Kernenergie des 21. Jahrhunderts

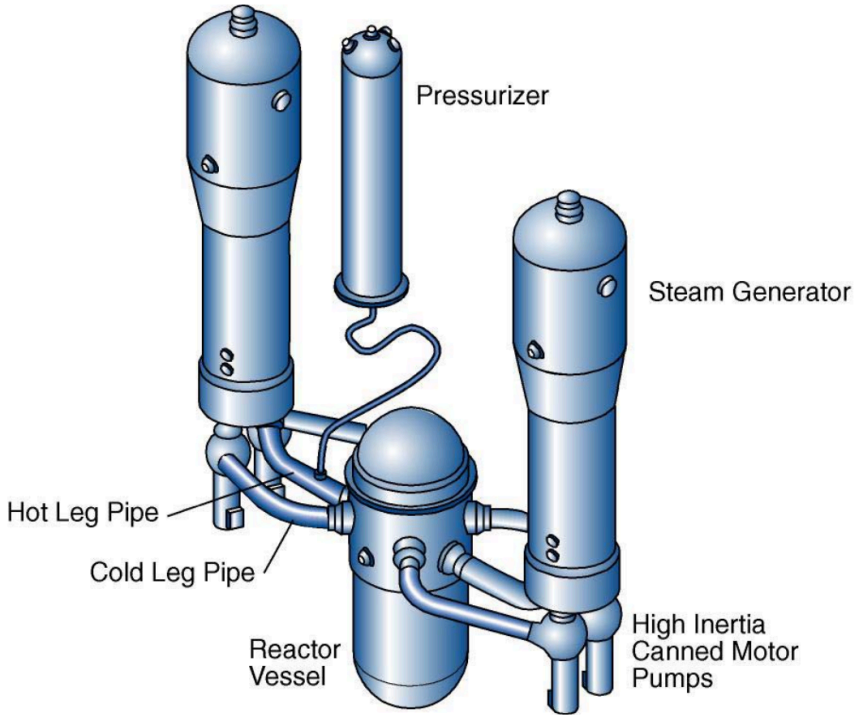
Entwicklungsstand und Ausblick

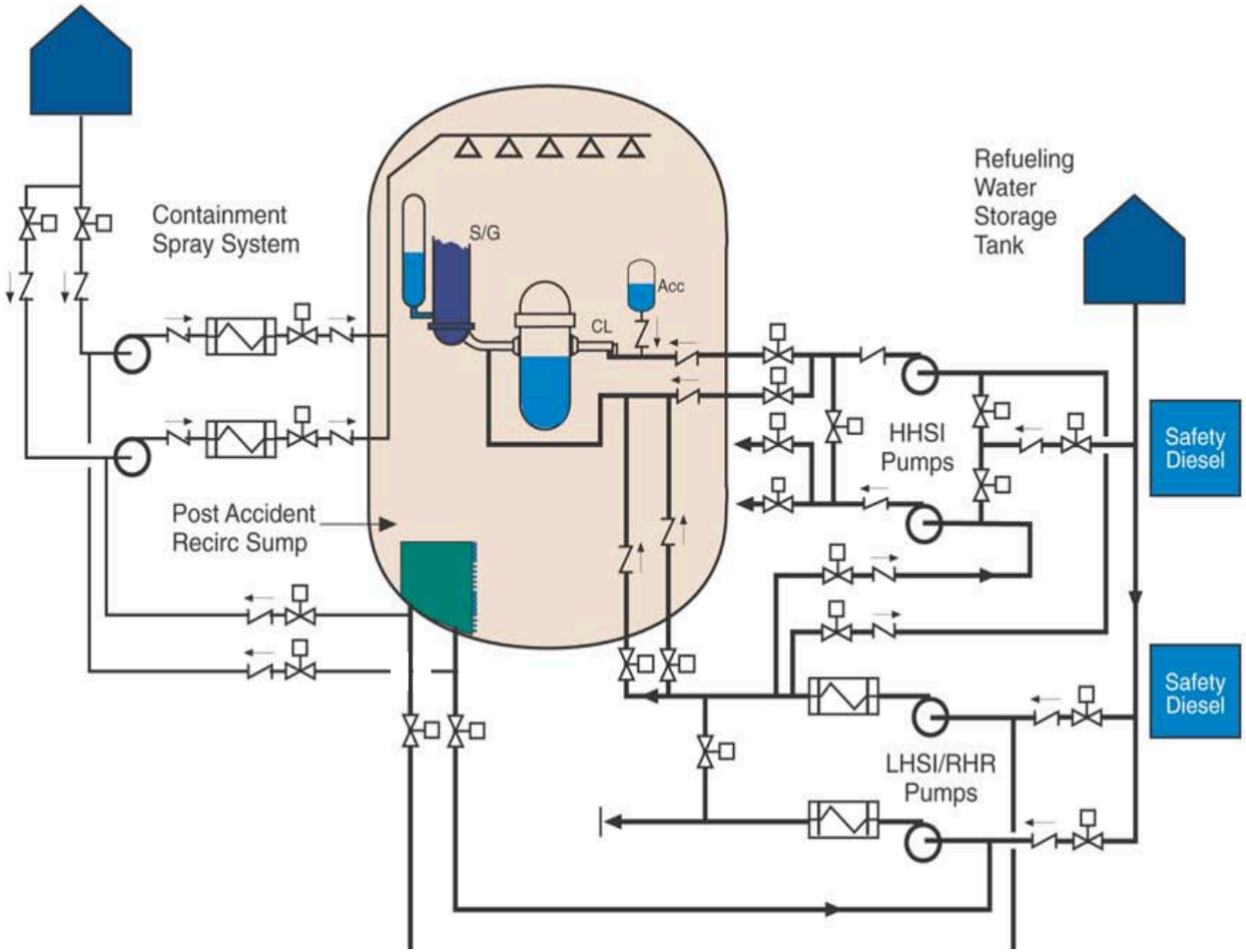
Dr. Humpich, Nov. 2022

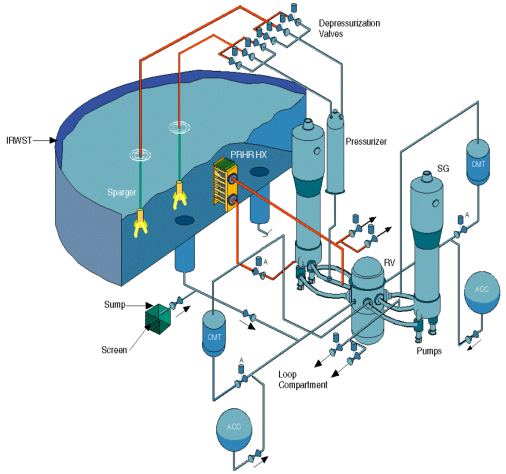
Klassischer Druckwasserreaktor z. B. AP-1000

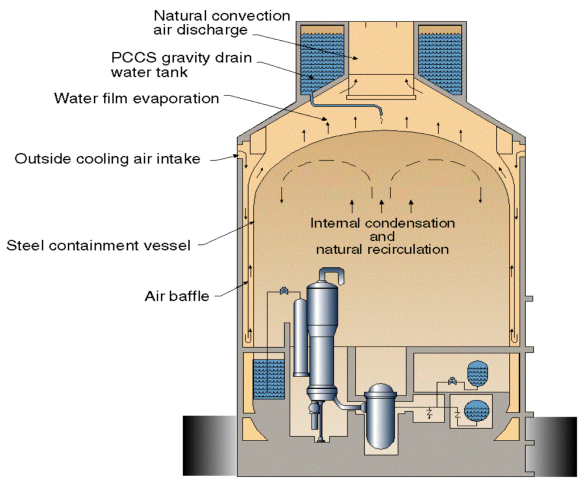
Zentrales Druckgefäss

2, 3 oder 4 Dampferzeuger jeweils mit Vor- und Rücklauf und Hauptkühlmittelpumpen



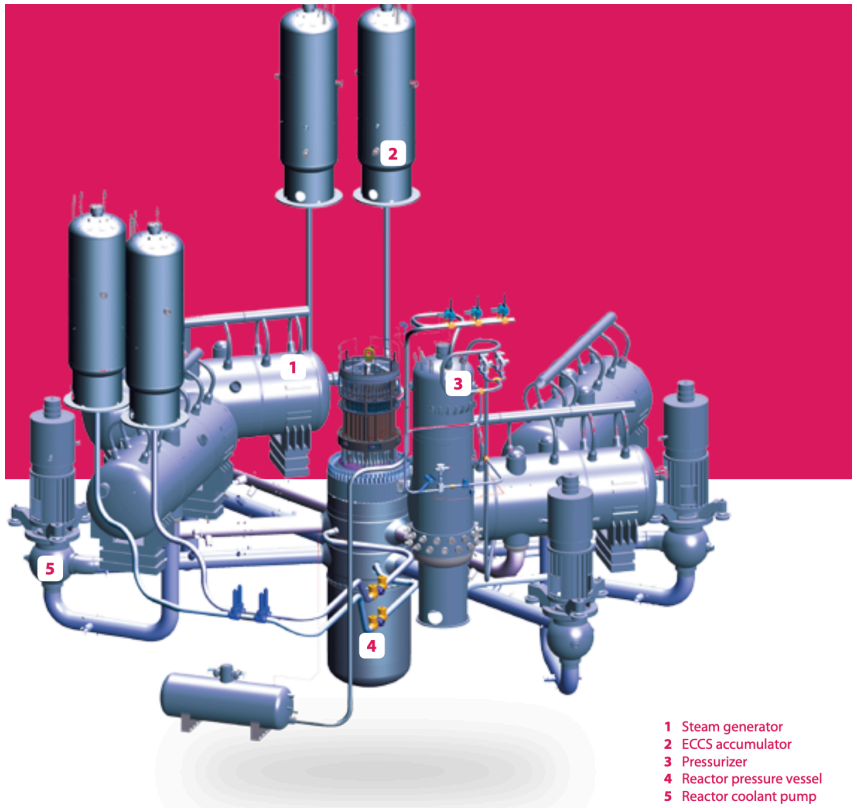

Containment
Spray System
S/G
Acc
CL
Refueling
Water
Storage
Tank
HHSI
Pumps
Safety
Diesel
Post Accident
Recirc Sump
Safety
Diesel
LHSI/RHR
Pumps


Depressurization
Valves
IRWST
Pressurizer
PRHR HX
Sparger
SG
CMT
RV
ACC
Sump
Screen
CMT
Pumps
Loop
Compartment
ACC

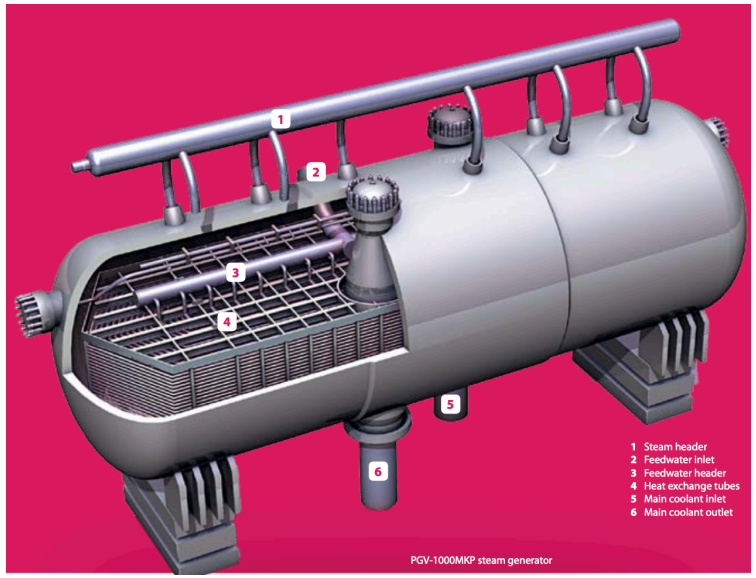

Natural convection
air discharge
PCCS gravity drain
water tank
Water film evaporation
Outside cooling air intake
Steel containment vessel
Air baffle
Internal condensation
and
natural recirculation

Dampferzeugung VVER

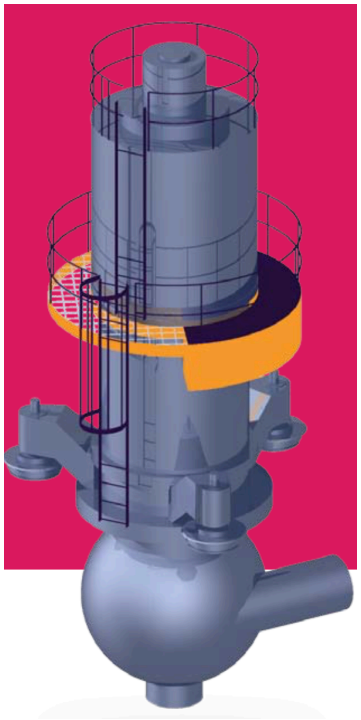
Dampferzeugung



Verdampfer

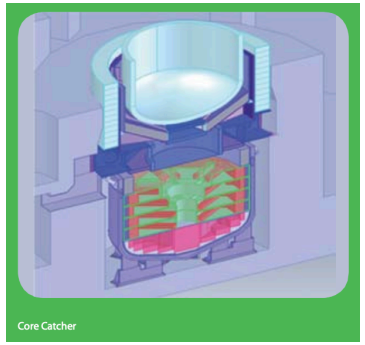


Kühlmittelpumpe

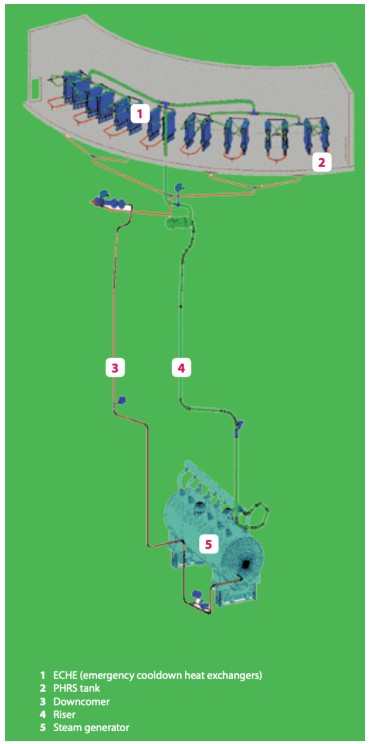


Komponenten eines VVER

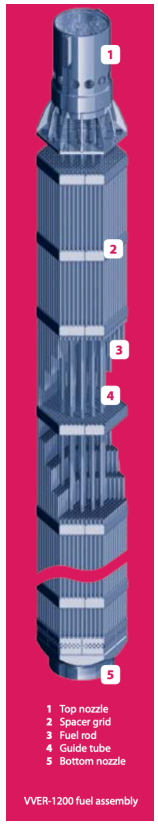
Core Catcher 800 to



Passive Notkühlung



Brennelement



Druckwasserreaktoren der Generation III(+)

	AP-1000 (CAP-1000) III+	VVER III+	EPR III	APR-1400 III	HPR-1000 (Hualong) III
Betrieb	4 x in China	4 x in Russland 2 x in Belarus 2 x in Indien 1 x in China	2 x in China 1 x in Finnland	2 x in Korea 4 x UAE	2 x in China
Bau	8 x in China 2 x in USA	4 x in Ägypten 2 x in Bangladesh 4 x in China 4 x in Indien 1x in Russland 4 x Türkei 2 x Ungarn	1 x in Frankreich 2 x in GB	4 x in Korea	2 x in Pakistan 10 x in China
Planung	3-6 x Polen 5-9 x Ukraine (?) 1 x Tschechien (?)	???	2 x in GB (?)	2 x in Korea 4 x in Polen (?) 2 x Saudi Arabien (?)	1 x in Argentinien

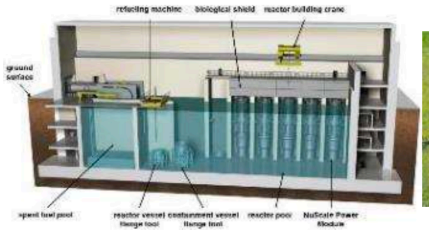
„Kleine“ Reaktoren:
nach IAEA Advanced Reactors Information System 2022 (ARIS) 2022 Edition

SMR (Small Modular Reactor)

Klasse	Neutronen	Kühlmittel	Reaktortyp
Small (bis 300 MWel)	thermisch	Leichtwasser	30 Druckwasser 5 Siedewasser
		Schwerwasser	2
		Gas	22
		Salz	15
	schnell	Natrium	5
		Blei	10
		Gas	3
		Salz	5
Micro		div.	24

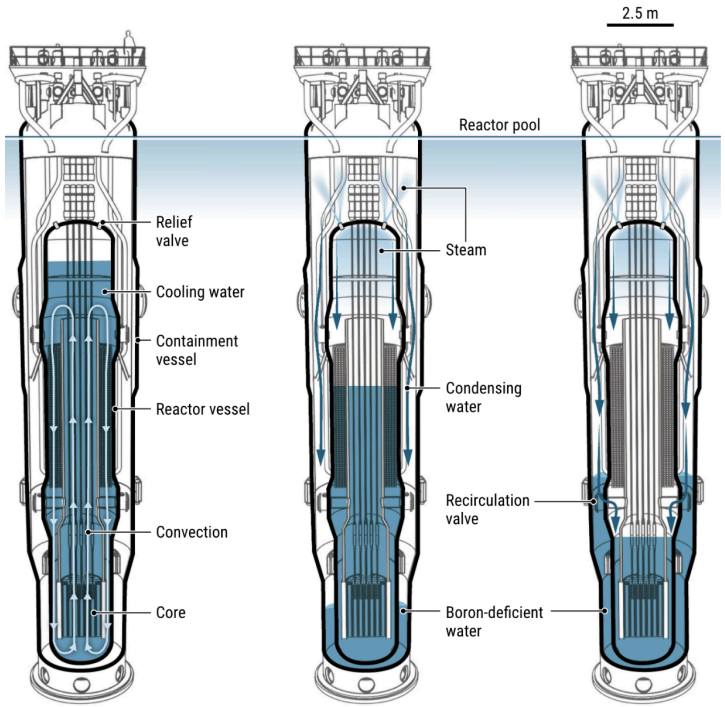
VOYGR™ Druckwasser-SMR von NuScale:

Reaktor-Gebäude auf Grundstück



Cut-away view of NuScale power plant

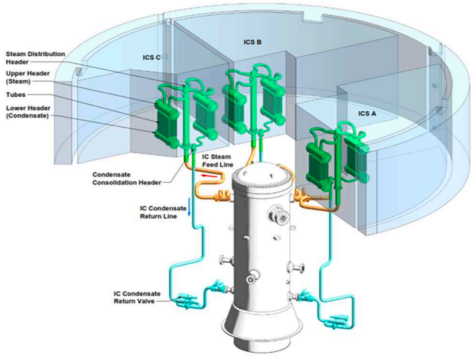
Site Layout of 12 module VOYGR-12 plant



MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	NuScale Power Corporation, USA
Reactor type	Integral PWR
Coolant/moderator	Light water / Light water
Thermal/electrical capacity, MW(t)/MW(e)	250 / 77 (gross)
Primary circulation	Natural circulation
NSSS Operating Pressure (primary/secondary), MPa	13.8 / 4.3
Core Inlet/Outlet Coolant Temperature (°C)	249 / 316
Fuel type/assembly array	UO_2 pellet / 17x17 square
Number of fuel assemblies in the core	37
Fuel enrichment (%)	≤ 4.95
Core Discharge Burnup (GWd/ton)	≥ 45
Refuelling Cycle (months)	Nominal 18
Reactivity control mechanism	Control rod drive, boron
Approach to safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	140 000 (VOYGR™-12)
RPV height/diameter (m)	17.7 / 2.7
RPV weight (metric ton)	TBC
Seismic Design (SSE)	0.5g
Fuel cycle requirements / Approach	Nominal three-stage in-out refuelling scheme
Distinguishing features	Unlimited time for core cooling without AC or DC power, or water addition, or operator action
Design status	Equipment Manufacturing in Progress

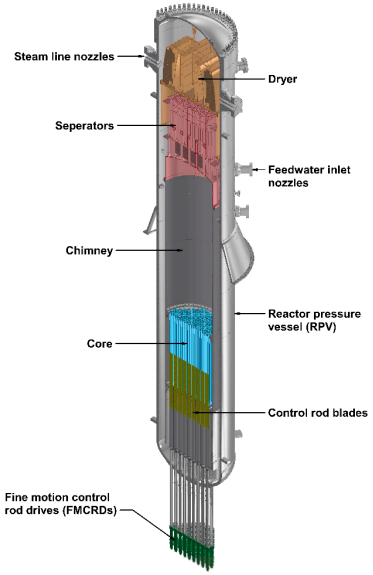
BWRX-300 Siedewasserreaktor von GE-Hitachi:

Notfallkühler

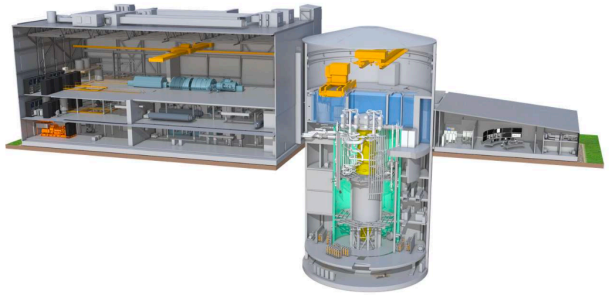


Isolation Condenser

Reaktor



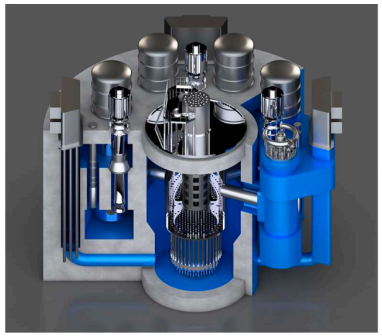
SMR Kraftwerk

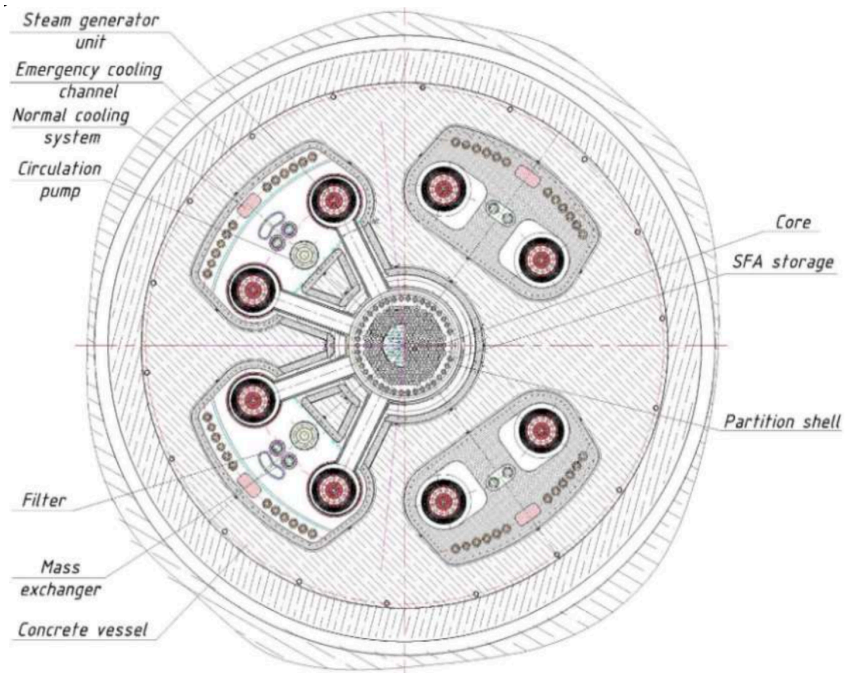


Plant Layout Arrangement

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	GE-Hitachi Nuclear Energy, United States and Hitachi-GE Nuclear Energy, Japan
Reactor type	Boiling water reactor
Coolant/moderator	Light-water / light-water
Thermal/electrical capacity, MW(t)/MW(e)	870 / 270 – 290
Primary circulation	Natural circulation
NSSS operating pressure (primary/secondary), MPa	7.2 / Direct cycle
Core inlet/outlet coolant temperature (°C)	270 / 288
Fuel type/assembly array	UO_2 / 10×10 array
Number of fuel assemblies in the core	240
Fuel enrichment (%)	3.81 (avg) / 4.95 (max)
Refuelling cycle (months)	12 - 24
Core discharge burnup (GWd/ton)	49.6
Reactivity control mechanism	Rods and solid burnable absorber (B_4C, Hf, Gd_2O_3)
Approach to safety systems	Fully passive
Design life (years)	60
Plant footprint (m^2)	9 800
RPV height/diameter (m)	26 / 4
RPV weight (metric ton)	485
Seismic design (SSE)	0.3g
Fuel cycle requirements/approach	Open fuel cycle utilizing standard BWR fuel
Distinguishing features	Natural circulation BWR, integral RPV isolation valves, isolation condenser
Design status	Detailed design

BREST-OD-300 Bleikühlung, schnelles Neutronenspektrum:

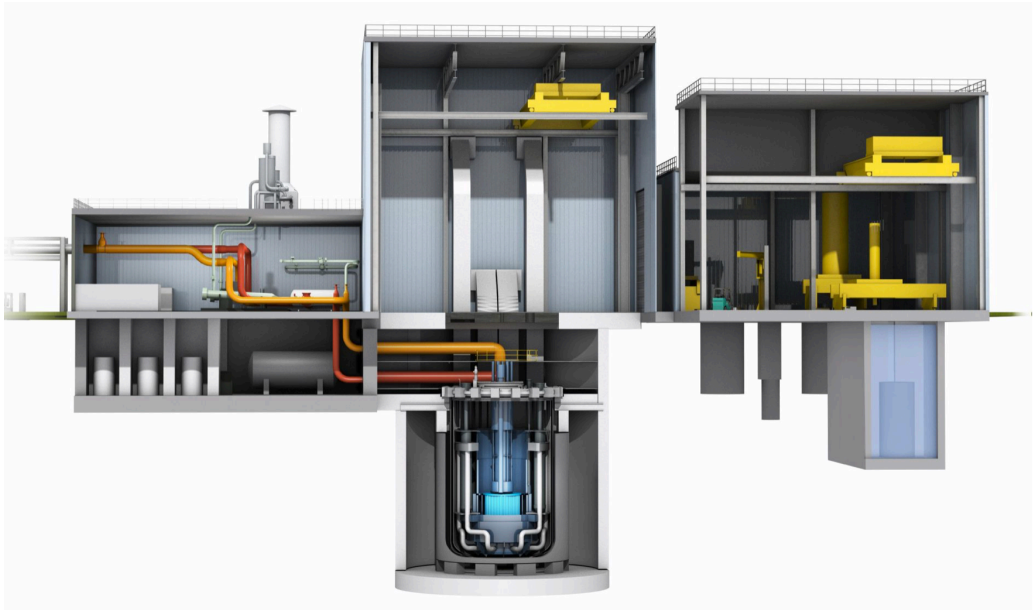


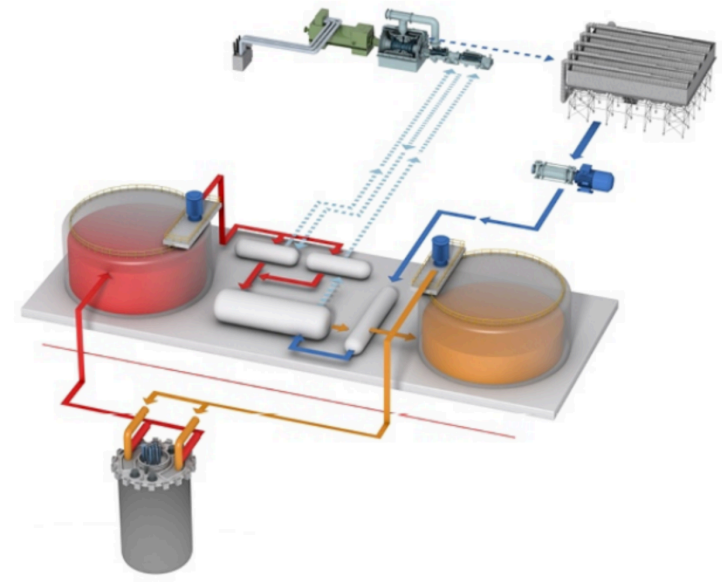


BREST-OD-300 Layout

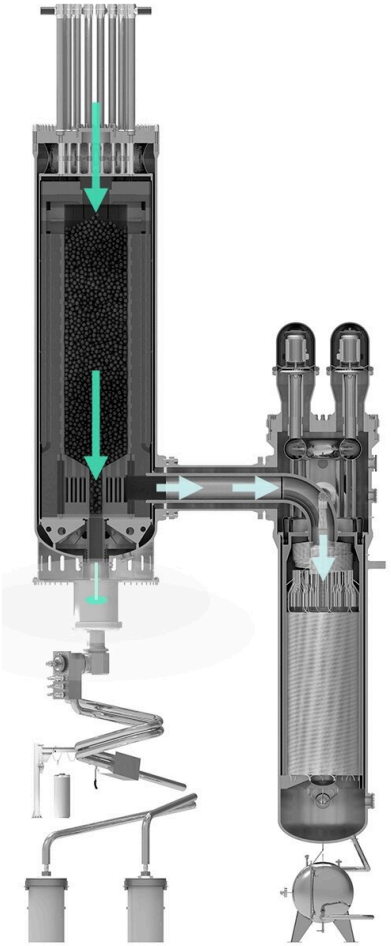
MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	NIKIET, Russian Federation
Reactor type	Liquid metal cooled fast reactor
Coolant	Lead
Thermal/electrical capacity, MW(t)/MW(e)	700 / 300
Primary circulation	Forced circulation
NSSS operating pressure (primary/secondary), MPa	0.1 / 17 – 18.5
Core inlet/outlet coolant temperature (°C)	420 / 535
Fuel type/assembly array	Mixed uranium plutonium nitride
Number of fuel assemblies in the core	169
Fuel enrichment (%)	up to 14.5
Refuelling cycle (months)	36 – 78
Core discharge burnup	61.45
Reactivity control mechanism	Reactivity compensation (RC), emergency protection (EP) and automatic control (AC) members
Approach to safety systems	Passive
Design life (years)	30
Plant footprint (m^2)	80 × 80
RPV height/diameter (m)	17.5 / 26
RPV weight (metric ton)	27 000
Seismic design (SSE)	VII-MSK 64
Fuel cycle requirements/approach	Closed fuel-cycle. It uses nitride of depleted U with Pu
Distinguishing features	High level of inherent safety due to natural properties of the lead, fuel, core and cooling design
Design status	Construction in progress

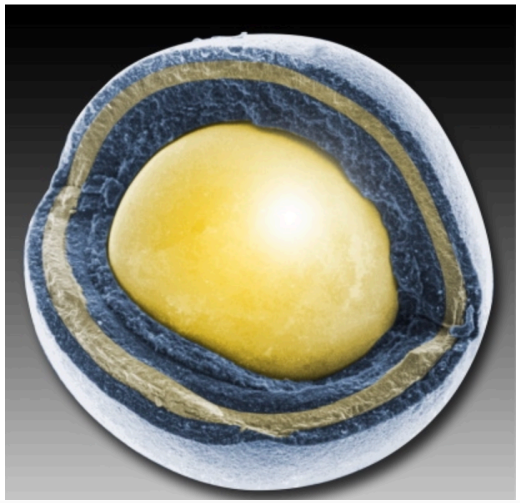
NATRIUM Integriertes Energiezentrum auf der Basis eines natriumgekühlten schnellen Reaktors (TerraPower / GE-Hitachi / Mitsubishi / Bechtel mit div. EVU):

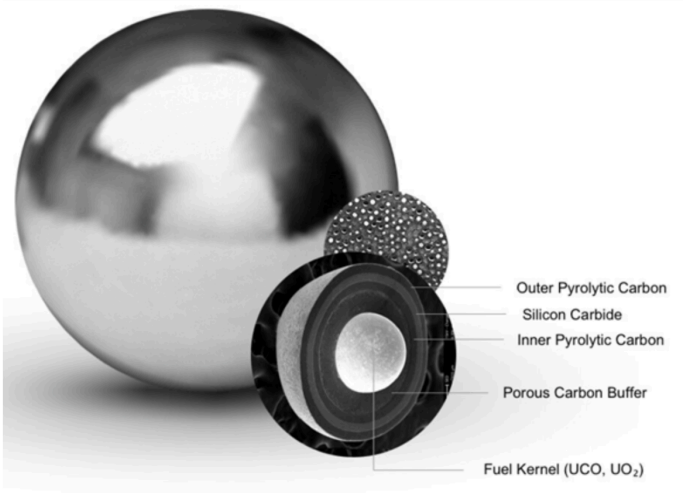




Xe-100 Helium HTR:

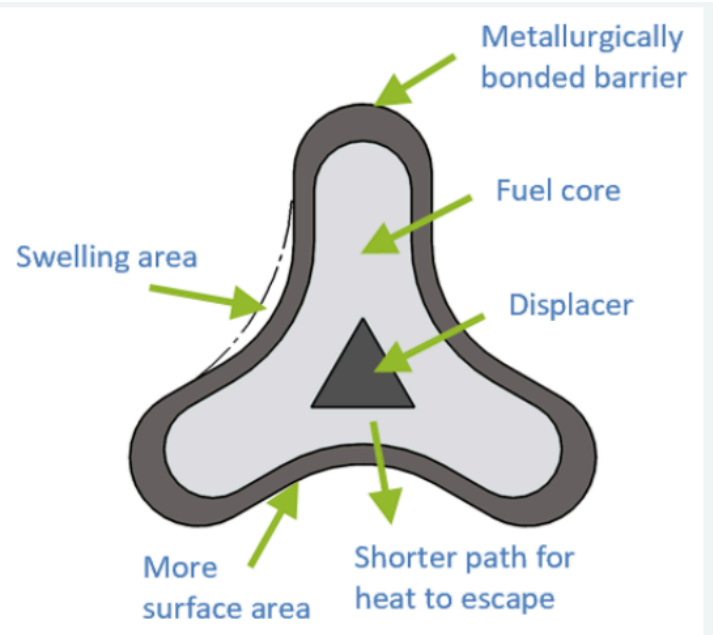


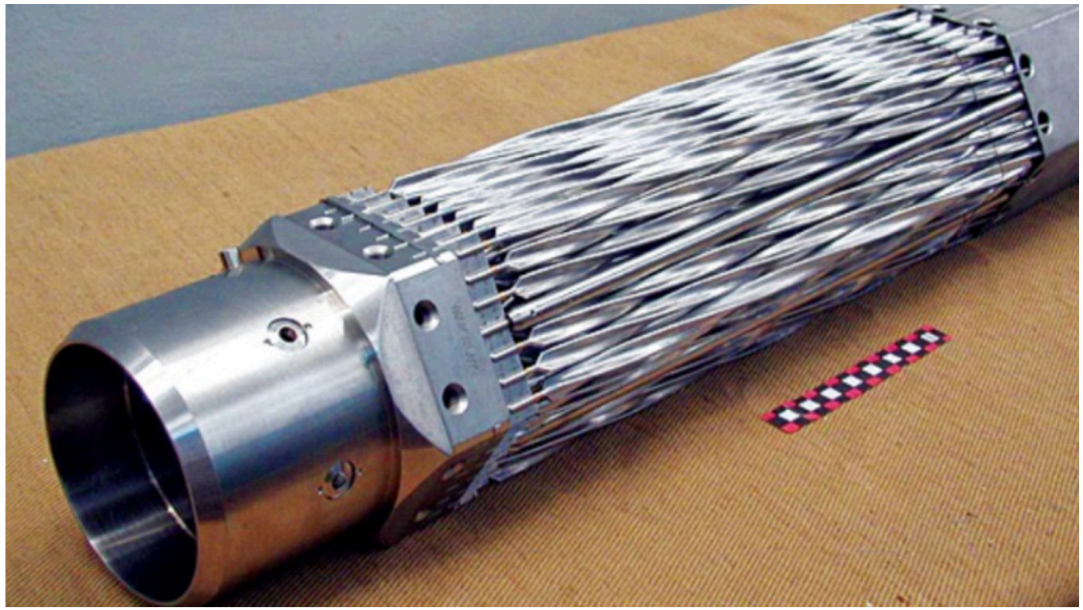




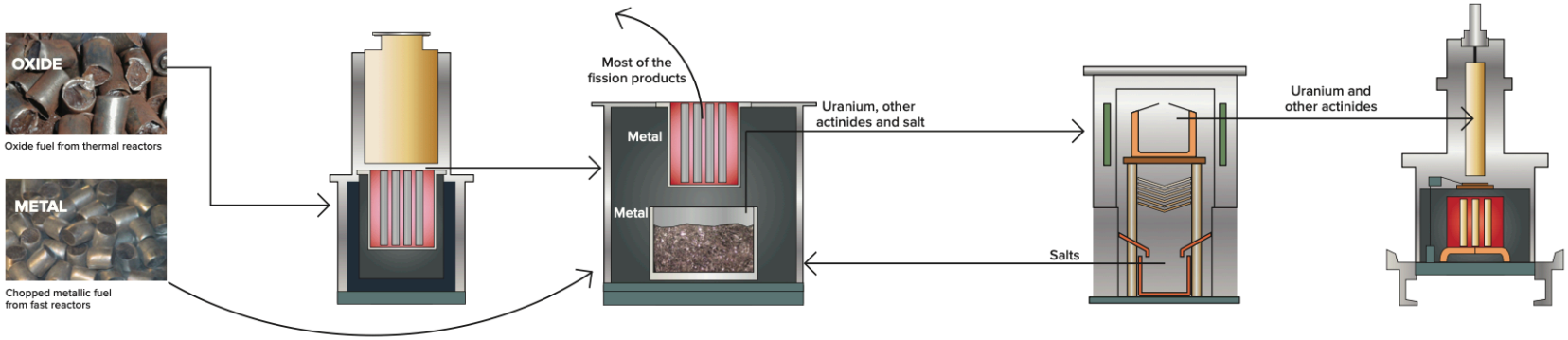
MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	X-energy, LLC, United States of America
Reactor type	Modular HTGR
Coolant/moderator	Helium/graphite
Thermal/electrical capacity, MW(t)/MW(e)	200 / 82.5
Primary circulation	Forced helium circulation
NSSS Operating Pressure (primary/secondary), MPa	6.0 / 16.5
Core Inlet/Outlet Coolant Temperature (°C)	260 / 750
Fuel type/assembly array	UCO TRISO/pebbles
Number of fuel assemblies in the core	220 000 pebbles per reactor
Fuel enrichment (%)	15.5
Core Discharge Burnup (GWd/ton)	165
Refuelling Cycle (months)	Online fuel loading
Reactivity control mechanism	Thermal feedback & control rods
Approach to safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	340m x 385m (4 reactor modules with 4 turbines)
RPV height/diameter (m)	16.4 / 4.88
RPV weight (metric ton)	274
Seismic Design (SSE)	0.5g
Fuel cycle requirements / Approach	Uranium once through (initially)
Distinguishing features	Online refuelling, core cannot melt and fuel damage minimized by design, independent radionuclide barriers, potential for advanced fuel cycles
Design status	Basic design

Beispiel für metallisches Brennelement (Lightbridge):





„Moderne“ Wiederaufbereitung abgebrannter Brennelemente:



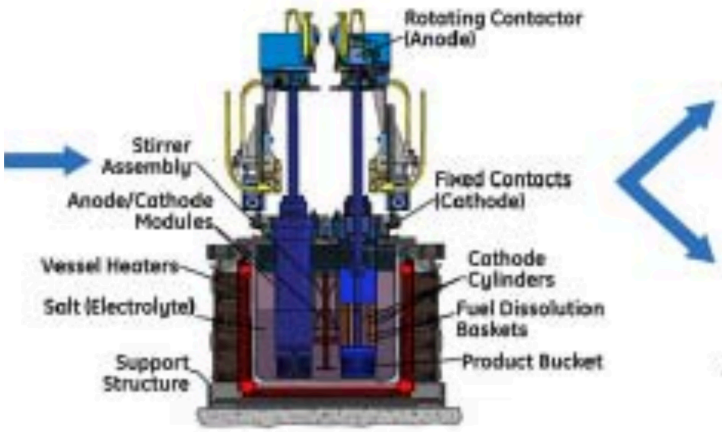
USED FUEL
Used fuel from today's light water, or thermal, reactors—uranium oxide with a small amount of plutonium and other actinide oxides—is converted to a metal through oxide reduction. While used metallic fuel—uranium, plutonium, and other actinides—from fast reactors goes straight to the refiner.

OXIDE REDUCTION UNIT
The oxide fuel is first converted to metal through oxide reduction.

ELECTROREFINER
Electrorefining is very similar to electroplating. Used fuel attached to an anode is suspended in a chemical bath; electric current then dissolves the used fuel and plates out the uranium and other actinides on the cathode.

CATHODE PROCESSOR
These extracted elements are then sent to the cathode processor where the residual salt from the refining process is removed and recycled back to the electrorefiner.

FUEL FABRICATION FURNACE
Finally, the remaining actinides and uranium are cast into fresh fuel rods and the salt is recycled back into the electrorefiner.



Uranium product collected during advanced refiner testing.