Rethinking Nuclear Power: Small systems, big potential

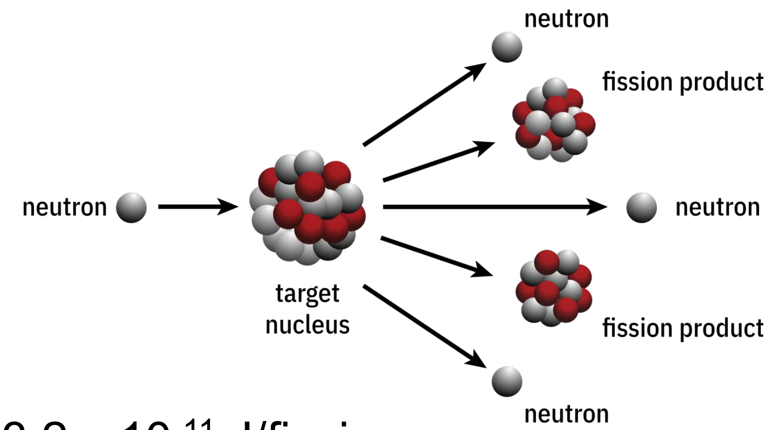
Caleb Brooks

September 2023

- What is nuclear power and what role does it play?
- What are ‘Advanced’, ‘Small Modular’, and ‘Micro’ reactors?
- How are ‘new’ nuclear reactors safer?
- What is the Illinois Microreactor Demonstration project?

Nuclear Power Basics: Energy conversion

Split the atom –> KE of fragments –> hot fuel –> hot water –> steam –> turbine –> generator –> grid



~3.2 x 10^{-11} J/fission

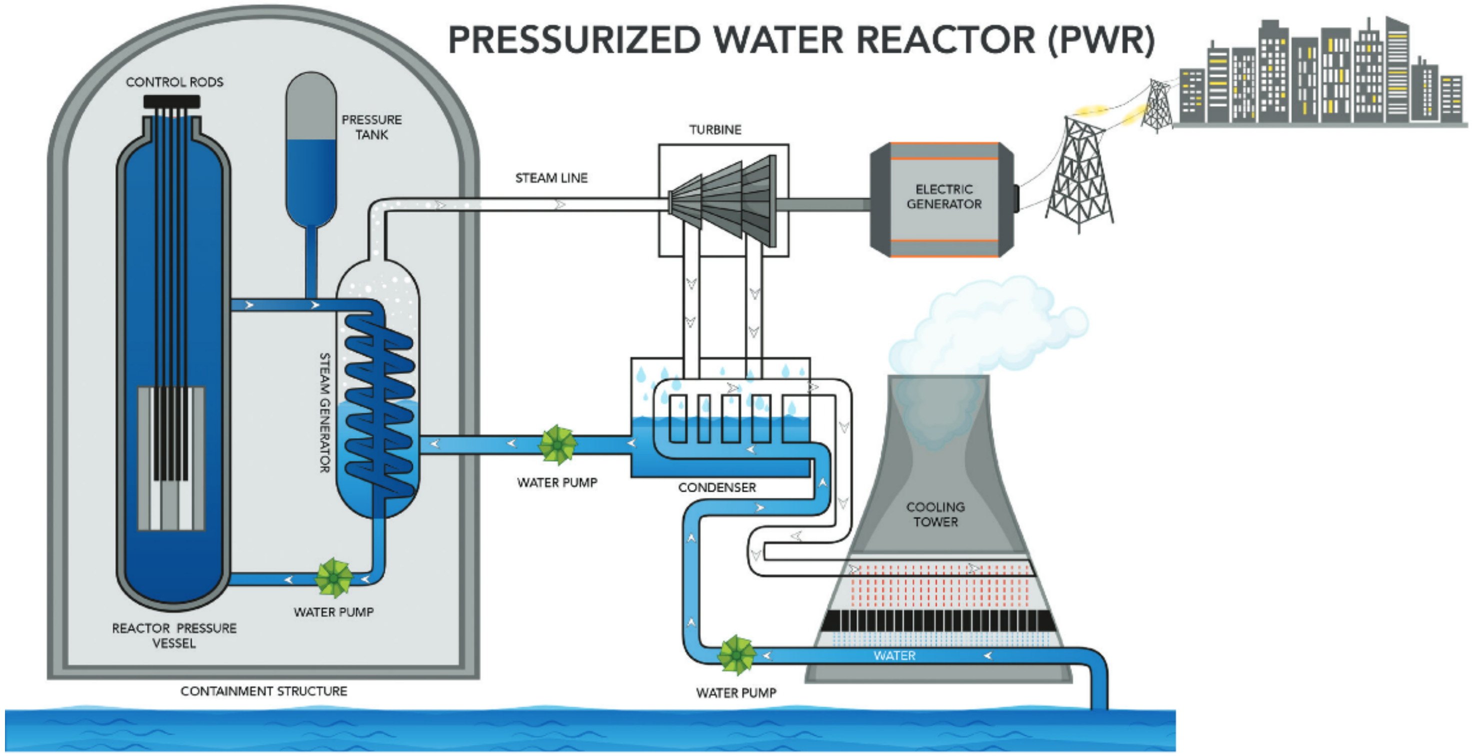
~95% recoverable as thermal energy

~ 2.6 x 10^{21} atoms in 1gram ^{235}U

^{235}U: ~8 x 10^{10} J/gram

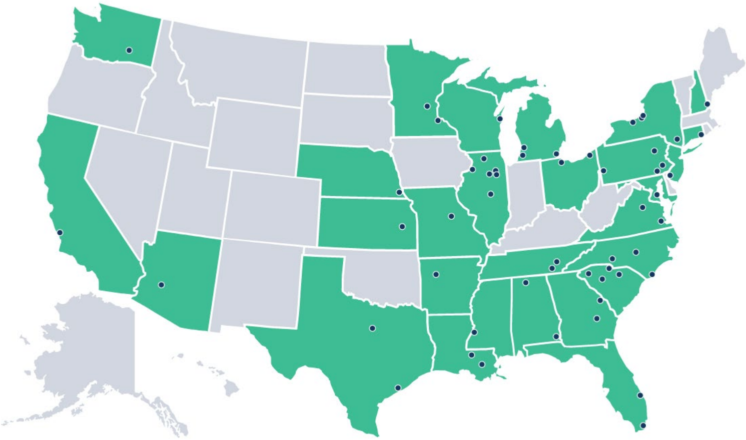
Coal: ~3 x 10^{4} J/gram

Oil: ~5 x 10^{4} J/gram



Credit: [DOE Office of Nuclear Energy]

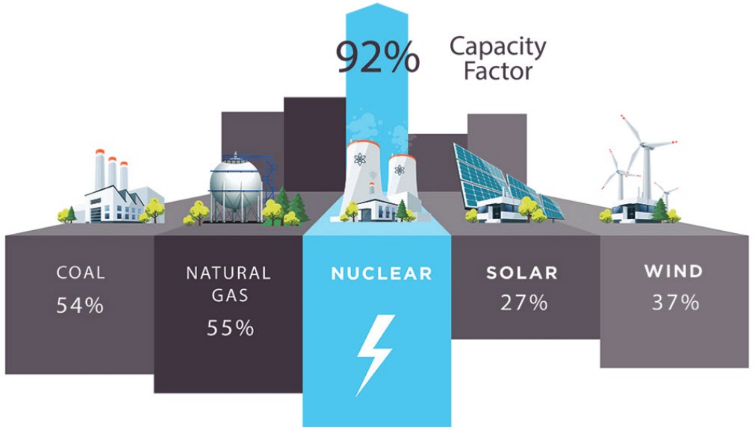
Nuclear Power Basics - US



U.S. Nuclear Power Plants Today

- 94 reactors across 55 sites
- 96,456 megawatts-electric of baseload capacity
- 809.4 billion kilowatt-hours of electricity produced in 2019
- 93.4 percent capacity factor in 2019
- Two nuclear power plants, responsible for over 11.7 billion kilowatt-hours of carbon-free electricity, prematurely retired in 2019

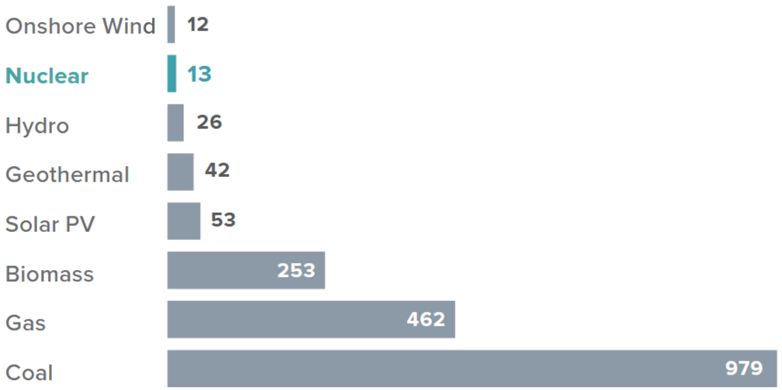
Credit: NEI, nuclear by the numbers, 2020



Credit: DOE Office of Nuclear Energy, Ultimate Fast Facts

Comparison of Life Cycle Emissions

Tons of Carbon Dioxide Equivalent per Gigawatt-Hour



IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

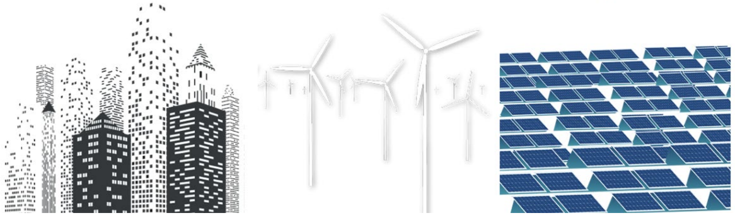
HOW MUCH POWER DOES A NUCLEAR REACTOR PRODUCE?

A typical reactor produces around 1 gigawatt of power or the same amount of power as:

100 million LED bulbs

431 utility-scale wind turbines

3.125 million PV panels



Illinois History of Nuclear Reactor Leadership

Illinois leadership

- 1942: Chicago, IL, First sustained fission chain reaction
- 1946: Lemont, IL, Argonne National Laboratory
- 1959: Morris, IL, First commercial nuclear power
- Today: Majority of Illinois electricity is nuclear

Credit: [NEI, Illinois nuclear energy fact sheet, 2020]

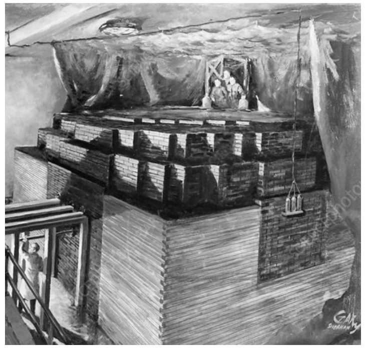
UIUC TRIGA

- 38 years of safe operation
- Thousands of public visitors
- 1,000 MW pulses, 1MW steady operating power
- Shutdown in 1998 and returned site to greenfield
- ANS National Historic Landmark

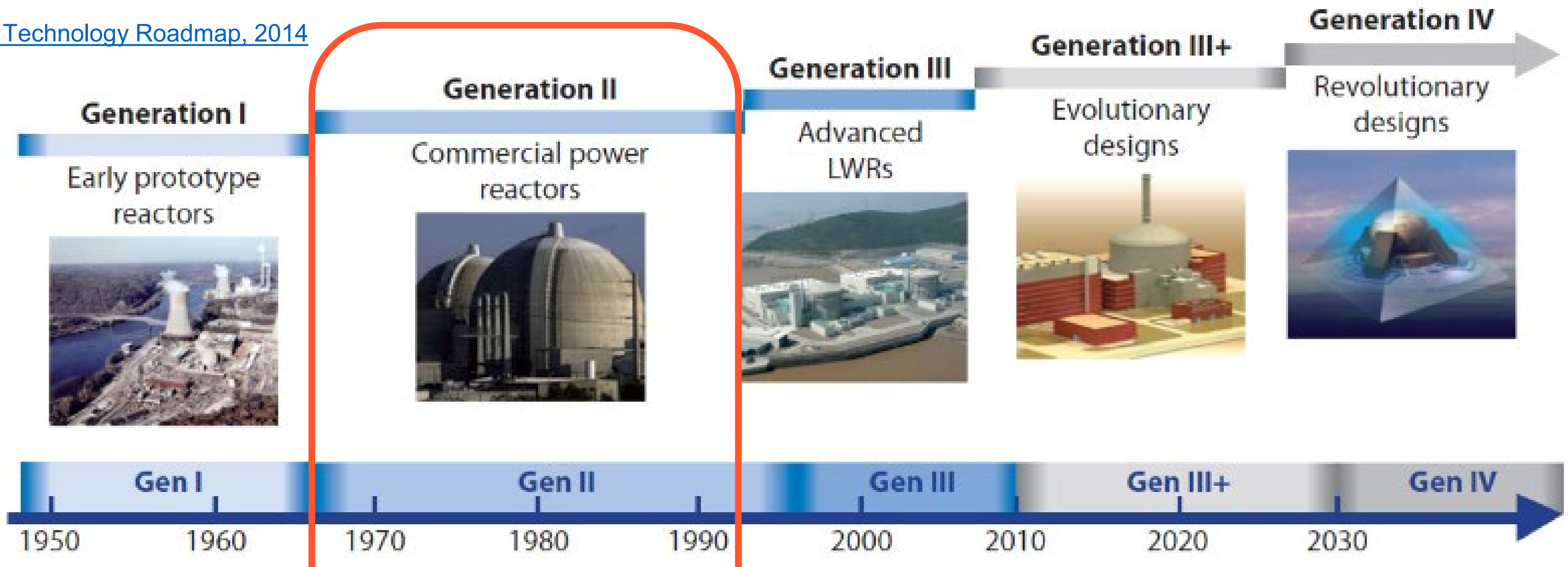
Nuclear Energy Facility	Company	Location	Capacity (MW)	Capacity Factor (%)[1]
1 Braidwood 1	Exelon	Braceville	1,183	97.7
2 Braidwood 2	Exelon	Braceville	1,154	96.2
3 Byron 1	Exelon	Byron	1,164	97.8
4 Byron 2	Exelon	Byron	1,136	98.5
5 Clinton	Exelon	Clinton	1,065	89.7
6 Dresden 2	Exelon	Morris	902	95.3
7 Dresden 3	Exelon	Morris	895	99.8
8 La Salle 1	Exelon	Marseilles	1,131	98.1
9 La Salle 2	Exelon	Marseilles	1,134	95.6
10 Quad Cities 1	Exelon	Cordova	908	96.3
11 Quad Cities 2	Exelon	Cordova	911	97.7
		State Totals	11,583	96.6

History of nuclear technology

Credit: GENIV IF, Technology Roadmap, 2014



1942
First sustained fission reaction

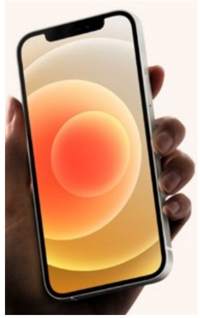


All but one current US commercial nuclear

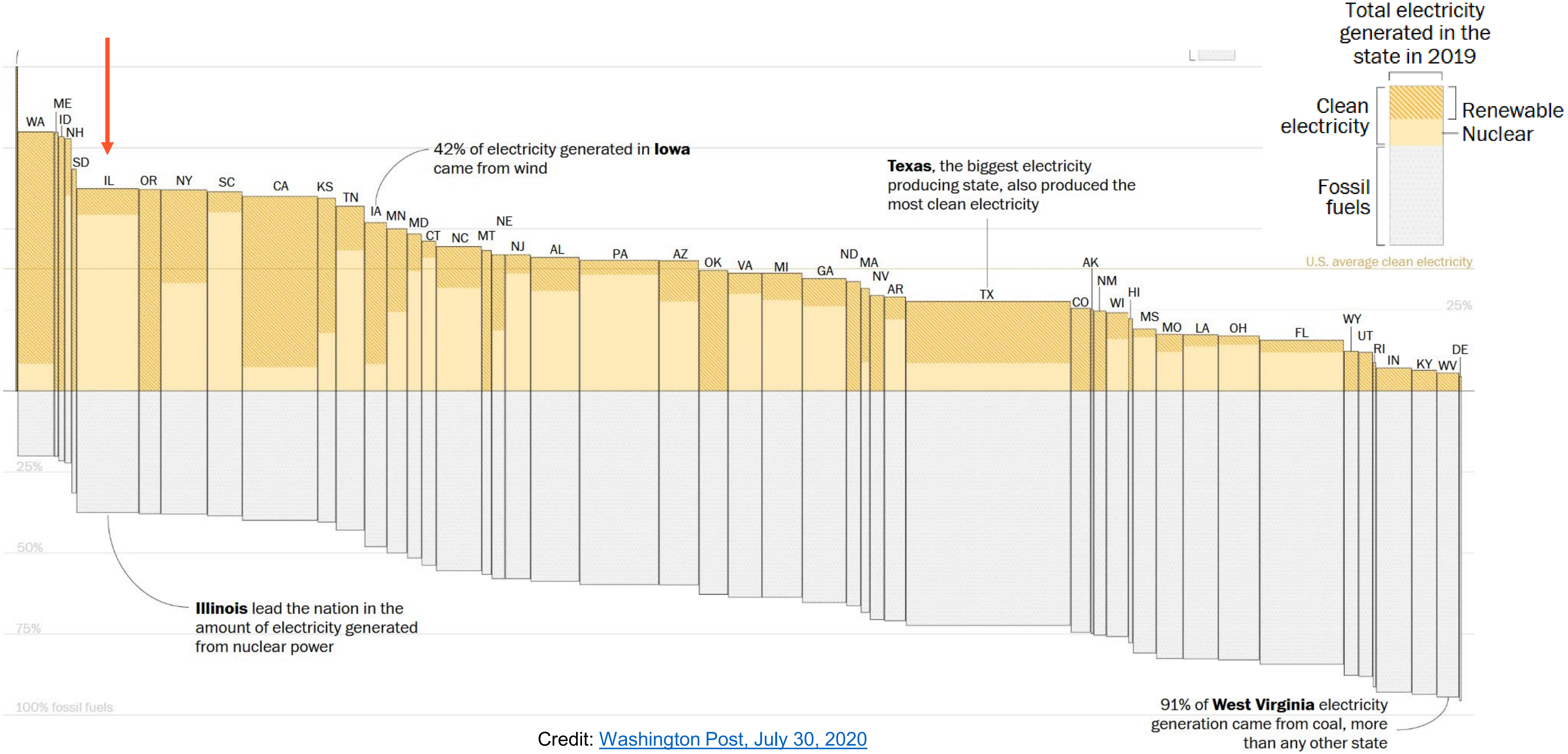
1940s
First Calls from car radiotelephone

1970s
First cell phone (4.4 lbs)

2000s
Modern 'smart' cell phone



US Clean electricity outlook



Credit: [Washington Post, July 30, 2020]

Nuclear Power Basics: Market challenge

	Unit size	Factory fabrication?	Licensing (testing)	High return product?
Fossil-fuel Plant	Large	No	Short	No
Chemical plant	Large	No	Medium	Yes
Jet engines	Small	Yes	Long	No
Robotics	Small	Yes	Short	Yes
Satellites	Medium	Yes	Long	No
Current Nuclear	*Large*	*No*	*Long*	*No*
SMR/Microreactors	*Small*	*Yes*	*Medium?*	*Yes?*

Pros:

- **reliable**
- **carbon free**
- **contains its 'waste'**
- **virtually unlimited fuel**
- **scalable**

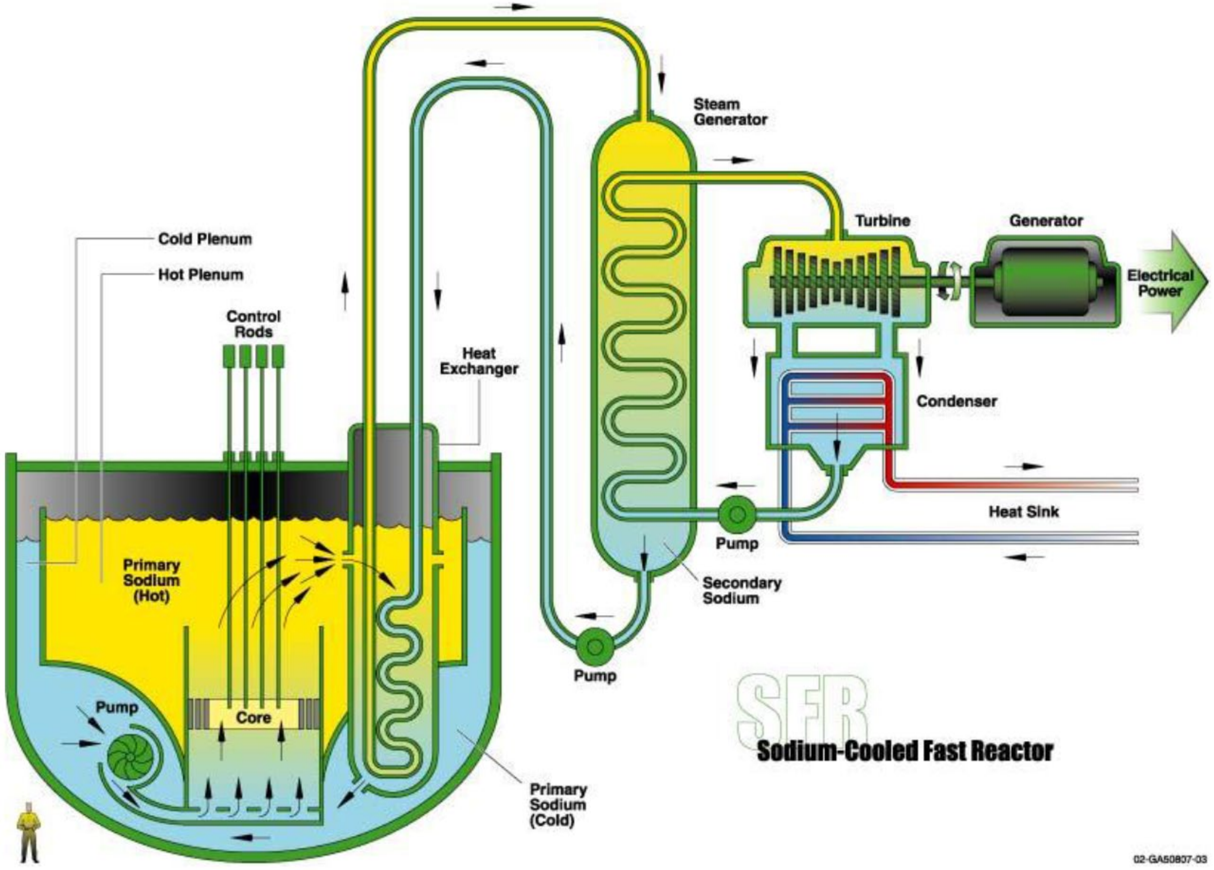
Traditional Concerns:

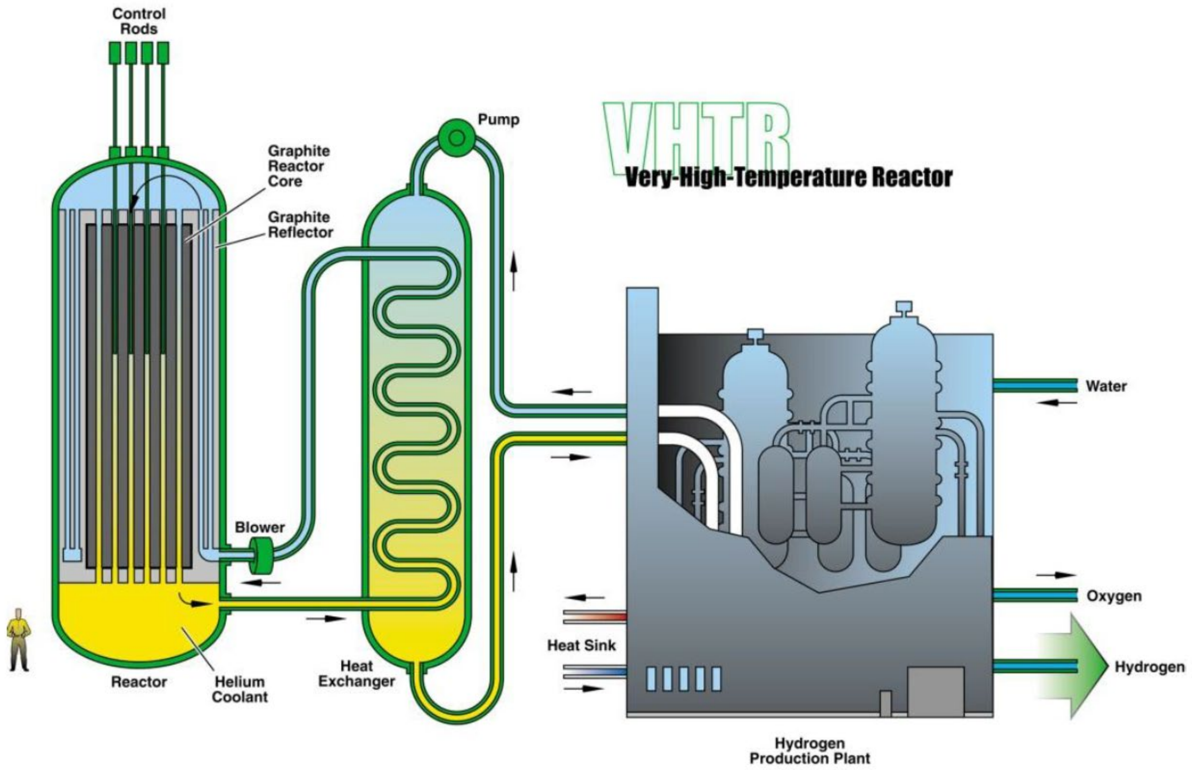
- **safety (radiation release to public)**
- **'waste'**
- **nefarious actors (nuclear safeguards)**
- ***cost***

What are 'advanced' Reactors?

Large Scale Nuclear systems with non-water coolants

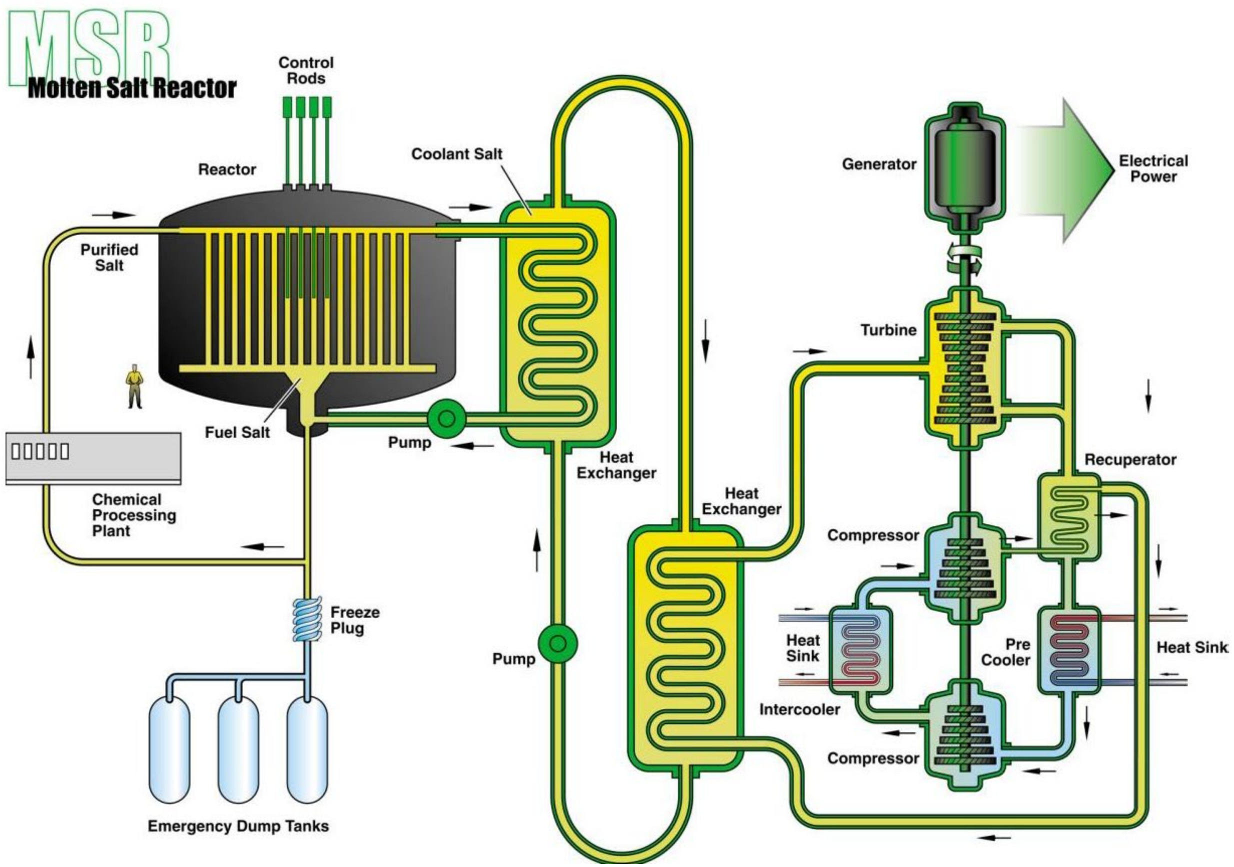
- Promise much higher operating temperatures (500-1000^{o}C)





Credit: Gen-IV International Forum

What is advanced?



Benefits

- Beyond electricity (500-1000^{o}C)
- Safety features
- Fuel security
- Fuel flexibility

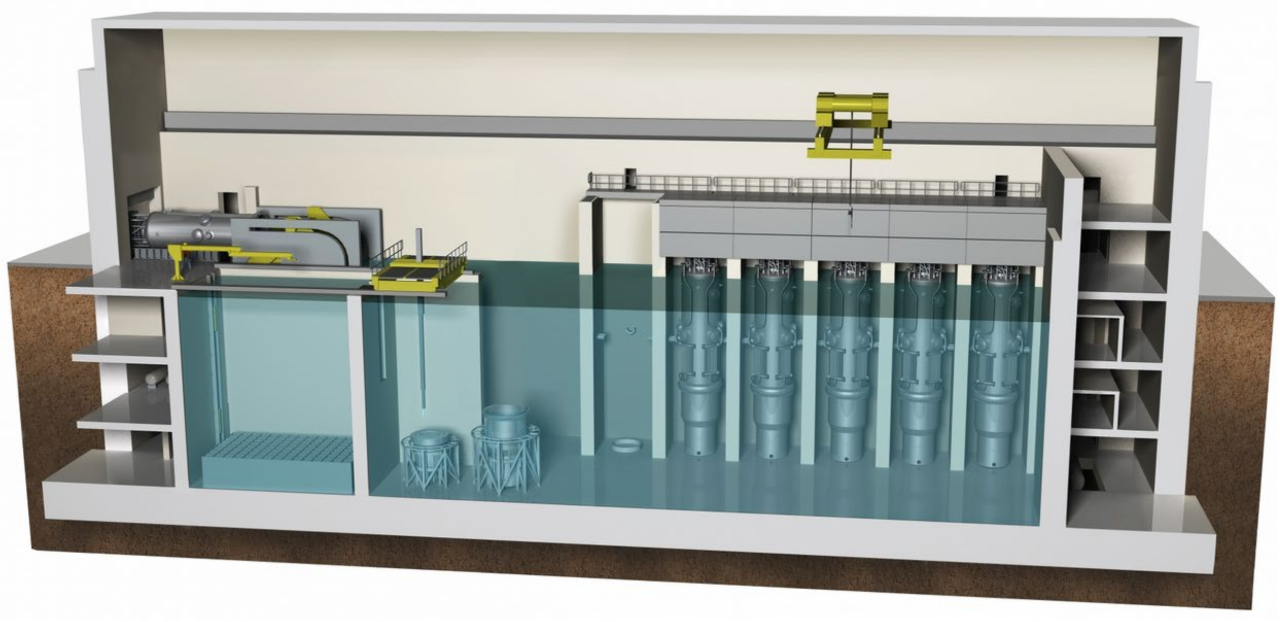
Concerns

- Large upfront capital investment
- Significant operations costs
- Regulatory uncertainty
- Materials challenges

Credit: Gen-IV International Forum

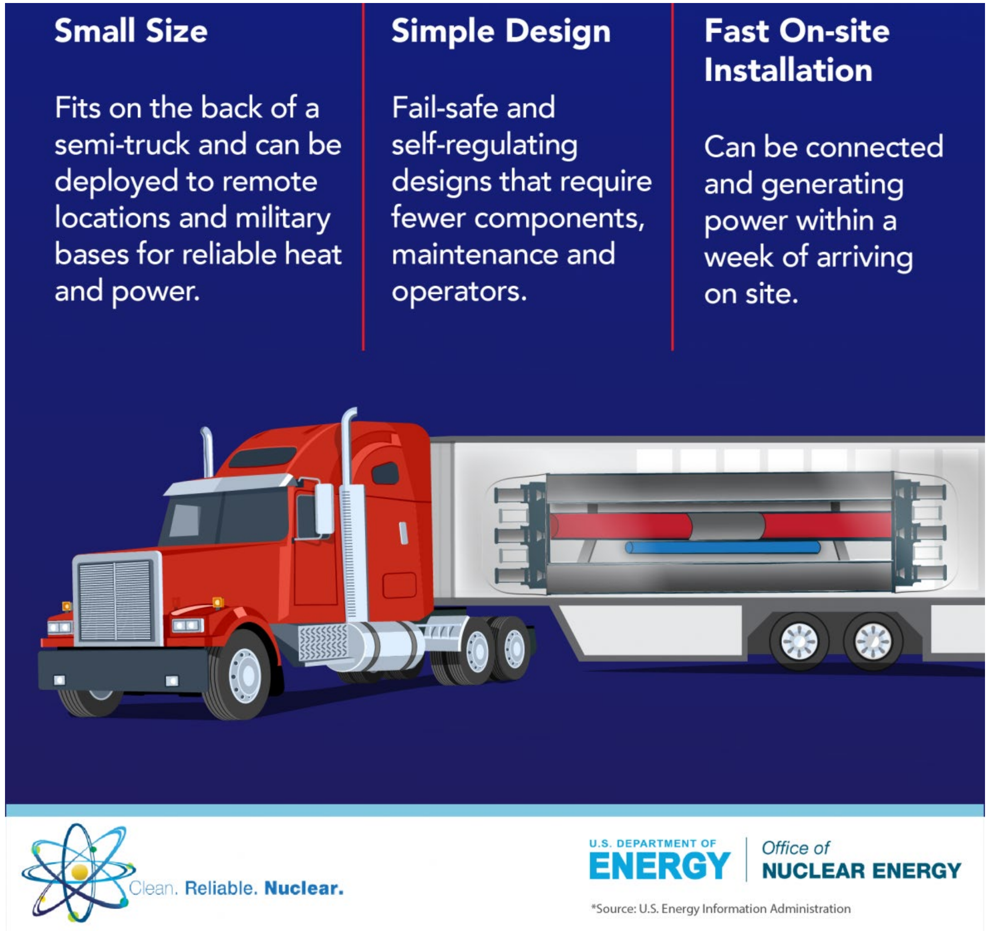
What is small?

Small Module Reactor (SMR): 50-300 MW



Credit: www.nuscalepower.com

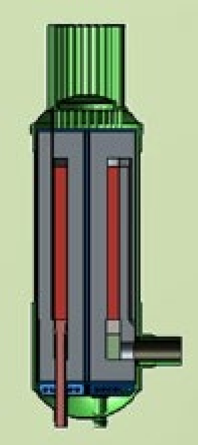
Microreactor: <1-50 MW

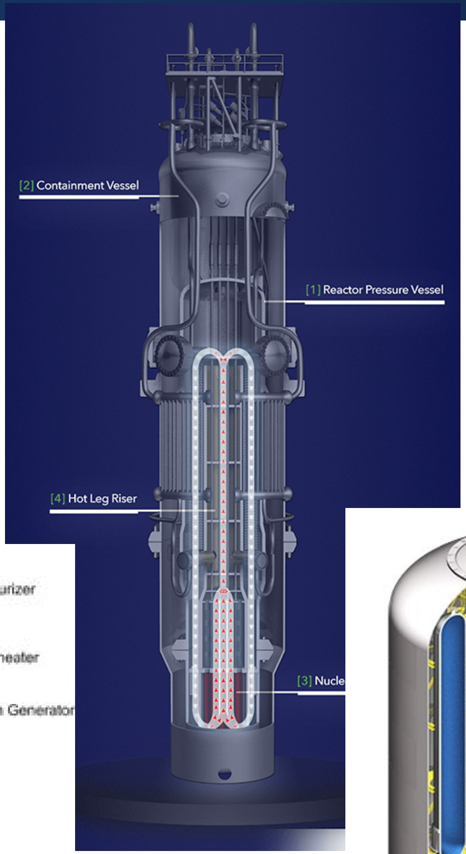


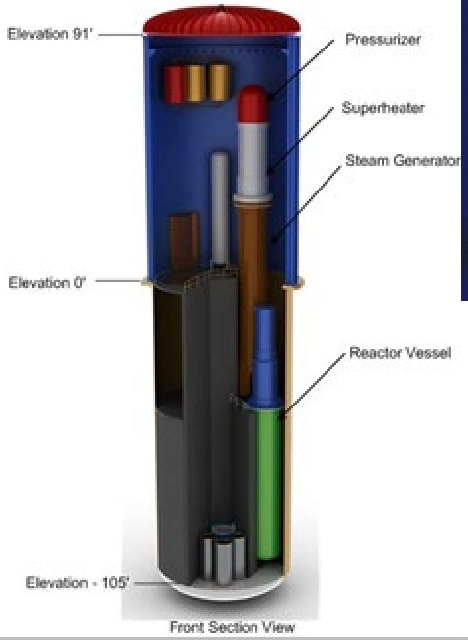
Small Modular Reactors

Small Module Reactor (SMR): 30-300 MW

- NuScale: 75 MWe (PWR)
- BWXT, mPower: 180 MWe (PWR)
- Holtec: 160 MWe (PWR)
- Westinghouse: 300 MWe (PWR)
- GE, BWRx: 300 MWe (BWR)
- X-energy, 30-600 MWt (GCR)
- Kairos Power, KP-FHR: 140 MWe (MSR)
- TerrraPower, MCFR: ?MWe (MSR)







‘Micro’ reactor technology

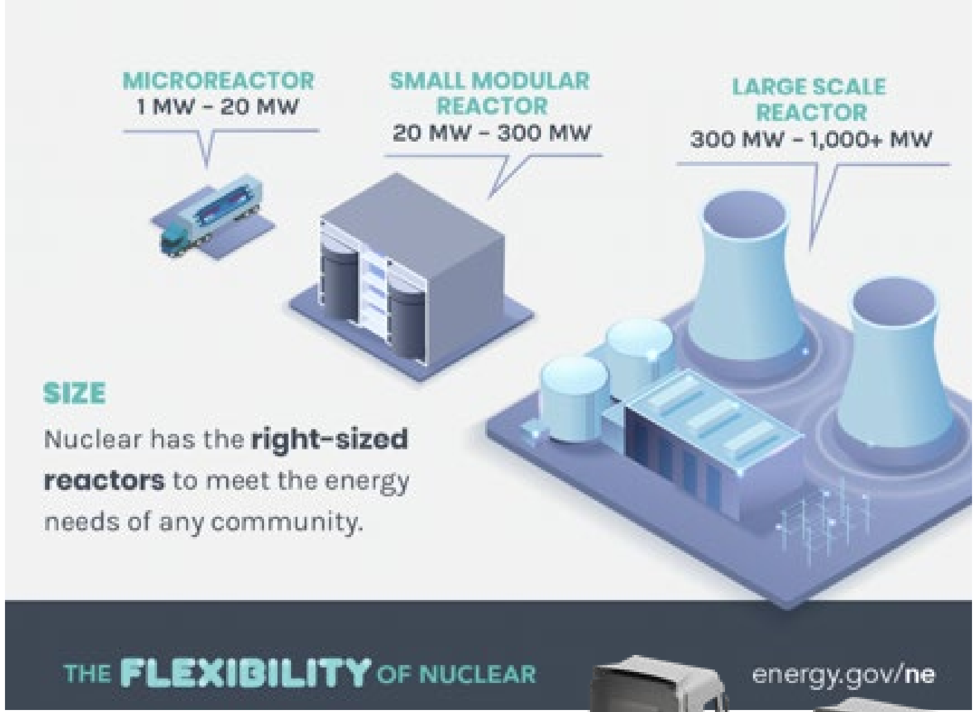
Small-scale:
- Power output <1 - 50* MW
- Long core life: up to 20yrs
- Similar in size to research & test reactors.

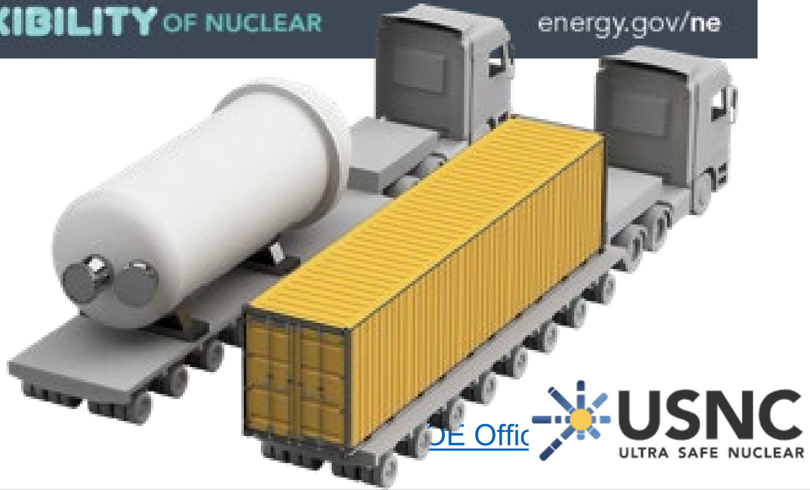
Transportable:
- Reactor vessel small enough for truck, railcar, or airplane.
- reduced onsite construction: plug-and-play

Factory fabricated:
- Fully assembled and tested at a factory before delivery.

Self-adjusting:
- Simple and responsive design concepts.
- Inherently safe.

Promising:
- Dozens of start-up companies have competing designs.
- Right-sized for space, disaster response, resilient energy, remote locations, developing grids, energy intensive industry, and more...

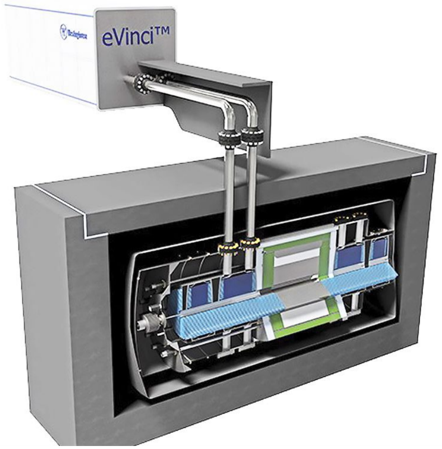


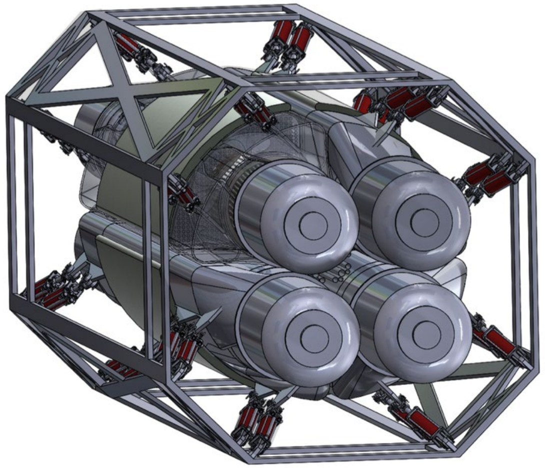


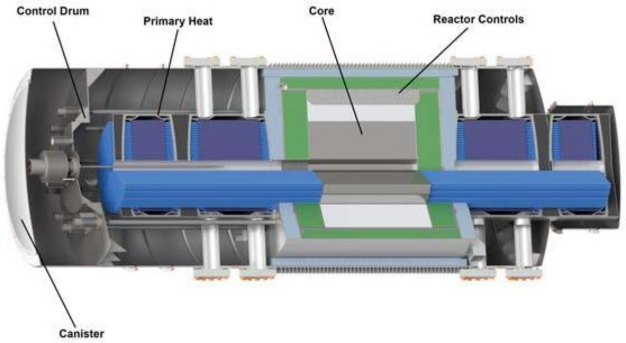
Micro-reactors

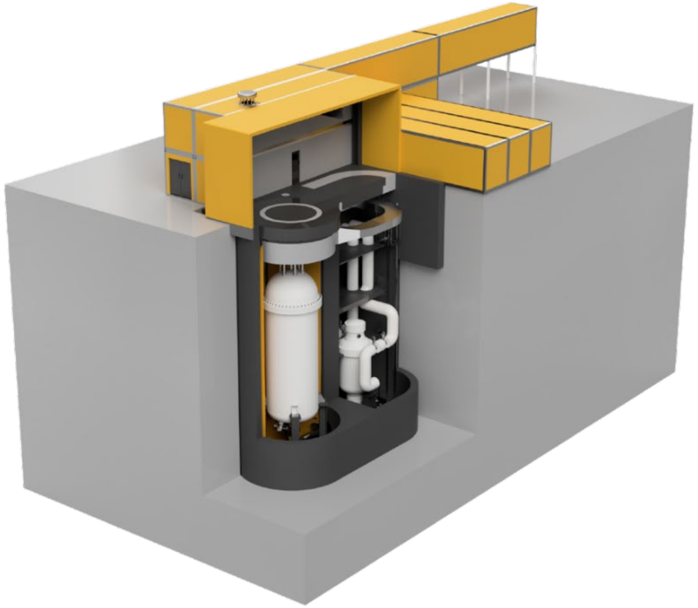
Current developers

- Westinghouse, eVinci: 15MWth (Heat pipe)
- Oklo: 4 MWth (Heat pipe)
- NuScale: 1-10 MWe (Heat pipe)
- Ultra Safe Nuclear Corp., MMR: 10-45 MWth (GCR)
- X-energy, 10? MWth (GCR)
- BWXT, 5? MWth (GCR)
- HolosGen, 5.5 MWth x 4 (GCR)
- Nano Energy, 20MW (GCR)



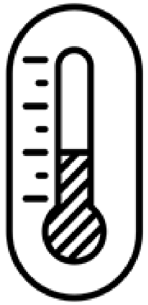


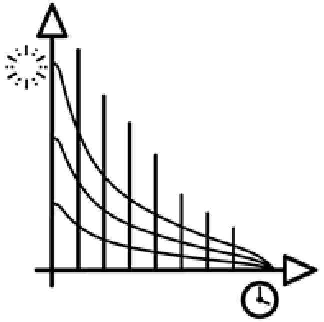


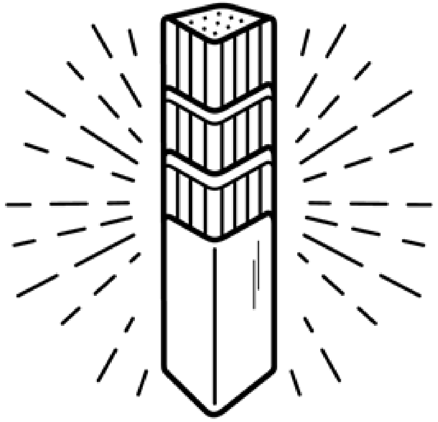


SMR/Microreactor safety

Safety in size & fuel form





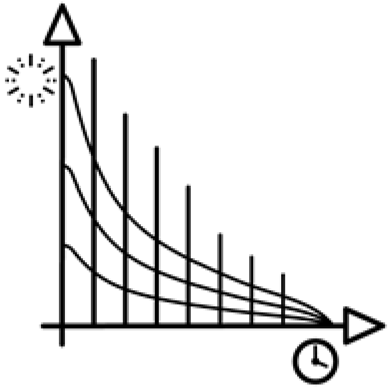


Physics-limited core temperature + Passive decay heat removal + Extremely thermally robust fuel = Fission products retained in any accident scenario.

Microreactor safety

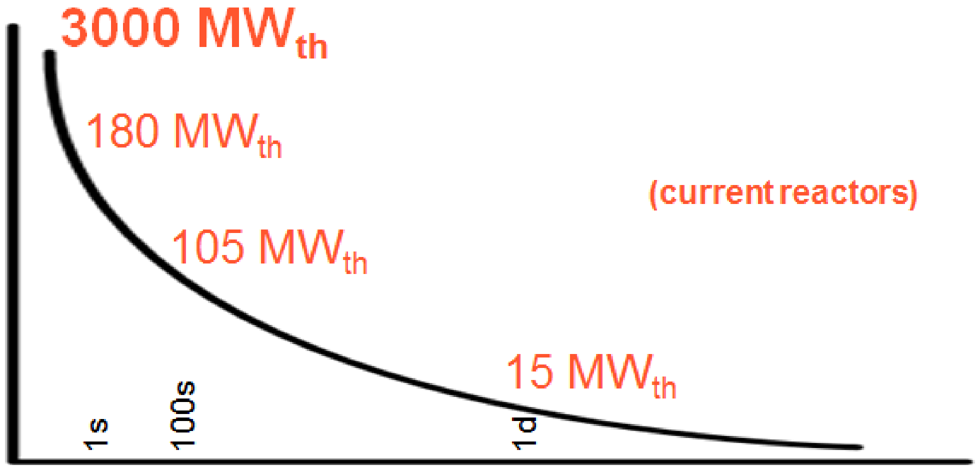
Safety in size

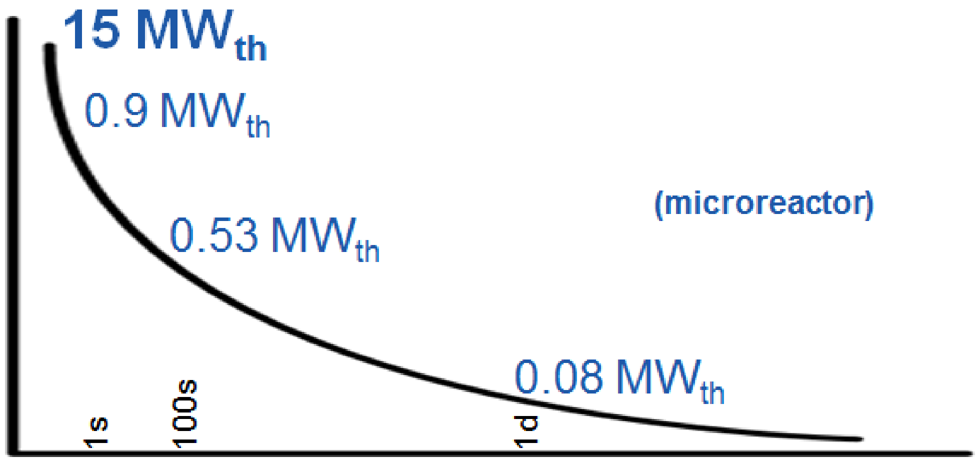
Conventional nuclear systems must be actively cooled after shutdown to remove residual power.



Micro-reactors are so small, they cool naturally, with all heat dissipating passively into the surrounding structures.

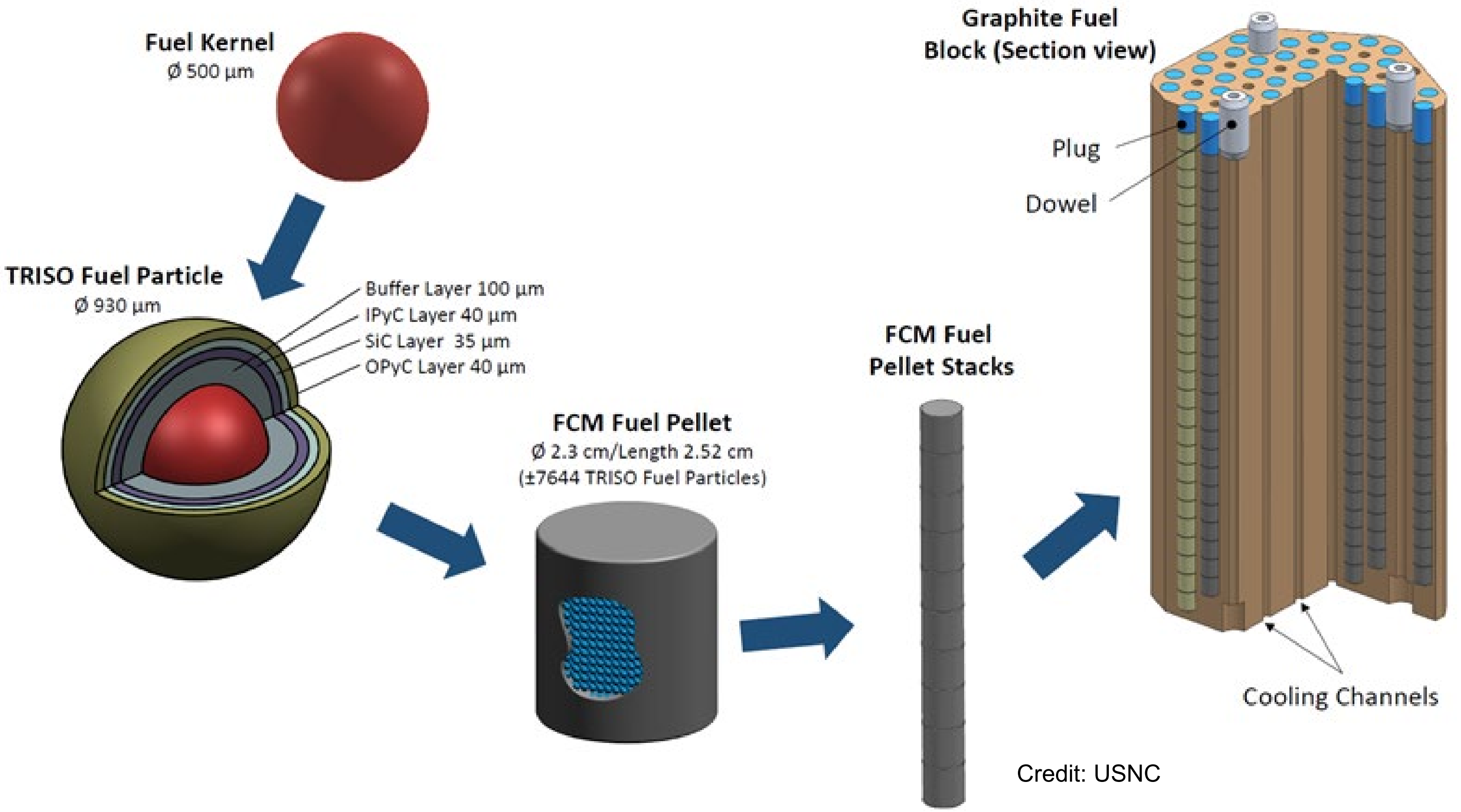
200x lower power means 200x less residual power after shutdown.



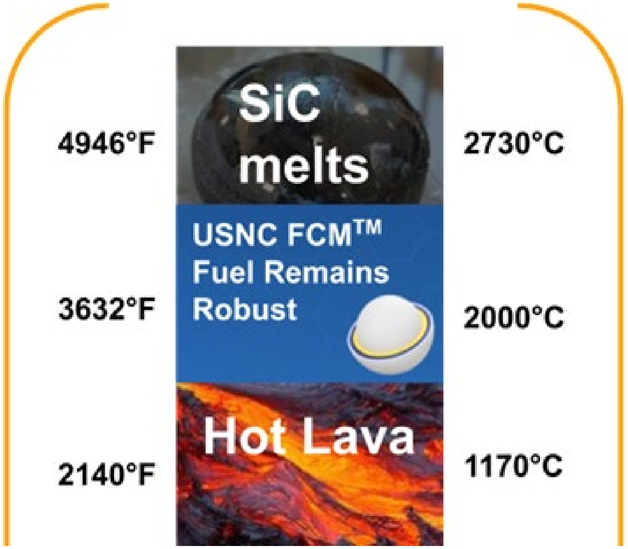


Microreactor safety

Safety in fuel form



Credit: USNC



Need: Next Generation Market Demonstration

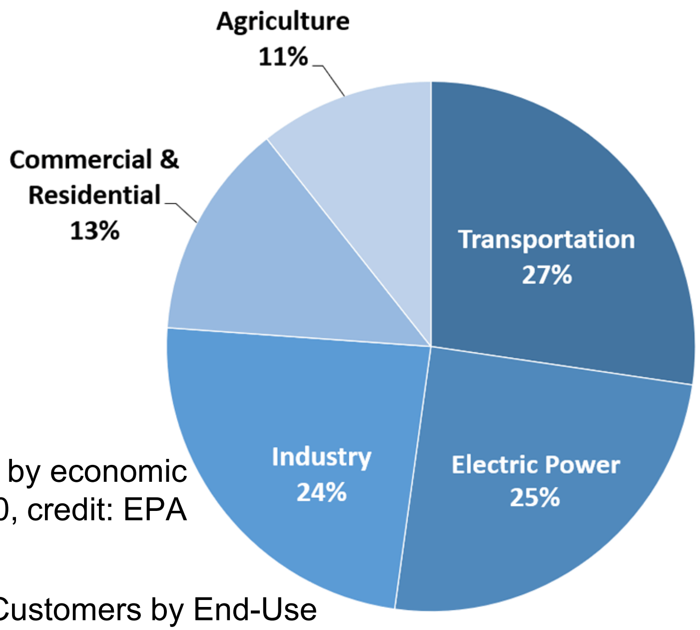
Microreactors (& SMRs) are expected to be attractive to markets and institutions that value:

Emissions Reductions & Sustainability
- Replacement of fossil generation
- Process heat for chemical and industrial processes

Small scale generation (1-300 MW)
- Microgrids
- Embedded Grids
- Small Communities
- Remote Communities

Thermal Power
- Combined Heat and Power Applications
- District Heating
- Energy Intensive Processes
- Process Heat Applications

Resilience & Reliability
- Critical Infrastructure
- Backup Power
- Data Centers



US Greenhouse gas by economic sector in 2020, credit: EPA

Average Price [cents/kWhr] of Electricity to Ultimate Customers by End-Use Sector, EIA, Nov 2022 and percent increase since Nov 2021 in ().

Region or State	Residential	Commercial	Industrial	All Sectors
New England	26.29 (20.2%)	18.13 (16.5%)	14.95 (10%)	20.83 (14.6%)
Alaska	23.07 (2.3%)	20.4 (2.7%)	17.12 (2.2%)	20.61 (2%)
Hawaii	43.91 (26.4%)	42.0 (30.9%)	38.64 (36.2%)	41.29 (31%)
California	26.14 (9.5%)	22.01 (25%)	16.94 (16.7%)	22.49 (19.1%)
Illinois	**17.27 (11.2%)**	**11.17 (7.8%)**	**8.43 (4.8%)**	**12.16 (12.4%)**
US Total	15.64 (11.2%)	12.5 (10.7%)	8.3 (12.5%)	12.46 (11.8%)

*Data from the US Energy Information Administration (EIA)

Illinois Microreactor Demonstration Project

The Illinois Microreactor Demonstration Project's mission is to de-risk advanced reactor deployment and enable a new paradigm of nuclear power through education, research, and at-scale demonstration.

Demonstrate the realizability of advanced nuclear in a representative setting

Seize the moment and cement the coming nuclear resurgence with leadership that only universities can provide

Perform the research and development needed to pave the way for safe and economic operation of advanced reactors

Project Missions

Core Mission
Education, Training, and Engagement

Engineers and scientists

general public

operator training

installation and maintenance

Producing the future workforce & redeeming public perception of nuclear power

Cross-cutting Mission:
At-scale Demonstration

electricity,

district heat,

hydrogen production,

Integrated thermal storage,

Other high value processes.

Demonstrating the future of nuclear power

Core Mission
Research & Development

Reactor and component optimization

critical enabling technologies

synergistic applications

Enabling a new paradigm of nuclear

Critical Path

Target Dates

- ➢ Engagement with NRC: Active
- ➢ Submission of PSAR: Q2 2024
- ➢ Issuance of CP: Q1 2026
- ➢ Submission of FSAR: Q1 2026
- ➢ Operations 2028

USNC/UIUC partnership

- Preliminary T&C
- Supporting team
- Institutional alignment

License Application

- Pre-ap engagement
- CP: PSAR & ER
- OL: FSAR

Public Engagement

Fuel Procurement & Fabrication

- Fuel fab. facilities
- UF4 supply (& approps)
- Fuel Qualification

Site preparation & Construction

- AE and Const. firm selection
- MMR manufacturing
- Abbott integration

Commissioning & Operations

- Reactor utilization
- Workforce and op. training
- Production demonstration

UIUC Project Team


Dr. C.S. Brooks


Dr. A. Di Fulvio


Dr. T. Kozlowski


Dr. J.F. Stubbins


Dr. R. Uddin


Mr. R. Dobey


Mr. L. Foyto


Dr. T. Grunloh

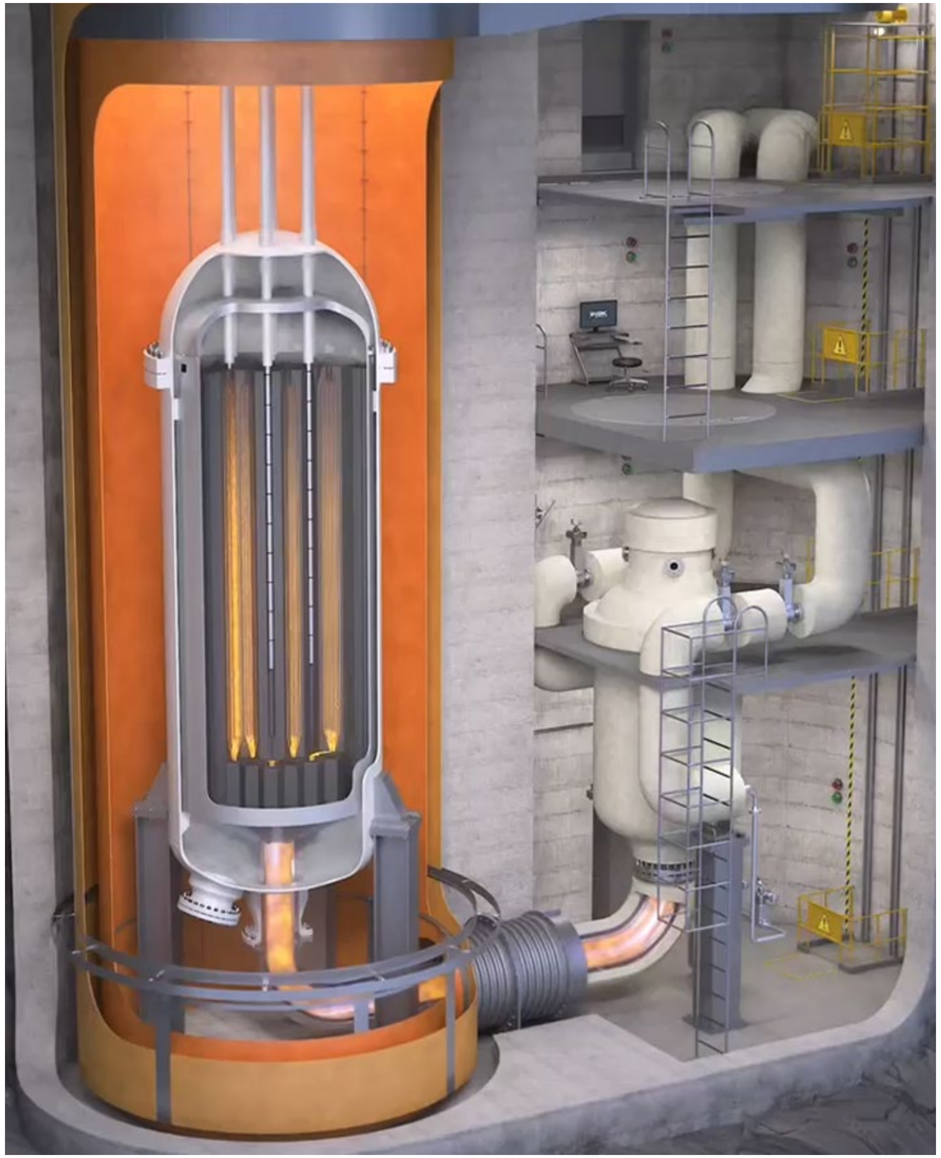

Dr. W.R. Roy


Mr. C. Townsend


Mr. D. Craig

Harun Ardiansyah
Anthony Boyd
Roberto Fairhurst
Kholod Mahmoud
Ethan Nicolls
Natalie Panczyk
Bella Paquette
Mouna Soumahoro
Luke Seifert
Bruce Ciccotosto

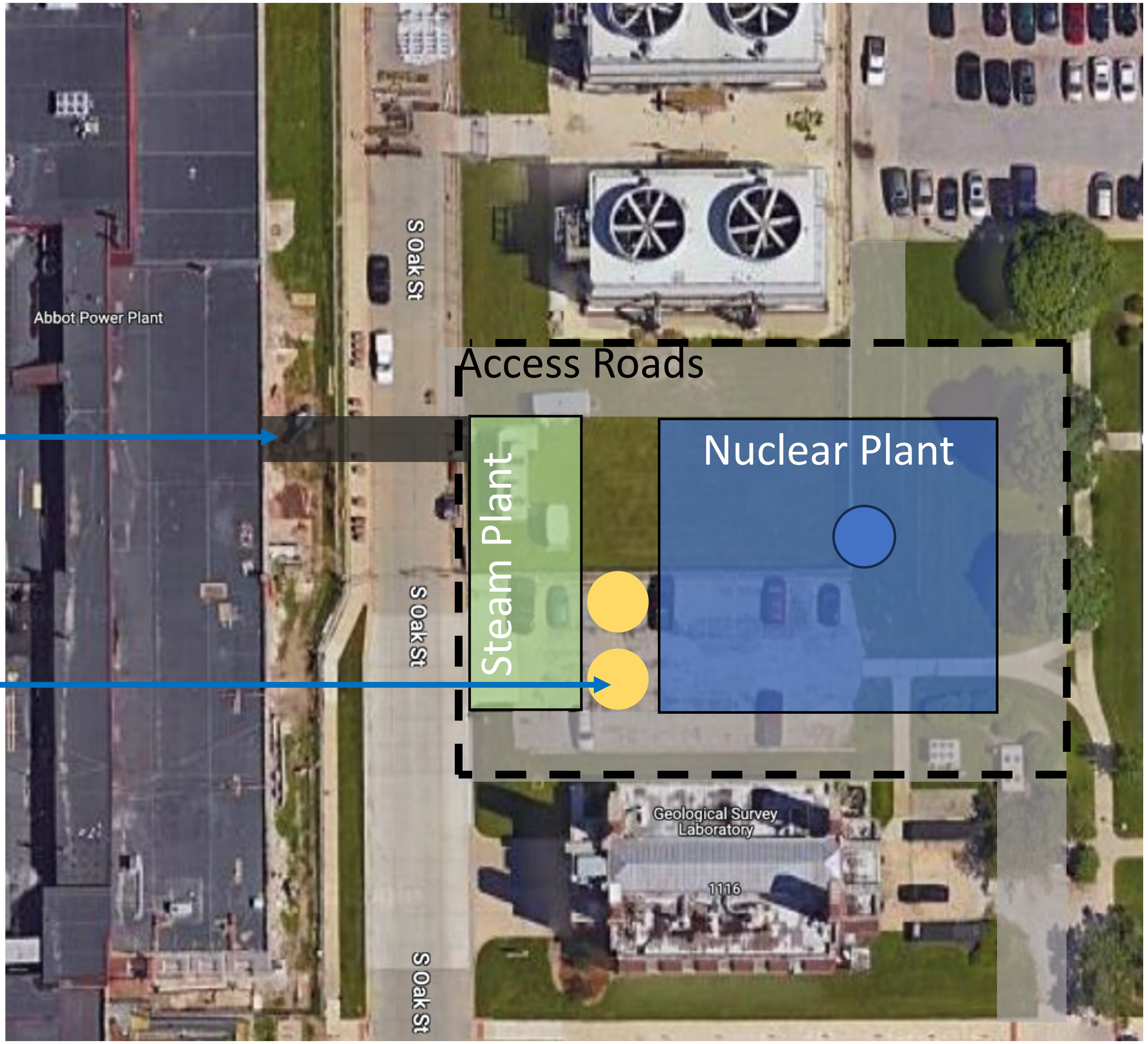
Technology Overview



Siting

Abbott steam connection

Molten salt energy storage



Sep-23

Summary

New Nuclear is coming and its going to look different

New nuclear will enable (and require) a new paradigm

- **Nuclear enables the clean energy future**
- **Small reactors, big potential**

- **Opportunity for Illinois leadership in clean energy**
- **Deep decarbonization without disruption**

Q & A

https://npre.illinois.edu/about/nuclear-powered-uiuc

Grainger College of Engineering

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN