Joint ICTP-IAEA-MAMBA School on Materials Irradiation: from Basics to Applications

Introduction to Generation IV reactors

Francisco Álvarez-Velarde

Nuclear Innovation Unit – CIEMAT (Spain)

francisco.alvarez@ciemat.es

Contents

Contents

Introduction

Generation IV systems

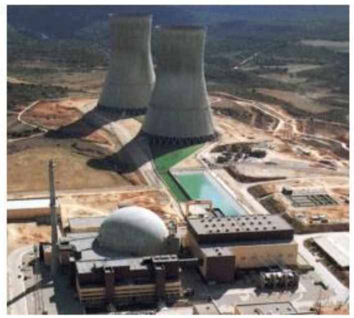
Generation IV fast reactors

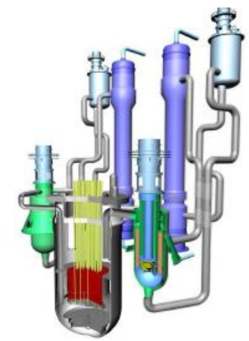
Other Generation IV systems

Conclusions

Evolution of Nuclear Reactors

Generation I	Generation II	Generation III+	Generation IV
Early prototype reactors	Commercial power reactors	Evolutionary/advanced LWRs	Innovative reactors



Generation I	Generation II	Generation III+	Generation IV
•Shippingport •Dresden, Fermi-I •Magnox	•LWR: PWR, BWR •CANDU, AGR •VVER/RBMK	• EPR • ABWR • AP1000 • ESBWR	• VHTR • SCWR • SFR • LFR • GCR • MSR

Optimistic!

1950 1960 1970 1980 1990 2000 2010 2020 2030 2040

Obninsk, 1954

Fermi-I, 1963

Soviet Alpha class submarines, 70s

Akademik Lomonosov, 2019

HTR-PM, Shidao Bay, 2023

GEN IV International Forum

Expertise | Collaboration | Excellence

- Co-operative international endeavor seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems (Gen-IV systems), and to make them available for industrial deployment by 2030.
- Founded in 2001 by Argentina, Brazil, Canada, France, Japan, Korea, South Africa, the United Kingdom and the United States.
- Signed by Switzerland (2002), EURATOM (2003), China and Russia (2006).
- Extension signed in 2011.
- Signed by Australia (2016).

Source: January 2000, U.S. DOE.

GOBIERNO DE ESPAÑA

GIF objectives

- **Sustainability-1**: long-term availability of systems and effective fuel utilization with clean air objectives
- **Sustainability-2**: Waste minimization and management
- **Economics-1**: Competitiveness
- **Economics-2**: Financial risk comparable to other energy projects
- **Safety and Reliability-1**: Excel in safety and reliability
- **Safety and Reliability-2**: Very low likelihood and degree of reactor core damage
- **Safety and Reliability-3**: Elimination of the need for offsite emergency response
- **Proliferation resistance and physical protection**: Unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism

Contents

Selected systems

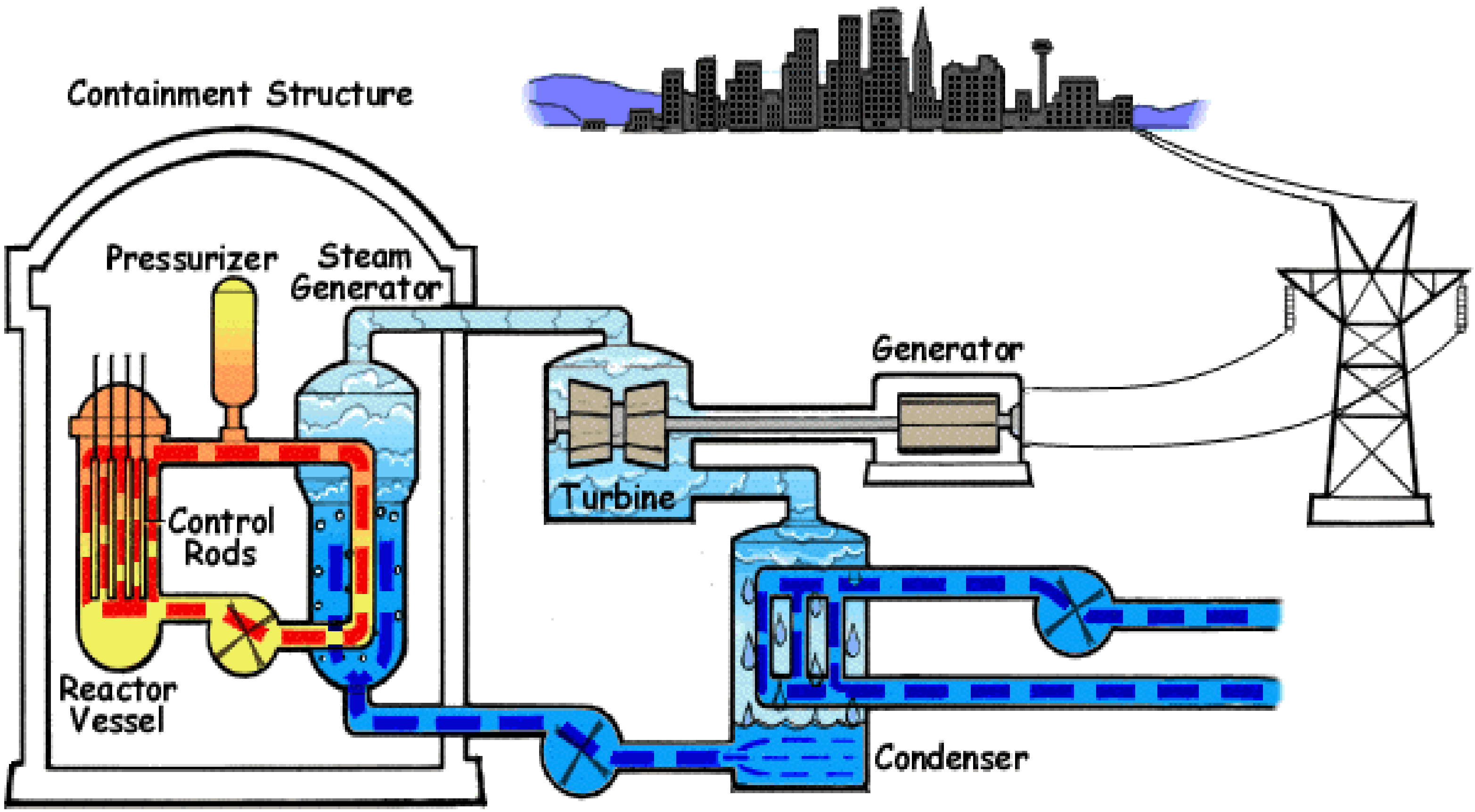
Generation IV system	Acronym
Very High Temperature Reactor	VHTR
Sodium-Cooled Fast Reactor	SFR
Super Critical Water Reactor	SCWR
Gas-Cooled Fast Reactor	GFR
Lead-Cooled Fast Reactor	LFR
Molten Salt Reactor	MSR

Gen-IV systems

System	Neutron spect.	Fuel/ Cycle	Coolant	Tª in/out ºC	Pressure	Power MWe MWth	Power density (MWth/m³)	Eff. (%)	Use *
VHTR	Thermal	UO_2 spheres Open	Helium	900-1000	Medium 70-90 bar	250-300 600	06-10	50	Electricity H_2 Heat
SFR	Fast	U-238 MOX Closed	Sodium	550	Low 1 bar	50-1500 1000-5000	350	40	Electricity H_2 Actinides
SCWR	Thermal/ Fast	$U0_2$ Open Closed	Supercrit. water	510-625	Very high 230 bar	300-1700		40	Electricity
GFR	Fast	U-238 Closed	Helium/ CO_2	490/850	High 90 bar	600 1200	100	48	Electricity H_2 Actinides
LFR	Fast	U-238 Closed	Lead Bismuth	480-800	Low 1 bar	300-1000 400-3600			Electricity H_2
MSR	Thermal/ Fast	UF_4 Closed	Fluoride salt	700-850	Low 1 bar	1000	22	44-50	Electricity H_2

Use of the technology

Water heating for electricity production

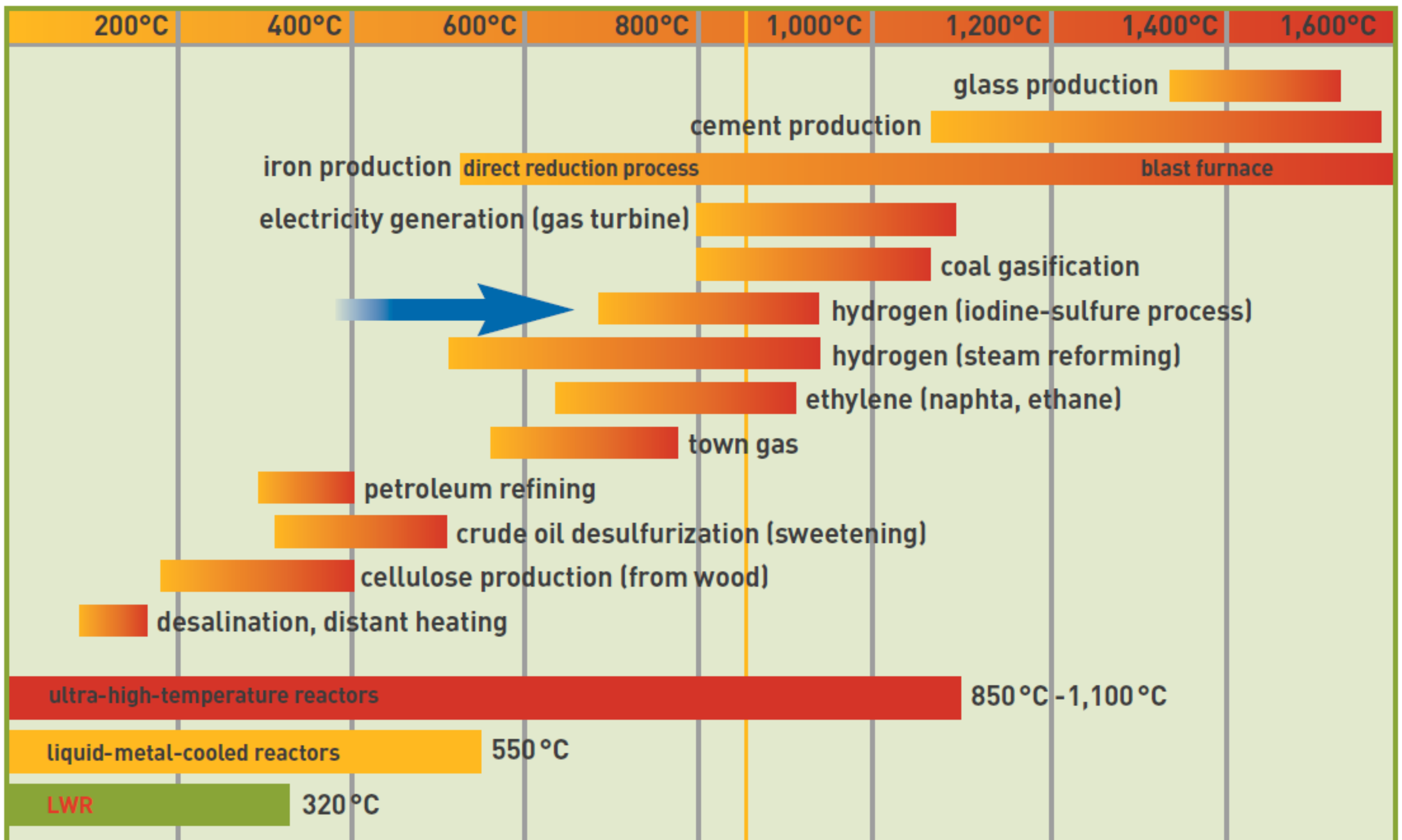


Source: Wikipedia.

Use of the technology

Taking advantage of the generated, other objectives can be fulfilled:

- Hydrogen production (ethanol, cellulose, etc.) using different methods
- Sea water desalination
- District heating
- Petroleum refining



Gen-IV systems

System	Neutron spect.	Fuel/ Cycle *	* Coolant	Tª in/out ºC	Pressure	Power MWe MWth	Power density ($MWth/m^3$)	Eff. (%)	Use
VHTR	Thermal	UO_2 spheres Open	Helium	900-1000	Medium 70-90 bar	250-300 600	06-10	50	Electricity H_2 Heat
SFR	Fast	U-238 MOX Closed	Sodium	550	Low 1 bar	50-1500 1000-5000	350	40	Electricity H_2 Actinides
SCWR	Thermal/ Fast	$U0_2$ Open Closed	Supercrit. water	510-625	Very high 230 bar	300-1700		40	Electricity
GFR	Fast	U-238 Closed	Helium/ CO_2	490/850	High 90 bar	600 1200	100	48	Electricity H_2 Actinides
LFR	Fast	U-238 Closed	Lead Bismuth	480-800	Low 1 bar	300-1000 400-3600			Electricity H_2
MSR	Thermal/ Fast	UF_4 Closed	Fluoride salt	700-850	Low 1 bar	1000	22	44-50	Electricity H_2

Reactor design

The three decisions with utmost importance in nuclear reactor design are:

- **Fuel** (natural U, enriched U, MOX, ...)
- **Moderator** (water, graphite, ...)
- **Coolant** (water, sodium, lead, gas, ...)

Fuel

The optimum use of fuel is sought:

- Long burn-up
- Low generation of waste
- Management of Pu and minor actinides

Fuel design

- Pellets
- Spherical fuel (TRISO)
- Alternatives (hexagonal, plates)
- Oxide/Carbide/Metallic, U, U+Pu, etc.
- Molten salt

Coolant

Main characteristics

- Operation temperature
- Heat capacity
- Thermal conductivity
- Density
- Neutronic aspects
- Corrosion
- Technology for the adequate operation (airtightness, pressure, in-service inspection, ...)
- Safety
- Chemical inertia
- Opacity

Neutron moderation

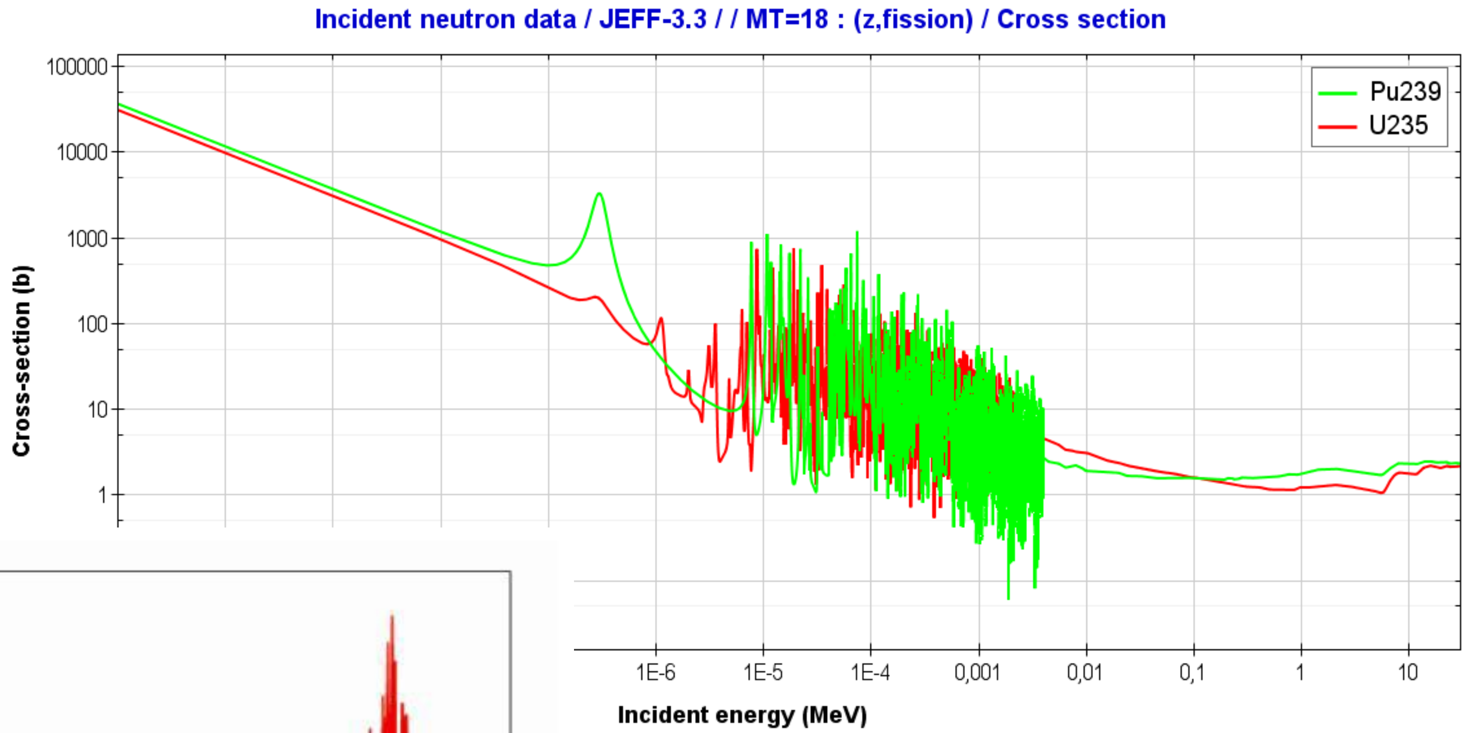
- Presence of moderating elements if required
  - Water in liquid state and organic compounds (C or H)
  - Gases (He, CO_2), liquid metals

- For Generation-IV reactors: Use of coolants compatible with low moderation as liquid metals at room temperature (mercury, sodium, sodium-potassium alloy, lithium, lead, lead-bismuth eutectic)

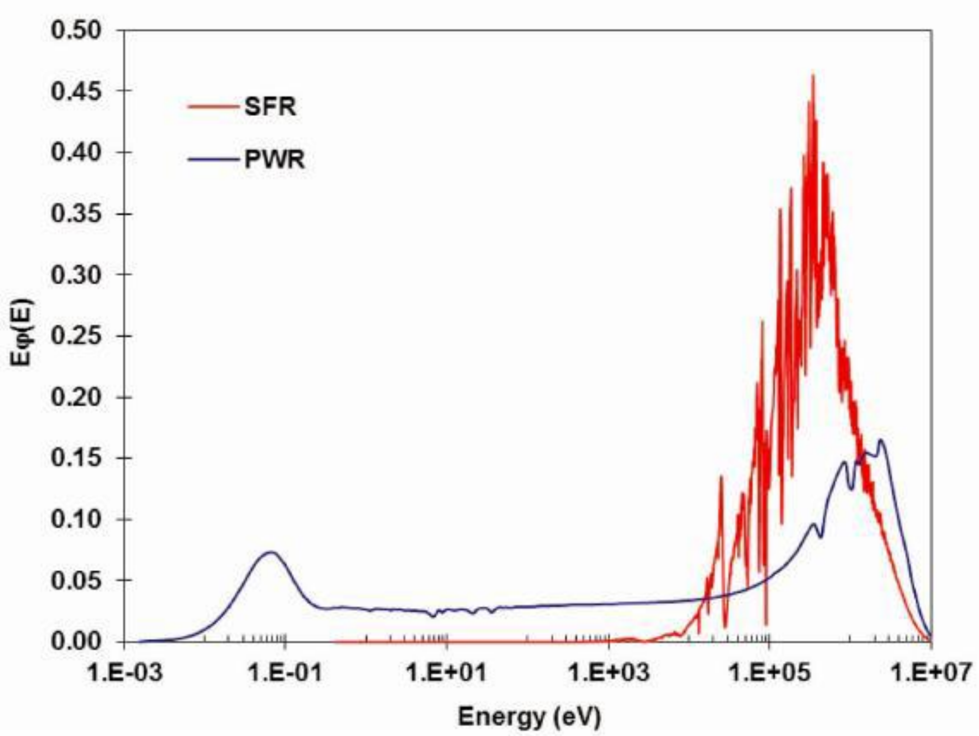
Gen-IV systems

System	Neutron spect. *	Fuel/ Cycle	Coolant	Tª in/out ºC	Pressure	Power MWe MWth	Power density ($MWth/m^3$)	Eff. (%)	Use
VHTR	Thermal	UO_2 spheres Open	Helium	900-1000	Medium 70-90 bar	250-300 600	06-10	50	Electricity H_2 Heat
SFR	Fast	U-238 MOX Closed	Sodium	550	Low 1 bar	50-1500 1000-5000	350	40	Electricity H_2 Actinides
SCWR	Thermal/ Fast	$U0_2$ Open Closed	Supercrit. water	510-625	Very high 230 bar	300-1700		40	Electricity
GFR	Fast	U-238 Closed	Helium/ CO_2	490/850	High 90 bar	600 1200	100	48	Electricity H_2 Actinides
LFR	Fast	U-238 Closed	Lead Bismuth	480-800	Low 1 bar	300-1000 400-3600			Electricity H_2
MSR	Thermal/ Fast	UF_4 Closed	Fluoride salt	700-850	Low 1 bar	1000	22	44-50	Electricity H_2

Neutron spectrum



Source: ***JANIS database***, NEA.



Source: ***Fast Reactor Physics and Computational Methods***. W.S. Yang. *Nuclear Engineering and Technology, 44(2), 2012*.

Neutron spectrum

In fast reactors, the process of moderation (fundamental in water cooled reactors) is avoided.

Advantages

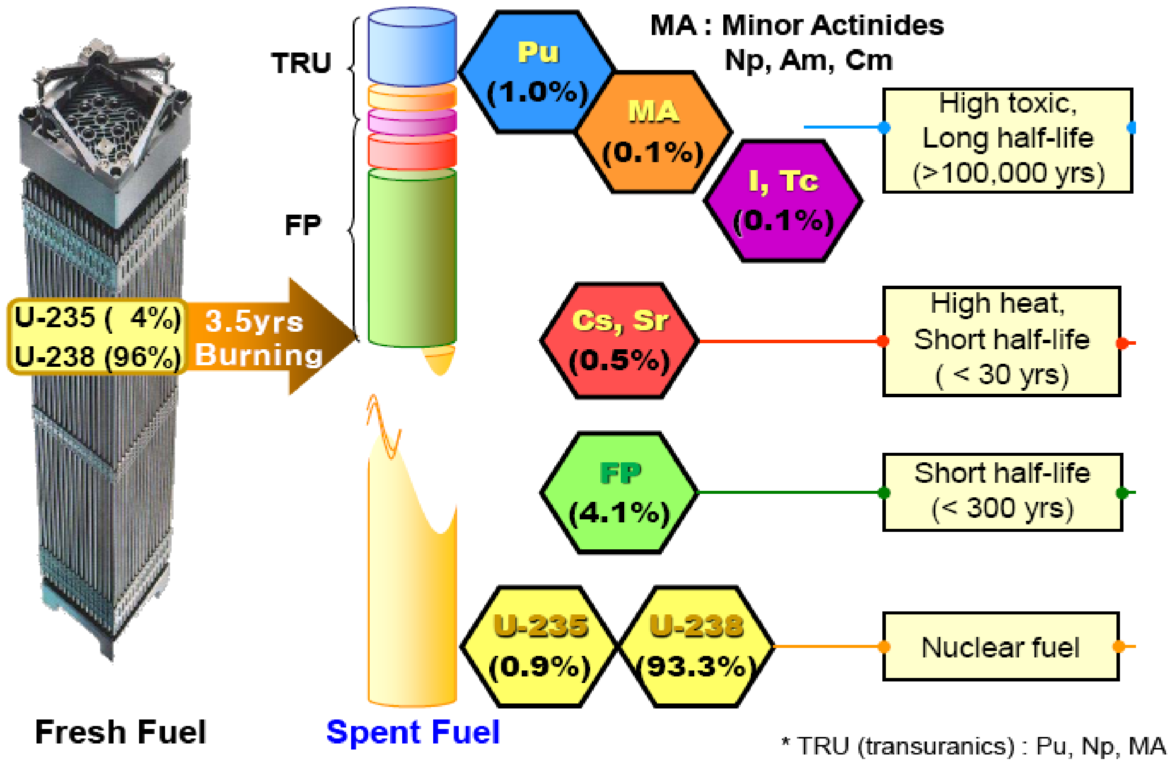
- Better neutron economy
- Access to interesting reactions
- Use of different coolant may improve the heat transference (natural circulation)

Disadvantages

- Larger enrichments
- Lower reaction time (delayed neutrons)
- Positive feedbacks
- Exotic coolants

Why fast spectrum?

- Reproduction/breeding: more efficient use of the uranium energy resources, since U-238 (fertile, no fissions) in Pu-239 (fissions)
- Partial removal of Minor Actinides (MA)



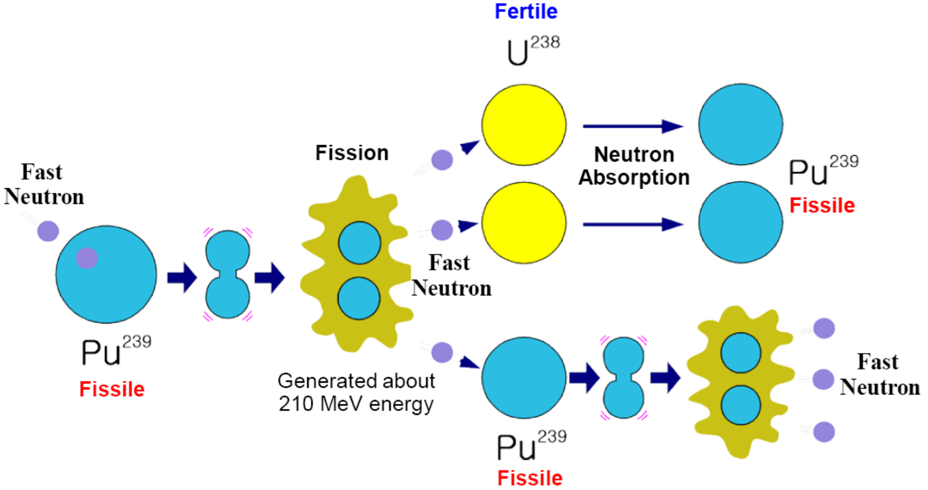
Plutonium breeding

- Reactors burn fissile material (FM) U-233, U-235 or Pu-239
- Additionally, they can generate them through fertile material (PM)

$$^{238}U \Rightarrow {}^{239}U \Rightarrow {}^{239}Np \Rightarrow {}^{239}Pu$$

$$^{232}Th \Rightarrow {}^{233}Th \Rightarrow {}^{233}Pa \Rightarrow {}^{233}U$$

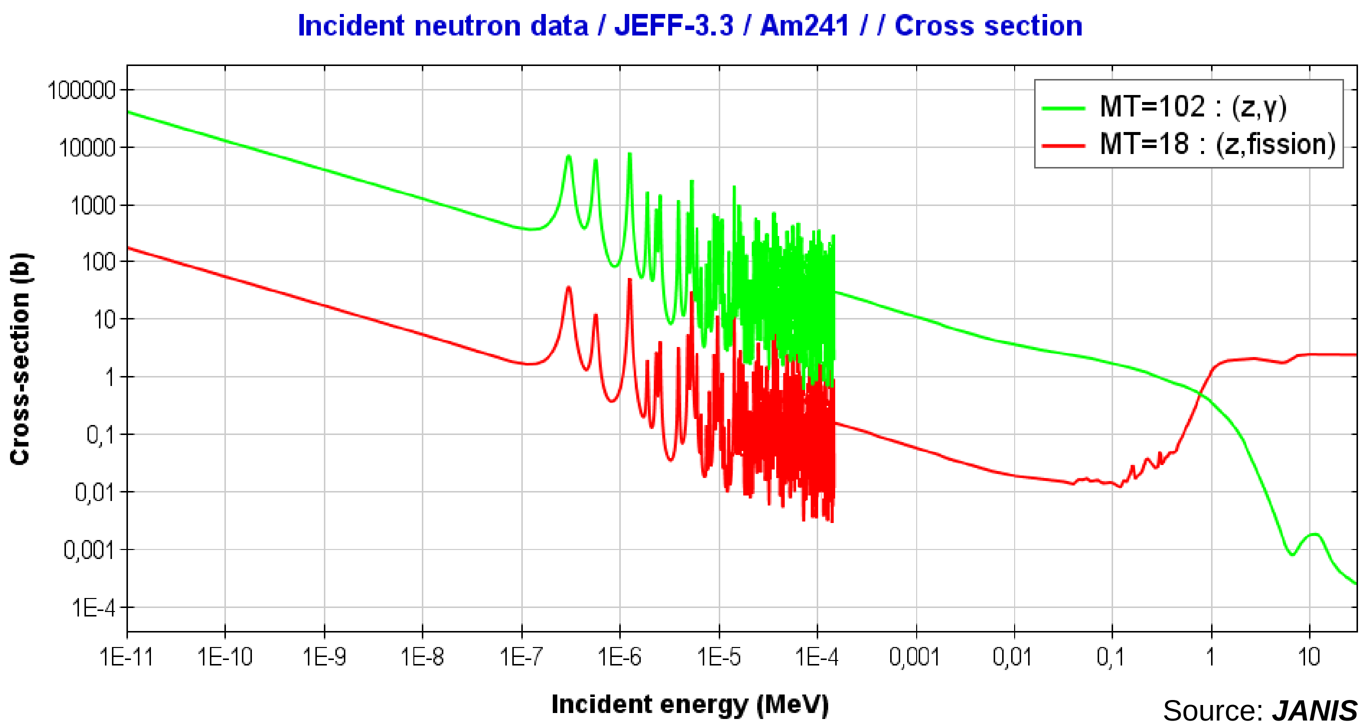
- PM/FM is the conversion ratio CR
  - Breeding gain is G = CR-1
- Only fast reactors obtain significant breeding gains



Transmutation of MA

Minor actinides: Np, Am y Cm

- Fission is favorable versus capture → larger elimination of heavy products

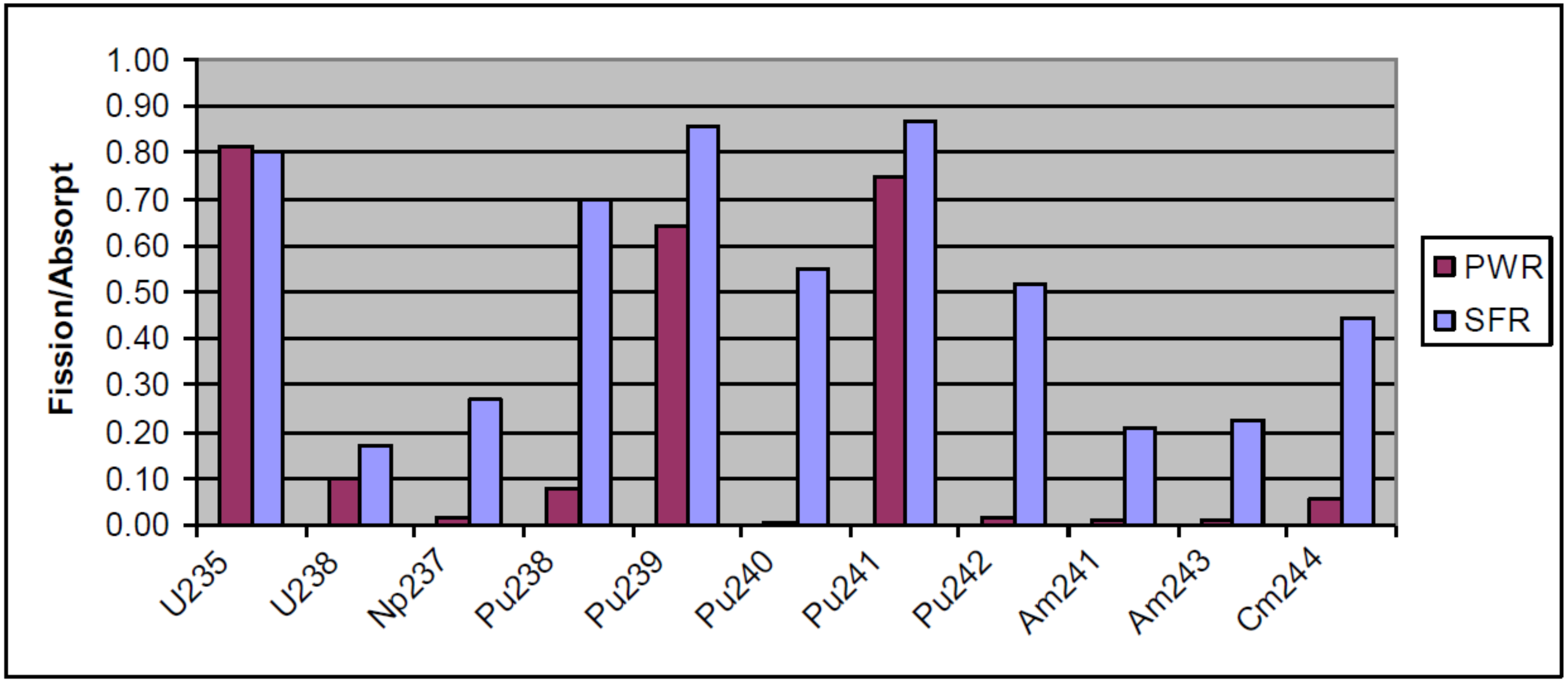


Source: ***JANIS database***, NEA.

Transmutation of MA

Minor actinides: Np, Am y Cm

- Fission is favorable versus capture → larger elimination of heavy products



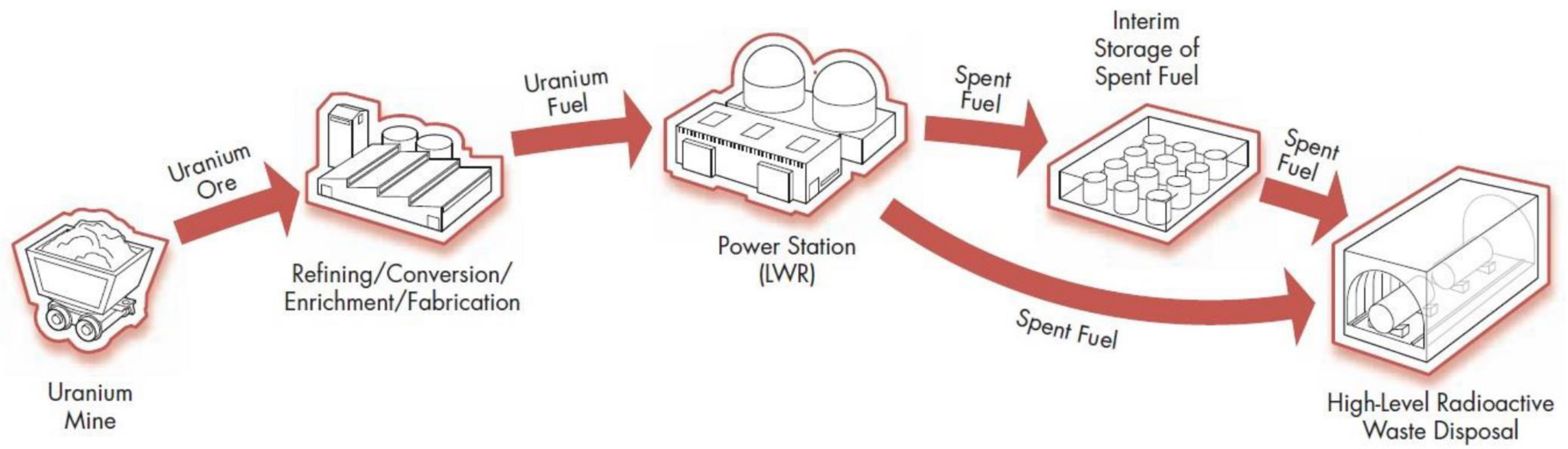
Source: ***Sodium-cooled Fast Reactor (SFR) Technology Overview***. T. Sofu. *IAEA Education & Training Seminar on Fast Reactor Science and Technology, Santa Fe, Mexico City, 2015.*

Gen-IV systems

System	Neutron spect.	Fuel/ Cycle *	Coolant	Tª in/out ºC	Pressure	Power MWe MWth	Power density ($MWth/m^3$)	Eff. (%)	Use
VHTR	Thermal	UO_2 spheres Open	Helium	900-1000	Medium 70-90 bar	250-300 600	06-10	50	Electricity H_2 Heat
SFR	Fast	U-238 MOX Closed	Sodium	550	Low 1 bar	50-1500 1000-5000	350	40	Electricity H_2 Actinides
SCWR	Thermal/ Fast	$U0_2$ Open Closed	Supercrit. water	510-625	Very high 230 bar	300-1700		40	Electricity
GFR	Fast	U-238 Closed	Helium/ CO_2	490/850	High 90 bar	600 1200	100	48	Electricity H_2 Actinides
LFR	Fast	U-238 Closed	Lead Bismuth	480-800	Low 1 bar	300-1000 400-3600			Electricity H_2
MSR	Thermal/ Fast	UF_4 Closed	Fluoride salt	700-850	Low 1 bar	1000	22	44-50	Electricity H_2

Nuclear fuel cycle

Open cycle (once-through)

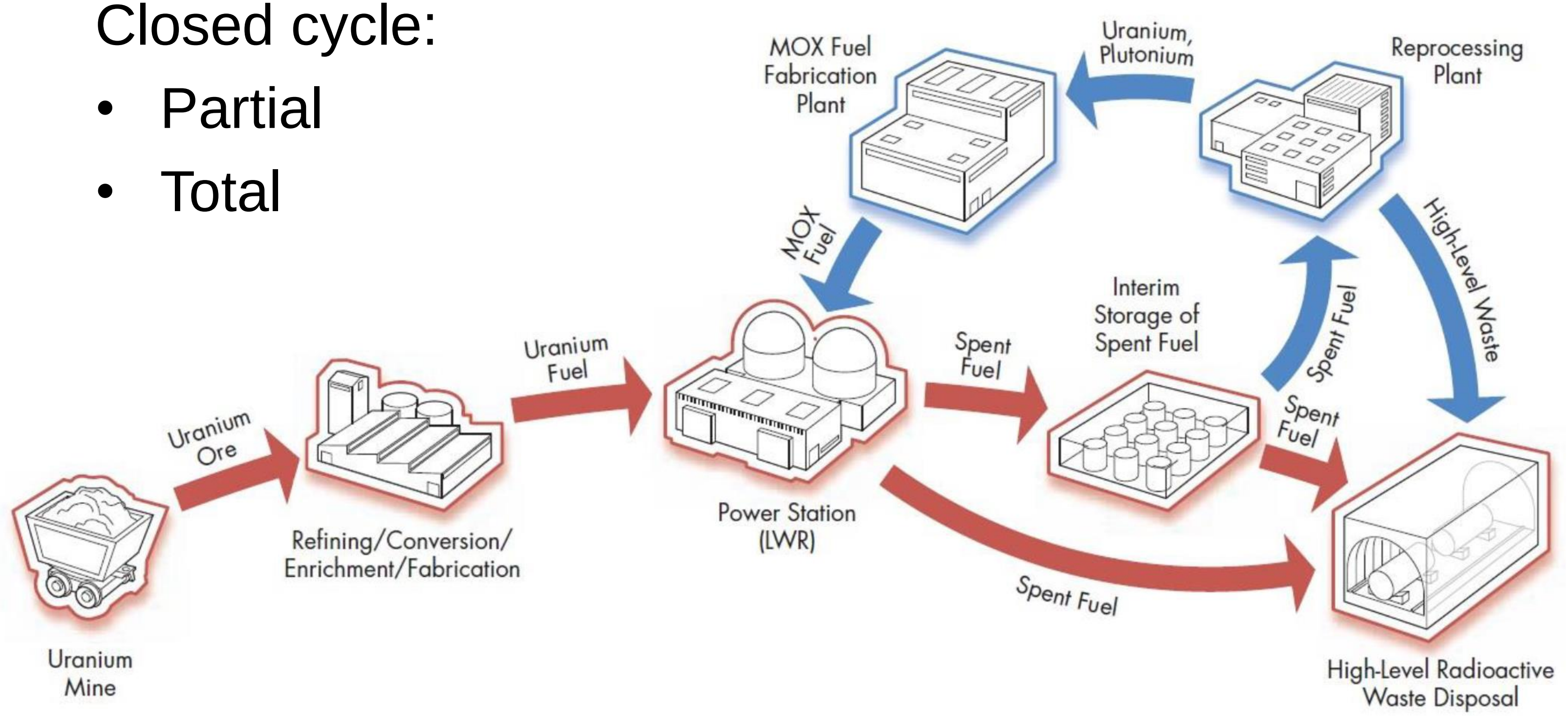


Source: A. Clamp. Toward an Integrated Nuclear Fuel Cycle. EPRI Journal, 2008 Spring

Nuclear fuel cycle

Closed cycle:

- Partial
- Total



Source: A. Clamp. Toward an Integrated Nuclear Fuel Cycle. EPRI Journal, 2008 Spring

Contents

Going back to previous ideas

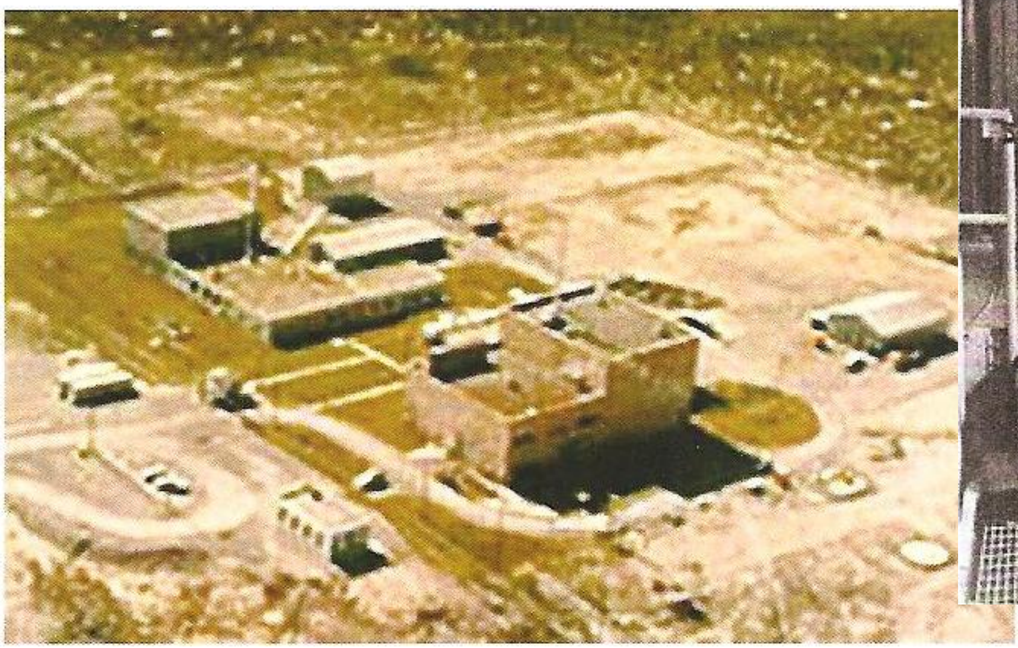
- Systems included in the Generation IV list are not new designs

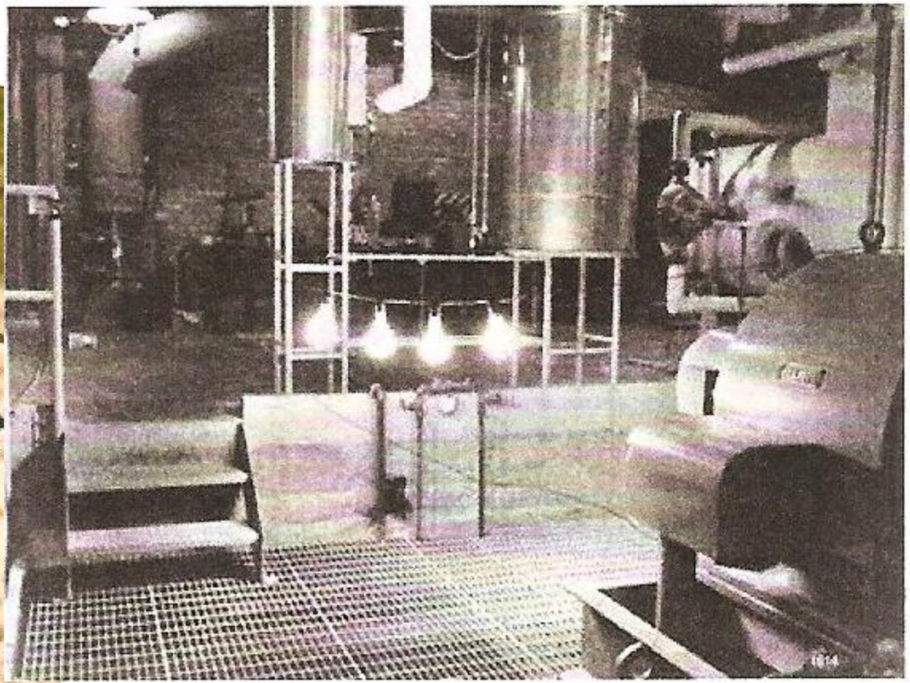
- Their studied began at the start of nuclear development, but due to the good response of thermal reactors, they were abandoned:
  - Insufficient development of turbomachines
  - Lack of proper technology for heat exchangers
  - Lack of experience with high pressures needed for the cycle

- Today, most of these issues have been solved thanks to engineering improvements

First nuclear electricity production

- The first fast reactor built was EBR-1 in 1951 in the Idaho National Engineering and Environmental Laboratory (INEEL) in Idaho Falls (USA).
- Besides, it was the first reactor (fast or not) used for the generation of electricity.





Development

Reactor	Type	Country	First critical	Coolant, Design	Fuel	MWth	Status
CEFR	E	CHI	2010	Na, Pool	oxide	65	In op.
Rapsodie	E	FRA	1967	Na, Loop	oxide	40	Shutdown
Phénix	D	FRA	1973	Na, Pool	oxide	563	Shutdown
Super-Phénix	C	FRA	1985	Na, Pool	oxide	2990	Shutdown
KNK-II	E	GER	1972	Na, Loop	oxide	58	Shutdown
FBTR	E	IND	1985	Na, Loop	carbide	40	In op.
JOYO	E	JAP	1977	Na, Loop	oxide	140	Suspended
MONJU	D	JAP	1994	Na, Loop	oxide	714	Suspended
BR-10	E	RUS	1958	Na, Loop	oxide carbide nitride	8	Shutdown
BOR-60	E	RUS	1968	Na, Loop	oxide	55	In op.
BN-350	D	KAZ	1972	Na, Loop	oxide	750	Shutdown
BN-600	D	RUS	1980	Na, Pool	oxide	1470	In op.
BN-800	C	RUS	2014	Na, Pool	oxide	2100	In op.
DFR	E	GBR	1959	NaK, Loop	metal	60	Shutdown
PFR	D	GBR	1974	Na, Pool	oxide	650	Shutdown
Clemen-tine	E	USA	1946	Hg, Loop	metal	0.025	Shutdown
EBR-I	E	USA	1951	NaK, Loop	metal	1.2	Shutdown
LAMPRE	E	USA	1961	Na, Loop	metal	1.0	Shutdown
EBR-II	E	USA	1963	Na, Pool	metal	65.5	Shutdown
Fermi-1	E	USA	1963	Na, Loop	metal	200	Shutdown
SEFOR	E	USA	1969	Na, Loop	oxide	20	Shutdown
FFTF	E	USA	1980	Na, Loop	oxide	400	Shutdown

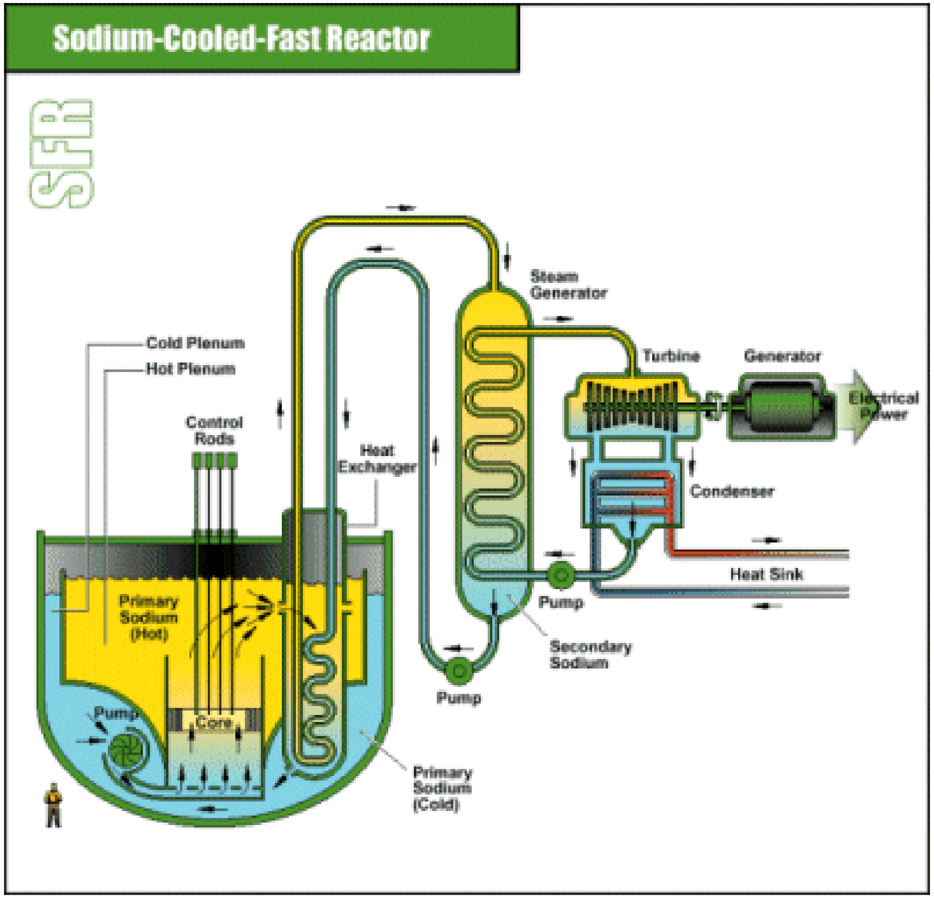
E – Experimental, D – Demonstrator, C – Commercial

Reactor	Type	Country	Plan	Coolant, Design	Fuel	MWe	Status
TWR-P	D	CHI	2022[a]	Na, Pool	metal	600	Design
TWR	C	CHI	2020s[a]	Na, Pool	metal	1150	Design
CFR-600	D	CHI	2025	Na, Pool	oxide	600	Design
CFR-1000	C	CHI	2030	Na, Pool	oxide, metal	1000	Design
ASTRID	D	FRA	2025	Na, Pool	oxide	600	Design
ALLEGRO	D	EU[1]	2030	He, Pool	oxide, carbide	75	Design
ALFRED	D	ROM	2025[b]	Pb, Pool	oxide	120	Design
MYRRHA	E	BEL	2025[c]	PbBi, Pool	oxide	100_{th}	Design
PFBR	D	IND	2016[d]	Na, Pool	oxide	1250	Under const.
JSFR	D	JAP	2025	Na, Loop	oxide	750	Susp.
Prototype SFR	D	KOR	2028	Na, Pool	metal	150	Design
SVBR-100	C	RUS	2025[e]	PbBi, Pool	oxide, nitride	100	Design
BREST-300	D	RUS	2020[f]	Pb, Pool	nitride	300	Design
MBIR	E	RUS	2020	Na, Pool	oxide, nitride	30	Under const.
BN-1200	C	RUS	2025	Na, Pool	nitride, oxide	1220	Postp.

R – Research, D – Demonstrator, C – Commercial

Source: E. Nikitin, PhD thesis: https://infoscience.epfl.ch/record/264193/files/EPFL_TH7264.pdf

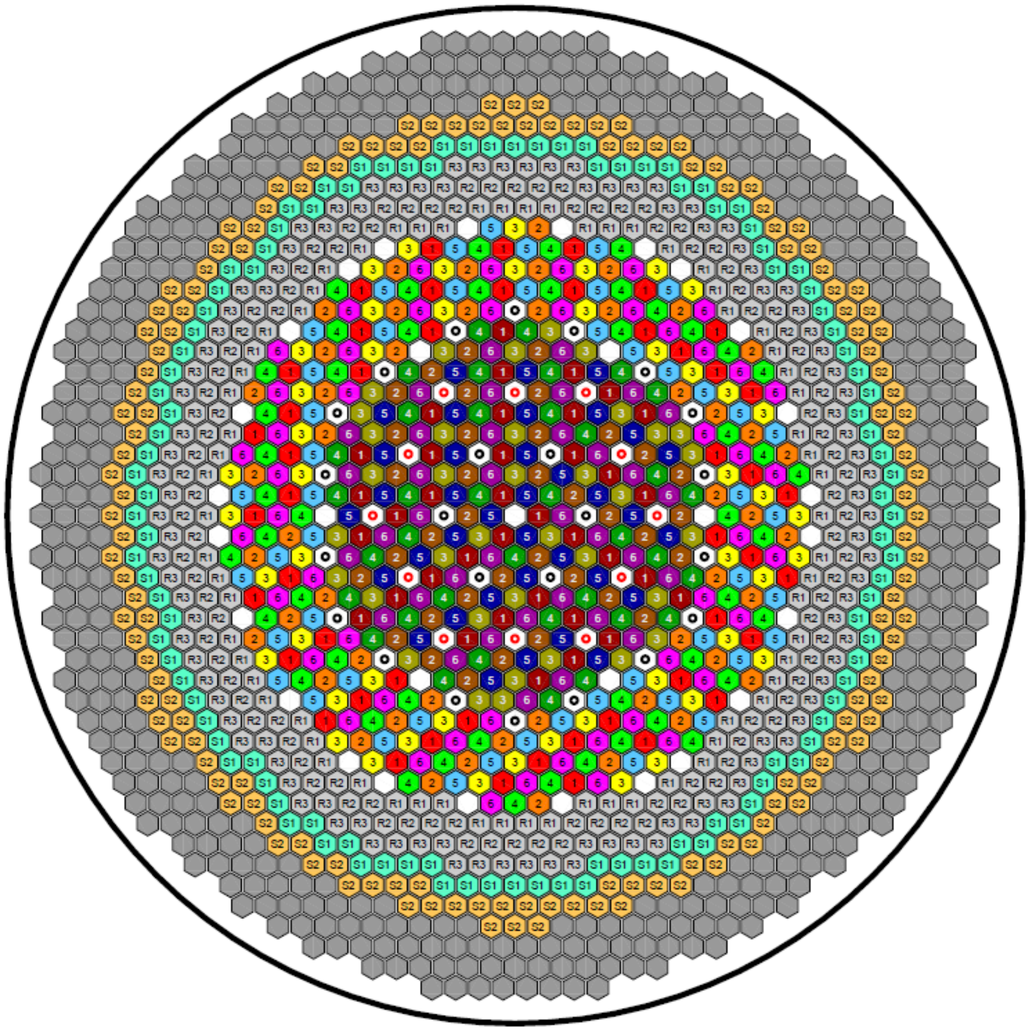
Sodium-cooled fast reactor

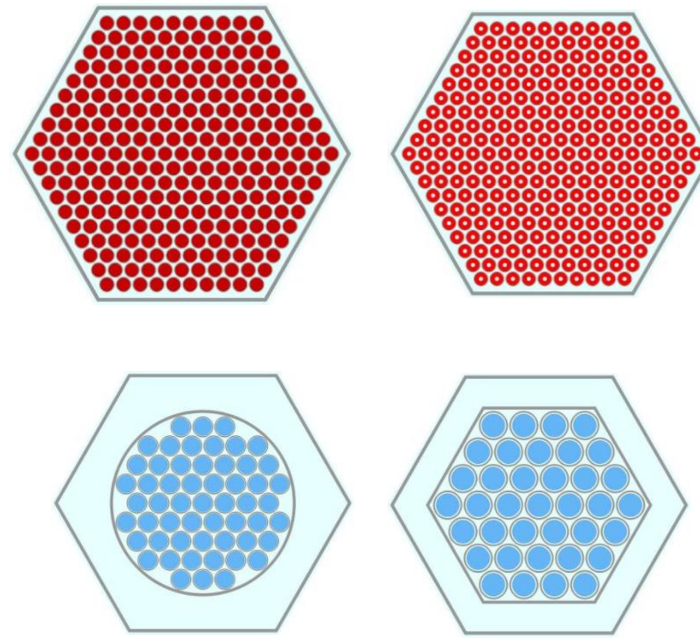


SFR characteristics

- Low pressure
- High temperature
- Large margin for sodium boiling
- Small margin for sodium solidification
- Single phase system
- Large difference in the temperatures of sodium and heat sink
- **Positive feedback in void worth**
- **Chemical reaction sodium-water-air**

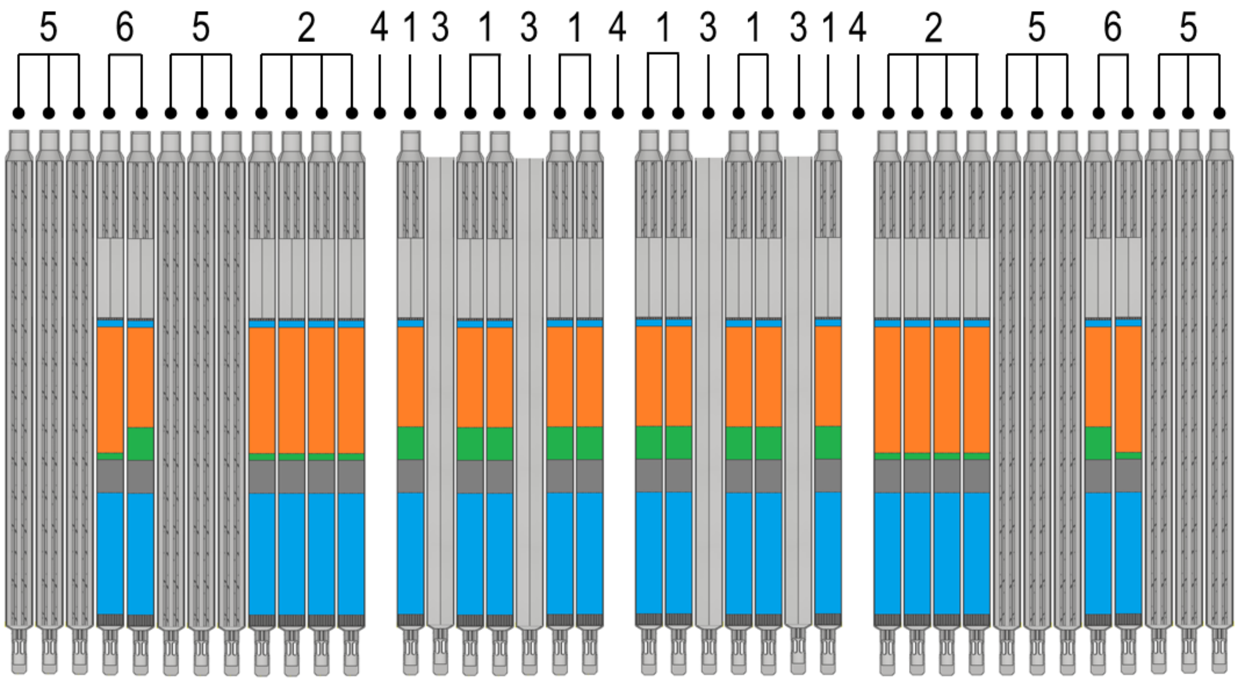
ESFR-SMART core (XY view)





Source: Specification of the new core safety measures. ESFR-SMART project: Deliverable1.1.2 Downloadable in: https://zenodo.org/record/1990703#.XM7V5egzZPZ

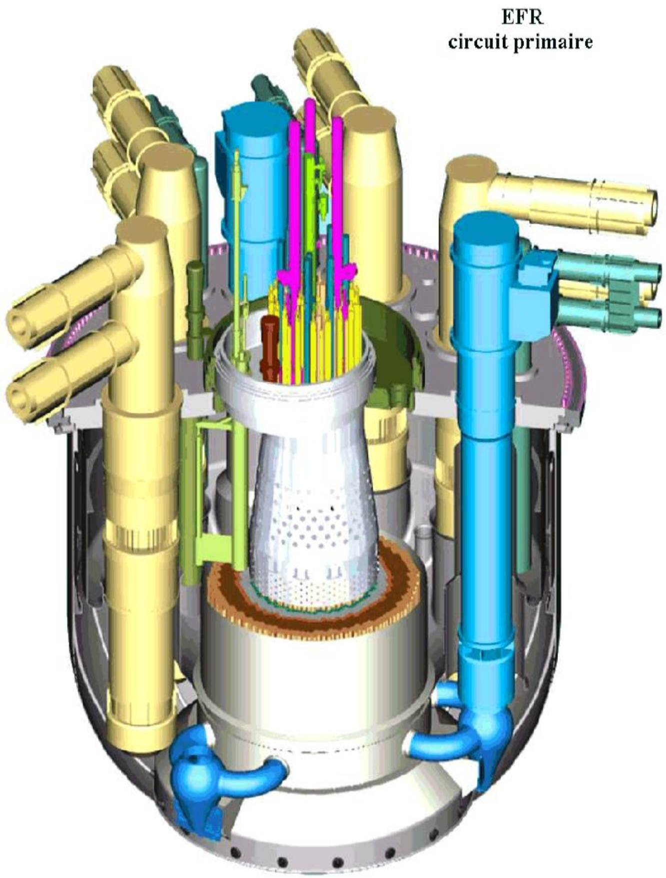
ESFR-SMART core (axial view)

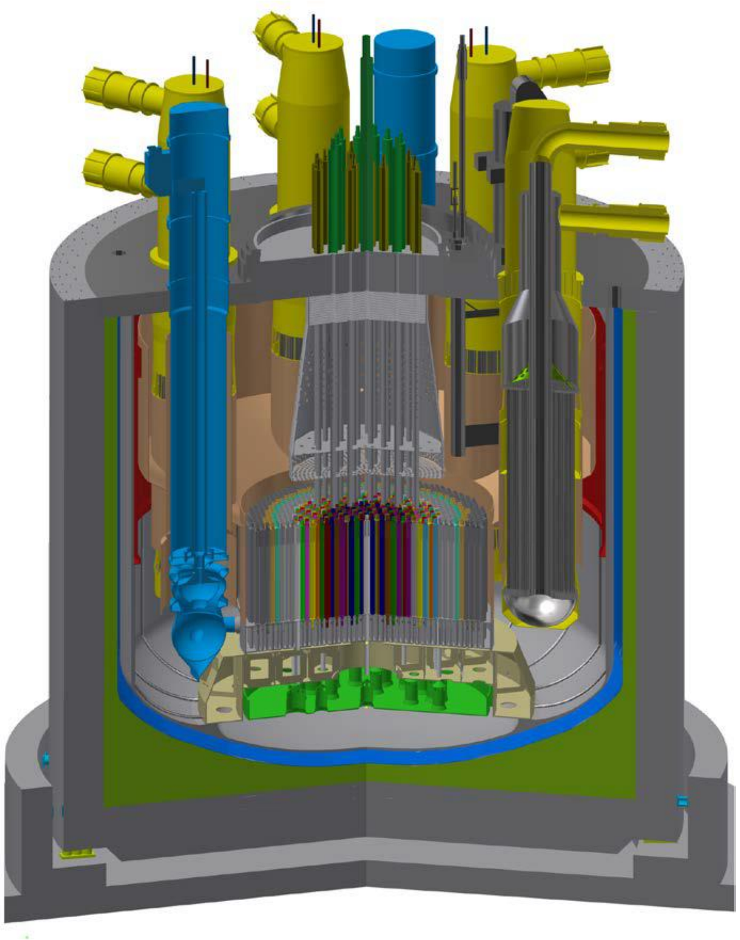


1 – Inner zone SA
2 – Outer zone SA
3 – Control assembly
4 – Corium discharge path
5 – Shielding SA
6 – Internal spent fuel storage

Fissile fuel (~18% Pu content)
Fertile blanket
Steel blanket
Fission gas plenum
Sodium plenum
Shielding (absorber)

Internals (EFR and ESFR-SMART)

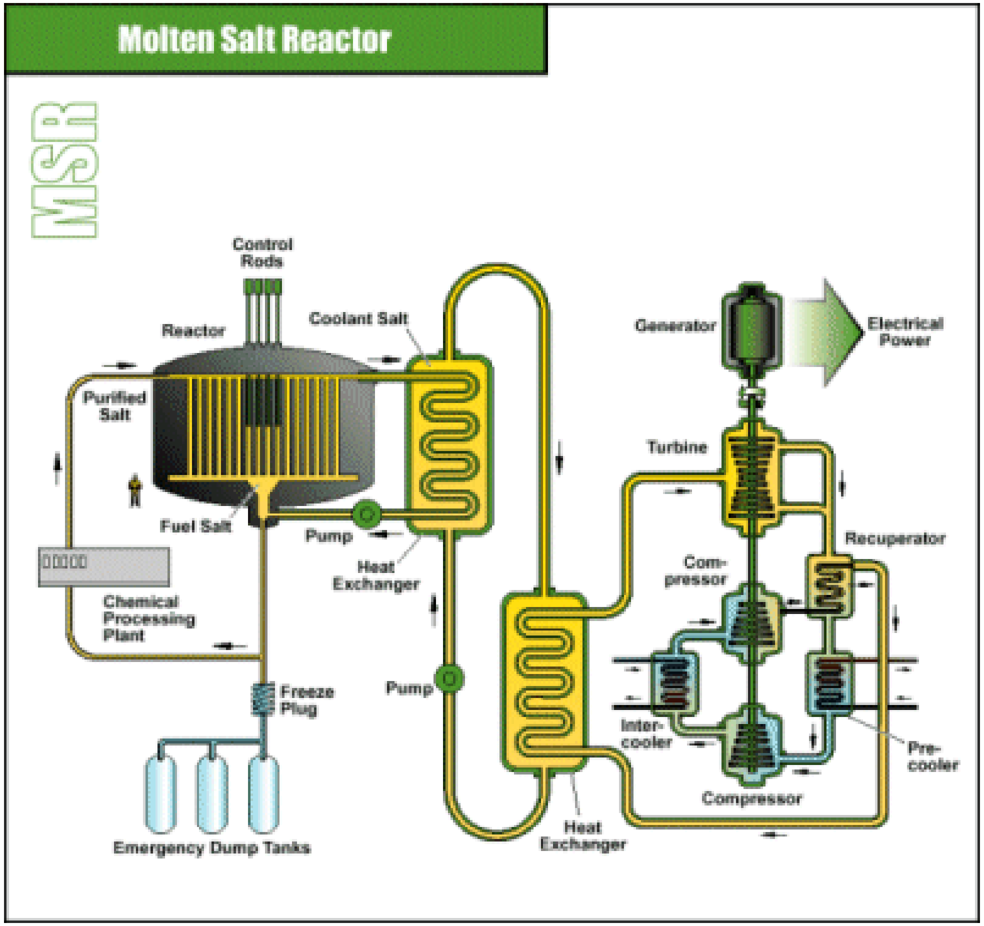




Source: New safety measures proposed for ESFR in H2020 ESFR-SMART project. J. Guidez et al., GIF Symposium, Paris (2018). https://zenodo.org/record/1479044#.XM8NnOgzZPa

Contents

Molten salt reactor (MSR)



MSR characteristics

- Very flexible for fuel contents, breeding gain and reprocessing
- Their high temperature is an advantage for high efficiency, but also an inconvenience due to preheating requisites in equipment and constant maintenance.
- Breeding gain is lower due to larger captures in the molten salt.
- Lower moderation leads to larger critical mass.
- Liquid fuel needs contention and need for remote repairs.
- High corrosion.

MSFR

- Better use of natural resources (thorium)
- Low pressure and high boiling temperature
- In-situ fuel reprocessing → research in pyrochemistry
- Improvements in T and ρ coefficients (negative).
- Lower fissile content, with homogeneous isotopic composition.
- Molten salt as coolant:
  - *Fluoride salt-cooled High-temperature Reactors* (FHRs)
  - Thorium: TMSRs, LFTRs

Contents

Conclusions

- Nuclear fission is a well-known technology
- The Generation IV international forum leads the way for safe, sustainable and competitive new designs
- Six technologies have been chosen
- Sodium technology is closer to implementation since it has a larger experience
- Other designs are also possible, with additional possibilities as SMR

Bibliography

- ***Fast Spectrum Reactors***, A.E. Waltar, D.R. Todd, P.V. Tsvetkov. Springer, 2012.
- ***Fast Breeder Reactors***. Waltar A. y Reynolds A. Pergamon Press, 1981.
- ***Handbook of Nuclear Engineering***. D.N. Cacuci (editor). Springer, 2010.
- ***Les systèmes nucléaires du futur*** (Clefs CEA n° 55) Revue Clefs CEA – Eté, 2007.
- www.gen-4.org/index.html
- www.snetp.eu
- www.jaea.go.jp/english/index.shtml
- www.nucleaire.cea.fr/fr/nucleaire_futur/generalites.html
- http://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-03-04-03-07-CF-NPTD/T3.1/T3.1.yamaguchi.pdf
- http://www.iaea.org/INPRO/cooperation/Second_IAEA-GIF_WS_on_SFRs/presentations/T5-JP-Kubo.pdf
- http://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-02-26-02-27-TM-SFR/day-1/2-J.Yllera-IAEA.pdf

Joint ICTP-IAEA-MAMBA School on Materials Irradiation: from Basics to Applications

Thank you for your attention

Francisco Álvarez-Velarde

Nuclear Innovation Unit – CIEMAT (Spain)

francisco.alvarez@ciemat.es