Öko-Institut e.V.
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Alternative Reactor Concepts and their Implications for Nuclear Waste Management: Insights from an Analysis of Seven “Gen IV” Concepts

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Agenda

1 „Alternative“ Reactor Concepts

2 Evaluation Criteria

3 Exemplary Discussion

4 Country Perspectives

5 Overall Conclusions

1

„Alternative“ Reactor Concepts

Expert opinion on „alternative“ reactor concepts

- Study on behalf of the Federal Office for the Safety of Nuclear Waste Management (BASE)
- 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

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→ English Translation available at:

https://www.base.bund.de/SharedDocs/Downloads/BASE/EN/expert-info/f/final-report-novel-reactor-concepts.pdf;jsessionid=0A89BD3F3689CBB5D95C3B48A5E8E978.internet982?__blob=publicationFile&v=6

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Important definitions

- Distinction between „technology lines“ vs. „reactor concepts“
  - General term for roughly similar concepts: „technology line“
  - Detailled concept within a technology line: „reactor concept“
  - One or more specific „plants“ can exist for a specific reactor concept

Seven „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	Differentiation criteria				Reactor concept /
	Criticality	Coolant	Moderation	Other features	Plant
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

Important definitions

- Distinction between „technology lines“ vs. „reactor concepts“
  - General term for roughly similar concepts: „technology line“
  - Detailled concept within a technology line: „reactor concept“
  - One or more specific „plants“ can exist for a specific reactor concept
- 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)

Technology line	Initial experimental reactors	Initial power reactors (Gen I)	Further developed power reactor concepts (Gen II)	Advanced reactor concepts (Gen III)
PWR	MTR, S1W, S2W, MZFR	Shippingport, Obninsk, Obrigheim	Konvoi	AP-1000, VVER-1200, EPR
BWR	BORAX-I to -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 and 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)*	-	-	-

Source: (IAEA 2023g; Greenspan 2021; GIF 2002), concepts planned but not yet in operation are written in italics and placed in brackets

2

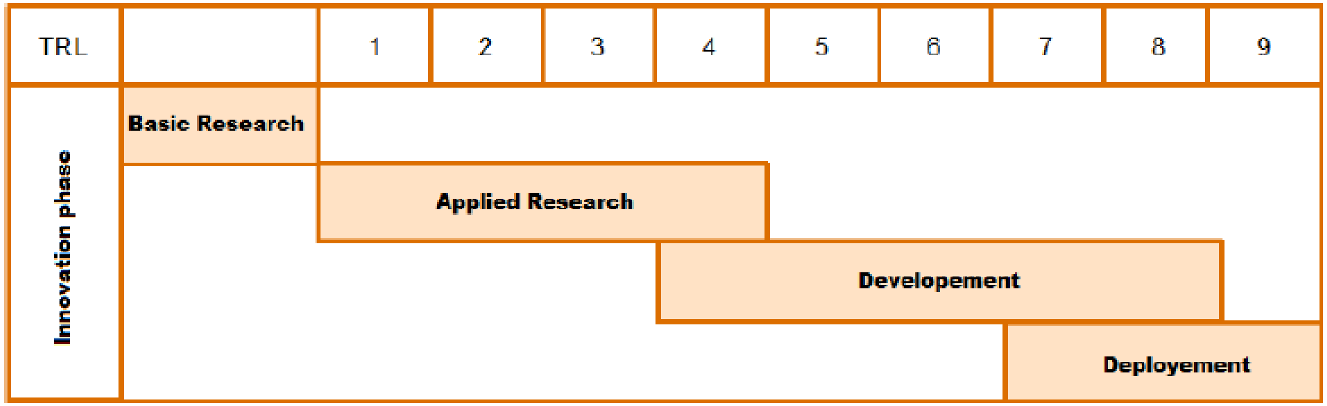
Evaluation Criteria

Technology readiness

Three levels each, „lowest“ classification defines overall level

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

Figure 2-2: Comparison of the 9-level TRL scale and a three-level technology classification



<table>
<tr><td>TRL</td><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td></tr>
<tr><td rowspan="4">Innovation phase</td><td>Basic Research</td><td colspan="9"></td></tr>
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<tr><td></td><td colspan="6"></td><td colspan="3">Deployement</td></tr>
</table>

Source: Own illustration

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)

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

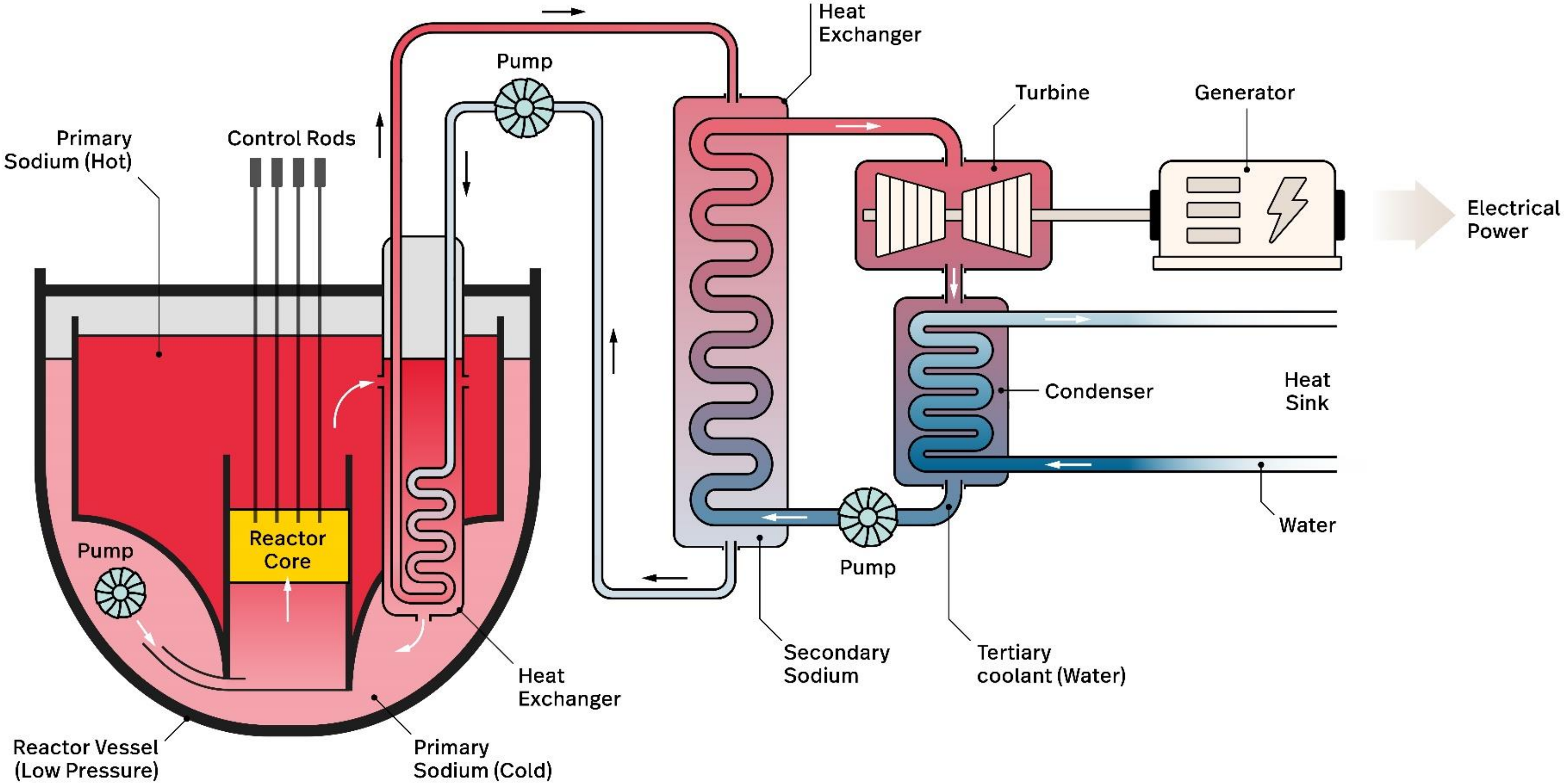
Indicators:

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

3

Examplary discussion

Sodium-cooled Fast Reactors (SFR)



Source: BASE

(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

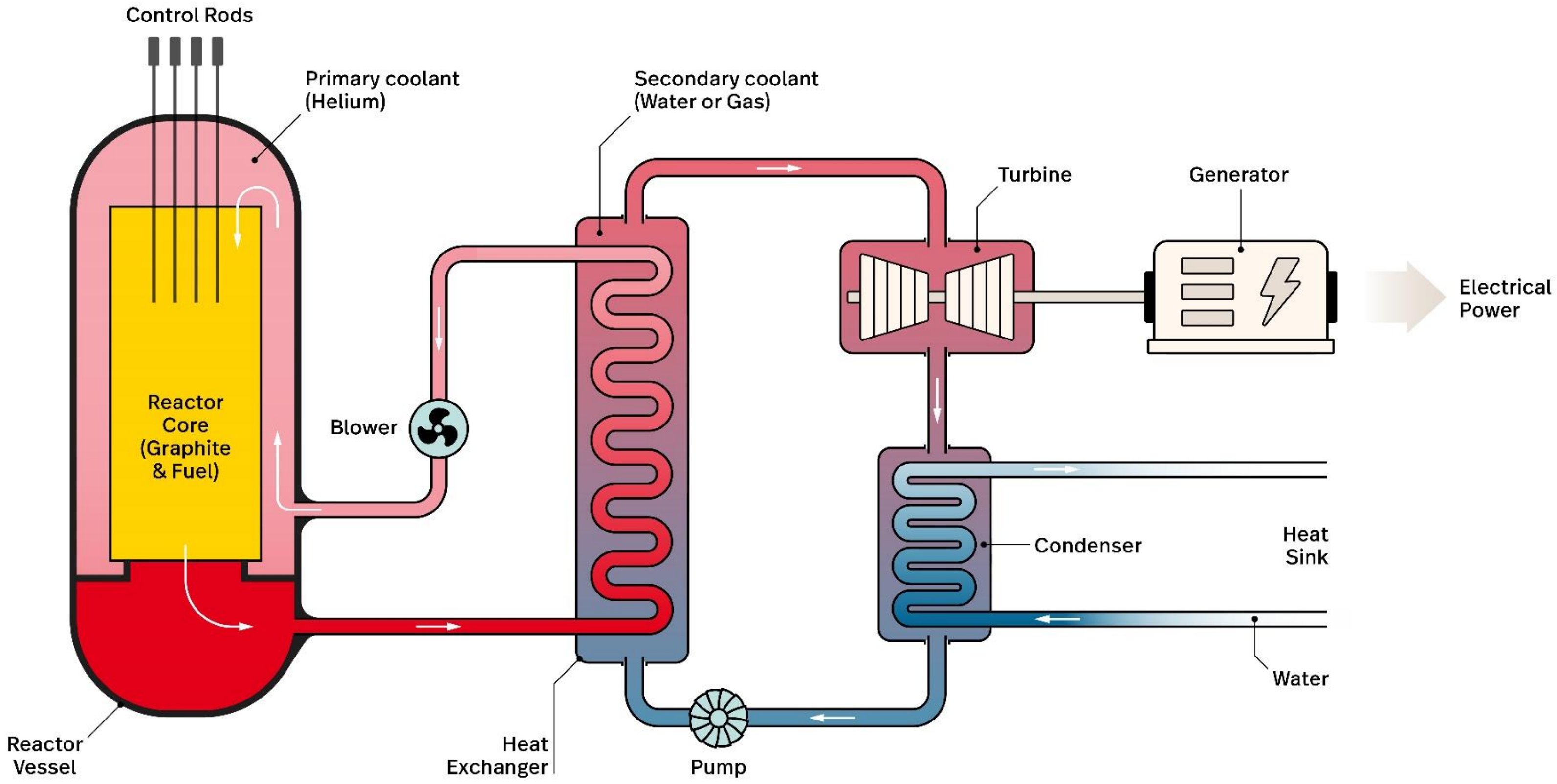
SFR – Specific waste aspects I

- Once-through MOX fuels would also have to be disposed of in final repository
- Increased heat generation and a high proportion of fissile material in the spent fuel compared to uranium fuels from LWRs
  - impact on the space required in the repository
  - increases the requirements for handling MOX regarding criticality safety and radiation protection
- Alternatively, multi-recycling would have to be developed industrially, but this is not to be expected from today's point of view
- Use of SFR has only marginal influence on the necessary criteria for a geological repository

SFR – Specific waste aspects II

- New fuels for SFR such as carbide and nitride fuels are being researched
- May have new characteristics such as the formation of large quantities of radioactive carbon, a long-lived mobile activation product with implications for long-term safety in disposal
- SFRs contain large quantities of sodium coolant in the primary circuit, which must be cleaned and then conditioned and disposed of as intermediate-level radioactive waste
- Coolant residues in the reactor are also problematic when components are replaced and during dismantling

(Very) High Temperature Reactors – (V)HTR



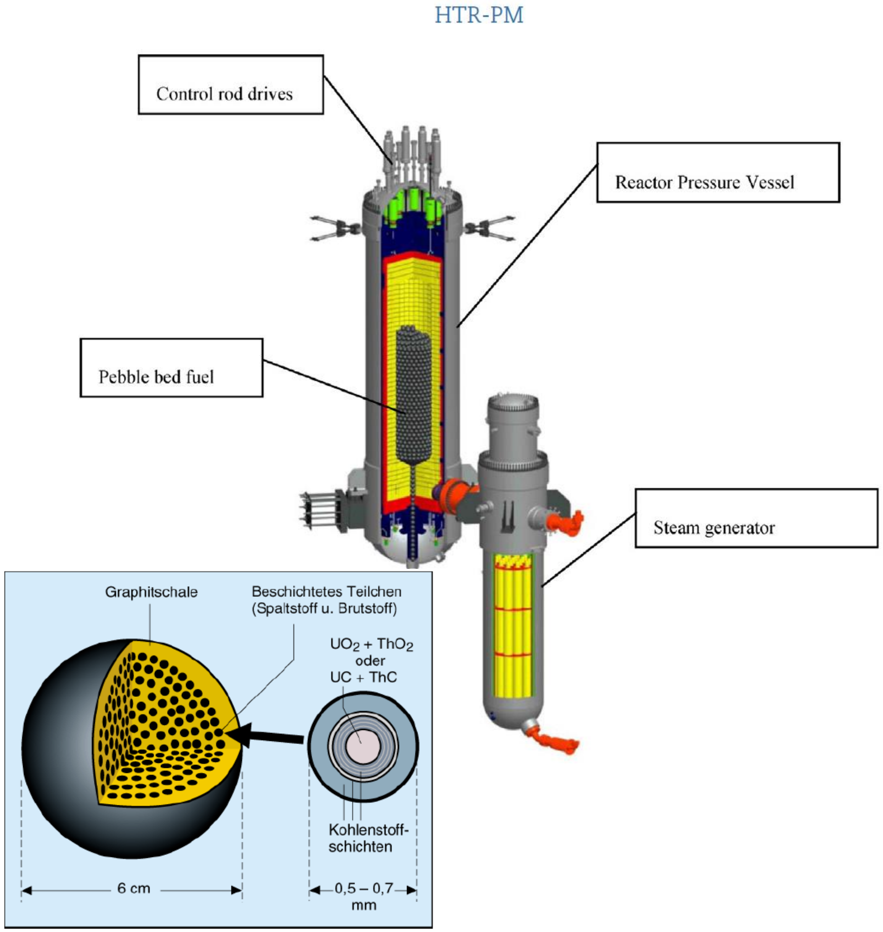
Source: BASE

(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 Brennstoffkugel 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

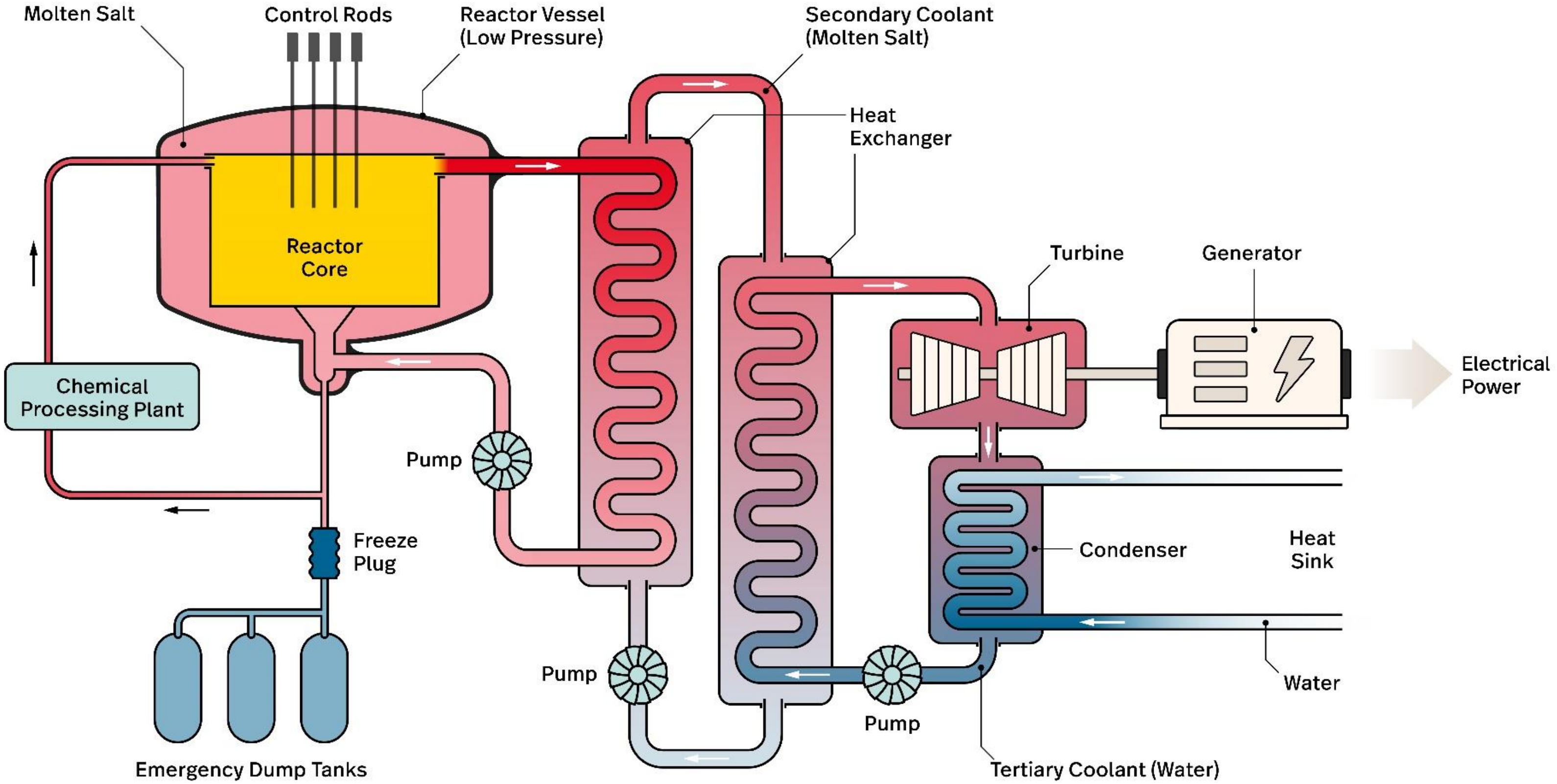
(V)HTR – A few conclusions

- Status: 60 years of development, several ambitious research and development programs (USA, Germany, South Africa) have failed. New attempt in China.
- 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.
- 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

(V)HTR – Specific waste aspects

- Due to the graphite matrix, significantly higher volumes of spent fuel are produced than with LWRs
- TRISO fuel particles are robust and in principle suitable for disposal
- Further research is required to determine and demonstrate the effectiveness of the barrier in a repository environment
- If HALEU will be used, criticality aspects will have to be taken into account
- Separation of the TRISO particles from the graphite to reduce volume requirements is being researched, but there is no generally accepted method for graphite treatment
- Further graphite waste is generated by structural elements in the reactor core and graphite dust, which contaminates reactor components due to adhering fission products

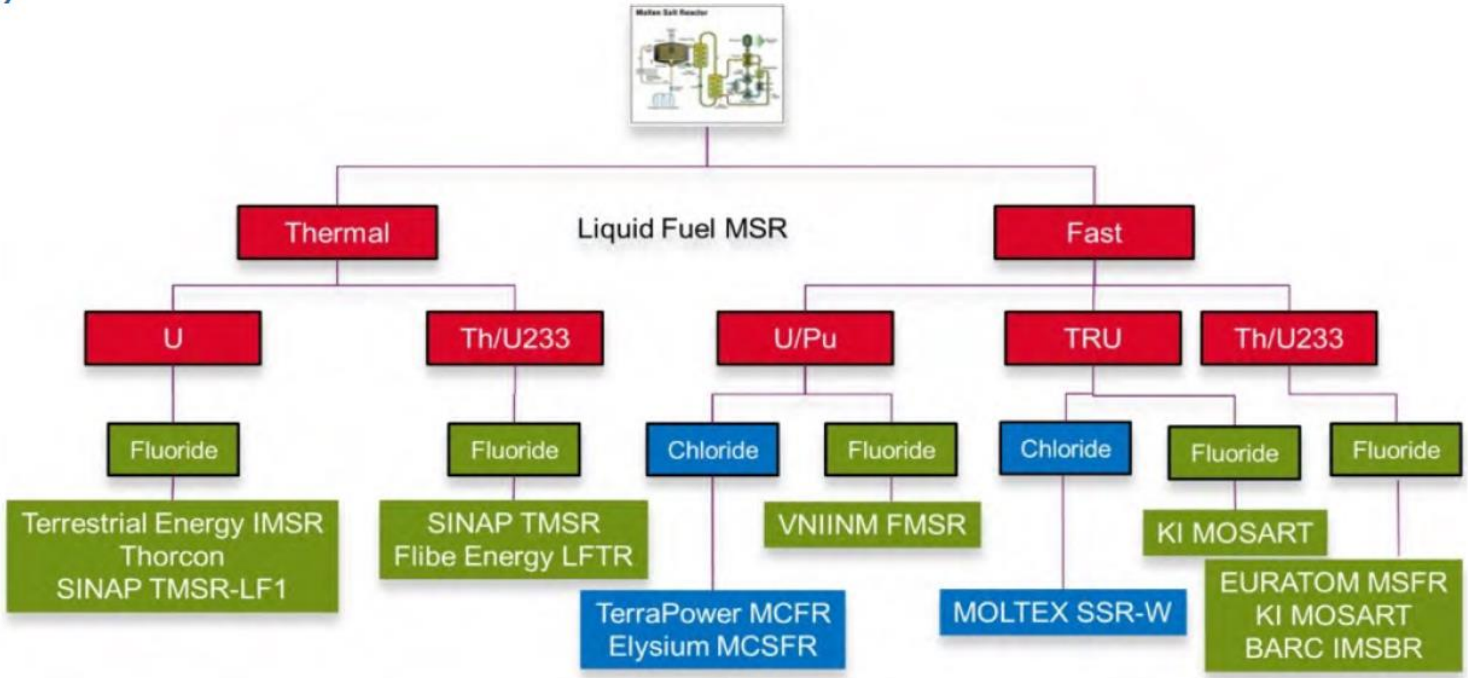
Molten Salt Reactors, MSR



Source: BASE

Many different reactor concepts possible

Figure MSR-1. The most studied MSR concepts, with key players (research & technology organization or vendors)



Liquid Fuel MSR

- Thermal
  - U
    - Fluoride
      - Terrestrial Energy IMSR
Thorcon
SINAP TMSR-LF1
  - Th/U233
    - Fluoride
      - SINAP TMSR
Flibe Energy LFTR
- Fast
  - U/Pu
    - Chloride
      - TerraPower MCFR
Elysium MCSFR
    - Fluoride
      - VNIINM FMSR
  - TRU
    - Chloride
      - MOLTEX SSR-W
    - Fluoride
      - KI MOSART
  - Th/U233
    - Fluoride
      - EURATOM MSFR
KI MOSART
BARC IMSBR

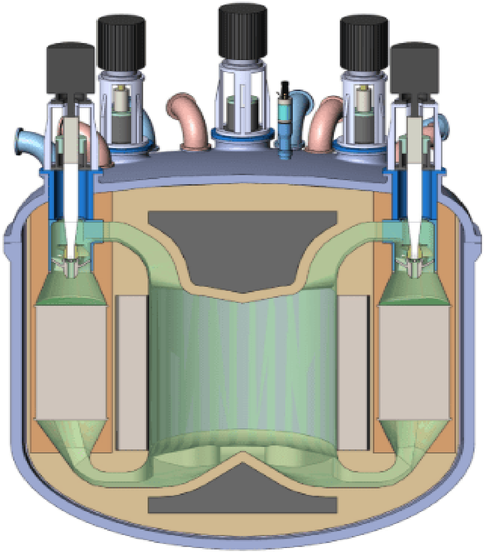
Source: GIF 2021

(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

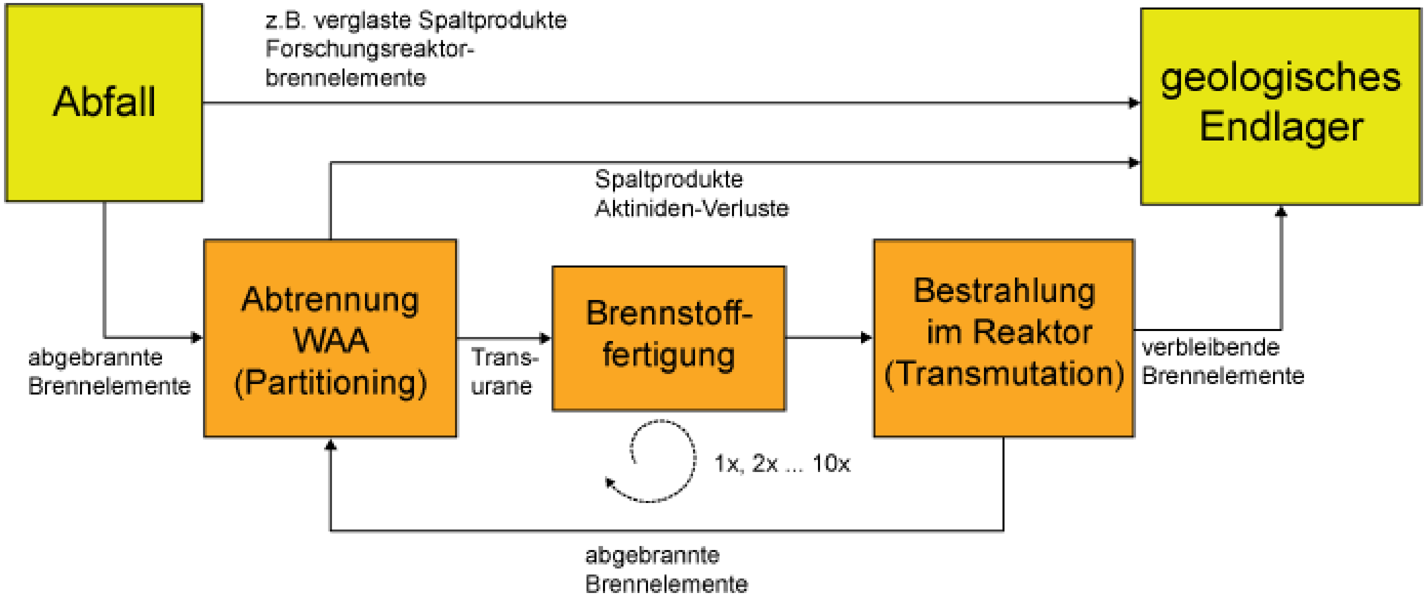
MSR – A few conclusions

- 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
- Proliferation: specific problems due to the required (online) reprocessing of fuel salt
- Waste: Different waste streams and other relevant radionuclides (Cl-36, C-14) to be taken into account

MSR – Specific waste aspects

- MSRs handle much larger quantities of radioactivity in completely different process streams
- Conditioning of the waste has to be adapted to the different waste streams
- It is unclear whether direct disposal of the fuel salt is possible, whether immobilisation will be necessary and whether the waste can be disposed of together with today's high-level waste
- For both chloride and fluoride salts, major gaps remain in the assessment of waste package functionality and separation processes to predict the long-term behaviour of the waste forms in a repository environment

Partitioning and Transmutation (P&T)



Abfall

z.B. verglaste Spaltprodukte Forschungsreaktor-brennelemente

geologisches Endlager

Spaltprodukte Aktiniden-Verluste

abgebrannte Brennelemente

Abtrennung WAA (Partitioning)

Trans-urane

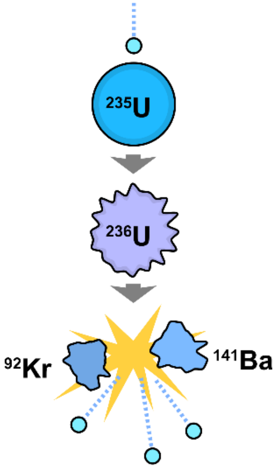
Brennstoff-fertigung

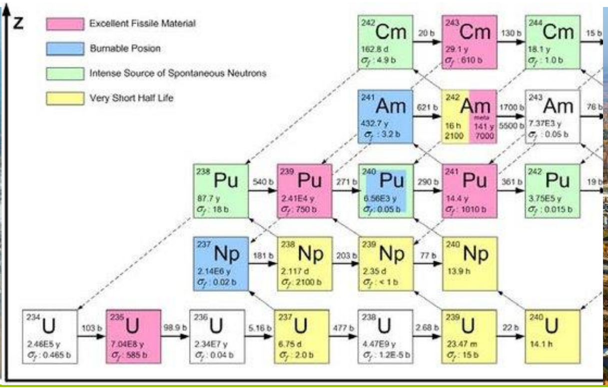
Bestrahlung im Reaktor (Transmutation)

verbleibende Brennelemente

1x, 2x ... 10x

abgebrannte Brennelemente





LaHague_www.atomenergie.ch.jpg
https://www.atomic-energy.ru/news/2020/07/08/105195 Правда УРФО
Kernspaltung: Wikipedia
Transmutation OI:10.2172/992769

P&T – What is it?

- HLW can be treated using nuclear transmutation to reduce the actinide content in HLW and the requirements for final disposal
- HLW has to be partitioned to separate uranium, plutonium, other transuranic elements and fission products with chemical separation technologies
- Fresh fuel assemblies are then manufactured from the separated transuranic elements
- Fresh fuel assemblies are used in special transmutation reactors where they are irradiated to fission the transuranic elements they contain
- After irradiation, only a small fraction of the originally used transuranics is split. The process has to be repeatedly applied

Source: Öko-Institut e.V., safeND 2021

P&T – Where are we?

- Partitioning and transmutation technologies are being developed since decades
- Only organic solvent extraction technologies for uranium and plutonium, mixed-oxide plutonium bearing fuel and sodium cooled fast reactors have reached technical maturity
- Other more advanced fuel cycle technologies such as minor actinide separation, pyrochemical separation technologies, minor actinide bearing fuels, molten-salt reactors or accelerator driven systems are being actively developed in a number of countries
- The IAEA and OECD estimate that their development will still need substantial R&D efforts to reach technological maturity

Source: Öko-Institut e.V., safeND 2021

P&T – What can be achieved?

- P&T can reduce the actinide content in HLW significantly
- However, actinides are immobile under reducing conditions in a repository. The long-term safety analysis of repositories is mainly determined by long-lived mobile fission products
- P&T does not obviate the need for a repository for high-level radioactive waste due to residual amounts of actinides because of separation efficiency, transmutation efficiency, specific waste types and time constraints
- However, the required final storage area might be reduced somewhat.
- Since much more fission products and operational wastes are produced, additional repository space for intermediate and low-level radioactive waste is necessary

Source: Öko-Institut e.V., safeND 2021

P&T – A few conclusions

- P&T requires
  - Large efforts (in terms of reactors and reprocessing facilities) for
  - Very long time frames (> 100 years)
- Relevant risks from a safety and non-proliferation perspective
- None of the scenarios for the use of alternative fuel cycles with SNR and P&T treatment of waste can do without a repository for high-level radioactive waste since residual quantities of transuranics and long-lived fission and activation products remain in the waste stream.
- In addition, the operation and dismantling of the partitioning facilities will generate much larger quantities of intermediate and low-level waste.

4

Country Perspectives

Methodical Approach to categorize and analyze global SNR - projects

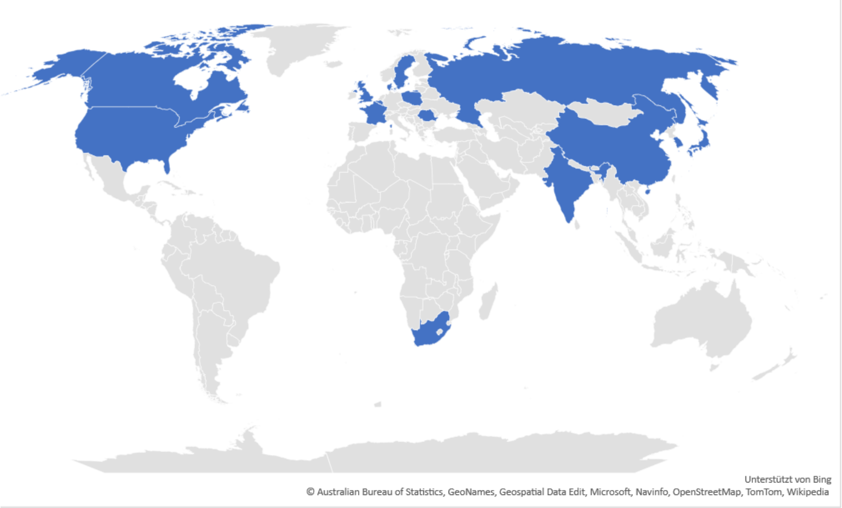
Projects were divided into three categories:

Category I: Nuclear active countries with military programs

Category II: Countries with nuclear activities but no nuclear weapons

Category III: Potential entrant countries

.. six countries were selected, and analyzed with respect of their build up phase (t_{-2}) adaption phase (t_{-1} and their current status (t_0)



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Overview of identified research activities [Category I]

Country	Concept	Technology – Lines	Commercial Nuclear Programs ?	Military Nuclear Program ?	GIF Member ?
Category I: Nuclear active countries with military programs					
USA	22	ADS (1), SFR (3), LFR (2), GFR (1), VHTR (4), MSR (11)	Yes	Yes	Yes
China	12	ADS(3), LFR(2), MSR(2), SCWR(1), SFR(2), VHTR(2)	Yes	Yes	Yes
Russia	7	LFR(2), SFR(5)	Yes	Yes	Yes
UK	2	ADS(1), MSR (1)	Yes	Yes	Yes
France	2	MSR(1), SFR(1)	Yes	Yes	Yes
India	3	ADS(1), SFR(2)	Yes	Yes	No

Overview of identified research activities [Category II]

Country	Concept	Technology – Lines	Commercial Nuclear Programs ?	Military Nuclear Program ?	GIF Member ?
Category II: Countries with nuclear activities but no nuclear weapons					
Belgium	1	ADS	Yes	No	Yes
Republik of Kroea	4	ADS(1), LFR(2), SFR(1)	Yes	No	Yes
Japan	8	GFR(1), MSR(1), SCWR(1), SFR(2), VHTR(2)	Yes	No	Yes
Sweden	3	ADS(1), LFR(2)	Yes	No	Yes
Canada	1	MSR	Yes	No	Yes
Romania	1	LFR	Yes	No	Yes
South Africa	1	VHTR	Yes	No	Yes

Overview of identified research activities [Category III]

Country	**Concept**	**Technology – Lines**	**Commercial Nuclear Programs ?**	**Military Nuclear Program ?**	**GIF Member ?**
Category III: Potential entry countries					
Poland	1	VHTR	No	No	ja
Denmark	1	MSR	No	No	ja
Luxembourg	1	LFR	No	No	ja

Today's perspective: No breakthrough in sight, neither in the USA, Russia and China, nor in the less developed countries [1/2]

Country	Build-up phase (t_{-2})	Adaptation phase (t_{-1})	Current status (t_{-0})
USA	**1940s - 1970s: Diversification with the construction of prototypes** ~ 1950s: Focus on fast reactors: initially with metallic fuels (EBR-I, EBR-II, Fermi-1, reprocessing plant FCF). ~ 1960s: SFR with MOX fuels: Plan for construction of Clinch River Demonstration Reactor; Molten Chloride Experiment	**1970s - 2000s: Demolition and decommissioning project and diffusion of LWR** ~ Discontinuation of fast reactor projects (e.g. Clinch River), decommissioning of fast reactors (e.g. EBR-II, Fermi)	**Since 2000: Reactivation of SNR development and diversification with planning of new demonstration projects** ~ Development push with diverse development portfolio: SFR; VHTR; MSR ~ Attempt to build up missing research infrastructure (VTR) ~ 2020: Focus on two demonstration projects (sodium from TerraPower, Xe-100)
Russia	**1940s - 1970s: First experimental reactors with a focus on SFR and the goal of a closed fuel cycle** ~ Development of the first fast test reactors (BR-10, later BOR-60) ~ No recognizable focus on other technology lines	**1970s - 2000s: Attempt to upscale SFR** ~ Attempt to upscale fast reactors (BN-350, BN-600, with time delay BN-800) ~ Construction of reprocessing plant RT-1	**Since 2000: delays and postponements** ~ Continuation of SNR development with focus on fast reactors (SFR, LFR): Commissioning of BN-800 (2016) ~ but: “commercial” reactor concept BN-1200 delayed ~ Development and construction of the Brest-OD-300 reactor (LFR)

Today's perspective: No breakthrough in sight, neither in the USA, Russia and China, nor in the less developed countries [2/2]

Country	Build-up phase (t_{-2})	Adaptation phase (t_{-1})	Current status (t_{-0})
China	**1950s - 1970s: Development of the first elements of an imported nuclear energy innovation system** ~ Completely imported from the Soviet Union ~ 1960s First plutonium reactor ~ Focus on atomic bomb, missiles and hydrogen bomb ~ Late 1960s: SFR research activities began with basic research and test facilities ~ No commercial developments yet	**1980s - 2000: Diversification of light water reactor imports and first experiments with SNRs** ~ Extensive imports of LWRs (USA, Russia, France, South Korea) ~ Development of domestic adaptation capacities ~ The aim was to develop one (or more) national LWRs (also for exports) ~ First research work on SNR: ~ 2000: in commissioning HTR-10 ~ 2010: CEFR critical for the first time ~ 2011: Start of MSR development (TMSR-LF1)	**Since 2000: Consolidation of LWR and diversification of SNR** ~ Consolidation of domestic LWR (Hualong 1000) and increasing export attempts (Pakistan, UK) ~ Diversification of SNR: ~ 2021: Commissioning of the demonstration project: HTR-PM ~ 2020: Start of construction of the CFR-600 demonstration project ~2021: Completion of the TMSR-LF1 prototype

Discussion of Motivations

Military-Commercial Synergy:

- Nuclear tech used for both military and commercial purposes (U.S., China).
- Plutonium breeding reactors have dual-use potential.
- Nuclear diplomacy by U.S., Russia, China influences global politics

Decarbonization:

- Paris Agreement pushes for low-emission tech.
- Nuclear energy gains support for reducing CO_2 (e.g., U.S., China, Poland).

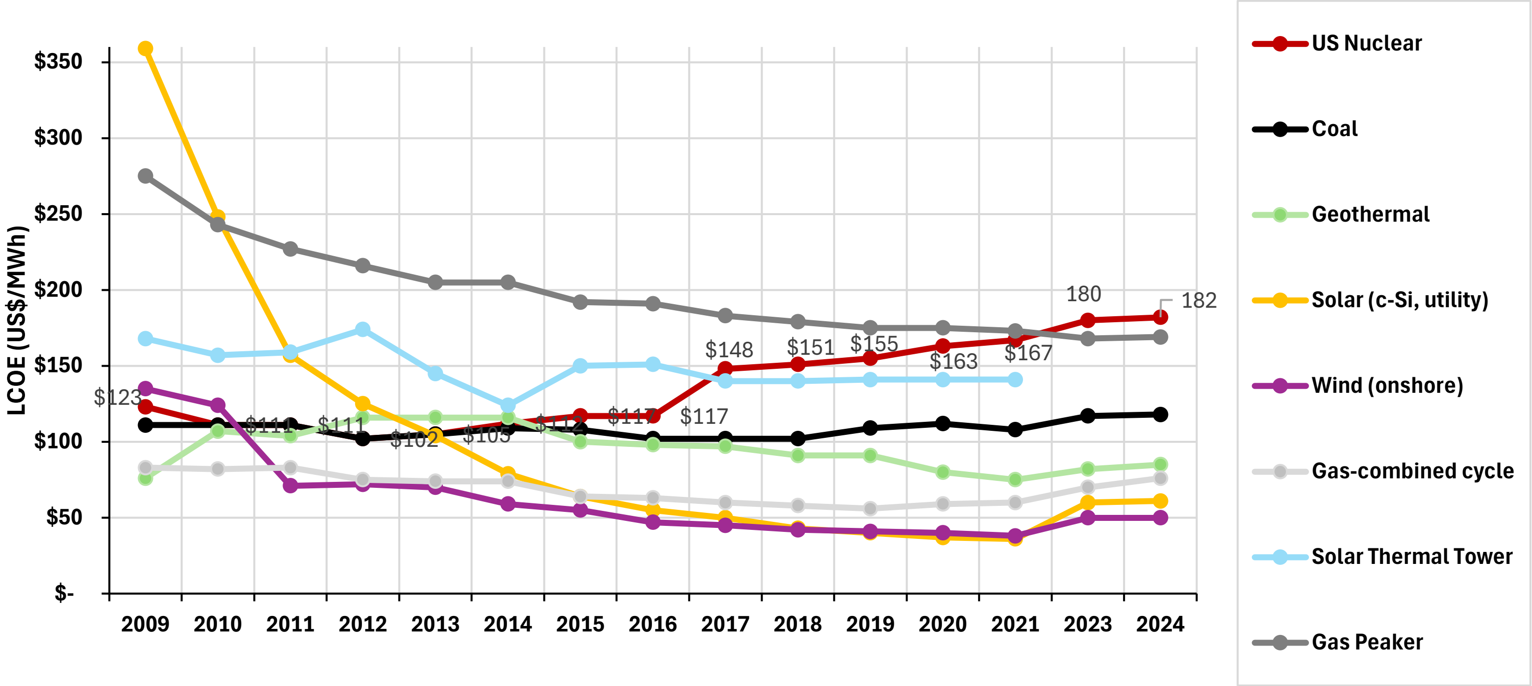
Waste Management:

- Plutonium waste and reprocessing raise proliferation risks.
- Transmutation reactors to reduce waste?

Innovation & Policy:

- U.S. focuses on developing SMRs/FNRs and maintaining nuclear infrastructure.
- Global tech dependence creates long-term ties (e.g., U.S.-South Korea).

From an economic perspective, none of the so-called novel reactor concepts represents an alternative to existing light water reactors ... … which, as is now commonly acknowledged, a multiple of the costs of “firm” energy from renewables (Jacobsen, 2009, Economist, 2024, et al.)



Since 1957 these have had no economic chance against other forms of energy, then coal and natural gas, now renewables.

Today's LWRs are not competitive with today's renewable energy generation technologies in terms of their levelized cost of electricity (LCOE). Moreover, historical cost trends show rising LWR LCOE over time, while the renewable energy sector has seen massively falling costs, especially in the last decade. For the future, there are no apparent reasons why this trend should reverse.

5

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

- Motivations of both an innovation policy and/or geostrategic nature
- In terms of organisational models (financing or industry regime), no breakthrough in sight from today's perspective
- 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?

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