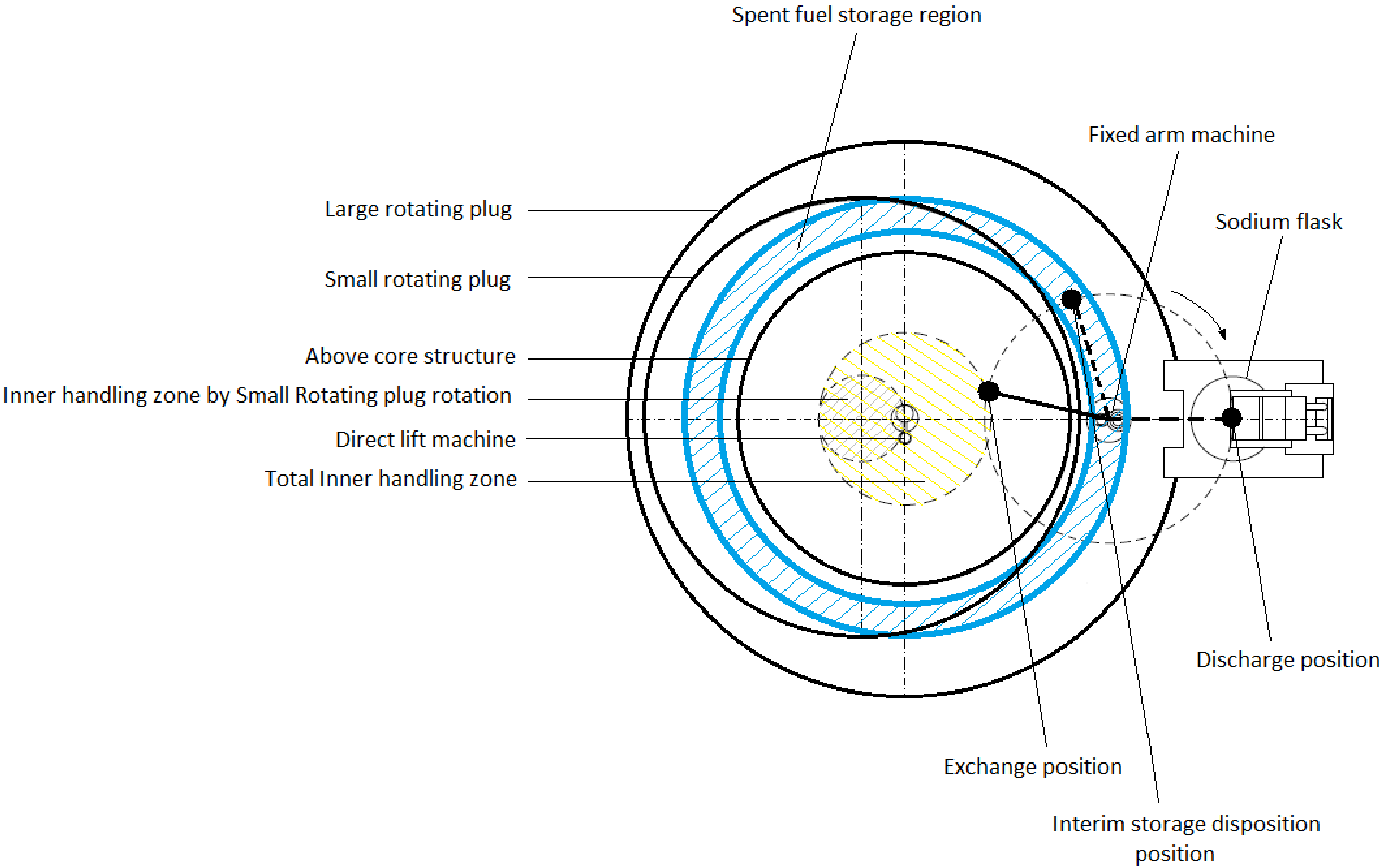
ESFR (EU): primary system



SCWR
(V)HTR
GFR
SFR
LFR
MSR

ESFR (EU): in-vessel fuel handling system

SCWR
(V)HTR
GFR
SFR
LFR
MSR

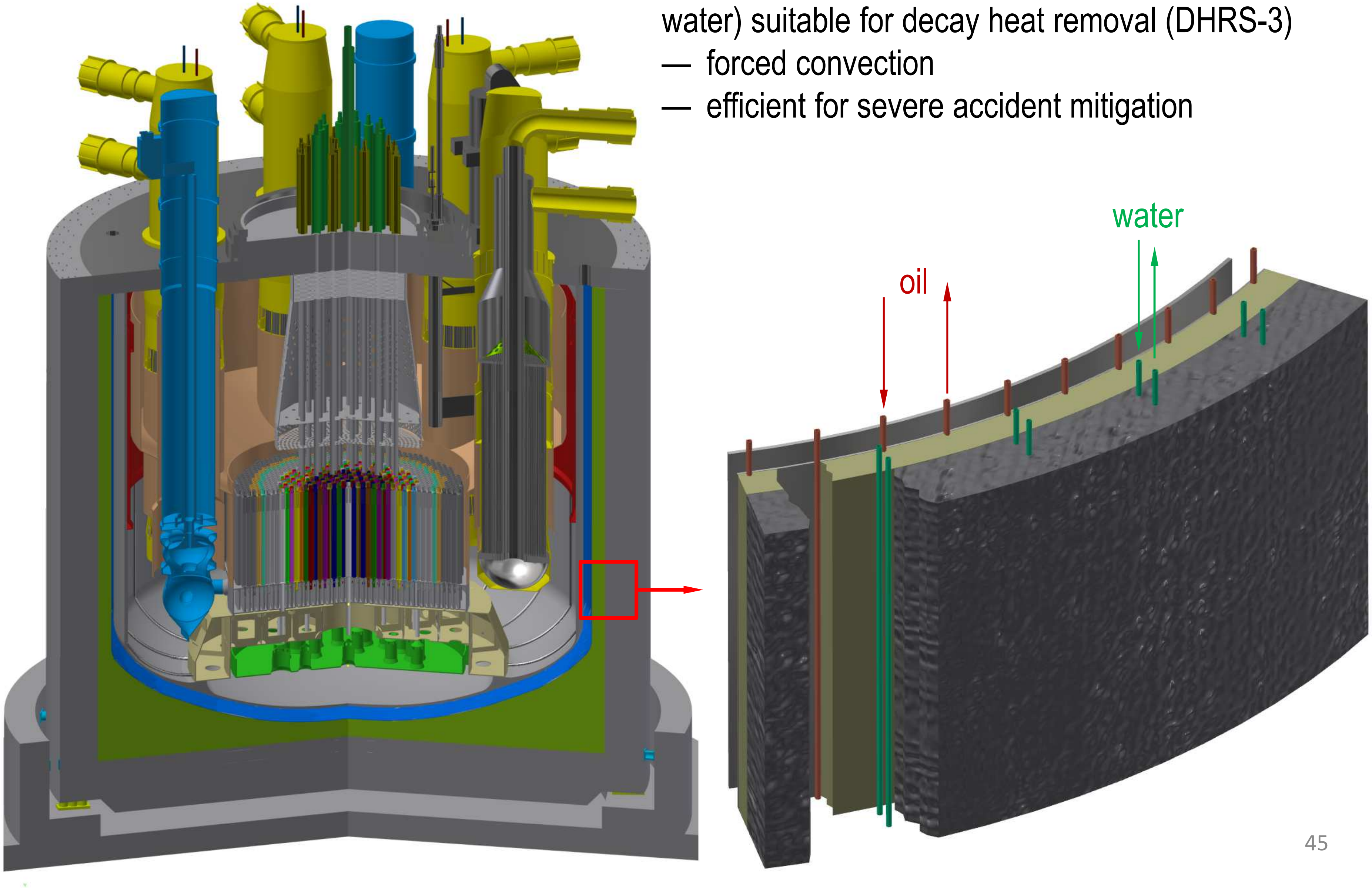


ESFR (EU): pit cooling

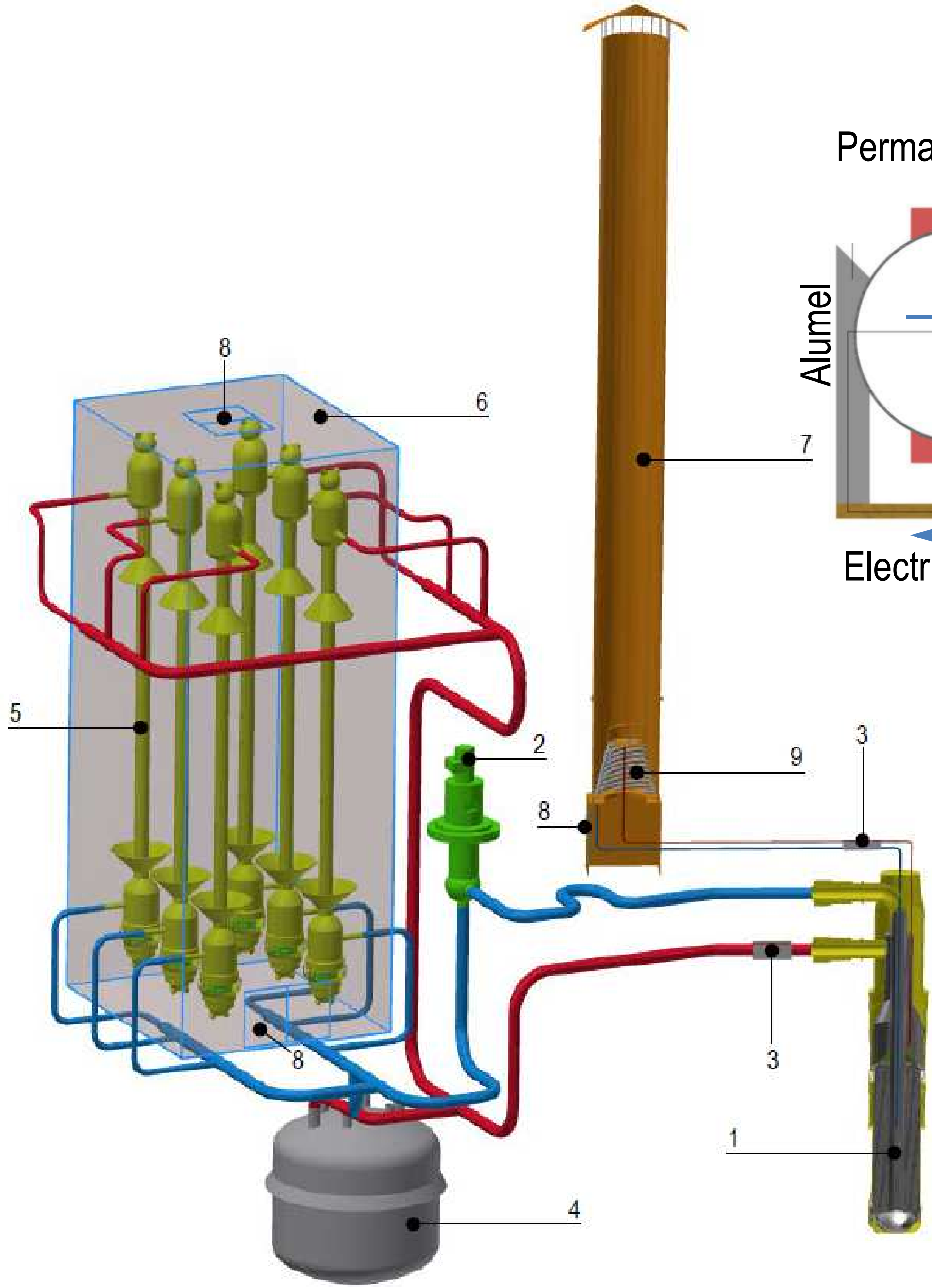
Two reactor pit concrete cooling systems (oil and water) suitable for decay heat removal (DHRS-3)

— forced convection

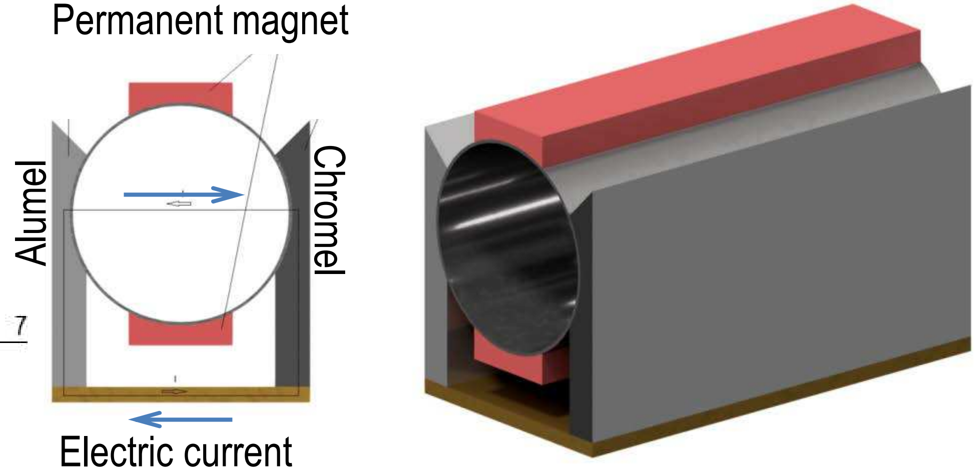
— efficient for severe accident mitigation



ESFR (EU): secondary system



Thermal pump concept

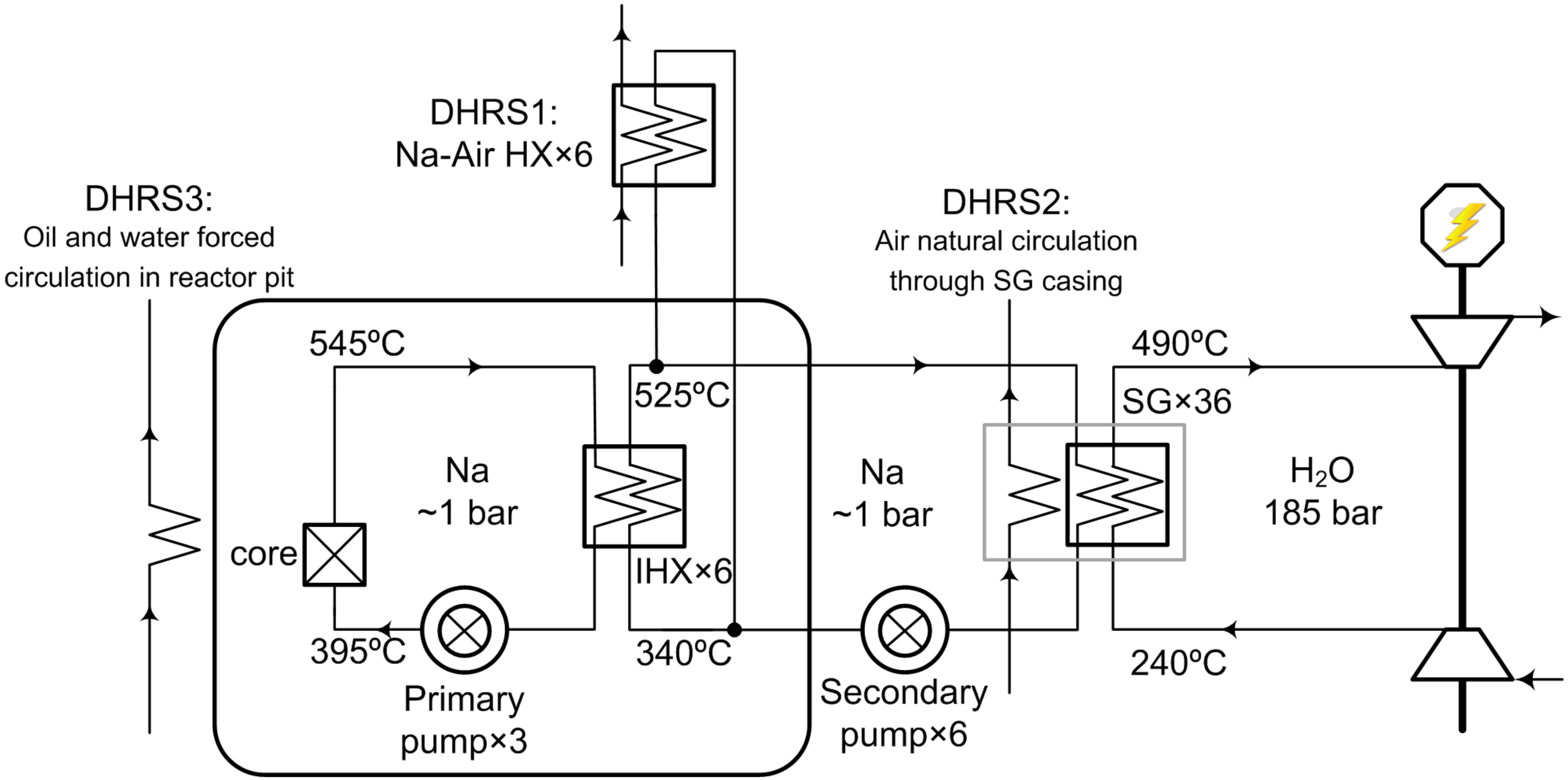


1 – Intermediate heat exchanger
2 – Secondary pump
3 – Thermal pumps
4 – Sodium storage tank
5 – Steam generator
6 – Casing of Decay Heat Removal System (DHRS-2)
7 – Air stack of DHRS-1
8 – Openings for air circulation
9 – Sodium-air heat exchanger of DHRS-1

ESFR (EU): BoP concept

SCWR
(V)HTR
GFR
SFR
LFR
MSR

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



From Gen-III to Gen-IV: improvements to reach the goal(s)

SCWR
(V)HTR
GFR
SFR
LFR
MSR

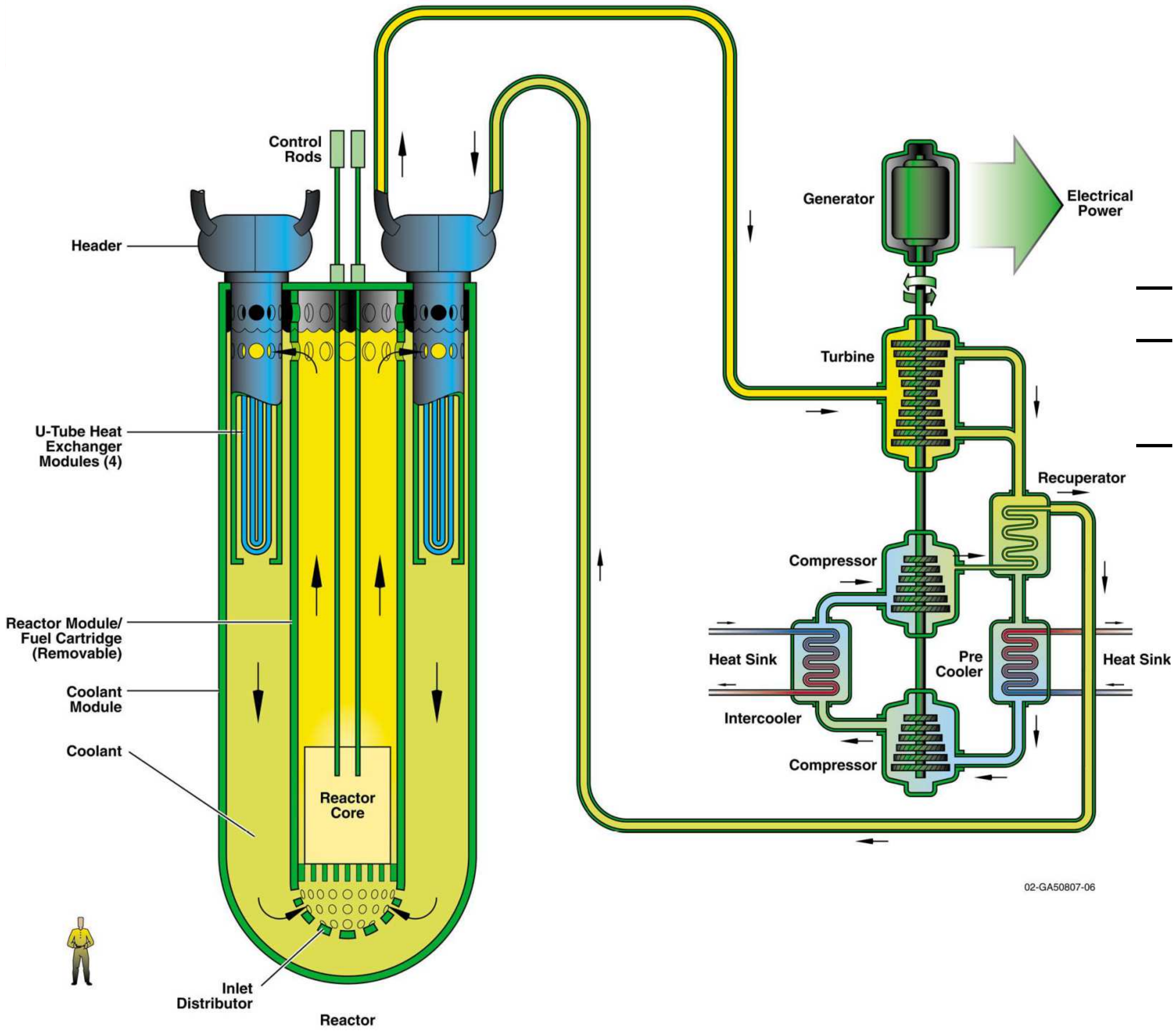
Concept	PWR		SCWR		(V)HTR		GFR		SFR	
Specific design*	EPR		HPLWR		HTR-PM		GCFR		ESFR	
Thermal power (MW)	4300		2300		458		2400		3600	
Efficiency (%)	37		~44		~45		~45		~42	
Primary coolant	H_2O		H_2O		He		He		Na	
Inlet/outlet temp. (C)	296	327	280	500	250	750	400	780	395	545
Pressure (MPa)	~16		~25	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

- SFR is the most mature concept among GIF fast reactors. However, the weakness of SFR is the risk of sodium-water and sodium-air reaction and corresponding design complication (e.g., intermediate loop). How to improve G2 and G3, keeping G1?

→ Use another liquid metal instead of sodium

Lead-cooled Fast Reactor: concept

SCWR
(V)HTR
GFR
SFR
LFR
MSR



- Simplicity
- No intermediate circuit
- Oxygen control for materials protection

Lead-cooled Fast Reactor: fact sheet

SCWR
(V)HTR
GFR
SFR
LFR
MSR

- **Advantages**
  - Potential for new fissile breeding due to fast neutron spectrum
  - High density → thermal inertia is VERY high
  - High thermal conductivity and expansion coefficient → efficient heat removal at low velocities and high natural circulation level
  - Passive with water and air → no intermediate circuit
  - Large margin to boiling (1740º C) → no pressurization required
- **Challenges**
  - High density → erosion, seismic refueling issues
  - At high temperature structural materials (such as iron or nickel) are slowly dissolving in lead flow → protection needed
  - High void reactivity effect (e.g. gas entry)
  - Low margin to freezing (327ºC) → special safety measures needed
- **Designs under development**
  - ELFR, ALFRED, BREST-OD-300, SSTAR
- **Reactors under operation**
  - None (very small operational experience)

ALFRED (EU): European LFR demonstrator project

SCWR
(V)HTR
GFR
SFR
LFR
MSR

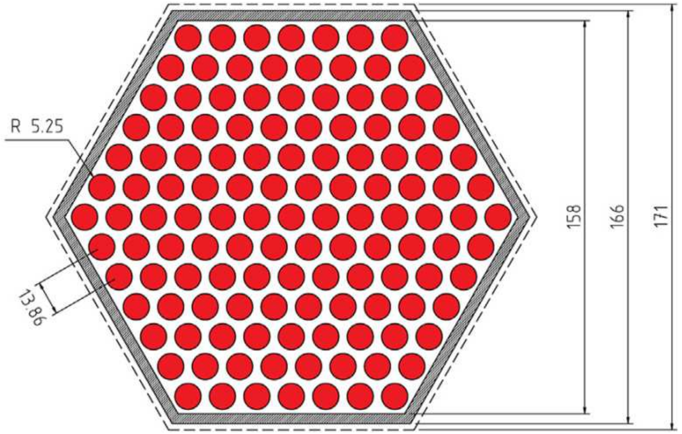
Concept	PWR		SCWR		(V)HTR		GFR		SFR		LFR	
Specific design*	EPR		HPLWR		HTR-PM		GCFR		ESFR		ALFRED	
Thermal power (MW)	4300		2300		458		2400		3600		300	
Efficiency (%)	37		**~44**		**~45**		**~45**		**~42**		**~42**	
Primary coolant	H_2O		**H_2O**		He		He		**Na**		**Pb**	
Inlet/outlet temp. (C)	296	327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

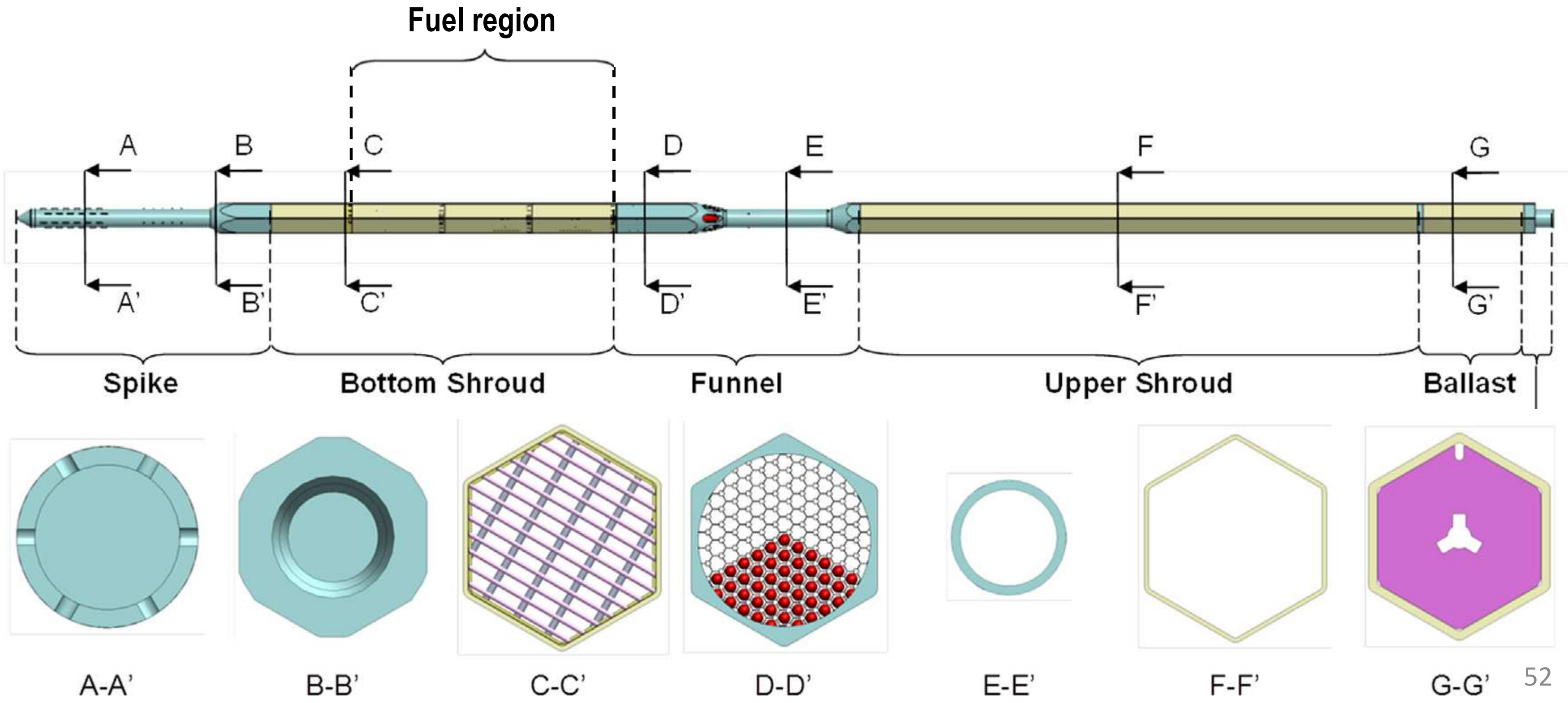
*Specific designs chosen by lecturer

Slow dissolution of structural materials (→ Pb)

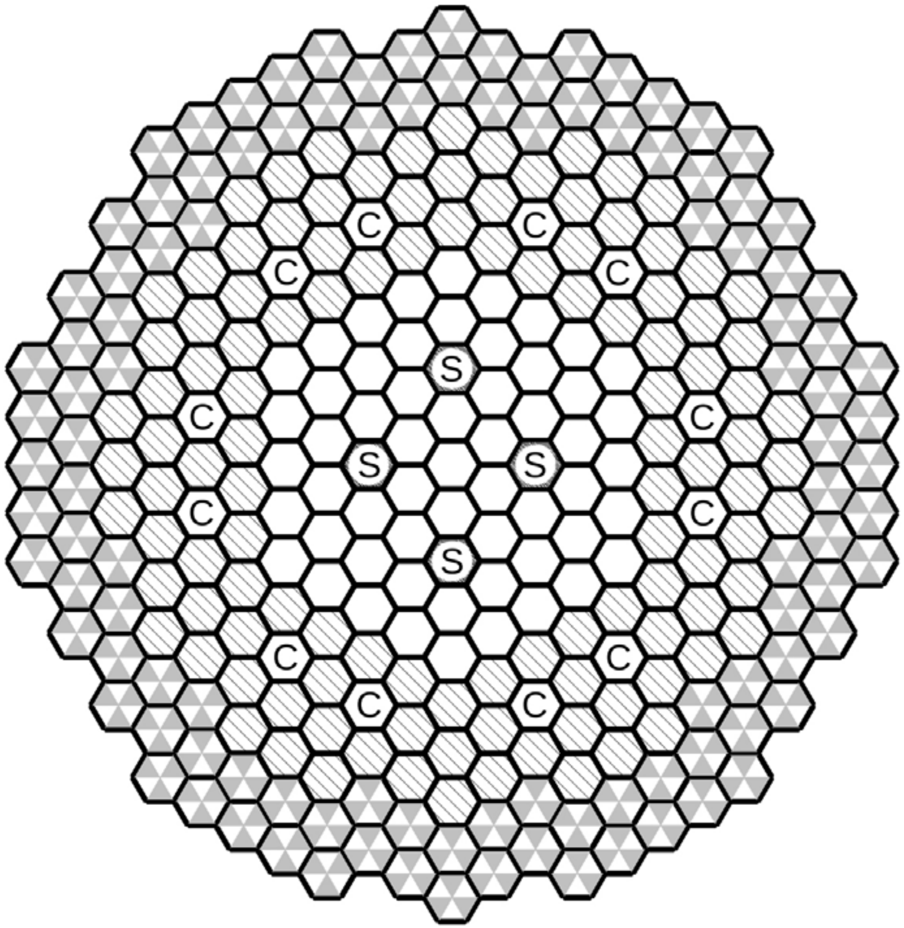
Limited operational experience (→ LFR G2: ↓↑)

ALFRED (EU): fuel subassembly





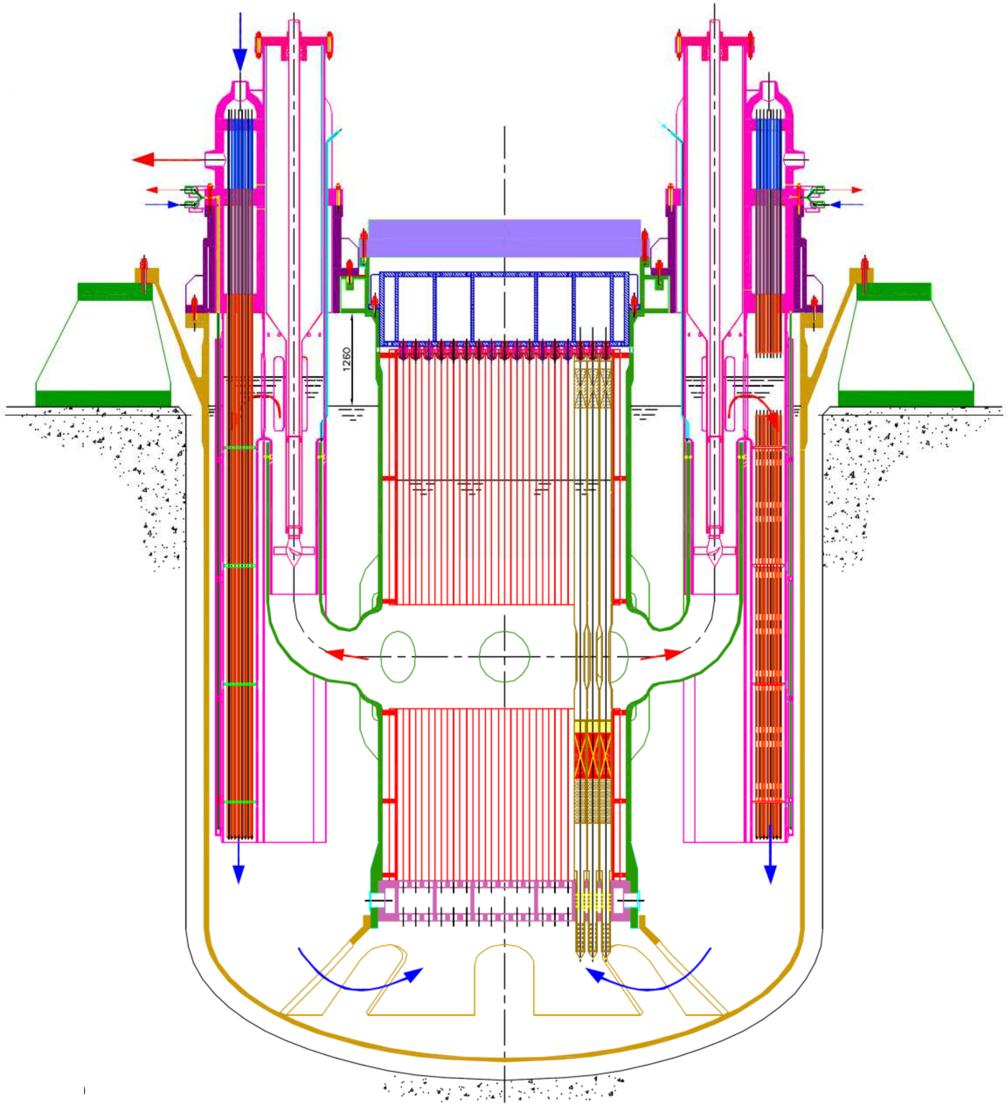
ALFRED (EU): core



- Inner Fuel Assembly
- Outer Fuel Assembly
- Control Rod
- Safety Rod
- Dummy Element (shield)

ALFRED (EU): primary system

SCWR
(V)HTR
GFR
SFR
LFR
MSR



Reactor roof: hot, standard flanged connections, *no rotational plugs*

Fuel assemblies: MOX, grid spacers, hexagonal, wrapped, *extended stem*

Reactivity control: two diverse and redundant systems, control and shut-down rods

Primary system configuration: pool-type, *enhanced natural convection* in accident conditions

Primary pumps: mechanical, at hot leg

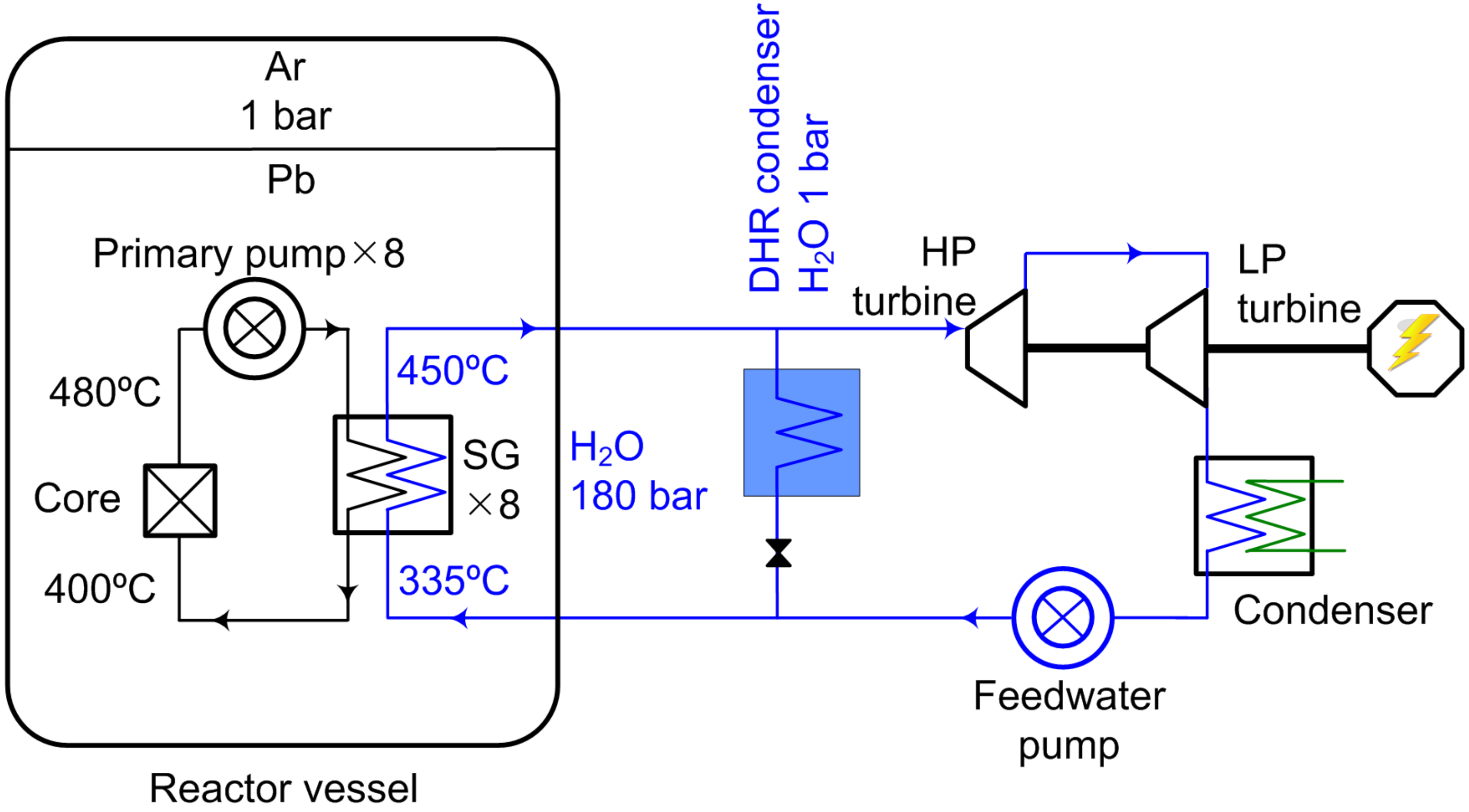
Decay heat removal: isolation condenser connected to dip-coolers with straight double-walled tubes

Reactor and safety vessels: hanged, toro-spherical bottom head

ALFRED (EU): BoP concept

SCWR
(V)HTR
GFR
SFR
LFR
MSR

Power: 300 MWth
Fuel: (U-Pu)O_2
Clad: Stainless steel



From Gen-III to Gen-IV: improvements to reach the goal(s)

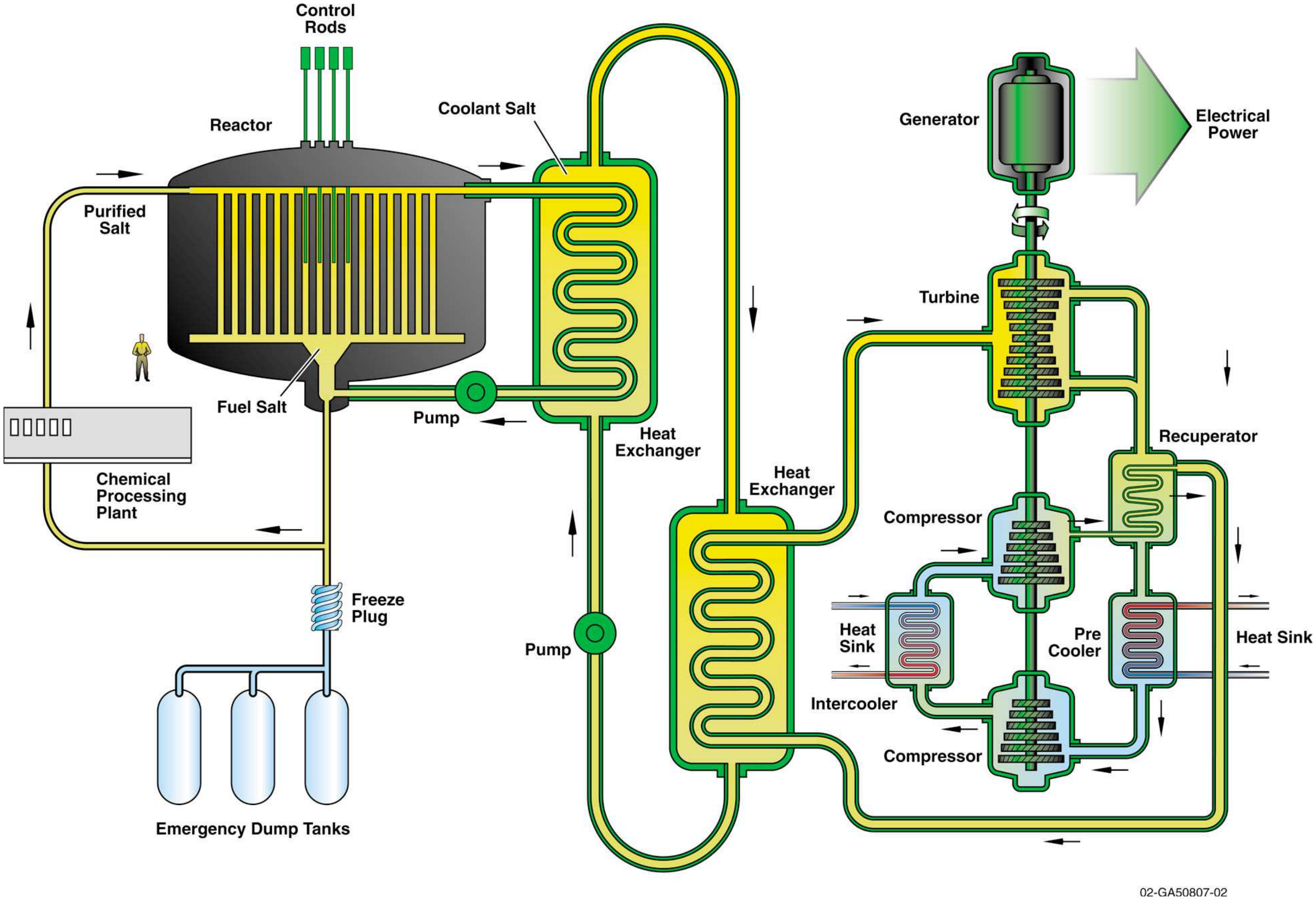
SCWR
(V)HTR
GFR
SFR
LFR
MSR

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

- In all considered systems the accidents with core meltdown has extremely low probability, but they are still possible. How to practically eliminate the core meltdown?

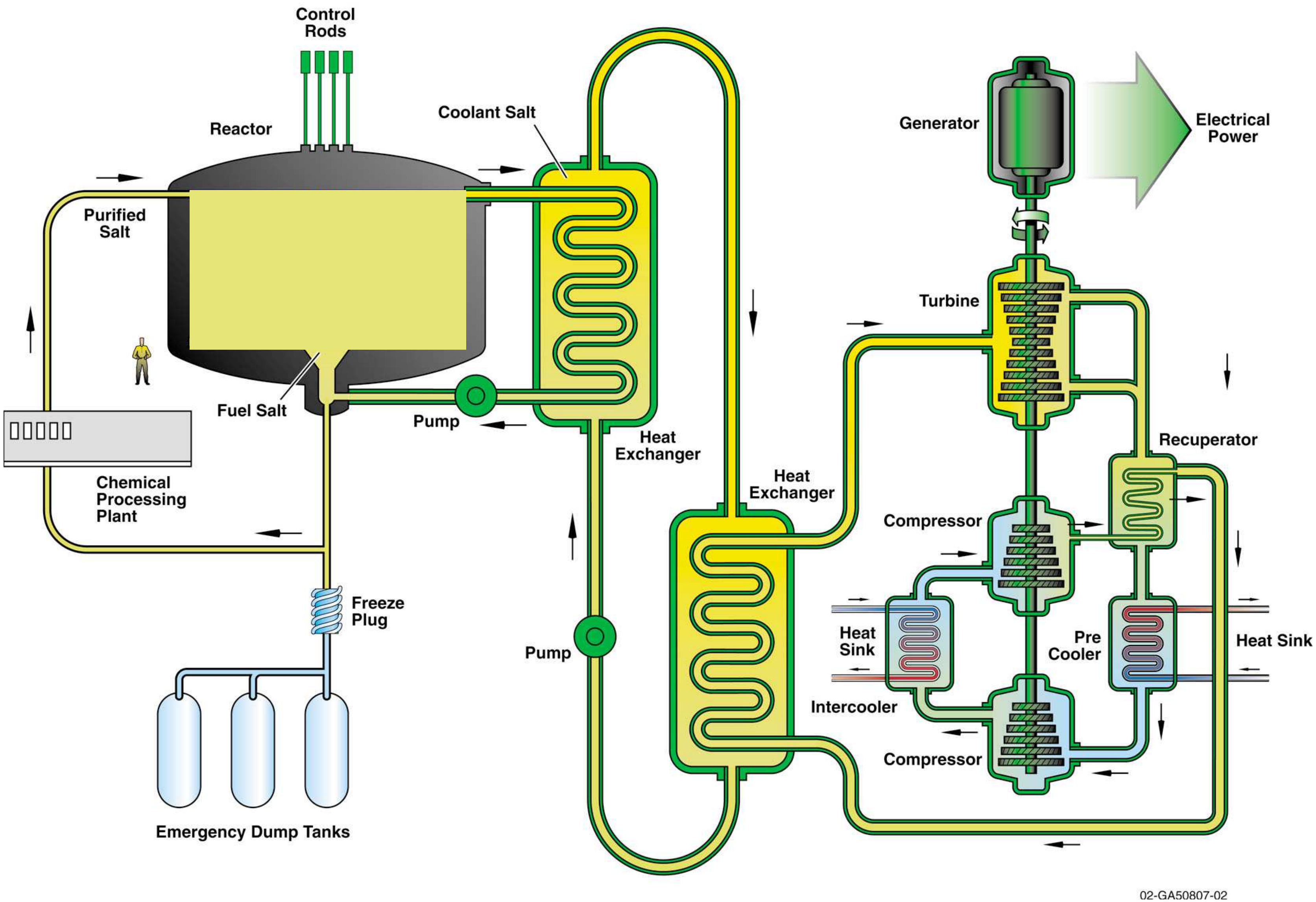
→ Use the design with liquid fuel

Molten Salt Reactor (thermal): concept



Molten Salt Reactor (fast): concept

SCWR
(V)HTR
GFR
SFR
LFR
MSR



Molten Salt Reactor (fast): fact sheet [7]

SCWR
(V)HTR
GFR
SFR
LFR
MSR

- **Advantages**
  - Potential for new fissile breeding due to fast neutron spectrum
  - Large margin to boiling → no pressurization required
  - Strongly negative fuel salt density (void) reactivity effect
  - High efficiency due to high temperatures
  - No structural materials → no radiation damages
  - Possibility to add or remove fuel salt and simpler reprocessing
  - Continuous removal of insoluble fission products
- **Challenges**
  - Strong corrosiveness of molten salt fuels
  - Lack of usual barriers (fuel cladding) → new safety approach needed
  - High fluence on vessel
  - Part of fuel always outside core → larger fuel inventory needed; reduced β
  - Low margin to freezing
  - Low or unknown solubility of compounds formed during operation
- **Designs under development**
  - MSFR, MOSART, FHR
- **Reactors under operation**
  - None

MSFR (EU): core and reactor

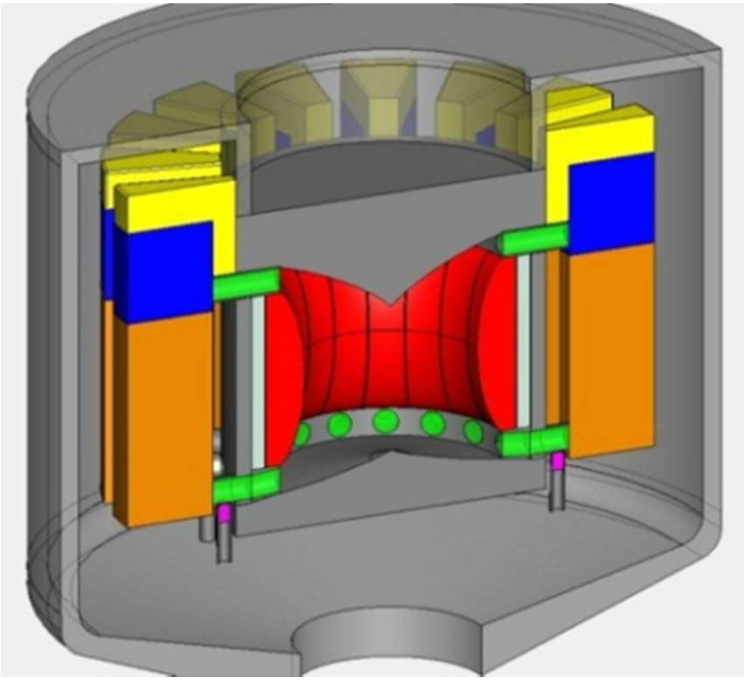
Fuel circuit includes:

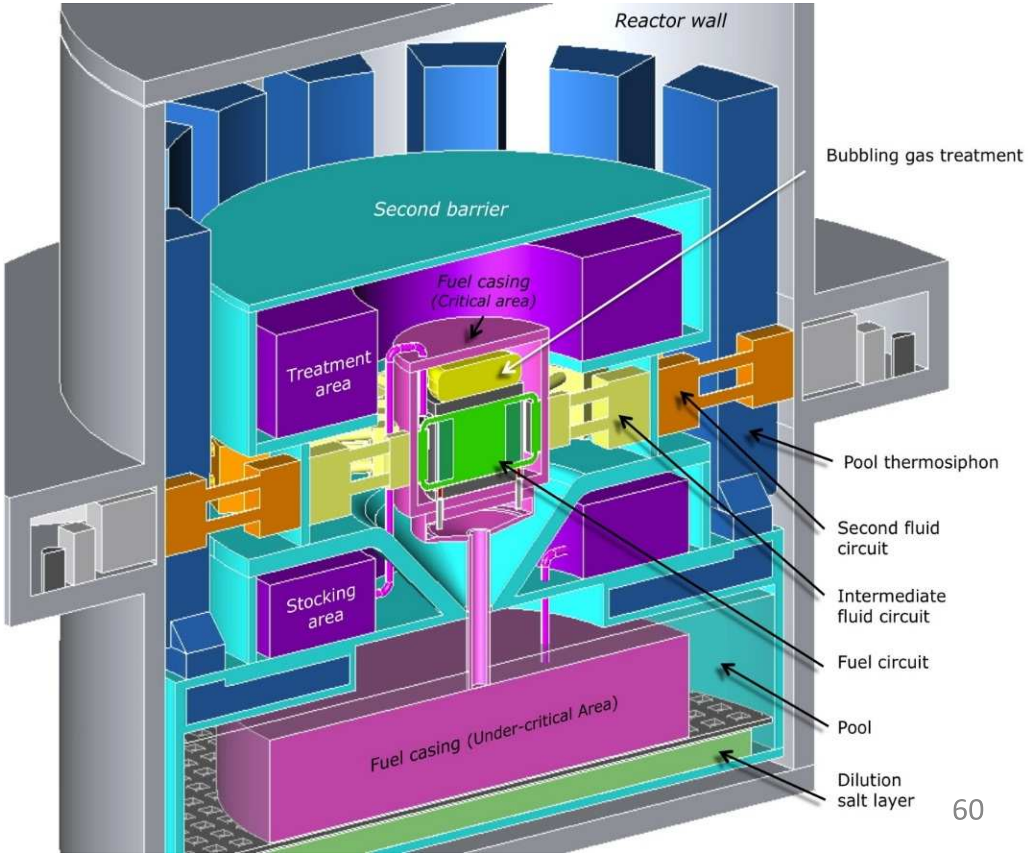
- core (open volume with shape optimized for fluid dynamics);
- 16 external recirculation loops, each includes
  - pipes (cold and hot region);
  - bubble separator;
  - pump;
  - heat exchanger;
  - bubble Injection.

3 circuits:

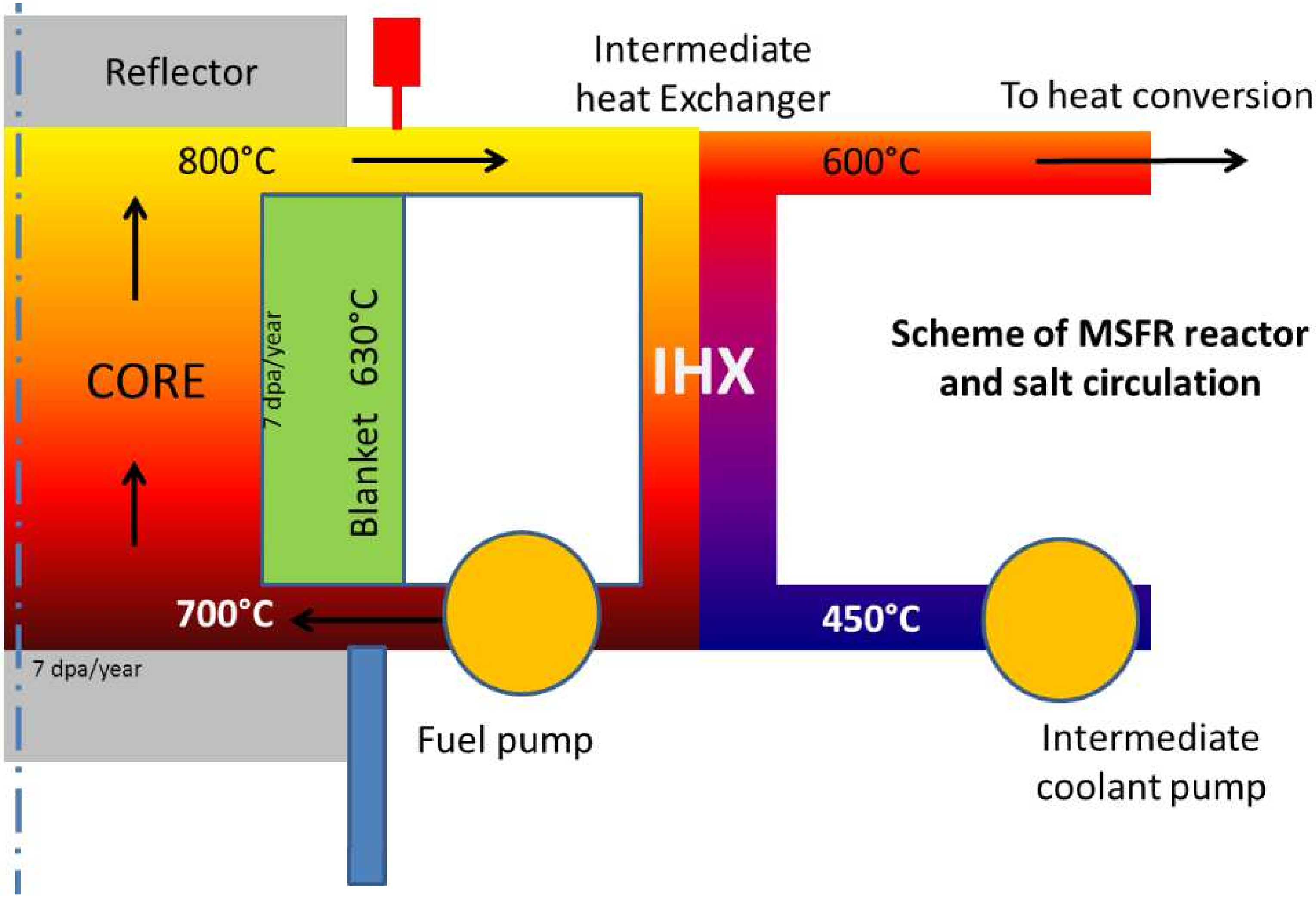
- Fuel circuit
- Intermediate circuit
- Energy conversion system

\+ Draining tanks

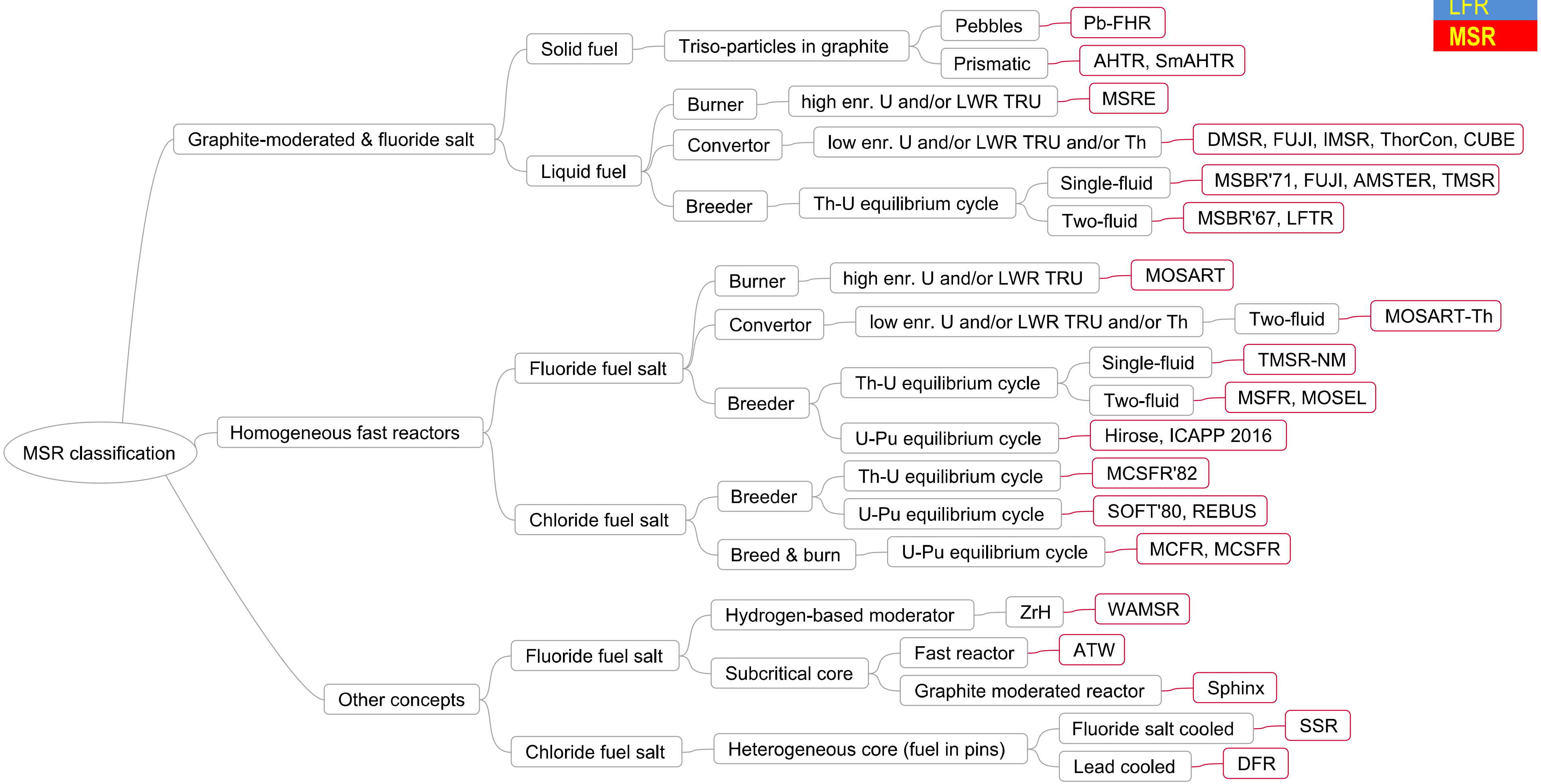




MSFR (EU): BoP concept



MSR: many concepts are currently studied



Summary

SCWR
(V)HTR
GFR
SFR
LFR
MSR

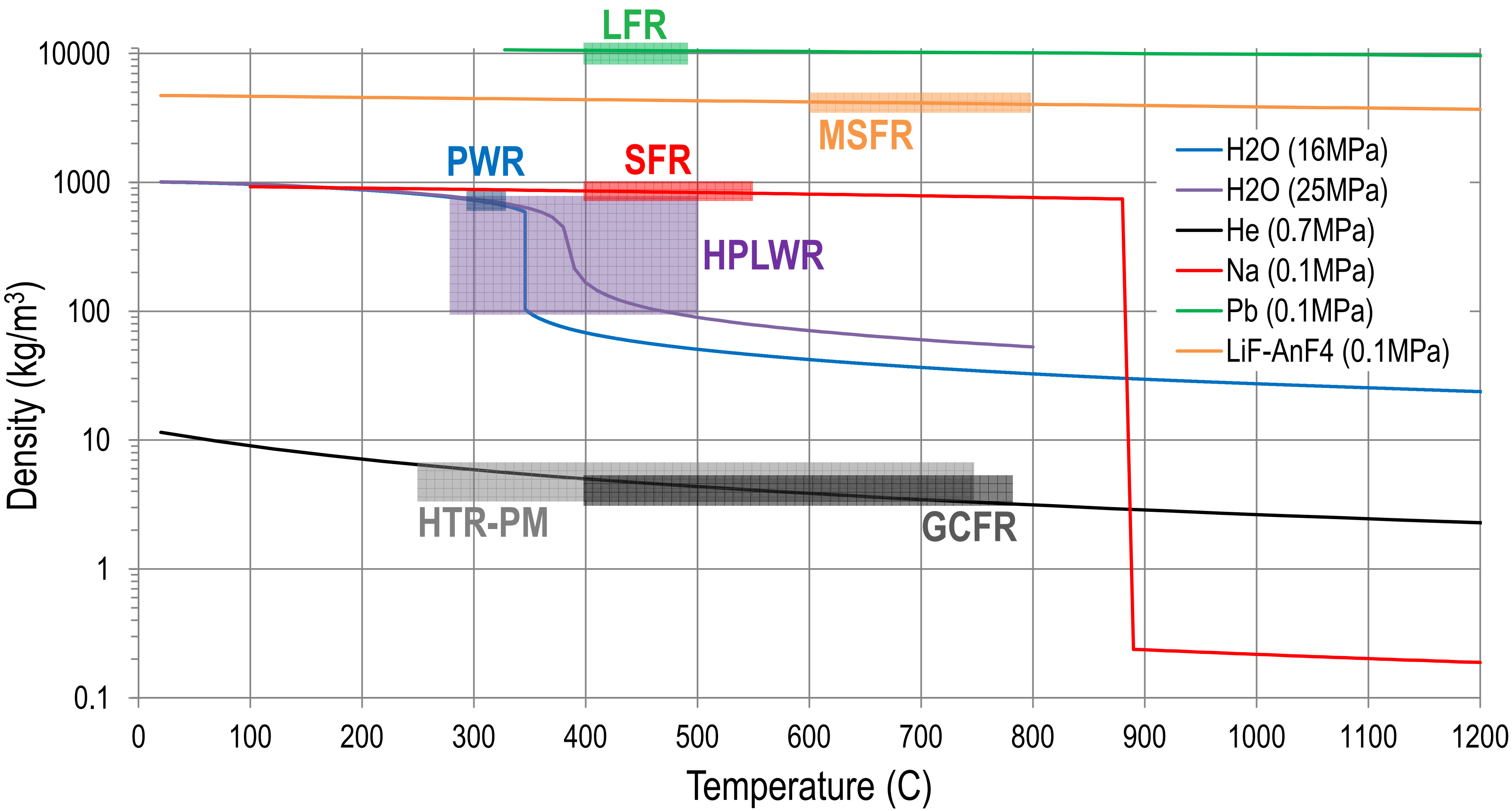
We briefly considered 6 specific reactor designs representing 6 GIF concepts in order to discuss some advantages and challenges of these designs (but not to rank the designs!)

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-ThF$_4$-(Pu-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	↑	↑	?	↓	?	?

*Specific designs chosen by lecturer

Coolant densities and operational ranges of GIF reactors

SCWR
(V)HTR
GFR
SFR
LFR
MSR



- What conclusions can we derive from this plot?

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