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Andreas Pautz :: Forschungsbereich Nukleare Energie und Sicherheit (NES) :: Paul Scherrer Institut (PSI)

Neue Reaktortechnologien und Notfallschutz

Gemeinsames Seminar der Eidgenössischen Kommissionen für Strahlenschutz KSR und ABC-Schutz KomABC, Freitag, 31. März 2023, Auditorium der Kaserne Bern

Content

- Reactor Generations II-IV
- Safety Features of LWR and LWR-SMR
- Emergency Planning Zone Determination

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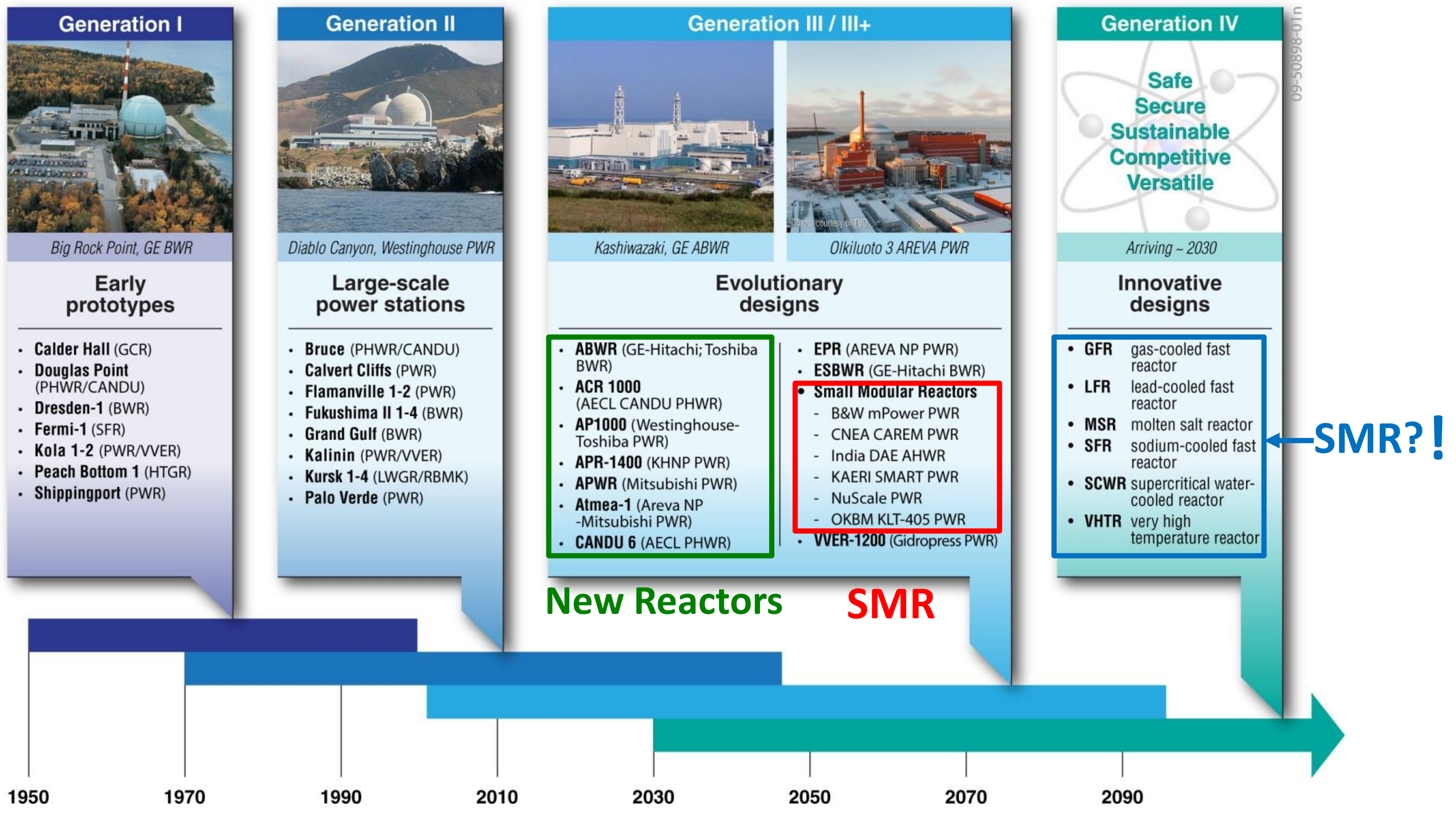
"New" Nuclear Power Plants: the Four Generations of NPP



New Builds of NPP of Generation-III

Practically all near-term new builds are Generation-III reactors/SMR, based on proven light water reactor technology (pressurized/boiling water reactors).

The 3rd generation reactors (Gen-III) extend the safety philosophy of the 2nd generation:

- Increased use of active and **passive safety systems**
- Consideration of severe accident sequences / core meltdown already in design
- Core damage probability < 10^{-6}/year
- **"Practical elimination"** of accident sequences leading to early release of radioactivity (<10^{-7}/year), with up to **one week grace period** before human intervention
- Consideration of accident scenarios with superimposition of **various initiating events and internal/external impacts** => Fukushima scenarios

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Safety Systems of Large Generation-III Plant: EPR

Internal Containment:
- Steel shell
- Leak-proof up to 6.5 bar
- Exclusion of H_2-Explosion

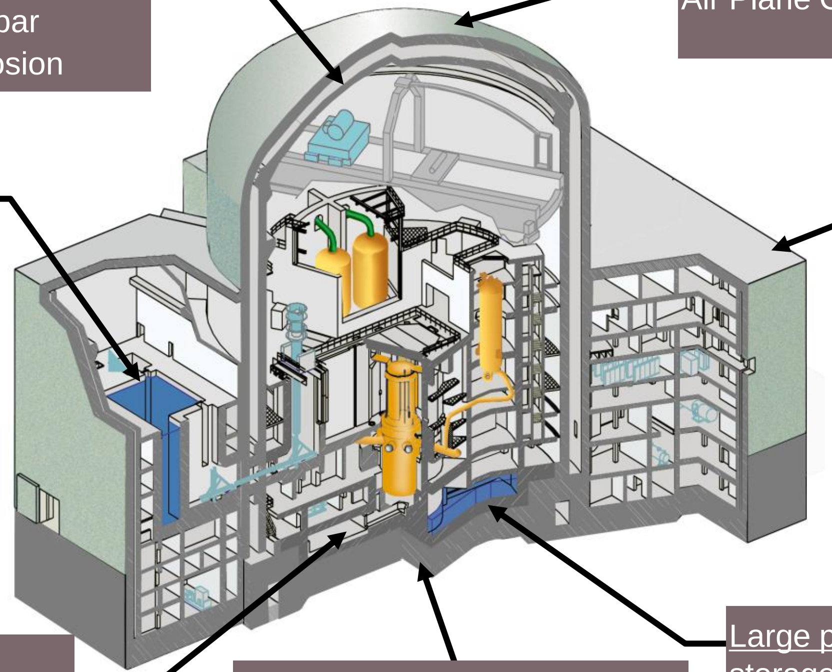
External Containment:

Air Plane Crash Protection

Wet Fuel Storage:
protected against air plane crash

Active/Passive Safety systems:

bunkered against external hazards, designed throughout 4-times (2v4) redundant with several diversified levels of safety systems



Probability of a core melt accident $<10^{-6}$/Jahr

Probability of an early release $<10^{-7}$/Jahr

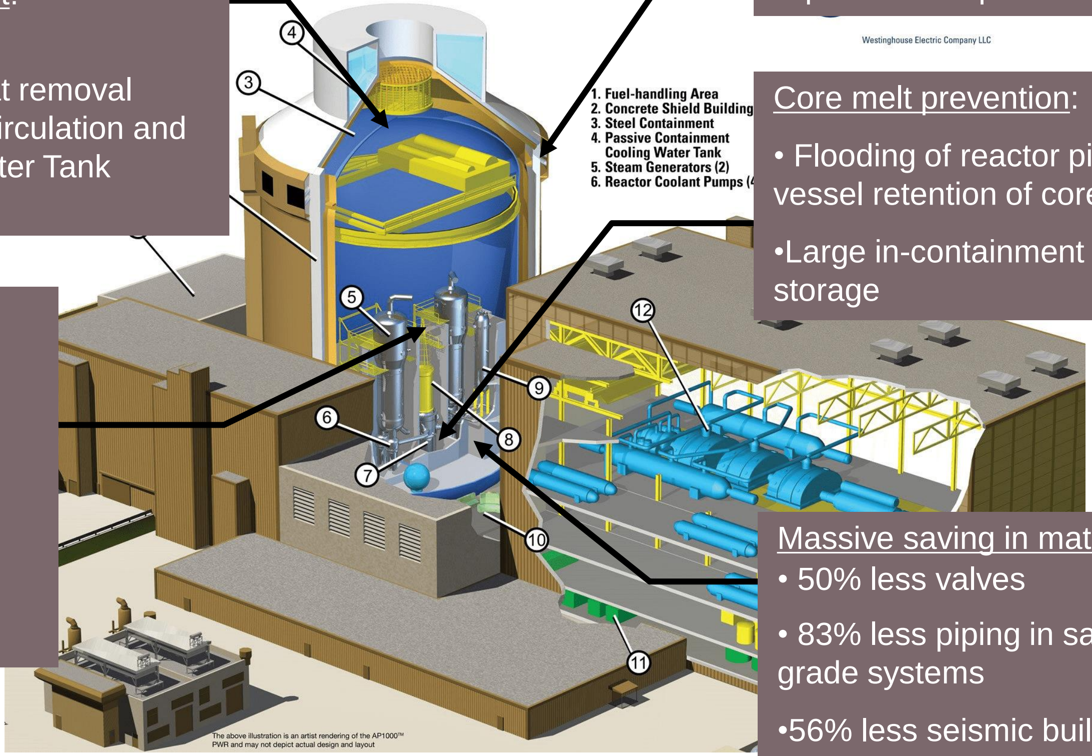
Core Catcher:

Safe containment of molten core

Earthquake-proof: designed against 100’000-year earthquake

Large protected in-containment water storage for coping with severe accidents

Safety Systems of Large Generation-III Plant: AP-1000



Internal Containment:
- Steel shell
- Passive decay heat removal through natural air circulation and Passive Cooling Water Tank

External Containment:

Air plane crash protection

Core melt prevention:
- Flooding of reactor pit for in-vessel retention of core melt
- Large in-containment water storage

Passive Safety Systems philosophy:
- Practically no more active components
- Controlled through gravity, buoyancy, natural convection
- Elimination of operator intervention

Massive saving in materials:
- 50% less valves
- 83% less piping in safety-grade systems
- 56% less seismic building volume

Generation-III Power Plants Available Today

EPR (Framatome) in Olkiluoto (FI), 1600 MW)

AP-1000 (Westinghouse) in Vogtle (USA), 1100 MW

Requirements for economic operation

Construction costs:

3’500-4’500 $/kW installed

Construction Time:

5-7 years

=> Levelized Costs of Electricity:

60-100 $/MWh

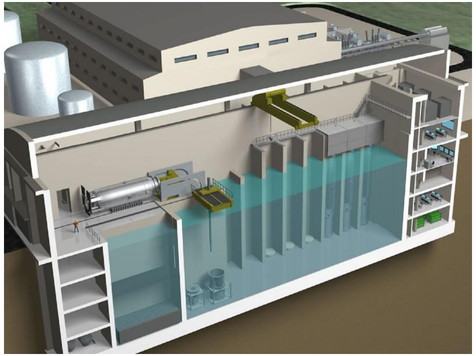
VVER-1200 (Rosatom) in Novovoronesh (RU), 1250 MW

APR-1400 (KEPCO) in Barakah (UAE), 1400 MW

Small Modular Light Water Reactors (LWR-SMR)

- **Small modular reactors (SMRs) are increasingly seen as an interesting option:**
- **Lower power (10-300 MW_e)** at comparable or lower cost (<$4,000/kW) than large plants, made possible by modular design and in-factory production
  - **Significantly simpler design** than large light-water reactors due to passive safety components
  - Depending on requirements, several modules can be built at the same time at the same site or constructed, connected and disconnected one after the other
  - **Significantly reduced construction time** for each individual module (1.5-2 years as target)
  - Compact design opens up the possibility of **construction below ground level**
  - **"Walk-away" safe**
  - **Strongly reduced size of Emergency Planning Zone (EPZ) proposed, down to the site level**
- In its SMR manual, the IAEA lists around 70 different SMRs; of these, about half are based on "traditional" light-water reactor technology (**Generation-III, ab 2027**), while the others rely on "revolutionary" concepts (gas and liquid metal cooling, molten salt reactors) => **Generation-IV**

SMR (Generation-III) with Credible Time Horizon around 2030

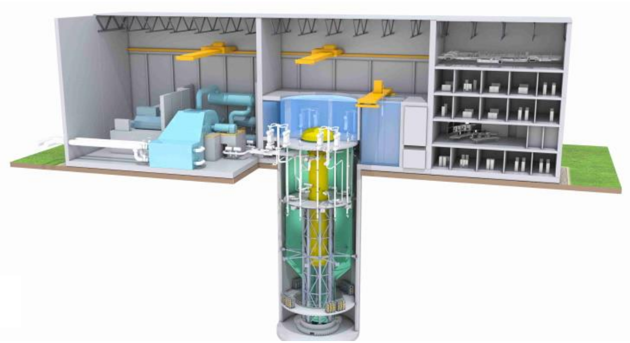


NuSCALE (6x77 MW), for Utah, from 2027
LCOE: 65$/MWh, 3’600 $/kW installiert

NUWARD (EdF/Technicatome), 170 MW, from 2030

UK SMR (Rolls Royce), 443 MW, from 2030

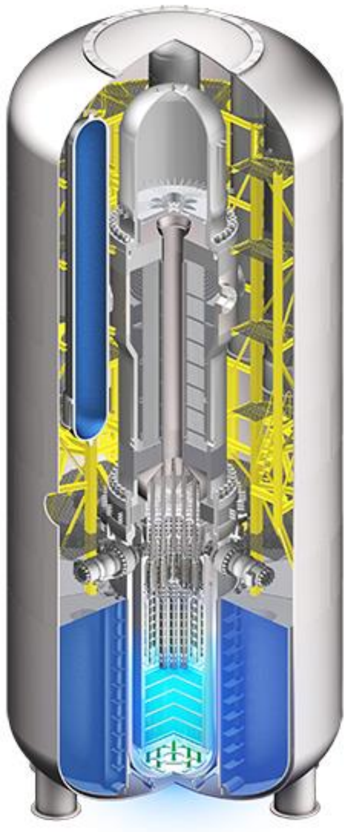
SMART (Korea), 100 MW, Saudi-Arabia from 2028



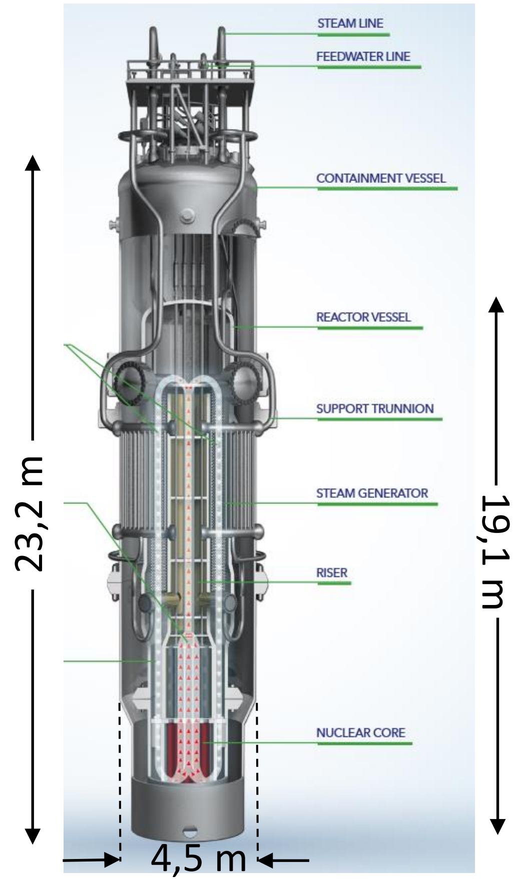
RITM-200 (Russia), Kirgistan from 2028

BWRX-300 (GE/Hitachi) for Ontario Power, operation from 2028, LCOE-target: **2’250 $/kW**

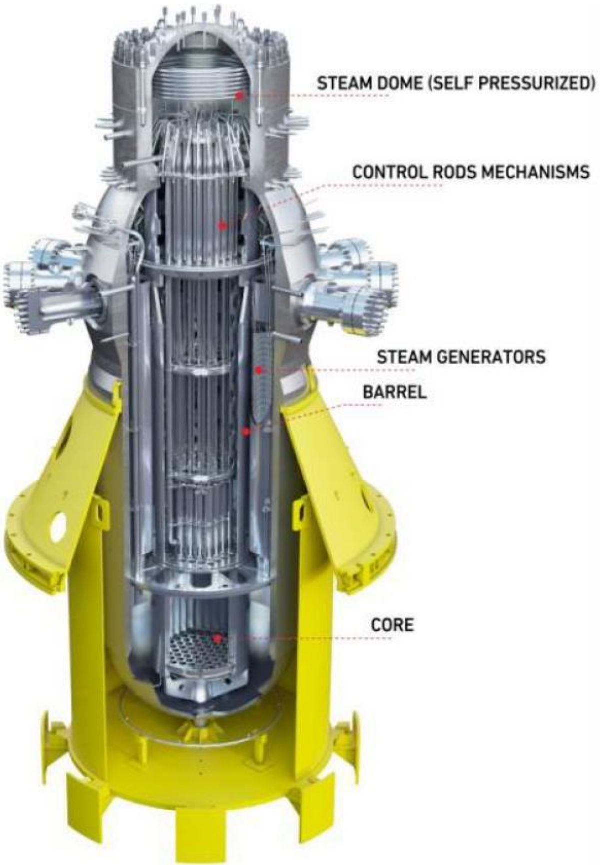
Small Modular Reactors (LWR-SMR): Integral Modules



Westinghouse Small Modular Reactor 225 MWe

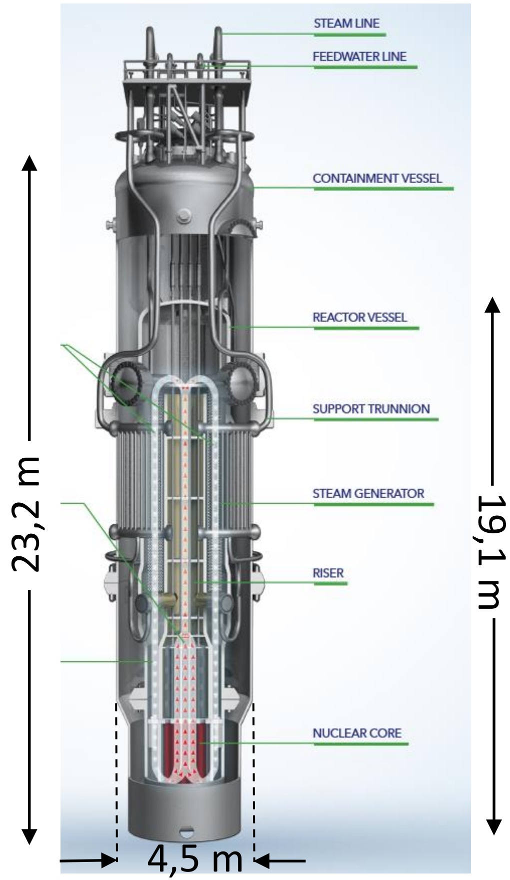


NuScale 77 MWe Module

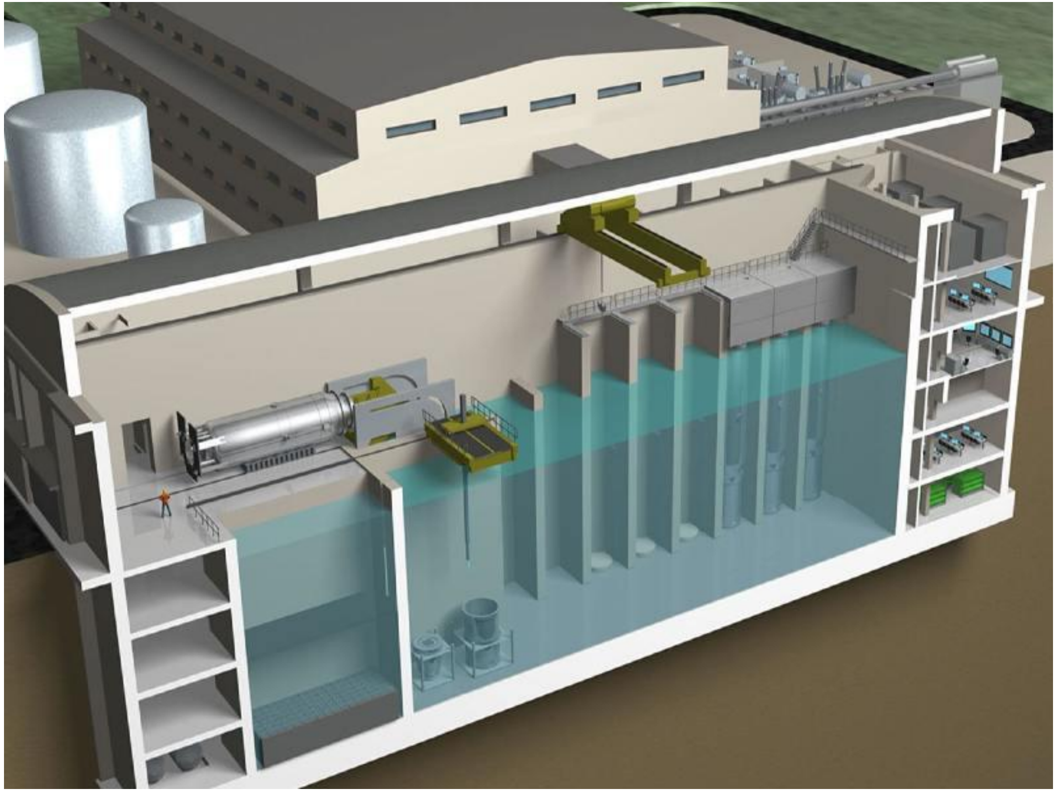


CAREM-25MW (3.2 x 11 m)

Small Modular Reactors (LWR-SMR): Integral Modules



NuScale 77 MWe Einzelmodul



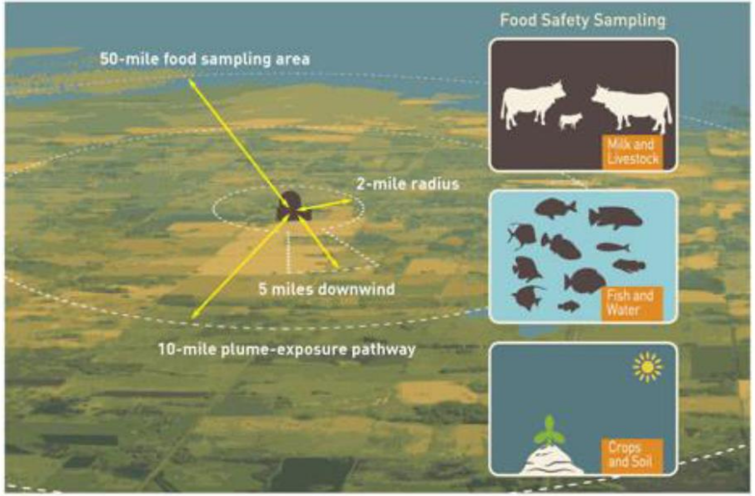
NuScale Design mit 6 x 77 MWe-Modulen

Claimed Safety Advantages of NuScale SMR

- **Up to 12 modules in parallel** (12 x 77 = 924 MW_e) that can be operated independently of each other, if desired also in hybrid mode (district heat/power generation)
- **Instrumentation and Control systems (I&C)** designed against geomagnetic disturbances and electromagnetic pulses
- **No safety-classified AC/DC emergency power devices**, no pumps or electrically controlled valves (emergency power case)
- **Unlimited core cooling capability by passive safety systems alone**, no additional water supplies necessary other than those available in the plant (transition from convective water to air cooling after approx. 30 days)
- All safety-relevant plant components are located **below ground level**, thus offering **much improved containment efficiency**, against both internal and external hazards
- **Cooling of the fuel pool is ensured for 150 days**, after which external refilling is necessary (via separate connections, e.g. via fire extinguishing lines).
- **Core damage frequency < 10^{-9}/year** for a 12-module plant

Emergency Planning Zone Regulation

Precautionary Action Zone (PAZ)	An area where comprehensive arrangements are made at the preparedness stage to notify the public and have the public start to take urgent protective actions and other response actions within one hour of the declaration of a General Emergency by the NPP supervisor (**CH: Notfallschutzzone 1**)
Urgent Protective action planning Zone (UPZ)	An area where comprehensive arrangements are made at the preparedness stage to notify the public and have the public start to take the urgent protective actions (**CH: Notfallschutzzone 2**)
Extended Planning Distance (EPD)	The distance to which arrangements are made at the preparedness stage so that upon declaration of a General Emergency: (a) instructions will be provided to reduce inadvertent ingestion; and (b) dose rate monitoring of deposition conducted
Ingestion and Commodities Planning Distance (ICPD)	The distance to which arrangements are made at the preparedness stage so that upon declaration of a General Emergency instructions will be provided to: (a) place grazing animals on protected feed, (b) protect drinking water supplies that directly use rainwater), (c) restrict consumption of non-essential local produce, and (d) stop distribution of commodities until further assessments are performed



Emergency zones and distances	Suggested maximum radius (km)	
	100 to 1000 MWth	≥ 1000 MWth
Precautionary Action Zone (PAZ)	3 to 5	
Urgent Protective action planning Zone (UPZ)	15 to 30	
Extended Planning Distance (EPD)	50	100
Ingestion and Commodities Planning Distance (ICPD)	100	300

Reduced EPZ Size for Small Modular Reactors (IAEA)

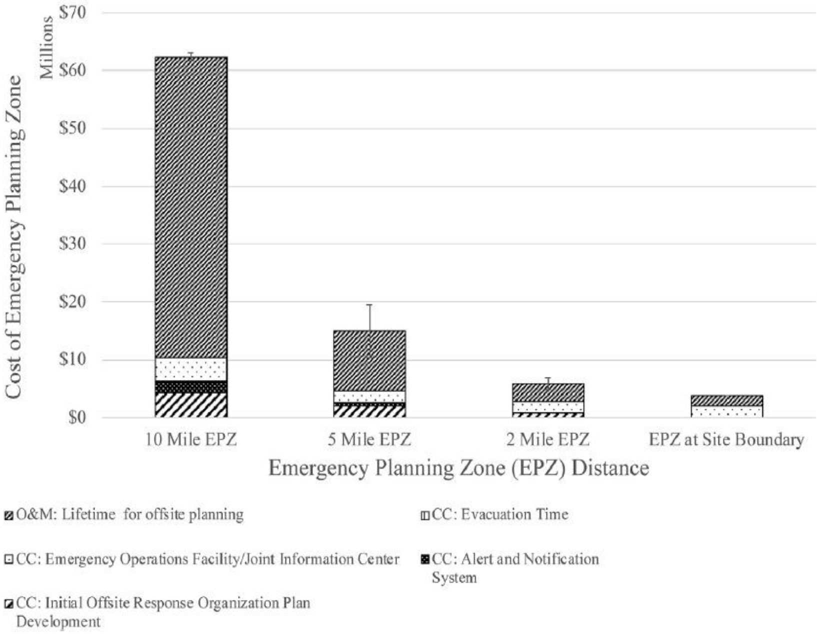
- **Significant efforts on EPZ size determination (since 2010) through safety performance and risk-informed (probabilistic) analysis**
  – IAEA, Small Reactors without On-site Refuelling: Neutronic Characteristics, Emergency Planning and Development Scenarios, IAEA-TECDOC-1652, IAEA, Vienna (2010).
  – IAEA SMR Regulators' Forum Pilot Project Report, "Report from Working Group on Emergency Planning Zone", (2018)
  – Case studies on some (hypothetical) SMR new builds in Italy and Lithuania performed

Zones and distances	SMR designs
No off-site EP plan	VK-300, GT-MHR, 4S
Simplified EP plan	CAREM-25, mPower, NuScale, CCR, HTR-PM, G4M
400 meters	PBMR
1000 m, no off-site evacuation	KLT-4S, VBER-300, ABV
1500 m	SMART
2000 m	IRIS
Not specified	IMR, GTHTR300, PASCAR

Reduced EPZ Size for Small Modular Reactors (USA)

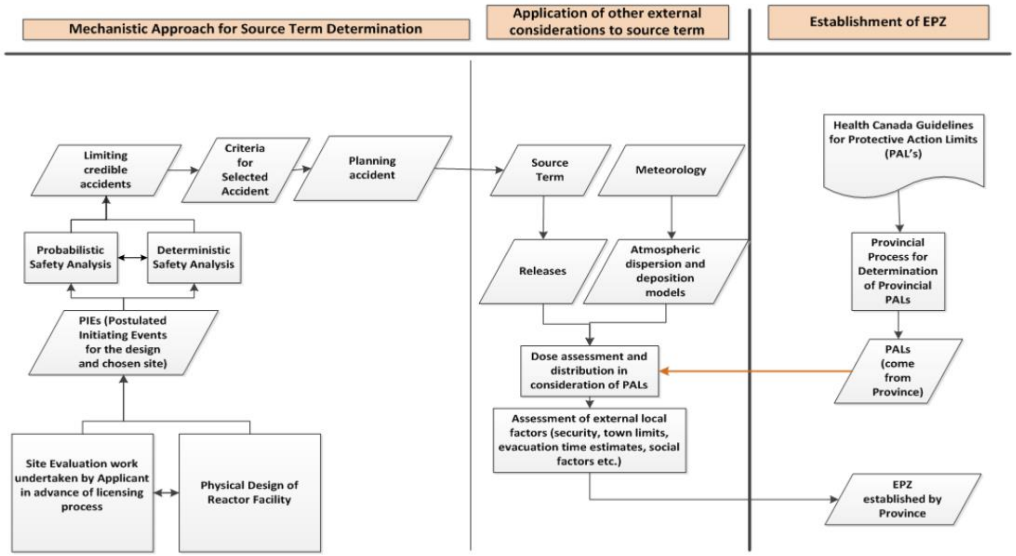
- **US NRC has been very strict on the 10/50-miles EPZ, with very few exceptions (one gas-cooled reactor, PWR < 250 MW with 5 miles plume exposure pathway)**

- **SMR vendors push for reduced EPZ:**
  - **Strongly decreased cost** of maintaining emergency preparedness
  - **Siting closer to densely populated areas**, particularly important for district heating applications
  - **New SMR can replace older coal-fired power stations,** with little additional siting requirements



Reduced EPZ Size for Small Modular Reactors (USA)

- NuScale submitted a "Methodology for Establishing the Technical Basis for Plume Exposure Emergency Planning Zones," TR-0915-17772-NP, Revision 2, August 2020. ADAMS Accession Number ML20217L422.



- The EPZ should encompass areas in which projected dose from design basis accidents (DBAs) could exceed 10 to 50 mSv TEDE (requiring evacuation and sheltering, respectively).
- Oct 2022: NRC / ACRS approves NuScale Methodology for SMR EPZ, resulting in an EPZ of approx. 500 meters radius (for a specific site in Utah)

Conclusion

- Large LWR will continue to be built; they exhibit excellent safety features achieved by combined active und passive safety systems. Core damage frequencies are 1-2 orders of magnitude lower than for Generation-II reactors
- SMR offer even increased safety performance, through small inventory, more heat transfer area per heat generated, passive systems, slow accident progression, and excellent decontamination factors. A CDF < 10^{-9}/year for a 1 GW multi-module seems achievable
- License requests for EPZ sizing with risk-informed (PSA level 3) approaches have been submitted and are mostly under scrutiny by regulators
- Several case studies and a recent NRC statement conclude that EPZ sizes of a few hundred meters (site extent) are possible

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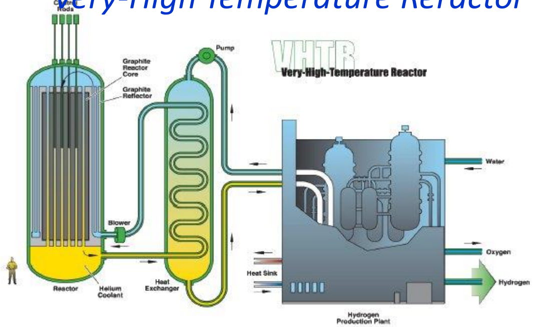
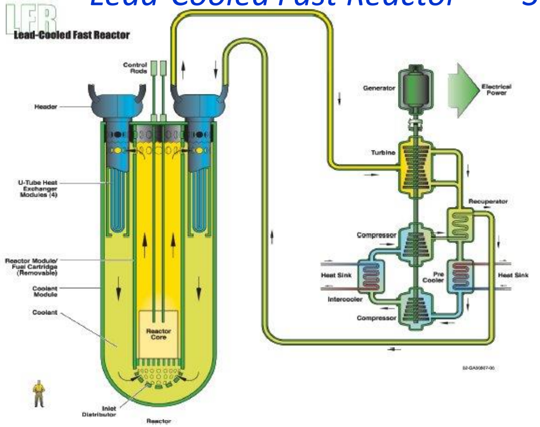
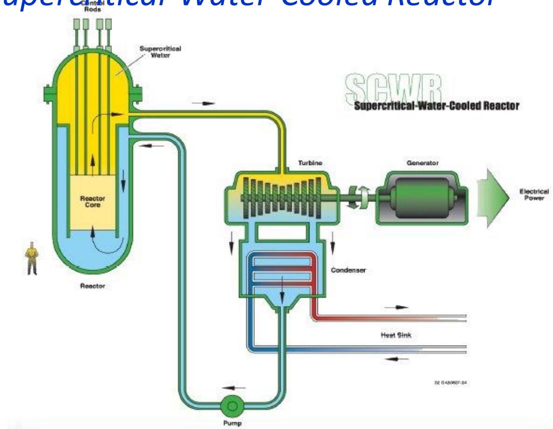
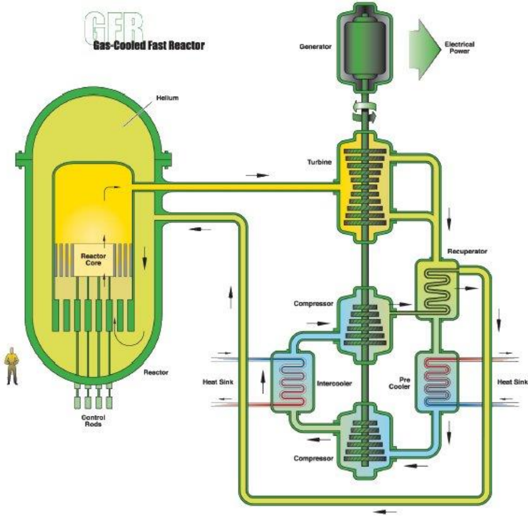
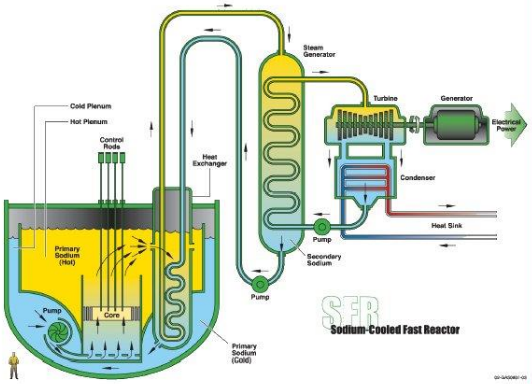
Very-High Temperature Reractor *Lead-Cooled Fast Reactor* *Supercritical-Water-Cooled Reactor*

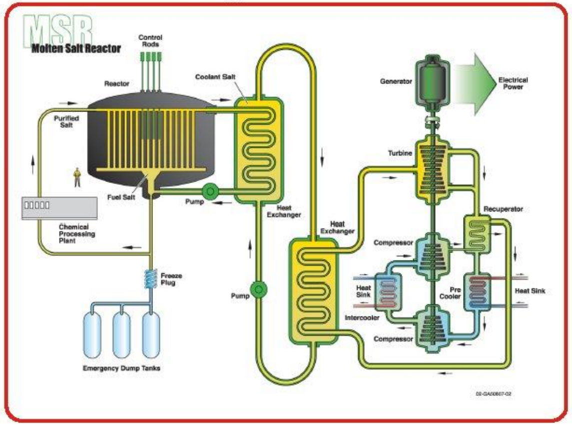






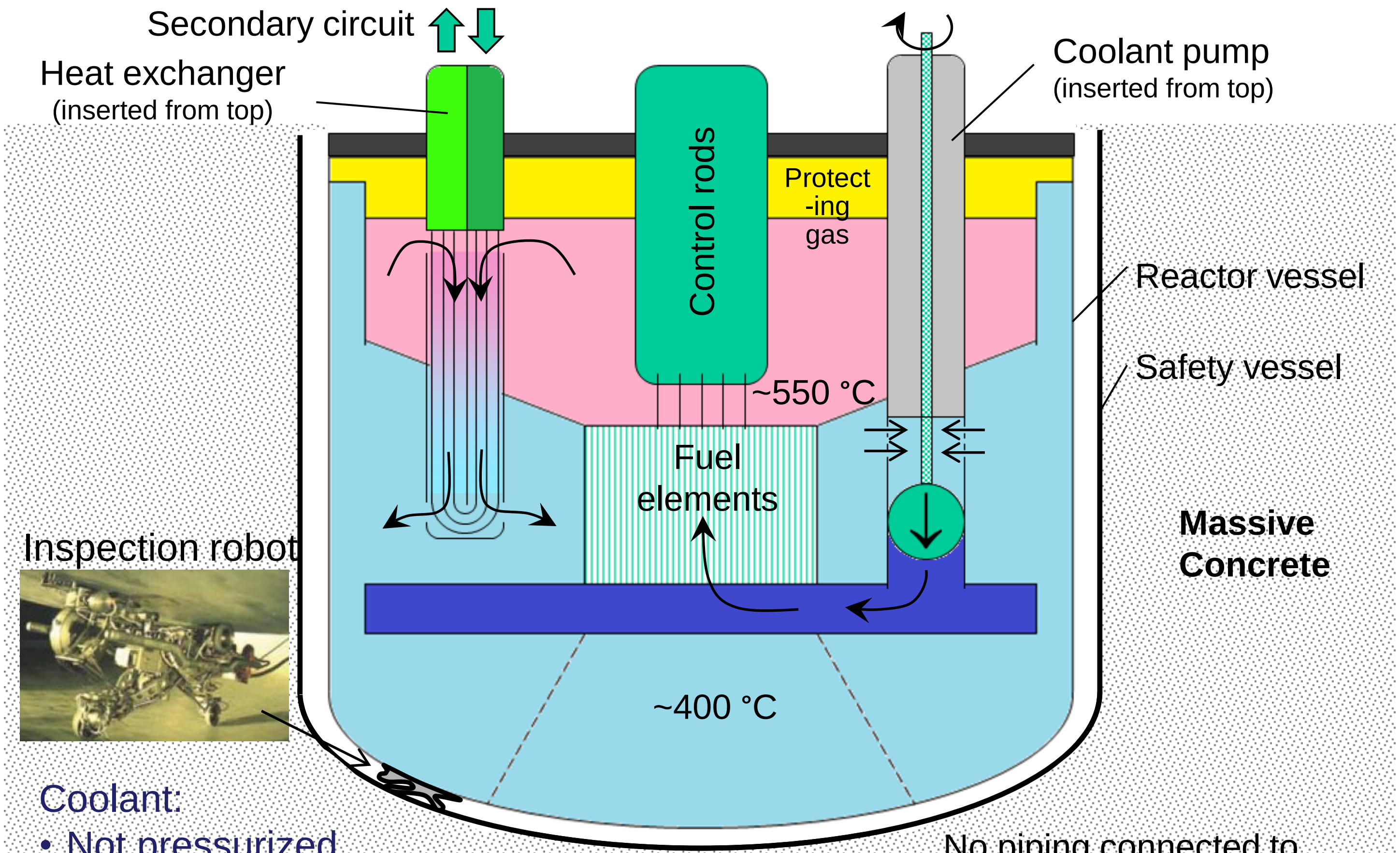






Gas-Cooled Fast Reactor Sodium-Cooled Fast Reactor Molten Salt Reactor

Pool type SFR – leak exclusion

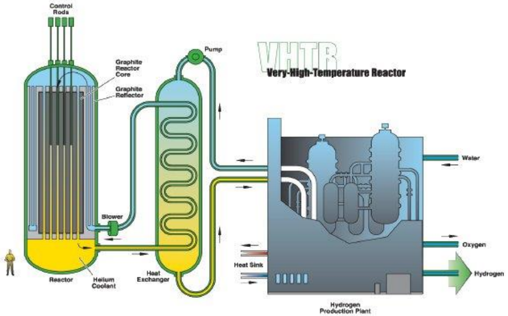


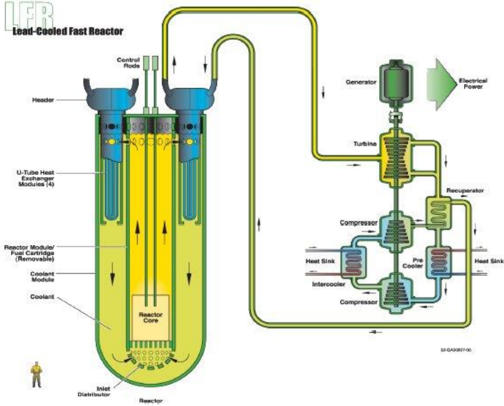
Coolant:
- Not pressurized
- Leak deterministically excluded

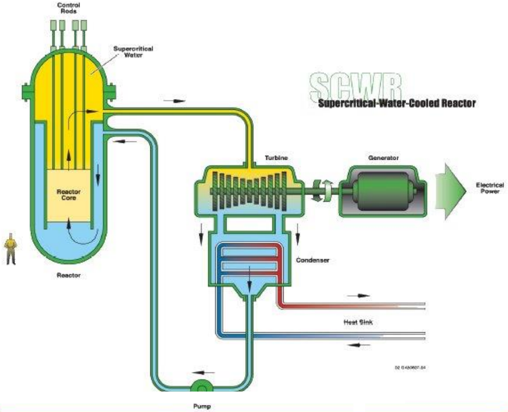
No piping connected to reactor vessel

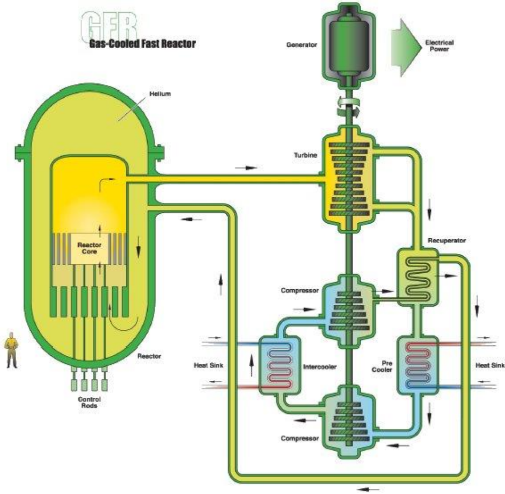
Die Reaktorkonzepte der Generation-IV

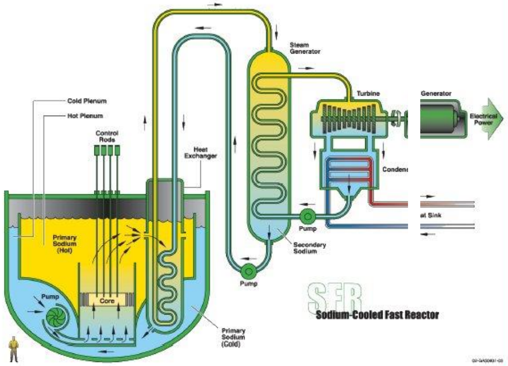
Hochtemperaturreaktor | Bleigekühlter Schneller Reaktor | Superkritischer LWR

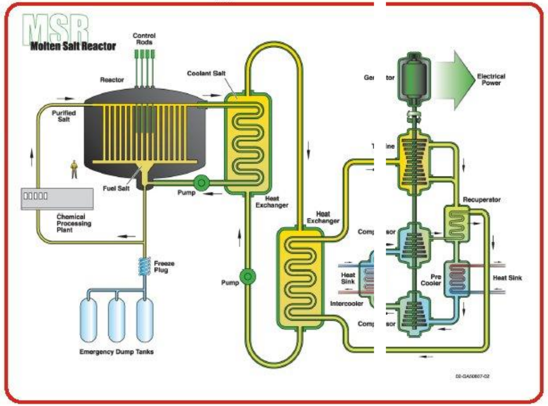












Gasgekühlter Schneller Reaktor | Natriumgekühlter Schneller Reaktor | Salzschmelze-Reaktor

Summary of Gen-IV safety features

	Light Water Reactor (**LWR** = PWR or BWR)	High Temperature Gas-cooled Reactor, pebble bed, modular (**HTR-PM**)	Sodium cooled Fast Reactor, pool type (**SFR**)	Lead (or lead-bismuth) cooled Fast Reactor , pool type (**LFR**)	Molten Salt Reactor (**MSR**)	Relevance
Excess reactivity	**high**	**no**	**medium**	**medium**	**no**	low excess reactivity = low relevance of RIAs
Reactivity feedbacks	**negative**	**negative**	**design dependent**	**design dependent**	**fuel regime dependent**	negative reactivity feedback coefficients stabilize kinetics
Shutdown (standby) temperature	**low**	**high**	**high**	**very high**	**high**	high shutdown temperature = easy decay heat removal
Reactor pressure	**high**	**high**	**low**	**low**	**low**	low reactor pressure = low relevance of LOCAs
Volatile radioactive core inventory	**high**	**high**	**high**	**high**	**low**	low volatile inventory = small release in case of SA
Fuel rod barrier function	**good**	**very good**	**good**	**medium**	**none**	good barrier function = no releases in DBAs

But “hot containment”

Response to risk aversion

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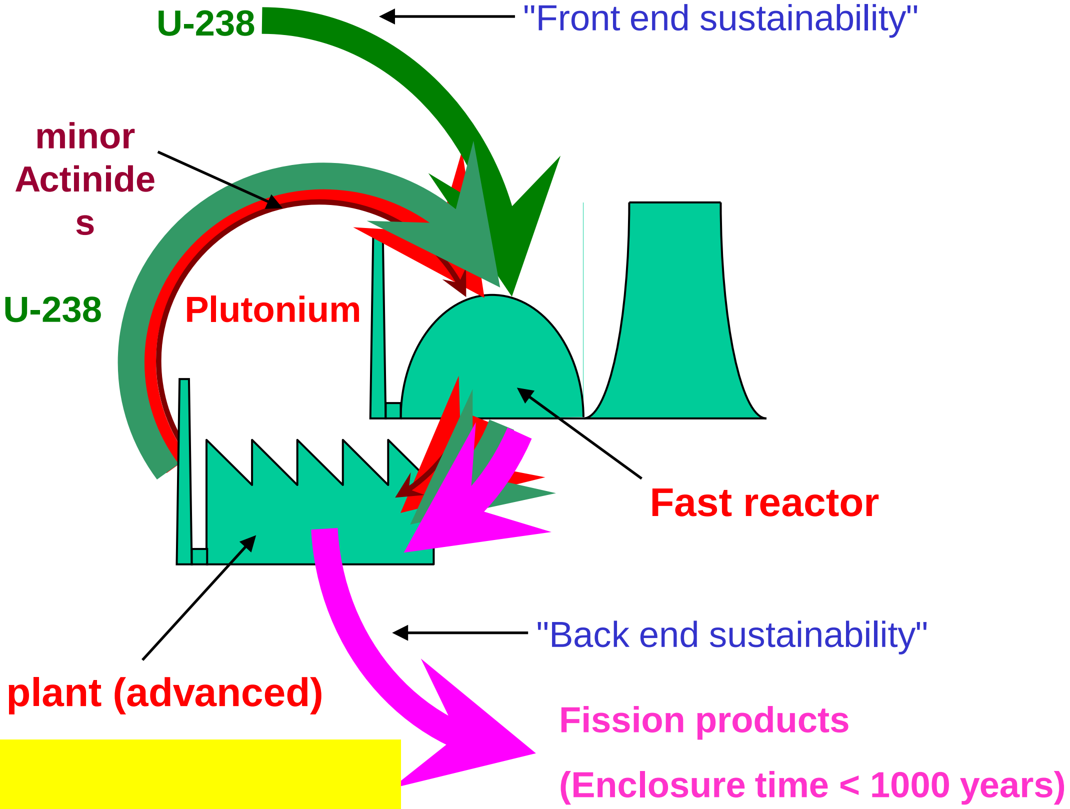
Full actinide recycling (closed fuel cycle)



Achtung:

Wachsende Aktinidenmengen bis zum Erreichen des Gleichgewichts zirkulieren im geschlossenen Brennstoffzyklus

(dafür weniger bis keine Umwelteinflüsse durch Uranbergbau)

Achtung:

Ggf. neue Risiken in WA-Anlagen

Weniger langlebige alpha-Toxizität im Endlager

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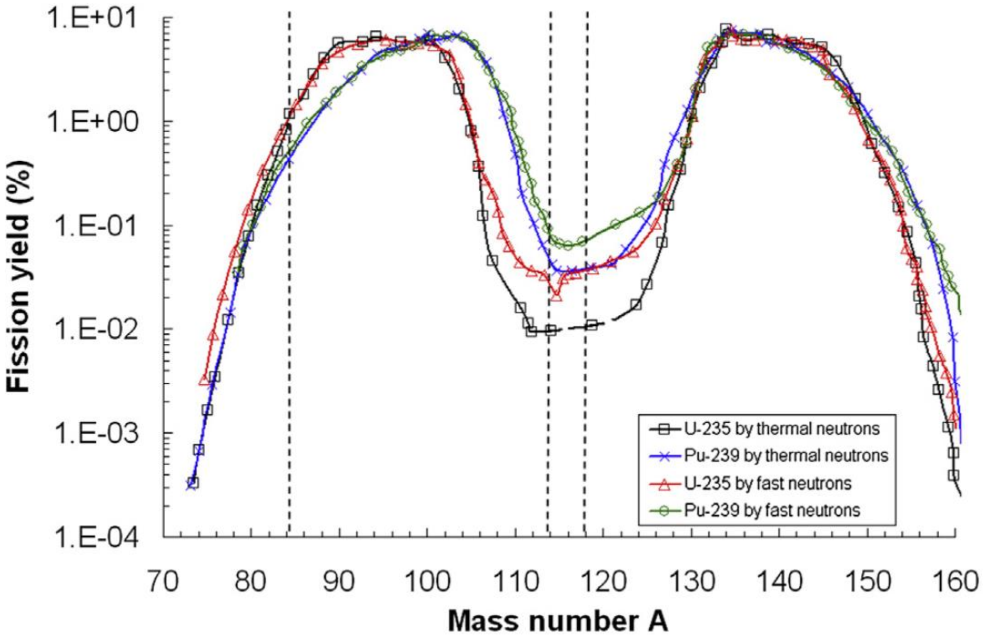
Comparison liquid metals / water

	Na	Lead/LBE	H_2O
Vapor pressure	Low	Low	High
Heat transfer	Excellent	Very good	Fair
Activation by neutrons	High (not long-live)	High	Lower
Corrosivity	Low	High	Medium
Chemical reactivity	High with H_2O / air	Low	Low
Optical properties	Opaque	Opaque	Transparent
Melting point	Solid at room temperature	Solid at room temperature	Liquid at room temperature
Lattice void feedback	Positive (without measures)	Positive, but hard to void	Negative (if undermoderated)

Sodium-water reaction: $2Na + 2H_20 \rightarrow 2Na^{+} + 2OH^{-} + H_2 \quad \left(\Delta h_R = -368 \ \frac{kJ}{mol} \right)$

Sodium-air reaction: $4Na + O_2 \rightarrow 2Na_2O \quad \left(\Delta h_R = -836 \ \frac{kJ}{mol} \right)$

Keine Überraschungen beim Spaltproduktinventar



Fission yield spectra of ^{235}U and ^{239}Pu for thermal and fast neutrons

Wenig Besonderheiten im Vektor der Spaltprodukte

- 2 Grössenordnungen mehr Ag-110 (nicht (sehr) flüchtig) und Ru-106 (flüchtig als RuO_4) bei Spaltung von Pu-239 mit schnellen Neutronen
- Ru-103 (t½ = 39 Tage), Ru-106 (t½ = 1 Jahr)
- RuO_4 (siedet bei 100 °C), Luftzutritt erforderlich
- Relevante Nuklide I-131, und Cs-137 haben sehr ähnliche Spaltausbeuten, wie in thermischen Reaktoren

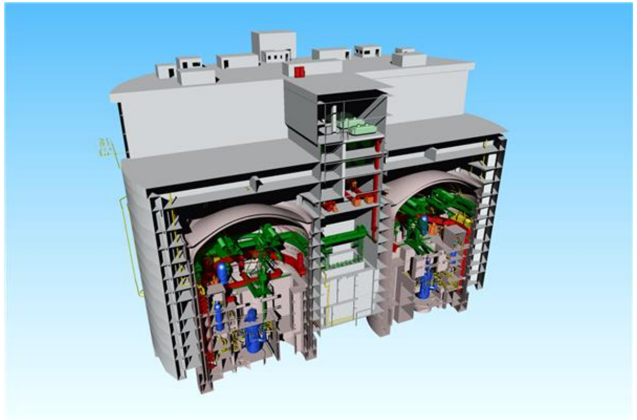
Generelle Feststellung

- Sr-90 (mehr in LWR) und Ru-106 (mehr in schnellen Reaktoren).

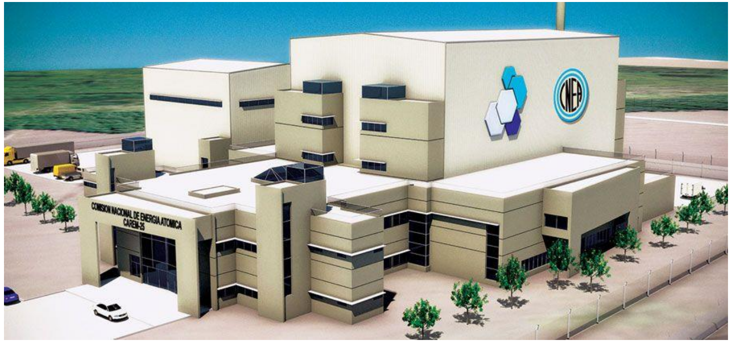
L.E. Herranz, M.P. Kissane, M. García: Comparison of LWR and SFR in-containment source term: Similarities and differences, Progress in Nuclear Energy 66(2013)7, 52-60.

Kleine modulare Reaktoren: heute schon erhältlich?

Akademik Lomonosov, Russland, 2 x 40 MW, seit Mai 2020 in Betrieb



ACP-100, China, seit Juli 2021 im Bau, Fertigstellung 2026



CAREM-25, Argentinien, im Bau geplante Fertigstellung 2023

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Reaktoren der Generation-III (LWR)

Evolutionäre Konzepte: Von Generation-II zu Generation-III

Fukushima Daichi, Blöcke I-IV, Japan

Olkiluoto-III (EPR), Finnland

1970
Generation-II

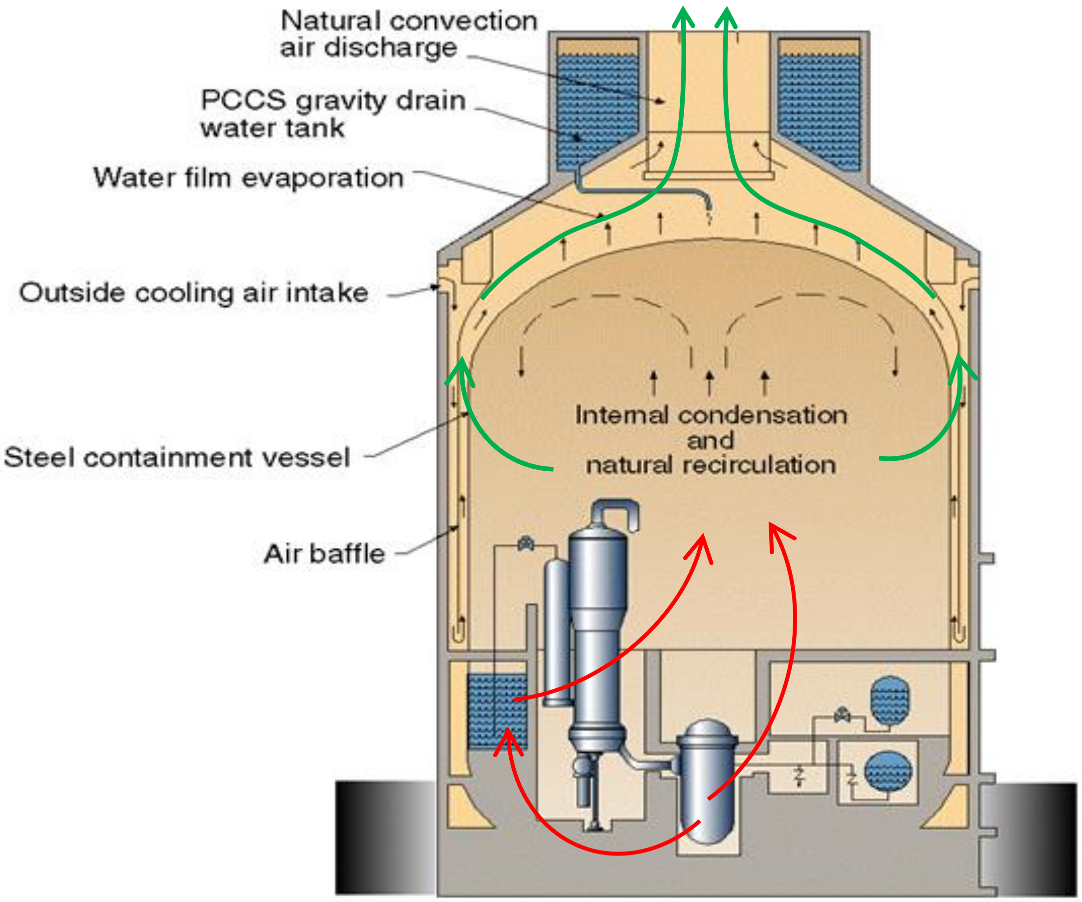
2020
Generation-III

Westinghouse AP-1000: Passive Sicherheitssysteme

1) Passives Kernkühlungssystem

- **Sicherheitseinspeisung** (Hoch- und Niedrigdrucksysteme)
- **Direkte Einspeisung** in den Druckbehälter
- Nachwärmeabfuhr und Druckabbau mit dem grossen **Vorratsbehälter IRWST** und dem Containment
- **Notflutung der Reaktorgrube** (als Massnahme bei Kernschmelze)

2) **Passives Wärmeabfuhrsystem** über das Containment



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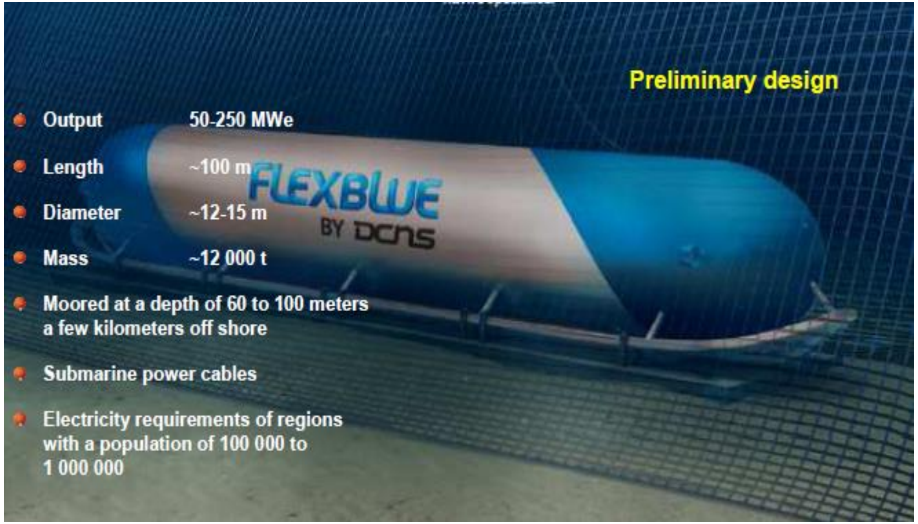
Small Modular Reactors (SMR) - LWR

FLEXBLUE (Design: DCNS): Concept 50-250 MW_e for a PWR in 100 m water depth

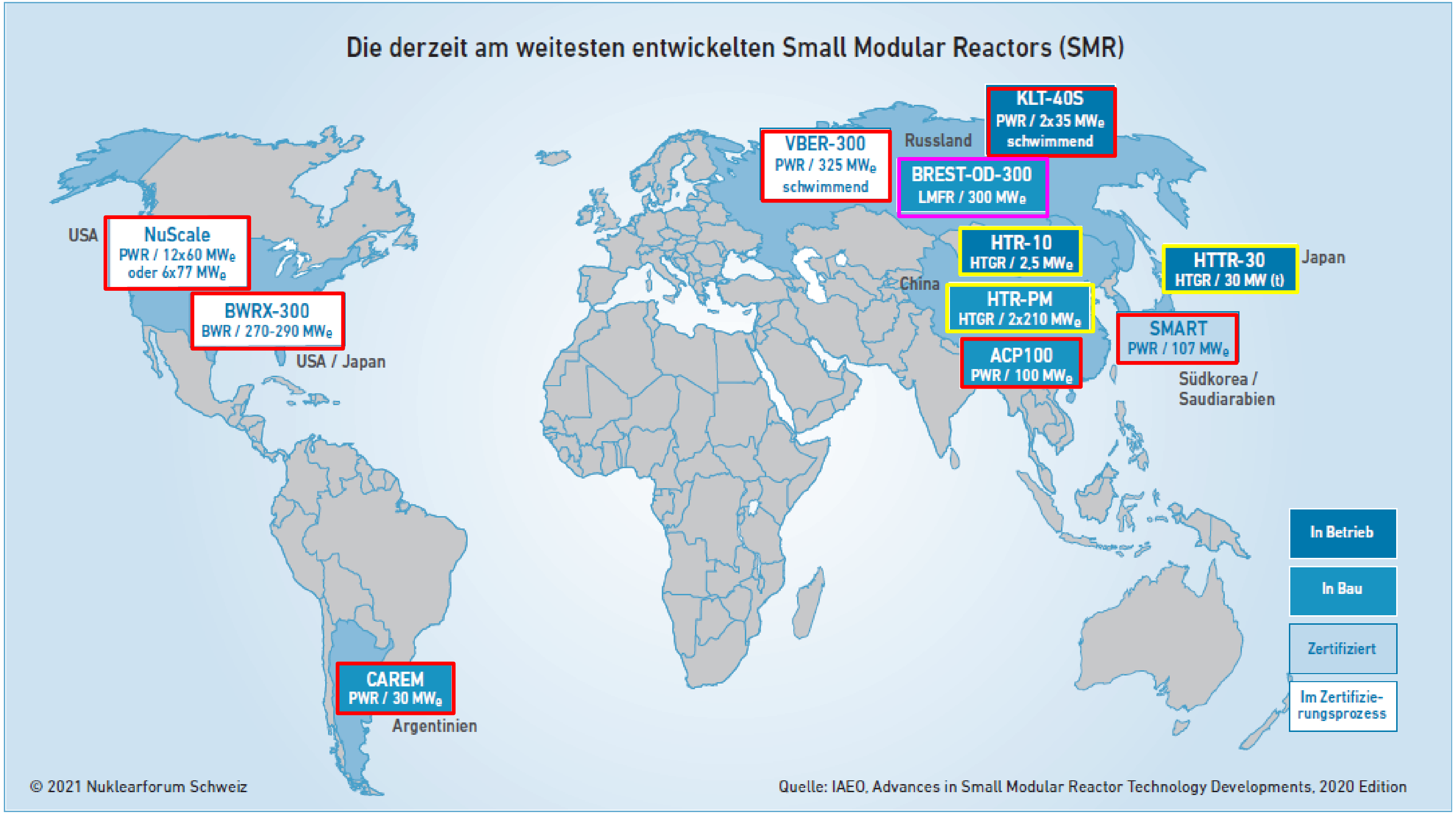
–Small PWR with passive safety systems similar to the AP-1000.

–Fully remote-controlled system (no operating crew on board).

–Emergency cooling system self-sufficient for approx. one week until human intervention (emergency measures) is required



Deployment Status of SMR (LWR + Generation-IV)



Kleine Modulare Leichtwasserreaktoren (LWR-SMR)

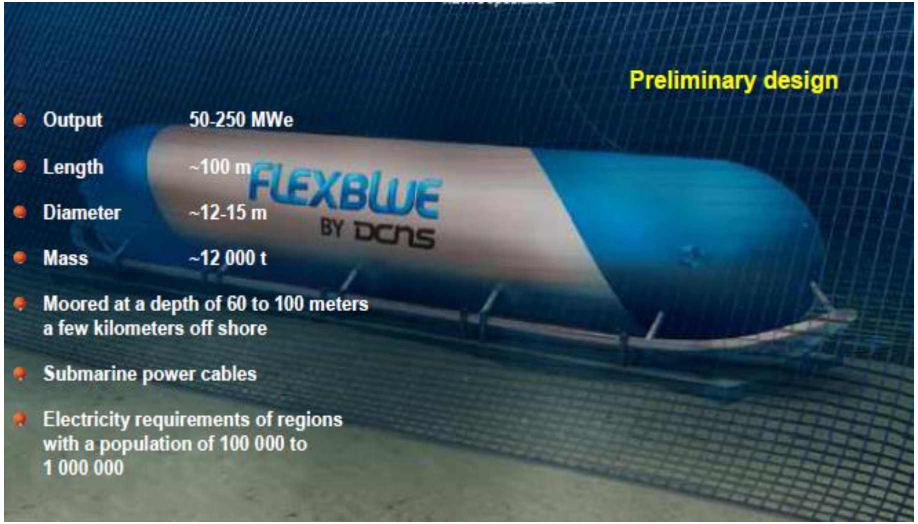
- **Kleine modulare Reaktoren** (SMR) werden zunehmen
  - **Geringere Leistung (45-300 MW$_e$)** bei vergleichba grosse Anlagen, ermöglicht durch **Modulbauweis**
  - **Deutlich einfacheres Design** als große Leichtwass Sicherheitskomponenten
  - Je nach Bedarf können **mehrere Module gleichzei** nacheinander errichtet, zu- und abgeschaltet wer
  - **Deutlich reduzierte Errichtungsdauer** für jedes Ei
  - **Kompakte Bauweise** eröffnet die Möglichkeit für
  - **«Walk-Away-Safe»**

- Die IAEA listet in ihrem SMR-Handbuch um die **70 vers** auf der bekannten Leichtwasserreaktor-Technologie, d Konzepte (Gas- und Flüssigmetallkühlung, Salzschmelz

Design	Net output per module (MWe)	Number of modules (if applicable)	Type	Designer	Country	Status
Single unit LWR-SMRs						
CAREM	30	1	PWR	CNEA	Argentina	Under construction
SMART	100	1	PWR	KAERI	Korea	Certified design
ACP100	125	1	PWR	CNNC	China	Construction began in 2019
SMR-160	160	1	PWR	Holtec International	United States	Conceptual design
BWRX-300	300	1	BWR	GE Hitachi	United States-Japan	First topical reports submitted to the US NRC and to the CNSC as part of the licensing process
CANDU SMR	300	1	PHWR	SNC-Lavalin	Canada	Conceptual design
UK SMR	450	1	PWR	Rolls Royce	United Kingdom	Conceptual design
Multi-module LWR-SMRs						
NuScale	50	12	PWR	NuScale Power	United States	Certified design. US NRC design approval received in August 2020
RITM-200	50	2	PWR	OKBM Afrikantov	Russia	Land-based nuclear power plant – conceptual design
Nuward	170	2 to 4	PWR	CEA/EDF/Naval Group/ TechnicAtome	France	Conceptual design
Mobile SMRs						
ACPR50S	60	1	Floating PWR	CGN	China	Under construction
KLT-40S	35	2	Floating PWR	OKBM Afrikantov	Russia	Commercial operation
Gen IV SMRs						
Xe-100	80	1 to 4	HTGR	X-energy LLC	United States	Conceptual design
ARC-100	100	1	LMFR	Advanced Reactor Concepts LLC	Canada	Conceptual design
KP-FHR	140	1	MSR	Kairos Power	United States	Pre-conceptual design
IMSR	190	1	MSR	Terrestrial Energy	Canada	Basic design
HTR-PM	210	2	HTGR	China Huaneng/CNEC/ Tsinghua University	China	Under construction
EM2	265	1	GMFR	General Atomics	United States	Conceptual design
Stable Salt Reactor	300	1	MSR	Moltex Energy	United Kingdom	Pre-conceptual design
Natrium	345	1	SFR	Terrapower/GE Hitachi	United States	Conceptual design
Westing-house Lead Fast Reactor	450	1	LMFR	Westinghouse	United States	Conceptual design
MMRs						
eVinci	0.2-5	1	Heat pipe reactor	Westinghouse	United States	Basic design
Aurora	2	1	LMFR	Oklo	United States	Licence application submitted to the US NRC
U-Battery	4	1	HTGR	Urenco and partners	United Kingdom	Basic design
MMR	5-10	1	HTGR	USNC	United States	Basic design

Kleine Modulare Reaktoren (LWR-SMR): Antwort auf Fukushima

- **FLEXBLUE (Design: DCNS): Konzept 50-250 MW$_e$ für einen DWR in 100 m Wassertiefe**
  - Kleiner DWR mit passiven Sicherheitssystemen ähnlich dem AP-1000
  - Vollständig ferngesteuerte Anlage (keine Betriebsmannschaft an Bord)
  - Notkühlsystem ca. eine Woche autark, bis menschliches Eingreifen (Notfallmaßnahmen) erforderlich wird



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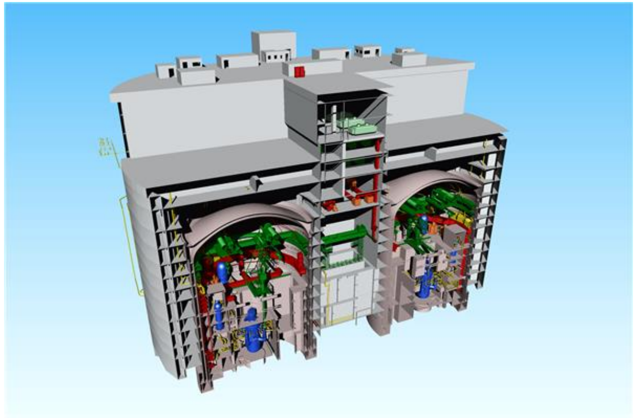
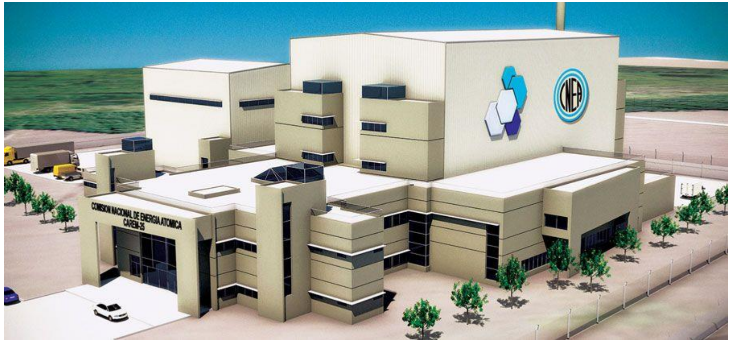
Kleine modulare Reaktoren: heute schon erhältlich?

Akademik Lomonosov, Russland, 2 x 40 MW, seit Mai 2020 in Betrieb

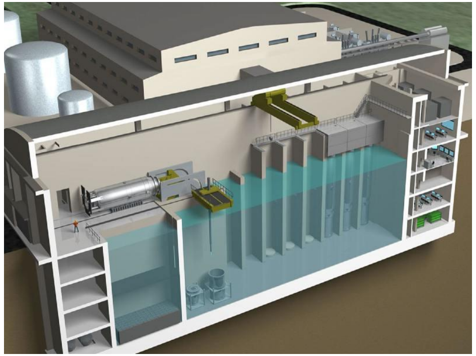


ACP-100, China, seit Juli 2021 im Bau, Fertigstellung 2026



CAREM-25, Argentinien, im Bau geplante Fertigstellung 2023

SMR (Generation-III) mit glaubhaftem Zeithorizont um 2030

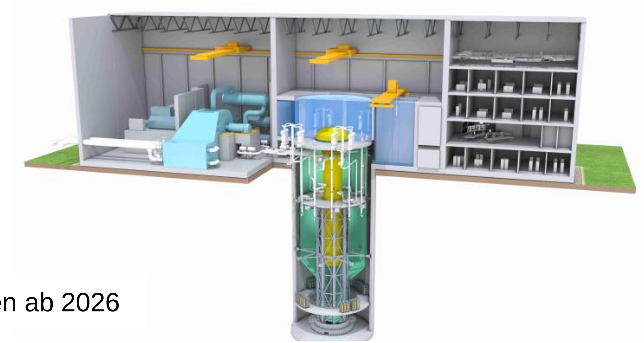


NuSCALE (6x77 MW), für Utah, ab 2027
LCOE: 65$/MWh, 3'600 $/kW installiert

NUWARD (EdF/Technicatome), 170 MW, ab 2030

UK SMR (Rolls Royce), 443 MW, ab 2030

SMART (Korea), 100 MW, Betrieb in Saudi-Arabien ab 2026

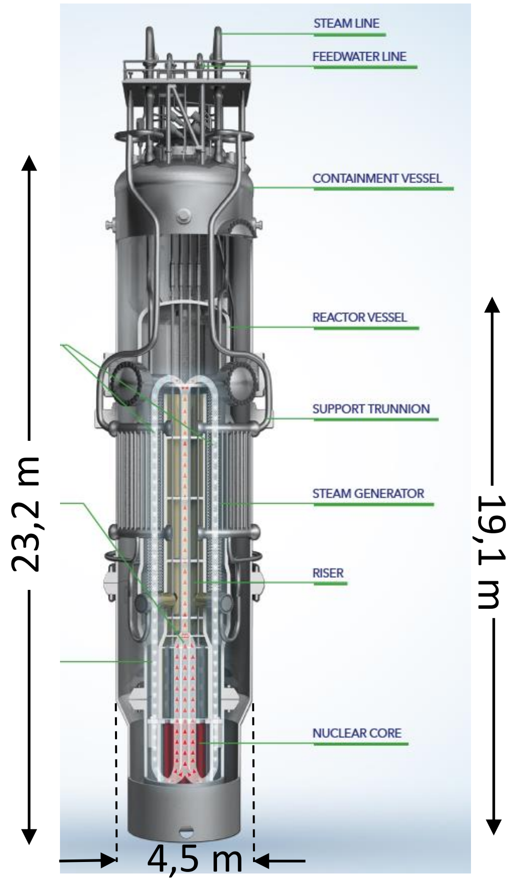


BWRX-300 (GE/Hitachi) für Ontario Power, Betrieb ab 2028, mittelfristiges Preistarget: **2'250 $/kW**

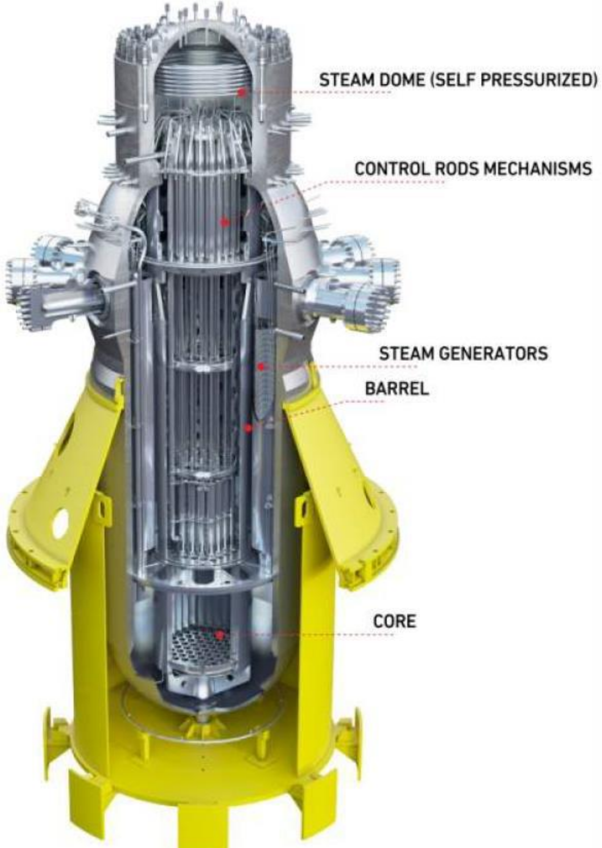
RITM-200 (Russia), Betrieb in Kirgistan ab 2028

Kleine Modulare Reaktoren (LWR-SMR): Integralbauweise

Westinghouse Small Modular Reactor 225 MWe

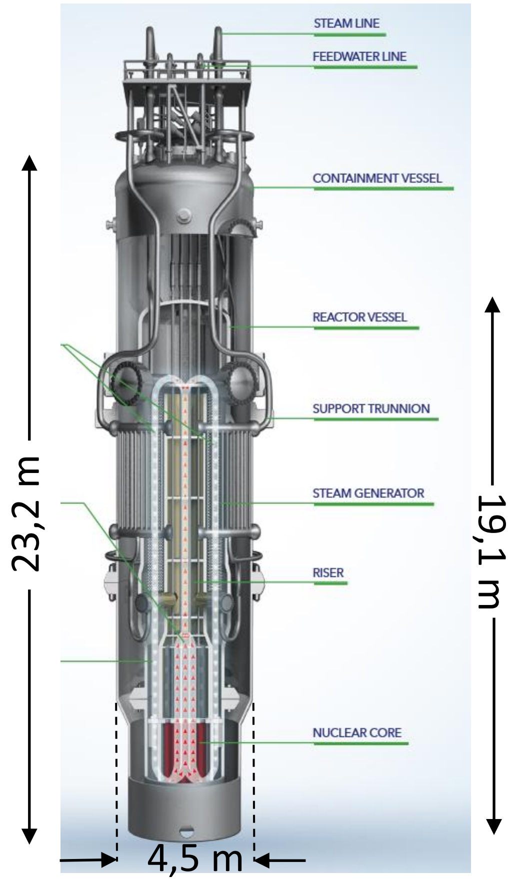


NuScale 77 MWe Module

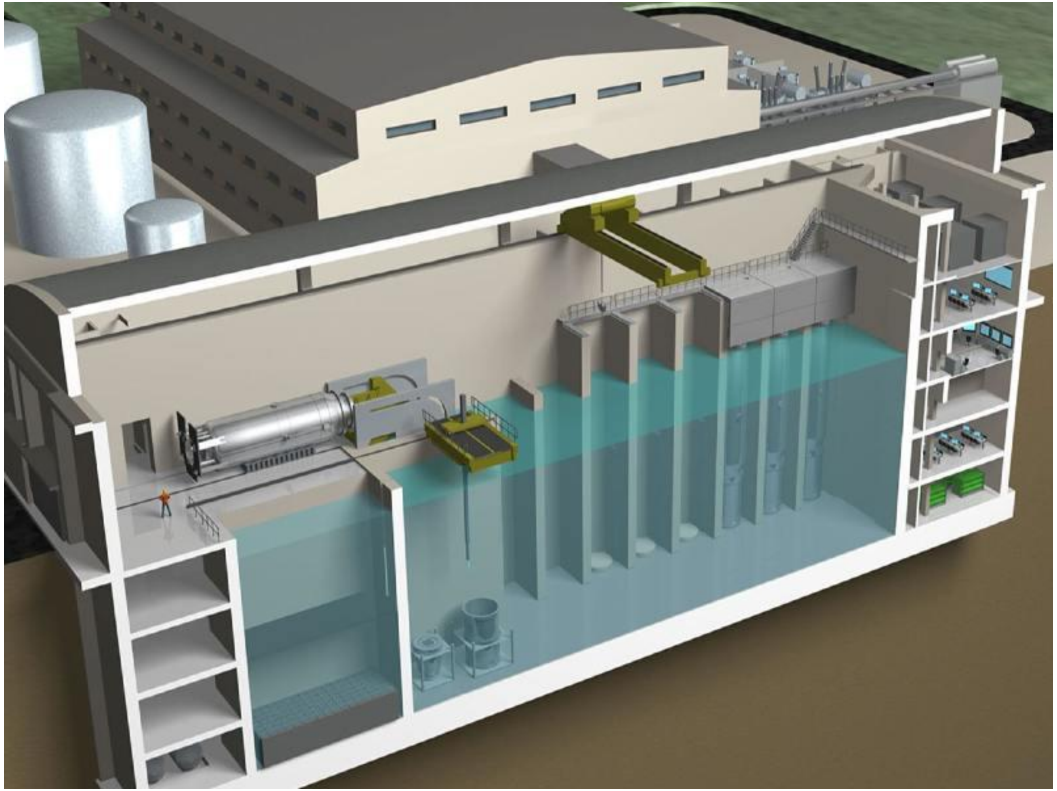


CAREM-25MW (3.2 x 11 m)

Kleine Modulare Reaktoren (LWR-SMR): Integralbauweise



NuScale 77 MWe Einzelmodul

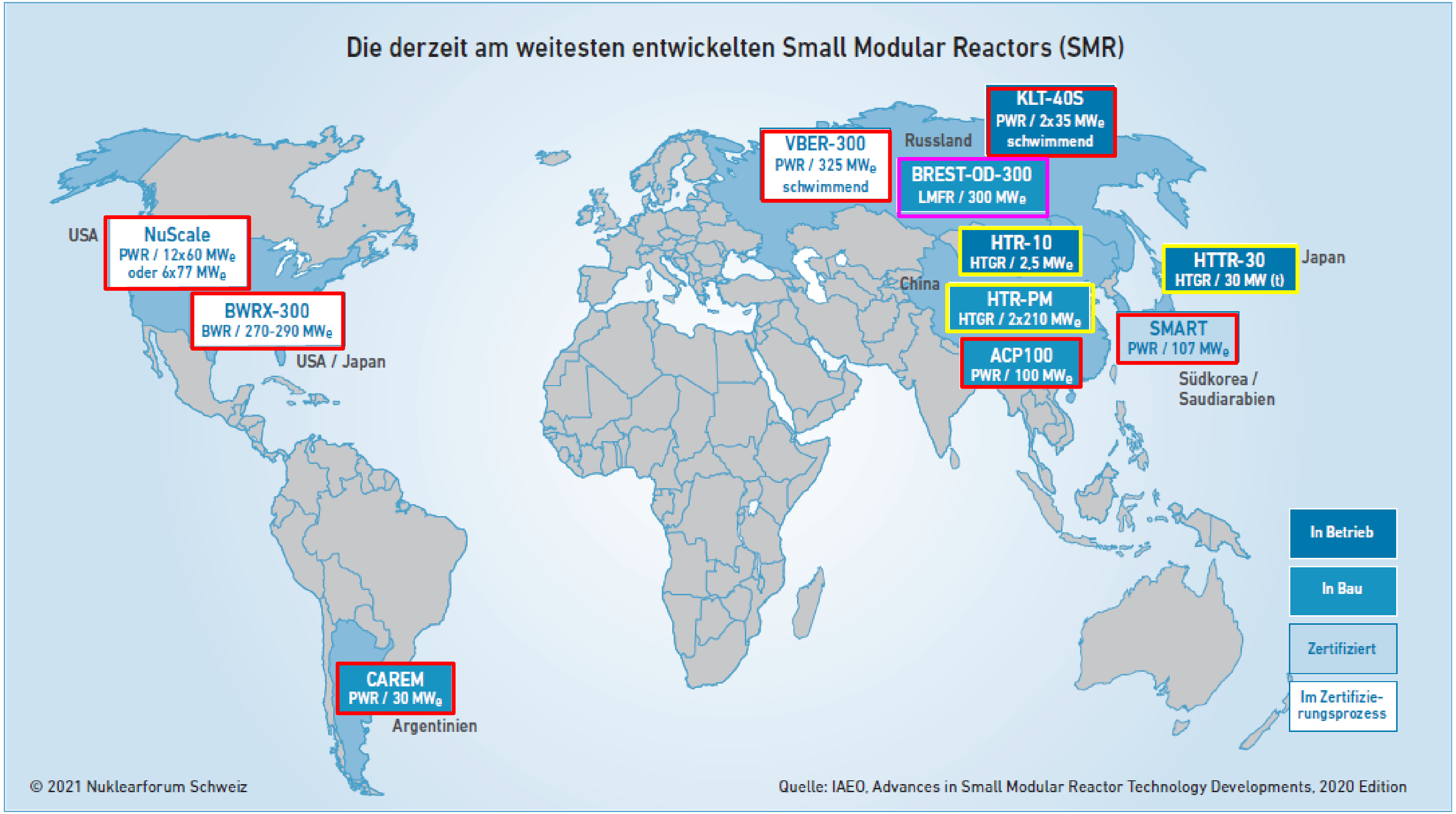


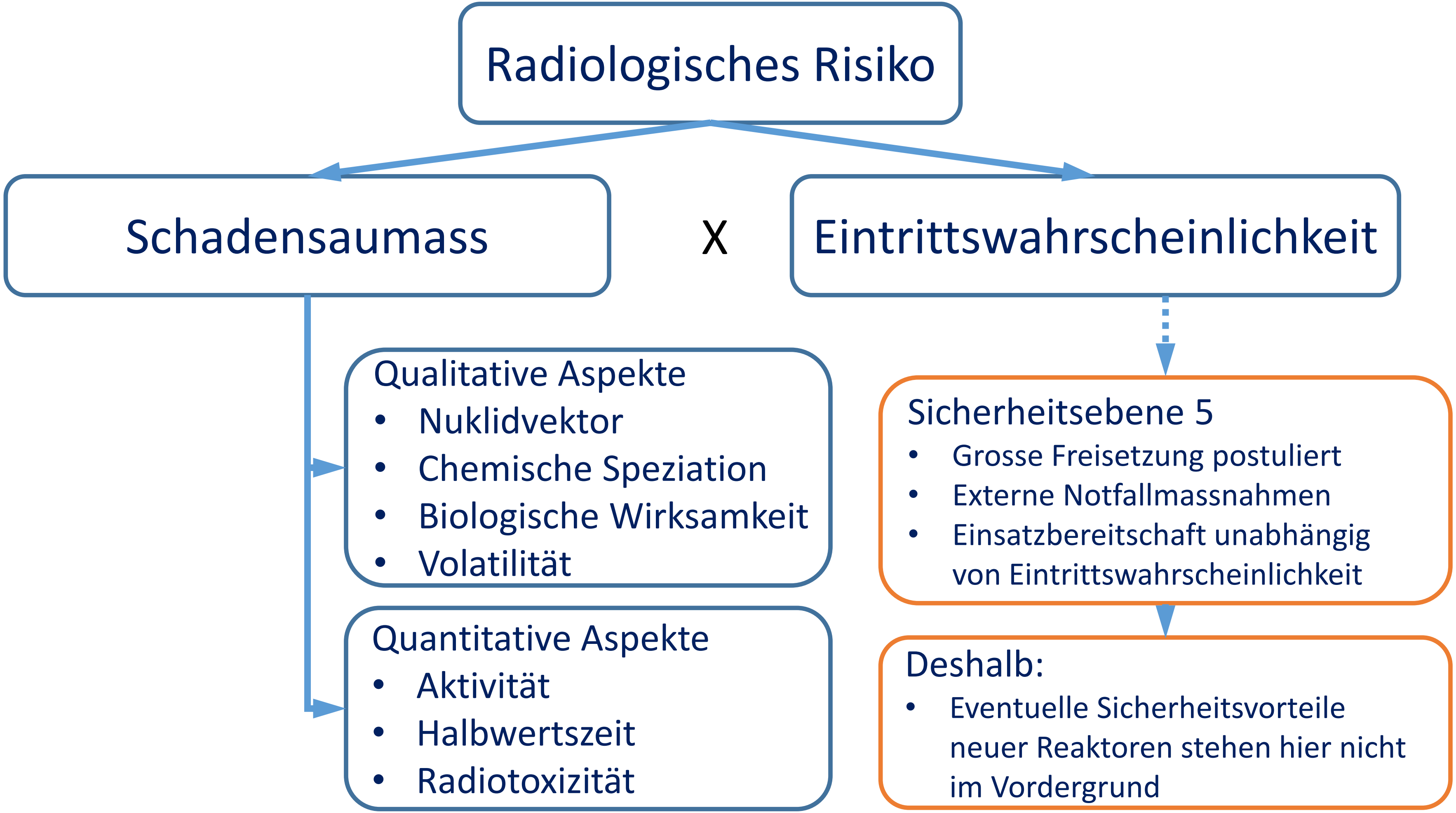
NuScale Design mit 6 x 77 MWe-Modulen

Claimed Advantages of NuScale SMR vs. large LWR

- Bis zu **12 Module parallel** (12 x 77 = 924 Mwe), die vollständig unabhängig voneinander betrieben werden können, ggf. auch in Hybridmode (Prozesswärme/Stromerzeugung)
- **Gestaffelte Zu-/Abschaltung, Inselbetrieb und Schwarzstartfähigkeit** ohne externe Netzanbindung
- I&C ausgelegt **gegen geomagnetische Störungen** und **elektromagnetische Pulse**
- **Keine sicherheitsklassierten AC/DC-Notstromeinrichtungen**, keine Pumpen oder elektrisch angesteuerte Ventile (Notstromfall)
- **Unbegrenzte Kernkühlbarkeit** allein durch passive Sicherheitssysteme, keine zusätzlichen Wasservorräte notwendig ausser denen in der Anlage vorhandenen (Übergang von konvektiver Wasser- auf Luftkühlung nach ca. 30 Tagen)
- Alle sicherheitsrelevanten Anlagenteile befinden sich unter Grund, und bieten damit **Schutz gegen Flugzeugabsturz**
- **Kühlung des Brennelementlagerbeckens sichergestellt für 150 Tage**, danach externe Wiederauffüllung notwendig (über separate Anschlüsse z.B. über Feuerlöschleitungen)
- **Kernschadensfrequenz < 10^{-8}/Jahr** für eine 12-Module-Anlage

Entwicklungsstand von SMR (LWR + Generation-IV)





Radiologisches Risiko
Schadensaumass
x
Eintrittswahrscheinlichkeit
Qualitative Aspekte
• Nuklidvektor
• Chemische Speziation
• Biologische Wirksamkeit
• Volatilität
Quantitative Aspekte
• Aktivität
• Halbwertszeit
• Radiotoxizität
Sicherheitsebene 5
• Grosse Freisetzung postuliert
• Externe Notfallmassnahmen
• Einsatzbereitschaft unabhängig von Eintrittswahrscheinlichkeit
Deshalb:
• Eventuelle Sicherheitsvorteile neuer Reaktoren stehen hier nicht im Vordergrund

Allgemeine Merkmale:

Verbesserte Neutronenbilanz	→	Brüten	→	Spaltstoff aus Brutstoff
Höhere Neutronenenergie	→	Transmutation	→	Entlastung Tiefenlager von minoren Aktiniden
Neue Brennstoffe	→	Plutonium, U-233, Th-232 als Brutstoff		
	→	Coated Particles, Brennstoffkugeln, metallisches Uran spaltstoffhaltige Salzschmelzen, Fluoride, Chloride ….		
Neue Kühlmittel / Fluide	→	Natrium, Blei-Wismut, Blei, Helium, Salzschmelzen		
	→	Vermeidung der Neutronenabbremsung		
Neue Reaktorkonzepte	→	Pool-Reaktoren, Beschleunigergetriebene Systeme kleine modulare Reaktoren		

Qualitativ neue Störfallszenarien bei entsprechenden postulierten auslösenden Ereignissen und ggf. Auslegungsfehlern:

- Freezing accidents in LBE und salt melts (the latter less relevant)
- Positive void RIAs (especially in Na-cooled reactors)
- Natriumbrände, Na-H_2O-Reaktion
- Integrity loss due to corrosion (salt, LBE, lead)
- Air and water ingress (+ recrit) in HTR-PMs (nicht sehr problematisch)
- Graphitstaub aus Kugelabrieb als Transportvehikel für adsorbierte Spaltprodukte (minor issue)
- Common external causes in SMR plants

Andererseits deterministischer Ausschluss einiger Szenarien:

- No LOCAs in pool type reactors (also in so-called compact loop types)
- No Zr-H_2O reaction → H_2 (but Na-H_2O in SFRs....)
- Less failure modes of ECCS (e.g. inherent cooling of HTR-PMs, small passive heat removal loops, passively cooled dump tanks with neutron absorbers in MSRs, high stand-by temperatures in non-H2O coolants)
- Easy core catching in SFRs and LBE/lead cooled reactors
- Less or no neutron embrittlement issues (no cool-down transients, high stand-by temperatures)

Kühlmittelaktivierung im Natriumgekühlten Brutreaktor

- Typisches Natriuminventar im Primärkreislauf (Grössenordnung): 2’000 t
- Reaktionen: Na-23 (n,γ) Na-24 σ = 283 μbarn β-, γ $T_{1/2}$ = 15 h

  Na-23 (n, 2n) Na-22 σ = 2.7 μbarn β+, γ $T_{1/2}$ = 2.6 a
- Aktivitätsinventare und Gesamtradiotoxizität (schnelles n-Spektrum, Toxizität basierend auf e_{ing}, gerundet):

Na-22	1.4	PBq	4.5E+06	Sv
Na-24	0.01	PBq	4.3E+03	Sv
I-131	4000	PBq	8.8E+10	Sv
Xe-133	6500	PBq	-	Sv
Cs-137	240	PBq	3.1E+09	Sv

→ Vergleichsweise geringe radiologische Relevanz

→ Cäsium und Iod in Natrium löslich **(+)** → Rückhaltevermögen bei Kernschäden → hauptsächlich nur Edelgasfreisetzung

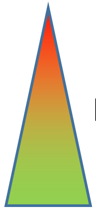
- **Aber:** Hohe chemische Toxizität
  - Natrium gefährlich im Hautkontakt
  - Natriumbrand → hohe Aerosoldichte (Na_2O, Na_2O_2, NaOH = lungen- und hautschädigend)

Proliferationsresistenz:

Allgemeine Ansätze → Rezyklierung von Aktinidengemischen anstatt von reinem (waffenfähigem) Spaltstoff = Selbstschutz durch Kontamination

WA-Technologien:

- PUREX + SANEX + DIAMEX
- GANEX
- Pyro-Reprocessing

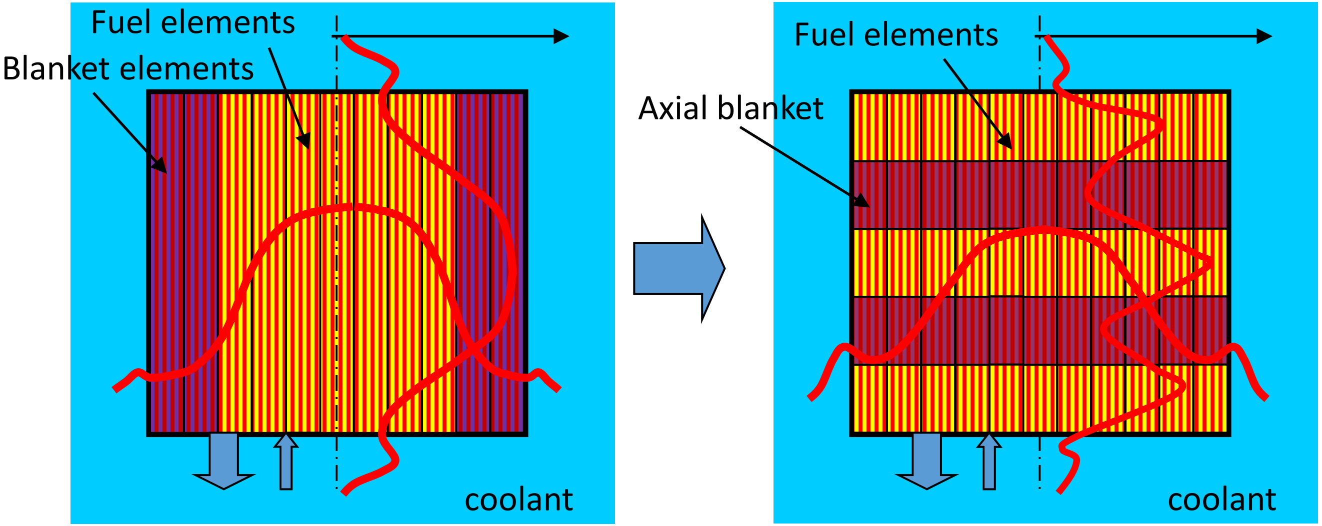


Proliferationsresistenz

→ Überbrüten des Plutoniumvektors, Erschwerung kurzzeitiger Bestrahlung von Brutstoff (auch in LWR)

→ Vermeidung leicht handhabbaren Spaltstoffs aus dedizierten Brutzonen

Sicherheit und Proliferationsresistenz synergetisch in Natriumgekühlten Brutreaktoren

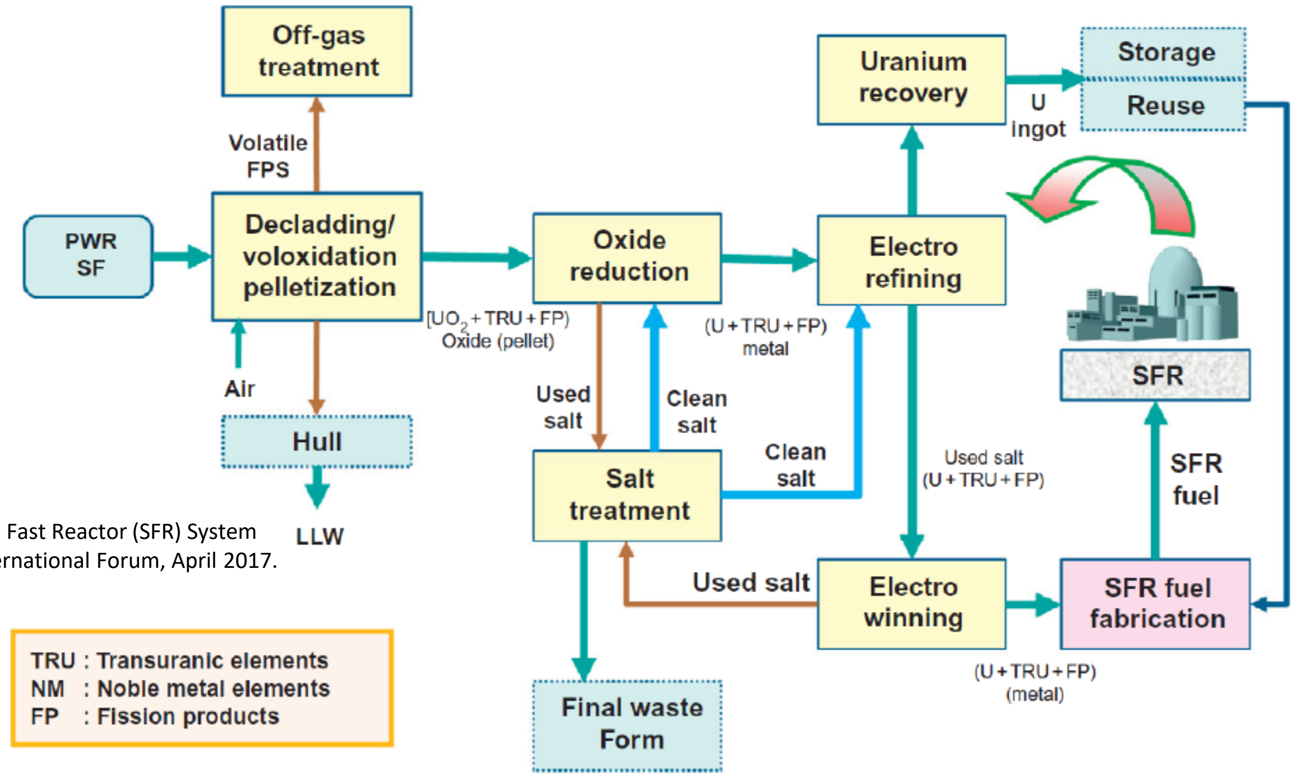


- Radial blanket: optimal breeding efficiency
- Easy removal of weapon grade Pu-239
- Criticized for low proliferation resistance

- “Parfait” core with axial breeding blanket zones inside the fuel rods
- Fissile fuel with fission products and blanket material cannot be easily separated
- Improved proliferation resistance

- Neutronics: “Parfait” core combines positive dynamic properties (negative void effect) with good breeding efficiency (leakage neutrons are absorbed by blanket material)

Sicherheit von neuen WA-Technologien bei grosstechnischer Einführung



Ruggieri et al., Sodium-Cooled Fast Reactor (SFR) System Safety Assessment, GenIV International Forum, April 2017.

TRU : Transuranic elements
NM : Noble metal elements
FP : Fission products

Salzschmelzeeletrolyse als Trennverfahren wenig selektiv wegen ähnlicher Redoxpotentiale der Aktiniden
→ Aktiniden (U, Pu, MA) warden gemeinsam abgeschieden und rezykliert → gute Proliferationsresistenz

Fazit:

- Keine grundsätzlich neuen potentiellen nukleare Bedrohungen durch GenIV-Reaktoren
- Graduelle Verschiebungen:
  - Quantitative Verschiebungen bei den Nuklid-Inventaren
  - Neue chemische Herausforderungen
  - Erweiterte Prozesse der Wiederaufarbeitung, grosstechnische Einführung von Pyro-Reprocessing
  - GenIV offeriert eine Reihe neuer intrinsischer Sicherheitseigenschaften
- In diesem Vortrag nur bruchstückhafte Zusammenstellung
- Literaturstudie und weitere Analysen (PSA Level 2 und Level 3) sind stark zu empfehlen
- Kompetenz in der Schweiz hauptsächlich im Paul Scherrer Institut