

IEEE/NPSS Climate Change Initiative Workshop

Lecture 2: Small Modular Reactor and Micro-reactor- Design, Deployment

Raymond Cao, PhD
Professor, Nuclear Engineering
Director, OSU-Nuclear Reactor Laboratory
The Ohio State University

Amazon goes nuclear, to than \$500 million to de modular reactors

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Nuclear F

Sam Altman Startup Explodes 150% This Month; Cathie Wood Makes Her Move As Nuclear Stocks Heat Up



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KIT NORTON | 09:09 AM ET 10/23/2024

Oklo ([OKLO](#)) — the nuclear power startup backed by OpenAI head Sam Altman — has surged more than 150% in October as major hyperscalers have decided to double down on the nuclear renaissance to fuel data centers and artificial intelligence.

Nuclear energy-related plays, including Oklo, have been on a tear since late September when **Microsoft** ([MSFT](#)) announced a [two-decade contract with](#) S&P 500 component **Constellation Energy** ([CEG](#)) to provide nuclear power for the tech giant's data centers.

Now, **Amazon.com** ([AMZN](#)) and **Alphabet** ([GOOGL](#)) have also inked nuclear deals, sending nuclear-related stocks higher. However, many of the stocks are extended.

Nuclear Energy Stocks Are Hot: Here's A List Of Tickers To Watch



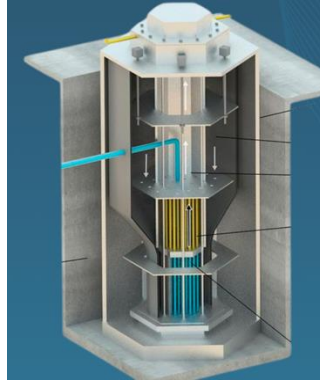


SMR and Microreactor



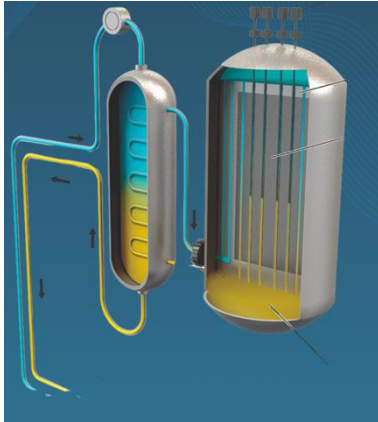
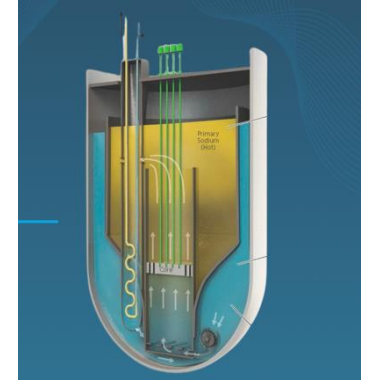
1.) Advanced Light Water Reactors

- Existing light-water reactor systems
- Use enhanced safety systems



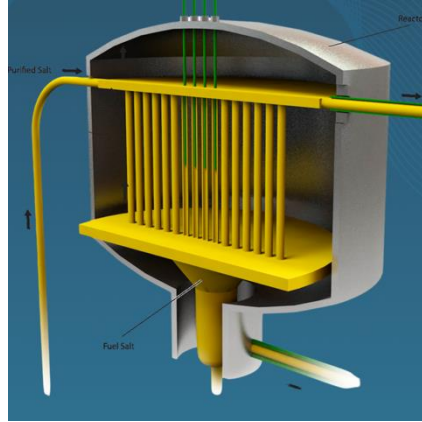
2.) Liquid Metal Fast Reactor

- Na or Pb
- High temperature
- Low pressure



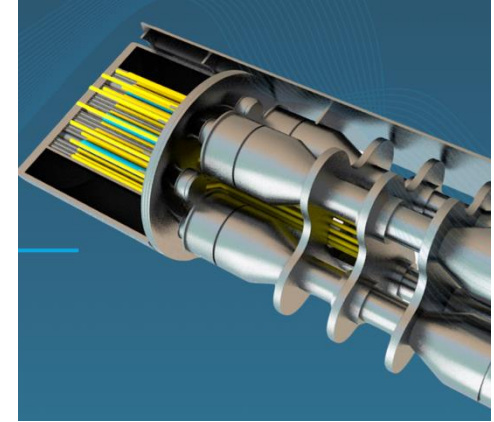
3.) High-Temperature Gas Reactor

- (750 - 900 Celsius)
- TRISO fuel



4.) Molten-salt Reactor

- Atmospheric pressure
 - On-line refueling



5.) Heat-pipe Reactor

- No pumps or moving parts



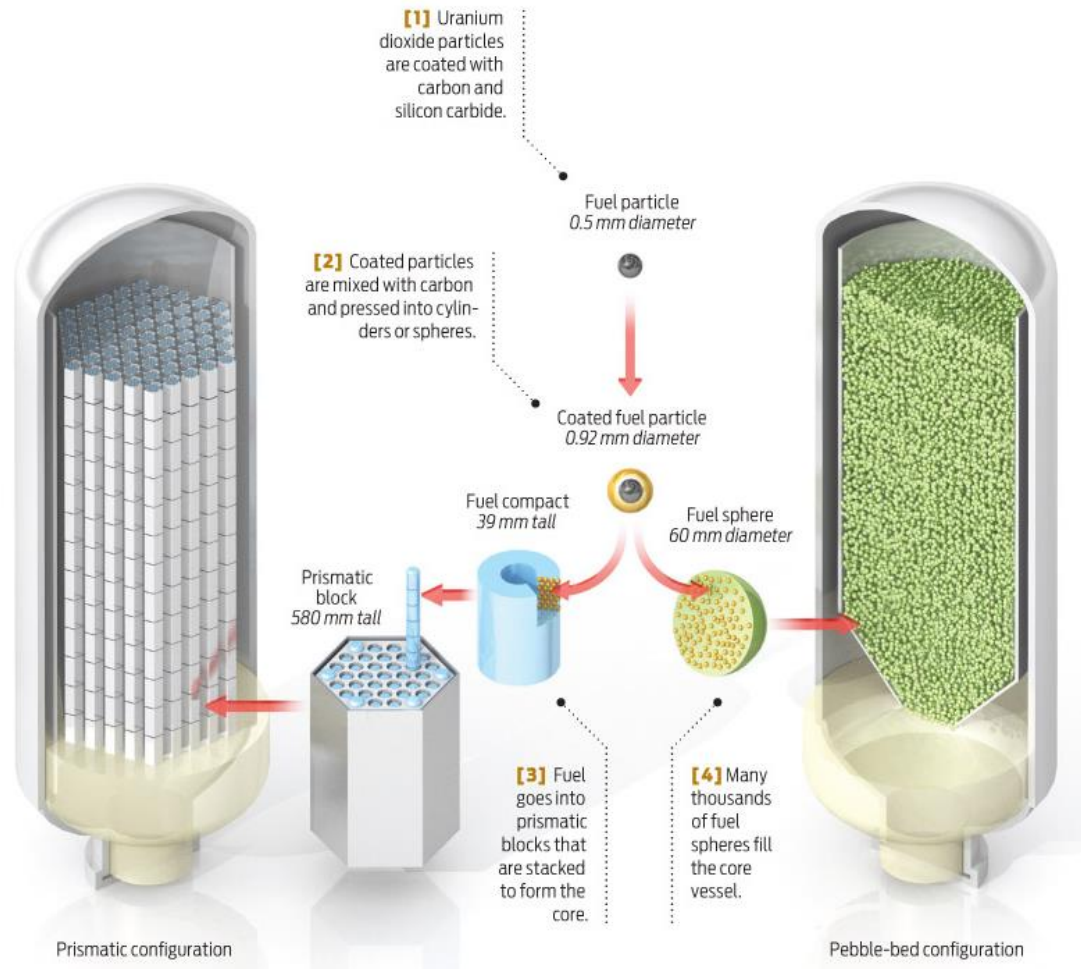
Next Generation Nuclear Plant Generation IV reactor

How it works:

This reactor's fuel consists of uranium particles known as tristructural isotropic, or TRISO, particles [1, 2].

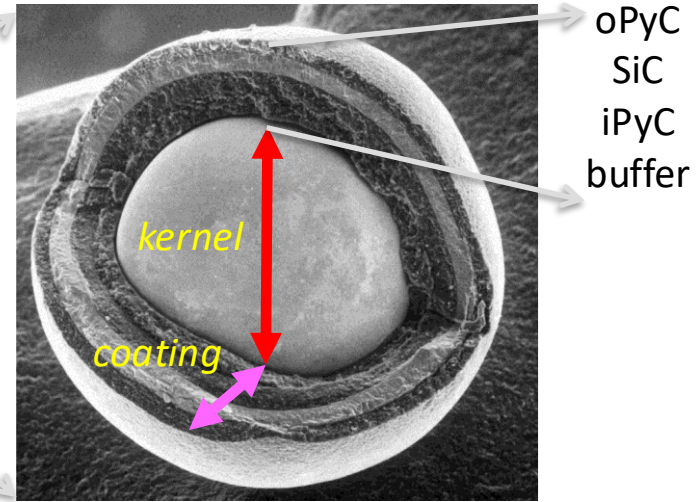
Blocks or spheres containing the TRISO fuel and carbon are arranged into a nuclear core [3, 4], producing a chain reaction.

Helium circulates through the core, removing heat. The helium drives a turbine directly, or it can generate steam to turn the turbines. Because the core consists of helium and graphite, it can withstand temperatures of 900 °C and even higher; pressurized-water reactors operate at about 300 °C.

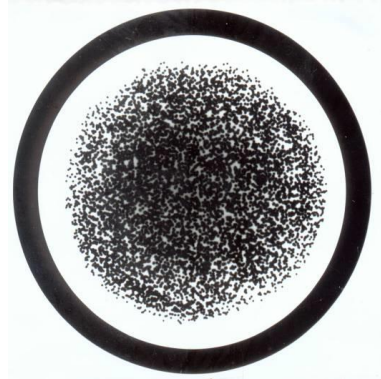




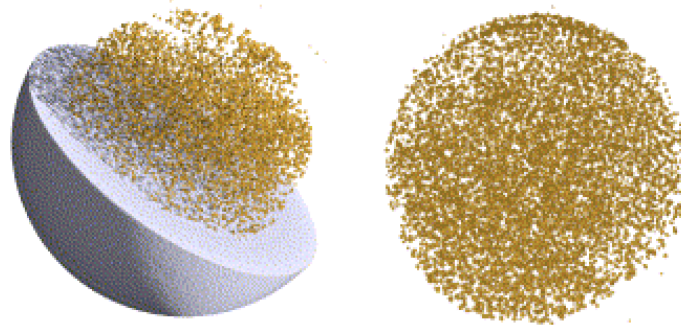
(a) Fuel Ball, 60 mm dia.



(b) Coated Particle, 1 mm dia.



(c) X-ray radiography of fuel ball



(d) Neutron tomography of fuel ball

Fig. 1. HTR spherical fuel element and its inner structure revealed by X-ray and neutron



Type: High-temperature gas-cooled reactor

THTR-300 (300MW), German, 1983-1989 in operation, helium-cooled high-temperature reactor, ~ 670,000 spherical pebble ball fuel, each 6 cm (2.4 in) in diameter, uranium-235 and thorium-232 fuel

Refueling: **The spent fuel is continuously replaced without shutting down the reactor. In the pebble-bed type, TRISO balls are removed from the bottom to have their fission levels measured, and new balls are added to the top.**

Coolant: Helium

Moderator: Graphite



Why Pebble Bed Reactor is inherently meltdown safe?

- Each fuel element has a diameter of 6cm and contains approximately 12,000 TRISO coated particles within its inner graphite matrix.
- Maximum operation temperature 1620 °C
- The power density (3.2 MW/m³) is about 1/30 of that of a commercial pressurized water reactor (PWR), meaning that the decay heat can be efficiently removed by conduction, radiation, and natural circulation, without using pump
- Negative feedback mechanism of nuclear fission to temperature



200-MWe demonstration plant of HTR-PM demo at the China Shandong Shidao Bay site.

Nearly 2 million fuel and graphite spheres have been loaded into and discharged from the cores of the two modules.

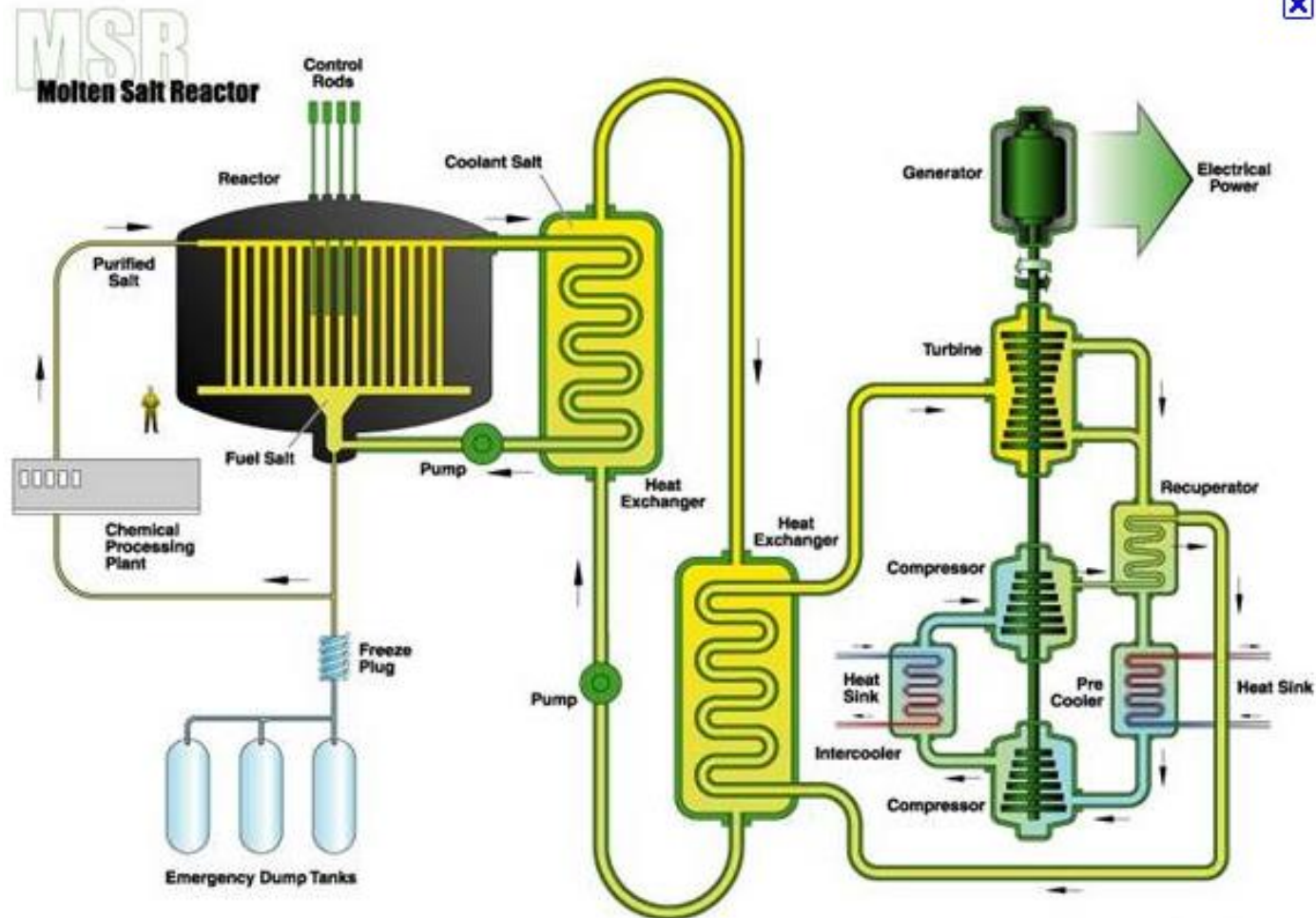


- Chinese pebble-bed reactor passes “meltdown” test, July 2024

Walk through the “loss of cooling” test China Pebble bed reactor

First test began at 9:16 a.m. August 13, 2023

1. switching off the power supply of the primary helium circulator and feed-water pump
 2. emergency shutdown signal,
 3. dropping of control rods,
 4. isolation of the steam generator
- ❖ Reactor power reduced to 2% within 20 s, the control rod positions were still at about 50% core height.
 - ❖ It takes 70 second for control rods descended by gravity from the top of the core to their lowest position
 - ❖ Temperature continue to rise, peaked at about 5 h, and cooled down in about 10 hours



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Advantageous physical and chemical properties offered by molten salts:

- good heat transfer capacity
- radiation insensitivity
- high boiling point
- wide range solubility for actinides.

Such appealing properties make molten salts unique and attractive in several applications.

- It is a better core coolant for solid fuels than gas.
- It is a good solvent for fuel and actinide that enables the 'on-line' reprocessing of circulating liquid (molten salt) to remove typical reactor poisons like xenon, krypton, lanthanides etc.
- The high working temperature of salts is promising to offer a primary energy source for hydrogen production



- Abilene Christian University (ACU) is constructing a Molten Salt Research Reactor (MSRR) on its campus in Abilene, Texas
- 1 MWth
- Liquid fuel



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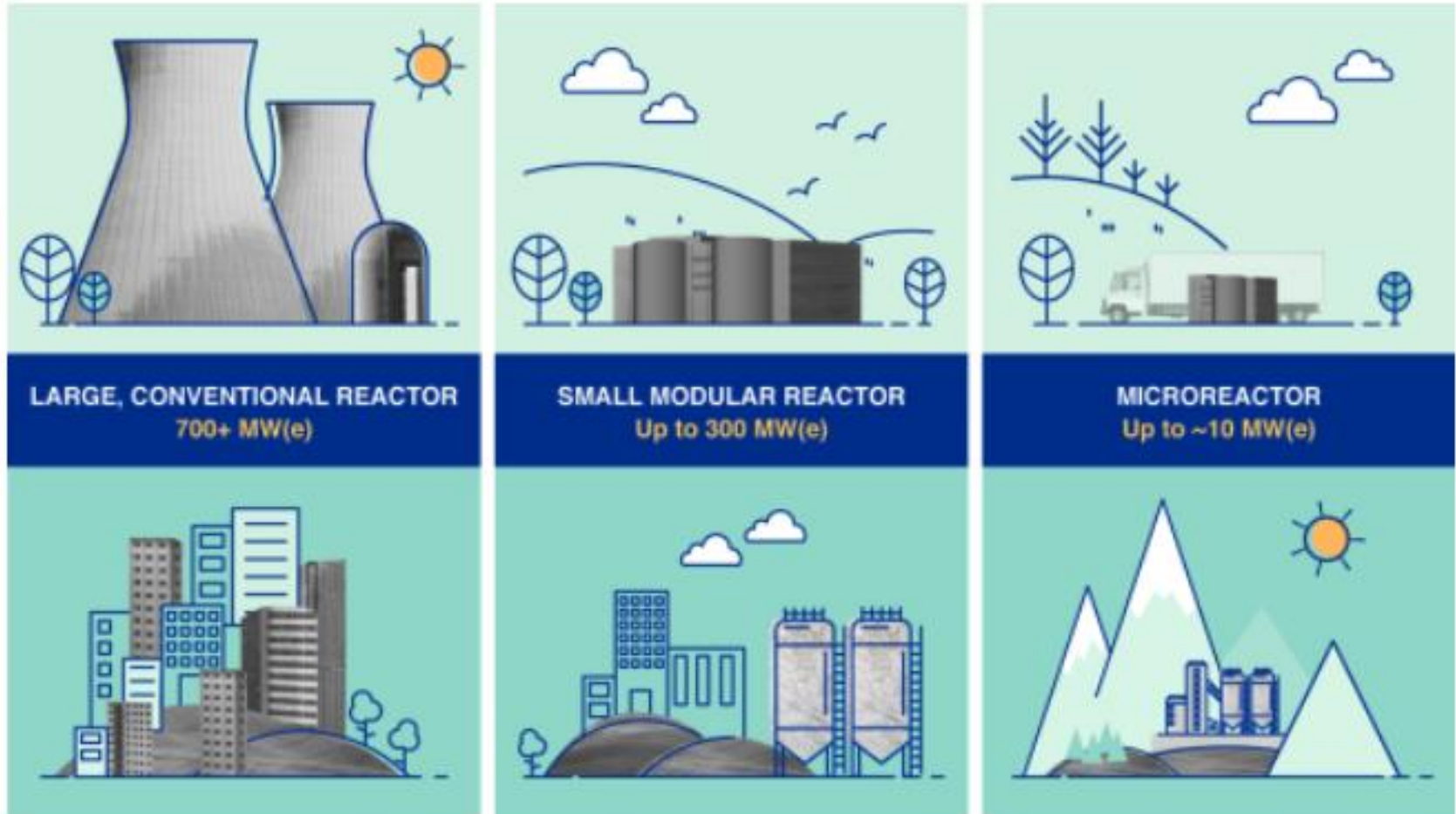
SEP. 17, 2024

Natura Resources' Molten Salt Reactor at ACU Receives Historic NRC Construction Permit

<https://www.naturaresources.com/natura-resources-molten-salt-reactor-at-acu-receives-historic-nrc-construction-permit>



The MSR is not a new untested concept. As early as in the end of 1940s, it was proposed at Oak Ridge National Laboratory (ONRL), USA to use liquid fuel based on molten fluoride salts. The first small molten salt reactor was running by Aircraft Reactor Experiment (ARE) for approximately 100 h around 1955 at a thermal power of 2.5 MWth. Its primary fuel circuit was cooled by helium gas and the circulating fuel was comprised by $\text{NaF-ZrF}_4\text{-UF}_4$ mixture with molar composition of 53–41–6. The maximal operating temperature of circulating fuel was 882 °C. Ten years later the molten salt reactor experiment (MSRE) started [4] an 8 MWth reactor fuelled with new fuel salt composed only $^7\text{LiF-BeF}_2\text{-UF}_4$. The moderator of the reactor was graphite. The structural material was nickel alloy INOR-8 (later called Hastelloy-N). The coolant of secondary circuit was LiF-BeF_2 eutectic. The power of MSRE was nearly 8 MWt and the working temperatures in the region of 600 °C. This reactor runs for four years without problems[5, 6].



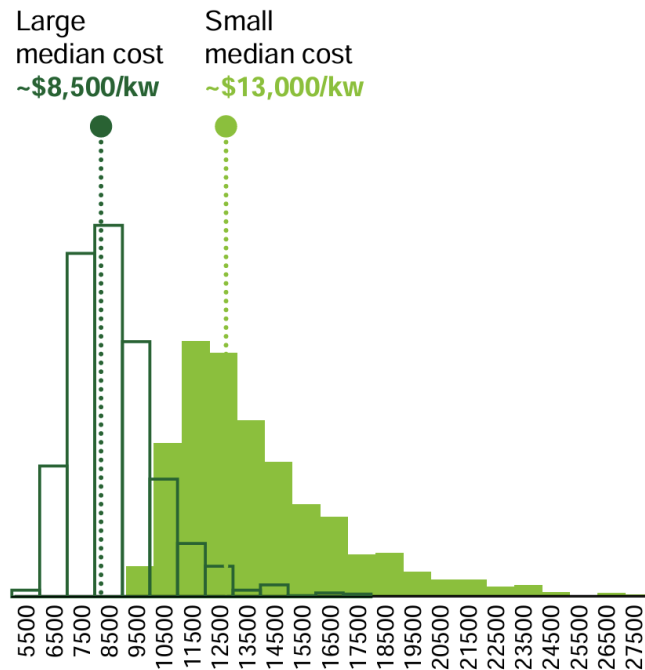
<https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs>

But the definition is changing, see later slides.

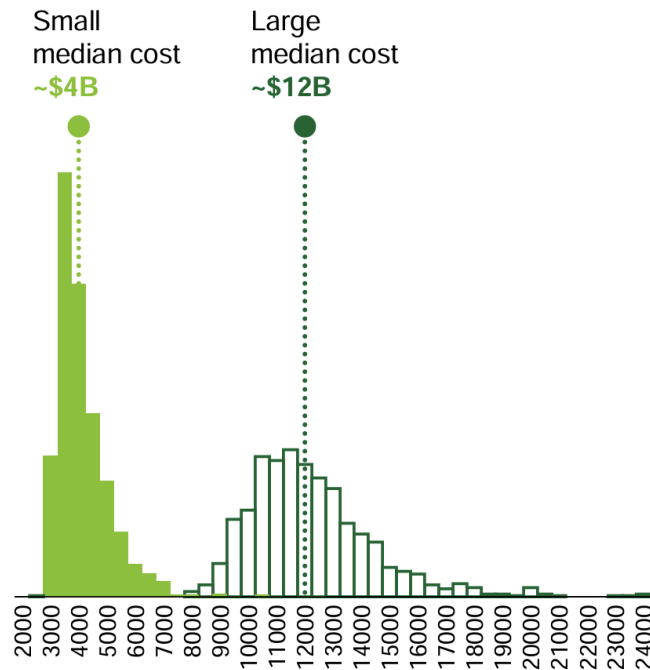


Large reactors are cheaper \$/kw with narrower cost distributions while SMRs may offer smaller overall project costs

Cost per kw



Total reactor cost



	Large	Small
MW	1400	300
StDv/Mean	0.19	0.26
Skew	1.46	2.64

Note: these are modeled costs for large and small boiling water reactors; specific designs will have their own cost profiles that will vary



- Modular construction and scalability
- **Lower upfront capital requirement**
- Siting flexibility
- **Safety advantages in many SMR designs**
- Industry, manufacturing



- As of 2020, there are about 50 SMR designs and concepts globally. Most of them are in various developmental stages and some are claimed as being near-term deployable.
- One SMR (PWR, [thermal neutron](#) spectrum, cogeneration of heat and power) began commercial operation in May 2020. It is the world's only floating NPP, the Akademik Lomonosov (KLT-40S), in the Russian Arctic region—the power capacity is 70 MW, the heat capacity is up to 60 MW - another joint product is [freshwater](#) made from [seawater](#).

Mamoru Ozawa & Yasushi Saito

- *Fundamentals of Thermal and Nuclear Power Generation* (Elsevier, 2021).



Small module reactor is not necessarily small in size

Reactor	Electrical Output	RPV Diameter	RPV Height
NuScale SMR	77 MWe	2.74* m	17.68* m
Westinghouse AP1000	~1117 MWe	~4.0 m	< 14 m
Typical 3-loop PWR	~900–1000 MWe	~4.0 m	< 14 m

NuScale's RPV is taller than an AP1000's, despite producing only about 7% of the electrical output. This is because the steam generators and pressurizer are inside the vessel, and natural circulation requires significant elevation difference

**Source: U.S. Nuclear Regulatory Commission. NuScale Design Certification Application – Safety Evaluation Report with No Open Items for Chapter 1, “Introduction and General Discussion.” Docket No. 52-048, ADAMS Accession No. ML20013D437, January 13, 2020.*



Example of large reactor's steam generator European Pressurized Reactor (EPR)



EPR Reactor Coolant System (Primary Circuit)

- Reactor Vessel (1)
- Control Rod Drive Mechanisms (2)
- Steam Generators (3)
- Reactor Coolant Pumps (4)
- Pressurizer (5): Maintains constant system pressure to prevent boiling in the primary loop.



Steam Generator for EPR:
25 meter (82 feet)



- Nuclear power plant has been at the high-power (gigawatts), enough for 1 million homes.
- Smaller, modular reactors could provide scalable, emissions-free power at lower financial risk.
- One of the modules could be shut down for maintenance while others keep generating.

Table. List of U.S. SMRs under development

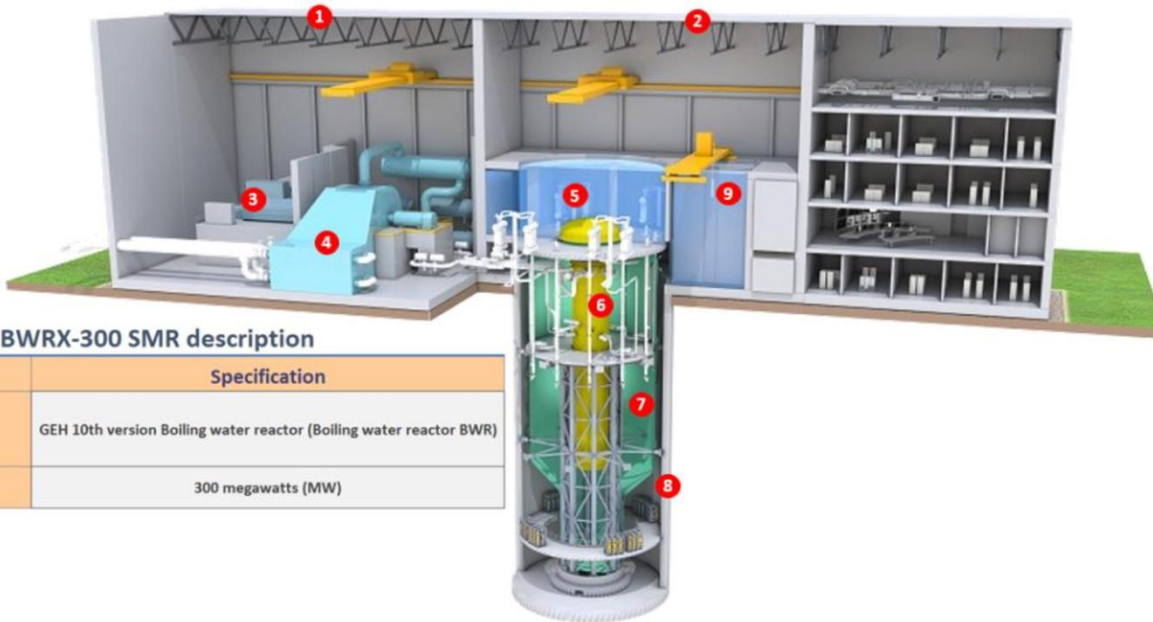
Developer	Name	Type	Power (MWe, MWth)
Nuscale	VOYGR	PWR	77, 250
GE-Hitachi	BWRX-300	BWR	275, 870
Holtec Int	SMR-300	PWR	300, 1050
Westinghouse	AP-300	PWR	225, 800
General Atomics	EM2	GFR	265, 500
General Atomics	FMR	GFR	50, 100
X-Energy	Xe-100	GFR	80, 200
Framatome Inc	SC	GFR	272, 625
Kairos Power	FHR	MSR	140, 320
UC Berkley	Mk1 PB-FHR	MSR	100, 236
Elysium Industries	MCSFR	MSR	4-200, 10-500
Flibe Energy	LFTR	MSR	250, 600
ThorCon Int	ThorCon	MSR	250, 557
Terrestrial Energy	IMSR	MSR	196, 442
Westinghouse	LFR	SFR	450, 950
TerraPower	Sodium	SFR	345, 840

- Note: “What many regard as the first commercial reactor built in the U.S., in 1957 at Shippingport, Pa., was only about 60 megawatts in size.”



- Natural-circulation Boiling Water Reactor (BWR)
- Electrical output: ~300 MWe
- Thermal output: ~870 MWt
- Coolant Light water:
- Coolant: Light water
- Moderator: Light water
- Fuel: Standard UO_2 fuel (enrichment <5% U-235)

GE Hitachi BWRX-300 Small Modular Reactor (SMR) design



BWRX-300 SMR description

Parameter	Specification
Reactor type	GEH 10th version Boiling water reactor (Boiling water reactor BWR)
Capacity	300 megawatts (MW)

1. Turbine building
2. Reactor building
3. Generator
4. Steam turbine
5. Isolation condenser system
6. Reactor pressure tank
7. Primary containment tank
8. Embedded reactor building
9. Cooling basin

- GE Vernova Hitachi and Element1 Power have announced plans to develop 1.5 GW advanced nuclear power plant in Ohio using up to five BWRX-300 small modular reactors.

- No steam generator, no pressurizer.
- Steam cycle: Direct cycle (steam from reactor goes directly to turbine)
- Design life 60 years

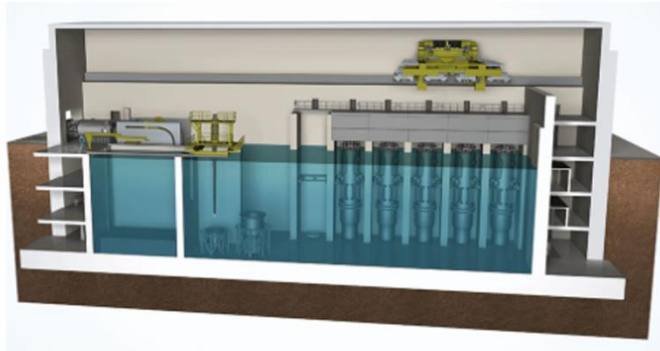


Source: GE Hitachi Nuclear Energy, *BWRX-300 General Description*, Fig. 17-1.



Developer	Nuscale
Name	VOYGR
Type	PWR
Power	77 MWe 250 MWth
Coolant	Light Water
Moderator	Light Water
Refueling Interval	18 months
Output Temperature	500 – 650 °C
Modules	4 - 12
Enrichment	4.95 %

Nuscale

VOYGR - 77 MWe, 250 MWth per module (x4, x6, x12)		
	Fuel Cycle	18 months
	Refueling	10 days
	Design Life	60 years
	Construction	39 months



Developer	X-Energy
Name	Xe-100
Type	HTGR
Power	80 MWe 200 MWth
Coolant	Helium
Moderator	Graphite
Refueling Interval	Online
Output Temperature	565 °C
Modules	4
Enrichment	15.5 %

X-Energy

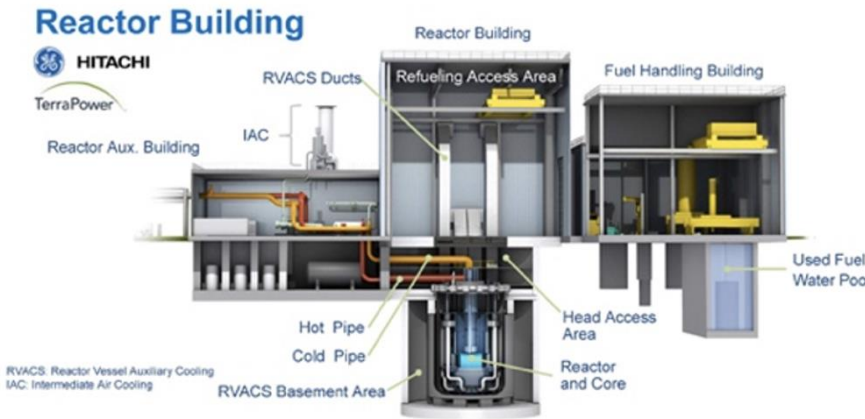
XE-100 – 80 MWe (x4), 200 MWt			
	Fuel Cycle	Design Life	
	Refueling	Online	
	Design Life	60 years	
	Construction	N/a	

Mulder, E. J., "Overview of X-Energy's 200 MWth Xe-100 Reactor," X-Energy, 2021.



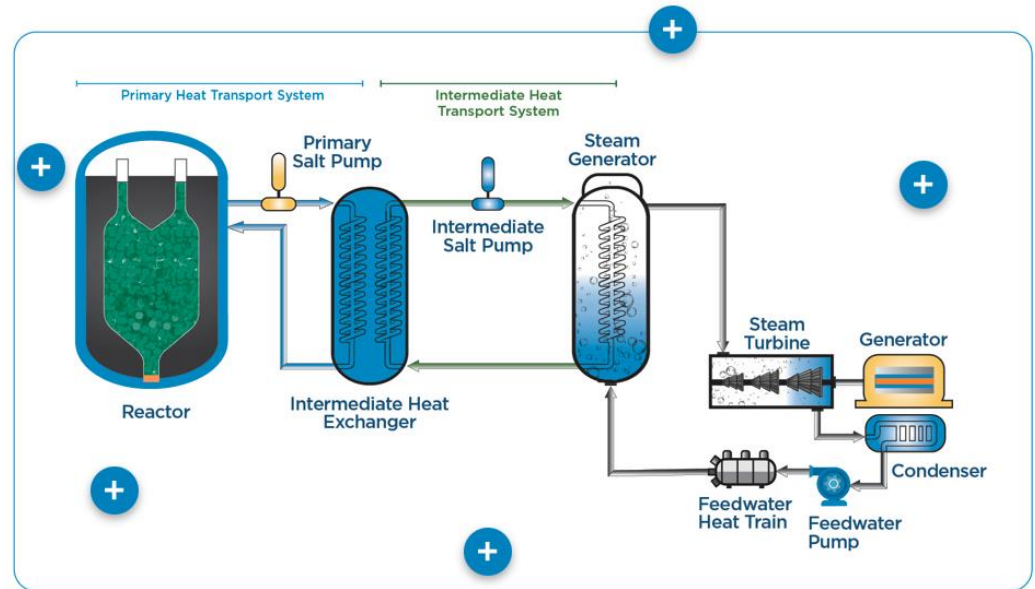
- Sodium-Cooled Fast Reactor (SFR)
- Integration of a molten salt energy storage system
- Passive safety systems

TerraPower

Natrium – 345 MWe, 840 MWth		
	Fuel Cycle	18-22 months
	Refueling	N/a
	Design Life	80 years
	Construction	36 months



Developer	Kairos Power
Name	FHR (Fluoride salt-cooled High temperature Reactor)
Type	MSR
Power	140 MWe 320 MWth
Coolant	FLiBe
Moderator	Graphite
Refueling Interval	Online
Output Temperature	650 °C
Modules	4
Enrichment	19.75 %



Ansys, "Simulating a Salt-Cooled Reactor for Safety," 2020.



- Remote and Off-Grid Power
- Resilience and Backup Power
- Flexible and Modular Design

Developer	Name	Type	Power Output (MWe/MWth)
Deep Fission	Deep Fission SMR	PWR	10, 30
Last Energy Inc	Open20	PWR	22, 73
Aalo Atomic	Aalo One	MSR	8, 20
Alpha Tech Research Corp	ARC Nuclear Generator	MSR	12, 30
BWXT	BANR	HTGR	17, 50
General Atomic	GA Micro	HTGR	1-10, unknown
HolosGen	HolosQuad	HTGR	13, unknown
Nano Nuclear	Zeus	HTGR	1.0, 2.5
Nano Nuclear	Odin	N/a	1.0, 2.5
NuGen, LLC	NuGen Engine	HTGR	2-4, unknown
Radiant Nuclear	Kaleidos Battery	HTGR	1.2, unknown
Ultra Safe Nuclear	MicroModular Reactor	HTGR	5, 15
X-Energy	XENITH	HTGR	5, 10
X-Energy	Mobile	N/a	N/a
Micro Nuclear, LLC	Micro Scale Nuclear Battery	Heat Pipe	10, unknown
NuScale Power	NuScale Microreactor	Heat Pipe	<10, unknown
Oklo	Aurora	Heat Pipe	1.5, unknown
Westinghouse	eVINCI	Heat Pipe	5, 15

MICROREACTORS: Small reactors **BIG** potential

Plug-and-play reactors able to produce 1-20 megawatts of thermal energy used directly as heat or converted to electric power

FEATURES:

- Factory Fabricated
- Transportable
- Self-adjusting.



BENEFITS:

Small Size

Fits on the back of a semi-truck and can be deployed to remote locations and military bases for reliable heat and power.

Simple Design

Fail-safe and self-adjusting designs that require fewer components, maintenance and operators.

Fast On-site Installation

Can be connected and generating power within a week of arriving on site.





Developer	Oklo Inc.
Name	Aurora Powerhouse
Type	SFR
Power	15 MWe
Coolant	Sodium
Moderator	-
Refueling Interval	10+ years
Fuel	TRISO





Developer	BWXT
Name	BANR
Type	HTGR
Power	17 MWe 50 MWth
Coolant	Helium
Moderator	Graphite
Refueling Interval	5 years
Fuel	TRISO



eVinci – 5 MWe , 13 MWth



Fuel Cycle	8 years
Refueling	N/a
Design Life	N/a
Construction	N/a

- **5 MWe / 15 MWth** microreactor using **HALEU TRISO fuel** and graphite moderator.
- **~12-ft (3.7 m) sodium heat pipes** passively transfer heat from the core; **no primary coolant pumps**.
- Passive heat removal and a compact, transportable design
- eVinci achieved zero-power criticality on August 24, 2026

Source: Westinghouse Electric Company, eVinci™ Microreactor.



Small module reactor definition is changing.

Conventional description versus regulatory rules

Historically, the U.S. NRC treat SMR as:

- **< 300 MWe per module.**
- Factory-fabricated or modular in construction.
- Transportable or assembled from factory-built modules.
- passive safety features.

But the new regulation (**10 CFR Part 53**) in 2026, NRC no longer consider a reactor is an "SMR." Instead, it is on:
**Risk-informed
Performance-based
Technology-inclusive**

New rules apply to **any reactor technology, any reactor size, and any commercial end use.**



Aspect	Old SMR Definition (U.S.)	New Regulation (10 CFR Part 53, 2026)
Power Output	< 300 MWe per module	No size limit (any reactor size)
Construction Method	Factory-fabricated or modular	No specific requirement (any construction method)
Transportability	Transportable or assembled from factory modules	No requirement
Safety Features	Emphasizes passive safety features	Risk-informed and performance-based (not technology-specific)
Technology Scope	Focused on Small Modular Reactors (SMRs)	Technology-inclusive (applies to all reactor technologies)
Regulatory Approach	Traditional, prescriptive rules	Risk-informed, performance-based
Applicability	Specific to SMR category	Applies to any reactor technology, size, or commercial end use