The Future of Nuclear Energy: Small Modular Reactors and Generation IV, A New Hope

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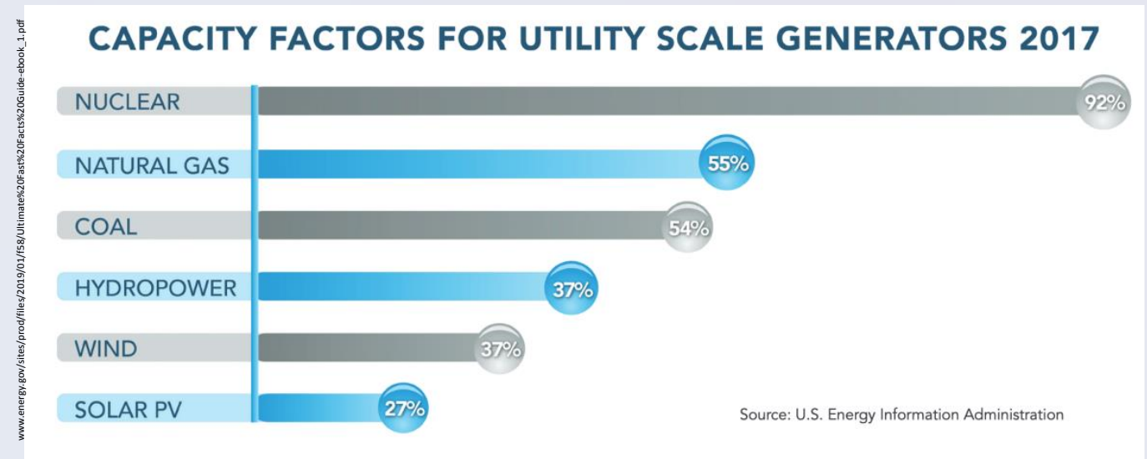
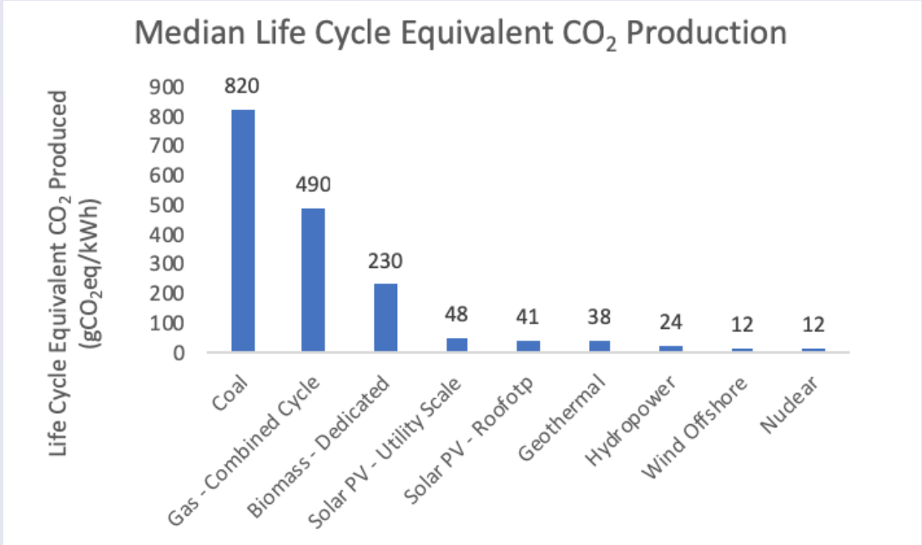
Introduction- Why Nuclear?

- Nuclear energy reliably supplies baseload energy
- Low greenhouse gas emissions



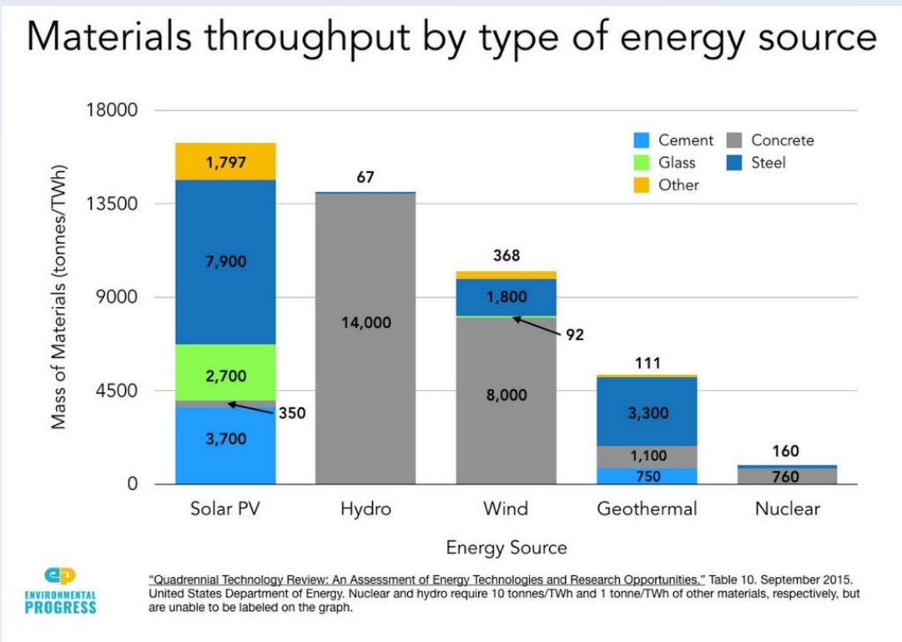


- Land and material-efficient
  - Energy density of ^{235}U is 2,000,000-3,000,000 greater than oil or coal[1]

[1] www.euronuclear.org/info/encyclopedia/f/fuelcomparison.htm

Land use for different sources of electricity

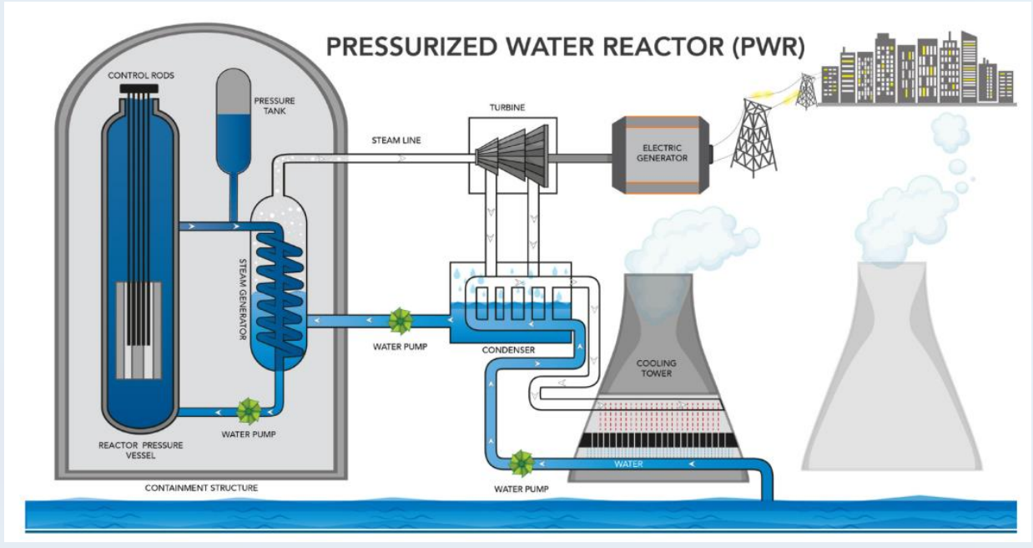
Electricity Source	Acres per Megawatt Produced
Coal	12.21
Natural Gas	12.41
Nuclear	12.71
Solar	43.50
Wind	70.64
Hydro	315.22

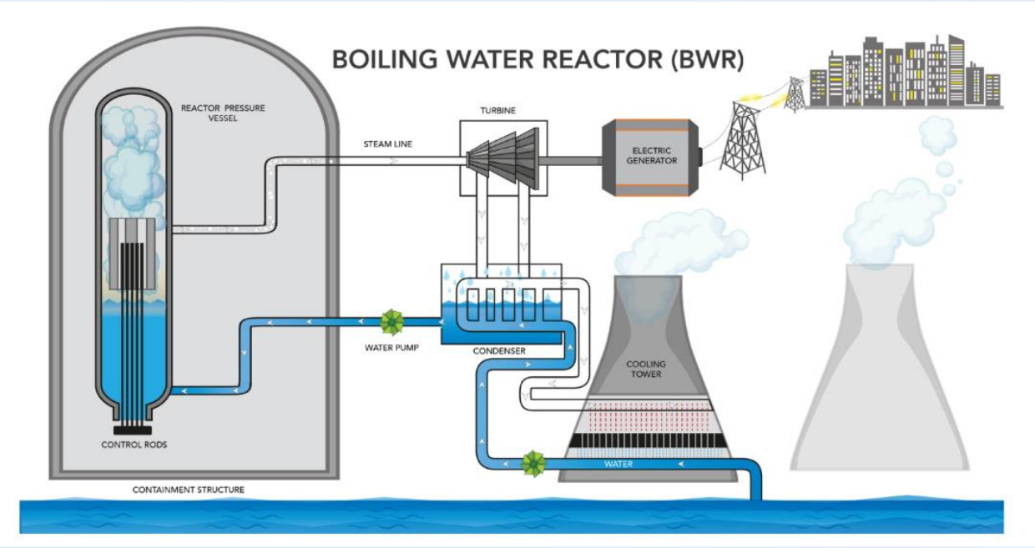


Nuclear is part of the most effective clean energy portfolios

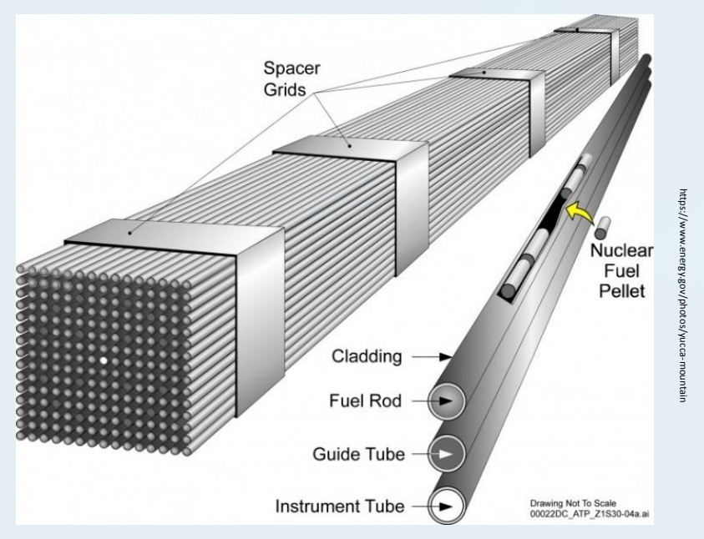
How is it currently done?

- Commercial nuclear reactors are light water reactors and typically come in two kinds, pressurized water reactors (~65% of reactors in the United States) and boiling water reactors. Normal water serves as coolant and moderator, generating a "thermal" or slow neutron energy spectrum for fission.





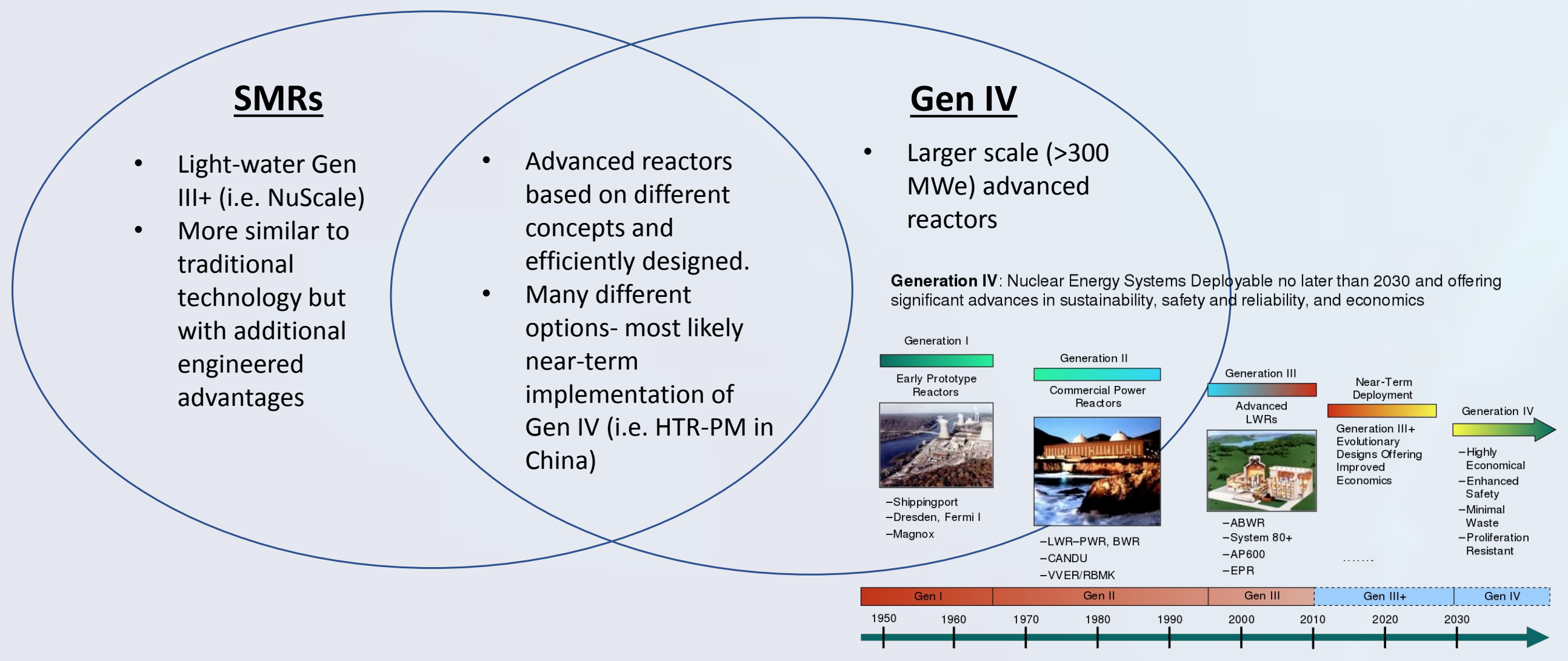
- Uranium fuel is typically enriched in the fissile isotope ^{235}U up to 3.5-5% and fabricated into UO_2 ceramic pellets.



- Refueling cycles typically last 18-24 months at which point used nuclear fuel is stored in wet storage (spent fuel pools) for up to five years, followed by dry storage.
- Considerations throughout the process: safety and security (redundant safety features, backup power requirements, etc.), proliferation (safeguards, export controls, etc.), economics, used nuclear fuel storage

While nuclear energy is currently clean and safe, advanced nuclear reactors would greatly aid in the continued use and further development of nuclear energy

Advanced Nuclear: Small Modular Reactors (SMRs) and Generation IV



SMRs

- Light-water Gen III+ (i.e. NuScale)
- More similar to traditional technology but with additional engineered advantages

- Advanced reactors based on different concepts and efficiently designed.
- Many different options- most likely near-term implementation of Gen IV (i.e. HTR-PM in China)

Gen IV

- Larger scale (>300 MWe) advanced reactors

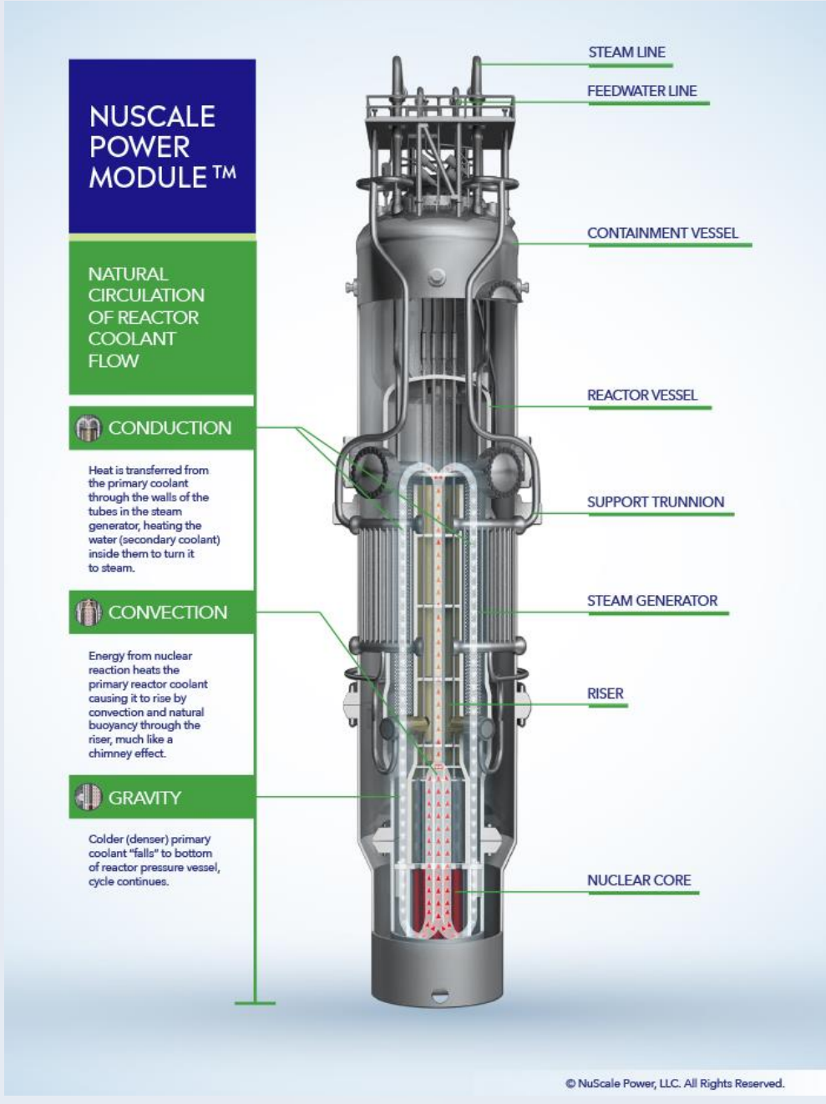
en.wikipedia.org/wiki/Generation_IV_reactor

Small Modular Reactors

- Generally reactors with generating capacities below 300 MWe (as opposed to ~1000 MWe) and designed with modular technology fabricated in factories.
- Economies of scale are replaced with economies of serial factory production
  - Cost-savings, improved manufacturing quality
  - Lowering start-up costs and offering possibility of generating income before full site installed
  - Smaller sizes make inherent safety and security easier to implement
- Increased flexibility and versatility for novel locations and applications
- Safety and Security by Design: incorporation of safety/security early in design process to more efficiently yield effective safety/security. Examples features:
  - Fully passive, natural convection cooling and air ventilation to remove decay heat (inherent safety in "physics", not "engineering")
  - Underground operation/resistance to projectile attacks
  - No on-site refueling and longer fuel cycles
  - Simpler design/fewer shutdown systems and components
  - Smaller physical footprints

Case Study: NuScale Small Modular Reactor

NuScale Model Plant showing five reactor modules

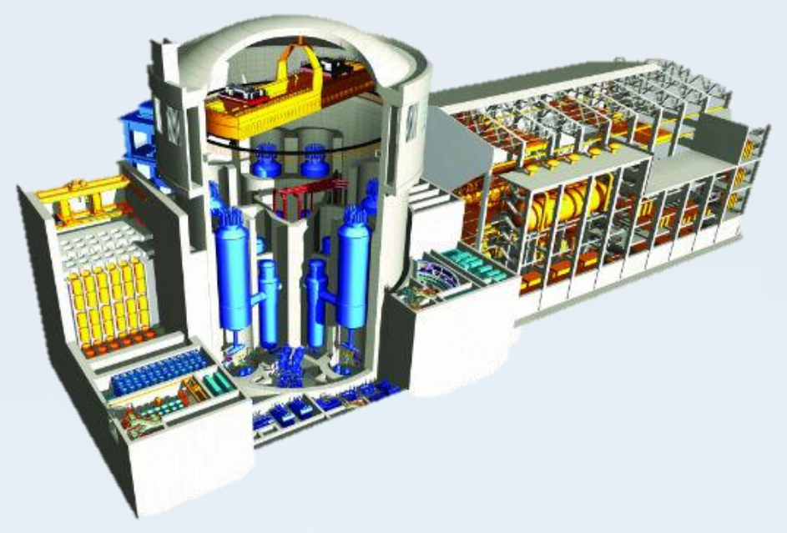


- Features- fully passive convection cooling in operation and after shutdown for an indefinite period; 24-month refueling cycle; installation in a water-filled pool below ground level; fully digital control system based on field programmable gate arrays[1]
- 2018- Nuclear Regulatory Commission concluded that NuScale's design eliminated the need for class 1E backup power, which is currently required for all U.S. nuclear power plants[2]
- 2026- Expected to be commercially operational[2]

[1] http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx
[2] International Atomic Energy Agency, "Advances in Small Modular Reactor Technology Developments," A supplement to *IAEA Advanced Reactors Information System 2018 Edition*, Sep. 2018.

Chinergy's HTR-PM

- To be connected to electric grid this year (2019) as first deployed SMR and Gen IV reactor[3]



Depiction of Chinergy's HTR-PM Reactor[3]

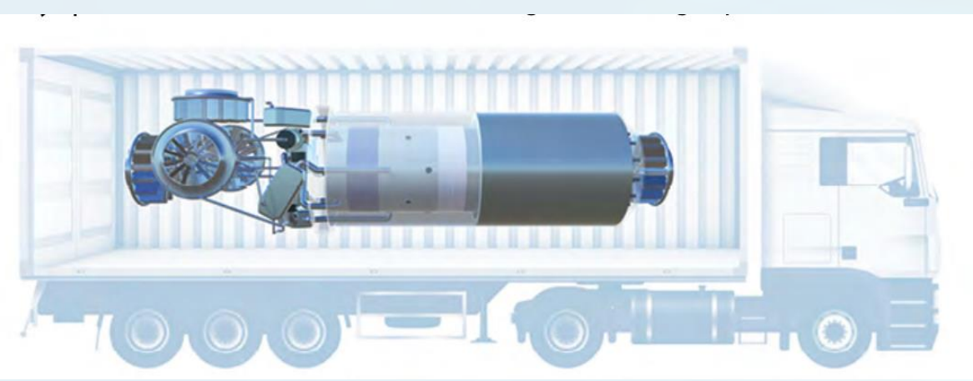
[3] www.neimagazine.com/features/featurehtr-pm-making-dreams-come-true-7009889/

SMRs offer inherently safe, versatile, and economical energy options

Micro Reactors

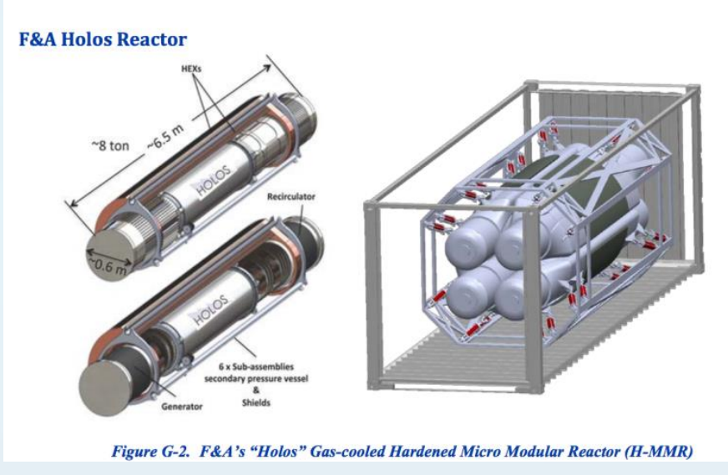
- Also called very small modular reactors (vSMRs)
- Similar to SMRs but on even smaller scales (1-10 MWe)
- Factory fabricated and transportable
- Targeted for even more remote or isolated locations
- More versatile applications- seawater desalination, district heating, hydrogen production, etc.
- Military applications-operating bases to reduce fuel transportation losses
- Could be used for emergency response to help restore power
- Longer core life-up to ten years without refueling

https://www.energy.gov/sites/prod/files/2019/01/f58/Ultimate%20Fast%20Facts%20Guide-ebook_1.pdf



Depiction of Megapower vSMR from Los Alamos National Laboratory

From www.lanl.gov/discover/publications/1663/2019-february/_assets/docs/1663-33-Megapower.pdf



Filippone and Associates LLC's Holos Gas-cooled Hardened Micro Modular Reactor

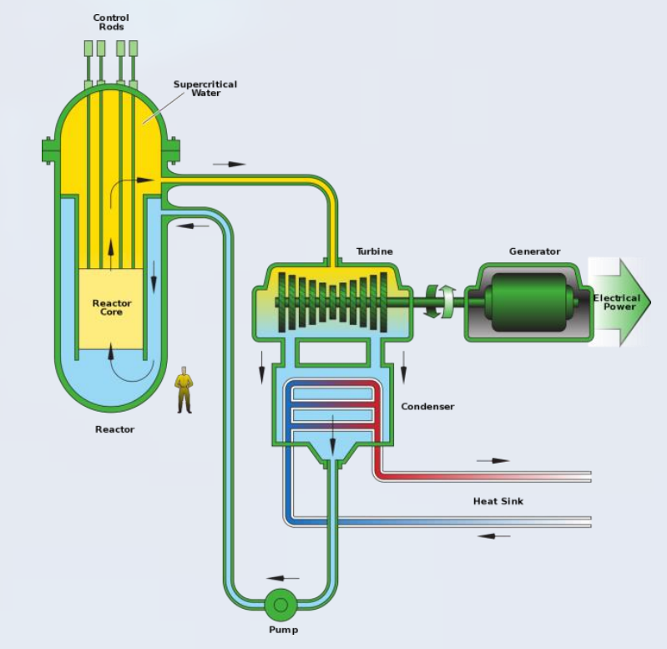
From www.nextbigfuture.com/wp-content/uploads/2017/07/fccb6b3b2f1058fbadee21cefa9403b3.png

Generation IV Reactor Types

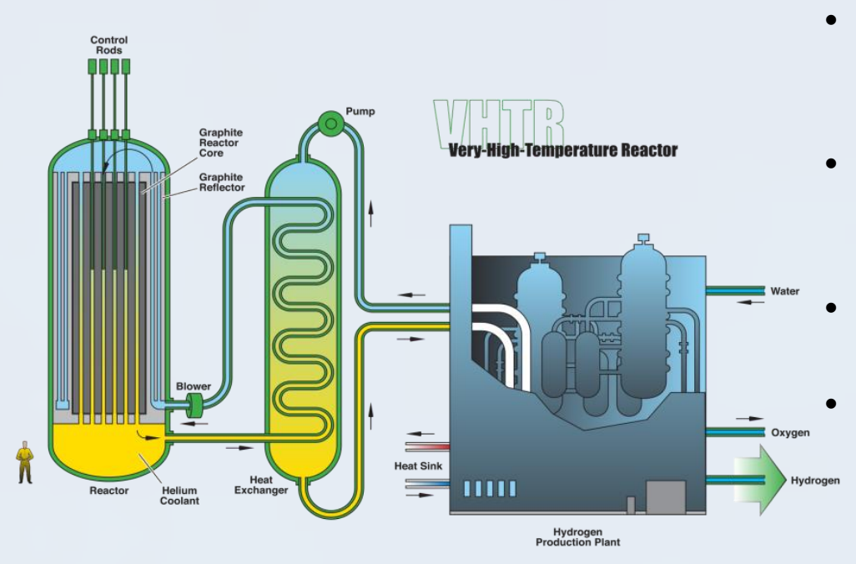
	neutron spectrum (fast/ thermal)	coolant	temperature (°C) / (°F)	pressure	fuel	fuel cycle	size(s) (MWe)	uses
Gas-Cooled Fast Reactor (GFR)	fast	Helium (He)	850 / 1562	high	^{238}U	closed, on site	288	electricity & hydrogen
Very-High-Temperature Reactor (VHTR)	thermal	Helium (He)	1000 / 1832	high	UO_2 prism or pebbles	open	250	electricity & hydrogen
Supercritical-Water-Cooled Reactor (SCWR)	thermal or fast	water	510 - 550 / 950 - 1022	very high	UO_2	open (thermal) closed (fast)	1500	electricity
Sodium-Cooled Fast Reactor (SFR)	fast	Sodium (Na)	550 / 1022	low	^{238}U & MOX	closed	150 -500 500 - 500	electricity
Lead-Cooled Fast Reactor (LFR)	fast	Lead (Pb) - Bismuth (Bi)	550 - 800 / 1022 - 1472	low	^{238}U	closed, regional	50 - 150 300 - 400 1200	electricity & hydrogen
Molten Salt Reactor (MSR)	epithermal	Flouride salts	700 - 800 / 1292 - 1472	low	UF in salt	closed	1000	electricity & hydrogen

- Thermal vs Fast Reactors
  - Refers to the energy spectrum of neutrons inducing fission
  - Fast neutrons have higher energy and can fission more isotopes including ^{238}U
  - Slow neutrons can only fission fissile isotopes like ^{235}U, but the likelihood of doing so is much higher
- Different physics involved leads to different advantages of each type

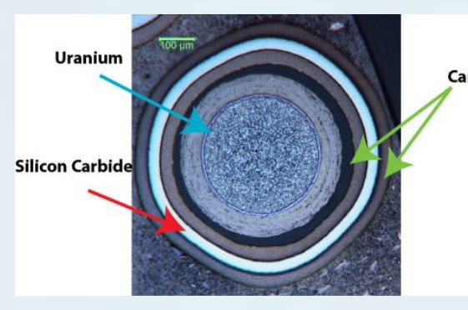
Generation IV Thermal Reactors



Supercritical Water Reactor:
- Improvements in thermal efficiency over normal water-cooled reactors
- Reactor coolant pumps unnecessary and containment can be substantially smaller
- Challenges with heat transfer model validation, and qualification of materials

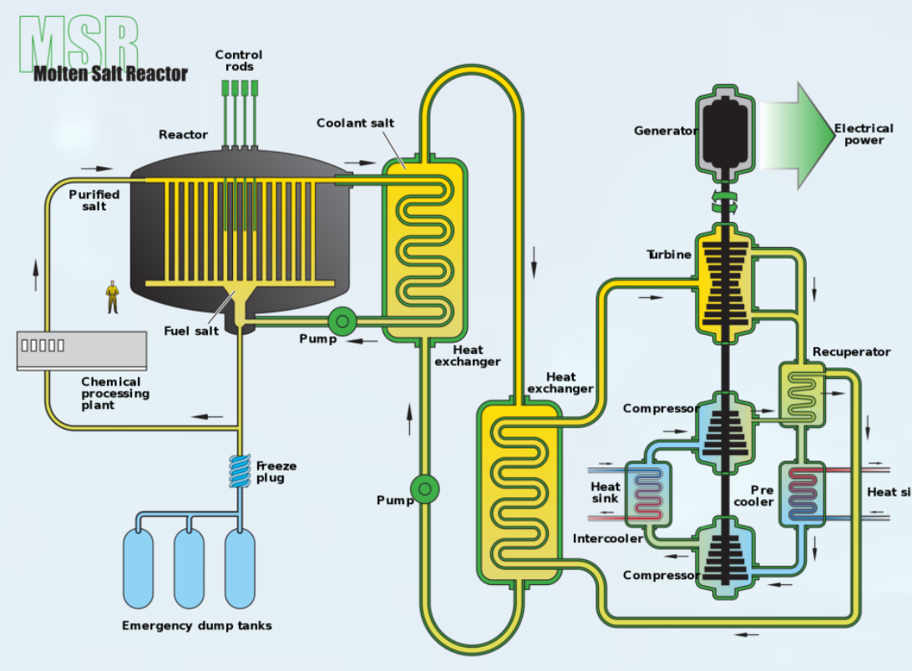


Very High Temperature Reactor:
- High outlet temperatures could be useful for industrial applications/cogeneration of hydrogen
- Uses special TRISO fuel that is a coated particle holding in uranium- "un-meltable"
- High inherent safety, high thermal efficiency
- Challenges with high demands on structural materials



TRISO fuel pellet cross section

From www.blog.ngnpalliance.org/triso-fuel-news/



Molten Salt Reactor:
- Unique fuel composition: fuel is dissolved in molten fluoride salt that serves as coolant
- Potential for online refueling, radiation damage of fuel unimportant, homogenous isotopic fuel
- Inherent safety in case of meltdown (draining of fuel)
- Challenges with safeguards

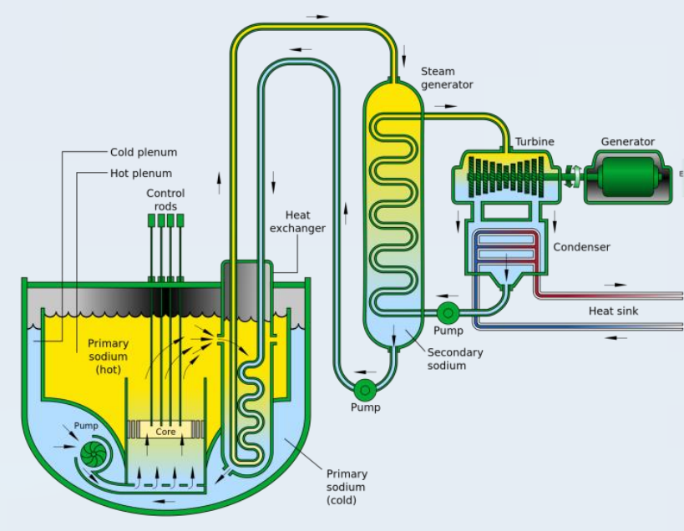
www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

Benefits:
- Cogenerative applications and industrial use
- Higher thermal efficiencies
- Enabling of more compact reactors
- Novel fuel types with inherent safety

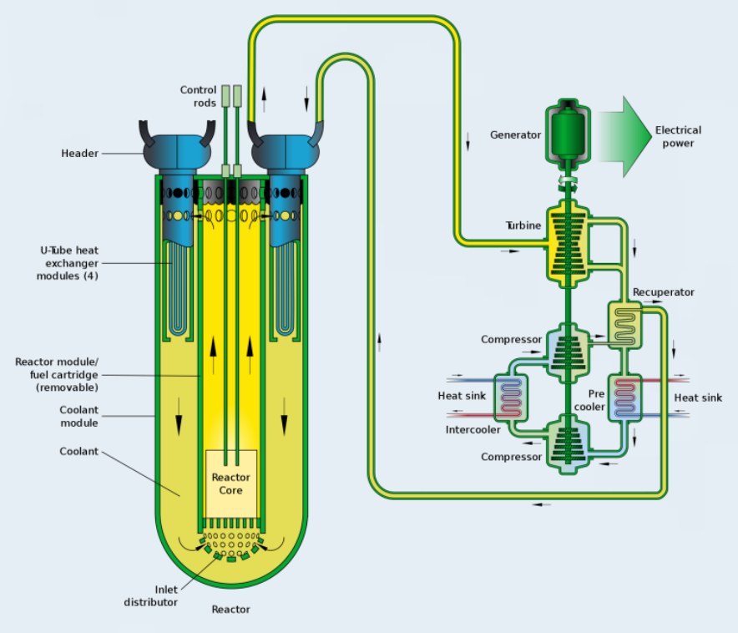
Gen IV improves efficiency and safety while offering additional applications. Fast reactors enable improved fuel utilization and reduced waste production

Generation IV Fast Reactors

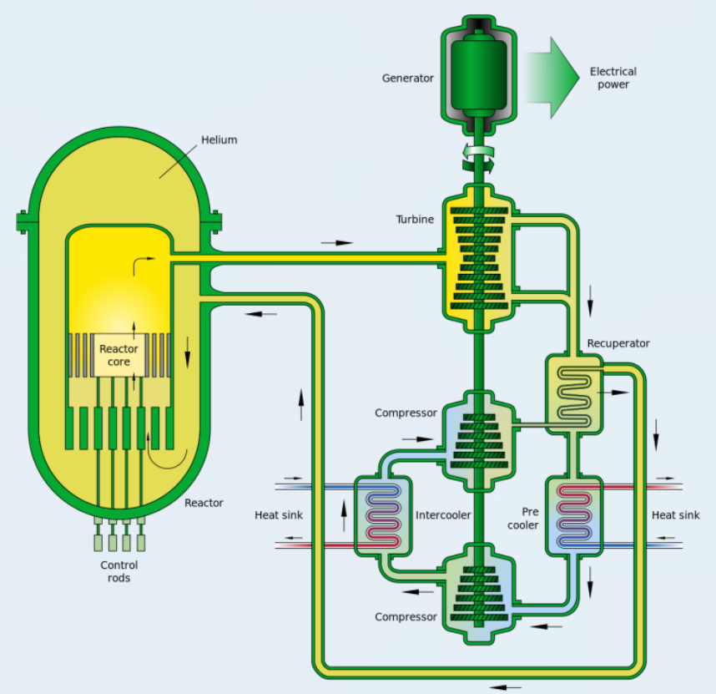
Supercritical water and molten salt can also be designed as fast reactors



Sodium-cooled fast reactor:
- Fast neutron spectrum more effectively uses uranium resources
- Higher temperatures and lower pressures than current reactors for improved efficiency and safety
- Most mature fast reactor design
- Challenges with chemical reactivity of sodium



Lead-cooled fast reactor:
- Similar to sodium-cooled fast reactor but with lead-based coolant
- Low pressure operation, good thermodynamic and neutronics properties, and relative inertness with air/water
  - Enhanced safety
- Challenges: high melting temperature of lead, opacity, high coolant mass, and potential corrosion



Gas-cooled fast reactor:
- Combines benefits of fast reactors with high temperature systems (efficiency and multiple-purpose systems; fuel management)
- Challenges: Poor heat transfer and without graphite for thermal inertia; severe materials requirements

www.gen-4.org/gif/jcms/c_59461/generation-iv-systems

Benefits:
- Primary appeal of fast reactors is fuel management: closed fuel cycle
  - Fast neutron spectrum enables fissioning of many nuclides, breeding of fissile material, and transmutation of undesirable waste nuclides to reduce waste burden
  - Enables recycling of used nuclear fuel as a fuel source
- Can also be smaller and simpler than light-water based reactors

Conclusions

Advanced reactors are a significant departure from previous reactor designs. While currently deployed nuclear reactor designs provide reliable, clean, and safe energy and should be maintained, exciting new reactors are on the horizon.

Small modular reactors and micro reactors
- Improve economic competitiveness and have reduced start-up capital costs of nuclear reactors
- Possess greater flexibility in power production capacities to accommodate more locations and applications
- Enable higher levels of inherent safety, security, and safeguards by design

Generation IV reactors
- Utilize designs with greater inherent efficiencies
- Employ fast neutron spectra that enables much more comprehensive and effective fuel management including recycling used nuclear fuel, reducing the quantity and quality of used nuclear fuel, and transmutation of less desirable heavy elements
- Provide industrial cogeneration capabilities

Advanced nuclear reactors bring a wide range of dramatic benefits to revitalize the industry as is necessary for the most effective climate drawdown- the future is bright!

Outlook-Near Term Developments

Global Developments-Gen IV on the way!
- Chinergy's HTR-PM (High Temperature Reactor-Pebble Bed Module) is scheduled to begin electricity generation in 2019[1]
- Russia's BN-800 sodium-cooled fast reactor was completed in 2016 and is capable of producing 880 MWe[2]

[1] https://www.nextbigfuture.com/2019/04/will-new-nuclear-reactors-displace-coal.html
[2] http://www.world-nuclear-news.org/NN-Russian-fast-reactor-reaches-full-power-1708165.html

In the United States-

NuScale Small Modular Reactor:
- 2018- Completed first and most intensive phase of review by Nuclear Regulatory Commission
- 2019- NuScale also signed a service agreement with Canadian Nuclear Safety Commission to submit an application under their pre-licensing Vendor Design Review
- September, 2020- Nuclear Regulatory Commission scheduled to complete its review process
- 2026- First NuScale plant is scheduled to be operated by Utah Associated Municipal Power Systems

www.nuscalepower.com/newsletter/nucleus-summer-2019/program-development-update

Legislative Support:

Nuclear Energy Innovation Capabilities Act (NEICA) passed in September 2018; Nuclear Energy Innovation and Modernization Act (NEIMA) passed in January, 2019; Nuclear Energy Leadership Act (NELA) currently in the full Senate (September, 2019). All aim to remove roadblocks to advanced nuclear in the United States and support their development from multiple angles.

www.nei.org/news/2019/advanced-reactor-bills-congress-leading-clean