Joint ICTP-IAEA Workshop on Physics and Technology of Innovative Nuclear Energy Systems
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GENERATION IV REACTOR DESIGNS

Brief Introduction

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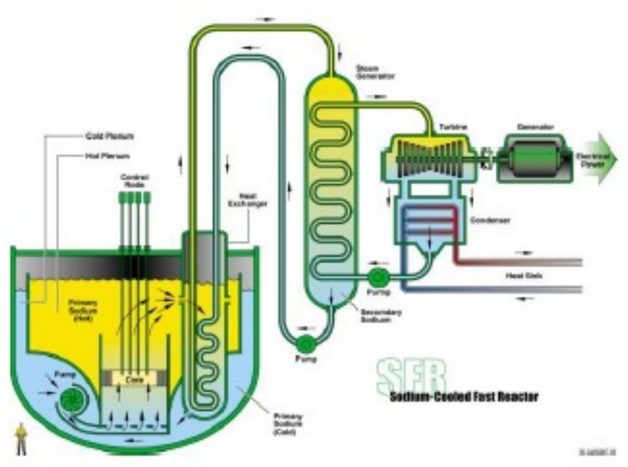
Acknowledgement

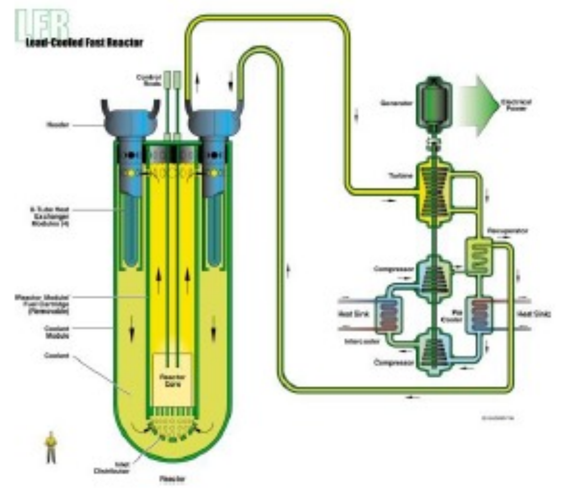
The following lecture is inspired by the presentation made by Prof Konstantin Mikityuk, PSI during the ICTP-IAEA workshop on physics and technology of innovative nuclear energy systems in 2018. There is a powerful storytelling involved in this lecture and with permission of Prof Mikityuk, I have taken that story to prepare this lecture with some modifications. The lecture recordings of 2018 are also available on YouTube

Outline

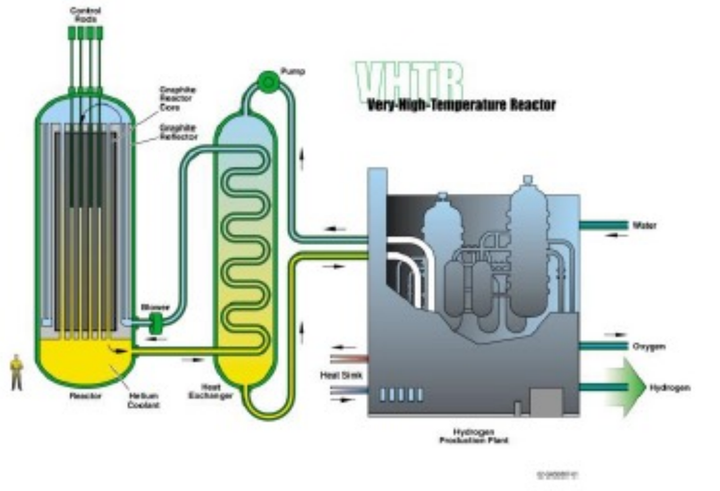
- Generation 4 International Forum Reactor Designs:
  - Broad introduction to GIF, GIF Goals and Technology selection
  - General features/characteristics of all GIF design
  - Specific design concept description
  - Speicific features of the selected design
  - Conclusions



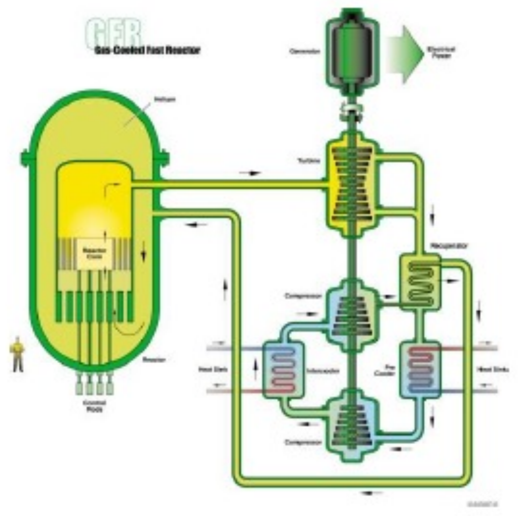
Sodium Fast Reactor



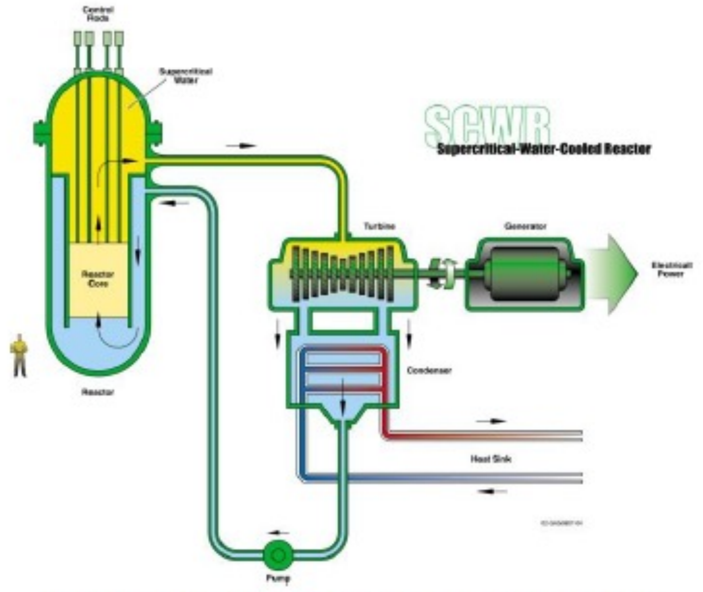
Lead Fast Reactor



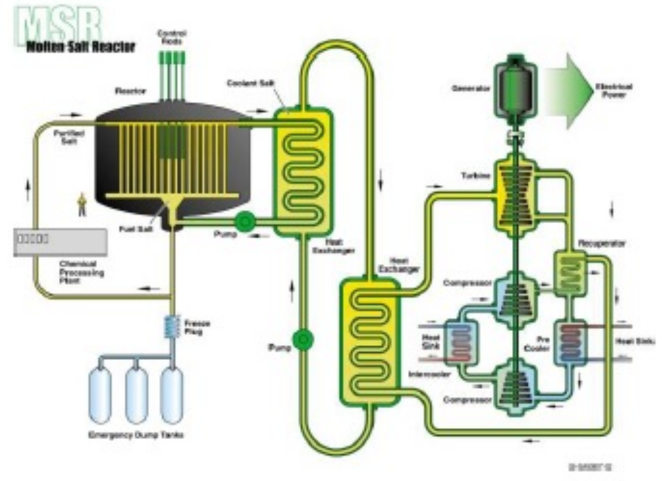
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

Reactor Technology Evolution

- **Generation I:** 1950s – 1960s (now probably only in UK)
- **Generation II:** 1970s – ~2040 – mainly present US and French operating Reactors
- **Generation III/III+:** 1996 – Evolutionary designs
  - Simpler design, reduced cost, efficient, safer
  - Higher availability, longer operating life, reduced CDF, higher burnup, better load following capabilities, modular designs Wesstinghouse AP600 – 1999
- **Generation IV**: Innovative Designs
  - Safe, Secure, Sustainable, Competitive, Versatile

We need both technical and institutional innovation

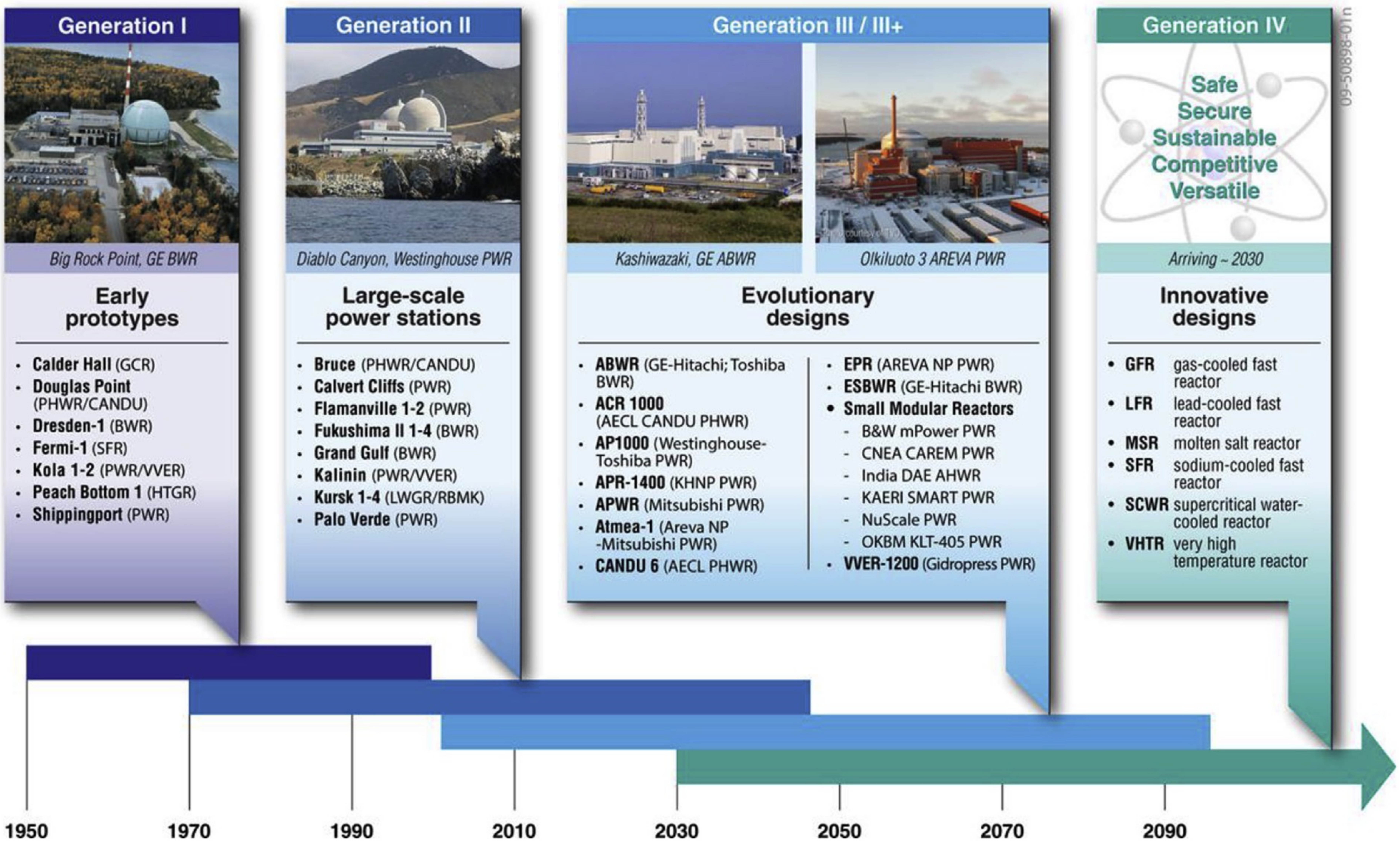
Gen I

Gen II

Gen III/III+

Gen IV

Reactor Technology: early prototypes to innovative designs



Generation I

Big Rock Point, GE BWR

Early prototypes

- **Calder Hall** (GCR)
- **Douglas Point** (PHWR/CANDU)
- **Dresden-1** (BWR)
- **Fermi-1** (SFR)
- **Kola 1-2** (PWR/VVER)
- **Peach Bottom 1** (HTGR)
- **Shippingport** (PWR)

Generation II

Diablo Canyon, Westinghouse PWR

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville 1-2** (PWR)
- **Fukushima II 1-4** (BWR)
- **Grand Gulf** (BWR)
- **Kalinin** (PWR/VVER)
- **Kursk 1-4** (LWGR/RBMK)
- **Palo Verde** (PWR)

Generation III / III+

Kashiwazaki, GE ABWR

Olkiluoto 3 AREVA PWR

Evolutionary designs

- **ABWR** (GE-Hitachi; Toshiba BWR)
- **ACR 1000** (AECL CANDU PHWR)
- **AP1000** (Westinghouse-Toshiba PWR)
- **APR-1400** (KHNP PWR)
- **APWR** (Mitsubishi PWR)
- **Atmea-1** (Areva NP -Mitsubishi PWR)
- **CANDU 6** (AECL PHWR)
- **EPR** (AREVA NP PWR)
- **ESBWR** (GE-Hitachi BWR)
- **Small Modular Reactors**
  - B&W mPower PWR
  - CNEA CAREM PWR
  - India DAE AHWR
  - KAERI SMART PWR
  - NuScale PWR
  - OKBM KLT-405 PWR
- **VVER-1200** (Gidropress PWR)

Generation IV

Safe
Secure
Sustainable
Competitive
Versatile

Arriving ~ 2030

Innovative designs

- **GFR** gas-cooled fast reactor
- **LFR** lead-cooled fast reactor
- **MSR** molten salt reactor
- **SFR** sodium-cooled fast reactor
- **SCWR** supercritical water-cooled reactor
- **VHTR** very high temperature reactor

3rd GIF Symposium 2015/ICONE 23 Conference - Makuhari Messe, Japan, May 2015

GIF: what is it?

- Established in 2001, the Generation IV International Forum (GIF) was created as a co-operative international endeavour seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems, and to make them available for industrial deployment by 2030.
- The GIF brings together 13 countries (Argentina, Australia, Brazil, Canada, China, France, Japan, Korea, Russia, South Africa, Switzerland, the United Kingdom and the United States), as well as Euratom – representing the 27 European Union members – to co-ordinate research and development on these systems.
- The GIF has selected six reactor technologies for further research and development:

Reactor Technology	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

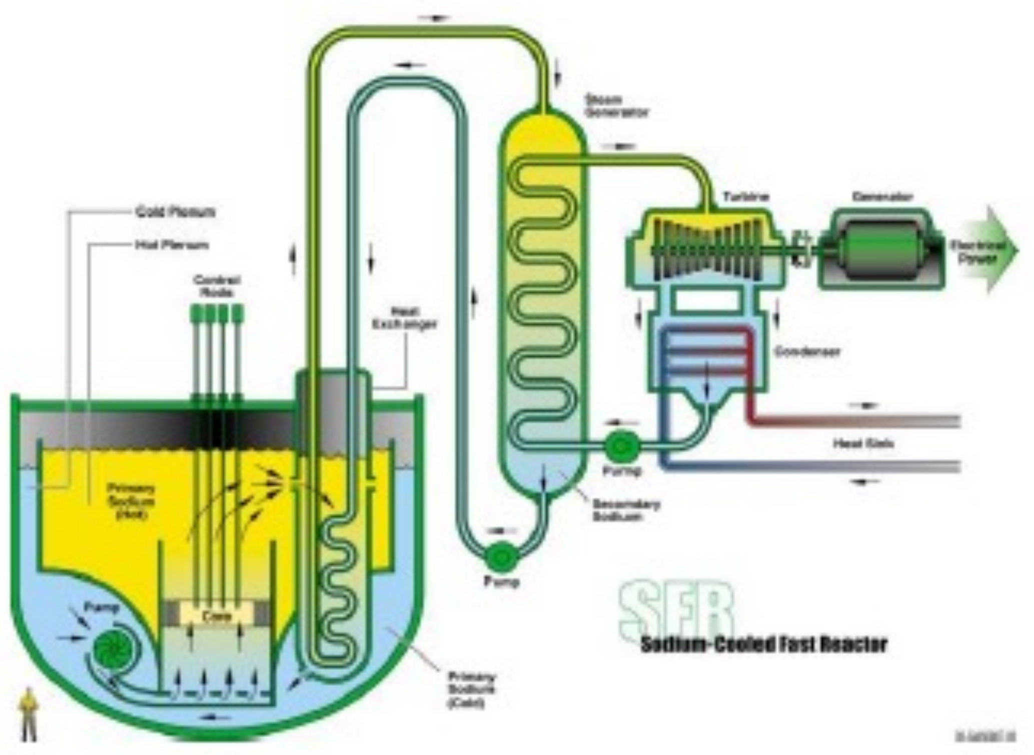
GIF Reactor Technologies

Type	Neutron Spectrum	Coolant	Temperature (°C)	Fuel Cycle	Size (MW)	Example developers
VHTR	Thermal	Helium	900–1000	Open	250–300	HTTR, JAEA, Japan, HTR-10, Tsinghua University, HTR-PM, Tsinghua University & China Nuclear Engineering Corporation; XE-100, X-Energy
SFR	Fast	Sodium	550	Closed	30–150, 300–1500, 1000–2000	TerraPower (Natrium), Toshiba -4S, GE Hitachi PRISM, BN-600/800/1200, OKBM Afrikantov, CFR-600, China; PFBR, India
SCWR	Thermal or fast	Water	510–625	Open or closed	300–700, 1000–1500	HPLWR
GFR	Fast	Helium	850	Closed	1200	Energy Multiplier Module (General Atomics)
LFR	Fast	Lead	480–800	Closed	20–180, 300–1200, 600–1000	BREST-OD-300 Rosatom; SVBR
MSR	Fast or thermal	Fluoride or chloride salts	700–800	Closed	250–1000	Seaborg Technologies, Copenhagen Atomics, TerraPower, Elysium Industries, Moltex Energy, Flibe Energy, Thorium Tech Solution (FUJI MSR), Terrestrial Energy (IMSR), ThorCon

Status of GIF Reactor Technologies

GIF name (Generation IV International Forum)		Coolant	Neutron spectrum	Reactors already built	Reactors in operation at present	Existing projects
SFR	Sodium cooled Fast Reactor	Sodium	Fast	Yes	Yes	Yes
LFR	Lead cooled Fast Reactor	Lead or Lead-Bismuth	Fast	Yes (submarines)	No	Yes
GFR	Gas cooled Fast Reactor	Gas	Fast	No	No	Yes
SCWR	Super Critical Water Reactor	Water	Thermal or Fast	No	No	Yes
MSR	Molten Salt Reactor	Salt	Thermal or Fast	Yes	No	Yes
VHTR	Very High Temperature Reactor	Gas	Thermal	Yes	Yes	Yes

GEN IV International Forum℠



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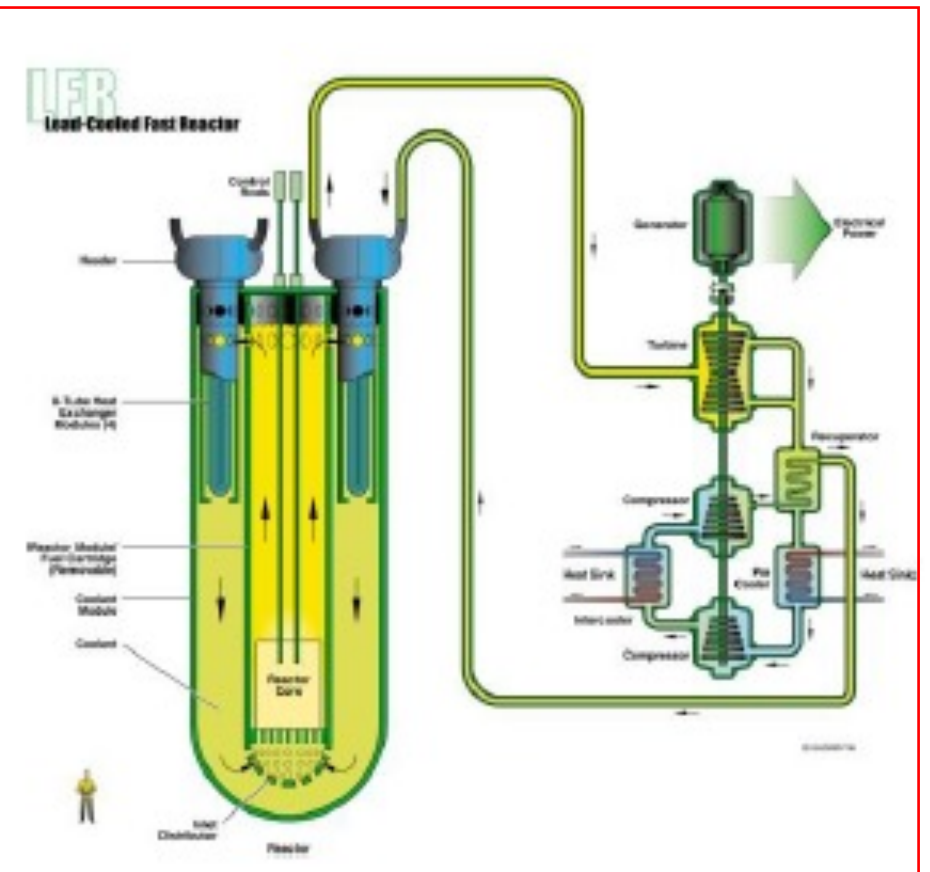

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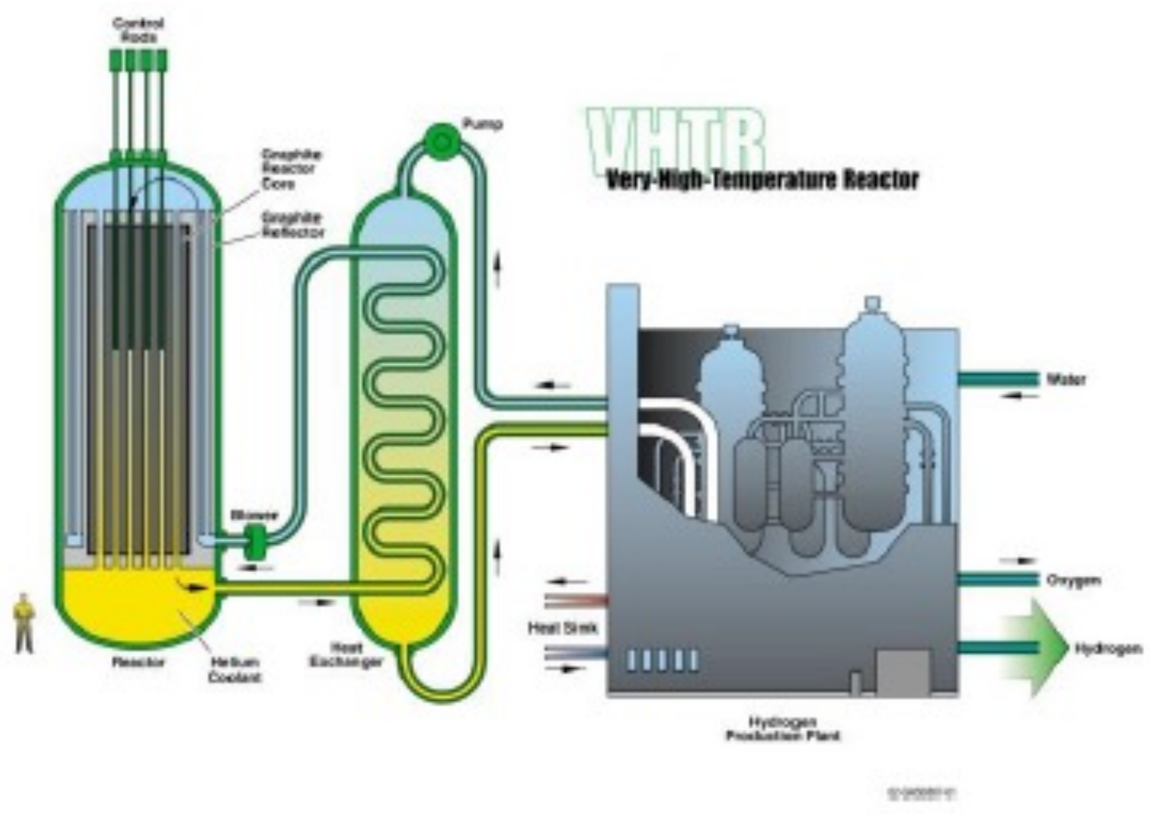
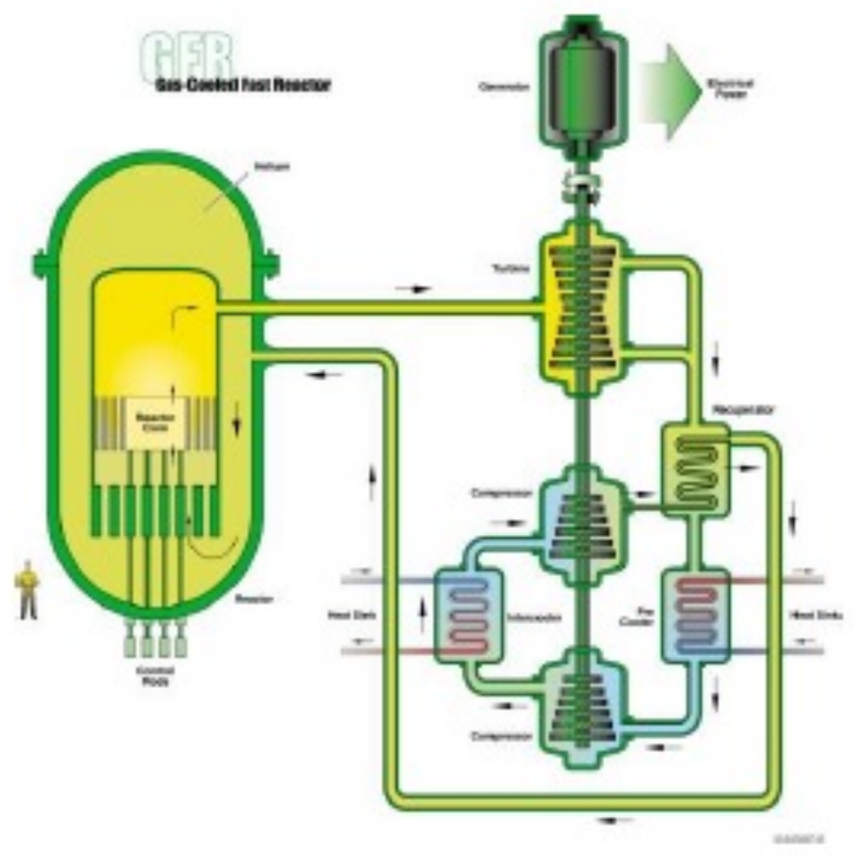
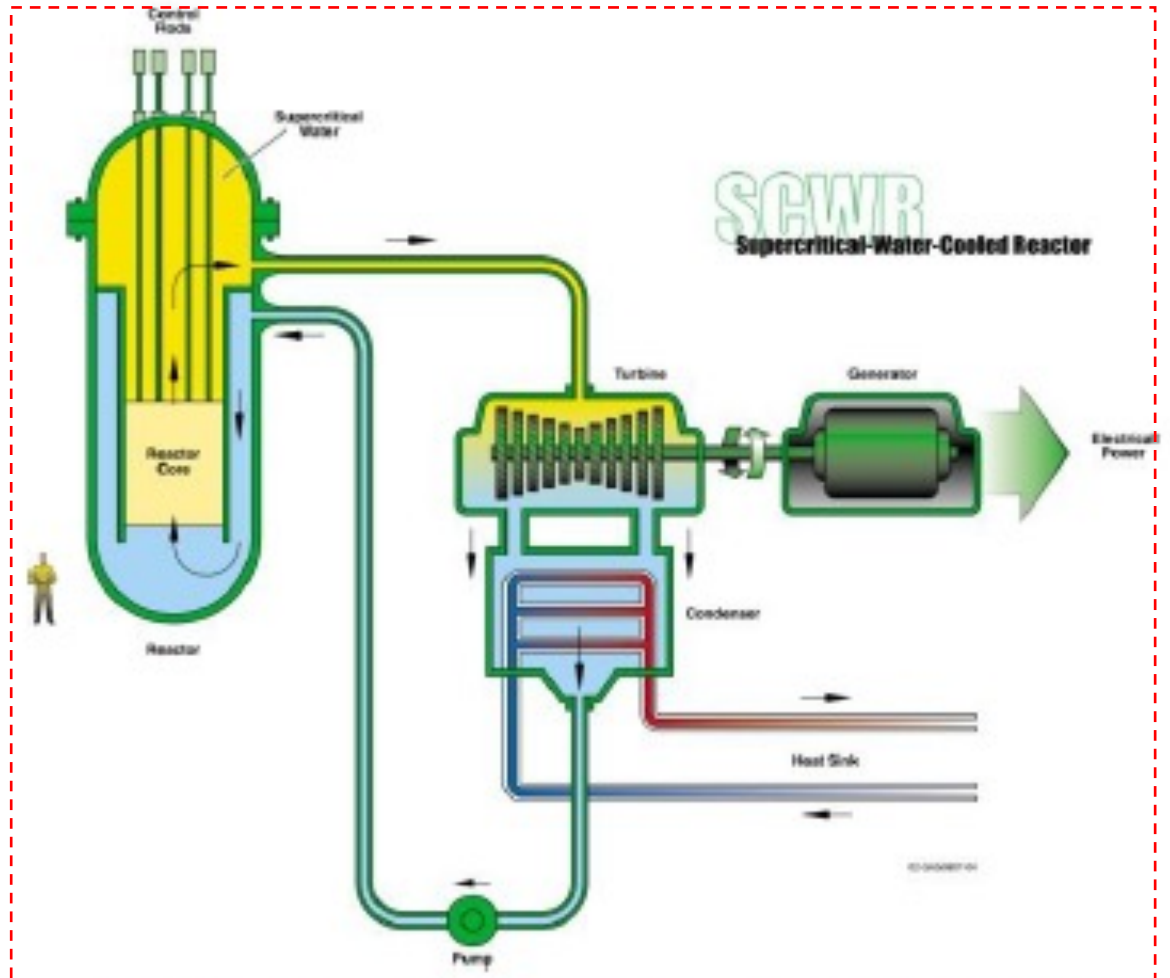


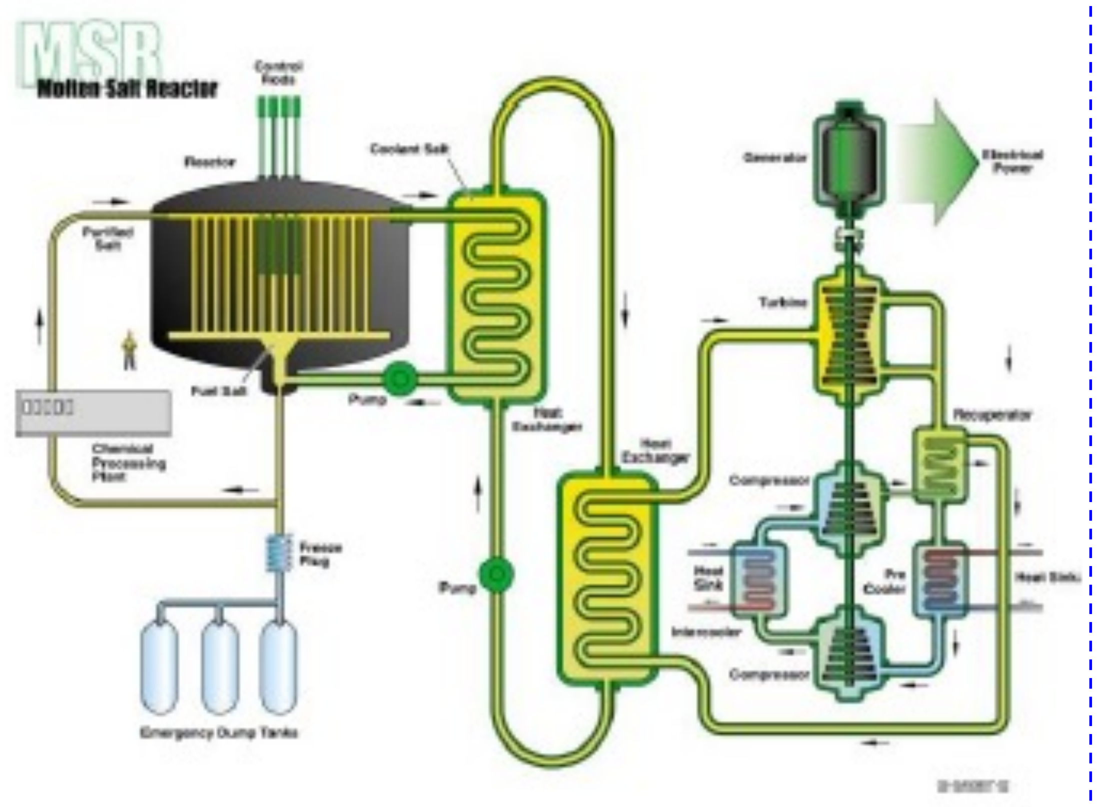
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

FAST

THERMAL

- Electricity Production
- Cogeneration application
- Hydrogen production
- Seawater Desalination
- Process heat
- Synthetic Fuel and Chemicals
- Cooling application

3rd GIF Symposium 2015/ICONE 23 Conference - Makuhari Messe, Japan, May 2015

Currently operating Fast Reactors

Reactor	Type, coolant	Power Th/E (MW)	Fuel type	Country	operation year
BOR-60	Experimental, loop, **sodium**	55/10	oxide	Russia	1969-
BN-600	Demonstration, pool, **sodium**	1470/600	oxide	Russia	1980-
BN-800	Experimental, pool, **sodium**	2100/864	oxide	Russia	2014-
FBTR	Experimental, pool, **sodium**	40/-	oxide & carbide (metal)	India	1985-2030
CEFR	Experimental, pool, **sodium**	65/20	oxide	China	2010-
Joyo	Experimental, loop, **sodium**	140/-	oxide	Japan	1978-2007, ??
Monju	Prototype, loop, **sodium**	714/280	oxide	Japan	1994-96, 2010- ?

5/6 GIF reactor designs are Fast Reactors

Designs under development

Reactor	Type, coolant	Power Th/E (MW)	Fuel type	Country	operation year
PRISM & Natrium	Demonstration, pool, sodium	840/311	metal	USA	From 2020s
ARC-100	Prototype, pool, sodium	260/100	metal	USA	
~~Astrid~~	~~Demonstration, pool, sodium~~	~~1500/600~~	~~oxide~~	~~France, with Japan~~	~~From 2024~~
Allegro	Experimental, loop?, gas	50-100 MWt	oxide	France	About 2025
MYRRHA	Experimental, Pb-Bi	57/-	oxide?	Belgium, with China	Early 2020s
ALFRED	Prototype, lead	300/120	oxide	Romania, with Italy & EU	From 2025
BN-1200	Commercial, pool, sodium	2900/1220	oxide, nitride	Russia	From mid-2020s
BREST-300	Demonstration, loop, lead	700/300	nitride	Russia	From 2020
SVBR-100	Demonstration, pool, Pb-Bi	280/100	oxide (variety)	Russia	From 2019
MBIR	Experimental, loop, sodium (Pb-Bi, gas)	100-150 MWt	oxide	Russia	From 2020
CDFR-1000	Demonstration, pool, sodium	/1000	oxide	China	From 2023
CDFBR-1200	Commercial, pool, sodium	/1200	metal	China	From 2028
PGSFR	Prototype, pool, sodium	400/150	metal	South Korea	From 2028
JSFR??	Demonstration, loop, sodium	3750/1500	oxide	Japan	From 2025?
TWR	Prototype, sodium	1475/600	metal	China, with USA	From 2023?
FBR-1,2	Commercial, sodium	1250/500	oxide, metal	India	?
VTR	Experimental, sodium	300 MWt	Mixed oxide	USA	2026

Fast SMRs under development

Reactor	Type, coolant	Power Th/E (MW)	Fuel type	Country	operation year
PRISM	Demonstration, pool, sodium	840/311	metal	GEH, USA	From 2020s
ARC-100	Prototype, pool, sodium	260/100	metal	ARC+GEH, USA	?
FMR	Demonstration, helium HTR	50	?	GA-EMS, USA	2035
EM2	Helium HTR	500/240	oxide?	GA, USA	?
Westinghouse LFR	Pool, lead	950/450	LEU oxide/silicide	Westinghouse, USA	?
Moltex SSR-U	MSR	750/300 (for 8 modules)	Pu+U chloride	Moltex UK	?
~~Astrid~~	~~Prototype, pool, sodium~~	~~100-200~~	~~oxide~~	~~France, with Japan~~	~~Delayed, after 2050~~
SVBR-100	Demonstration, pool, Pb-Bi	280/100	oxide (variety)	Russia	Cancelled
Gen4 module	Lead-Bi	70/25	LEU nitride	Gen4, USA	?
Sealer	Lead	3-10 MWe	LEU oxide/nitride	LeadCold, Sweden	By 2025
Aurora	Heatpipe	4/1.5	U-Zr metal	Oklo, USA	COL application
eVinci	Heatpipe	0.2-5.0 MWe	various	Westinghouse, USA	?

Characteristics of Generation IV reactors

The key factors characterizing the development and deployment of nuclear power reactors:

- Safety
- Economic Competitiveness
- Proliferation Resistance and safeguards
- Waste Management
- Efficiency of resource use – higher burnup, recycling, increased efficiency
- Flexibility of applications – cogeneration, process heat

To make nuclear sustainable

Ref: OECD-NEA report on Innovative nuclear reactor development

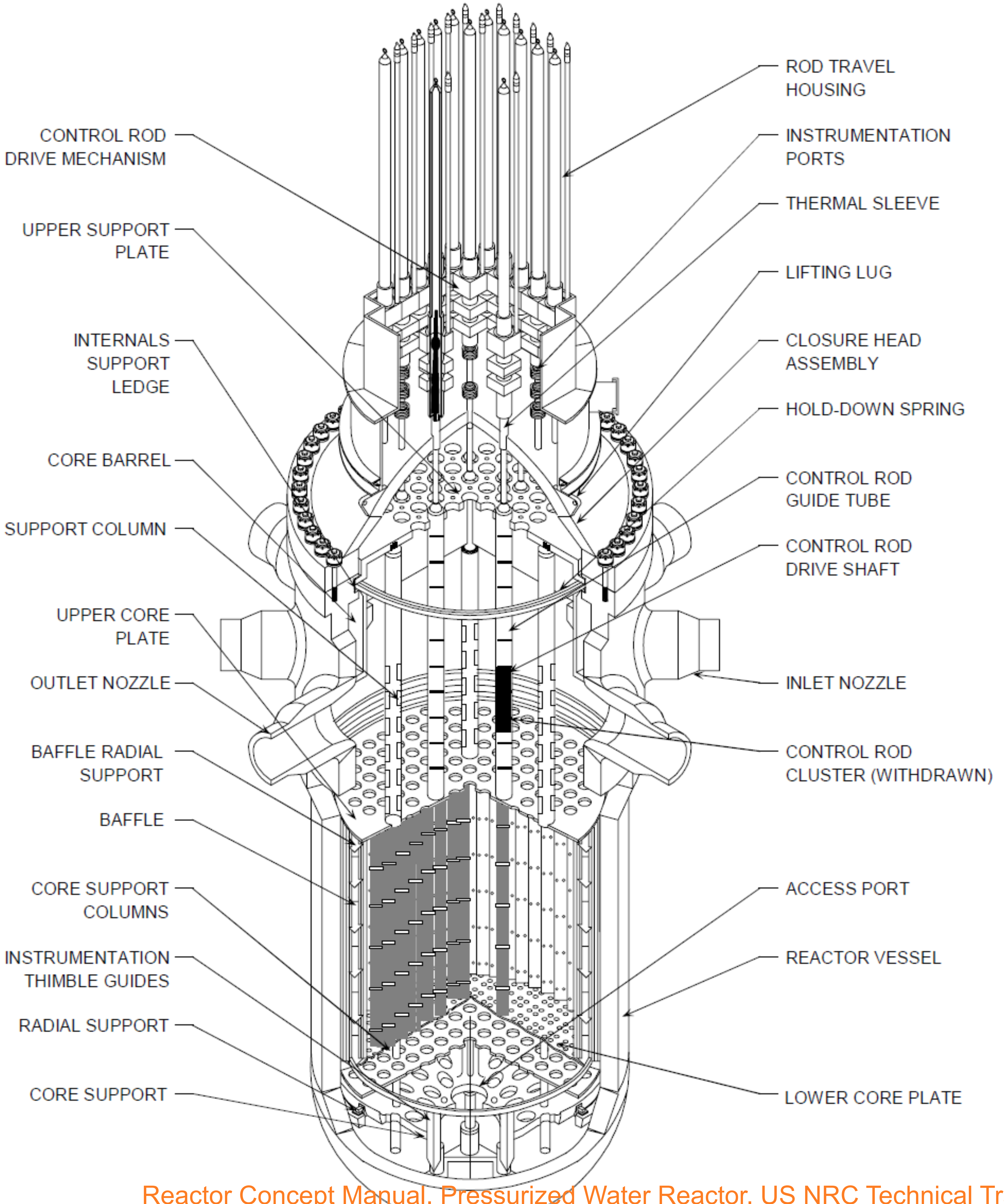
Goals/Criteria for Generation IV reactors

- **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



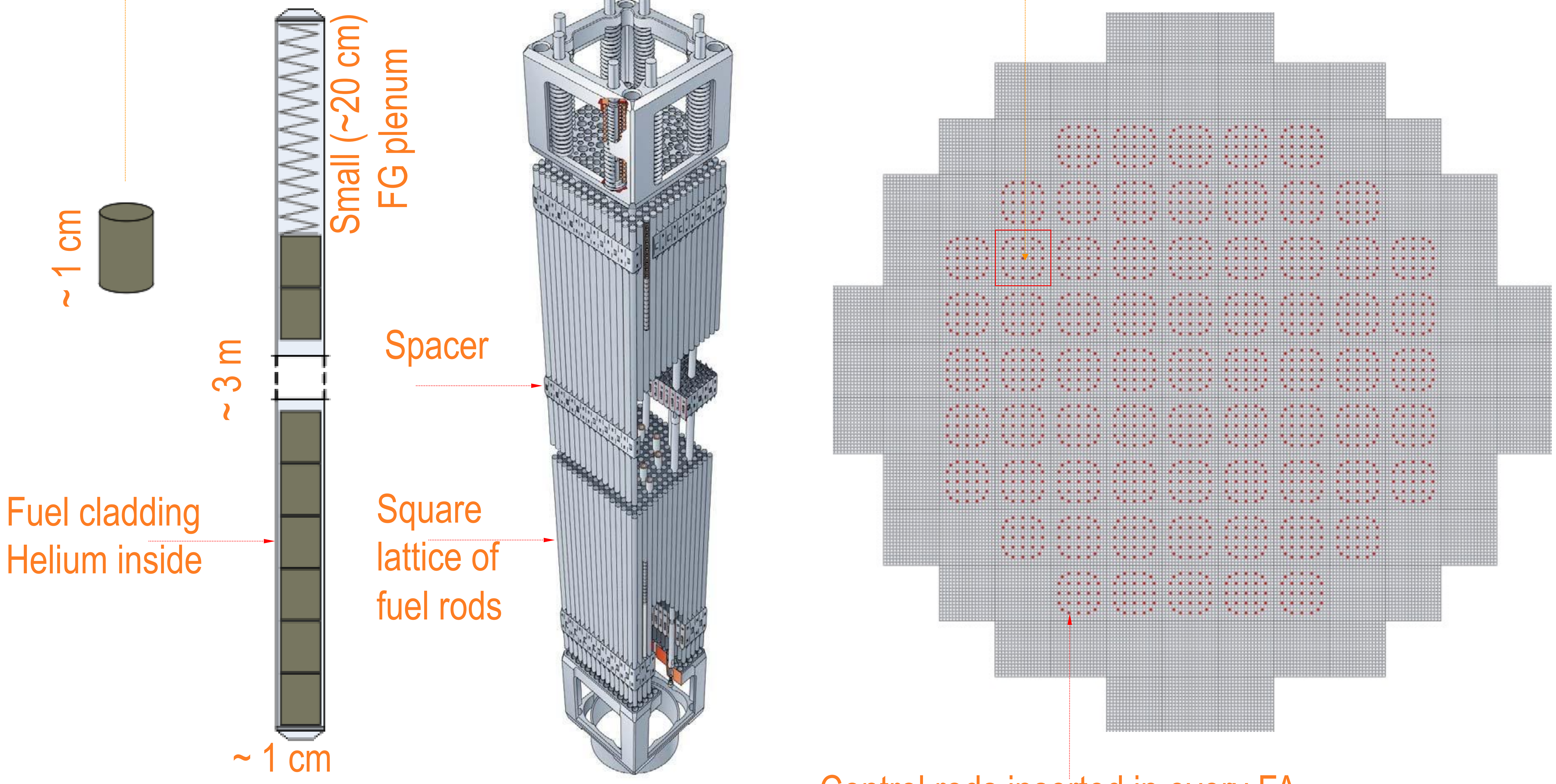
Concept	**PWR**
Specific design*	EPR
Thermal power (MW)	4300
Efficiency (%)	37
Primary coolant	H_2O
Pressure (MPa)	~16
Inlet/outlet temp. (C)	296 / 327
Moderator	H_2O
Neutron spectrum	Thermal
Breeding gain	<< 0
Reference	[1]
G1: Sustainability	Poor
G2: Safety & reliability	Good
G3: Economics	Good

*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, AP-1000, APR-1400
  - ...
- **Reactors under operation**
  - As of December 2022, 303 operable reactors (290 GWe)

https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByType.aspx

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

Concept	**PWR**
Specific design*	EPR
Thermal power (MW)	4300
Efficiency (%)	37
Primary coolant	H_2O
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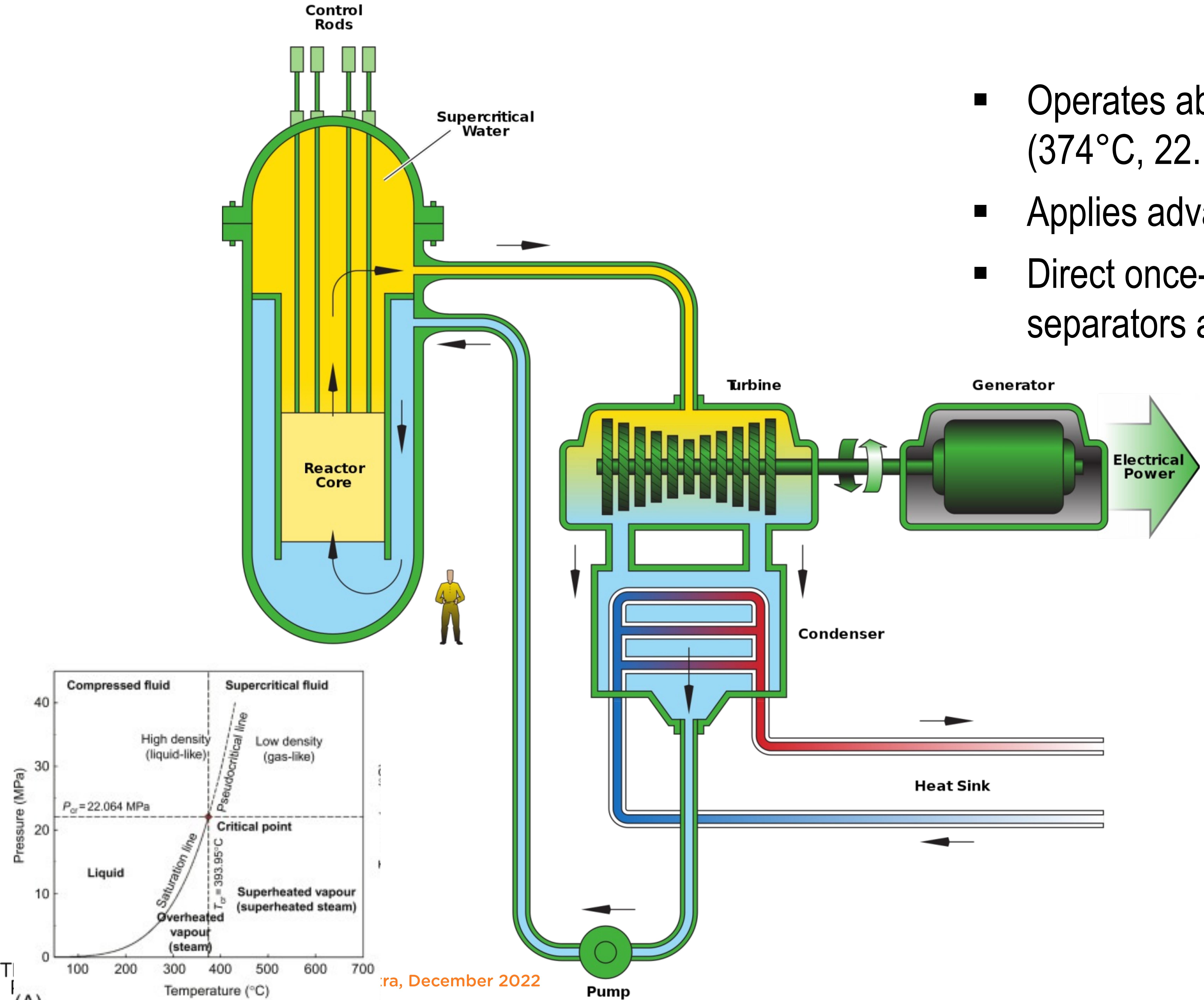
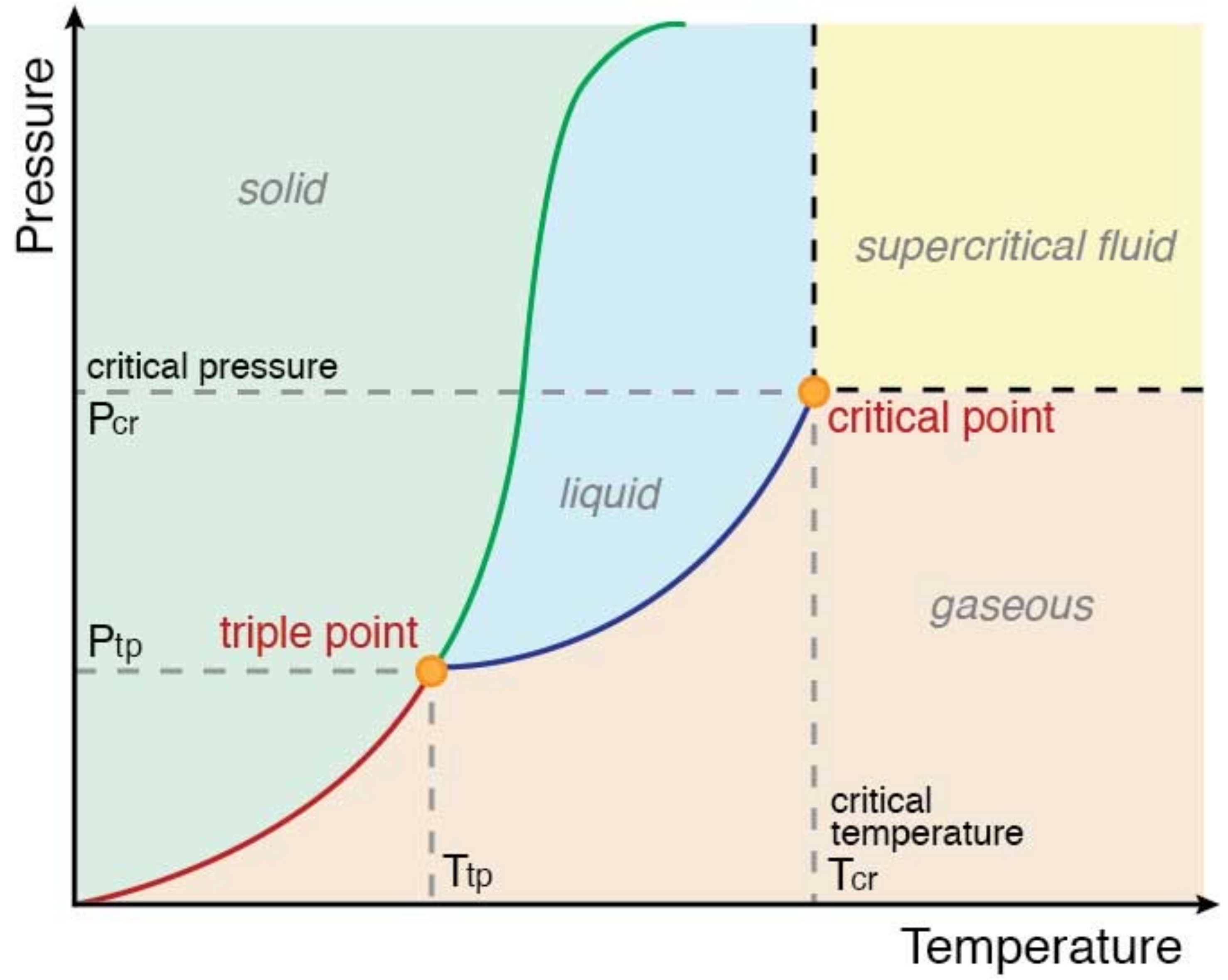
*Specific designs chosen by lecturer

- How to increase efficiency (improve G3)?

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

- **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. (°C)	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 31°C (PWR) to 220°C (HPLWR) – issue for peak cladding temperature (target 630°C).

Possible solution:
→ Heating in three steps

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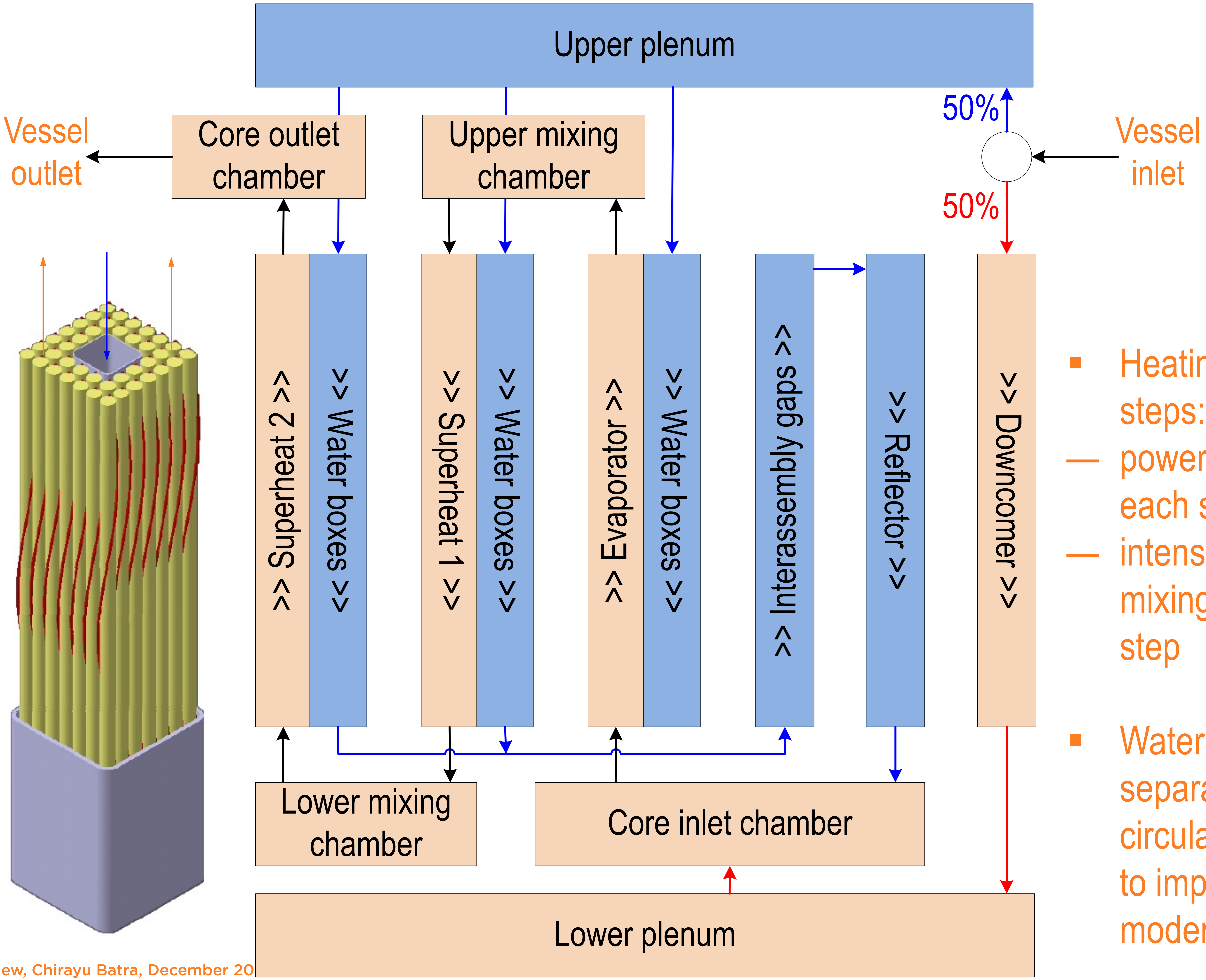
*Specific designs chosen by lecturer

HPLWR (EU): water circulation paths [2]



Upper plenum

Vessel outlet

Core outlet chamber

Upper mixing chamber

50%

Vessel inlet

50%

>> Superheat 2 >>

>> Water boxes >>

>> Superheat 1 >>

>> Water boxes >>

>> Evaporator >>

>> Water boxes >>

>> Interassembly gaps >>

>> Reflector >>

>> Downcomer >>

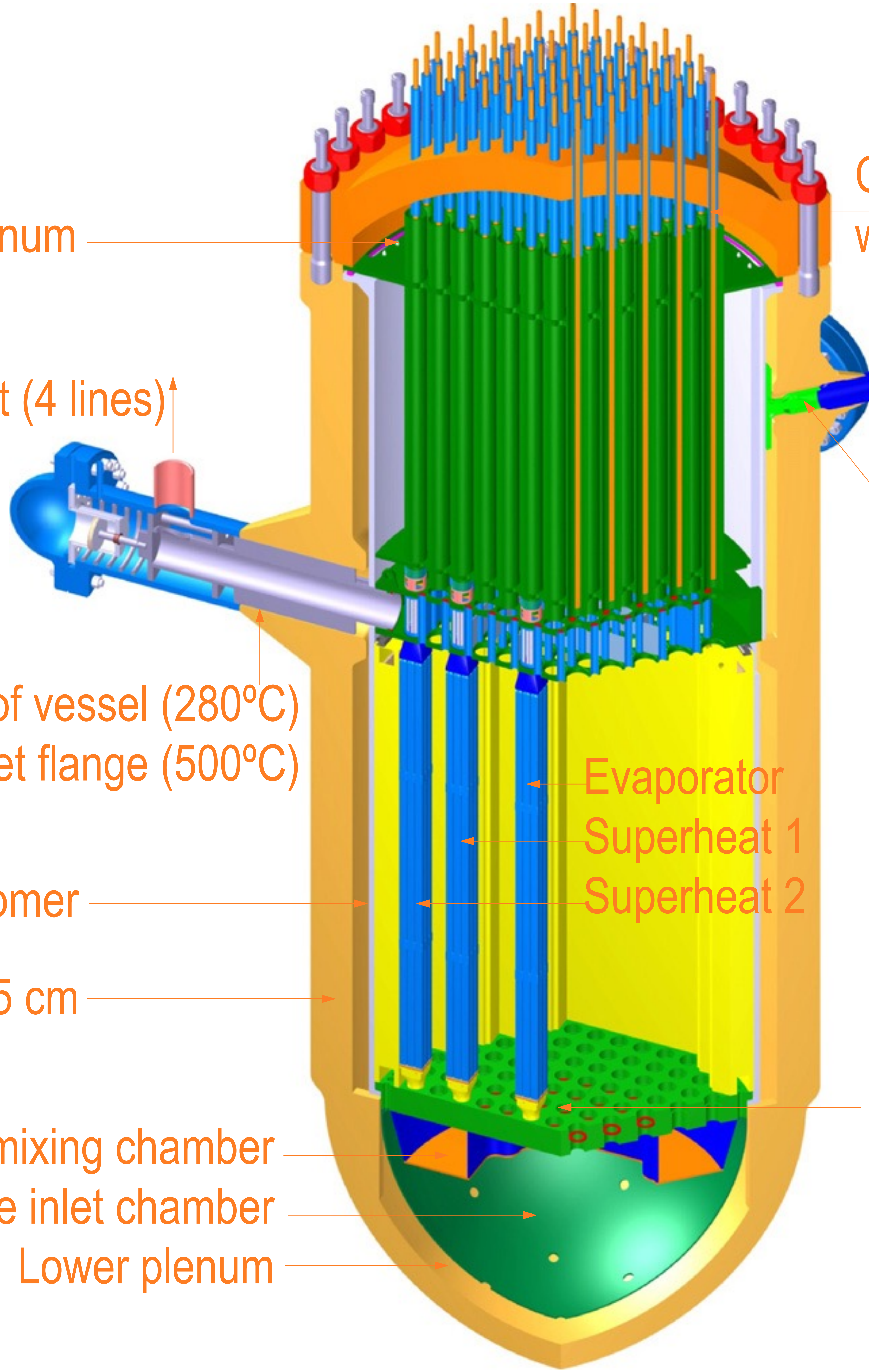
Lower mixing chamber

Core inlet chamber

Lower plenum

- 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]



Upper plenum

outlet (4 lines)

Thermal insulation of vessel (280ºC) from outlet flange (500ºC)

Downcomer

Wall thickness 45 cm

Lower mixing chamber

Core inlet chamber

Lower plenum

Control rods inserted in water channels

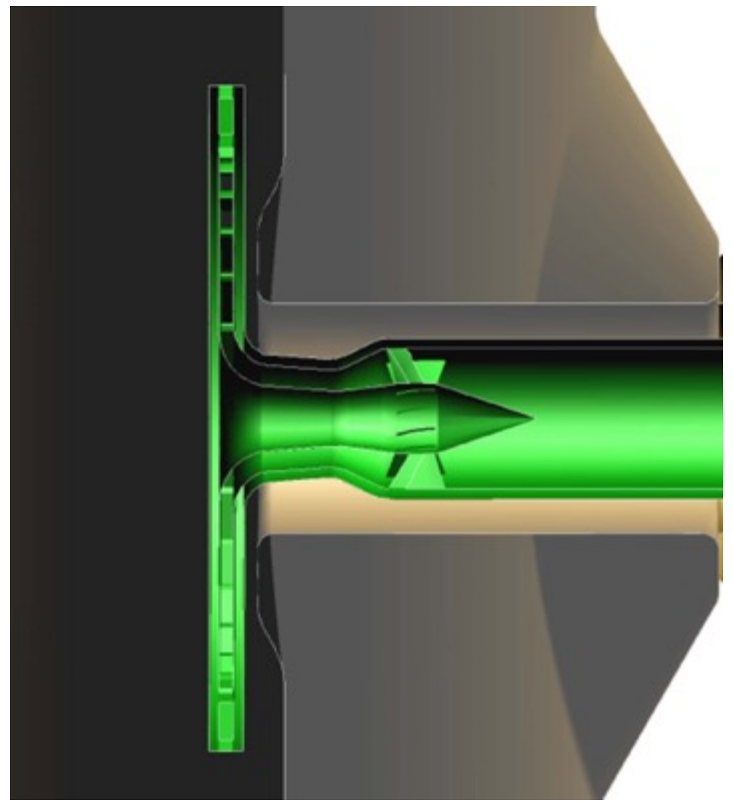
feedwater inlet (4 lines)

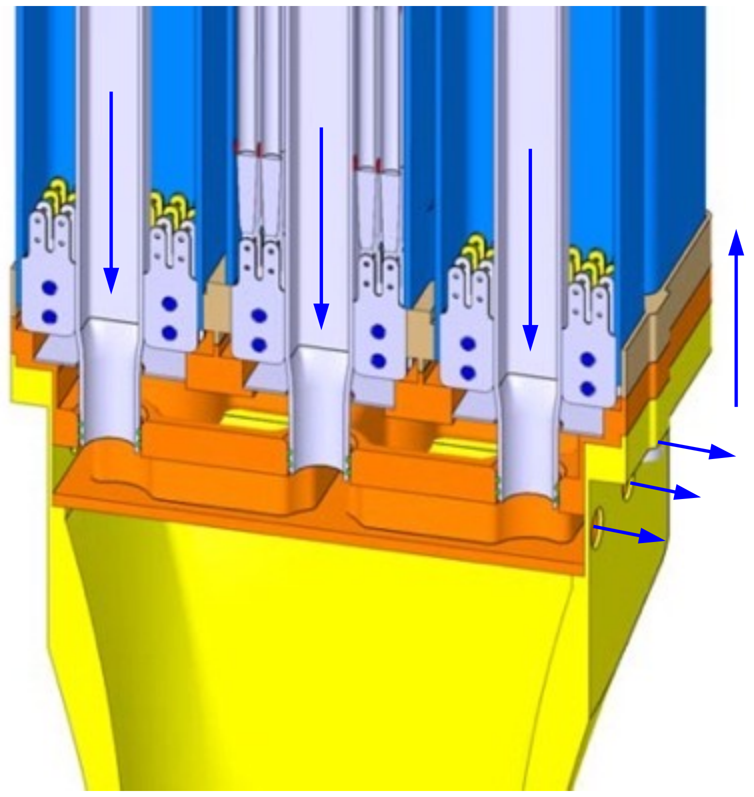
Backflow limiter

Evaporator

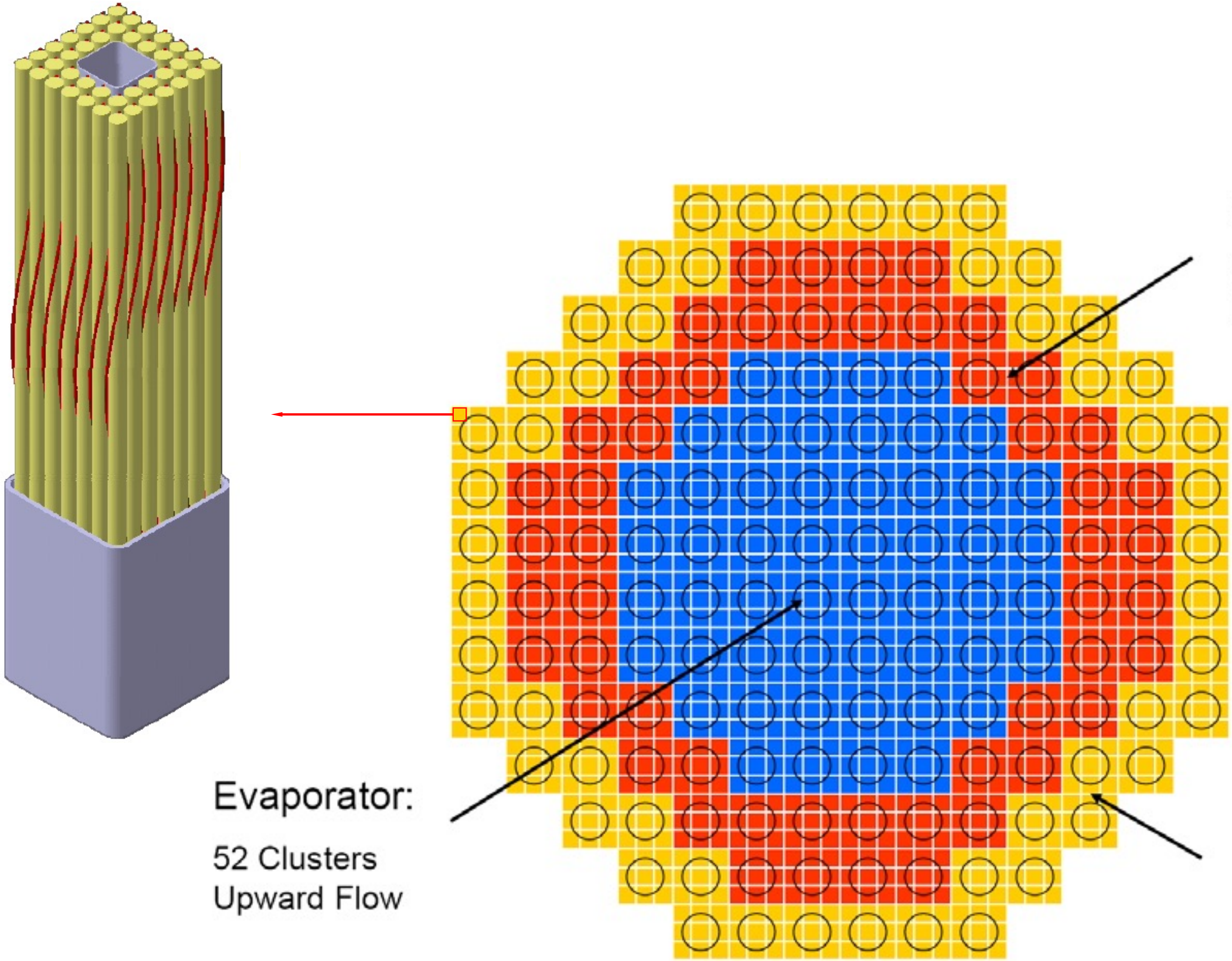
Superheat 1

Superheat 2





HPLWR (EU): core design [2]



Superheater 1:

52 Clusters
Downward Flow

Evaporator:

52 Clusters
Upward Flow

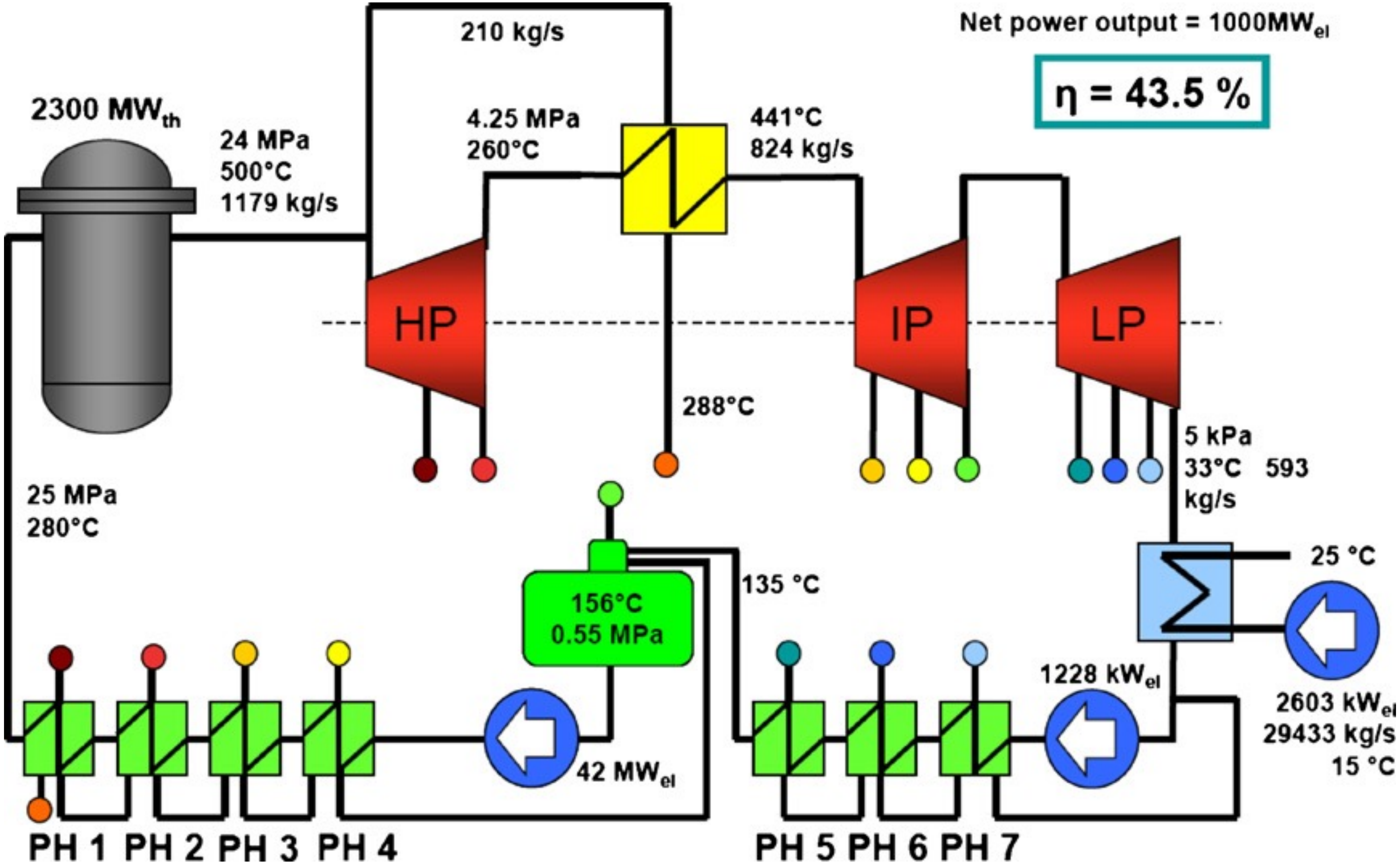
Superheater 2:

52 Clusters,
Upward Flow

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)

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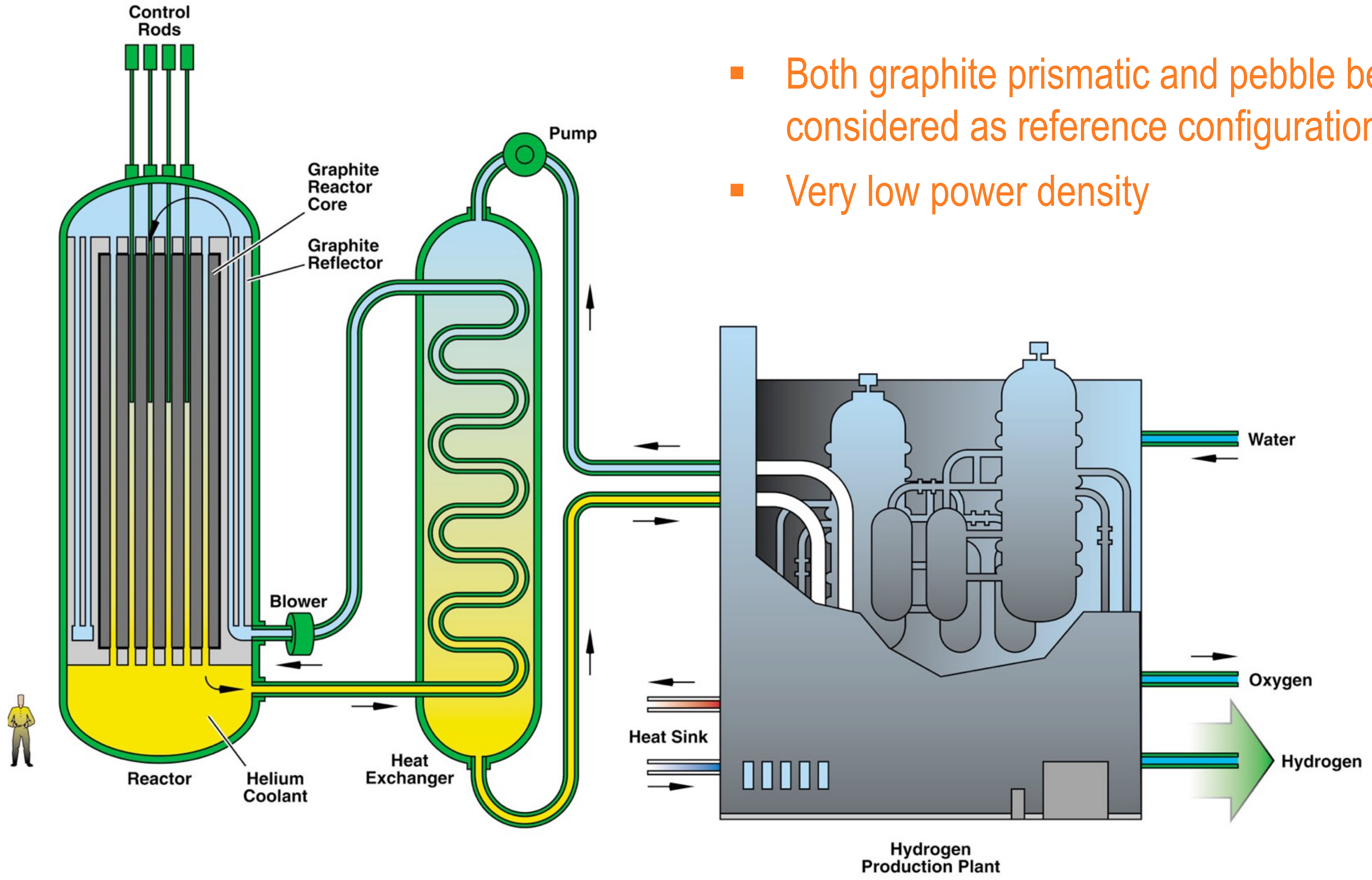
Specific design*	EPR	HPLWR
Thermal power (MW)	4300	2300
Efficiency (%)	37	**~44**
Primary coolant	H_2O	**H_2O**
Inlet/outlet temp. (°C)	296 327	280 **500**
Pressure (MPa)	~16	**~25**
Moderator	H_2O	H_2O
Neutron spectrum	Thermal	Thermal
Breeding gain	<< 0	**<< 0**
Reference	[1]	[2]
G1: Sustainability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

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

→

Very-High-Temperature Reactor: concept



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

02-GA50807-01

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

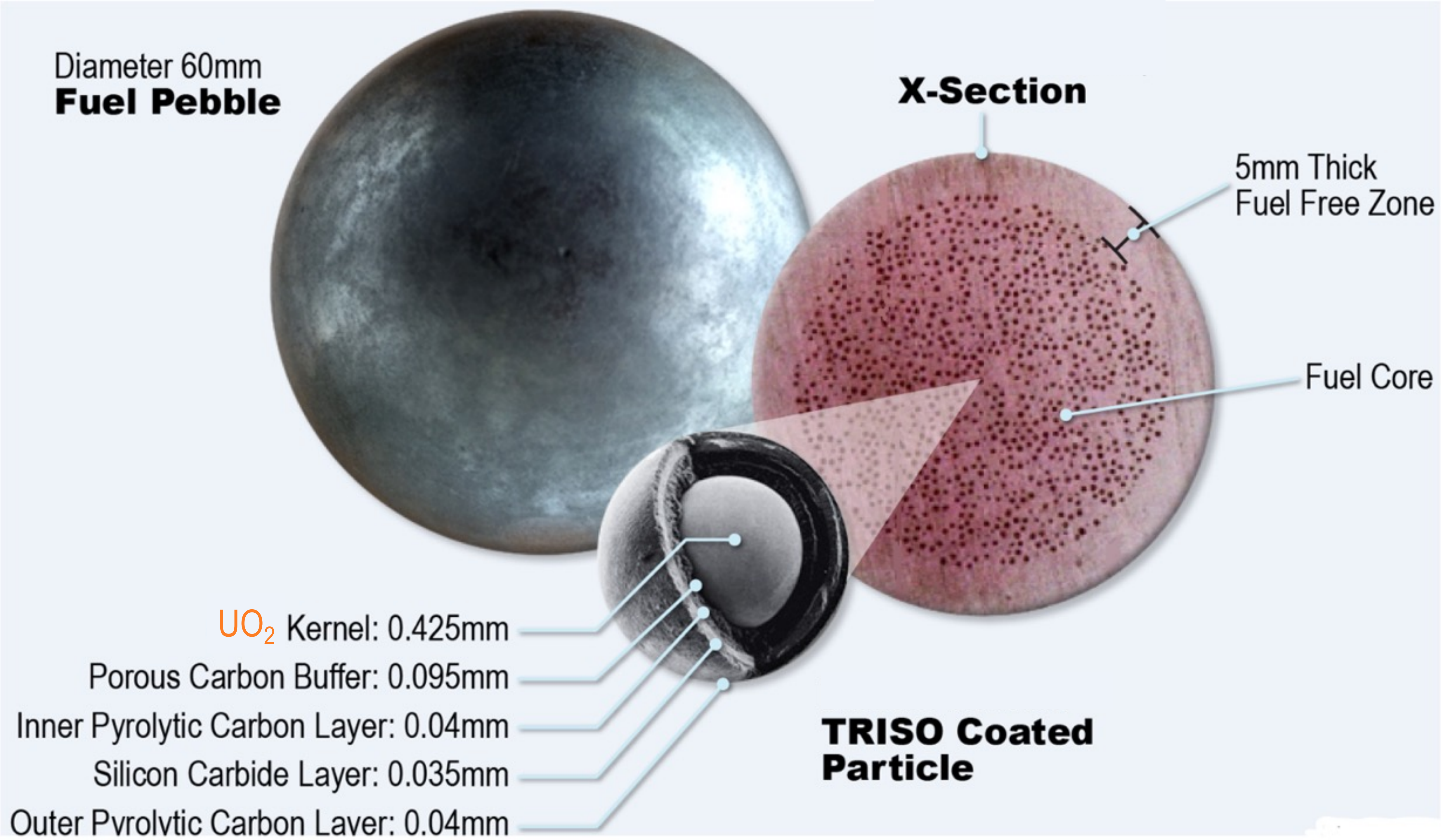
HTR-PM (China)

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)

*Specific designs chosen by lecturer

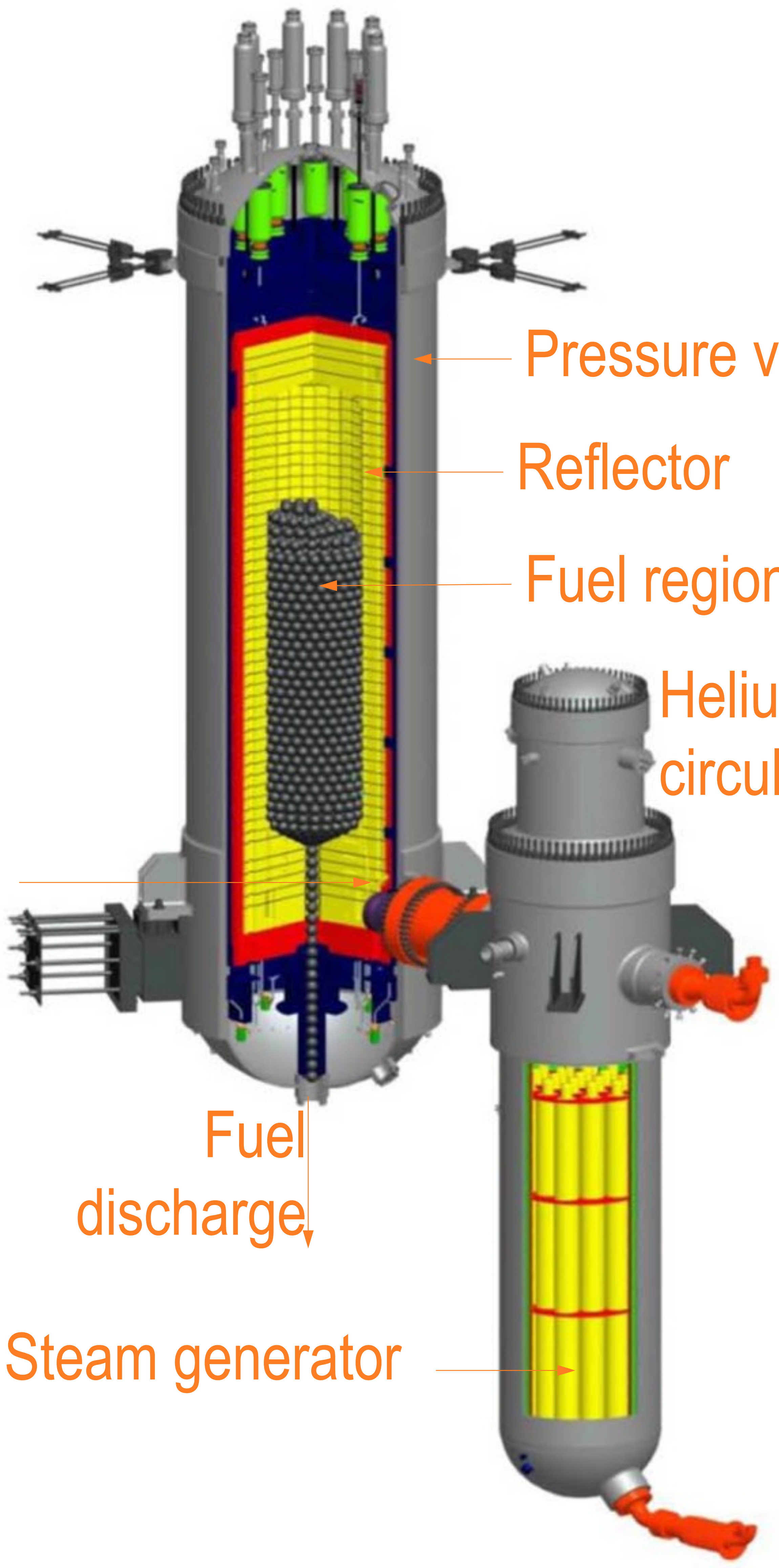
HTR-PM (China): fuel

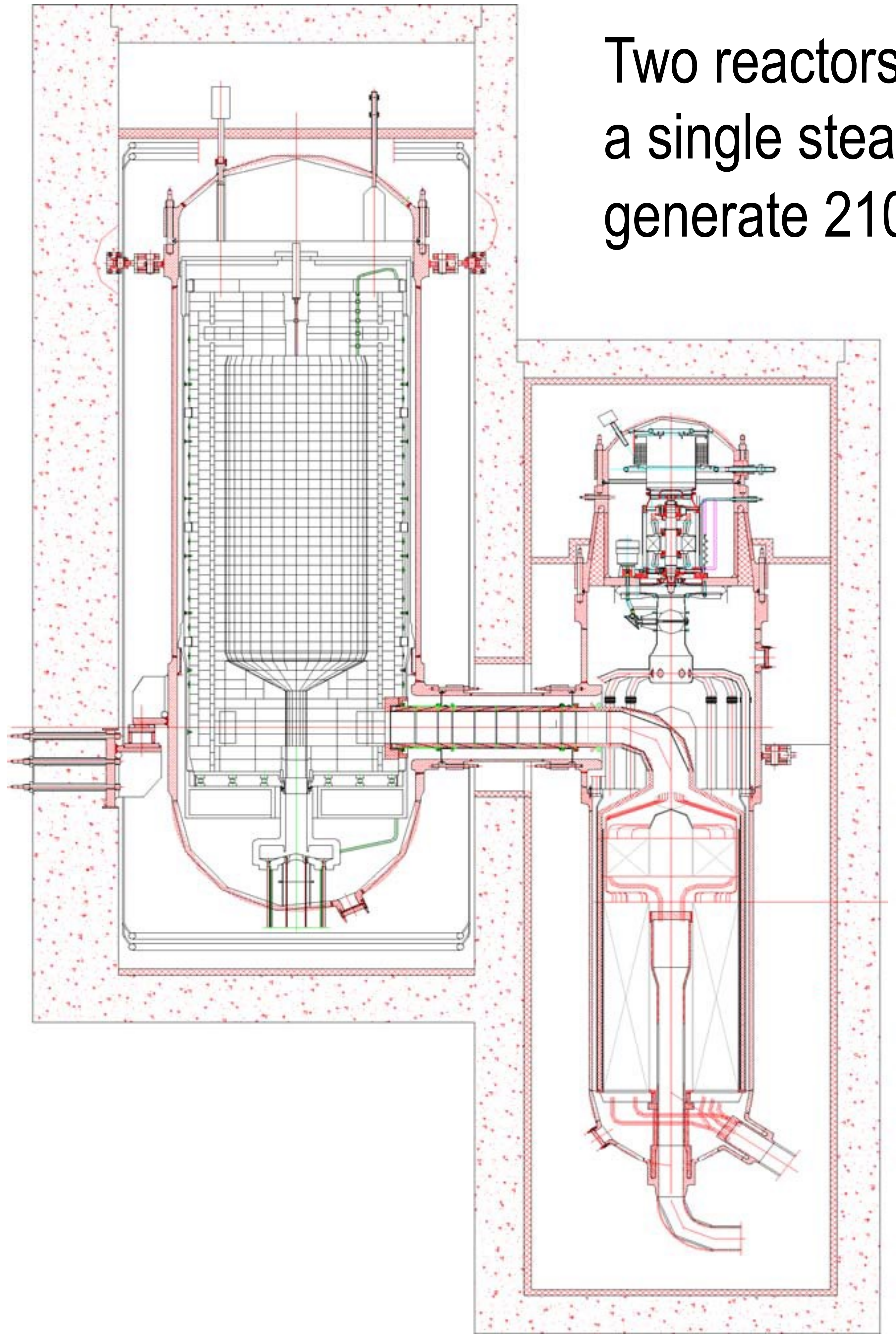


https://www.x-energy.com/copy-of-xe-100-reactor

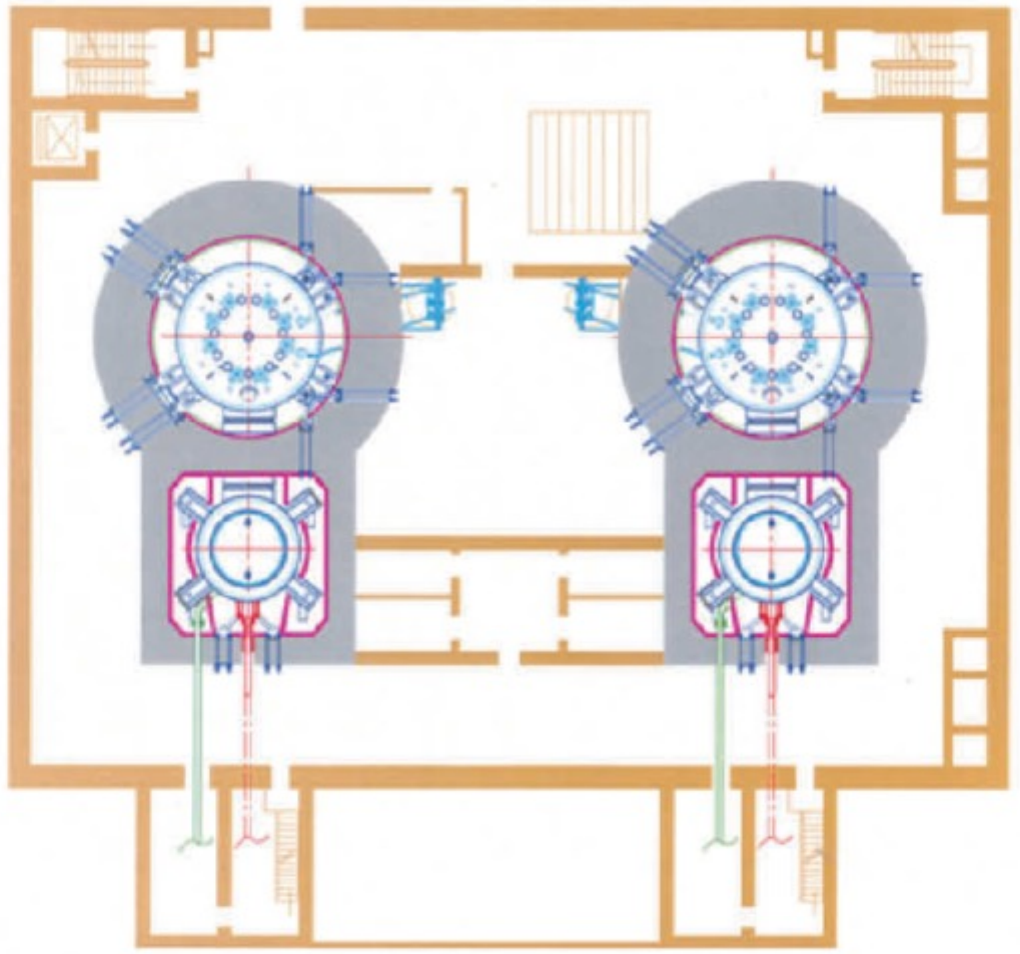
Fuel	UO_2
Number of pebbles in the core	420’000
Heavy metal per pebble	~7 g
Number of coated particles in each pebble	~ 11’660
Fuel loading scheme	Multi-pass (six times)
Average discharge burnup	90 MWd/kgU

HTR-PM (China) [3]: reactor





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



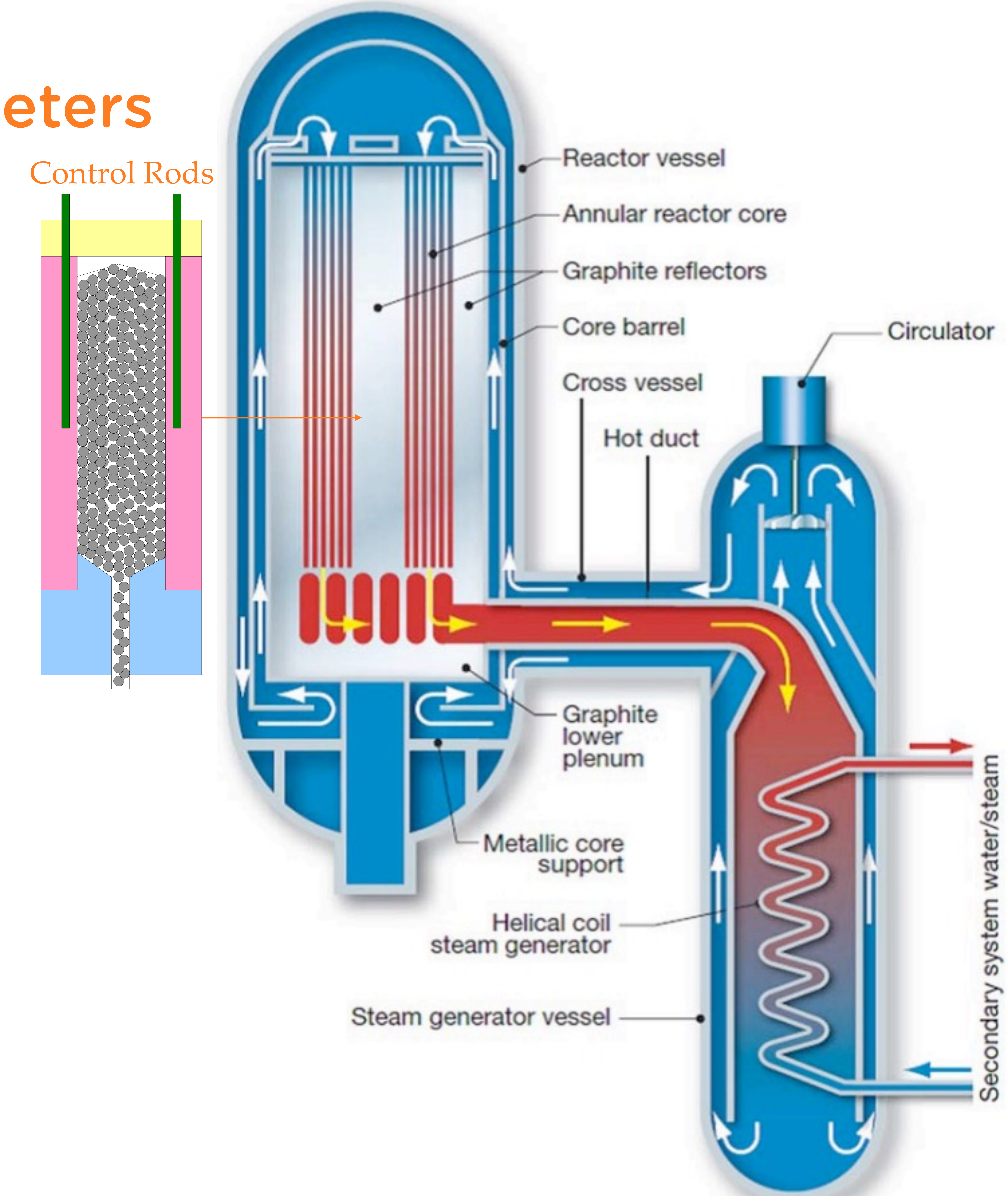
- Power density ~ 3.3 MW/m^3 (factor of 30 lower than in PWR)
- High thermal inertia
- There is no need in core emergency cooling system since decay heat is removed by natural mechanisms in case of accidents

Courtesy of Tsinghua University

Pebble-bed Reactor design parameters

Example: HTR-PM Parameters

Plant electrical power, MWe	210
Core thermal power, MW (one module)	250
Number of NSSS Modules	2
Core diameter, m	3
Core height, m	11
Primary helium pressure, MPa	7
Core outlet temperature, °C	750
Core inlet temperature, °C	250
Fuel enrichment, %	8.5
Steam pressure at turbine, Mpa	13.25
Steam temperature at turbine, °C	566
Efficiency, %	42



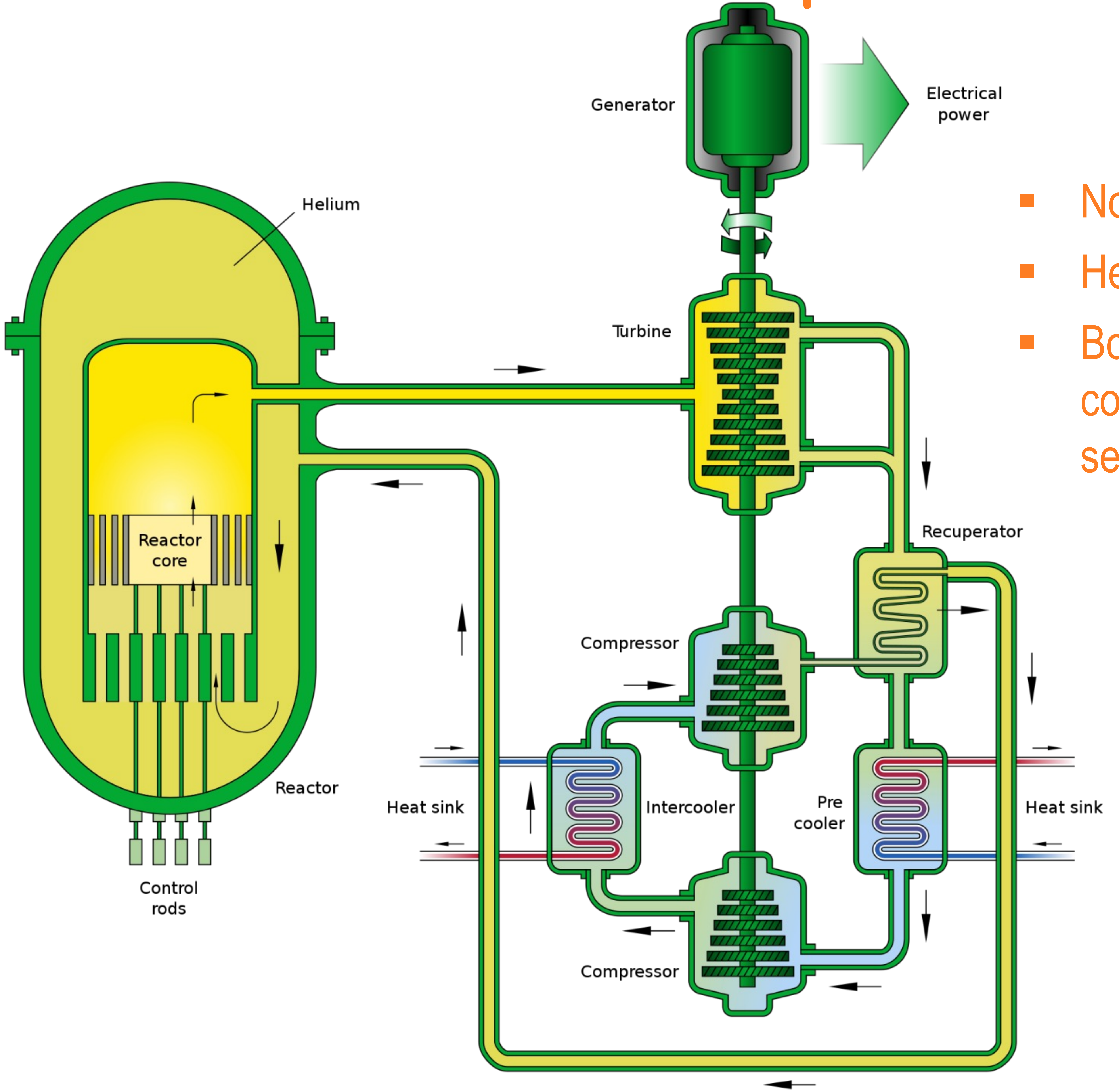
From Gen-III to Gen-IV: improvements to reach the goal(s)

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

- 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?

→

Gas-cooled Fast Reactor: concept



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

Gas-cooled Fast Reactor: fact sheet

- **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

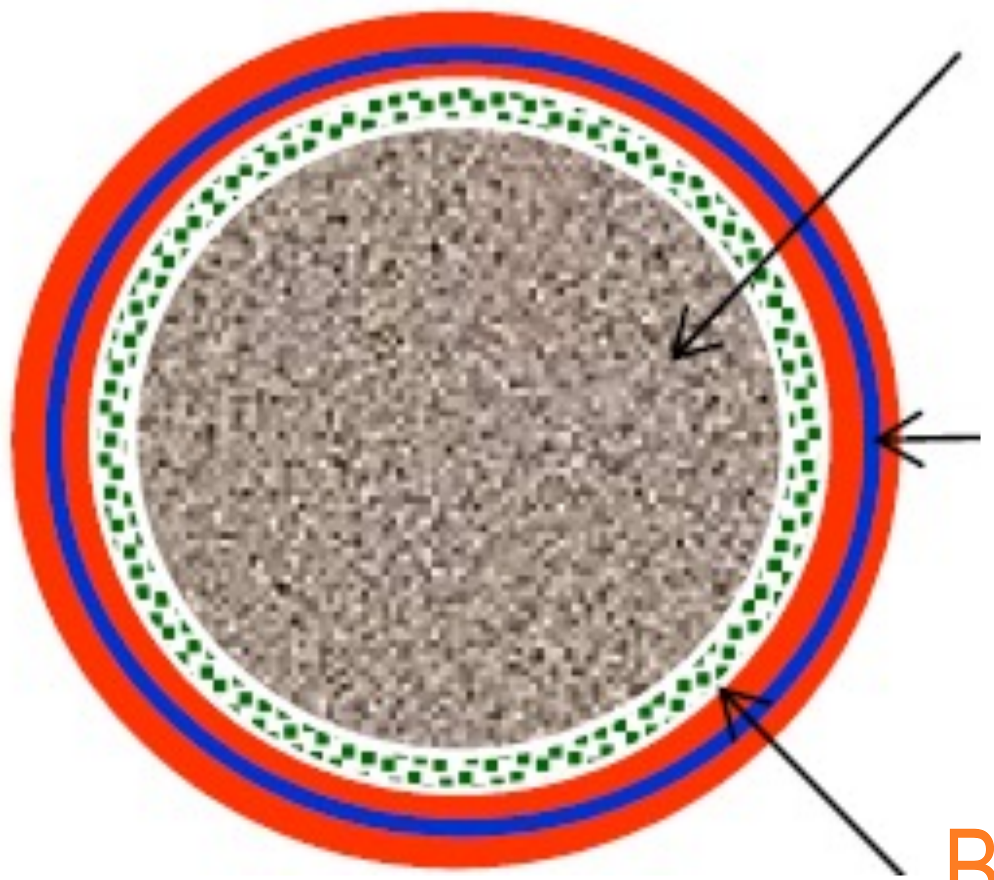
Concept	**PWR**		**SCWR**		**(V)HTR**		**GFR**	
Specific design*	EPR		HPLWR		HTR-PM		GCFR	
Thermal power (MW)	4300		2300		458		2400	
Efficiency (%)	37		**~44**		**~45**		**~45**	
Primary coolant	H_2O		$\mathbf{H_2O}$		He		He	
Inlet/outlet temp. (C)	296	327	280	**500**	250	750	400	780
Pressure (MPa)	~16		**~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

← Low thermal inertia

*Specific designs chosen by lecturer

GCFR-2400 (EU): fuel

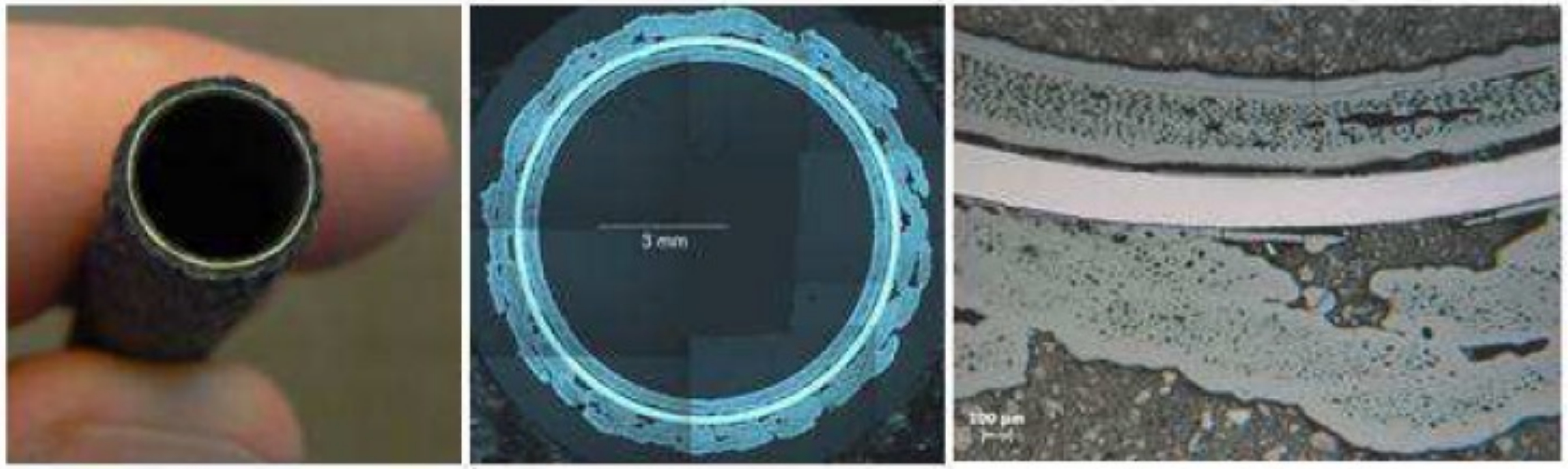


(U-Pu)C fuel pellet

Sandwich cladding Ø~9 mm:
- inner SiC/SiC layer
- middle metalic liner
- outer SiC/SiC layer

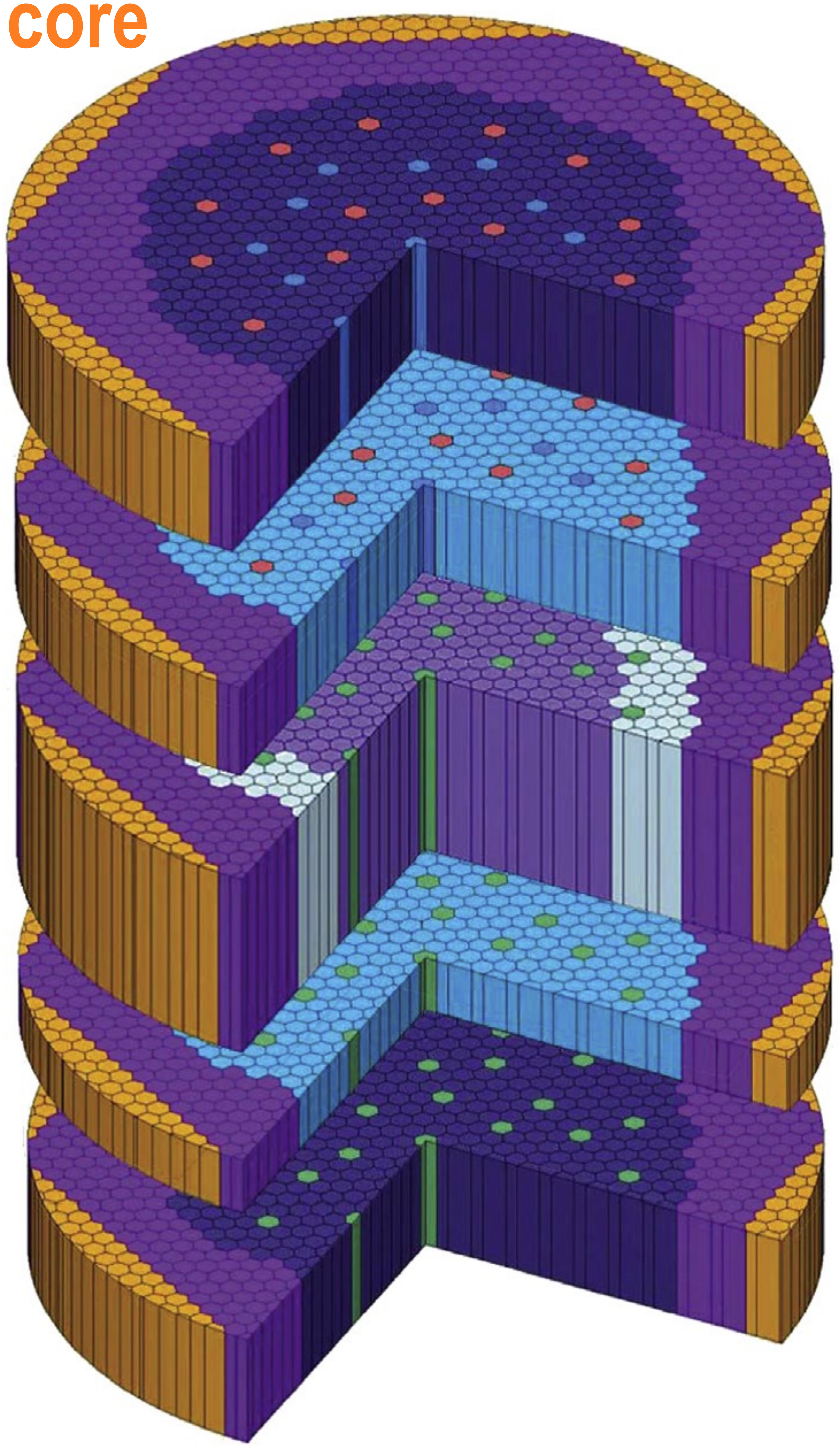
Buffer bond:
- high-porosity C-based braid

CEA manufactured “Sandwich” cladding



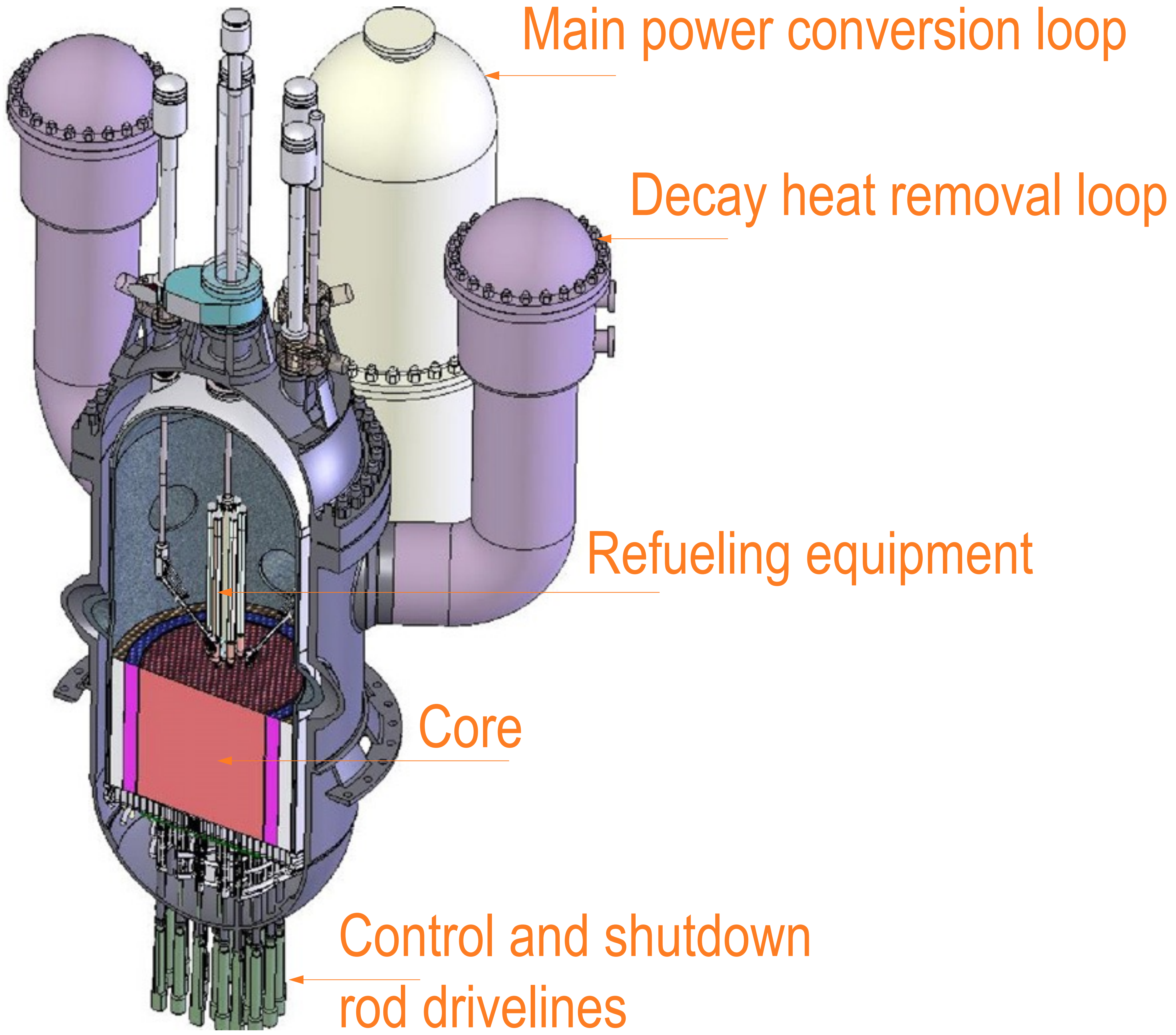
M. Zabiégo, et al. “Overview of CEA's R&D on GFR fuel element design: from challenges to solutions”, FR’13 conference proceedings

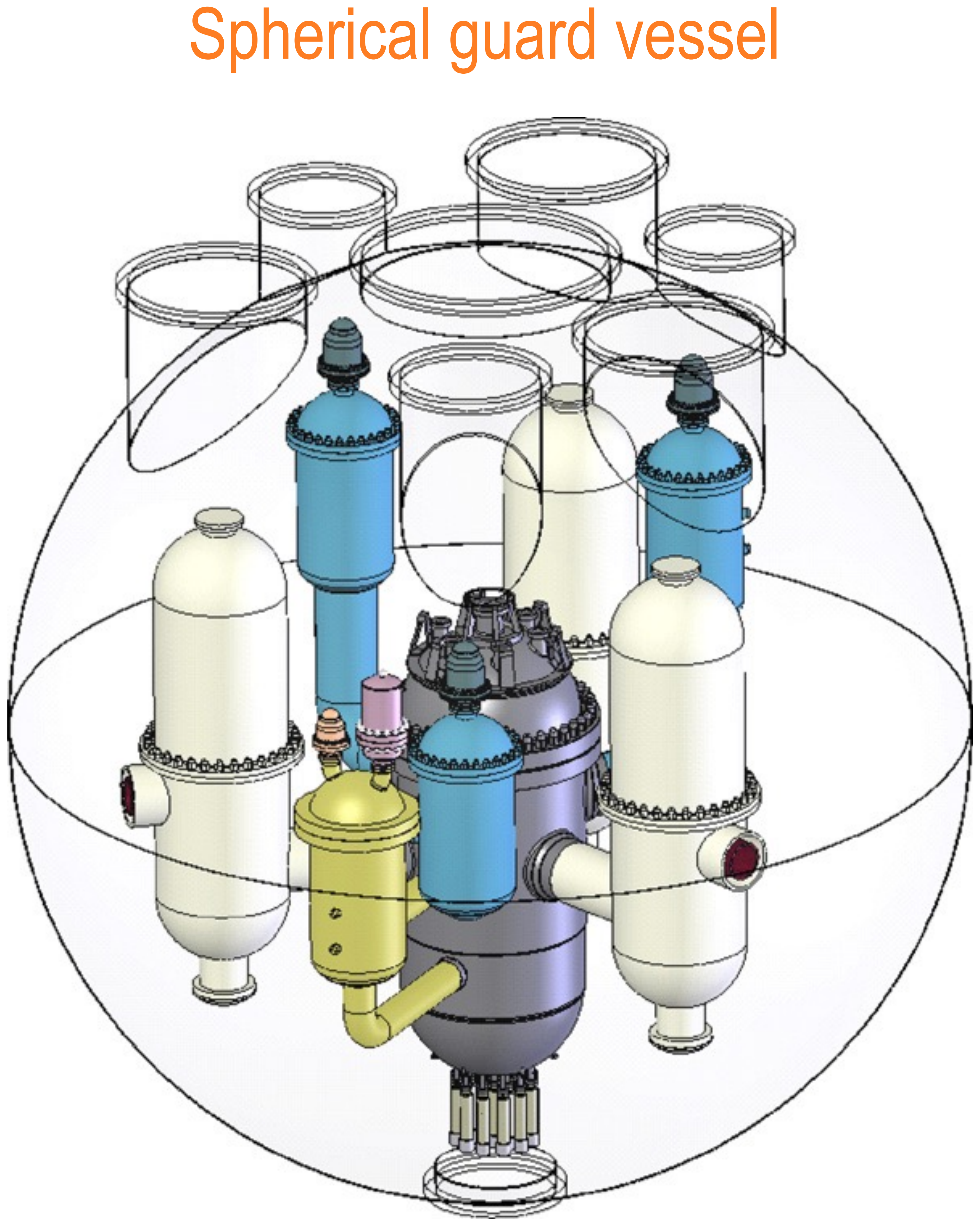
GCFR-2400 (EU): core



- ⬢ Inner core fuel assemblies
- ⬢ Outer core fuel assemblies
- ⬢ Fission gas plenums
- ⬢ Axial reflectors
- ⬢ Diverse and shutdown devices
- ⬢ Control and safety devices
- ⬢ Rod followers
- ⬢ Radial reflectors

GCFR-2400 (EU): reactor

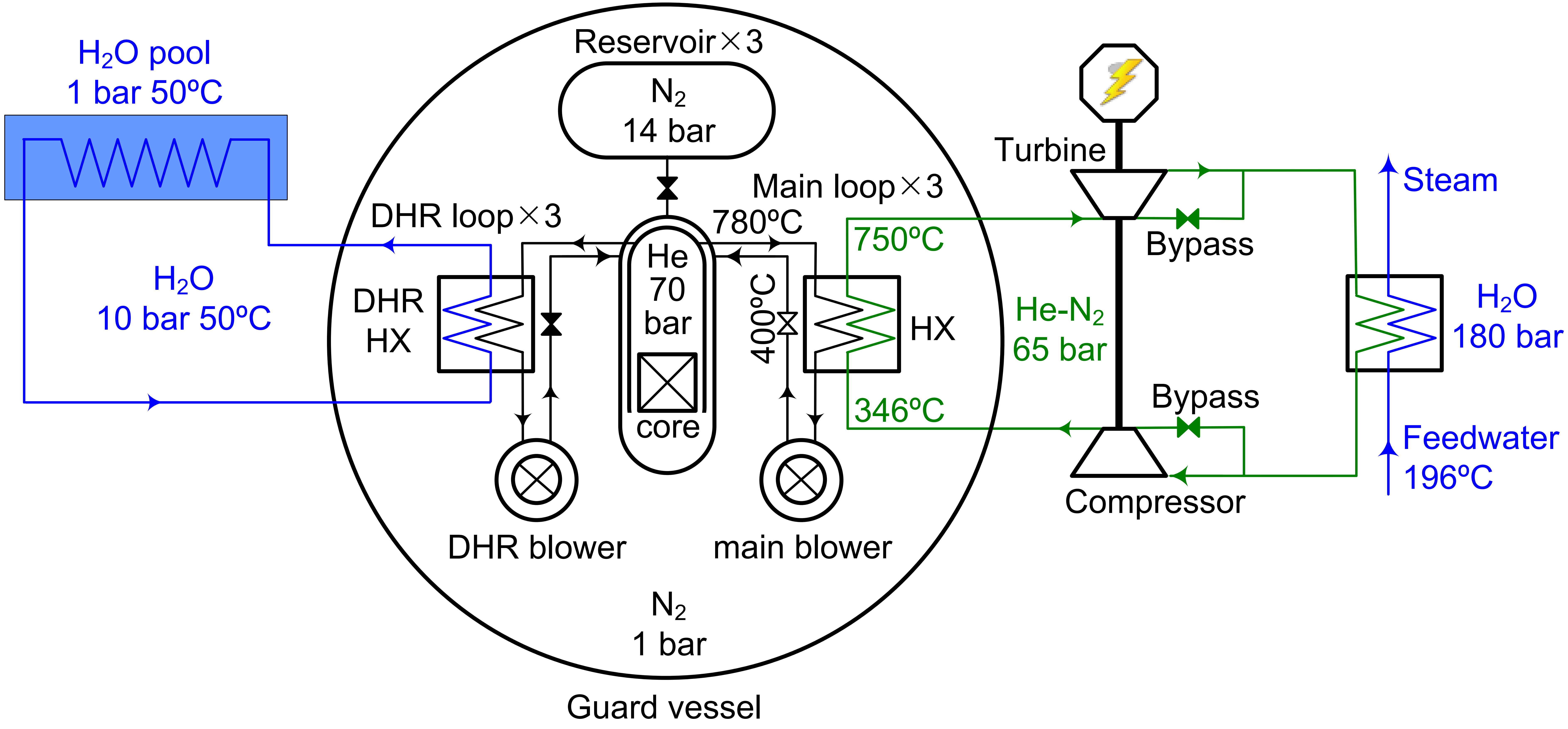




GCFR (EU): BoP concept

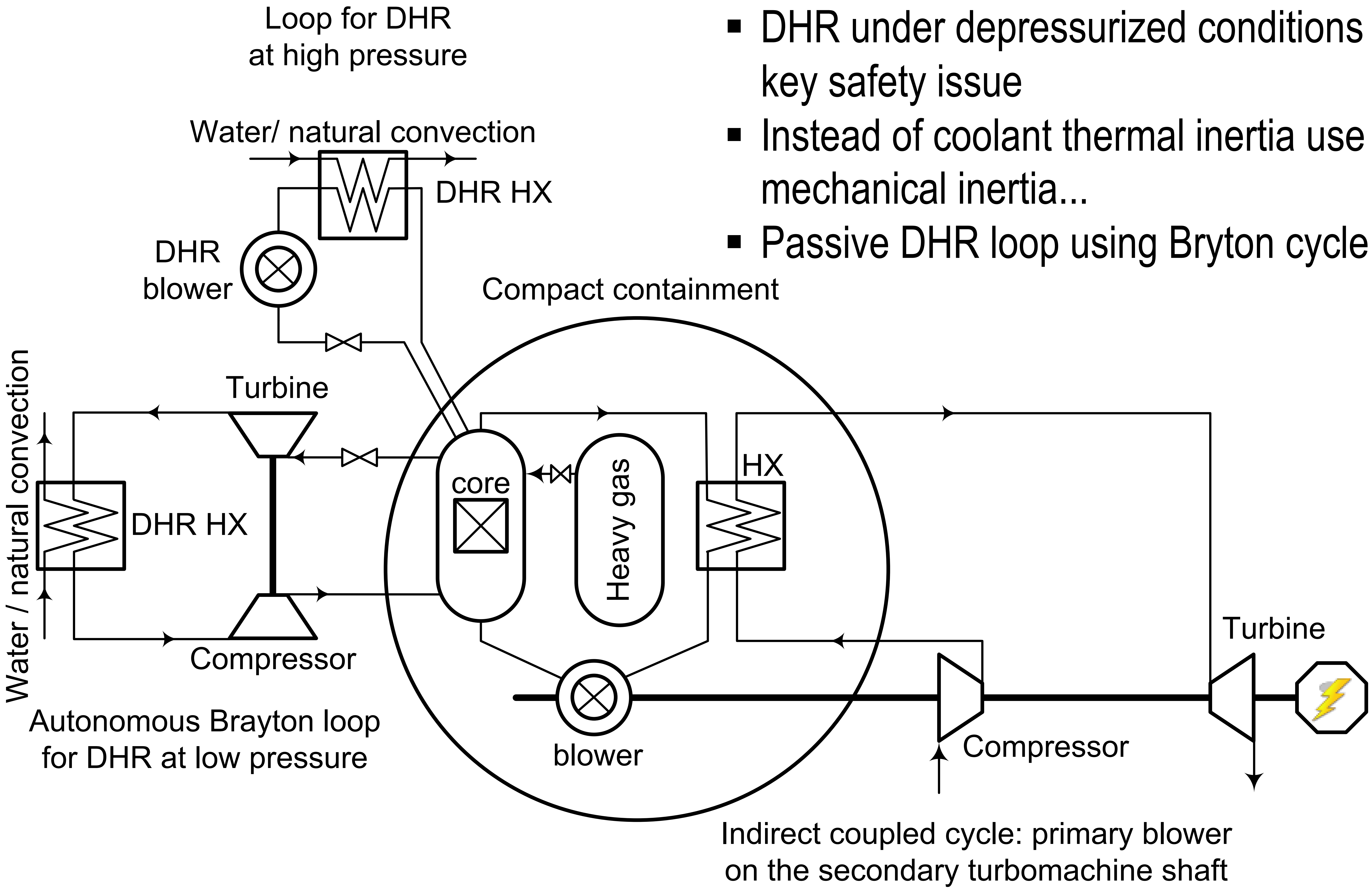
Power: 2400 MWth
Fuel: (U-Pu)C
Clad: SiC-SiC_f

- 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



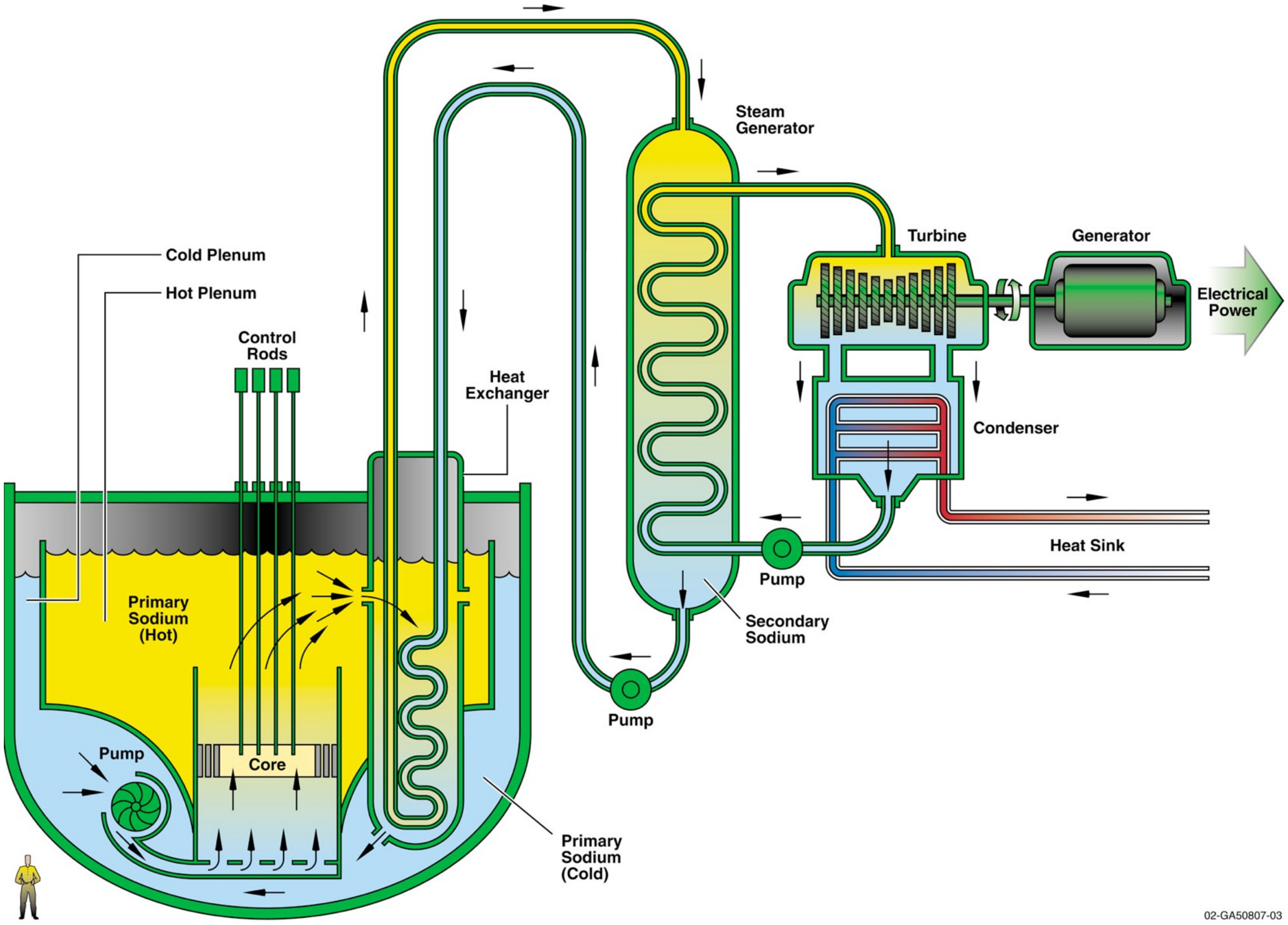
From Gen-III to Gen-IV: improvements to reach the goal(s)

Concept	**PWR**		**SCWR**		**(V)HTR**		**GFR**	
Specific design*	EPR		HPLWR		HTR-PM		GCFR	
Thermal power (MW)	4300		2300		458		2400	
Efficiency (%)	37		**~44**		**~45**		**~45**	
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		↑		↑		?	

- 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?

→

Sodium-cooled Fast Reactor: concept



Sodium-cooled Fast Reactor: fact sheet

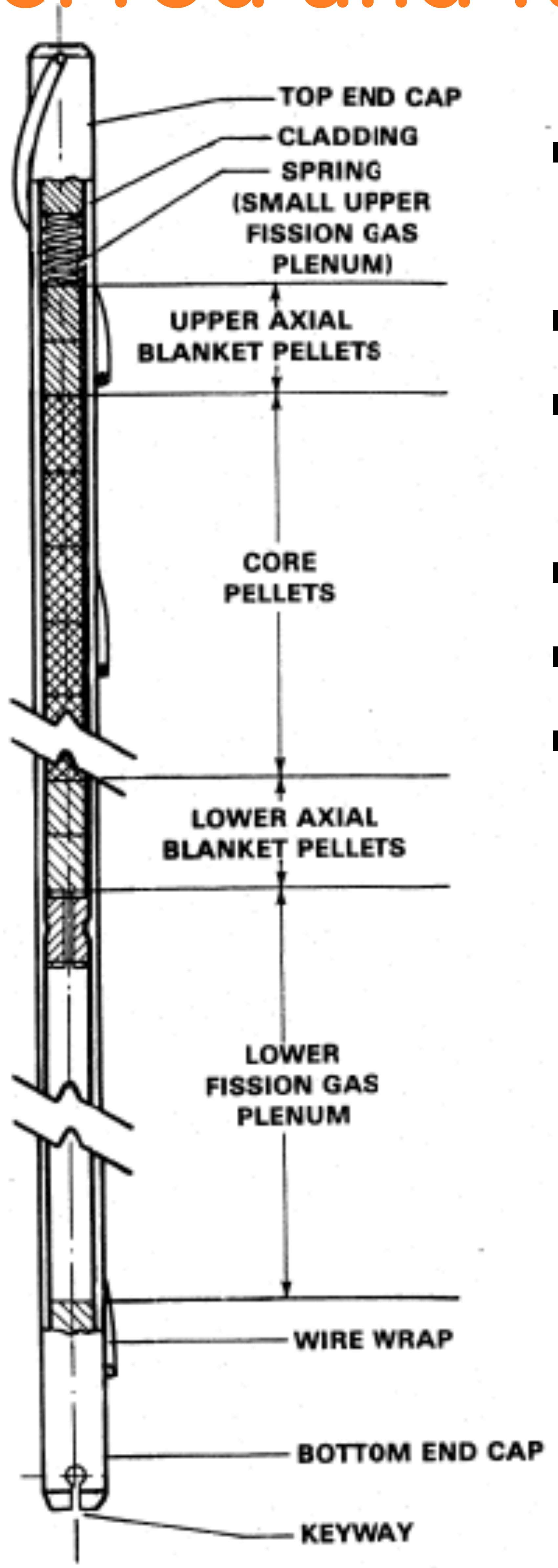
- **Advantages**
  - Potential for new fissile breeding due to fast neutron spectrum
  - Excellent thermal conductivity of sodium → VERY efficient cooling
  - Large margin to boiling (~300°C) → no pressurization required
  - Significant operational experience (300+ reactor-years)
- **Challenges**
  -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

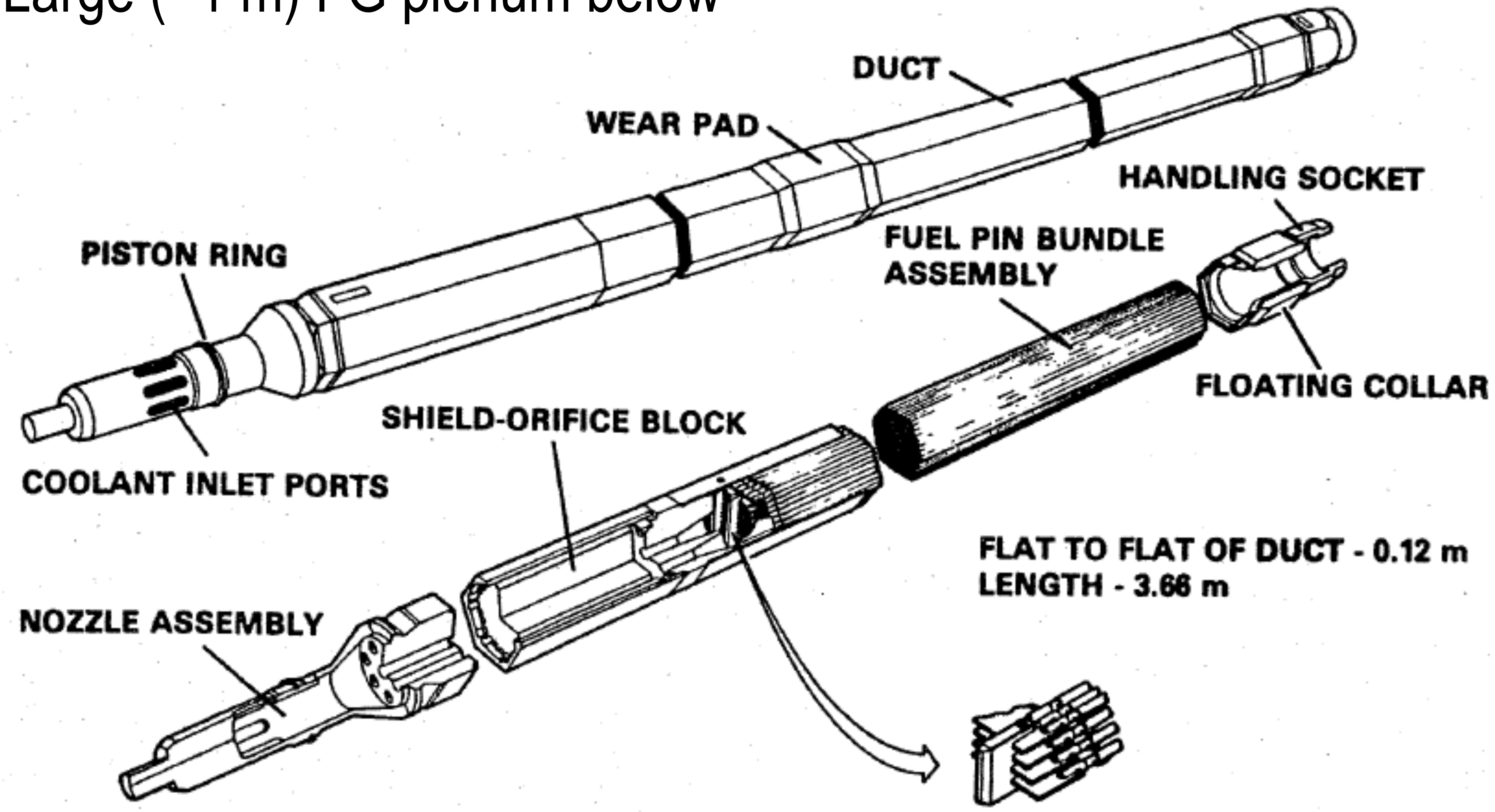
Concept	PWR		SCWR		(V)HTR		GFR		SFR	
Specific design*	EPR		HPLWR		HTR-PM		GCFR		ESFR	
Thermal power (MW)	4300		2300		458		2400		3600	
Efficiency (%)	37		**~44**		**~45**		**~45**		**~42**	
Primary coolant	H_2O		**H_2O**		He		He		**Na**	
Inlet/outlet temp. (C)	296	327	280	**500**	250	750	400	780	395	545
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

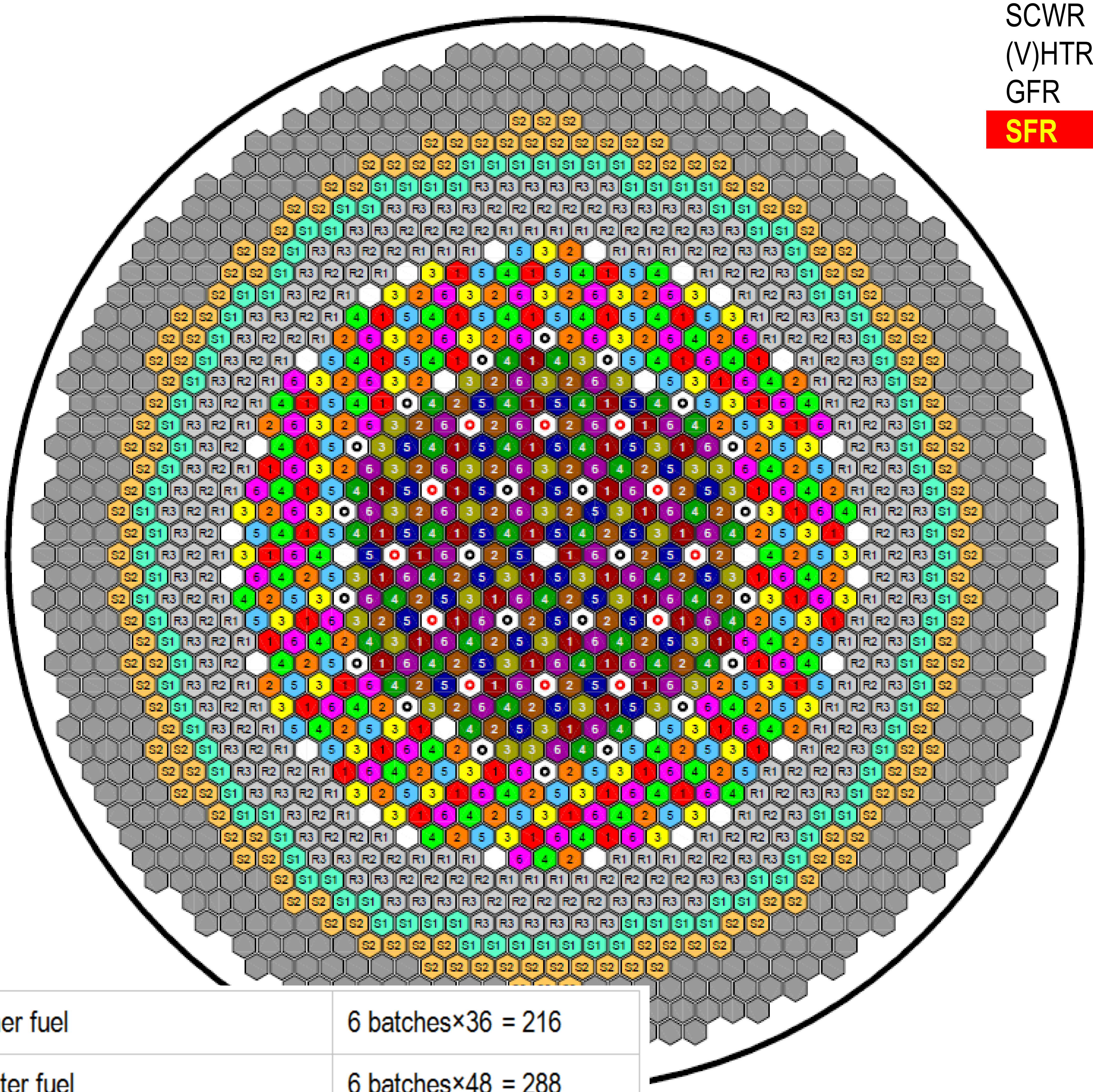
SFR fuel rod and fuel subassembly



- 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

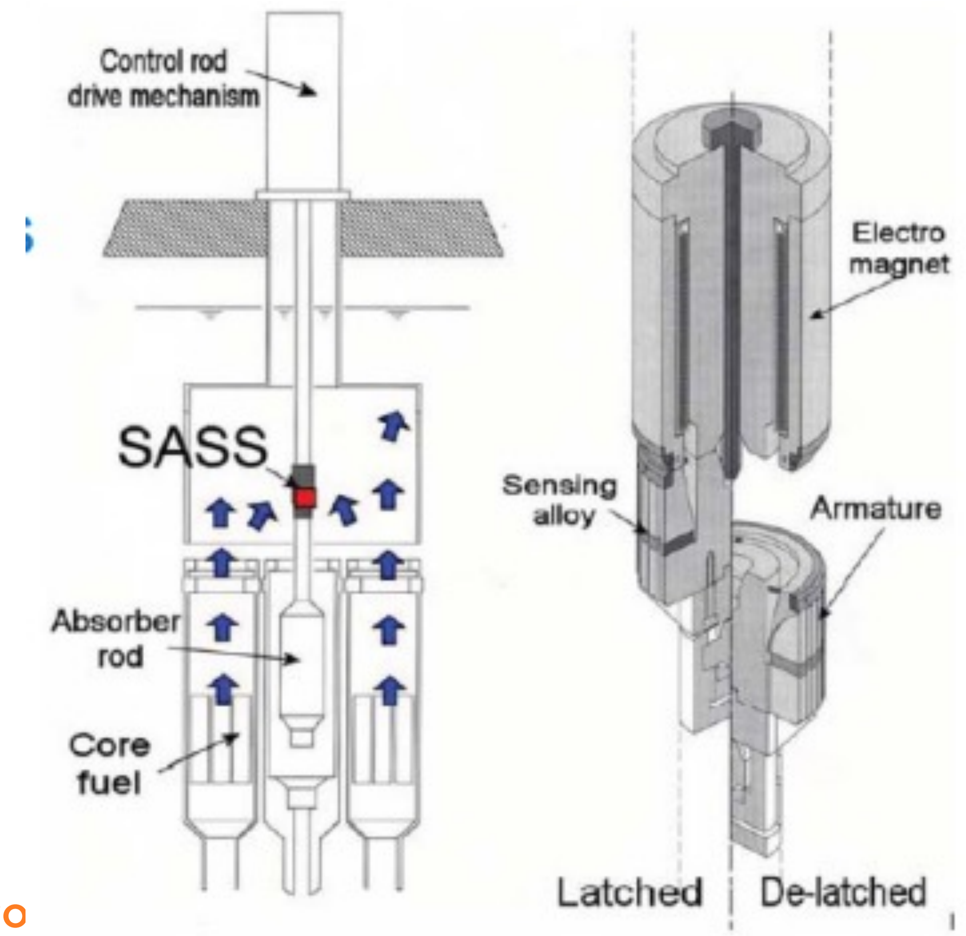


ESFR (EU): radial core layout



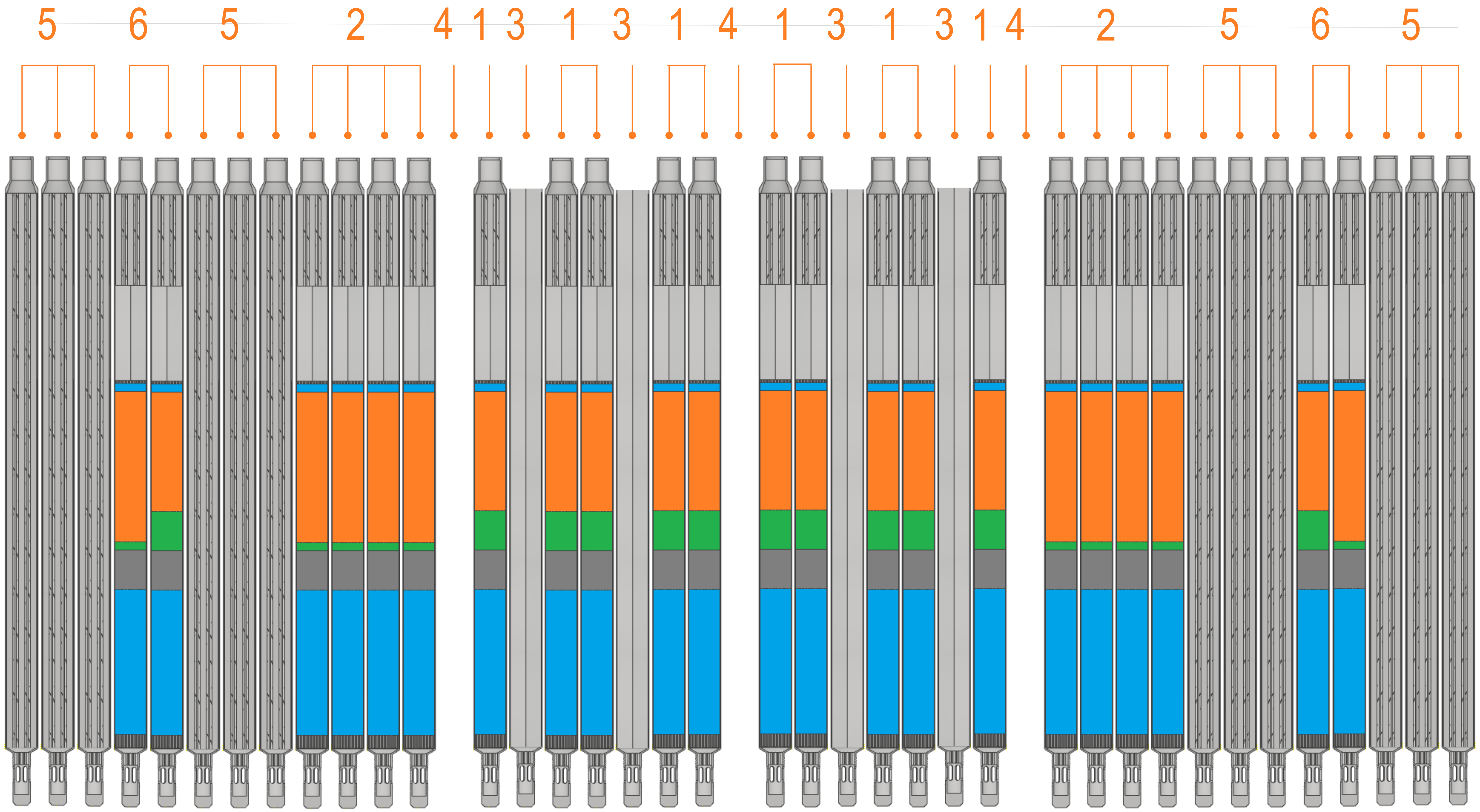
- Perfectly symmetric
- 6 batches = 6-year fuel cycle
- Mixed scheme (no reshuffling)
- Internal storage for 50% of core loading
- Corium discharge tubes
- All DSD rods equipped with passively-activated Curie-point electromagnetic locks

ESFR has two groups of the absorber rods for reactor shutdown:
1. Control and Shutdown Devices/Rods (CSD)
2. Diversified Shutdown Devices/Rods (DSD)



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

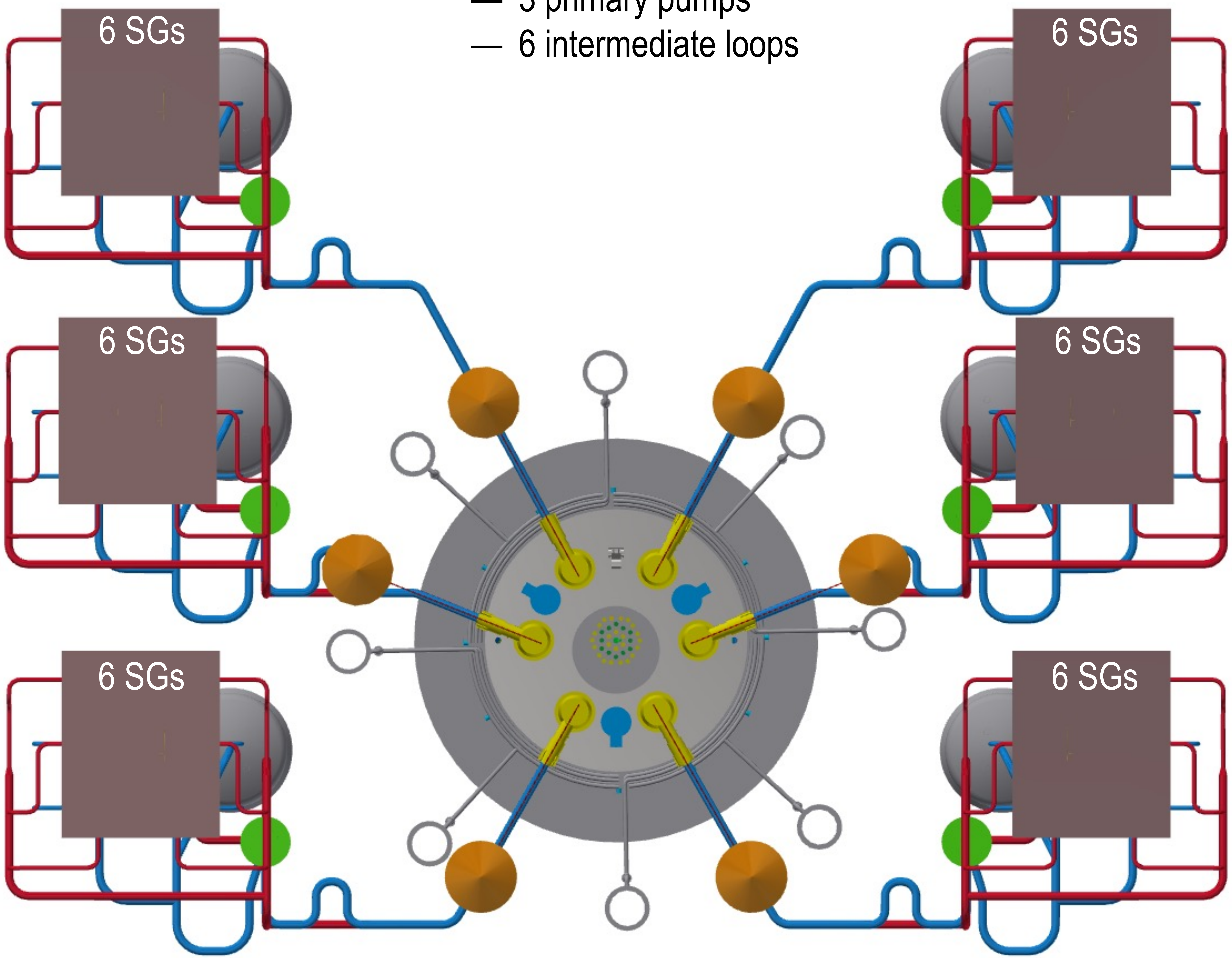


1 – Inner zone SA
2 – Outer zone SA
3 – Control assembly
4 – Corium discharge path
5 – Shielding SA
6 – Internal spent fuel storage

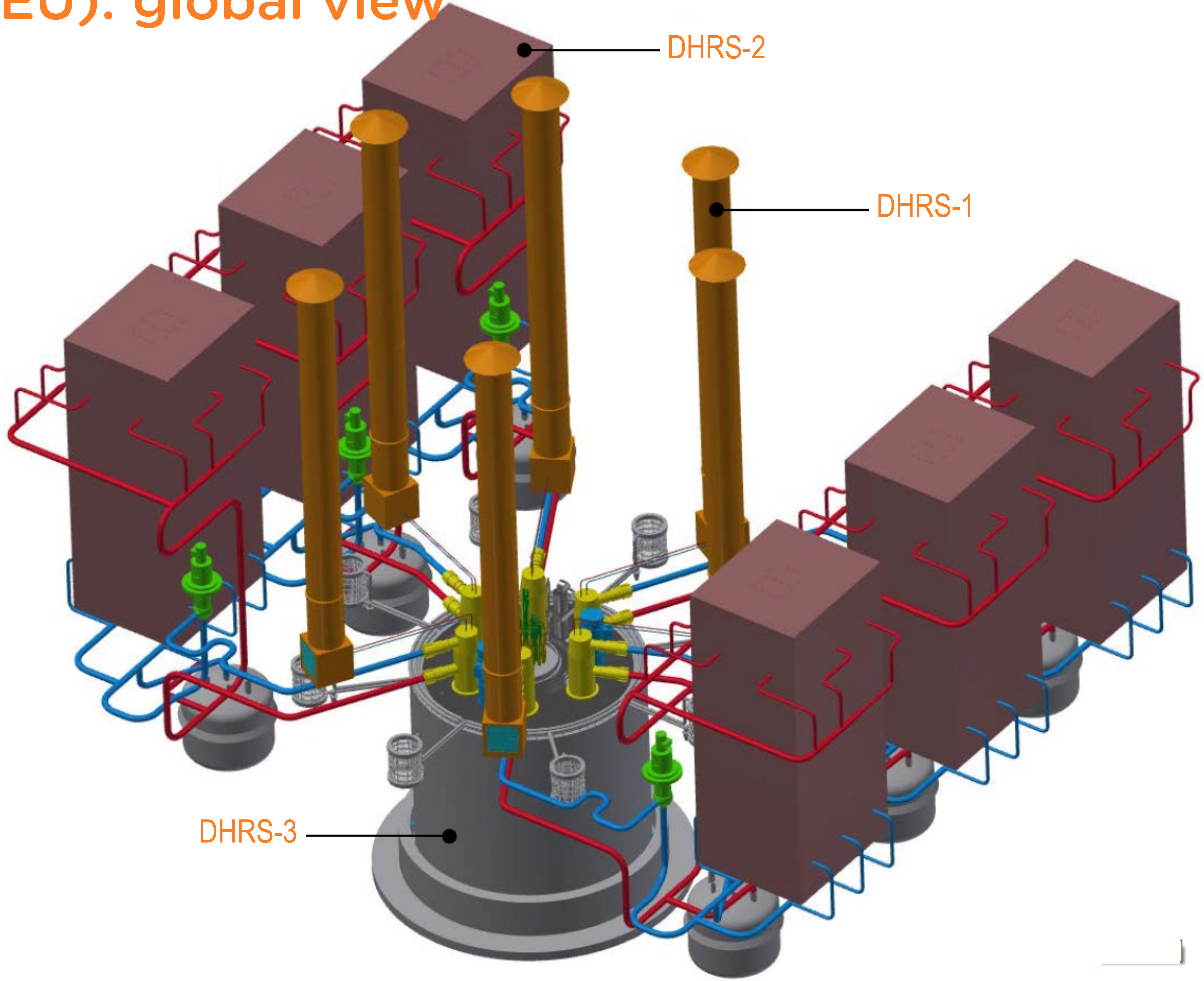
🟧 Fissile fuel (~18% Pu content)
🟩 Fertile blanket
◼ Steel blanket
🟦 Fission gas plenum
⬜ Sodium plenum
▨ Shielding (absorber)

ESFR (EU): global view from above

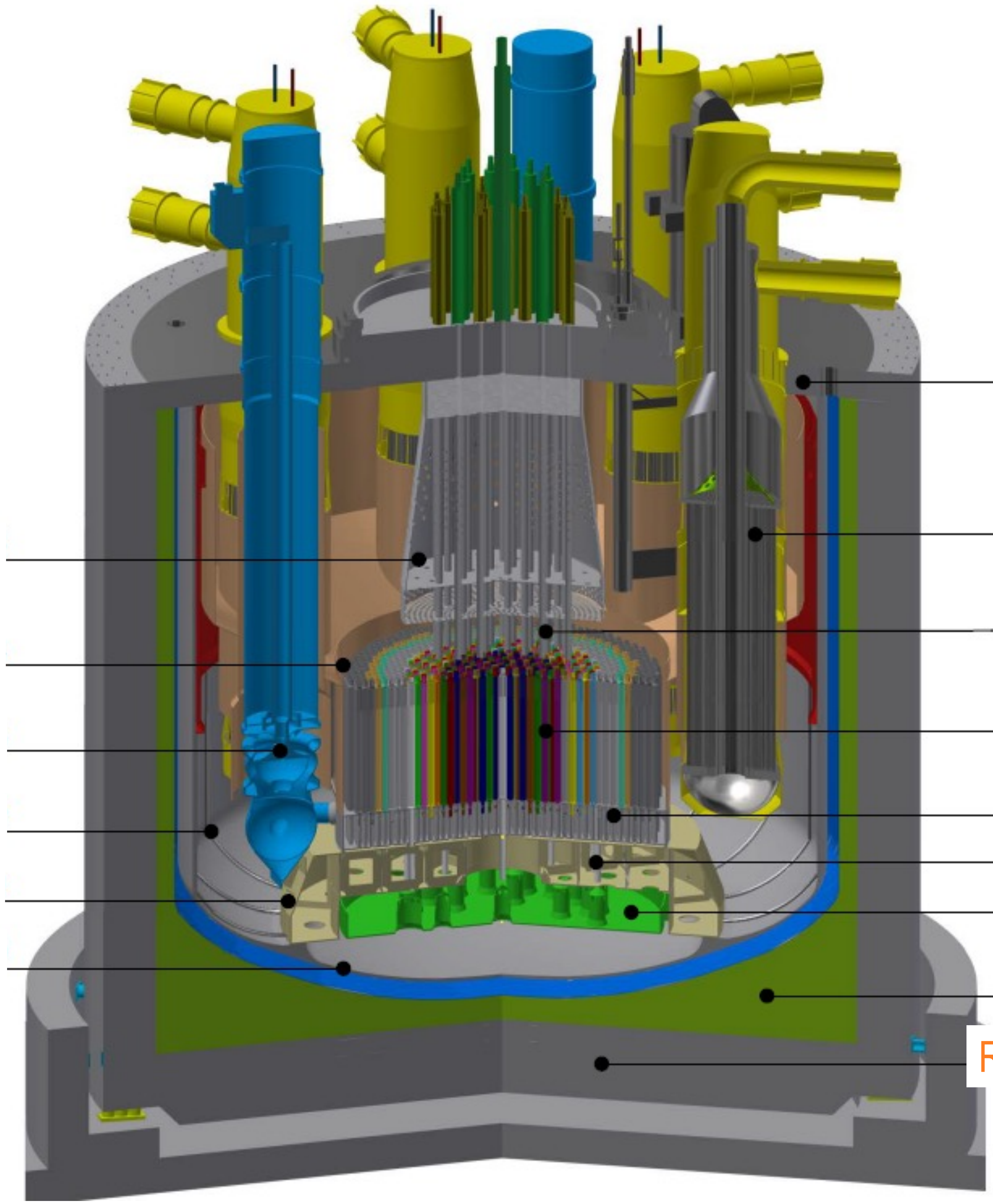
- 3 primary pumps
- 6 intermediate loops



ESFR (EU): global view

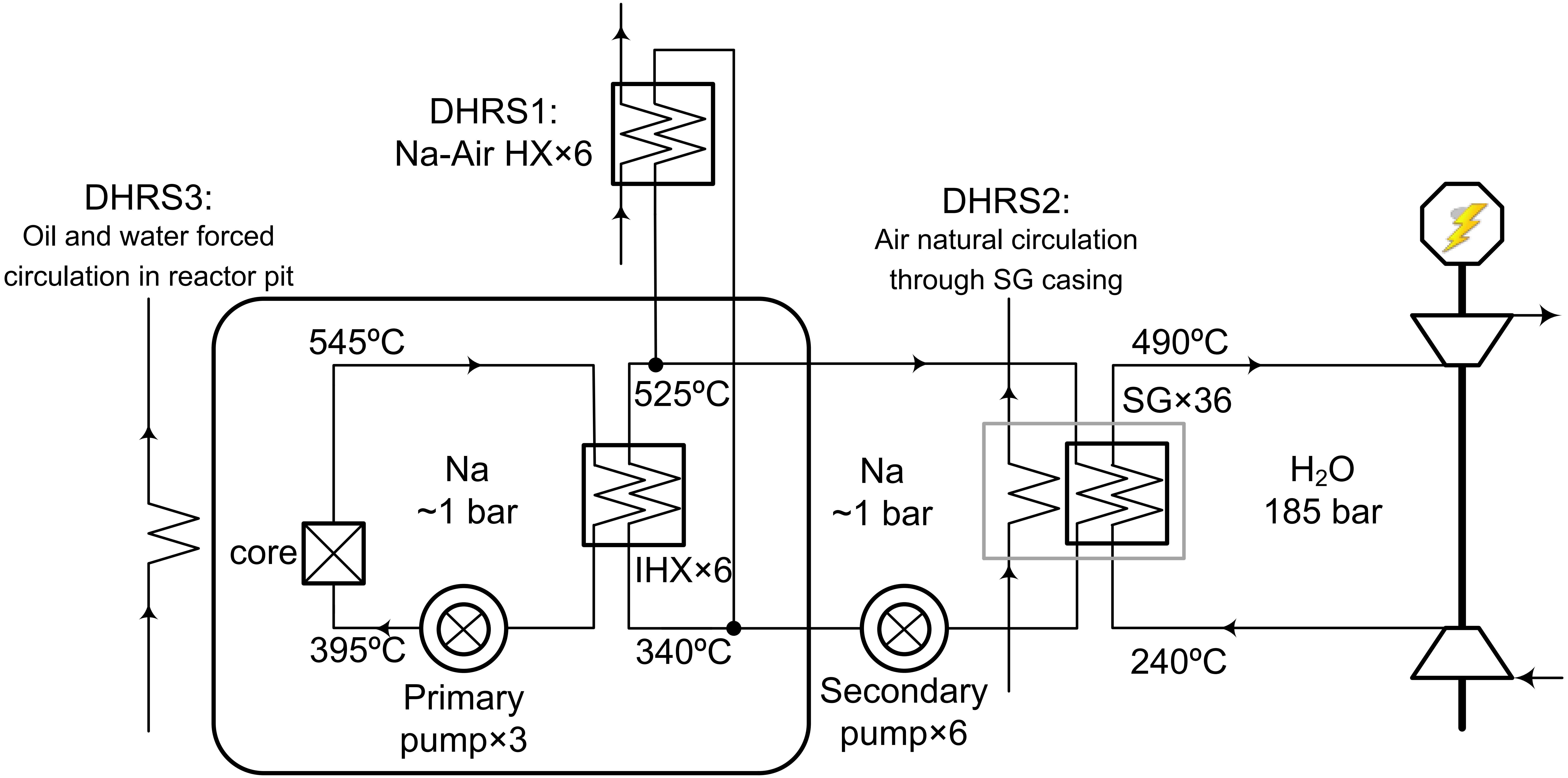


ESFR (EU): primary system



ESFR (EU): BoP concept

Power: 3600 MWth
Fuel: (U-Pu)O_2
Clad: stainless steel



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

Concept	**PWR**	**SCWR**	**(V)HTR**	**GFR**	**SFR**
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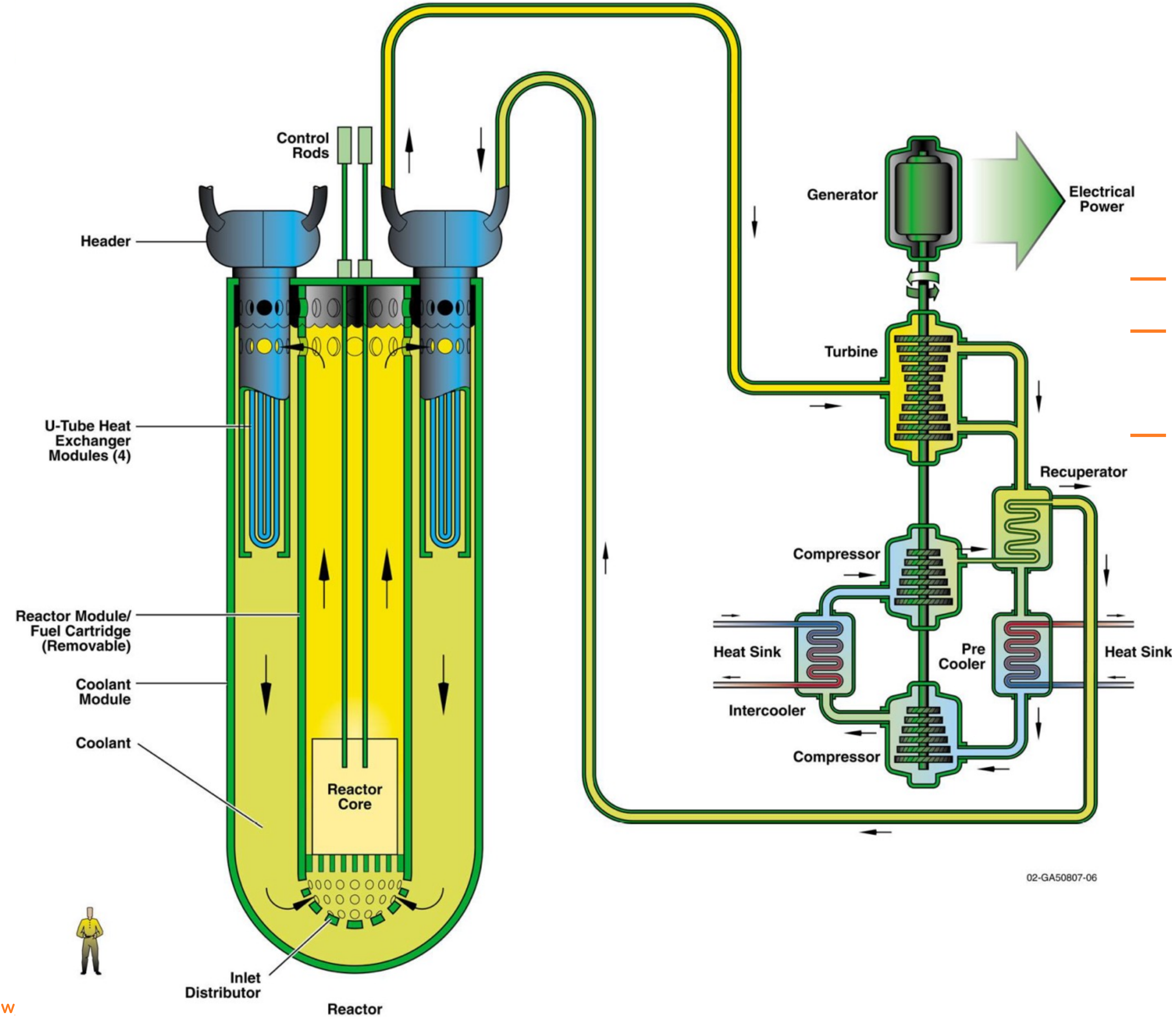
Efficiency (%)	37	**~44**	**~45**	**~45**	**~42**
Primary coolant	H_2O	**H_2O**	He	He	**Na**
Inlet/outlet temp. (C)	296 327	280 **500**	250 750	400 780	395 545
Pressure (MPa)	~16	**~25**	~7	**~7**	**~0.2**
Moderator	H_2O	H_2O	C	**None**	None
Neutron spectrum	Thermal	Thermal	Thermal	Fast	Fast
Breeding 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?

→

Lead-cooled Fast Reactor: concept



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

Lead-cooled Fast Reactor: fact sheet

- **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

<table>
<tr><th>Concept</th><th colspan="2">PWR</th><th colspan="2">SCWR</th><th colspan="2">(V)HTR</th><th colspan="2">GFR</th><th colspan="2">SFR</th><th colspan="2">LFR</th></tr>
<tr><td>Specific design*</td><td colspan="2">EPR</td><td colspan="2">HPLWR</td><td colspan="2">HTR-PM</td><td colspan="2">GCFR</td><td colspan="2">ESFR</td><td colspan="2">ALFRED</td></tr>
<tr><td>Thermal power (MW)</td><td colspan="2">4300</td><td colspan="2">2300</td><td colspan="2">458</td><td colspan="2">2400</td><td colspan="2">3600</td><td colspan="2">300</td></tr>
<tr><td>Efficiency (%)</td><td colspan="2">37</td><td colspan="2">~44</td><td colspan="2">~45</td><td colspan="2">~45</td><td colspan="2">~42</td><td colspan="2">~42</td></tr>
<tr><td>Primary coolant</td><td colspan="2">H_2O</td><td colspan="2">H_2O</td><td colspan="2">He</td><td colspan="2">He</td><td colspan="2">Na</td><td colspan="2">Pb</td></tr>
<tr><td>Inlet/outlet temp. (C)</td><td>296</td><td>327</td><td>280</td><td>500</td><td>250</td><td>750</td><td>400</td><td>780</td><td>395</td><td>545</td><td>400</td><td>480</td></tr>
<tr><td>Pressure (MPa)</td><td colspan="2">~16</td><td colspan="2">~25</td><td colspan="2">~7</td><td colspan="2">~7</td><td colspan="2">~0.2</td><td colspan="2">~0.5</td></tr>
<tr><td>Moderator</td><td colspan="2">H_2O</td><td colspan="2">H_2O</td><td colspan="2">C</td><td colspan="2">None</td><td colspan="2">None</td><td colspan="2">None</td></tr>
<tr><td>Neutron spectrum</td><td colspan="2">Thermal</td><td colspan="2">Thermal</td><td colspan="2">Thermal</td><td colspan="2">Fast</td><td colspan="2">Fast</td><td colspan="2">Fast</td></tr>
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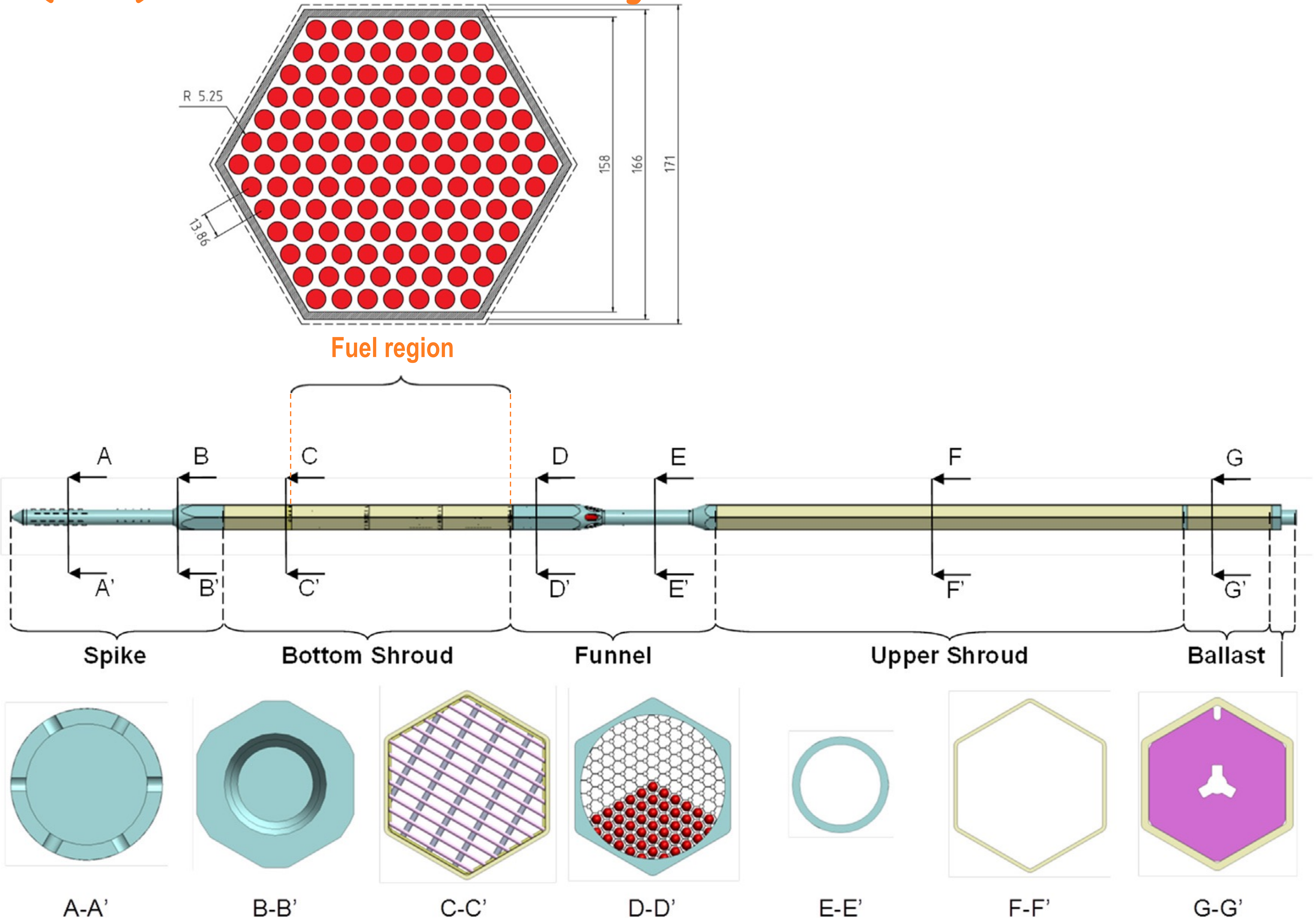
<tr><td>G2: Safety & reliability</td><td colspan="2">Good</td><td colspan="2">↓</td><td colspan="2">↑</td><td colspan="2">↓</td><td colspan="2">↓↑</td><td colspan="2">↓↑</td></tr>
<tr><td>G3: Economics</td><td colspan="2">Good</td><td colspan="2">↑</td><td colspan="2">↑</td><td colspan="2">?</td><td colspan="2">↓</td><td colspan="2">?</td></tr>
</table>

*Specific designs chosen by lecturer

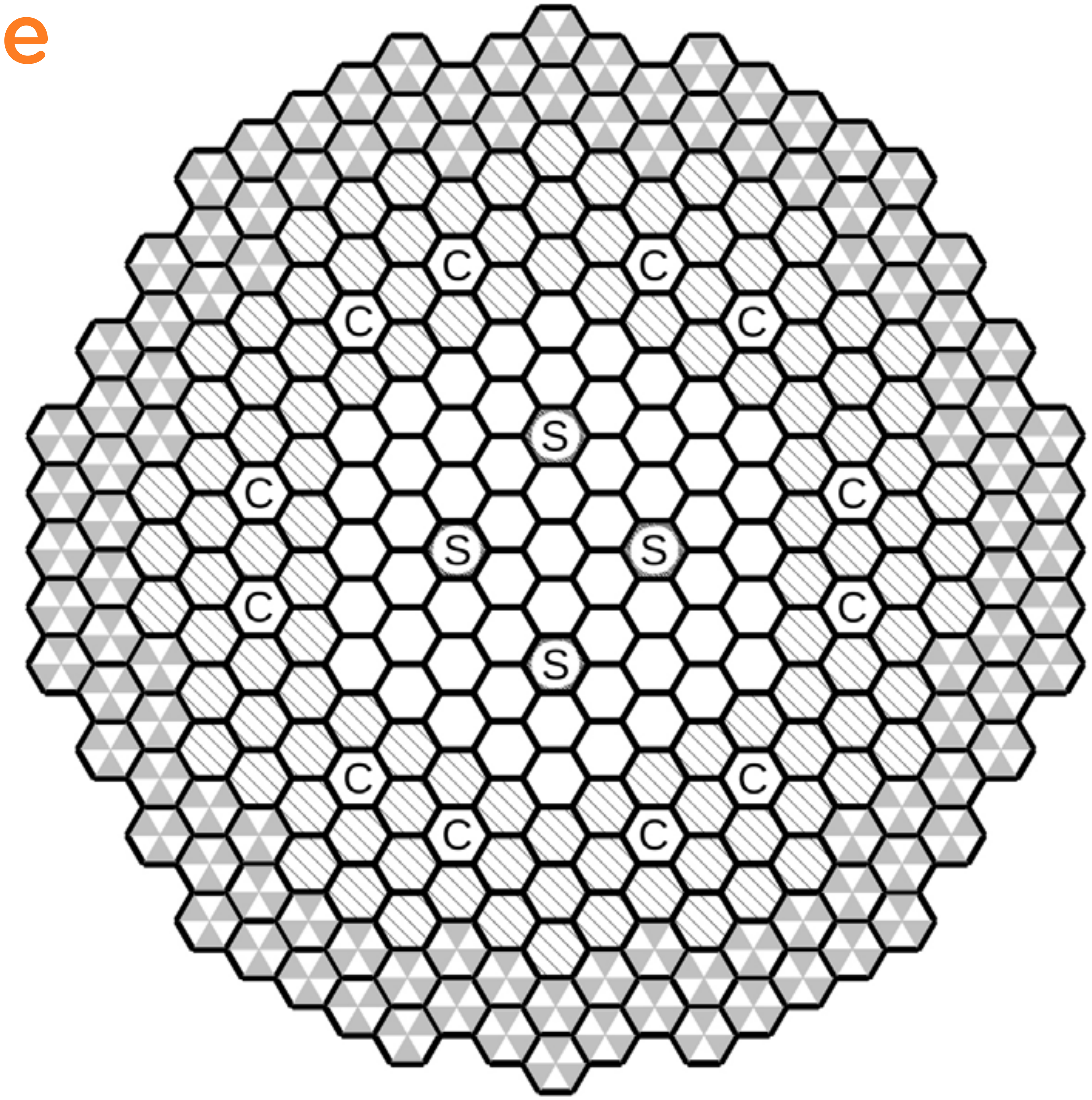
Slow dissolution of structural materials

Limited operational experience

ALFRED (EU): fuel subassembly

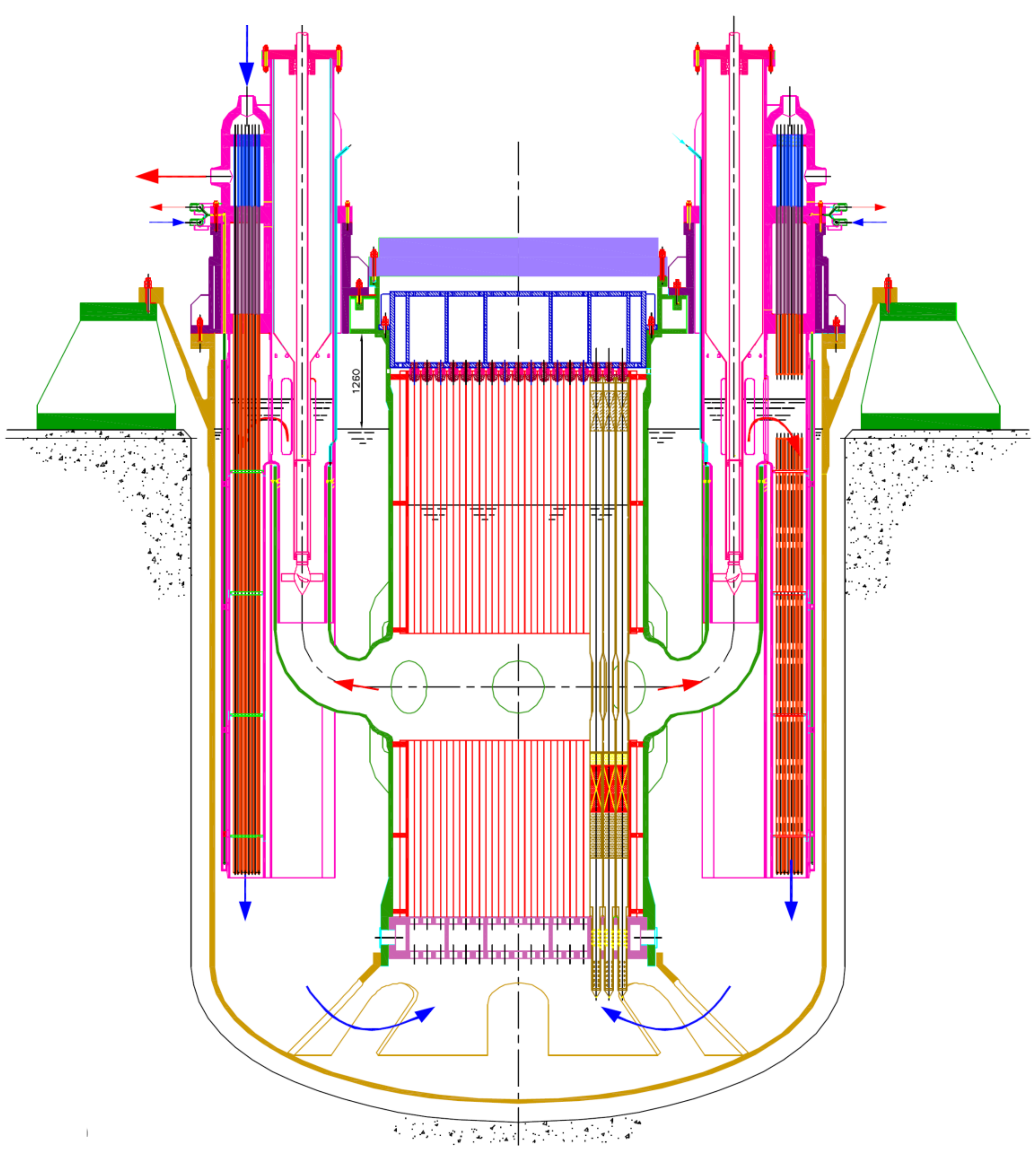


ALFRED (EU): core



- ⬡ Inner Fuel Assembly
- ▨ Outer Fuel Assembly
- Ⓒ Control Rod
- Ⓢ Safety Rod
- ⬡ Dummy Element (shield)

ALFRED (EU): primary system



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

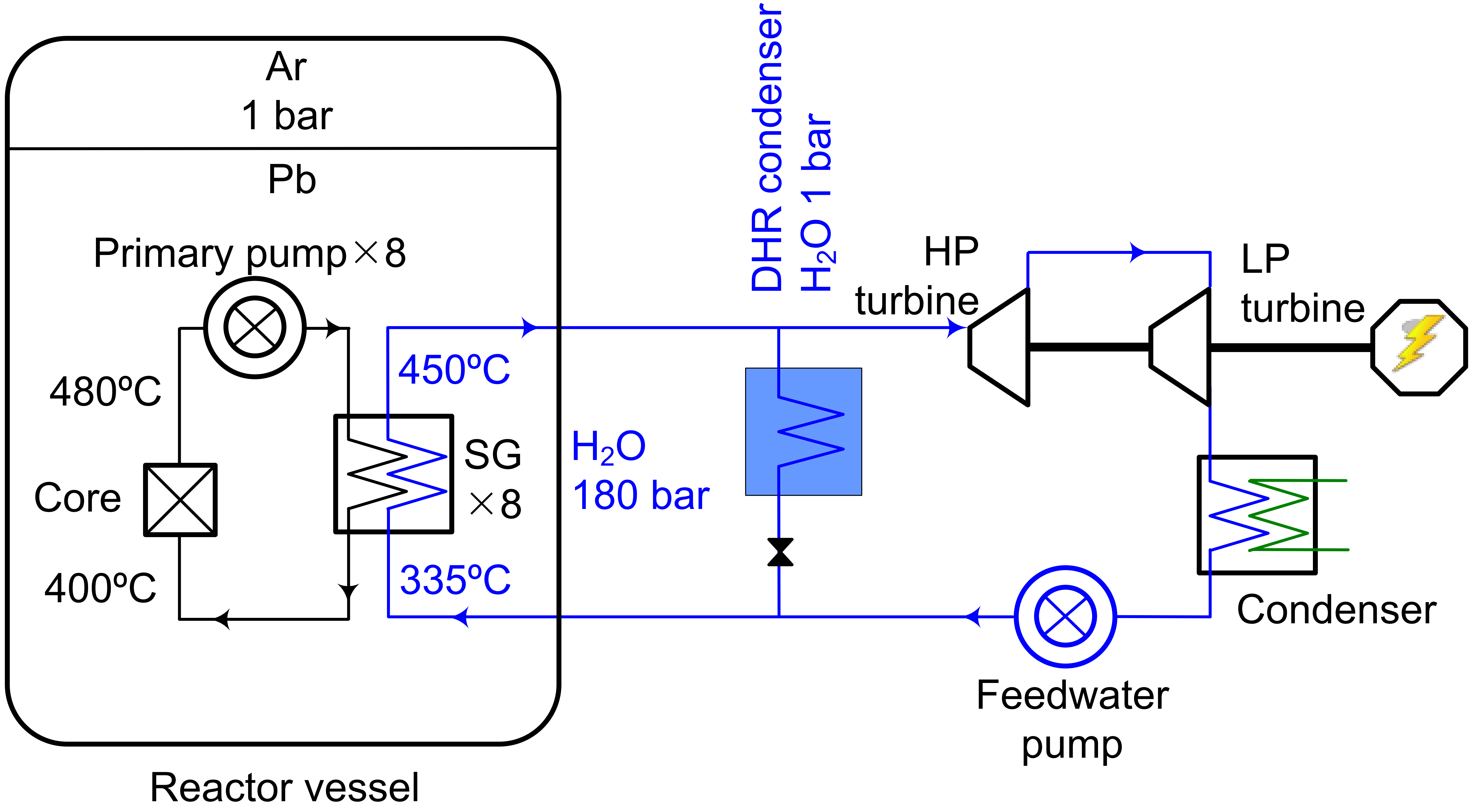
Primary pumps: mechanical, at hot leg

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

Power: 300 MWth
Fuel: $(U\text{-}Pu)O_2$
Clad: Stainless steel



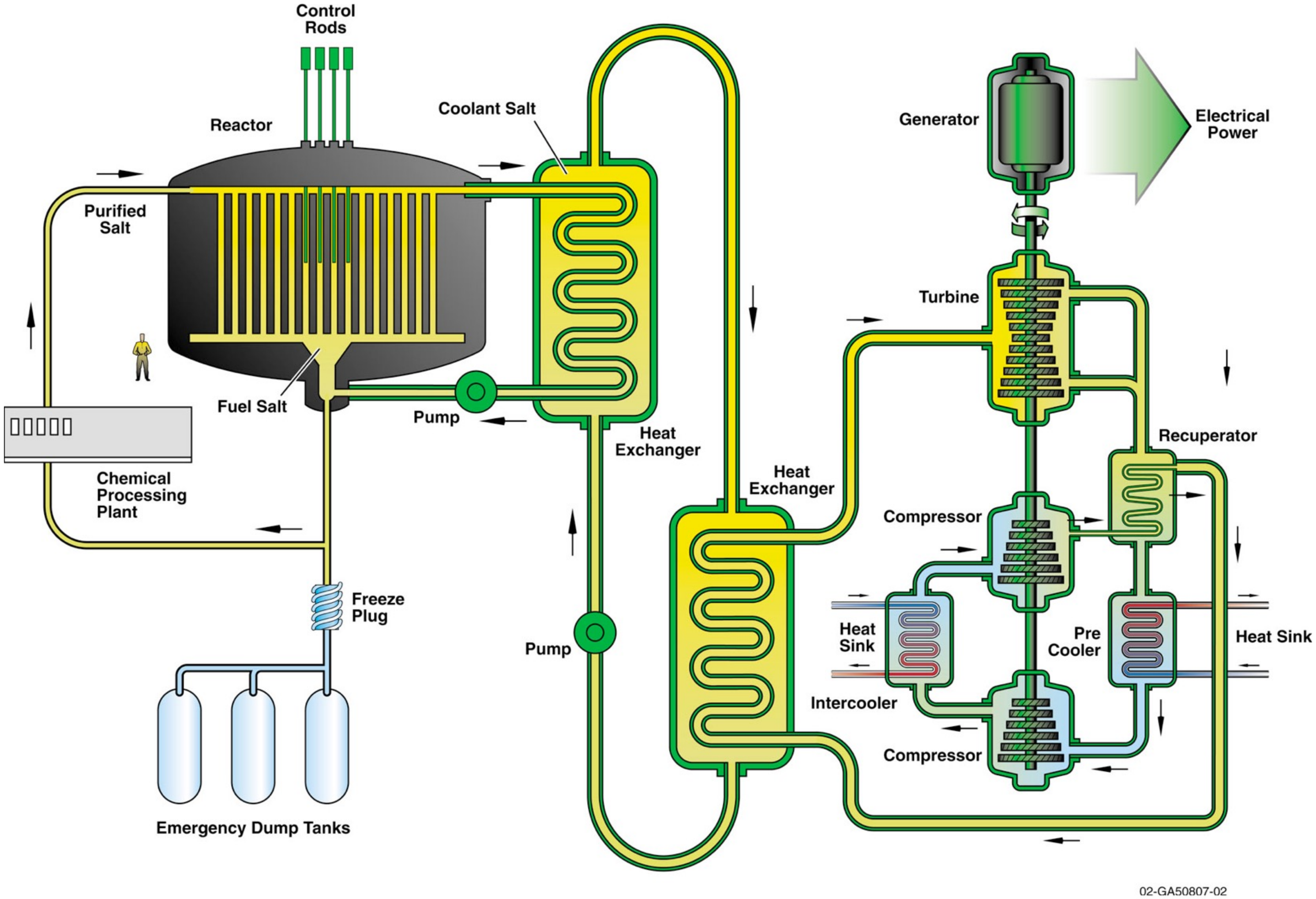
From Gen-III to Gen-IV: improvements to reach the goal(s)

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	↑	↑	?	↓	?

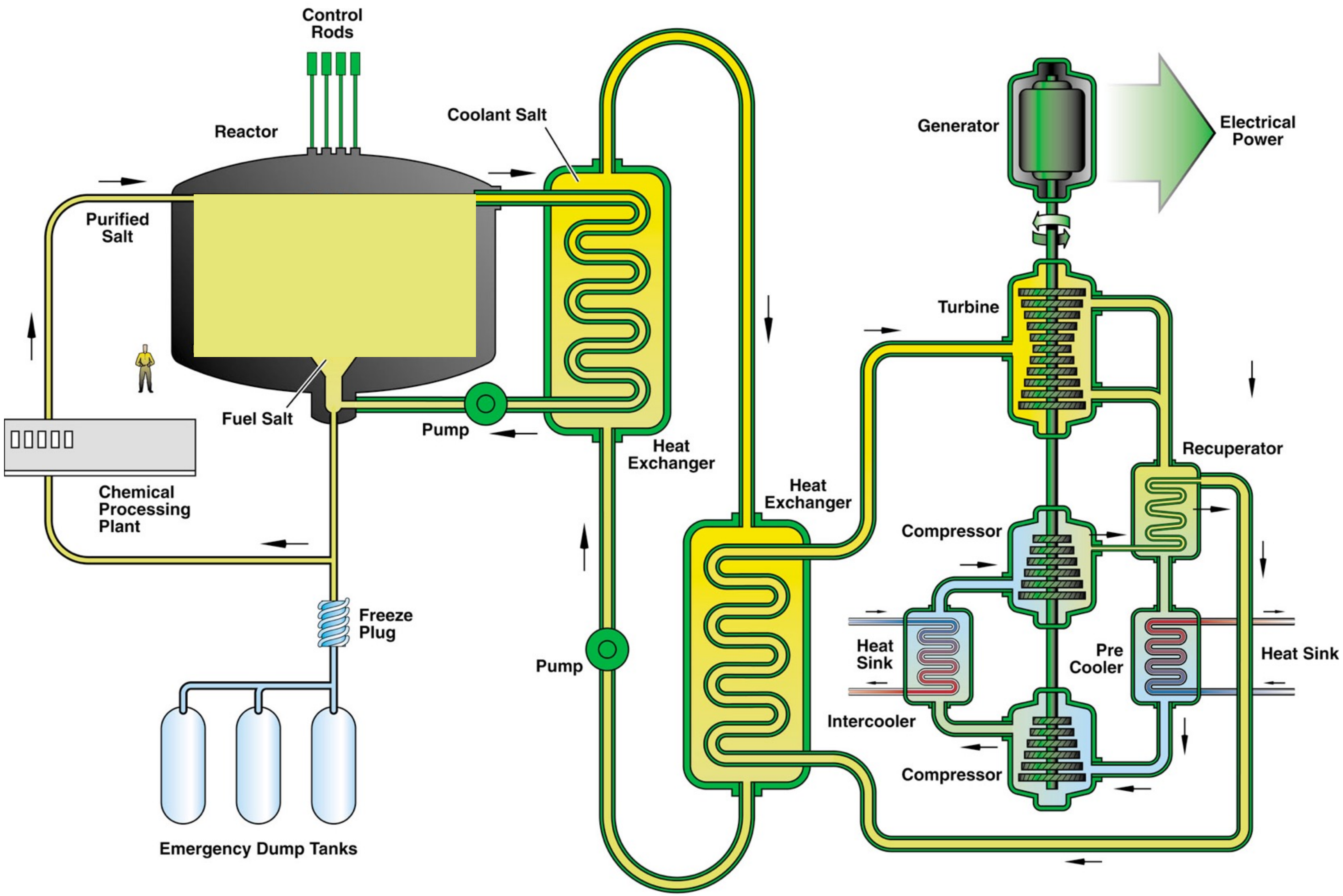
- In all considered systems the accidents with core meltdown has extremely low probability, but they are still possible. How to practically eliminate the core meltdown?

→

Molten Salt Reactor (thermal): concept



Molten Salt Reactor (fast): concept



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

- **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

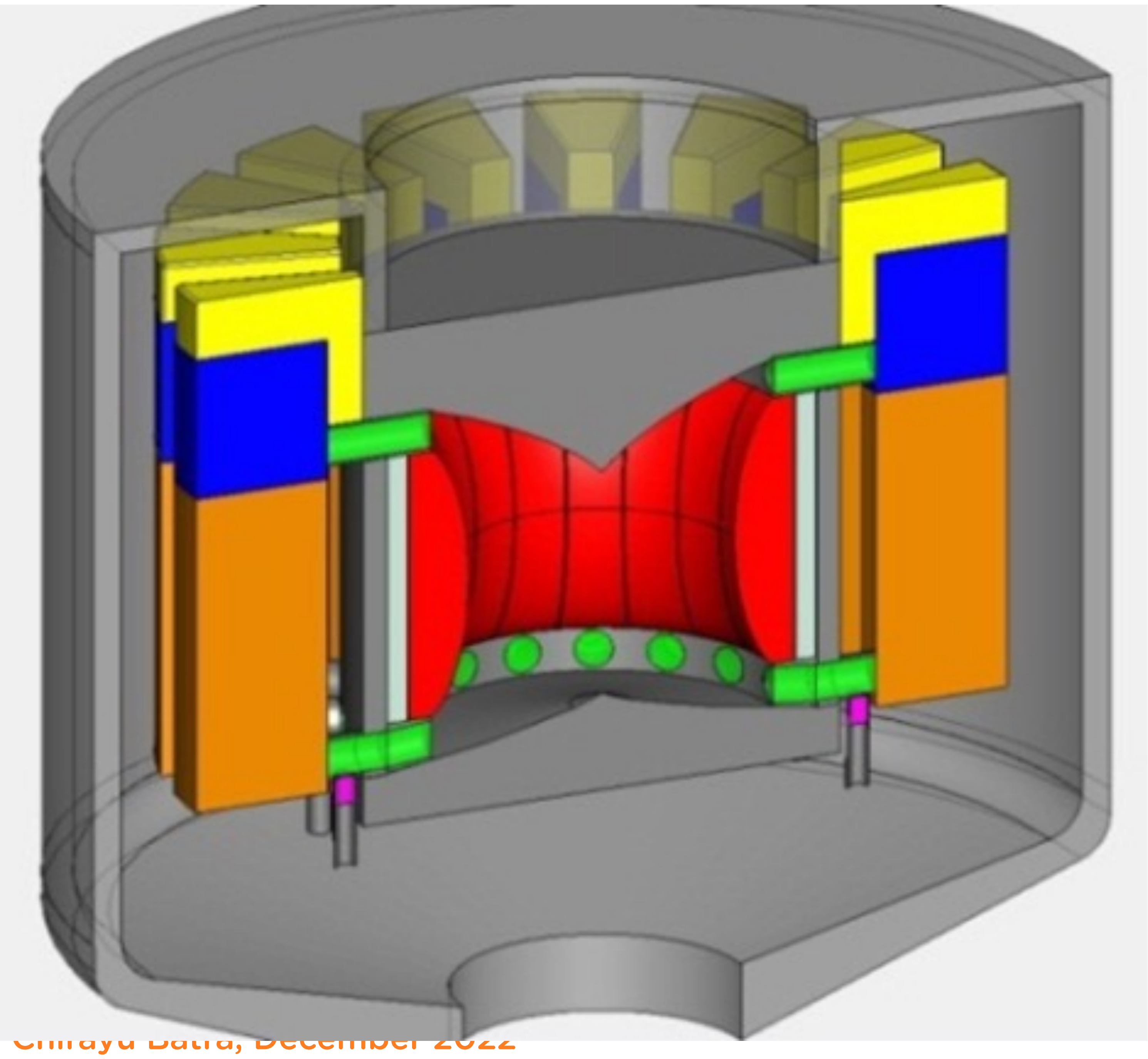
Fuel circuit includes:

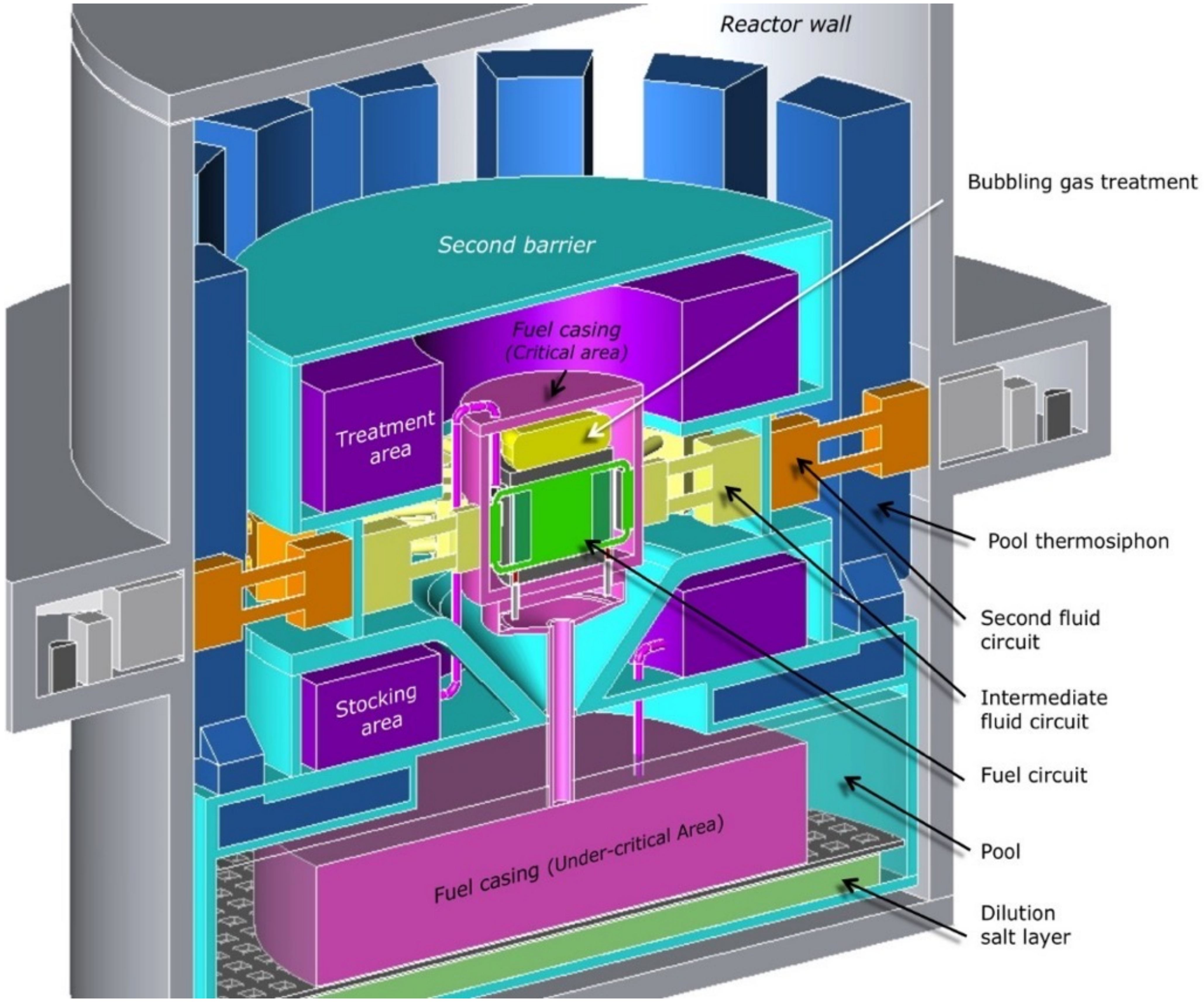
- core (open volume with shape optimized for fluid dynamics);
- 16 external recirculation loops, each includes
  - — pipes (cold and hot region);
  - — bubble separator;
  - — pump;
  - — heat exchanger;
  - — bubble Injection.

3 circuits:

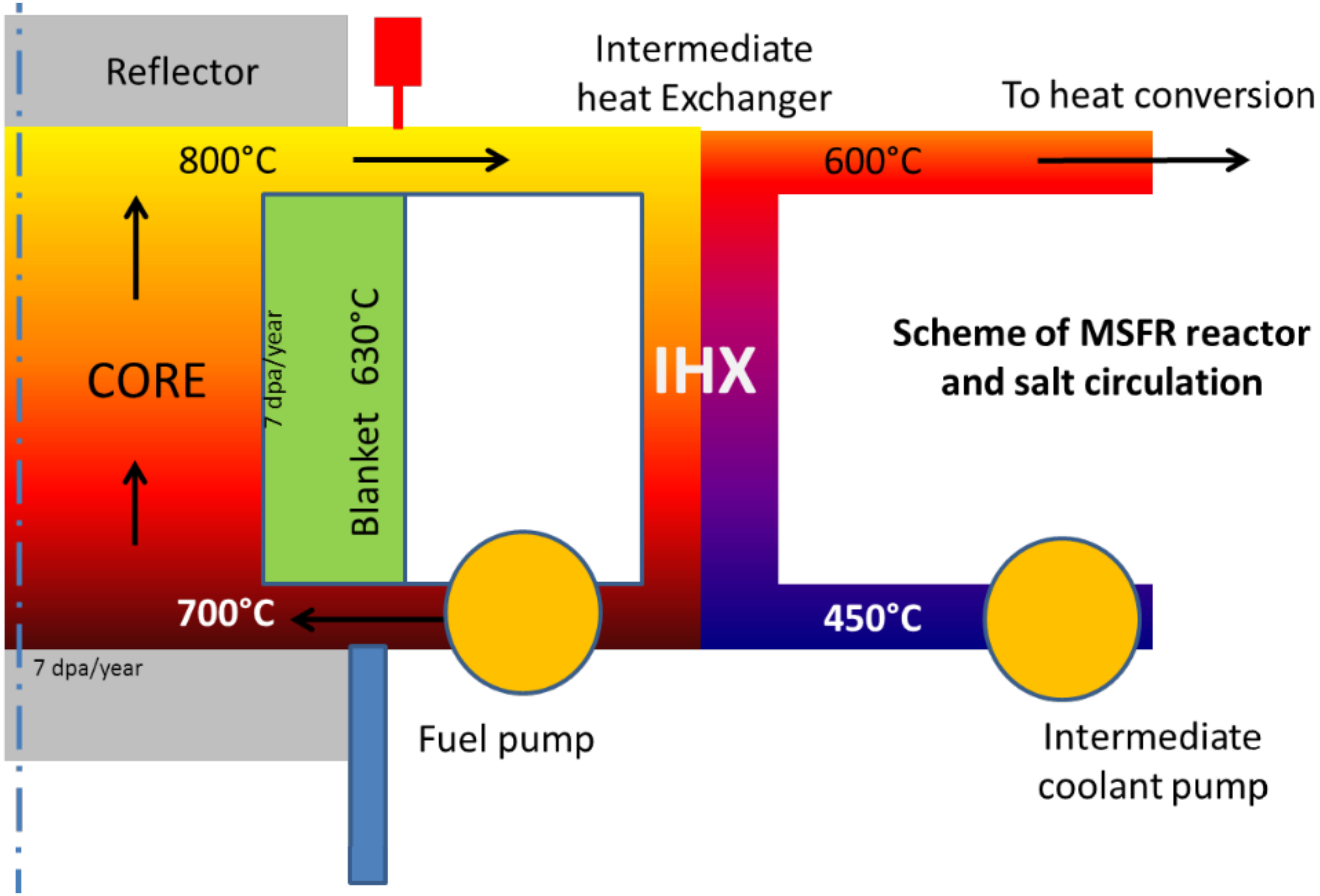
- — Fuel circuit
- — Intermediate circuit
- — Energy conversion system

+ Draining tanks

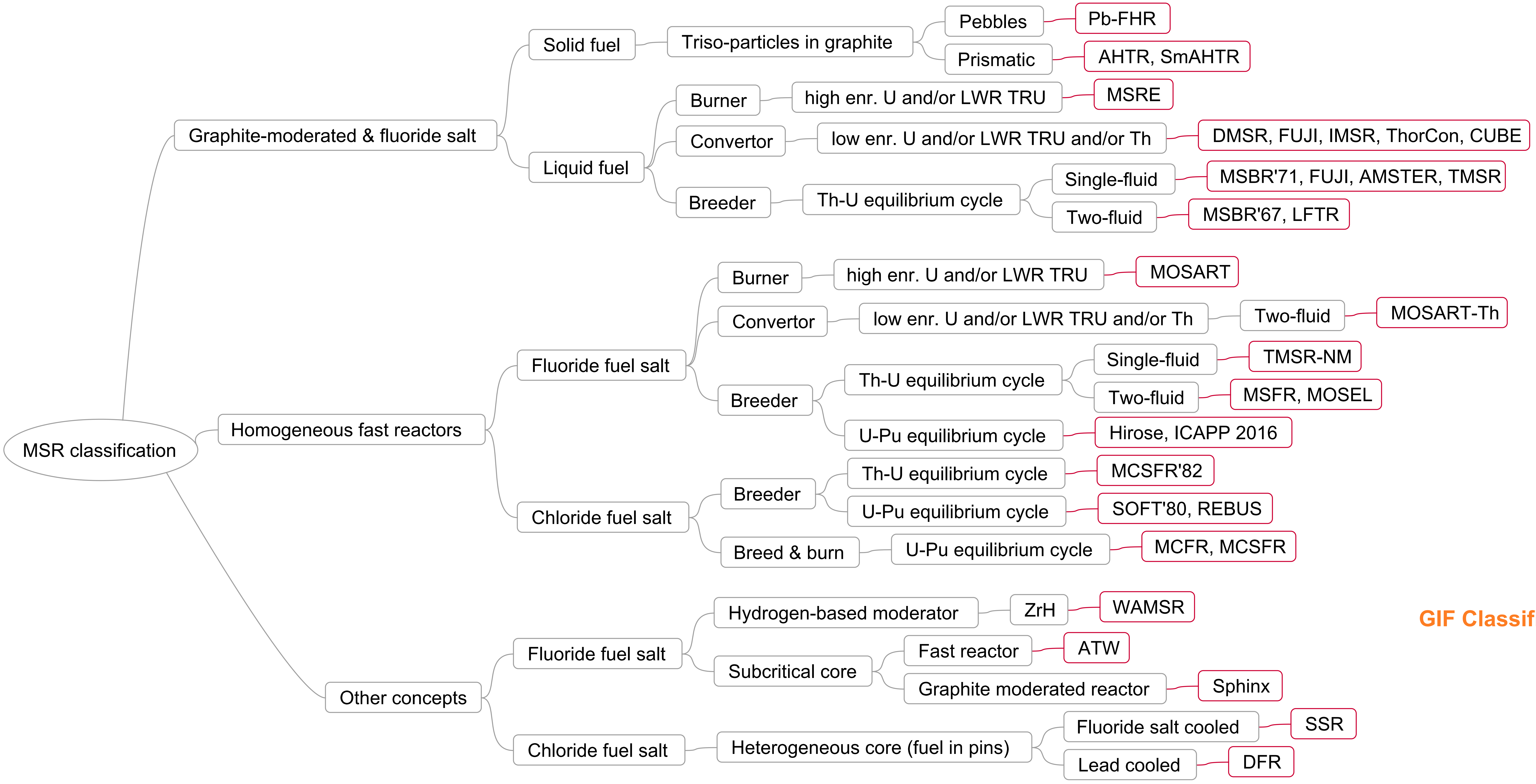




MSFR (EU): BoP concept



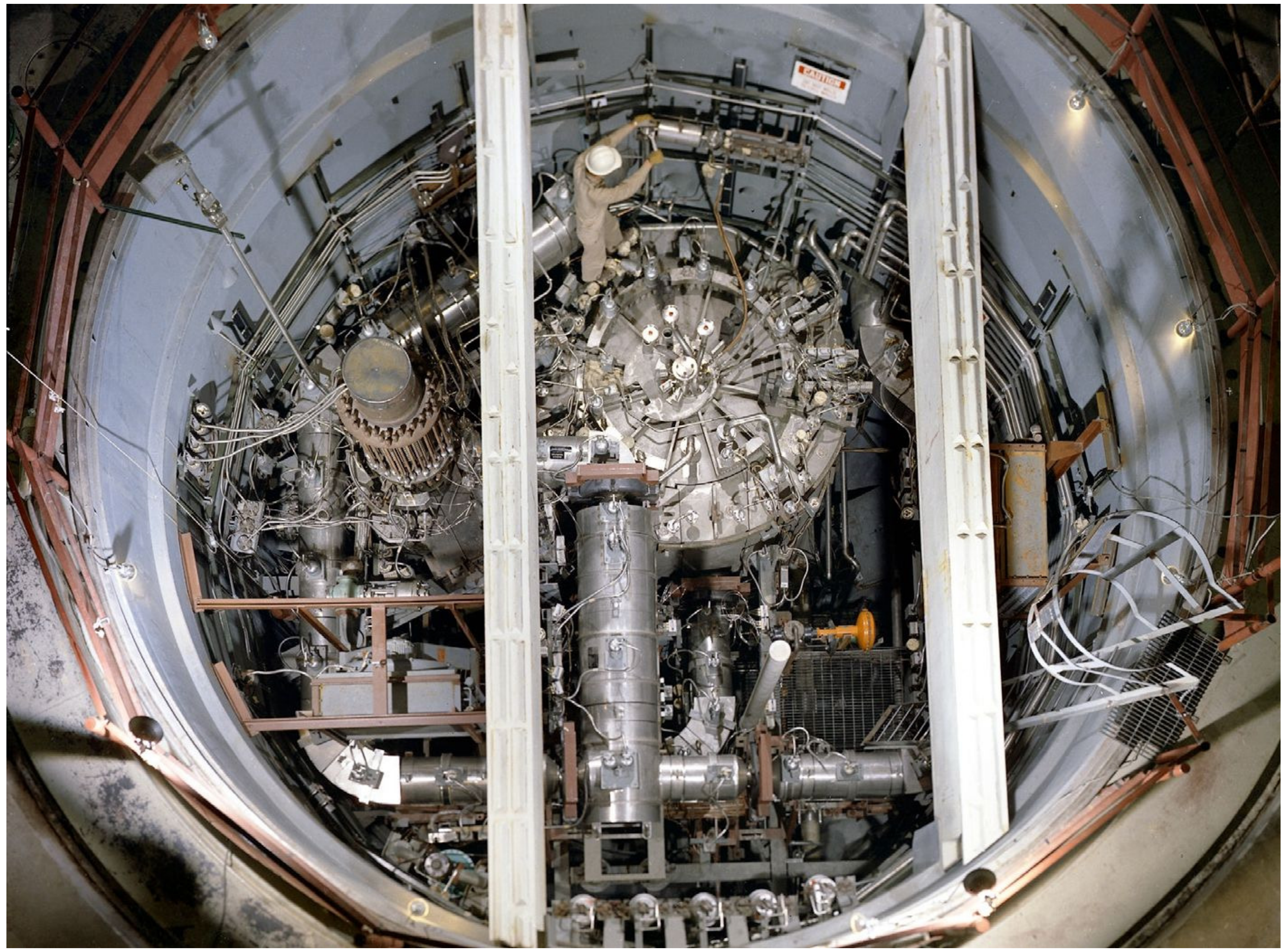
MSR: many concepts are currently studied

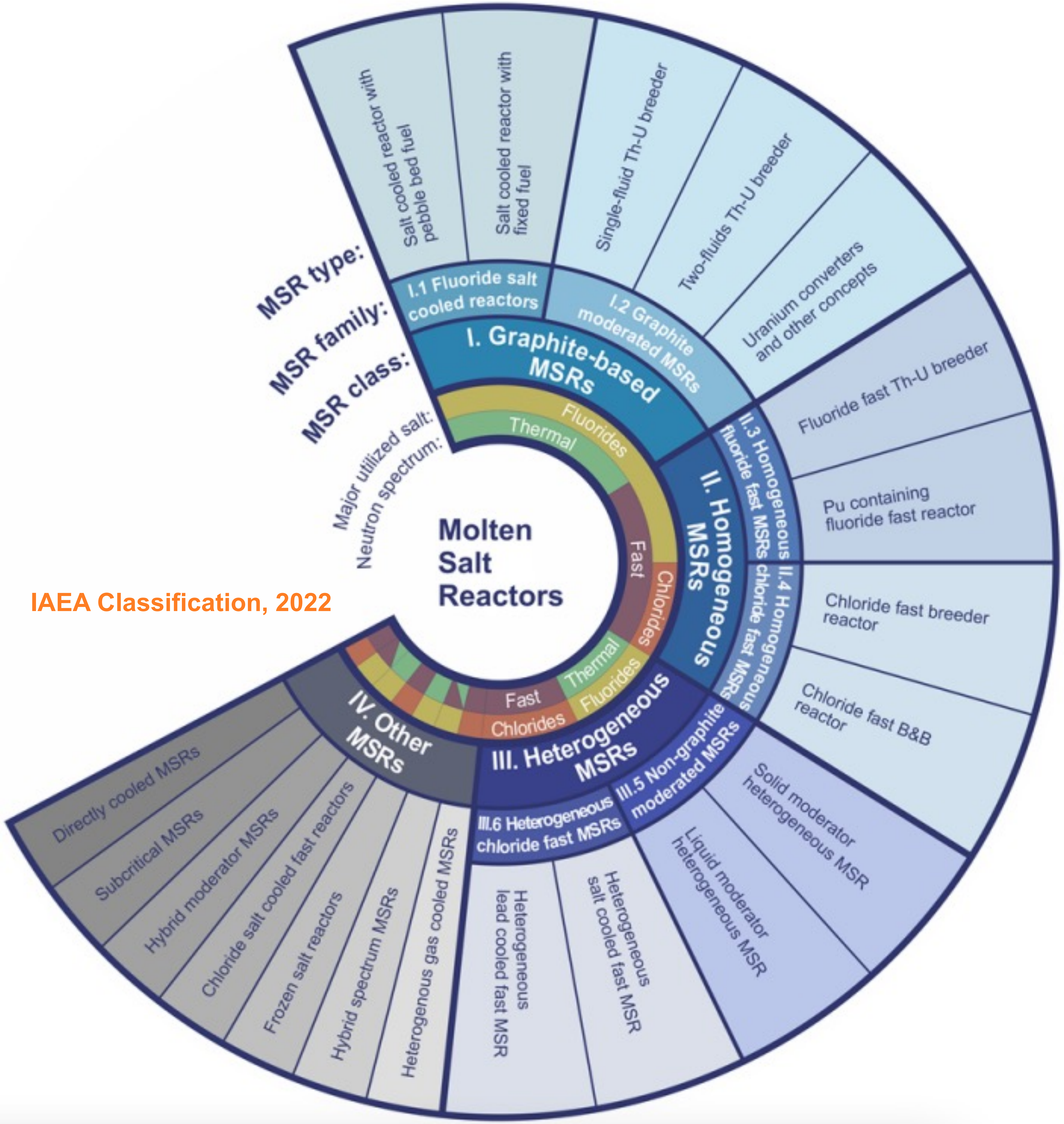


- MSR classification
  - Graphite-moderated & fluoride salt
    - Solid fuel
      - Triso-particles in graphite
        - Pebbles
          - Pb-FHR
        - Prismatic
          - AHTR, SmAHTR
    - Liquid fuel
      - Burner
        - high enr. U and/or LWR TRU
          - MSRE
      - Convertor
        - low enr. U and/or LWR TRU and/or Th
          - DMSR, FUJI, IMSR, ThorCon, CUBE
      - Breeder
        - Th-U equilibrium cycle
          - Single-fluid
            - MSBR'71, FUJI, AMSTER, TMSR
          - Two-fluid
            - MSBR'67, LFTR
  - Homogeneous fast reactors
    - Fluoride fuel salt
      - Burner
        - high enr. U and/or LWR TRU
          - MOSART
      - Convertor
        - low enr. U and/or LWR TRU and/or Th
          - Two-fluid
            - MOSART-Th
      - Breeder
        - Th-U equilibrium cycle
          - Single-fluid
            - TMSR-NM
          - Two-fluid
            - MSFR, MOSEL
        - U-Pu equilibrium cycle
          - Hirose, ICAPP 2016
    - Chloride fuel salt
      - Breeder
        - Th-U equilibrium cycle
          - MCSFR'82
        - U-Pu equilibrium cycle
          - SOFT'80, REBUS
      - Breed & burn
        - U-Pu equilibrium cycle
          - MCFR, MCSFR
  - Other concepts
    - Fluoride fuel salt
      - Hydrogen-based moderator
        - ZrH
          - WAMSR
      - Subcritical core
        - Fast reactor
          - ATW
        - Graphite moderated reactor
          - Sphinx
    - Chloride fuel salt
      - Heterogeneous core (fuel in pins)
        - Fluoride salt cooled
          - SSR
        - Lead cooled
          - DFR

GIF Classification, 2020

MSR Classification





IAEA Classification, 2022

MSR Classification

Class	I. Graphite based MSRs		II. Homogeneous MSRs		III. Heterogeneous MSRs	
Family	I.1 Fluoride salt cooled reactors	I.2 Graphite moderated MSRs	II.3 Homog. fluoride fast MSRs	II.4 Homog. chloride fast MSRs	III.5 Non-graphite moderated MSRs	III.6 Heterog. chloride fast MSRs
Fuel state	Solid	Liquid	Liquid	Liquid	Liquid	Liquid
Spectrum	Thermal	Thermal	Fast	Fast	Thermal	Fast
Salt type	Fluorides	Fluorides	Fluorides	Chlorides	Fluorides	Chlorides
Neutronics performance	Burner, Converter	Burner, Converter, Breeder	Burner, Converter, Breeder	Burner, Converter, Breeder, Breed & Burn	Burner, Converter, Breeder	Burner, Converter, Breeder, Breed & Burn
Actinides	Enriched U, TRU, Th as semi-inert matrix	Enriched U, TRU, closed Th-U cycle	Enriched U, TRU, closed Th-U cycle and U-Pu cycle	Enriched U, TRU, closed Th-U cycle, and U-Pu cycle	Enriched U, TRU, closed Th-U cycle	Enriched U, TRU, closed Th-U cycle, and U-Pu cycle
Irradiation induced issues	Limited burnup of fuel in graphite matrix	Limited graphite moderator lifespan	Limited vessel lifespan	Limited vessel lifespan	Limited vessel and str. material lifespan	Limited vessel and str. material lifespan
Fuel extensive pumping	No	Yes	Yes	Yes	Yes (No if cooled by moderator)	No
Heat transp. medium	Fluoride coolant salt	Fluoride fuel salt	Fluoride fuel salt	Chloride fuel salt	Fluoride fuel salt (or moderator)	Molten salt or lead coolant
Primary heat exchange	In core	Ex. core	Ex. core	Ex. core	Ex. core (In core)	In core

Summary

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**
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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
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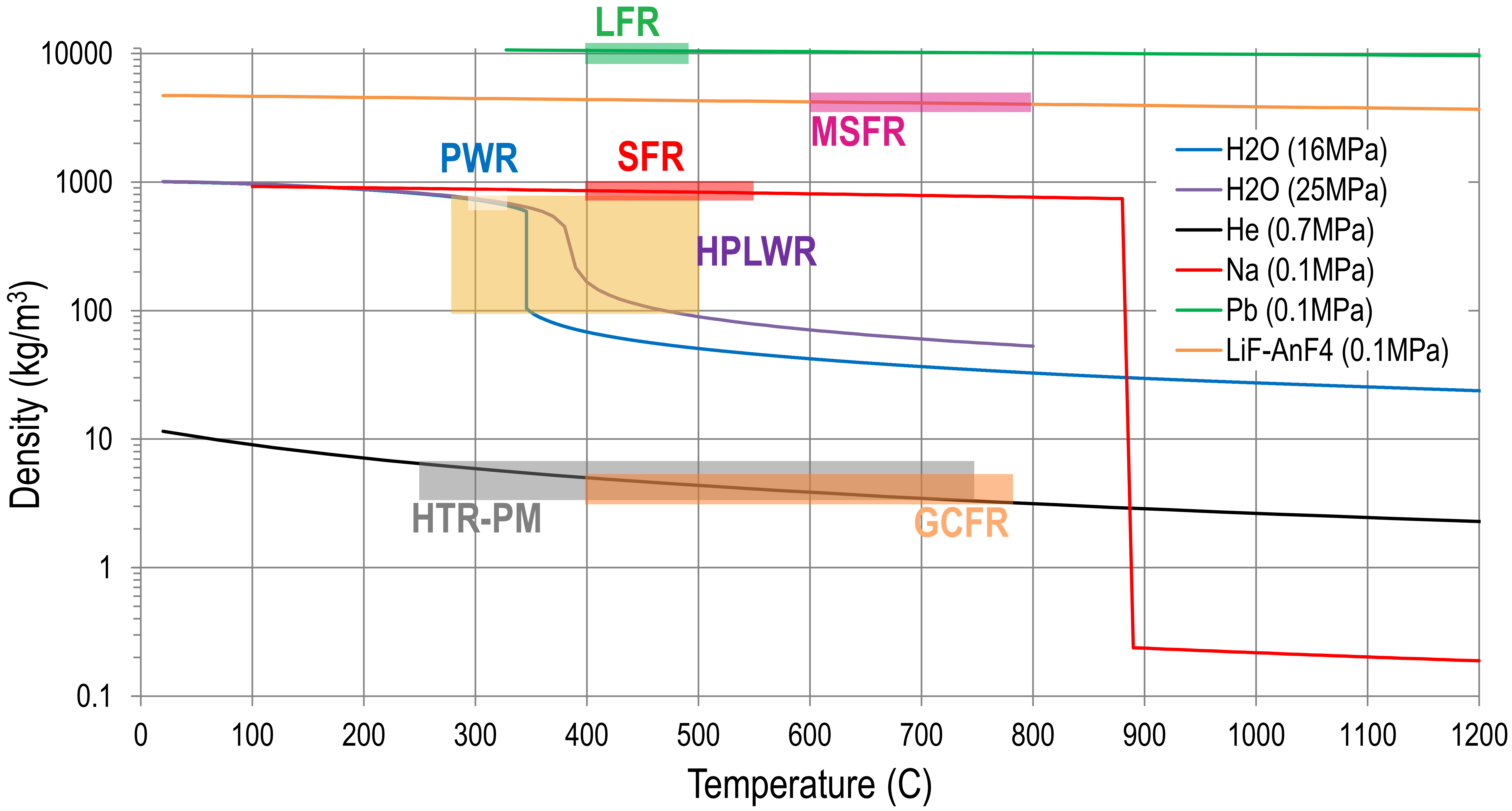
Reference	[1]	[2]	[3]	[4]	[5]	[6]	[7]
G1: Sustainability	Poor	↔	?	↑	↑	↑	↑
G2: Safety & reliability	Good	↓	↑	↓	↓↑	↓↑	?
G3: Economics	Good	↑	↑	?	↓	?	?

*Specific designs chosen by lecturer

Coolant densities and operational ranges of GIF reactors



- What conclusions can we derive from this plot?

References

1. R. Leverenz, L. Gerhard, A. Göbel, "The European Pressurized Water Reactor: A Safe and Competitive Solution for Future Energy Needs", Proc. of International Conference Nuclear Energy for New Europe 2004, Portorož , Slovenia, September 6-9, 2004.
2. T. Schulenberg, J. Starflinger, P. Marsault, D. Bittermann, C. Maráczy, E. Laurien, J.A. Lycklama à Nijeholt, H. Anglart, M. Andreani, M. Ruzickova, A. Toivonen, "European supercritical water cooled reactor", Nuclear Engineering and Design 241 (2011) 3505– 3513.
3. Z. Zhang, Y. Dong, F. Li, Z. Zhang, H. Wang, X. Huang, H. Li, B. Liu, X. Wu, H. Wang, X. Diao, H. Zhang, J. Wang, "The Shandong Shidao Bay 200 MWe High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: An Engineering and Technological Innovation", Engineering 2 (2016) 112–118.
4. R. Stainsby, K. Peers, C. Mitchell, C. Poette, K. Mikityuk, J. Somers, "Gas Cooled Fast Reactor research in Europe". Nuclear Engineering and Design 241 (2011), 3481-3489.
5. K. Mikityuk, E. Girardi, J. Krepel, E. Bubelis, E. Fridman, A. Rineiski, N. Girault, F. Payot, L. Buligins, G. Gerbeth, N. Chauvin, C. Latge, J.-C. Garnier, "ESFR-SMART: new Horizon-2020 project on SFR safety", IAEA-CN245-450, Proceedings of International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable, Development FR17 conference, 26-29 June 2017, Yekaterinburg, Russia.
6. P. Lorusso, S. Bassini, A. Del Nevo, I. Di Piazza, F. Giannetti, M. Tarantino, M. Utili, "GEN-IV LFR development: Status & perspectives", Progress in Nuclear Energy 105 (2018) 318–331.
7. B. Hombourger "Conceptual Design of a Sustainable Waste-BurningMolten Salt Reactor", EPFL, PhD thesis, 2018.

Thank you🙏

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> *“I have been driven by the conviction that much more than 1 percent of the energy contained in uranium must be utilized if nuclear power is to achieve its real long-term potential.”*
>
> - Enrico Fermi

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