IAEA
International Atomic Energy Agency

"Atoms for Peace and Development"

IAEA Interregional Workshop on Advances in Design of Generation-IV SMRs
Beijing, 3-7 June 2024

Progress in Technology of Innovative Reactors and SMRs

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FastRTeam

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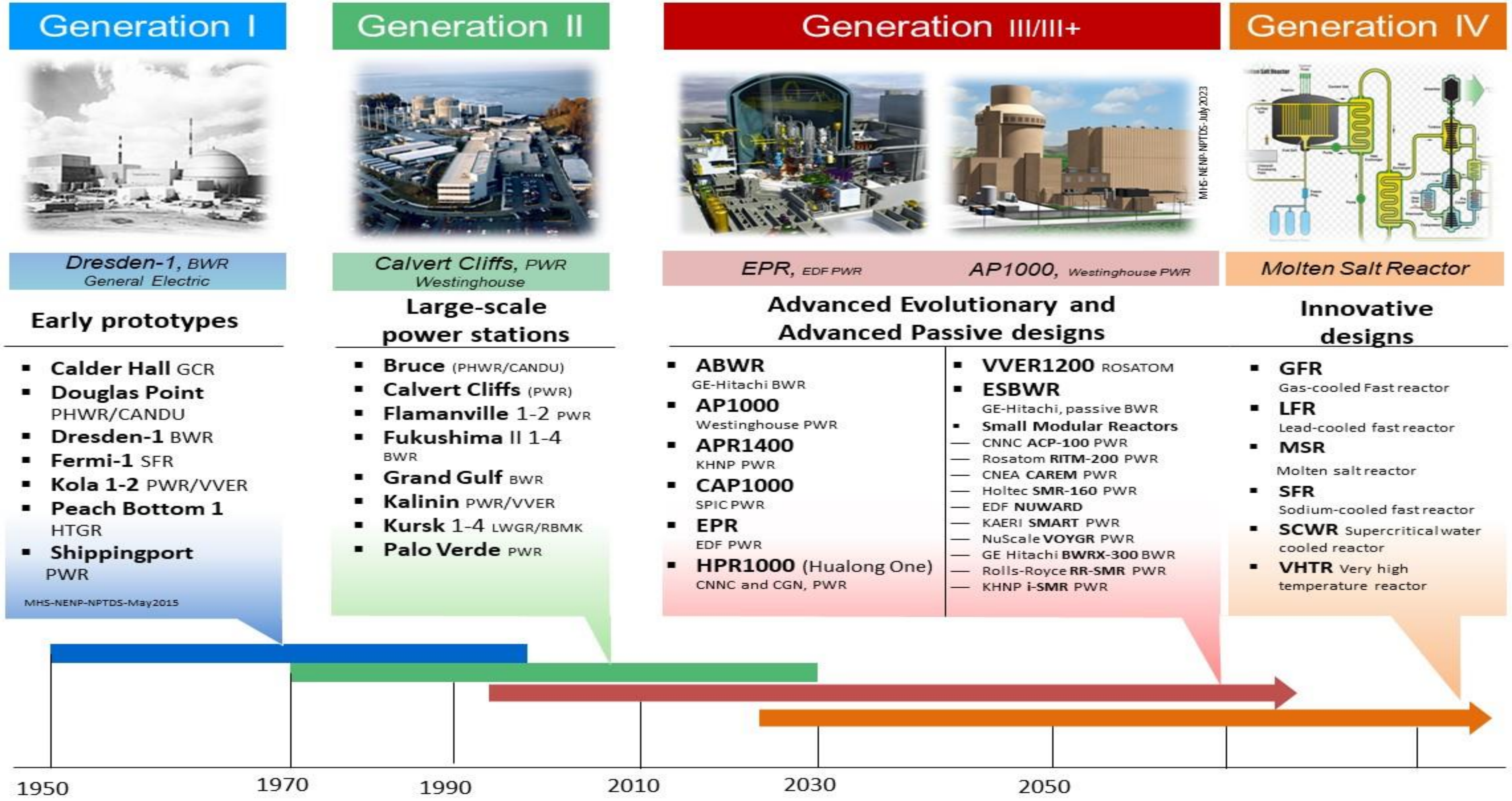
Outline

- Reactor Classification and Innovative Nuclear Energy Systems Systems
- Gen-IV Systems and IAEA Terminology
- Six GIF Gen-IV reactor concepts and other innovative systems
  - *Super Critical Water cooled Reactor (SCWR)*
  - *Very High Temperature Reactor (VHTR)*
  - *Gas cooled Fast Reactor (GFR)*
  - *Sodium cooled Fast Reactor (SFR)*
  - *Lead and LBE cooled Fast Reactor (LFR)*
  - *Molten Salt cooled Reactor (MSR)*
- Fast Reactors: World Status
- Innovative SMRs
- IAEA Advanced Reactors Information System (ARIS)

Evolution of Nuclear Power Reactor Technology



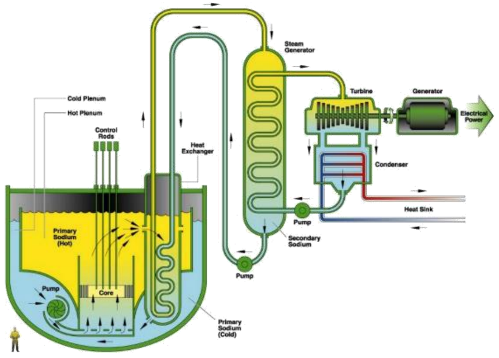
Classification of Nuclear Fission Reactors

- Moderator
  - Water / Heavy Water
  - Graphite
  - None (fast neutron systems)
- Coolant
  - Water/Heavy Water
  - Liquid Metal
    - Sodium/Lead/Lead-Bismuth Eutectic (LBE)
  - Gas
    - Air
    - CO_2
    - He
  - Molten Salt
    - Fluoride
    - Chloride
- Fuel
  - UO2
  - MOX (UO_2 + PuO_2)
  - Metallic
  - U/Pu Nitride
  - U/Pu Carbide
  - Molten Salt
- Purpose
  - Electricity Generation
  - Non-Electric Application
    - District Heating
    - Water Desalination
    - Industrial Purposes
    - H_2 Production
- Power
  - Low/Middle/High

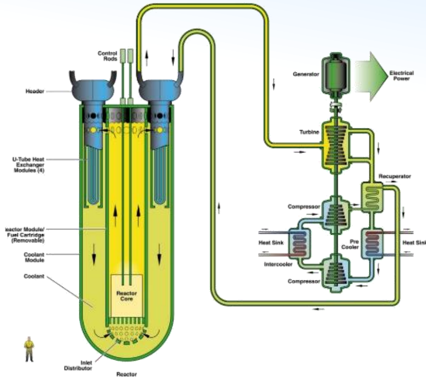
Terminology of Gen-IV Innovative Reactors

- **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/

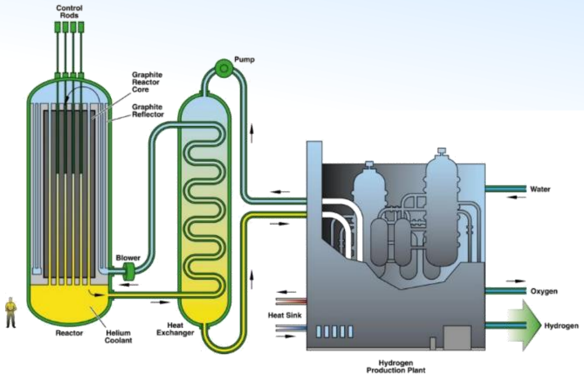
Sodium cooled Fast Reactor (SFR)

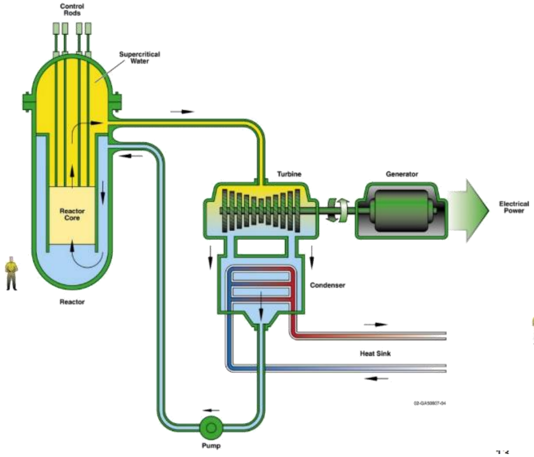


Lead cooled Fast Reactor (LFR)

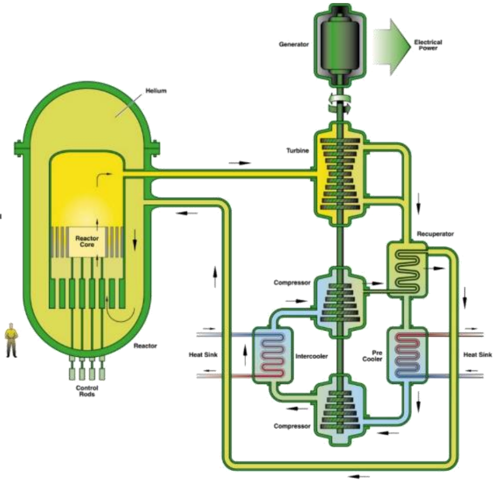


Very-High-Temperature Reactor (VHTR)

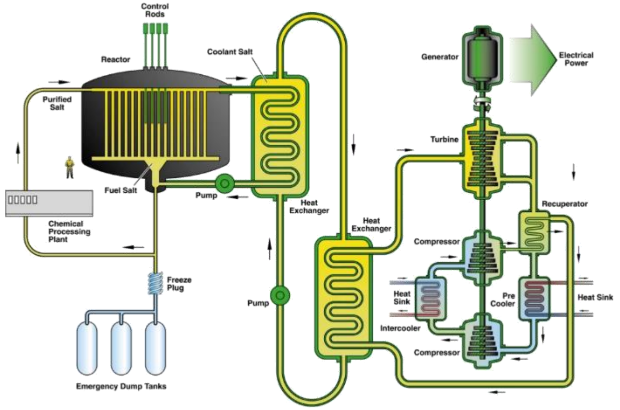




Supercritical Water cooled Reactor (SCWR)



Gas cooled Fast Reactor (GFR)



Molten Salt Reactor (MSR)

GIF website: www.gen-4.org

GIF: Goals for Gen-IV Nuclear Energy Systems

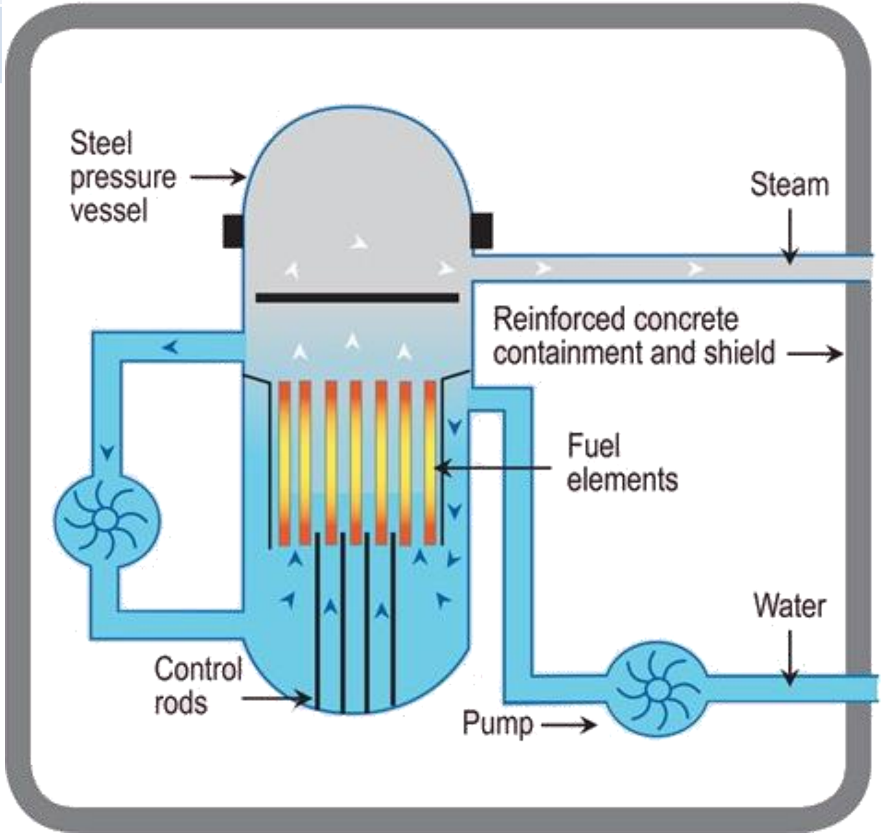
Sustainability-1	Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production.
Sustainability-2	Generation IV nuclear energy systems will minimise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

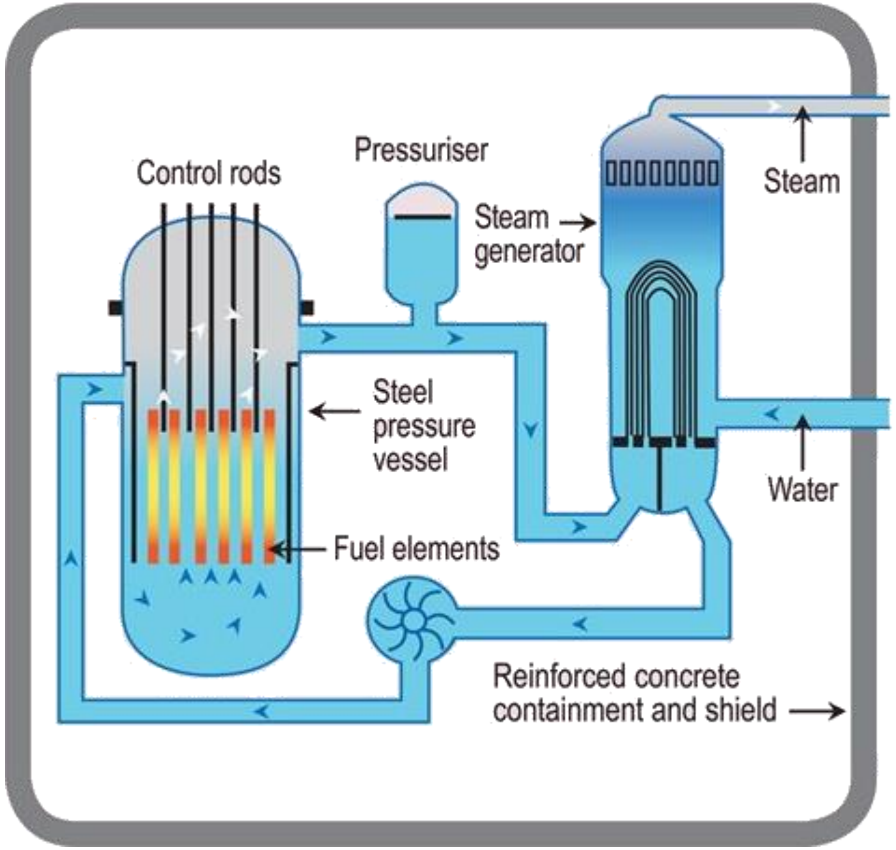
See at: www.gen-4.org

Water Cooled Reactors

	WCR
coolant	H_2O/D_2O
outlet T, C	288-329
efficiency, %	35
max P, MPa	7-17
spectrum	thermal

- *Mature Technology*
- *Low T => Low Efficiency*
- *High Pressure => safety issues*
- *Only thermal spectrum => not sustainable*

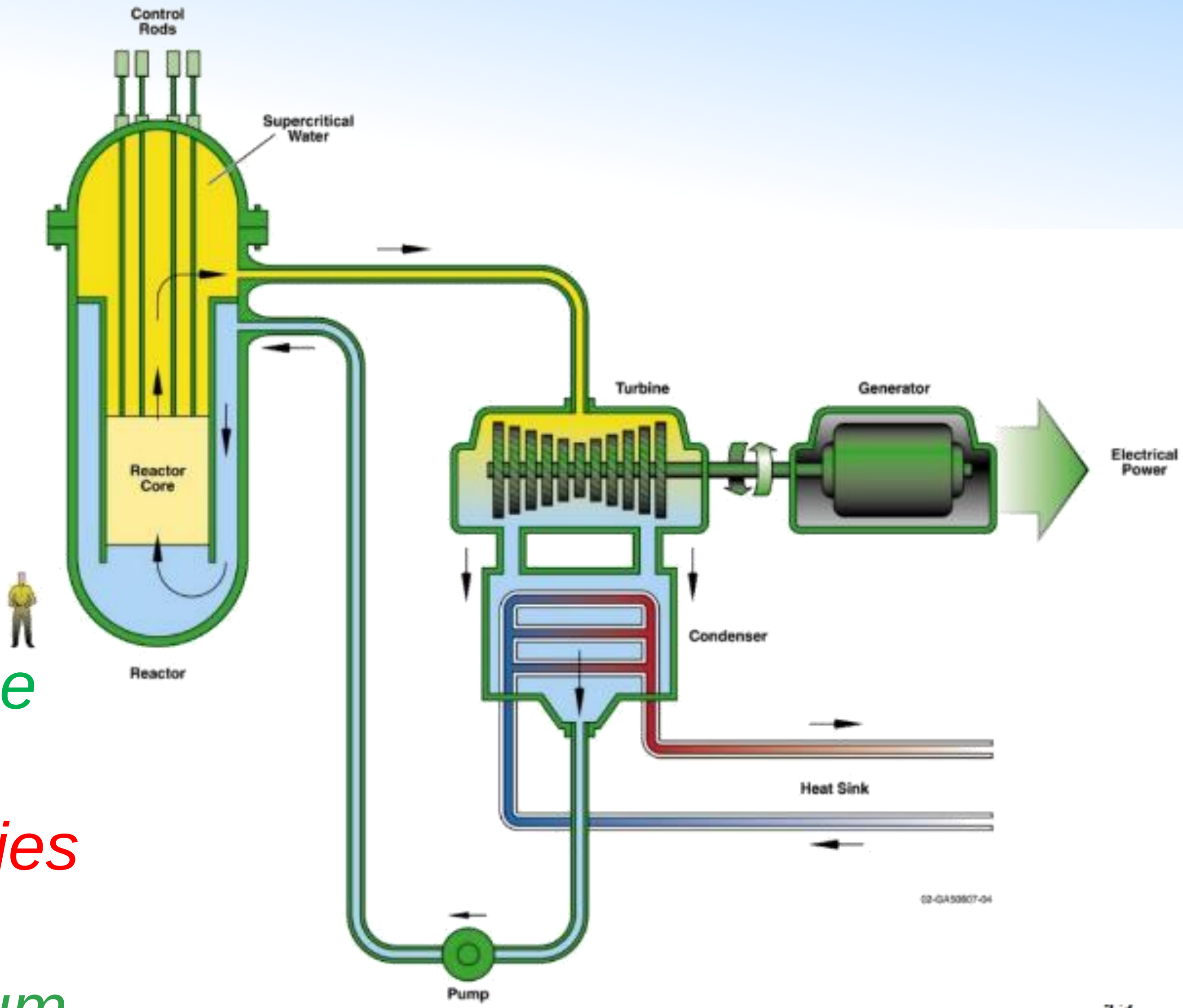




Super-Critical-Water cooled Reactor

	WCR	SCWR
coolant	H_2O	H_2O
outlet T, C	288-329	500
efficiency, %	35	45
max P, MPa	17	25
spectrum	thermal	thermal/fast

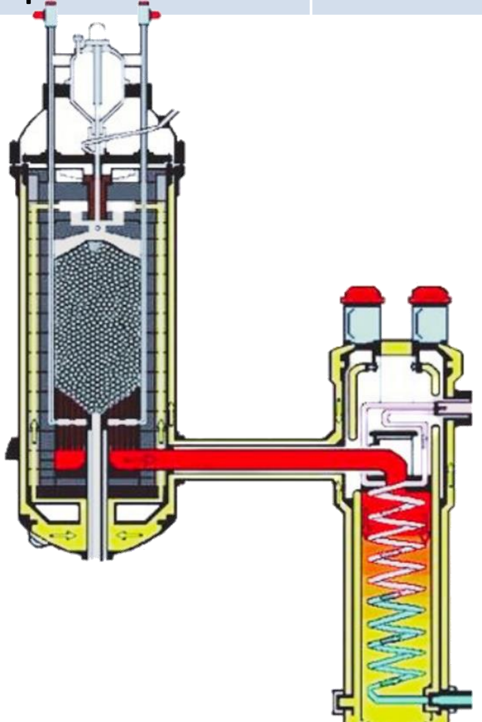
- *Known Technology*
- *Hight T => High Efficiency*
- *Single Loop; High Pressure Turbine*
- *High Pressure => safety issues*
- *Sharp Change of Physical Properties Near Critical Point*
- *Sustainable if works in fast spectrum*

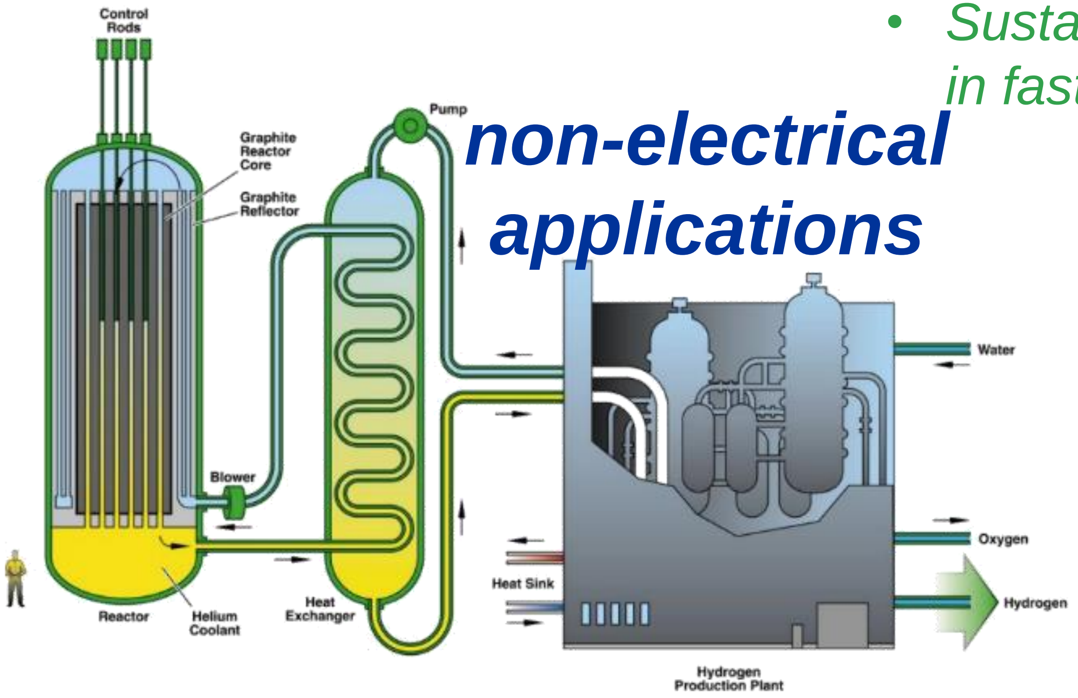


Gas cooled Reactors (HTGR, VHTR, GFR)

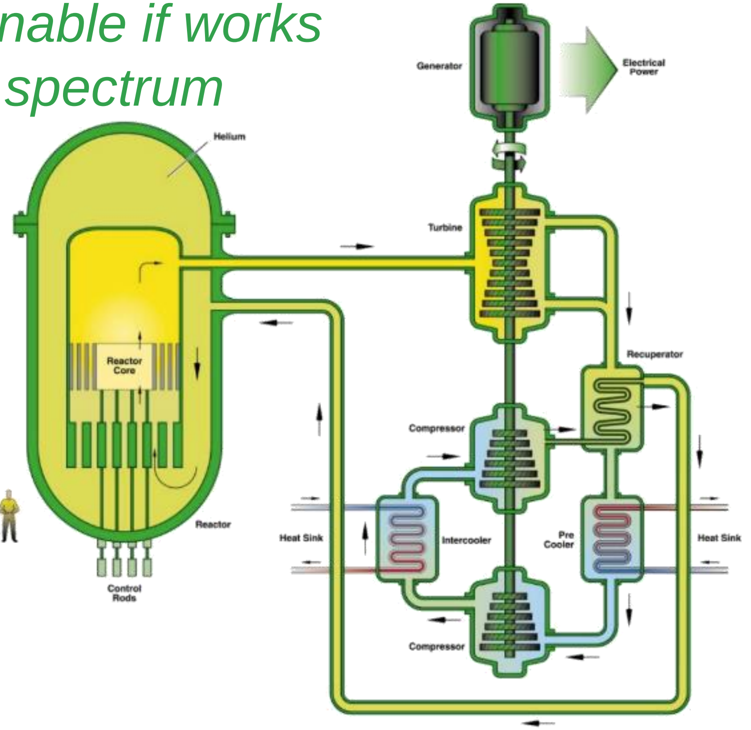
	WCR	SCWR	HTGR	GFR
coolant	H_2O	H_2O	He	He
outlet T, C	288-329	500	750	750
efficiency, %	35	45	50	50
max P, MPa	17	25	7	7
spectrum	thermal	thermal/fast	thermal	fast

- *New Technology*
- *Hight T => High Efficiency*
- *Direct Gas Turbine Brayton Cycle*
- *Low Voiding Reactivity*
- *High Pressure => safety issues*
- *Low Density*
- *Non-condensable*
- *Low Thermal Inertia*
- *Sustainable if works in fast spectrum*





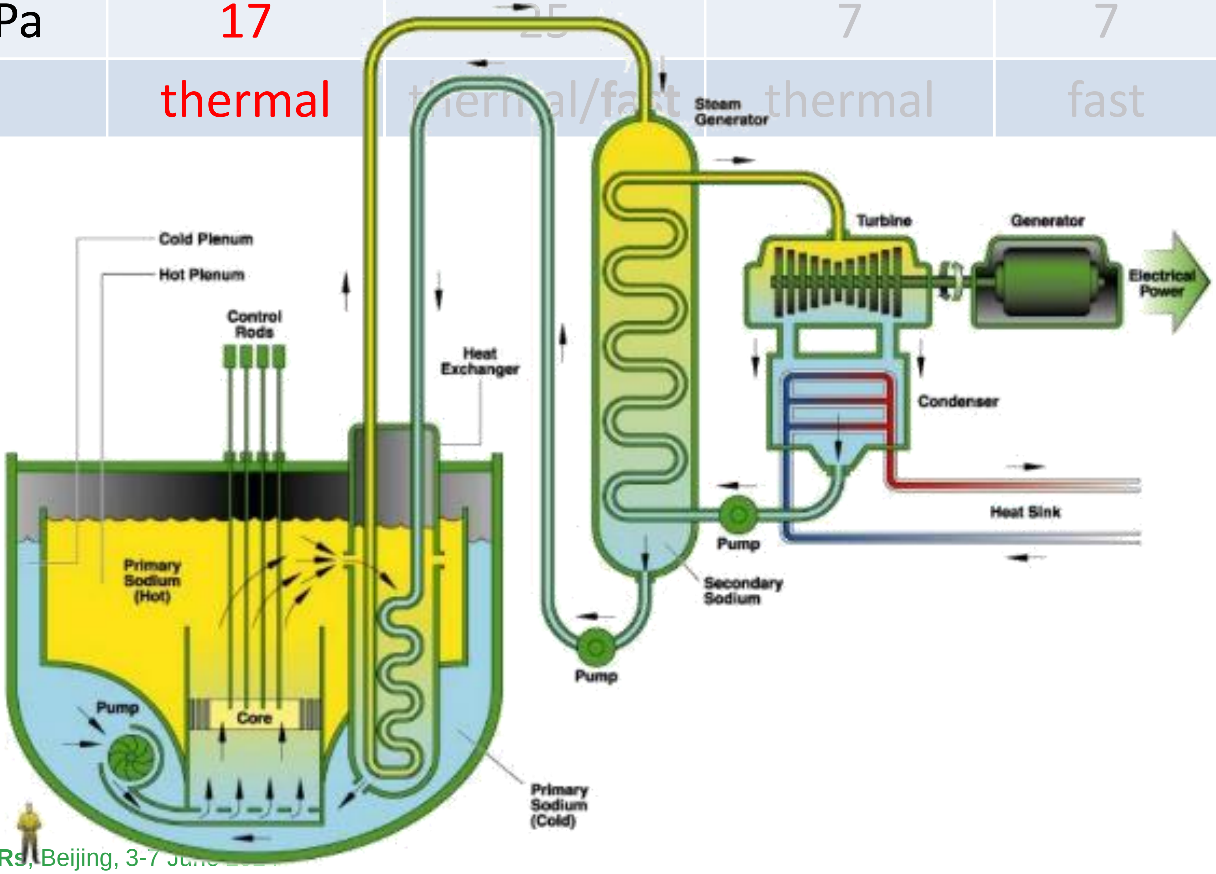
non-electrical applications



Sodium cooled Fast Reactor

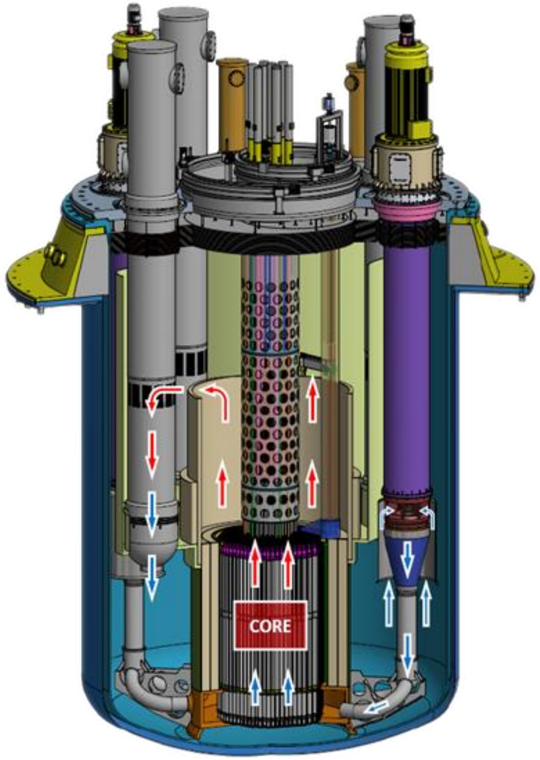
	WCR	SCWR	HTGR	GFR	SFR
coolant	H_2O	H_2O	He	He	Na
outlet T, C	288-329	500	750	750	550
efficiency, %	35	45	50	50	45
max P, MPa	17	25	7	7	~0.2
spectrum	thermal	thermal/fast	thermal	fast	fast

EBR-I 1951



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

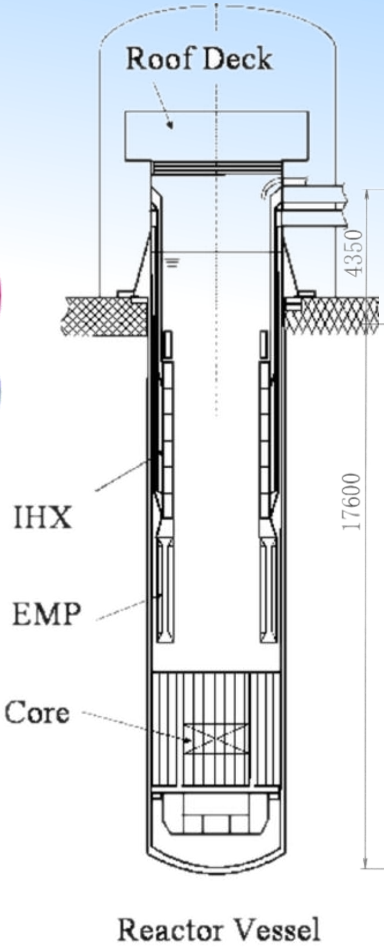
Sodium cooled Fast SMRs



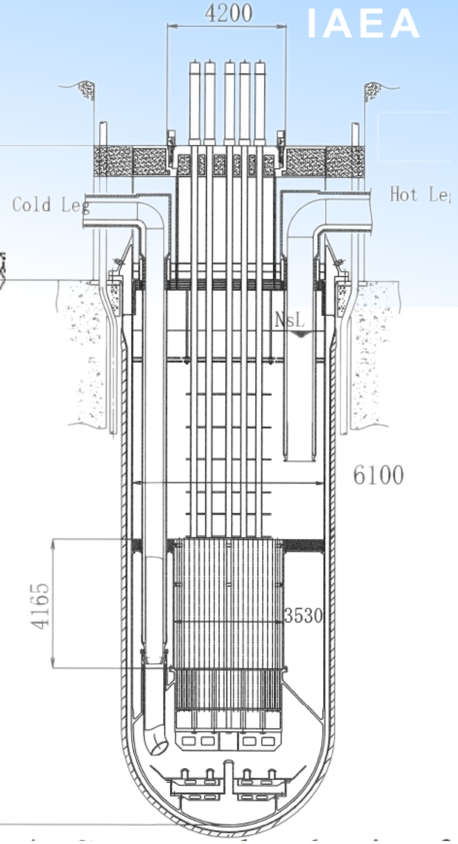
150 MW(e) PGSFR
Rep. of Korea

400 MW(th) HEXANA
France

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



50 MW(e) SMFR
Japan

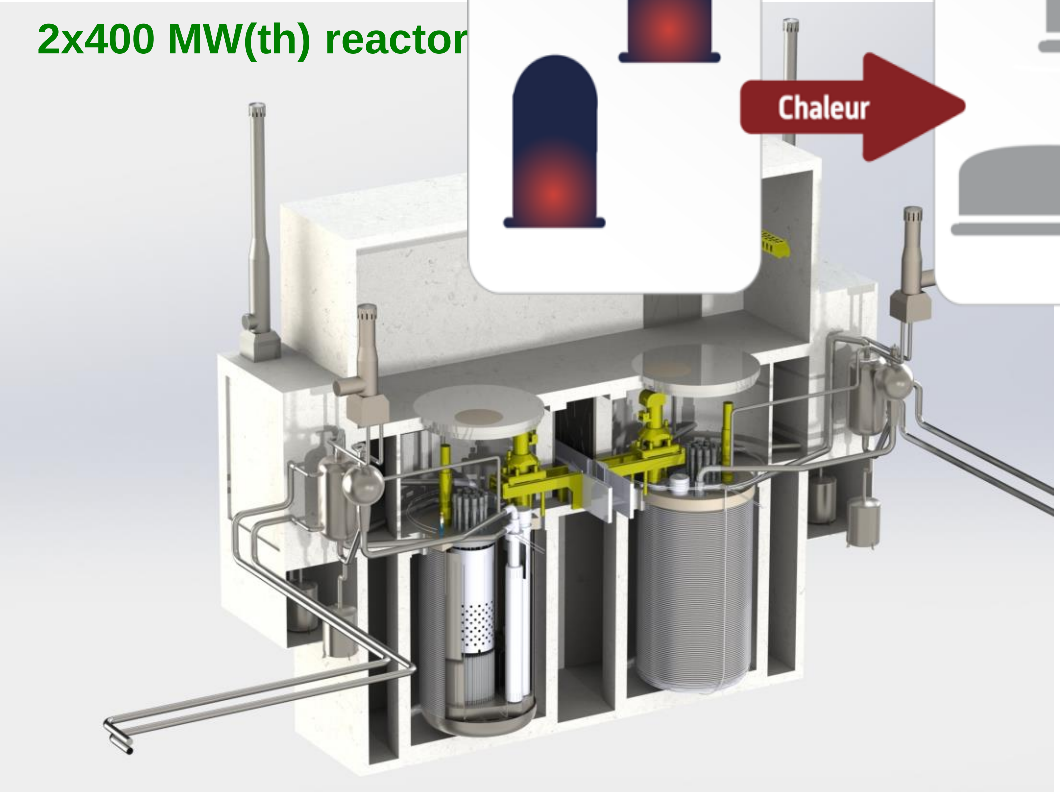


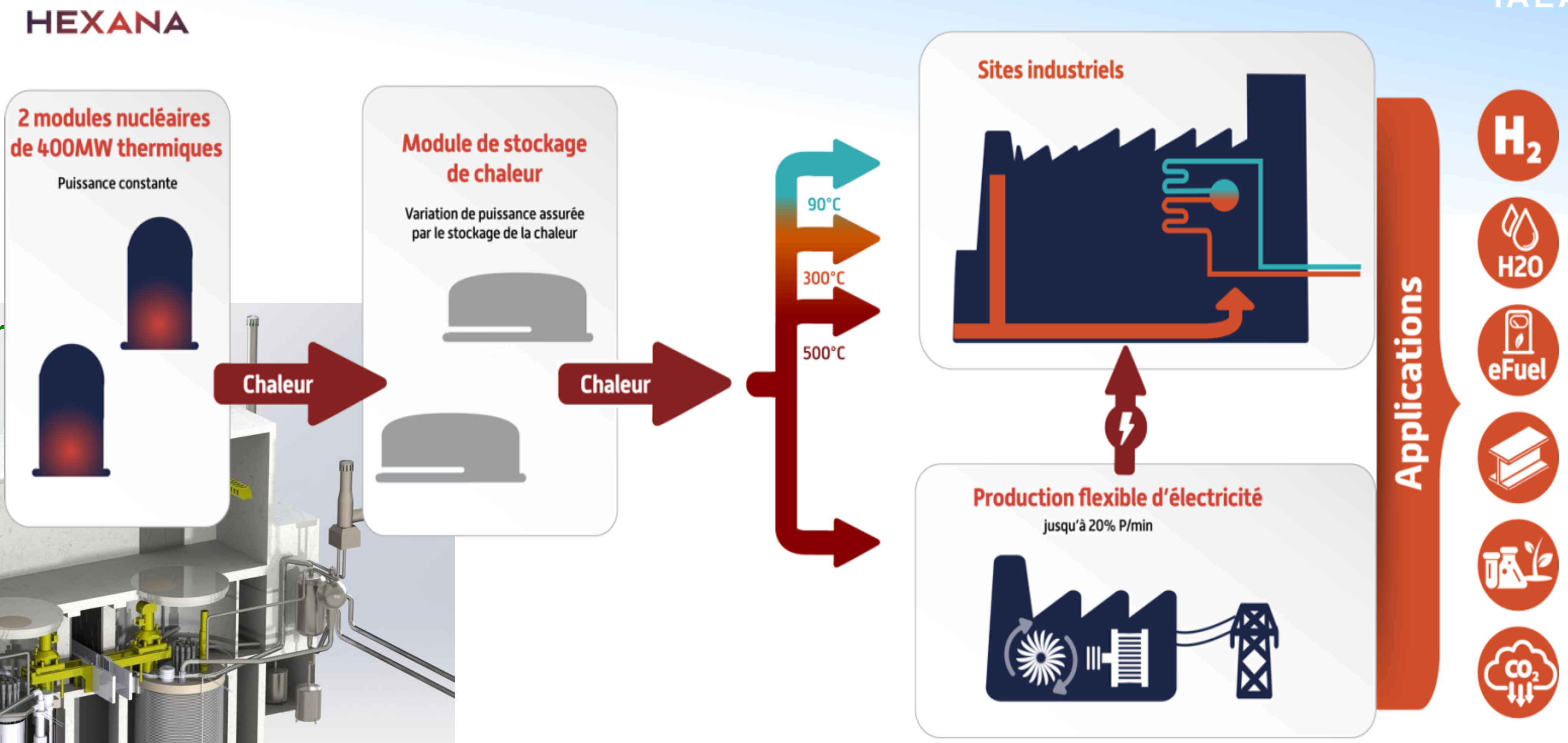
300 MW(e) SFR
Japan

Innovative Sodium cooled SMRs

HEXANA: multi-purpose SFR

2x400 MW(th) reactor

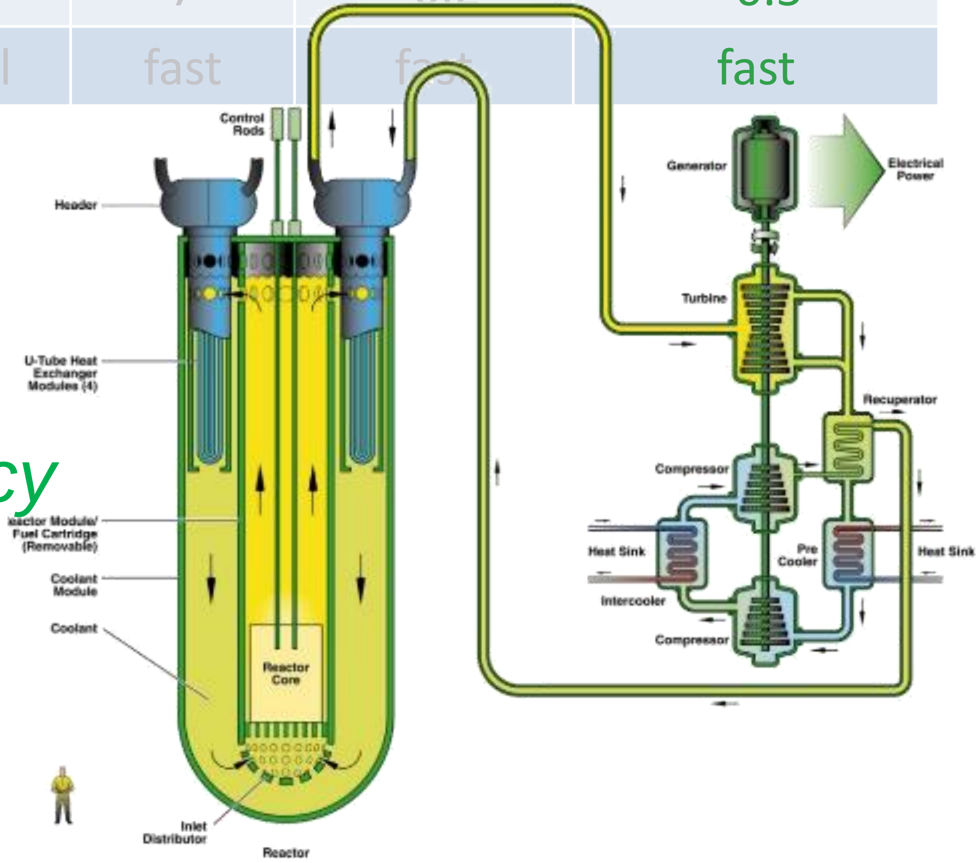




Heavy Liquid Metal cooled Fast Reactors

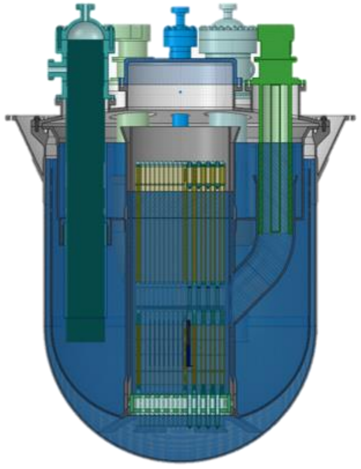
	WCR	SCWR	HTGR	GFR	SFR	LFR
coolant	H_2O	H_2O	He	He	Na	Pb/LBE
outlet T, C	288-329	500	750	750	550	500
efficiency, %	35	45	50	50	45	43
max P, MPa	17	25	7	7	~0.2	~0.5
spectrum	thermal	thermal/fast	thermal	fast	fast	fast

- *New Technology*
- *Compatibility of Materials*
- *No intermediate circuit*
- *Hight coolant T => High Efficiency*
- *Low Pressure*
- *Fast spectrum*
- *Pb/LBE O2 Control*

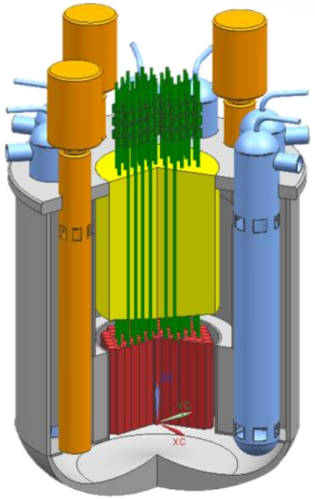


Heavy Liquid Metal cooled Fast SMRs

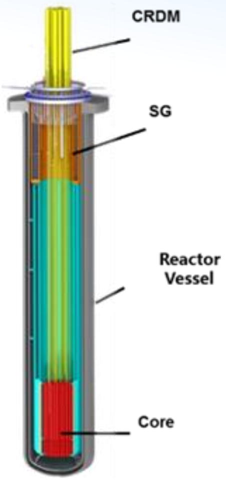
LFR: both Lead and LBE (lead-bismuth eutectic alloy)



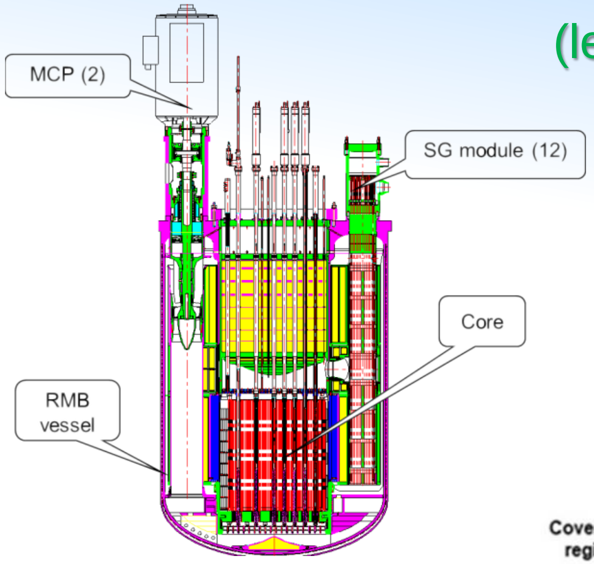
ALFRED
125-250 MW(e)
EU



CLFR-300
China

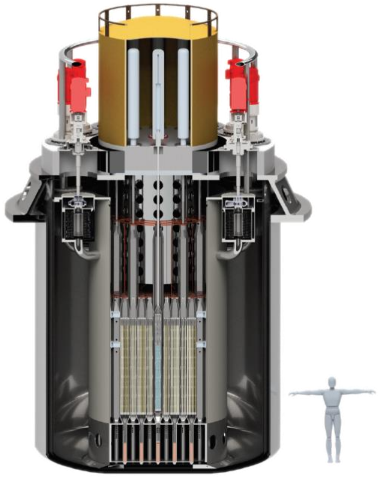


14 MW(e) CLEAR-M10d
China

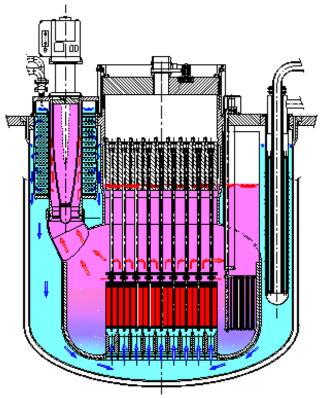


СВБР-100 (LBE)
Russia

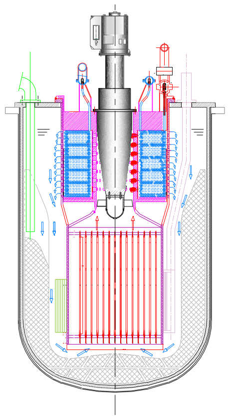
3-10 MW(e) SEALER
Sweden



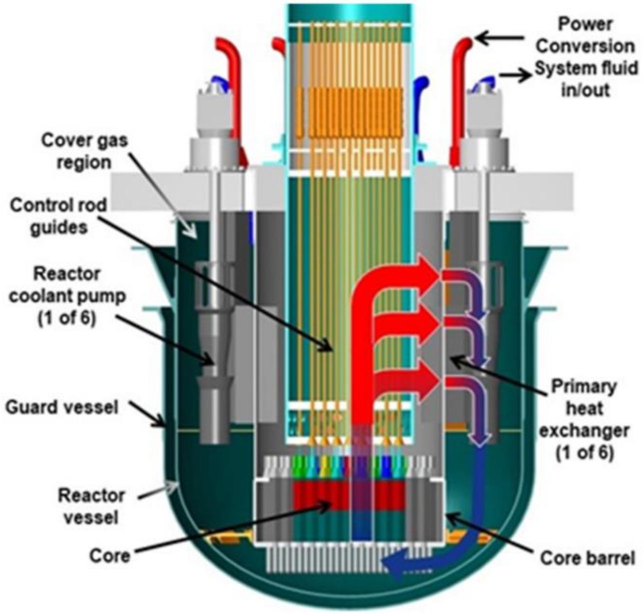
55 MW(e) SEALER
Sweden



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



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

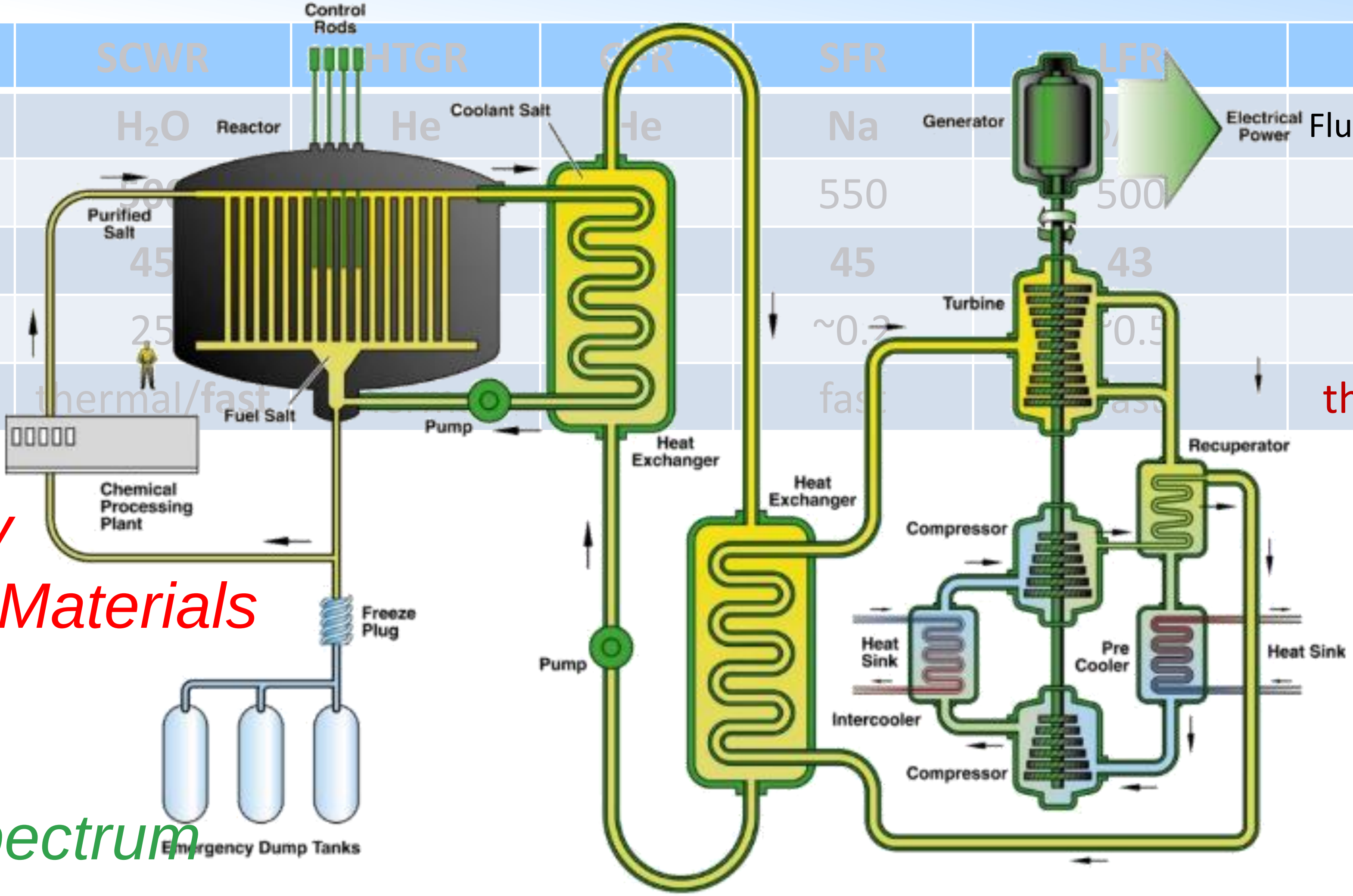


Westinghouse LFR 450 MW(e)
WEC, USA

Innovative Lead/LBE cooled SMRs

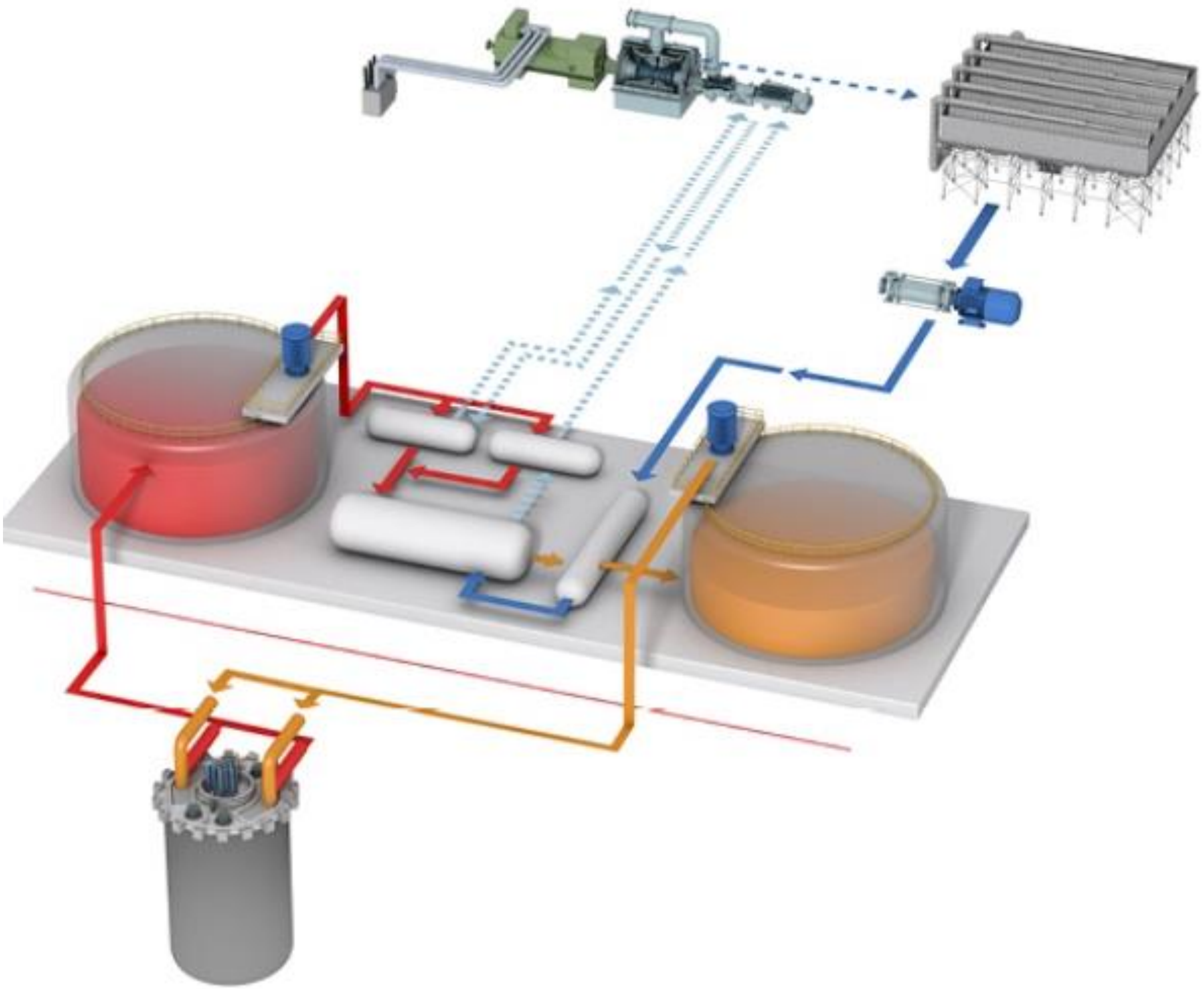
Molten Salt Reactors

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



- *New Technology*
- *Compatibility of Materials*
- *Hight coolant T*
- *Low Pressure*
- *Thermal/Fast spectrum*
- *Very safe*
- *Online Waste/Fuel Management*

NATRIUM: SFR with Molten Salt Storage System

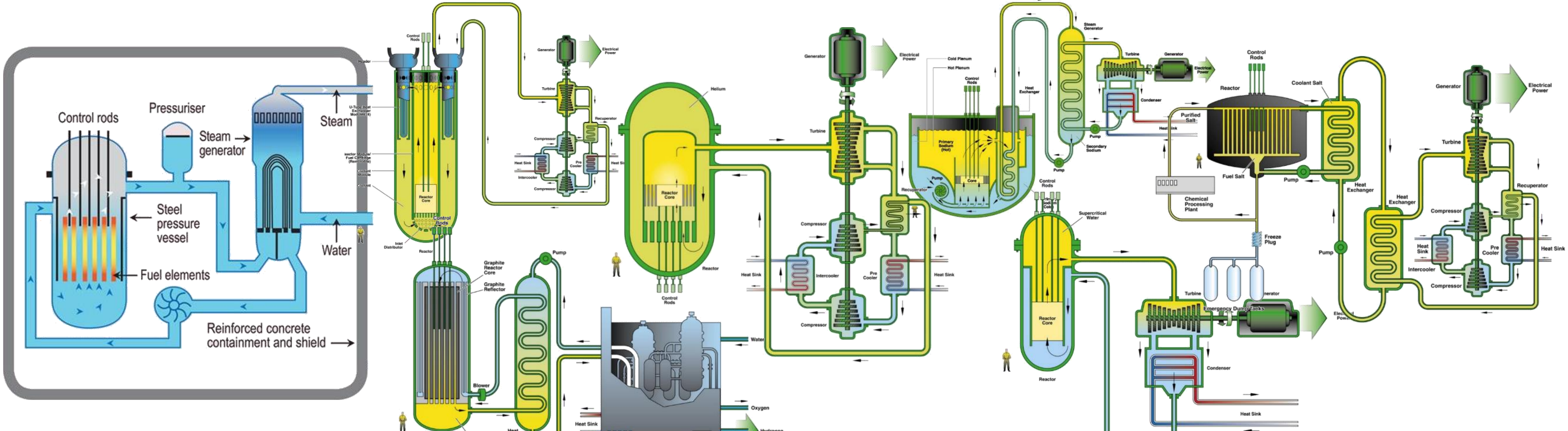


Announced by Terrapower

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

Comparing Innovative Reactor Concepts

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



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

Innovative Reactor Concepts: What else to consider?

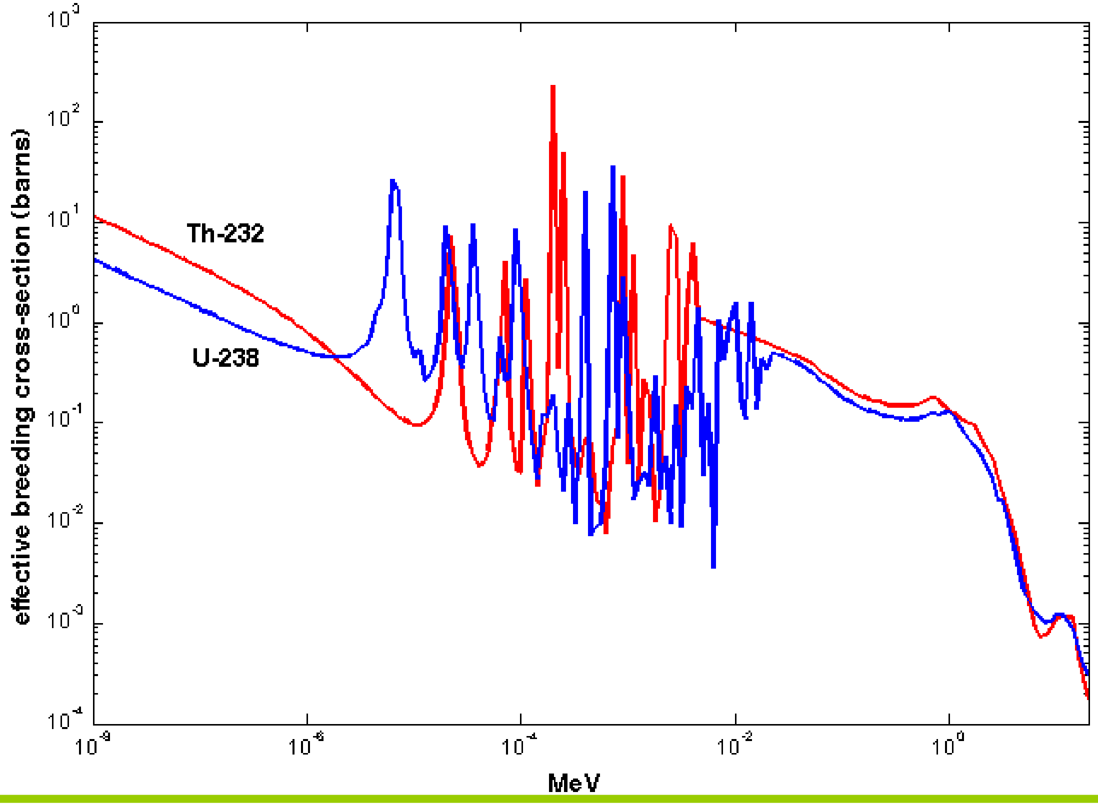
IAEA

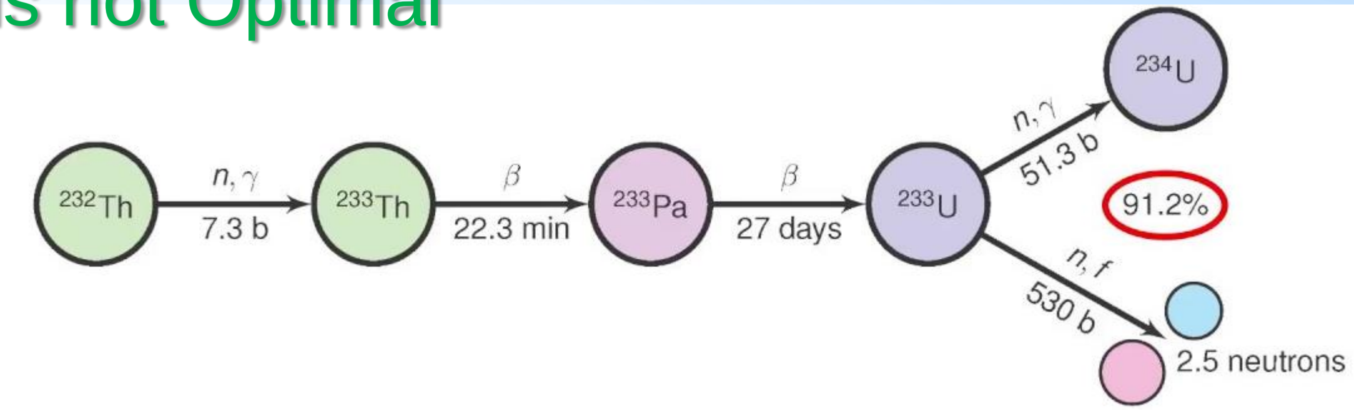
	WCR	SCWR	HTGR	GFR	SFR	LFR	MSR
coolant	H_2O	H_2O	He	He	Na	Pb/LBE	Fluoride/Chloride
outlet T, C	329	500	750	750	550	500	800
efficiency, %	35	45	50	50	45	43	48
max P, MPa	17	25	7	7	0.2	0.5	0.2
n. spectrum	thermal	thermal/fast	thermal	fast	fast	fast	thermal/fast
ρ, kg/m³	700	800/90	0.12/8.5		830	10000	3200
C_P, kJ/kg/K	5.7	5/4	5.2/5.2		1.3	0.15	1.4
ρC_P, MJ/m³/K	4	0.35	$6x10^{-4}$/0.4		1	1.5	4.5
k, W/m/K	0.6	0.1 - 0.4	0.15/0.24		70	18	0.01
boiling T, C	350				880	1700	1700
melting T, C					98	208	500
CMI[1]	ok	ok	good	good	ok	?	?
enrichment, %	<5	<5/<20	<5	<20	<20	<20	<5/<20

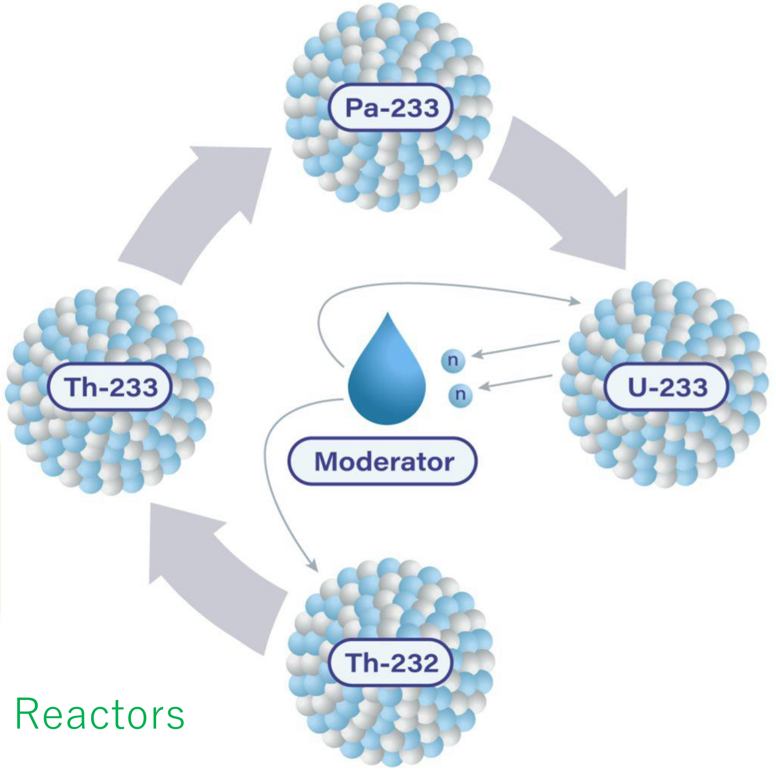
1) CMI: Coolant – structural Materials Interaction

Thorium Fuel Cycle: Works in Thermal Spectrum

TH-232 >> U-233: Fast Reactor is not Optimal







Absorption of neutrons by thorium-232 initiates the series of transformations leading to the production of fissile uranium-233. Uranium-233 is by far the best 'fissile' isotope for thermal neutron spectrum and can be used for breeding in both thermal and fast reactors.

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

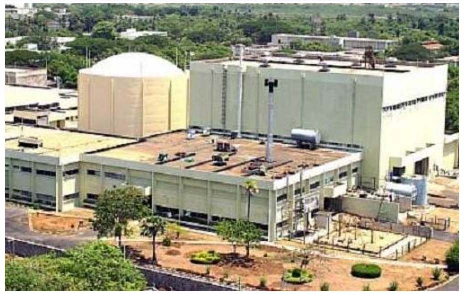
Fast Reactors in Operation & under Commissioning

Country	Name	Coolant	Fuel	Purpose	Power (th/e) MW	Year (Op.)	Status
Russia	BOR-60	sodium	UO_2/MOX	experimental	**60/10**	1969	operating
	BN-600	sodium	UO_2	prototype	**1470/600**	1980	operating
	BN-800	sodium	UO_2/MOX	commercial	**2100/880**	2015	operating
China	CEFR	sodium	UO_2	experimental	**65/20**	2011	operating
	CFR600-1	sodium	UO_2/MOX	prototype	**1500/600**	~2024	commissioning
India	FBTR	sodium	(Pu,U)C	experimental	**40/13**	1985	operating
	PFBR	sodium	MOX	prototype	**1250/500**	~2024	commissioning
Japan	JOYO	sodium	UO_2/MOX	experimental	**150/--**	1978	lic renew (2024?)


BN-600
Russia, 1980


BN-800
Russia, 2015

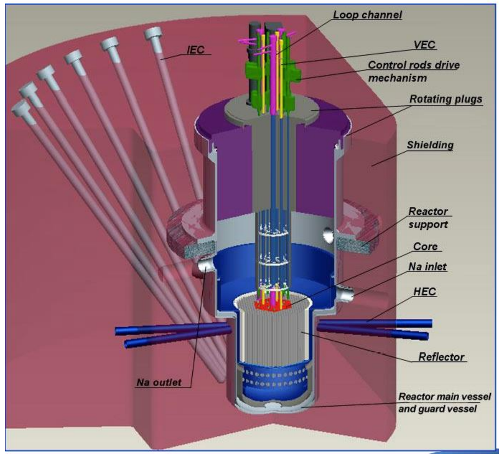

CEFR, 20 MW(e)
China, 2011


FBTR, 13 MW(e)
India, 1985


PFBR, 500 MW(e)
India, 2024

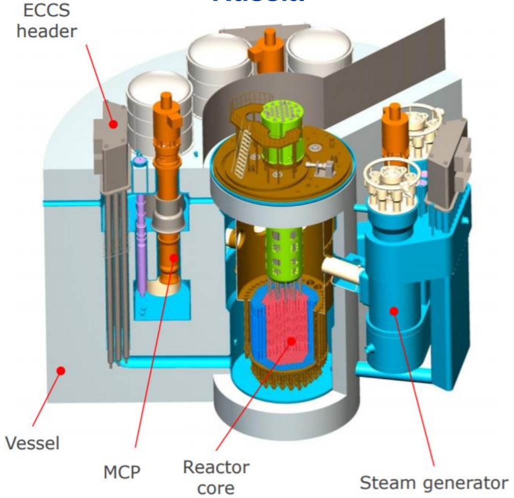
Fast Reactors under Construction and Decommissioning

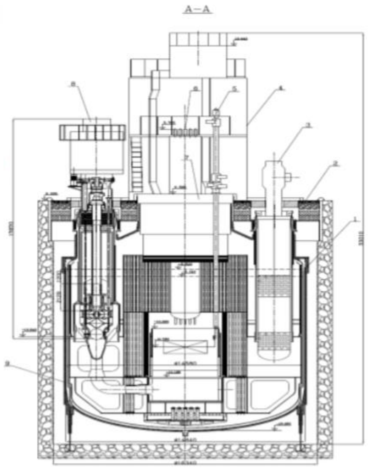
Country	Name	Coolant	Fuel	Purpose	Power (th/e) MW	Year (Op.)	Status
Russia	MBIR	sodium	MOX	experimental	**150/50**	~2028	construction
	BREST-OD-300	lead	PuN/UN	demonstrator	**700/300**	~2026	construction
China	CFR600-2	sodium	UO_2/MOX	prototype	**1500/600**	~2028	construction
France	Phenix	sodium	MOX	prototype	**590/250**	1973	decommissioning
	Superphenix	sodium	MOX	FOAK	**3000/1242**	1986	decommissioning
Japan	MONJU	sodium	MOX	prototype	**714/280**	1994	decommissioning
USA	FFTF	sodium	UO_2	experimental	**400/--**	1980	decommissioning



MBIR, Russia

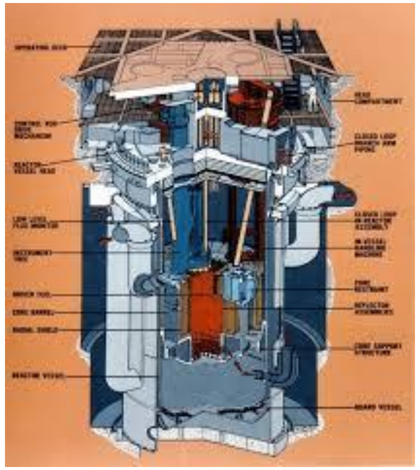
BREST-OD-300
Russia





CFR600, China

MONJU, Japan



FFTF, USA

Fast Reactors under Development and Design

Country	Name	Type	coolant	fuel	Purpose	Power (th/e), MW	Status
Russia	**BN-1200**	SFR	sodium	PuN/UN/MOX	Gen-IV, industrial	2900/1220	design
	SVBR-100	LFR	LBE	UO_2	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-I	LFR	LBE	UO_2	experimental	10/-	design
	CLEAR-M10d	LFR	lead	UO_2	demonstrator	25/10	concept
EU	ALLEGRO	GFR	helium	MOX	Gen-IV, demonstrator	75/-	design
	MSFR	MSR	molten salt (LiF-AFn)		Gen-IV, prototype	3000/	concept
Belgium	**MYRRHA**	LFR ADS	LBE	MOX	experimental	100/-	design
France	ASTRID	SFR	sodium	MOX	demonstrator	1500/600	suspended
	HEXANA	SFR	sodium	MOX	SMR prototype	2x400/Flexible	concept
	OTRERA	SFR	sodium		Gen-IV SMR prototype	295/110	concept
	STELLARIA	MSR	chloride salt		SMR prototype	250/100	concept
India	FBR 1&2	LFR	lead	MOX	prototype	1250/500	design
Italy	LFR-AS-30/200	LFR	lead	MOX	experimental/prototype	/30 or /200	concept
Romania/Italy	**ALFRED**	LFR	lead	MOX	Gen-IV, demonstrator	300/120	design
R. of Korea	KALIMER-600	SFR	sodium		GEN-IV, prototype	1523/600	design
	PGSFR	SFR	sodium	U-Zr/U-TRU-Zr	GEN-IV, demonstrator	400/150	suspended
	SALUS-100	SFR	sodium		GEN-IV, prototype	267/100	design
Sweden	**SEALER-55**	LFR	lead	CN/UN?	demonstrator	140/55	design
UK/USA	**Westinghouse LFR**	LFR	lead	MOX	demonstrator	950/450	design
USA	**NATRIUM**	SFR	sodium		demonstrator	1000/345-500	design
	VTR	SFR	sodium	U-Pu-Zr?	experimental	300/-	design
	SSTAR	LFR	lead		experimental	45/20	supended
	MCFR	MSR	chloride salt		experimental	1800/800	design
	EM2	GFR	helium	UC	demonstrator	500/265	concept
	KP-FHR	MSR	fluoride salt		demonstrator	310/140	concept
	PRISM	SFR	sodium	U-Pu-Zr	demonstrator	840/311	concept
	LLC ARC-100	SFR	sodium		demonstrator	260/110	concept

Small and Medium-sized or Modular Reactors (SMRs)

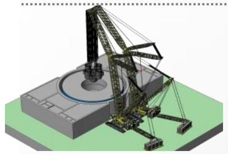
IAEA

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

- Enhanced Safety
- Versatile
- Modular
- Reduced Waste
- Affordable
- Non-electric applications

Economic
- Lower Upfront capital cost
- Economy of serial production

→ Better Affordability

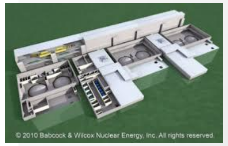


Modularization
- Multi-module
- Modular Construction

→ Shorter construction time

Flexible Application
- Remote regions
- Small grids

→ Wider range of Users

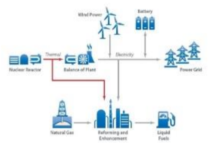


Smaller footprint
- Reduced Emergency planning zone

→ Site flexibility

Replacement for aging fossil-fired plants

→ Reduced CO_2 production



Potential Hybrid Energy System

→ Integration with Renewables

Paris Agreement — 2015

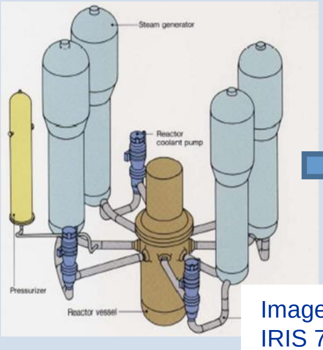
2024 — Commissioning of the FOAK SMR projects

2030 — Global mass deployment of SMRs

2050

SMR Key Design Features

Simplification by Modularization and System Integration



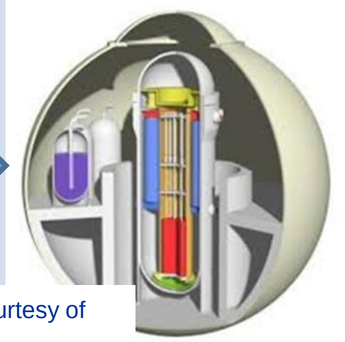
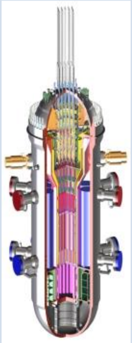



Image courtesy of IRIS 7 .

Multi-module Plant Layout Configuration

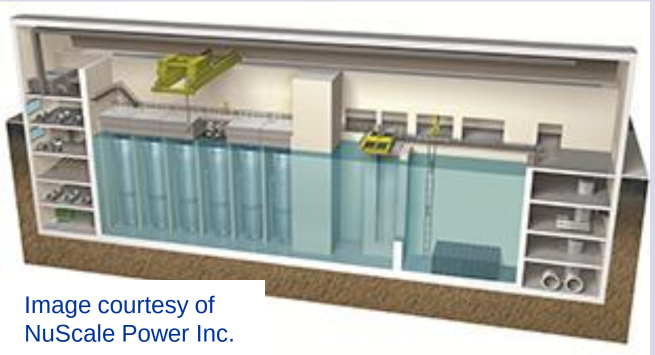
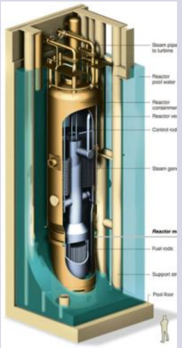



Image courtesy of NuScale Power Inc.

Underground construction for enhanced security and seismic

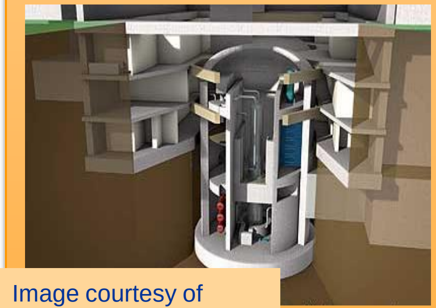



Image courtesy of BWX Technology, Inc.

Enhanced Safety Performance through Passive System

- Enhanced severe accident features
- Passive containment cooling system
- Pressure suppression containment

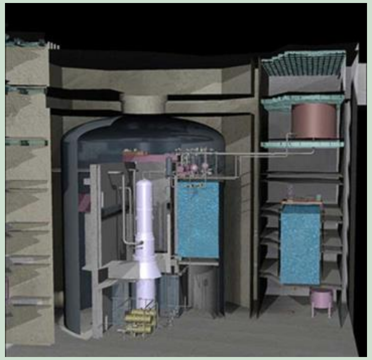
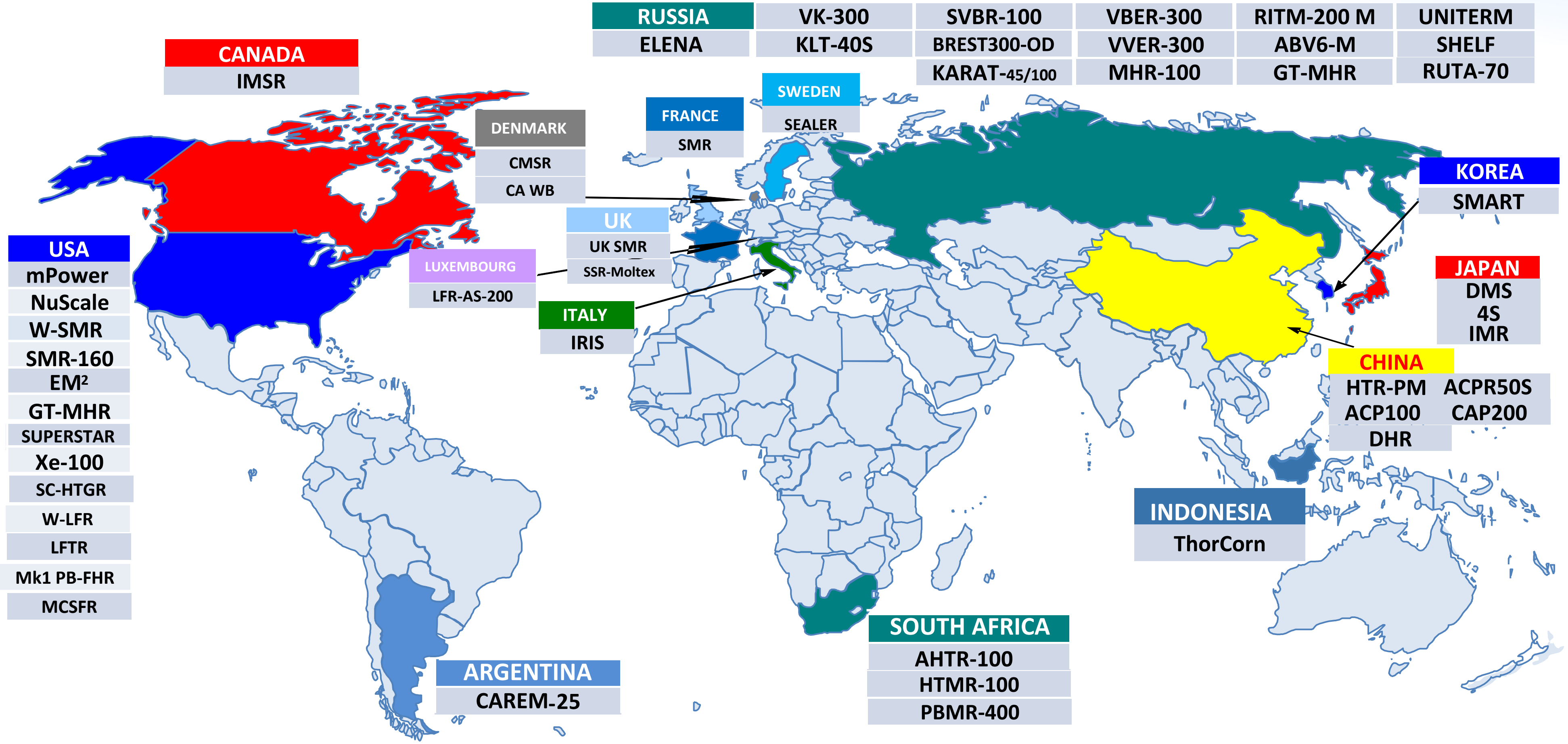
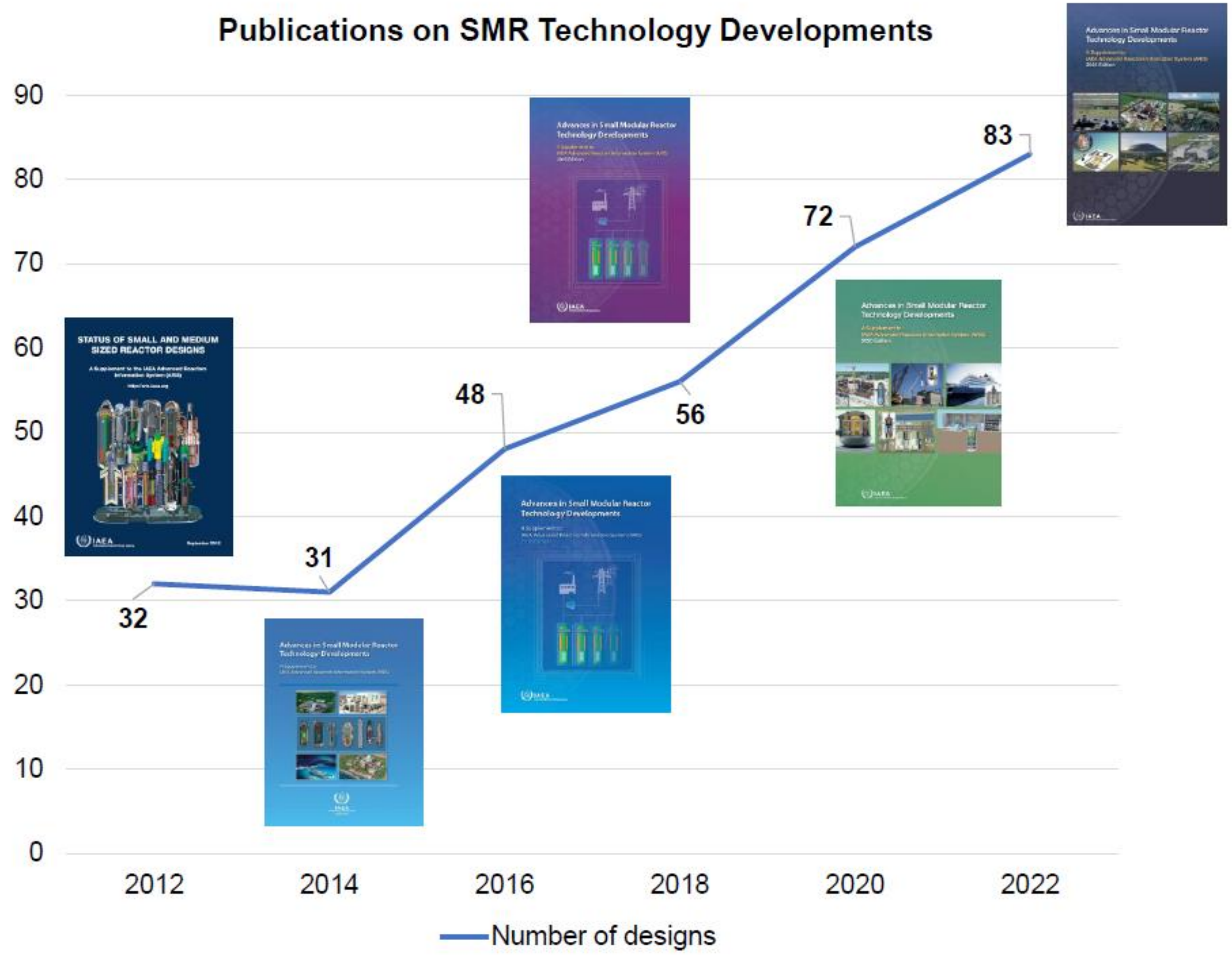


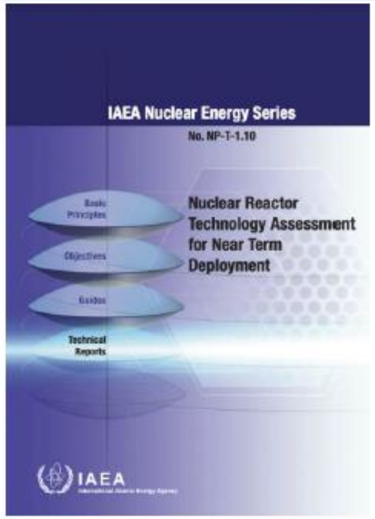
Image courtesy of BWX Technology, Inc.

SMR Technology Developers

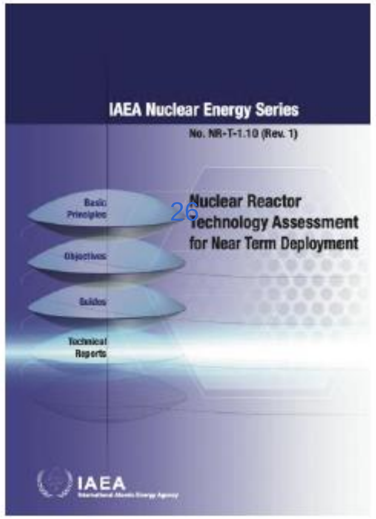


Dynamics in SMR Designs (ARIS SMR Booklet 2022)





Nuclear Reactor Technology Assessment for Near Term Deployment, 2013

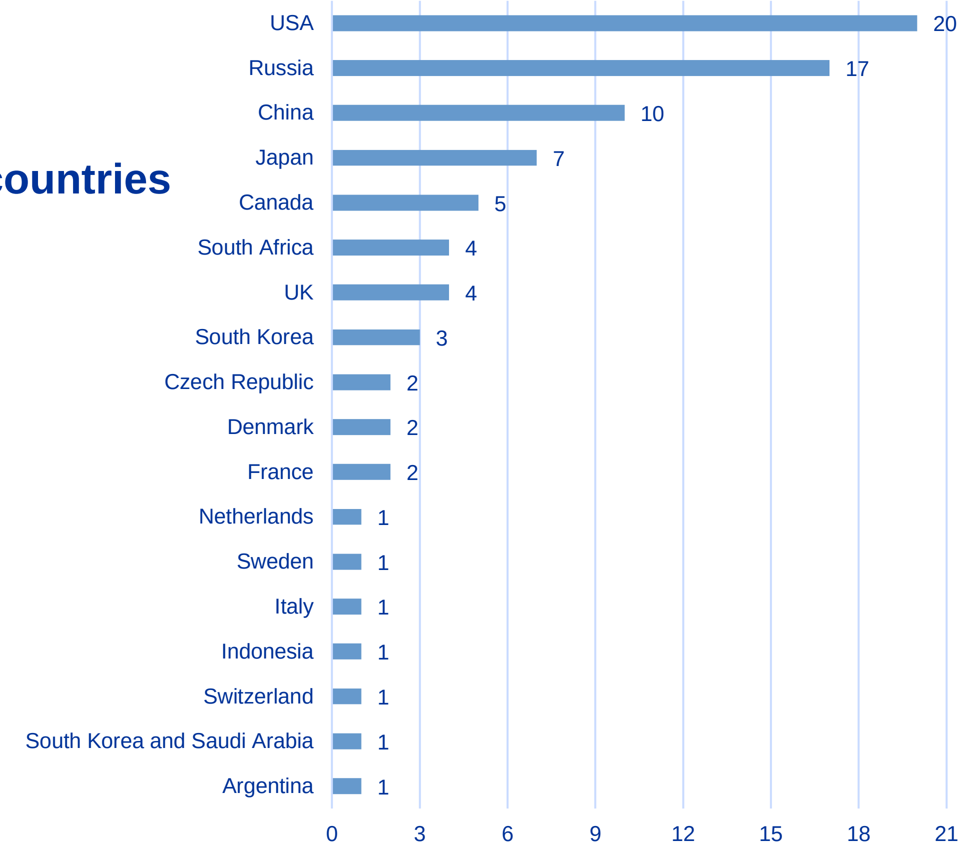


Nuclear Reactor Technology Assessment for Near Term Deployment, 2022

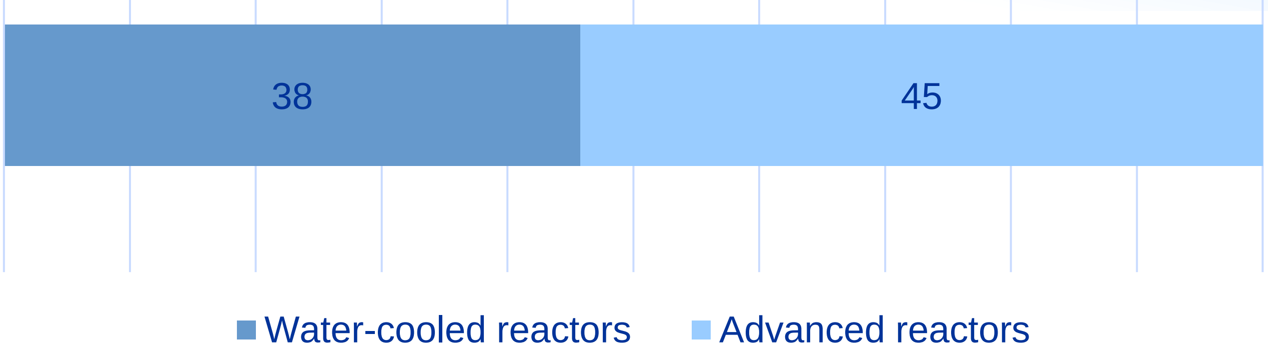
SMR Developers and Designs – ARIS SMR Booklet 2022

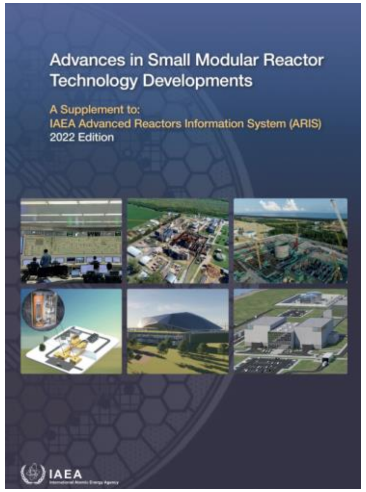
18 countries

Number of SMR designs under development per country



Number of SMR designs under development: 83





27

HTGR 21

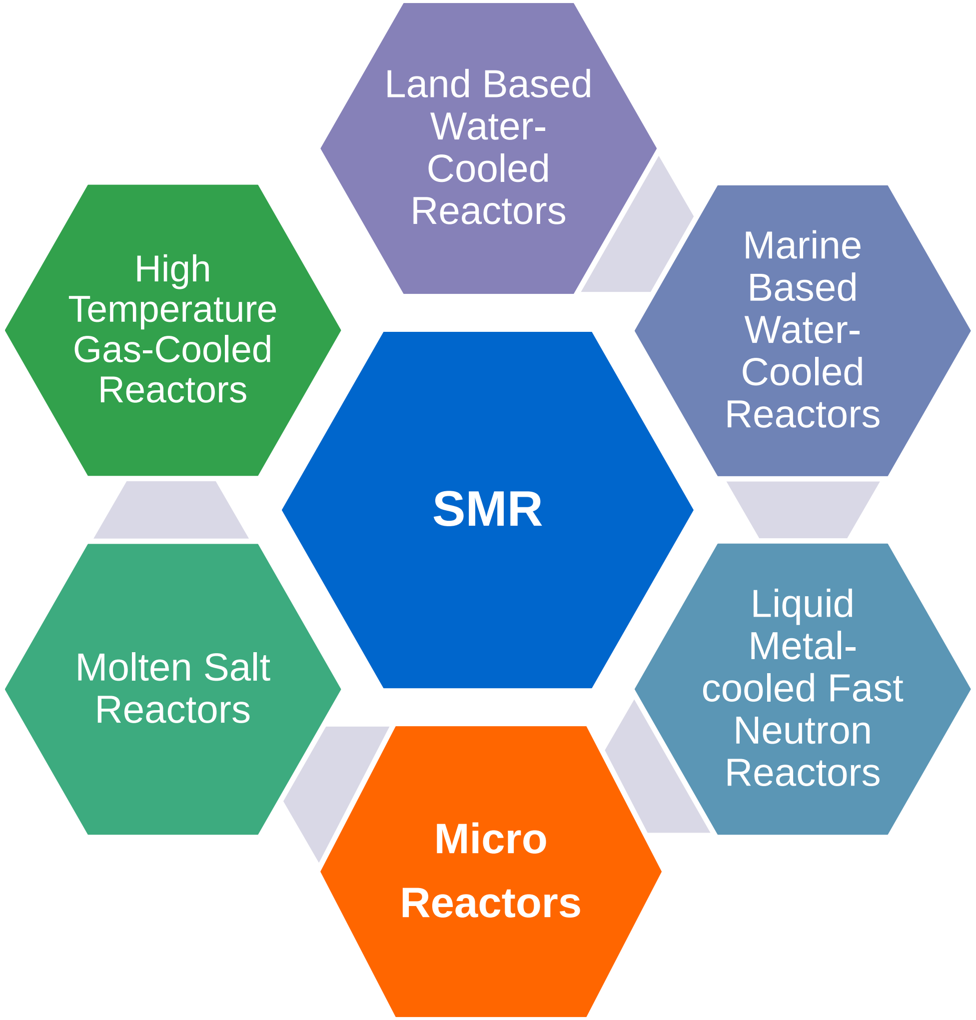
MSR 13

LFR 8

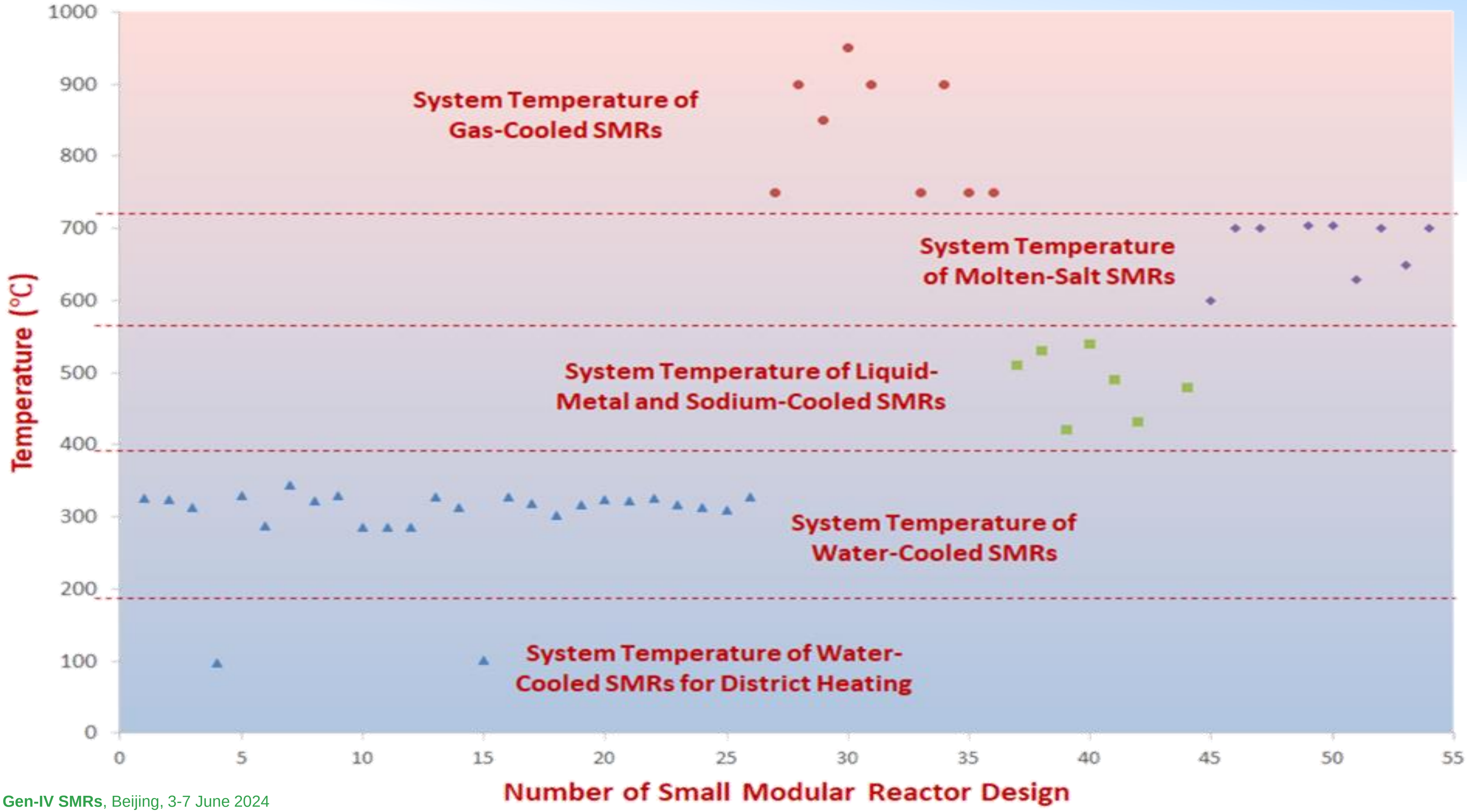
SFR 3

aris.iaea.org/Publications/SMR_booklet_2022.pdf

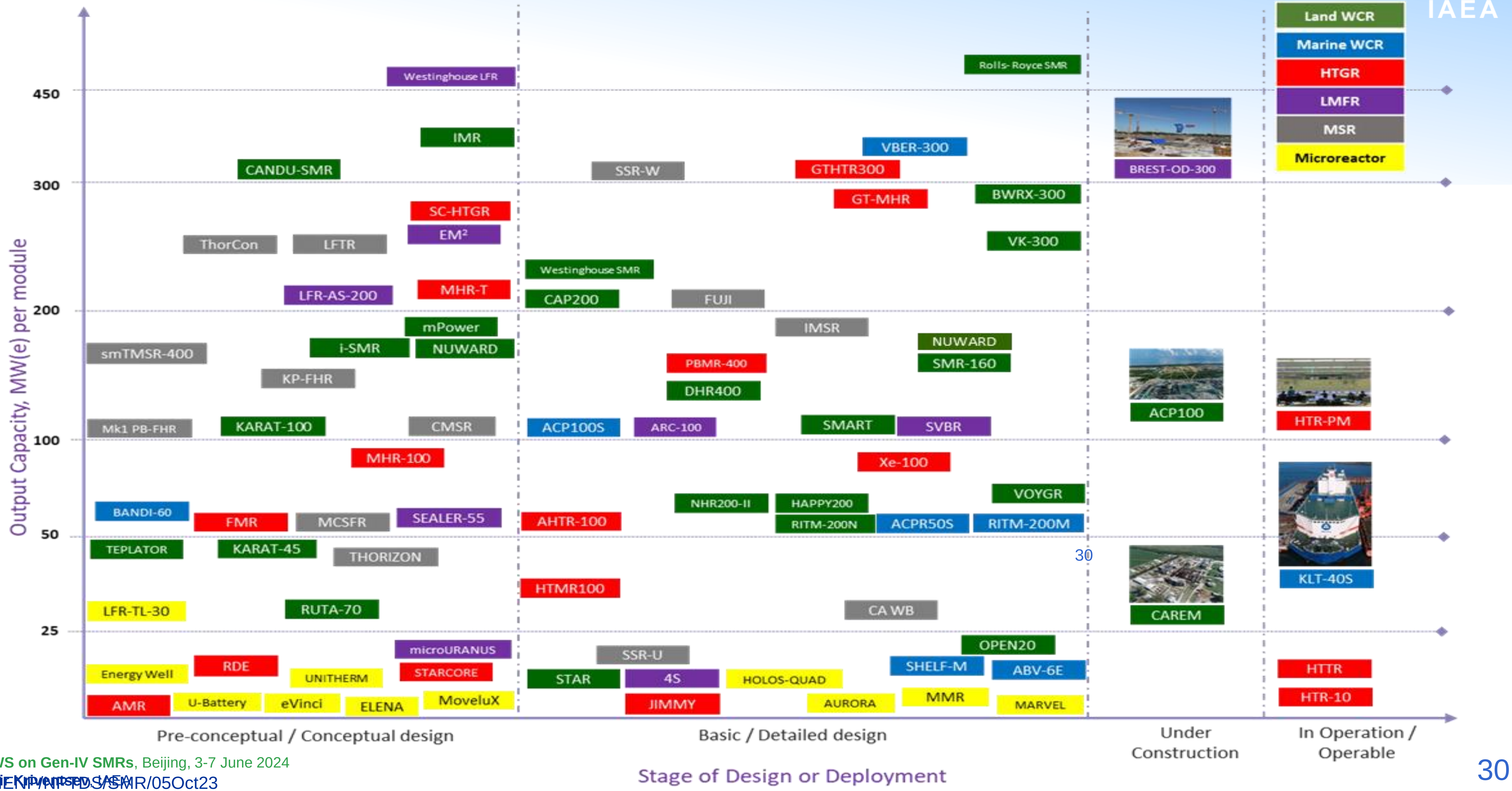
Categorization of SMR Technology



SMR Designs Based on Core Outlet Temperature

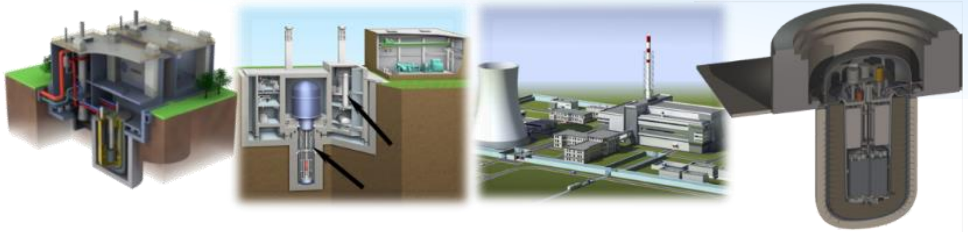


Stages of Development and Deployment of SMRs



SMRs for Non-Electric Applications

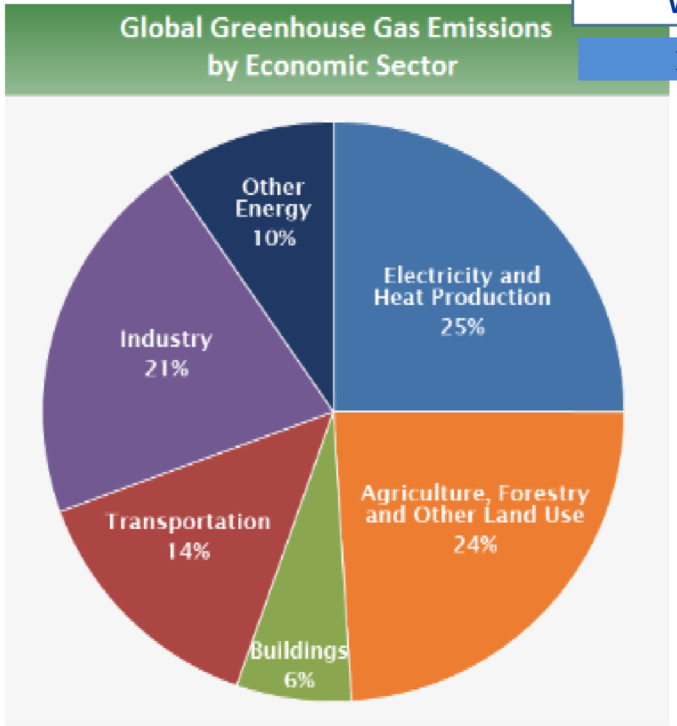
- Very high temperature reactors
- Gas-cooled fast reactors
- Molten Salt reactors
- Supercritical water-cooled reactors
- Sodium-cooled fast reactors
- Liquid metal cooled reactors
- Water cooled reactors



100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 (ºC)

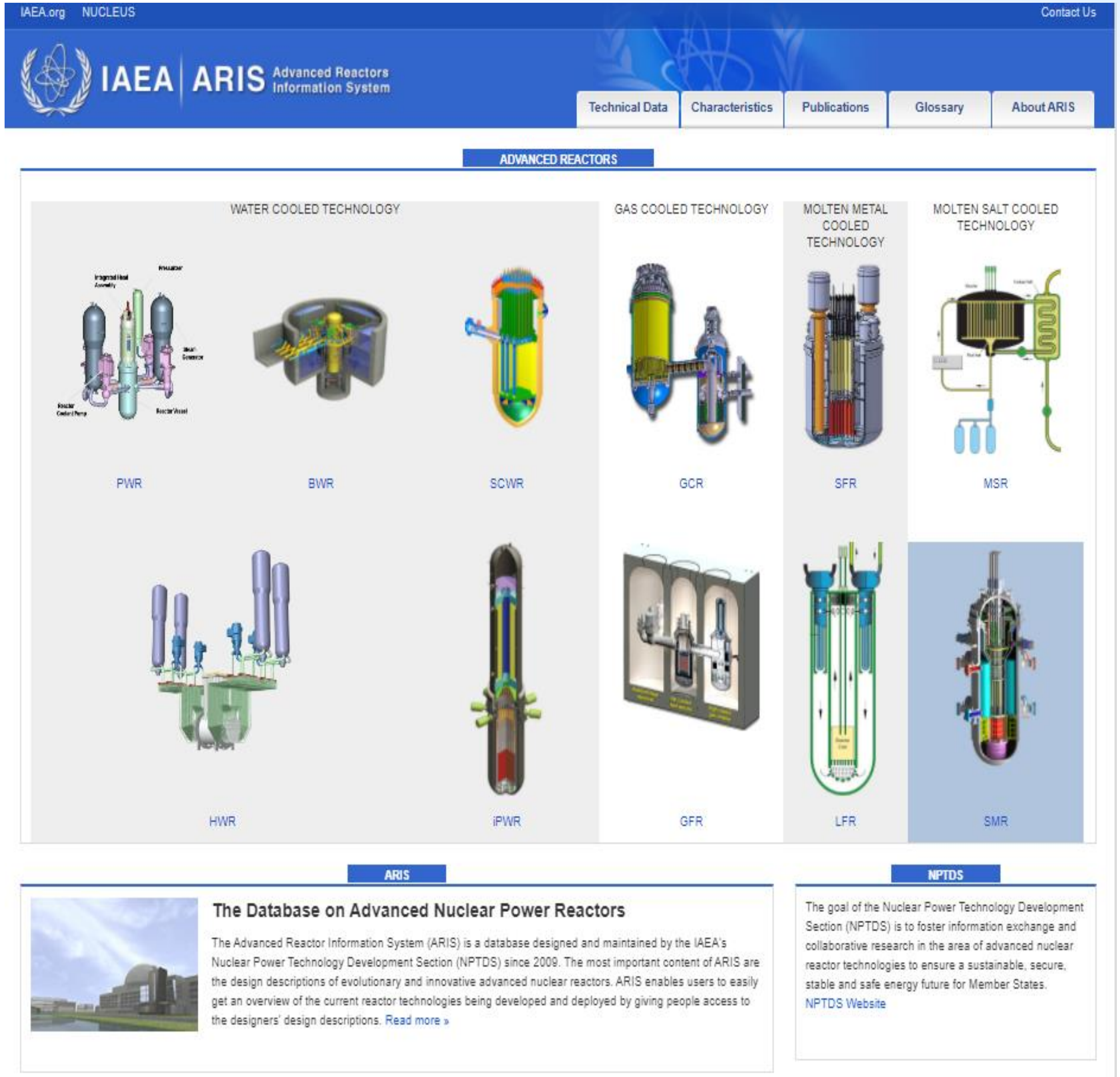
- District heating
- Seawater desalination
- Pulp & paper manufacture
- Methanol production
- Heavy oil desulfurization
- Petroleum refining
- Methane reforming hydrogen production
- Thermochemical hydrogen production
- Coal gasification
- Blast furnace steel making

31



Wide spectrum of SMRs can cover various types of applications

IAEA Advanced Reactors Information System (ARIS)



- New User Interface
- Display Contents
  - More Organized Way
  - More Filters
- Comparison of Several Designs
- Dynamic Graphs/Maps for Plant Sites
- Dashboard for Vendor and Admins
- New Reporting System

IAEA International Conference on SMRs: 21-25 October 2024

The First International Conference on Small Modular Reactors and their Applications in Vienna on 21-25 October 2024.

- The Conference is being prepared as a joint event organized with inter-Agency cooperation between:
  - *Department of Nuclear Energy*
    - Division of Nuclear Power
  - *Department of Nuclear Safety and Security*
    - Division of Nuclear Installation Safety
- Supported by
  - Department of Safeguards, and
  - Department of Technical Cooperation
- About 450 contributions have been accepted

IAEA
International Atomic Energy Agency

Atoms for peace and Development…

Thank You!

email: FR@IAEA.ORG