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Technological readiness of alternative reactor concepts

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Agenda

1

„Novel“ Reactor Concepts

Expert opinion on „novel“ reactor concepts

- Overview of currently internationally pursued technology lines and reactor concepts
- Assessment of technology readiness, safety, fuel supply, waste disposal and proliferation risks, as well as costs
- Small modular reactor concepts not considered in depth

Bundesamt für die Sicherheit der nuklearen Entsorgung

BASE – FORSCHUNGSBERICHTE ZUR SICHERHEIT DER NUKLEAREN ENTSORGUNG

Analyse und Bewertung des Entwicklungsstands, der Sicherheit und des regulatorischen Rahmens für sogenannte neuartige Reaktorkonzepte

Zwischenbericht zu AP-1 und -2
Vorhaben 4721F50501

AUFTRAGNEHMER:
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Fanny Böse
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Lukas Gast

→ Available at:

https://www.base.bund.de/DE/themen/kt/kta-deutschland/neuartige-reaktorkonzepte/sogenannte-neuartige-reaktorkonzepte_node.html

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  - Fanny Böse
  - Björn Steigerwald
  - Lukas Gast

Important definitions

- So-called „novel“ reactor concepts or „alternative“ reactor concepts
  - History of concepts is often decades old
  - Questioning the „linear“ generation concept of the GIF (Generation IV)

Concept of reactor generations (within a technology line)

Techno-logielinie	Erste Experimental-reaktoren	Erste Leistungsreaktoren (Gen I)	Weiterentwickelte Leistungsreaktor-konzepte (Gen II)	Fortgeschrittene Reaktorkonzepte (Gen III)
PWR	MTR, S1W, S2W, MZFR	Shippingport, Obninsk, Obrigheim	Konvoi	AP-1000, VVER-1200, EPR
BWR	BORAX-I bis -V, Kahl	Dresden I, Gundremmingen-A	SWR-72	*(KERENA)*, ABWR
PHWR	ZEEP, NRX, NRU	Rolphton	CANDU 500, CANDU 6	*(EC 6, ACR-1000)*
GCR	CP-1, Windscale	Calder Hall, Marcoule	AGR	-
VHTR	Dragon, AVR, HTR-10	Peach Bottom, THTR, HTR-PM, *(VHTR)*	-	-
SFR	Fermi I, Br-10, CEFR, KNK I und II, Rapsodie, TWR	BN-800, Monju, Super-Phoenix	*(BN-1200)*	-
LFR	*(BREST-OD300)*	-	-	-
GFR	*(GFR)*			
MSR	ARE, MSRE	*(LFTR, MCFR)*	-	-
SCWR	HDR	*(CSR1000)*	-	-
ADS	*(MYRRHA)*	-	-	-

Quelle: (IAEA 2023c; Greenspan 2021; GIF 2002), geplante, jedoch bislang nicht in Betrieb befindliche Konzepte sind kursiv geschrieben und in Klammern gesetzt

Important definitions

- So-called „novel“ reactor concepts or „alternative“ reactor concepts
  - History of concepts is often decades old
  - Questioning the „linear“ generation concept of the GIF (Generation IV)
- Distinction between „technology lines“ vs. „reactor concepts“
  - Superordinate term for roughly similar concepts: „technology line“
  - Detailled concept within a technology line: „reactor concept“

„Technology lines“

- Accelerator Driven Systems, ADS
- Supercritical Water-cooled Reactors, SCWR
- Sodium-cooled Fast Reactors, SFR
- Lead-cooled Fast Reactors, LFR
- Gas-cooled Fast Reactors, GFR
- Very High Temperature Reactors, VHTR
- Molten Salt Reactors, MSR

Systematization of technology lines and corresponding reactor concepts

Technology line	Distinguishing criteria				Reactor concept /
	Criticality	Coolant	Moderation	Further features	Facility
ADS	No				MYRRHA
SCWR	Yes	Water			CSR1000
SFR		Sodium		With Rep.	BN-800
				Without Rep.	TWR
LFR		Lead			Brest OD-300
GFR		Gas	No		GFR
VHTR			Yes	Spherical FE	HTR-PM
				Prismatic FE	Prismatic HTR
MSR		Salt	No		MCFR
			Yes		LFTR

Own systematization

2

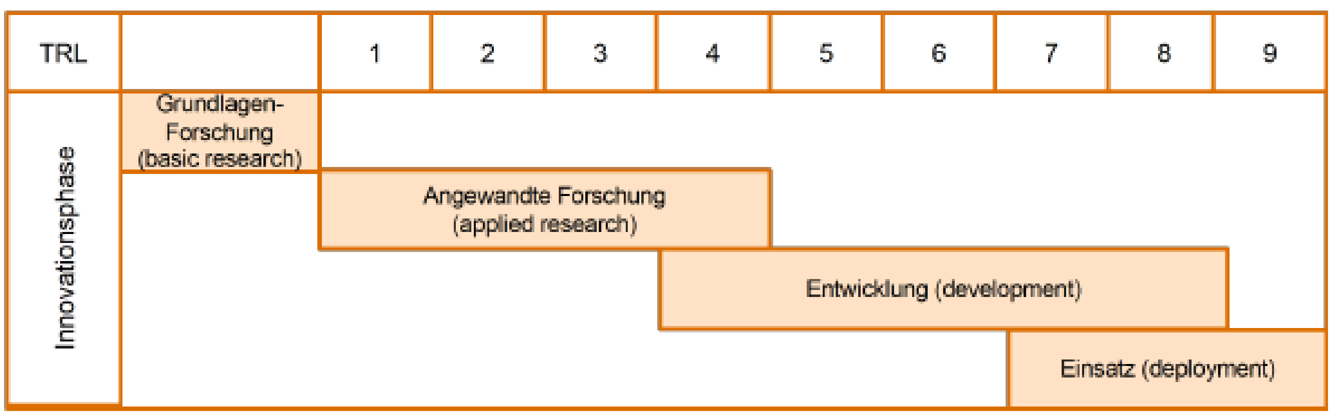
Evaluation Criteria

Technology readiness

Three levels each, „lowest“ classification defines overall level

- „Applied Research“
- „Development“
- „Deployment“

Abbildung 2-2: Gegenüberstellung der 9-stufigen TRL-Skala und einer drei-stufigen Technologieeinordnung



Quelle: Eigene Darstellung

Technology readiness

Three levels each, „lowest“ classification defines overall level

- „Applied Research“
- „Development“
- „Deployment“
- Indicators:
  - Fuel/Materials
  - Operational requirements, inspection, maintenance, aging management
  - I&C
  - Safety functions
  - Safety assessment

Other evaluation criteria

Reference is today‘s LWRs

Three levels:

- Advantage
- No significant advantage or disadvantage
- Disadvantage

Assessement

- is based on inherent properties (technology line)
- depends (mostly) on the specific design (reactor concept)

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Safety

Indicators:

- Normal operation
- Safety functions:
  - Reactivity control
  - Cooling
  - Confinement of radioactivity
- Event spectrum
- Safety verification

Fuel supply and waste

Indicators:

- Fissile material demand/Fuel production
- Waste streams (qualitative)
- Waste inventories (heat production, activity, volume, mass)
- Long-term safety aspects

Proliferation

Indicators:

- Uranium enrichment requirements
- Reprocessing planned/necessary
- Pu vector and Pu quantities

Costs

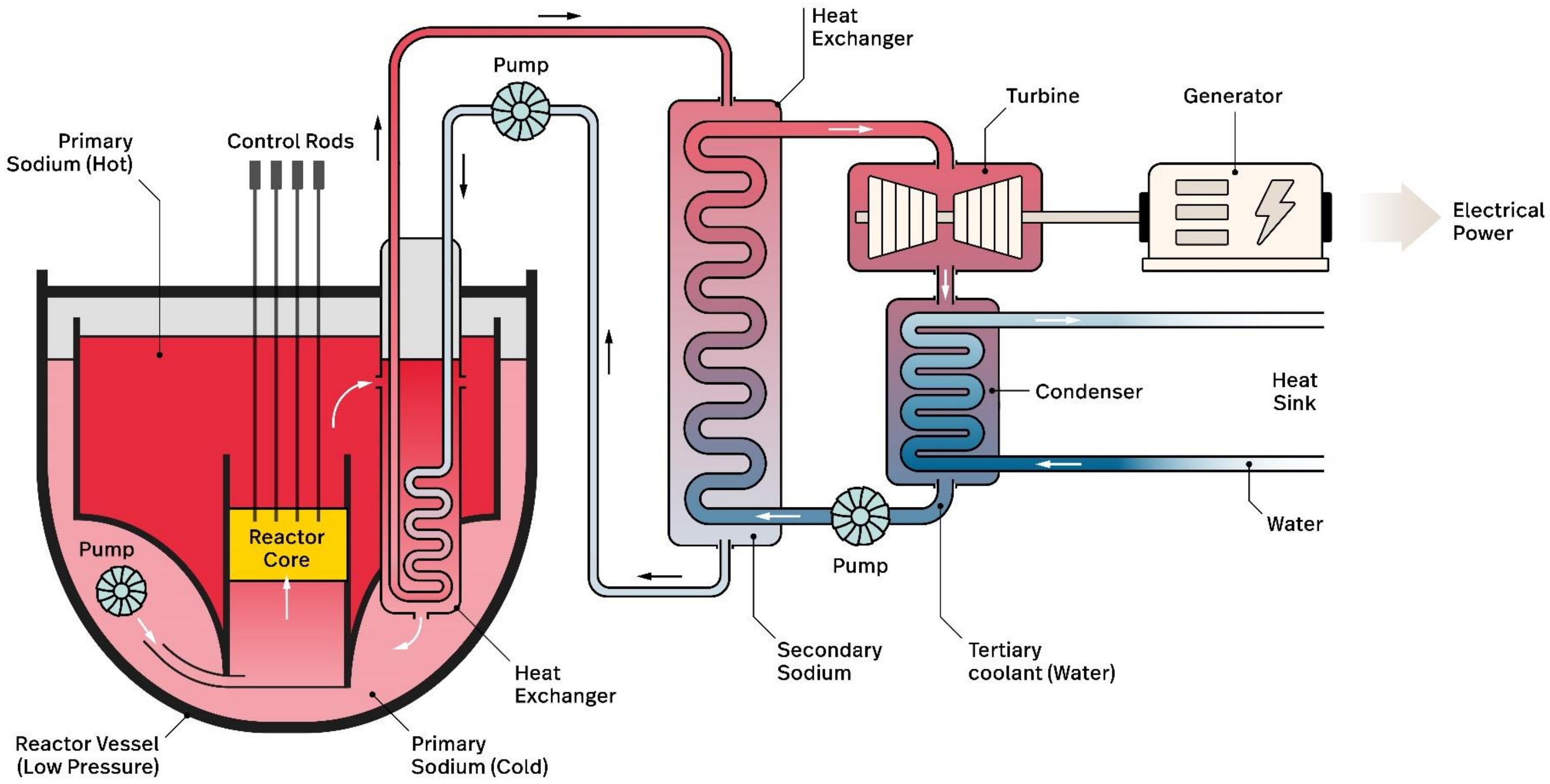
Indicators:

- Investment costs
- Operation costs
- Construction times
- Investment risks
- Planned service life/load factors

3

Examplary discussion

Sodium-cooled Fast Reactors (SFR)



(Major) Advantages/Disadvantages

- Better utilization of uranium
- Low pressure of primary coolant (loss-of-coolant events less demanding)
- Higher operating temperature

- Opaque (non-transparent) coolant (problematic for inspection and maintenance)
- Reactivity control more demanding (positive feedback effects)
- Chemically reactive coolant (sodium fires)
- Higher proliferation risks with closed fuel cycle
- Higher investment costs

BN-800

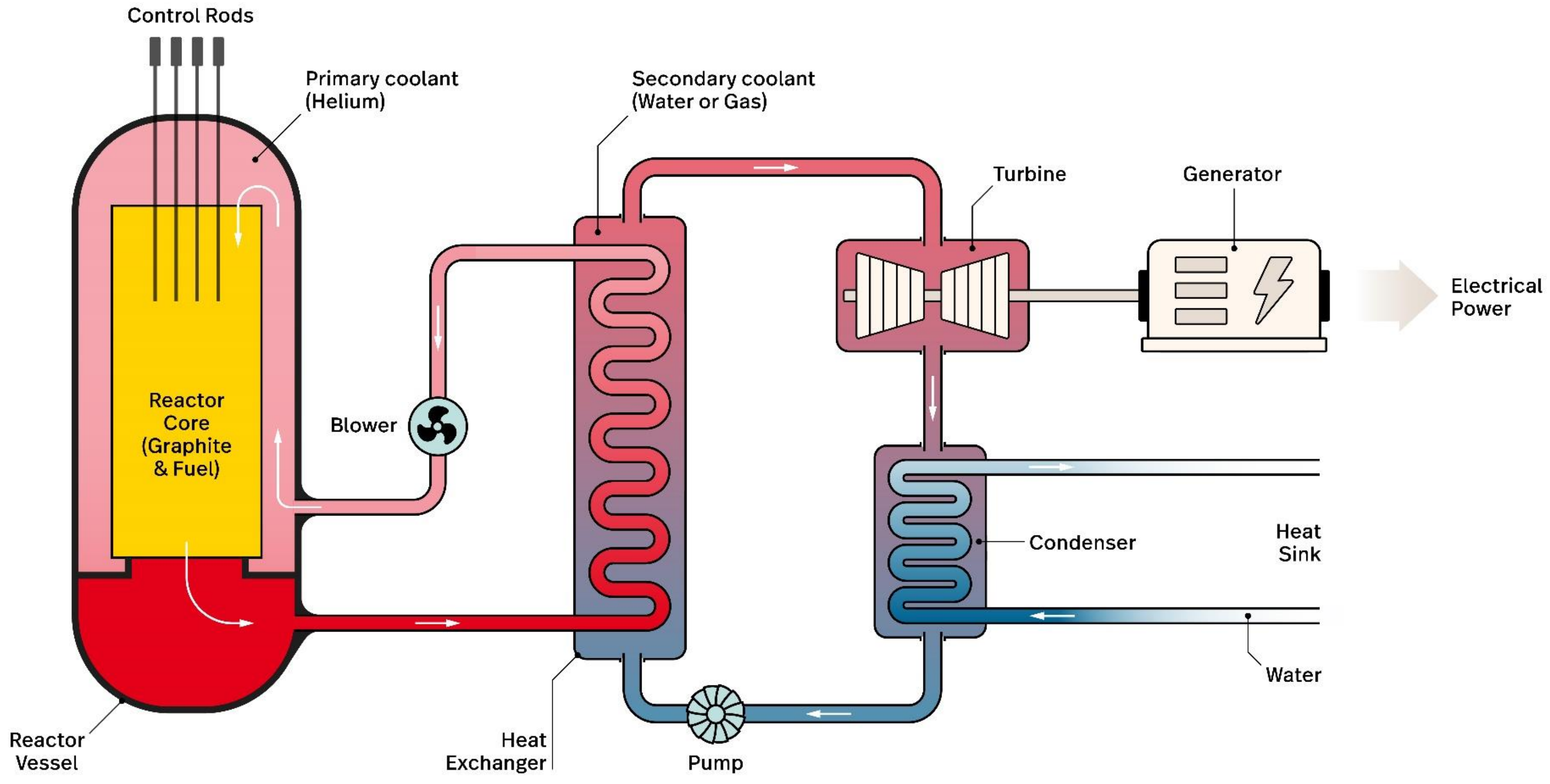
Quelle: Nori, DOI: 10.13140/RG.2.2.31153.81761/1

Line:	SFR
Name:	Beloyarsk-4
Country:	Russia
Developer:	Rosenergoatom
Power:	820 MWe (Net) / 885 MWe (Gross)
Coolant:	Sodium
Moderator:	/
Fuel:	MOX (with Rep.)
Neutron spectrum:	Fast

SFR – A few conclusions

- Status: more than 20 prototype reactors and 400 years of operating experience for 70 years of research and development, but still no commercially viable system
- Fuel utilization: fundamental aspect of breeding of new fissile material, but not needed in the foreseeable future
- Safety: specific advantages as well as disadvantages, actual safety performance so far is poor
- Proliferation: potentially significant disadvantage, since weapons-grade fissile material can be produced, but highly dependant on actual technical design

(Very) High Temperature Reactors – (V)HTR



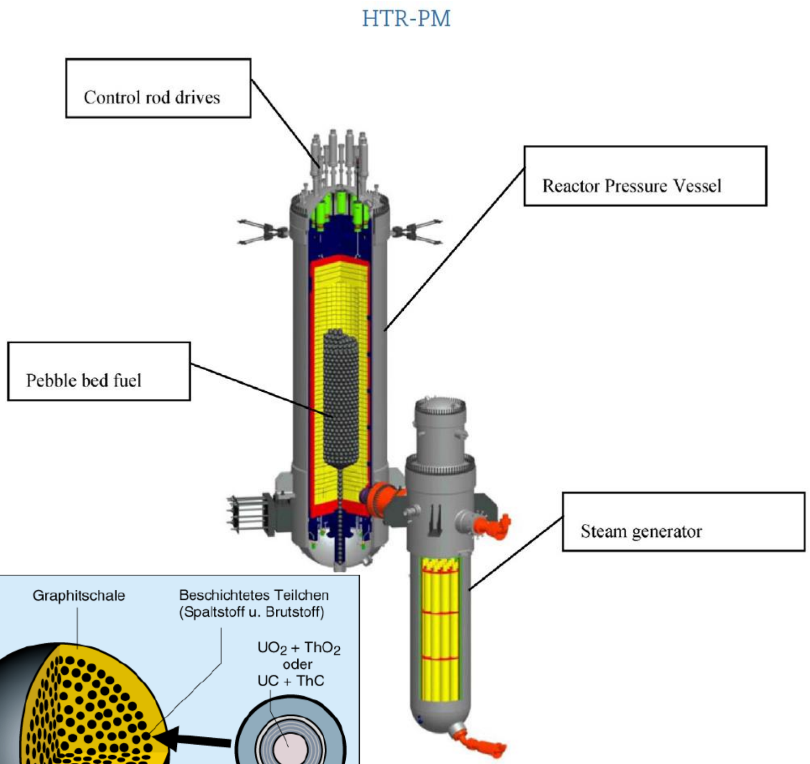
Source: BASE

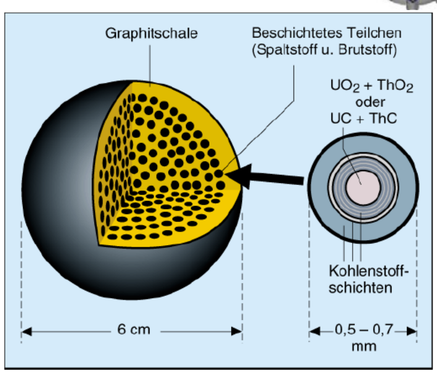
(Major) Advantages/Disadvantages

- High working temperatures of the coolant
- Chemically inert and optically transparent coolant
- Strong negative reactivity feedback
- Possible passive residual heat removal from the reactor core
- Confinement by TRISO-fuel up to approx. 1600°C

- Limitation of the power size for passive properties
- Exclusion or control of other accident sequences needed (air/water intrusions, graphite fire)
- High amounts of graphite waste

HTR-PM (Tsinghua University, China)





Schematische Darstellung der Brennstoff-kugel des Kugelhaufen-Reaktors

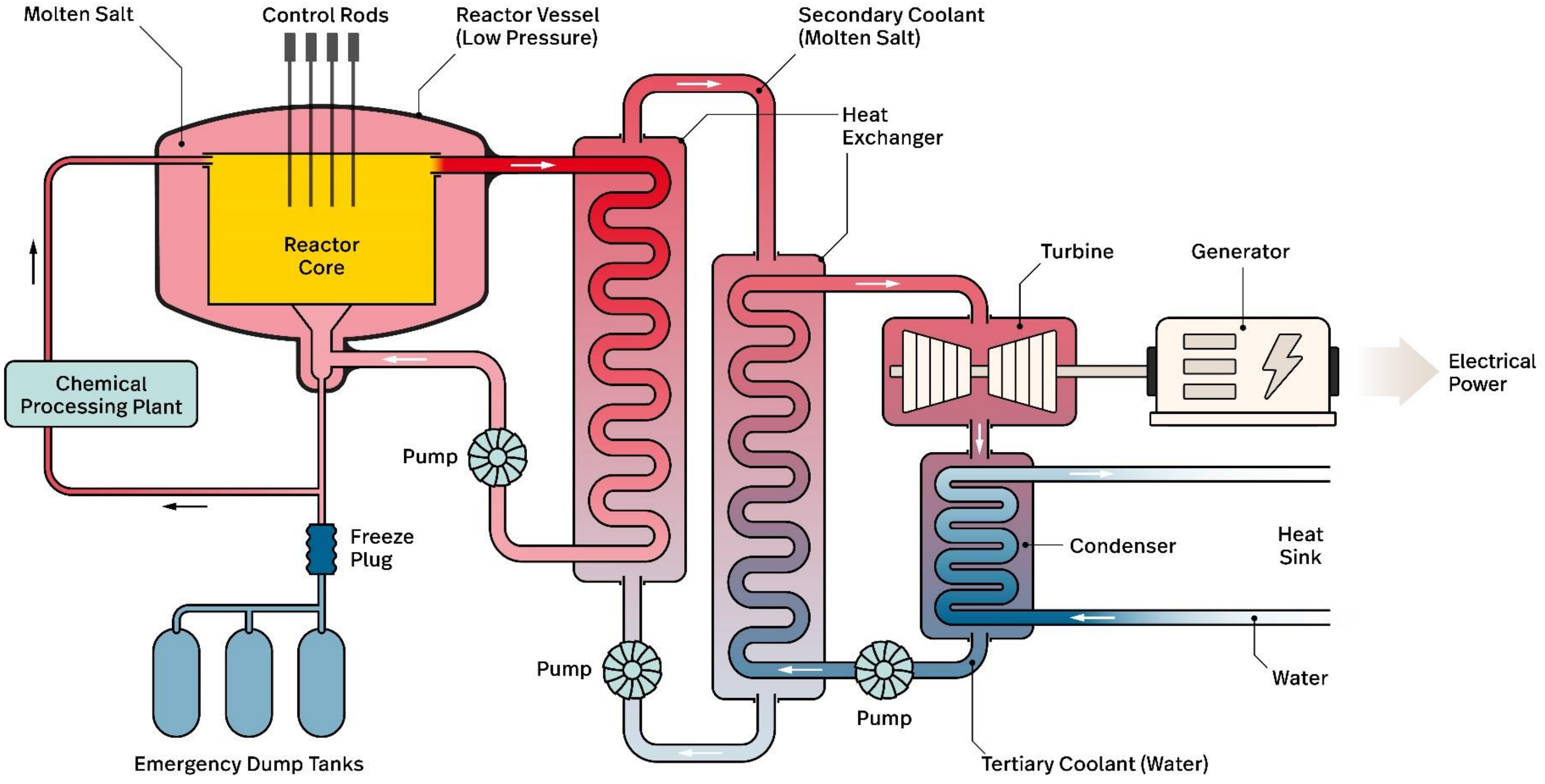
- Development (in China) since 2001, commissioning December 2021
- 210/2 MWe, gas cooled (Helium), graphite moderated pebble bed
- 8.5% enriched UO_2–TRISO fuel
- Partial passive safety properties (strongly negative temperature coefficients, high heat capacity)
- Continuous refuelling
- 750°C Output temperature
- No Containment
- Thermal neutron spectrum

Sources: GIF 2018, Kölzer 2011, IAEA ARIS 2018
According to manufacturer

(V)HTR – A few conclusions

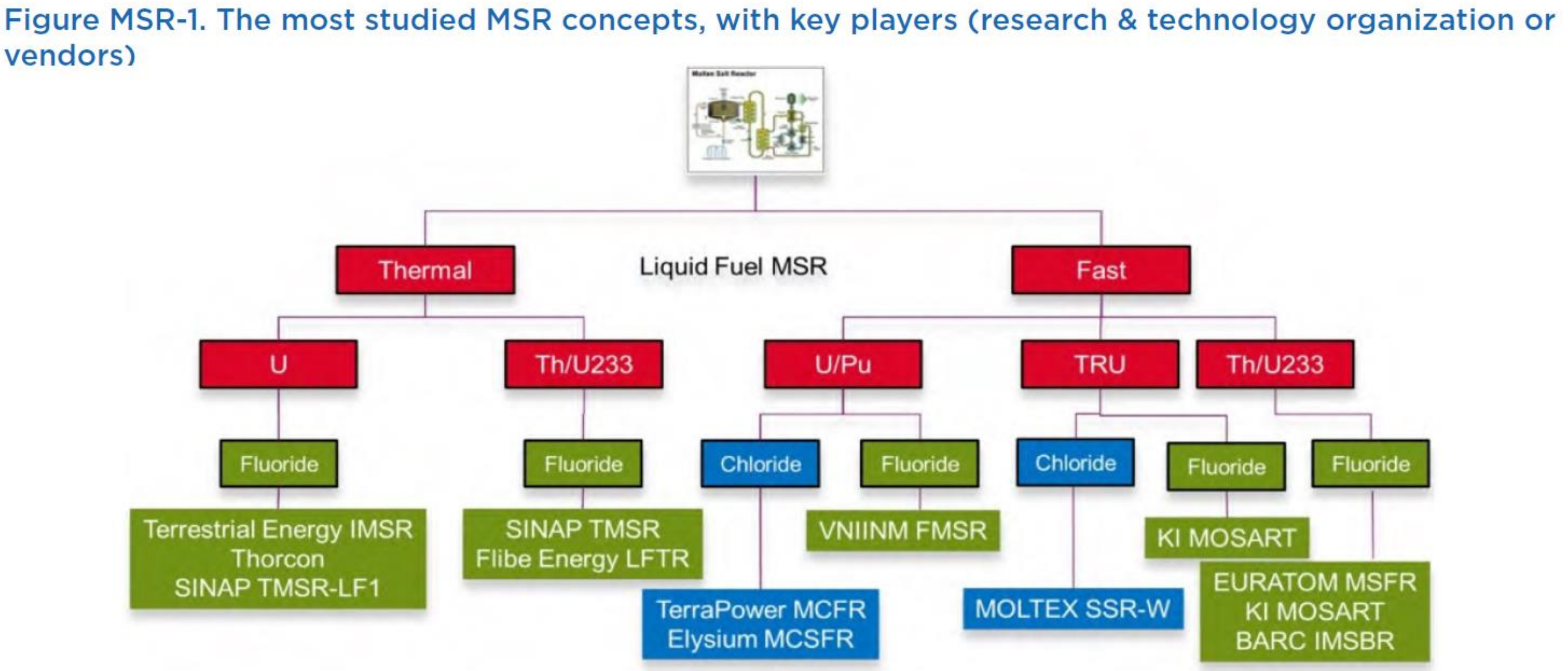
- Status: 60 years of development, several ambitious research and development programs (USA, Germany, South Africa) have failed. New attempt in China.
- Safety: Possibly specific advantages with respect to loss-of-coolant events (passive heat removal), but other accident scenarios need to be considered in detail (air and water intrusion, graphite fires …)
- Waste: comparable waste problem, but different waste properties (graphite) to be considered
- Economics: limitation to low total power to maintain passive cooling characteristics. Temperature < 750°C and water-steam secondary cycle to minimize development time and risks.

Molten Salt Reactors, MSR



Source: BASE

Many different reactor concepts possible



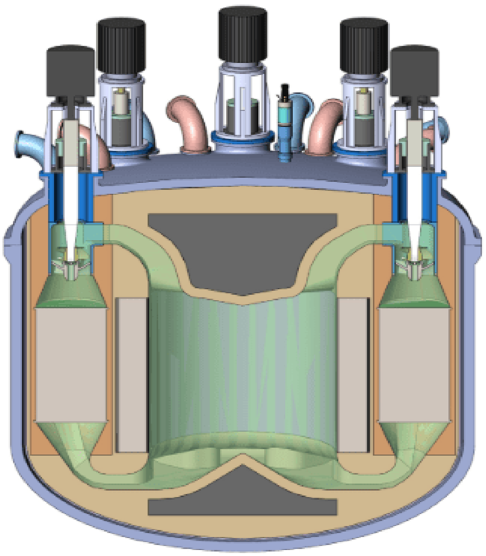
Source: GIF 2021

(Major) Advantages/Disadvantages

- High coolant temperature
- Low pressures in primary coolant
- Possibly strong negative reactivity feedback
- High and flexible fuel utilization

- Development of a suitable molten salt needed
- Corrosive properties of molten salt
- Free-flowing radioactive inventory (radiation protection, fissile material control)
- Required (on-site) reprocessing

MCFR



Quelle: https://www.terrapower.com/wp-content/uploads/2022/03/TP_2022_MCFR_Technology.pdf

Line :	MSR
Name:	Molten Chloride Fast Reactor
Country:	USA
Developer:	TerraPower
Power:	1200 MWe
Coolant:	Chlorid salt
Moderator:	/
Fuel:	U/Pu
Neutron spectrum:	Fast

MSR – A few conclusions

- Status: considerable efforts between the 1940s and 1970s, revival after 2000, a commercially viable system not expected before ~2050
- Safety: Some advantages possible, but
  - significant technological development still needed (materials, instrumentation, safety assessment methods)
  - serious radiation protection aspects to be solved even in normal operation
- Waste: Different waste streams and other relevant radionuclides (Cl-36, C-14) to be taken into account
- Proliferation: specific problems due to the required (online) reprocessing of fuel salt

4

Conclusions

Conclusions I

- Principles of technology lines (SFR, VHTR, GFR, LFR, SCWR, MSR) known since 1950s (possible exception ADS)
- Development of technology lines not „linear“: classification as generaton IV is highly questionable, generation II-B would often be more appropriate
- In terms of technlogical readiness, many technology lines and reactor concepts remain in early stages of development, no system has advanced to the „market penetration“ phase
  - no extensive findings from smaller experimental reactors available for GFR, SCWR, ADS
  - no demonstration reactor so far for LFR, MSR
  - most extensive technical experience available for the SFR and VHTR

Conclusions II

- Developers' schedules often characterized by overly optimistic assumptions, delayed by years or even decades, in many cases specific approaches are discontinued completely
- Demonstration reactors to date are not yet suitable for widespread (market) deployment, additional FOAK reactors still needed
- Fuel/material development in particular is time-limiting
- Time still required for the development of novel reactor concepts is probably in the range of several decades

Conclusions III

- Individual technology lines – with rigorous design – may deliver advantages over today's LWRs in individual evaluation criteria
- With respect to wastes, an overall reduction of actinide inventories may be achieved, but no significant reduction in the requirements upon a geological repository is to be expected. At the same time, additional low- and intermediate-level radioactive waste streams would be generated. Some technology lines would also generate novel waste materials (such as salts) for which novel disposal pathways would have to be developed
- None of the technology lines can be expected to have an advantage over today's LWRs in all areas, disadvantages compared to today's LWRs are possible in individual areas

Vielen Dank für Ihre Aufmerksamkeit!
Thank you for your attention!

Haben Sie noch Fragen?
Do you have any questions?