Nuclear Fission

Prime Movers Lab
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Prime Movers Lab

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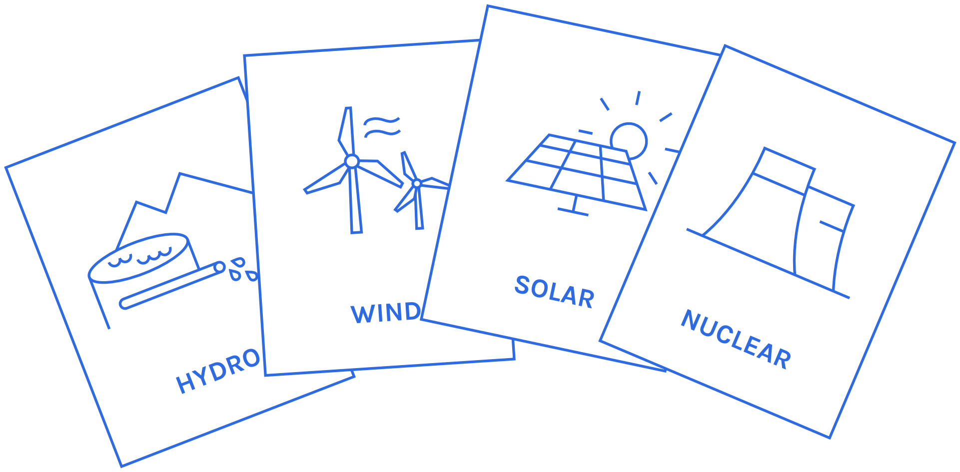


In this thought paper, we'll cover **nuclear fission**, which is what we typically mean by nuclear power. Today's nuclear power plants make electricity from uranium *fissioning* into smaller atoms at commercial scale all over the world. Nuclear fission and nuclear fusion (which I've written about elsewhere) are two VERY DIFFERENT sources of energy!

Introduction and Industry Background

Why the World Will Use More Nuclear

Nuclear power is needed to meet CO_2 emissions targets and address climate change. At this point, we all know that increasing CO_2 levels are changing the climate[1], and the effects of this are pretty bad[2]. Add to this volatile fuel prices, resource-driven geopolitics, the negative effects of increasing air pollution on our health, and environmental impacts, and it's clear that a shift to other energy sources needs to happen ASAP.[3]

The challenge is that the scale of the transition needed to decarbonize is massive. Humans used roughly 23,000 terawatt-hours (TWh)[4] of electricity in 2019, not including energy for heat or transportation. **Burning coal is still the most common way we generate electricity worldwide (38.2% of the world's electricity)**, followed by burning natural gas (23.1%).[5] Transitioning to low-carbon electricity sources means replacing over half of the world's existing electricity generation. To keep the average rise in global temperatures below 2 deg C, the International Energy Agency (IEA) predicts that all coal would have to close by 2040 - that's roughly one coal unit every day until 2040.[6, 7]

"Singapore: Where Air Conditioners Live" by pmorgan

Compounding this problem, the world will use more electricity in the future. Globally, IEA predicts that electricity generation will increase by 35-50% in the next 20 years. Most of this growth comes from increased electricity consumption in developing (non-OECD) countries.[8] Per person electricity use in less developed countries *has more than doubled* between 2000 and 2017. That's just electricity use (not gasoline or natural gas). Energy-intensive forms of consumption, such as car ownership, are rapidly expanding in China, India, and other rapidly industrializing nations.

In western developed countries like the USA and Europe, electricity demand has flattened or fallen slightly over the past decade. However, energy forecasters like the National Renewable Energy Lab (NREL) project that US electricity use will increase by 36% between now and 2050.[9] Switching just today's passenger cars to electric vehicles would increase the US's demand for electricity by 12%, or 520 terawatt-hours (TWh). This alone would require 70 more traditional nuclear power plants, 210 small modular reactors (SMRs), 150 coal power plants, or 47,000 wind turbines.[10]

Other ambitious projects not captured in these projections, such as an increase in demand for green hydrogen, large scale direct air capture or desalination, and/or launching 20 Falcon Heavy rockets a week could add many GW of energy demand in the next 15 to 50 years. Clearly, the world will need to replace and build out a lot of new power plants in the next few decades.

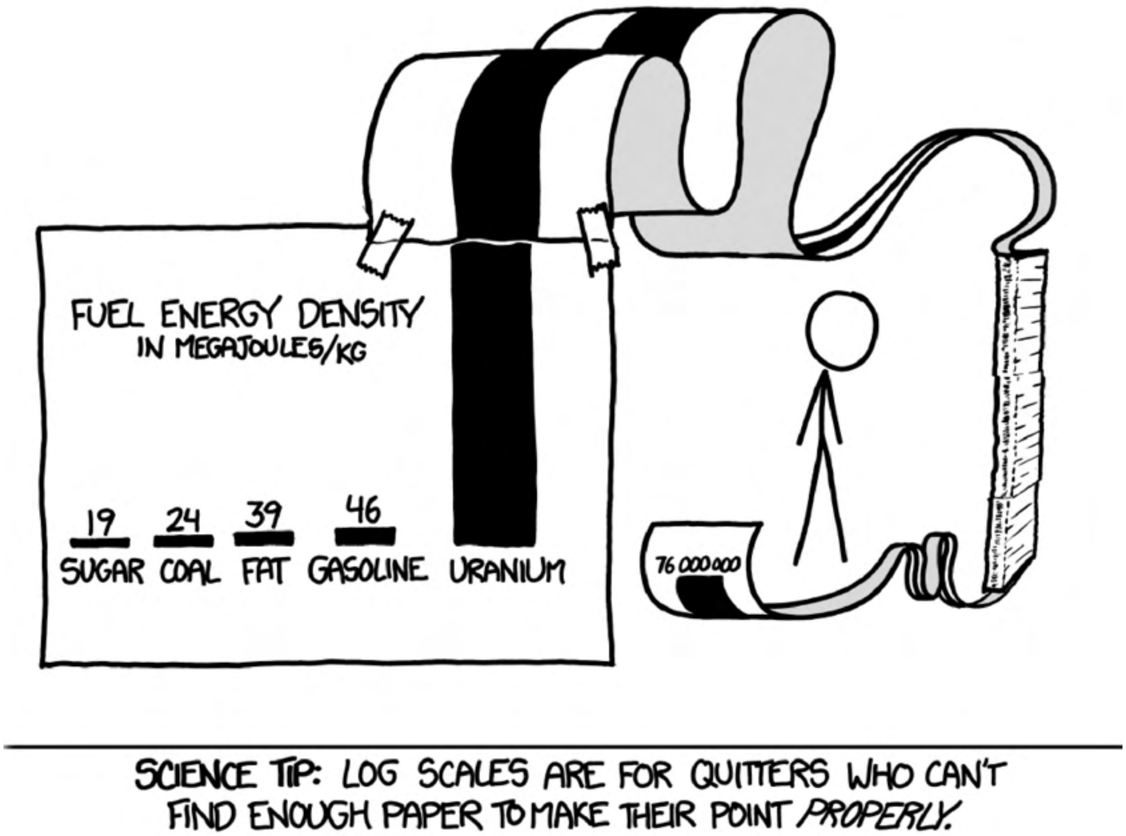
Could we generate all this electricity from solar, wind and hydro? This has been a hot topic of debate in academic communities for many years.[11] In an ideal "Sim City" style world where we could build new transmission lines and site renewables wherever we wished and were willing to pay a premium…sure, we could make it work. See this detailed study from NREL (published in May 2021).

However, reality is complicated. The cost for new electricity transmission lines and interconnection to the grid can add up to 50% of the cost of a new wind project. Electric utility procurement processes are slow, with proposals for new procurement requested according to a utility's "Integrated Resource Plan" (IRP), which is created on a four-year cycle. Areas like Washington state and countries like Poland and Romania need to comply with climate targets, and don't have great sun or wind.

The transition to low-carbon energy sources is happening too slowly — we need to deploy whatever technologies make sense for regions and communities as quickly as possible. Which brings us to the final reason we expect to see more nuclear electricity generation deployed: **Nuclear fission is actually a pretty awesome way to generate heat and electricity.**

Unlike combustion processes — coal, natural gas, diesel and biomass — nuclear power releases no carbon dioxide, smog, particulates, or volatile organic compounds. Nuclear power plants also have the highest **capacity factors** of any type of power plant. The capacity factor refers to how often the power plant is producing electricity. Nuclear plants in the US have a capacity factor of 93% (they are producing electricity 93% of the time) vs 35-42% for wind and 25% for solar plants. A nuclear plant will generate almost 3x as much energy as a wind farm of the same size.

Nuclear fuel is the most dense energy carrier on the planet. Uranium-235 contains so much energy that all the electricity you use in a year could be generated from about 2 fuel pellets, or 20 grams of standard nuclear fuel.[12] This means that the amount of nuclear waste generated per person is actually quite small.



One of my favorite XKCD comics: https://xkcd.com/1162

To summarize why interest in nuclear power is increasing again:
- Nuclear power is increasingly seen as a necessary component of a low-carbon electricity portfolio as pressure to reduce CO2 emissions from the electricity generation increases, particularly in parts of Europe.
- Nuclear fission has many advantages as an energy source, including near-constant power generation, no emissions, and small fuel requirements. Designs for both small nuclear reactors (SMRs) and reactors based on new advanced nuclear technology promise additional advantages.
- Global electricity demand is increasing and is primarily driven by increased consumption in the developing world. This means a huge demand for power plant technologies in the next few decades, particularly those that can be deployed internationally.
- For the US and other western countries, being left out of the global nuclear industry means ceding the technical and economic opportunity to other major world powers.

Today's Nuclear Landscape

The US must find a way to participate in supplying and constructing nuclear technology, or cede this responsibility to Russia and China. Russia is the leading supplier of nuclear reactors to other countries - 17 of the 53 traditional nuclear plants under construction around the world are Russian VVER power plants.[13] China is in second with 12 nuclear plants under construction around the world. This means that Russia and China will supply the nuclear fuel, equipment, and engineering for these plants for decades to come.

"Equipment arrives at Vogtle nuclear plant — August 2013" by NRCgov
Courtesy of Georgia Power Company ©. (August 2013)

The US nuclear industry has struggled to build commercial nuclear plants on time and on budget in recent decades. While the US currently has more operating nuclear power plants than any other country (94 nuclear reactors, which generated 809 TWh of power last year), almost all of these were built between 1970 and 1990. (For comparison, China's first nuclear reactor wasn't connected to the grid until 1991 — they now have

46 nuclear plants operating domestically, and another 15 scheduled to come online in the next five years.) The US-based Westinghouse Electric Company sold several new nuclear reactors (AP1000s) to China and began construction on two new nuclear power reactors in Vogtle, Georgia in the 2010s. However, problems and cost overruns with Vogtle led Westinghouse to file for bankruptcy in 2017, creating uncertainty around plans for other international AP1000 projects.

The South Korean nuclear company KEPCO (which is building 7 plants globally) has been the best option for countries who want to build nuclear power on time and on budget, without strings attached. However, the new South Korean government elected in 2017 has stated that they will phase out nuclear power in the future. The future of KEPCO (a state-run company) as an international nuclear supplier is therefore uncertain. [Note[14]]

A few other nations have strong or growing domestic nuclear industries. France's EDF (Areva) and India (state-owned NPCIL) each have a few reactors under construction.

For a complete list of nuclear plants operating and under construction, see the World Nuclear Association's 2020 Nuclear Performance Report and NEI's list of reactors under construction by location and supplier country.

Financing is a huge barrier to building conventional Gen3 nuclear plants. Existing nuclear power plants typically generate a lot of power, 1000 MW or more, and are huge construction projects. Overnight costs for new nuclear plants in western industrialized countries are typically $6B-$10B, which comes out to ~$5000-$6000 per kilowatt of capacity.[15] (This is much higher than typical costs for nuclear power in South Korea, $2700/kW and in China). Russia and China, where nuclear companies are state owned, are more easily able to finance nuclear exports, and are already exploring emerging markets. (Source)

Americans don't get to choose whether or not nuclear power plants are built around the world. Instead, we can choose whether we sit back and allow others to build the next generation of the world's nuclear plants, or develop the capabilities to build new commercial nuclear technology on time, and on budget.

Emerging Trends

Announcements by governments, financial institutions and technology companies in 2020 signal that a shift in the global nuclear landscape may be coming. In October 2020, the US and Poland signed an agreement to cooperate on the development of Poland's first nuclear power plant.[16] A draft collaboration agreement was also signed between the US and Romania.[17] These agreements are not unique to the US. Canada and the UK announced an action plan for joint nuclear research projects in early 2020.

In the past, financing has been a huge barrier to building large new nuclear plants, but new models and partnerships are being explored. Today's nuclear technology companies are developing smaller power plant designs (≤300 MW vs 1000MW) that require less capital and can be constructed more quickly. This reduces both the upfront financing burden, and the time to revenue from electricity sales. Many of the new reactors in development also use very different technologies to extract energy from uranium. These concepts should in theory be more efficient and cost effective when commercial, and vary in size from 1 MW (the size of a single wind turbine) up to 1000+ MW. (See Technology for more info!)

"NuScale Power Plant Design — Eyelevel" by Oregon State University

To help new technologies overcome the financing hurdle, the US Dept of Energy (DOE) has made several major awards across multiple programs to companies with the goal of commercializing new reactor designs. The light-water SMR company NuScale was granted up to $1.355 billion through the DOE's initial SMR R&D Program (a multi-year cost-share award) to fund their first power plant. The more recent Advanced Reactor Demonstration Program awarded TerraPower and X-Energy significant financial support to complete their first power plant demonstrations.[18]

Looking towards larger markets overseas, last year the US International Development Finance Corporation[19] (DFC) announced a change in its policy to allow it to fund nuclear power projects abroad. (Neutron Bytes) This creates a mechanism for the US government to help provide financing for new plants in developing nations - a key barrier to their construction, and one that China and Russia's state-owned nuclear reactor suppliers have been willing to step in and help with.

In short, national governments, engineering companies and a new wave of startups are positioning themselves for a large build-out of nuclear power plants in the next few decades.

Market and Drivers

Market Opportunities

As described in the previous section, the electricity markets are massive and growing. Nuclear energy is an especially good option for firm, low-carbon US states and countries with strong decarbonization goals and poor wind and solar resources; and in non- OECD countries where electricity demand is expected to rise dramatically in the next three decades. Canada's Minister of Natural Resources, Seamus O'Regan, said the global market for small modular nuclear reactors (SMRs) is expected to be worth up to $300 billion a year by 2040. Across the pond, UK-based Rolls-Royce similarly estimates the global market for SMRs to be 250-400 billion euro in 2035.[20]

I want to highlight one use case for advanced nuclear – specifically, small modular reactors – that I believe is important. A successful SMR demonstration unlocks a massive opportunity for new nuclear to replace coal-fired and old nuclear power plants as they retire. Between 2015 and 2020, more than 100 of 427 US coal-fired power plants were retired or converted to run on natural gas.[21] These plants generated sixty-five thousand megawatts (65,000 MW). Another 62,000 MW of retirements by 2030 are planned. The turnover in coal power plants alone could support 100–200 new small modular nuclear reactors if there were shovel-ready options!

Many of these retirements are in areas of the US with limited solar and wind, or at sites without enough unoccupied space to build out renewables (see this S&P Global article for a list of retiring plants). Building out transmission has been maddeningly difficult due to challenges obtaining right-of-way, permitting, and the high cost of new transmission lines. Nuclear provides a key tool for generating low carbon power but also helps stabilize sections of the grid while it adapts (hopefully as fast as possible) to the massive build-out of low-cost renewables over the next few decades.

The Columbia Generating Station in Washington state, where X-Energy plans to demonstrate its Xe-100 reactor. "Columbia Generating Station, Unit 2" by NRCgov under CC

There are many good reasons why the first advanced nuclear reactors in the US are planned at retired coal and existing nuclear plant sites. These "brownfield" former power plant sites already have high capacity connections to the electric grid and key power infrastructure (e.g. transformer substations) that are right-sized for small modular reactors (SMRs). Replacing retiring fossil fuel plants with other "firm" (you can always turn it on) electricity generation like nuclear helps maintain reliability in the surrounding transmission network (that was built based on the assumed availability of this power plant). There may be other power plant infrastructure (e.g. cooling towers, air coolers, site buildings and offices) that can be repurposed.

Our view is that the biggest opportunity for advanced nuclear power is in the small modular reactor regime, particularly 150-400 MW. This is based on considering the average size of new electric generation facilities built in the US in 2020 and 2021. While there are more communities that could use 20 MW of additional generation, there is a trade off with increased volume of customer acquisition costs, grid interconnection costs, and economies of scale that make this range attractive. This is also consistent with projections from other western countries (see June 2021 study examining four scenarios for nuclear build out in the UK.)

Nuclear Power Plant Cost and Financing Considerations

The reason for the relative slowdown in nuclear plant build-outs in the past few decades, particularly in western countries, is the cost of conventional nuclear power plants. A typical nuclear power plant, generating 900-1400 megawatts (MW) of electricity, costs upwards of $10B to build. Construction timelines for these power plants are long, often ten years or more. Median construction time for nuclear reactors in 2019 was almost ten years (117 months). However, this included several first-of-a-kind (FOAK) reactors. (Source: WNA 2020 Report) Typical construction times since 2015 for non-FOAK plants have been 5-6 years.

Notably, the cost of building nuclear reactors is significantly higher in Europe and North America ($115/MWh, on average) than in the rest of the world ($52/MWh) (see The ETI Nuclear Cost Drivers Project). To be competitive with other types of grid-scale electricity generation in the US, nuclear needs to come in at a "levelized cost of electricity" (LCOE) of about $50 per megawatt-hour or less (the approx. cost of solar + storage). This is part of why other parts of the world are willing to build out nuclear – it makes economic sense. (For a summary of LCOE across countries and types of electricity generation, see the International Energy Association's (IEA) 2020 report, pg 50.)

New Small Modular Reactor (SMR) technologies and advanced reactors are designed to be significantly smaller, cheaper, and easier to regulate and construct, creating paths for US companies to get back to a competitive price point. The US Energy Information Association (EIA)'s projections for the LCOE of major energy generation and storage technologies, including advanced nuclear is shown below for reference.

Table 1b. Estimated unweighted levelized cost of electricity (LCOE) and levelized cost of storage (LCOS) for new resources entering service in 2026 (2020 dollars per megawatthour)

Plant type	Capacity factor (percent)	Levelized capital cost	Levelized fixed O&M[1]	Levelized variable cost	Levelized transmission cost	Total system LCOE or LCOS	Levelized tax credit[2]	Total LCOE or LCOS including tax credit
Dispatchable technologies								
Ultra-supercritical coal	85%	$43.80	$5.48	$22.48	$1.03	$72.78	*NA*	$72.78
Combined cycle	87%	$7.78	$1.61	$26.68	$1.04	$37.11	*NA*	$37.11
Combustion turbine	10%	$45.41	$8.03	$44.13	$9.05	$106.62	*NA*	$106.62
Advanced nuclear	90%	$50.51	$15.51	$2.38	$0.99	$69.39	-$6.29	$63.10
Geothermal	90%	$19.03	$14.92	$1.17	$1.28	$36.40	-$1.90	$34.49
Biomass	83%	$34.96	$17.38	$35.78	$1.09	$89.21	*NA*	$89.21
Battery storage	10%	$57.98	$28.48	$23.85	$9.53	$119.84	*NA*	$119.84
Non-dispatchable technologies								
Wind, onshore	41%	$27.01	$7.47	$0.00	$2.44	$36.93	*NA*	$36.93
Wind, offshore	44%	$89.20	$28.96	$0.00	$2.35	$120.52	*NA*	$120.52
Solar, standalone[3]	29%	$23.52	$6.07	$0.00	$3.19	$32.78	-$2.35	$30.43
Solar, hybrid[3, 4]	28%	$31.13	$13.25	$0.00	$3.29	$47.67	-$3.11	$44.56
Hydroelectric[4]	55%	$38.62	$11.23	$3.58	$1.84	$55.26	*NA*	$55.26

Source: US EIA's Annual Energy Outlook 2021 PDF

Like wind and solar, the bulk of the cost of nuclear power is the **capital cost** of building the plant. For combustion-based technologies like coal and natural gas, fuel costs (**variable costs**) make up 30-70% of the cost of electricity. While this makes financing nuclear plants more challenging – a larger amount of capital is needed to construct the plant, before revenues from electricity sales start coming in – it greatly reduces price uncertainty from fuel cost volatility or supply disruptions. (Remember the 2021 Texas freeze, when natural gas production dropped by 20%.)

Unlike wind and solar, advanced nuclear is a "dispatchable" or "firm" source of energy – it can always be turned on. In the EIA's analysis, the "hybrid solar" model includes four hours of battery storage. This is enough to cover peak electricity demand for four hours in the evening, when solar panels stop producing but not enough to store electricity overnight. Advanced nuclear can also be deployed anywhere, unlike solar, wind and geothermal. For example, most of the wind resource is in the middle of the US, while the population and electricity demand is concentrated on the coasts. Building transmission lines to connect renewables far from load centers can **double the cost** of a wind project and introduce huge permitting challenges.

Business Models

New companies in the nuclear industry have several options. The first is to be solely a technology provider, licensing the technology for a nuclear plant to an energy company or utility who will manage the construction and operation of the power plant. Alternatively, they can sell key nuclear reactor equipment, maintenance services, and/or fuel a utility who will operate the plant. For small microreactors (<20MW) in remote areas where there may not be a utility, a nuclear tech company could build and operate power plants and sell power directly.

The (simulation) control room at the Shearan Harris Nuclear Power Plant, 2017 (Image by RadarMan under CC)

Technology

In the previous section, we looked at trends in the commercial nuclear power industry and why we expect the number of nuclear plants to grow. There are currently 440 nuclear power reactors operating around the world, and more than 50 more are under construction (mostly by Russia and China).[22]

When you take a closer look at these reactors, however, you realize that nuclear power plant technology in most of the world has stayed the same for a long time. And I really mean THE SAME – despite the year being 2021, the control rooms in US nuclear plants look like a 1971 museum exhibit.

There are signs that new advanced reactors, or "Generation IV" reactors are gaining the maturity and traction (read: gov funding for demonstration plants) to steal the show within the next decade. These technologies include new safety features, produce less radioactive waste, make electricity more efficiently, and could become more cost effective than today's reactors.

Interestingly, most of the ideas for advanced reactors were first proposed and tested decades ago. Early versions of gas-cooled reactors, liquid metal reactors, breeders, and molten salt reactors were built in many countries and largely abandoned for a variety of technical, economic, and political reasons.

A handful of advanced reactors are operational in Russia, China, and India, and there are several more that are expected to come online in the next decade. Will these become the new normal? With western governments beginning to invest in advanced nuclear pilot and demonstration projects again, perhaps we will see new commercial technology on this side of the pond in the next decade too.

What has changed that will make the redesigns of these reactors successful? Greater computing power and simulation capabilities are once again a huge factor. In the 1970s when most nuclear technology was developed, modern computers didn't even exist! Now simulation tools are critical for predicting and optimizing what will happen to the fuel inside the nuclear reactor (neutronics), and new reactor configurations can be explored and tested without building multiple prototypes. Metallurgy, welding techniques, and how we analyze material failures have also come a long way since the 70s and 80s. We have better sensors, industrial automation, chemical analysis tools, and process control. We also have several decades more research in related areas, and a growing amount of experience from test and prototype advanced reactors around the world.

In this section, we'll review current nuclear reactor technologies and those in development. What advantages do these technologies have?

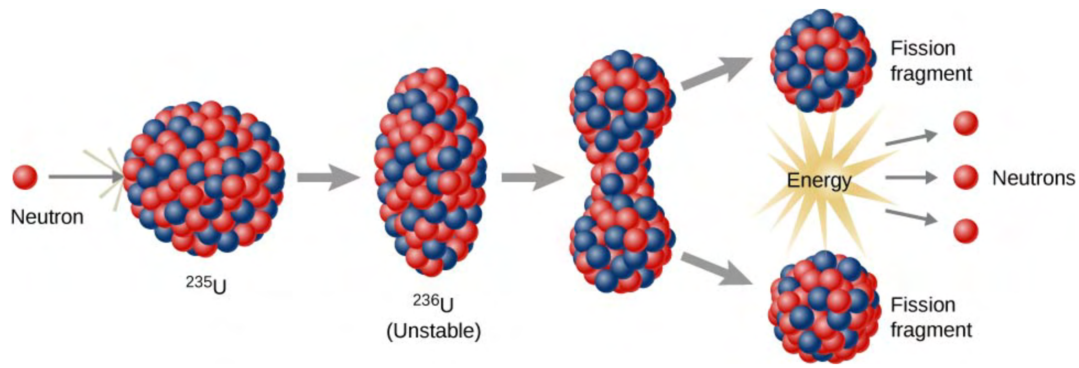
Current Reactor Technology: A Fancy Way to Boil Water
Nuclear energy (the fission variety) comes from splitting atoms into smaller atoms, neutrons, and energy. In nuclear power plants, the energy from splitting atoms is turned into heat, which usually is used to boil water and make steam. The steam drives a turbine and – voilà! – electricity is produced.

Today's nuclear reactors are really just a fancy way to boil water.

That's the engineering version. Now let's shift to physics and what's happening inside a conventional reactor, aka tea kettle.

When a uranium-235 atom splits, most of the energy created causes the new, smaller atoms to quickly fly away from each other. In most of the world's reactors, these smaller atoms bump into the water that fills the reactor, heating it up. The water is the **coolant**, and does a good job of capturing the energy produced by fission reactions as heat, and carrying it away to make power.

Importantly, uranium-235 also releases neutrons during fission. These neutrons initially have a lot of energy and are creatively called **fast neutrons.**[23] Making more neutrons is critical to keeping the nuclear reactor running… neutrons hitting uranium-235 atoms are what cause them to split.



Fission starts by a neutron striking uranium-235, which splits into smaller atoms (fission fragments), neutrons, and energy. (Image from BC Open Textbooks under CC)

However, there's an element of finesse involved. When a neutron with the right amount of energy hits a uranium-235 atom, it is more likely to undergo fission and split. However, the fast neutrons released from uranium-235 fission have too much energy to efficiently start more fission reactions. So most nuclear reactors use a **moderator** — like a traffic cop — to slow the neutrons down. Slower moving **thermal neutrons** are much more likely to cause uranium-235 atoms to split.

Scientists and the Navy[24] quickly found that water is both a good coolant AND a reasonable moderator. Most nuclear power plants that are operating today — 84% — use water as both a moderator and a coolant. These nuclear reactors are called "**light water reactors**".

The world's first nuclear-powered submarine, the USS Nautilus, was launched in 1954. (Image Source) US Navy played a critical role in LWR development.

Unfortunately, water is a good but not perfect moderator. A perfect moderator would just slow down the neutrons without capturing any of them. The hydrogen atoms in water sometimes capture neutrons, reducing the number that can start new fission reactions.

One solution is to use "heavy" water (deuterium), which captures fewer neutrons than normal "light" water. With more neutrons around, **heavy water reactors** can use un-enriched or "natural" uranium as fuel (see Nuclear Fuel). There is a trade-off for lower fuel costs — deuterium is expensive. Still, roughly 11% of nuclear power plants use heavy water as the moderator and coolant (mostly in Canada and India).[25]

A few nuclear plants still use water as the coolant and solid graphite (a form of carbon) as the moderator. This combination was used in many of the earliest experimental reactors — the first nuclear reactor ever built (by Enrico Fermi in 1942) was graphite moderated.

The Russian RBMK reactors, including the Chernobyl power plant in Ukraine, are/were also graphite-moderated and water cooled.[26] (RBMK is a long Russian acronym describing the reactor.) As of 2019 there were still nine RBMK reactors and three smaller graphite-moderated EGP-6 nuclear power plants operating in Russia (with **some safety updates** following the 1986 Chernobyl accident).

To summarize, three critical elements of a nuclear reactor's design are:
- The **FUEL** used in the reactor
- The **COOLANT** used to capture the heat, and
- The **MODERATOR** or other strategy to promote more fission reactions.

Today, water (and less often heavy water) are almost exclusively used as the coolant in nuclear reactors. Most nuclear plants run on slightly enriched fuel (~4% uranium-235), with the exception of heavy water reactors that can run on natural uranium.

New Reactor Technology: Advanced Reactors

Unlike conventional nuclear reactors, **advanced reactors do not use water as a coolant.** The most promising advanced reactors use liquid sodium (or other metals), a liquid molten salt mixture, or helium.

All advanced reactors can operate at temperatures well above 320 deg C, which makes generating electricity more efficient. They also all use coolants that won't spread radiation if there was an emergency or accident, offering more passive safety. Depending on the technology, some advanced nuclear reactor designs (also called Generation IV reactors) have additional advantages:

- They produce significantly less high-level nuclear waste
- They generate nuclear waste that has less long-term radioactivity
- Some gas-cooled reactors can operate at VERY high temperatures, enabling hydrogen production
- Some coolants are more dense than water and can operate at atmospheric pressure rather than high pressure, enabling smaller or less expensive reactor vessels

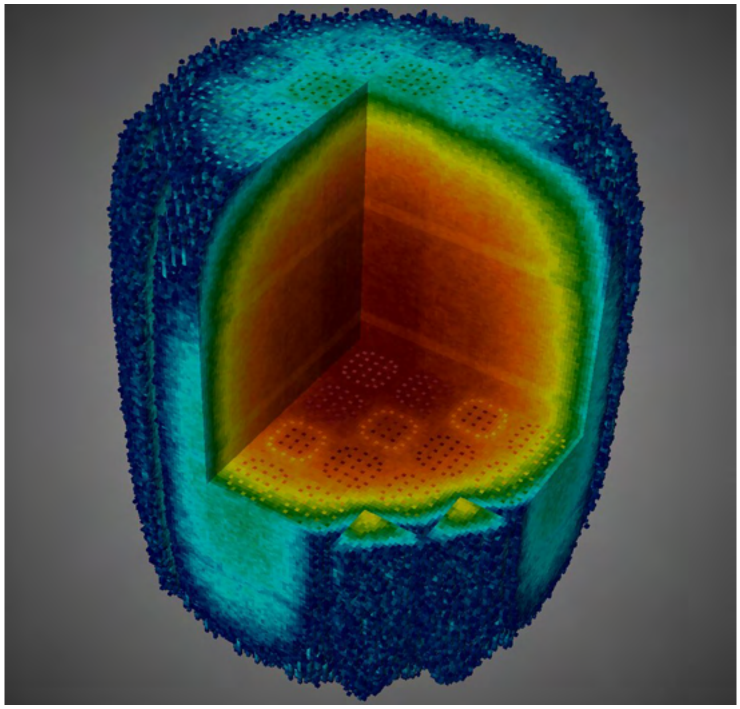
All flavors of advanced reactors also come with trade-offs and technical challenges as well. Establishing that the reactor materials (e.g. metals) will hold up in concentrated salts or liquid metals for the life of the nuclear plant is an obvious one. Another issue to address is fuel supply — many advanced reactors need fuel with a higher enriched uranium content (20% vs 4%). New facilities will need to be built to fabricate this fuel.

Below are short descriptions of the terminology around "small" vs "micro-" reactors, and the major advanced reactor technologies that companies are seriously pursuing.

*Perhaps the biggest change between the Gen II[27] nuclear plants that dominate today and many of the reactor designs proposed is their **size**.*

Reactor Size: Small Modular Reactors and Microreactors

Today, the average nuclear plant makes about 1000 MW of power, enough to supply about a million homes, and comes with a multi-billion dollar price tag. In contrast, most of the advanced reactors that companies are developing (and the US DOE is helping to fund) are either small modular reactors (20–300 MW), or microreactors (less than 10 MW). The terminology makes about as much sense as Starbucks sizes: "small modular reactors" (SMRs) are generally **medium** sized power plants (similar to the size of a coal or natural gas power plant), and "microreactors" are just **small** power plants.



Advanced simulations of fluid flow in a small modular reactor.
(*[Image]* by *[Oakridge Leadership Computing Facility]*)

There are several market-driven reasons to go small, but SAFETY is closely related to nuclear plant SIZE. Larger nuclear plants have more radioactive material in the reactor core at any time. A larger plant also means more heat needs to be removed in an emergency. Instead, several companies plan to dig a hole lined with concrete where the (small) nuclear reactor will sit — if something REALLY went wrong or melted despite all the safety systems in place, it would be contained in the concrete vault. By limiting the “worst case” scenario, reactor developers also make it easier to prove to the US NRC and other regulatory agencies that their reactor designs are sufficiently safe.

Gas-Cooled Reactors

Two major types of gas-cooled reactors are in development — fast reactors and very high temperature reactors (VHTRs). Gas-cooled fast reactors (GFRs) are more compact because they don’t have a moderator, and like other fast reactors produce less radioactive waste. Very high temperature reactors use graphite as a moderator, and can (ideally) heat the gas to over 1000 deg C. Most of today’s gas-cooled reactors use helium as the coolant — helium is easier to drive turbines with!

Historically, early gas-cooled reactors like the UK's Magnox and the UNGG in France used carbon dioxide as the coolant and graphite as the moderator, and could run on unenriched uranium. The US built two early helium-cooled reactors, Peach Bottom and Fort St. Vrain.

Advantages: Gas-cooled reactors can reach very high outlet temperatures, higher than other advanced reactors. This increases the efficiency of power production, or allows the plant to provide high temperature heat for other industrial processes. Gases also do not dissolve contaminants or absorb neutrons. Because of this, gas-cooled reactors can also be fast reactors. While fast reactors use neutrons less efficiently and thus need fuel with a higher U-235 content, they use less uranium overall (which reduces waste). The higher enrichment costs are balanced by better power plant efficiencies at high temperature.

Challenges: Gases are worse at transferring heat than liquids, so these reactors need a larger volume of gas to carry the same amount of heat. Operating the reactor at high temperatures (over 800 degC) or very high temperatures (over 1000deg C) creates materials challenges. Previous examples are the German prototype AVR (1967–1988), and the two US units that were technically successful but required more maintenance than expected (as first-of-a-kind units) and proved uneconomical.

Status of this technology today? Two high-temperature gas cooled nuclear reactors are in advanced testing in China.

Companies to Watch: X-Energy, General Atomics, USNC, Urenco, and Radiant

Sodium-Cooled Fast Reactors

The world has more experience with sodium-cooled fast reactors than other advanced reactor technologies — twenty or so experimental and demonstration reactors have been built, and sodium-cooled reactors have operated for more than five decades. This means a lot when a utility or country is weighing whether to invest in a new, expensive technology (all advanced reactors will be expensive at first!) with a new set of safety considerations.

Advantages: Sodium or other liquid metals can remove the same amount of heat as water while taking up less space, allowing reactors to be smaller and cheaper. Unlike water, sodium doesn't need to be pressurized to stay liquid at high temperatures (again, smaller cheaper reactors). Sodium also has other chemical properties that make it a good coolant.[28]

Sodium hardly moderates neutrons at all, so these designs are typically fast (not thermal) reactors. Without a moderator, the reactor design is less complex and can be smaller. Fast reactors can also destroy some fission fragments that have particularly long half-lives (americium, curium), so they generate nuclear waste that has lower long-term radioactivity.

Challenges: Sodium metal reacts with both air and water, burning when exposed to either. Sodium also has a reputation for being very… leaky. Because they are fast reactors, uranium enrichment of 20% or more is generally needed to sustain fission reactions. Fast reactors also generally require more fuel to be present per unit of energy generated, because fast neutrons are less likely to cause fission.

The Argonne-West site in Idaho, a primary site for testing and demonstrating advanced nuclear reactor components and designs. The silver dome in the photo is Experimental Breeder Reactor II. (Image by Argonne National Laboratory)

Many experimental sodium-cooled fast reactors were built between 1950 and 1990, including four in the US. A prototype called Phenix was built in France, followed by the Superphenix. The Phenix program's poor operating performance cooled interest in these reactors.

Status of this technology today? Two sodium-cooled fast reactors are currently operating in Russia, the BN-600 and the BN-800. China is building a sodium-cooled fast breeder reactor that is expected to be commissioned in 2023, and a second is also underway. India is also building a Prototype Fast Breeder Reactor (500 MWe) based on learnings from their test reactor program, though there have been many delays.

Companies to Watch: TerraPower (Natrium), Advanced Reactor Concepts (ARC) Energy, Oklo, Space Nukes

Breeder Reactors

In the 1960s and 70s, no one knew how much uranium the world had, and there were concerns that it would run out. This led to great interest in **breeder reactors** designed to make plutonium-239 out of uranium-238 (the less useful isotope). Since plutonium-239 can also be used as a reactor fuel, this would address the problem of uranium scarcity — plutonium could be used instead. Technically, a breeder reactor is any nuclear reactor that produces more "fissile material" (stuff that can undergo fission) than it consumes.

The US, France, and the USSR did a ton of research on breeder reactor technology in the 1970s, and each built test reactors. Then in the 1980s, the price of uranium fell, and processing the fuel from the breeder reactors turned out to be more expensive than buying enriched uranium. Proliferation concerns, poor track records, and a terrorist attack on the Superphenix, a large prototype breeder reactor in France (which did not have nuclear fuel in it at the time), also helped kill interest.

Advantages: The advantages of breeder designs are that they hugely increase the amount of energy extracted from uranium and **significantly decrease the nuclear waste generated**. Less than 1% of the fuel's energy is used in a normal once-through light water reactor fuel cycle. Breeder reactors can increase this to 60% or more, cutting the amount of uranium needed and waste produced by almost two orders of magnitude.

Challenges: Expensive; generally involves isolating plutonium-239, creating proliferation concerns.

The Superphenix, a large (1200 MW) prototype fast breeder reactor (Image by I, Yann)

Status of this technology today? Two sodium-cooled fast breeder reactors are operational in Russia and one is under construction in China — see below. India is building a new breeder reactor design that uses thorium as fuel (and has been for over a decade).

Molten Salt Reactors
These reactors use a combination of fluoride, chloride and nitrate salts as the coolant. Molten salt reactor technology isn't exactly new either; Oak Ridge was researching this as early as the 1960s. However, given the complexity of molten salt chemistry, molten salt reactor technology has arguably benefitted the most from other advancements in technology.

In some designs, the fuel is mixed in with the molten salt. Other nuclear reactor designs use molten salt as the coolant only (e.g. Kairos Power). Most of the molten salt designs are thermal reactors by necessity because lithium and beryllium in the "more standard" molten salts moderate neutrons. Moltex's fast reactor concept uses other salts to avoid this.

Advantages: Like sodium-cooled reactors, molten salt reactors operate at or near atmospheric pressure, reducing containment needs and explosion risk. Molten salts also have high volumetric heat capacities — they can store more heat in a small amount of liquid, allowing the reactor to be smaller. The high boiling point of molten salts ensure that the coolant will stay liquid, even if temperatures rise. The ability to operate at high temperatures lets them produce electricity more efficiently, and opens up other applications that require high temperatures like hydrogen production.

Challenges: Molten salt chemistry is very complicated — the chemical composition of the salt changes with reactor radiation. Many molten salts are corrosive and require the equipment to be made of particular metals. Compared to sodium-cooled reactors, there is less operating data available for molten-salt cooled reactors.

Status of this technology today? Only experimental reactors to date; still in development.

Companies to watch: Southern Company, Kairos, Terrestrial Energy, TerraPower (Molten Chloride Fast Reactor), Moltex, Flibe Energy, HolosGen

Nuclear Fuel

There are five types of fuel that nuclear power plants could conceivably use. Three are based on uranium. The other two are thorium and plutonium. All commercial nuclear plants use uranium-235 as the fuel, although plutonium and thorium could be used too.

Uranium Extraction

The fuel used in most of today's nuclear reactors is made from naturally occurring uranium oxide (U308), which is mined on almost every continent. Kazakhstan (42%), Canada (13%) and Australia (12%) produce the largest share of the world's uranium, but many other nations also produce significant amounts.

Less than 15% of the uranium the US uses as fuel is mined domestically. Current mining activities are mostly located in Wyoming and Utah, with many facilities on standby. Wyoming, New Mexico, and Colorado have the largest uranium ore reserves. Uranium is mined with conventional underground or open pit methods or by in-situ leach mining (description). In in-situ leaching processes, carbonated water is shot into underground deposits and piped up to the surface.

Naturally occurring uranium is a mixture of two isotopes, uranium-238 (~99.3%) and uranium-235 (~0.7%). Uranium-235 is the one that is important for nuclear fuel and weapons. Most nuclear power plants use fuel that is about 4% U-235, or "standard assay" low enriched uranium.

Enriching uranium (concentrating the uranium-235) is not a simple process. The chunks of rock from the mines have to be separated and purified to get pure uranium oxide (U3O8), or "yellowcake." This process is called uranium "milling." As of 2020 there was only one operational uranium milling facility in the US, the White Mesa Mill in Utah.

White Mesa uranium mill in Blanding, Utah, by NRC (under CC)

After milling, the solid U308 (yellowcake) then has to be converted into a gas, uranium hexafloride (UF6) to separate the two uranium isotopes. The UF6 gas is spun at very high speeds in a specialized gas centrifuge; because the gas molecules with uranium-238 as the "U" are heavier, they migrate outwards towards the sides. The uranium-235 rich gas is collected from the middle. The enriched rich gas is then sent to another centrifuge and the process is repeated many times until the product contains about 4% uranium-235. By looping the gas through the same equipment many more times, it's possible to enrich the uranium gas to weapons-grade (greater than 90% uranium-235).

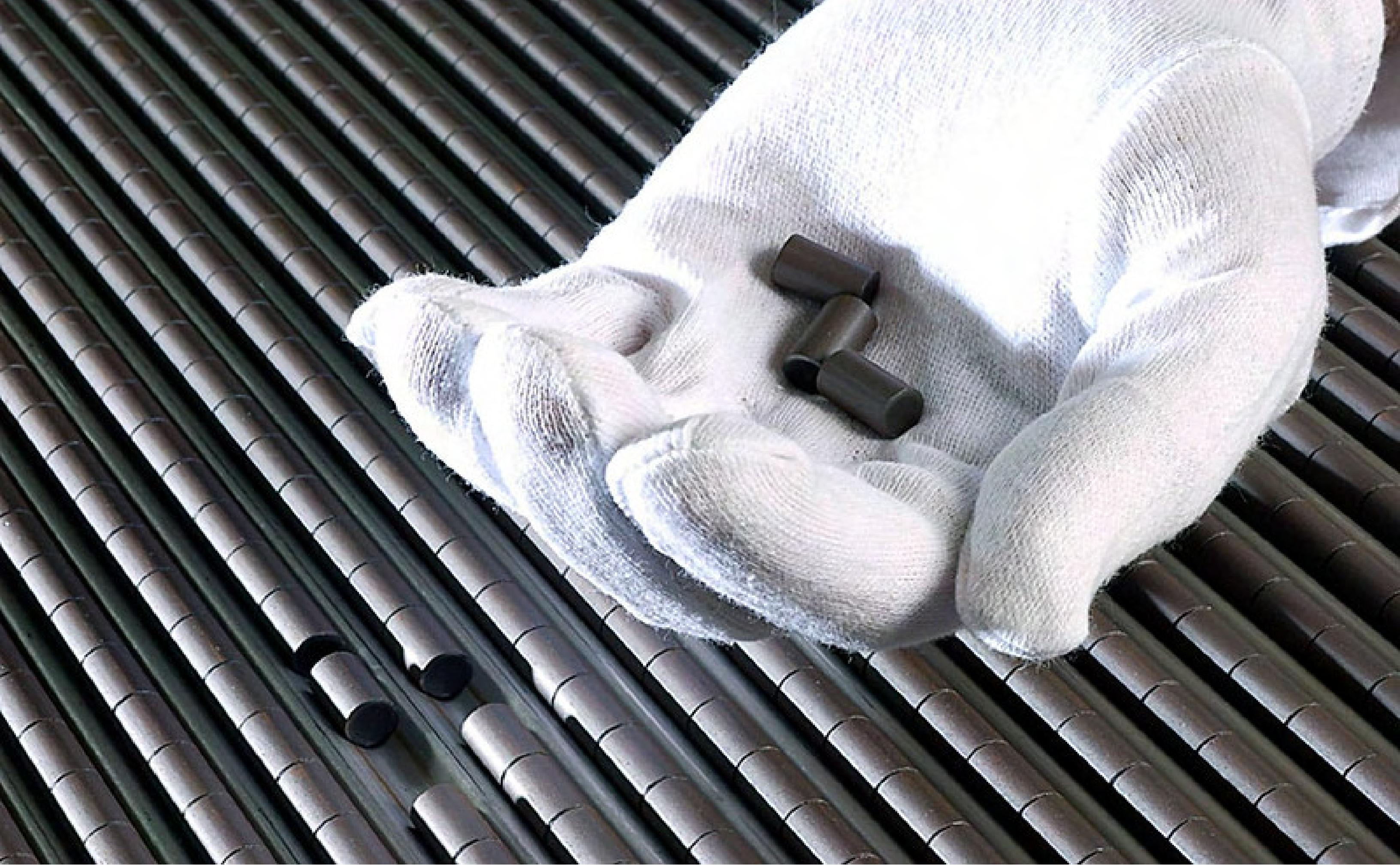
This is part of why nuclear power is linked to proliferation concerns — an enrichment facility that can make 4% uranium-235 can (in theory) make enriched uranium with higher U-235 contents as well. However, because the equipment needed to enrich uranium is complex and expensive, there are relatively few facilities with these capabilities. Urenco USA operates the only enrichment facility in the US (in New Mexico), and supplies about a third of the enriched uranium needed to run US nuclear reactors. (Urenco is a British company that operates enrichment facilities in the UK, USA, Netherlands and France.) Other nuclear fuel companies with uranium enrichment facilities are based in Russia (45%), France (12.7%), and China (9.8%), and there are smaller facilities in other countries.

After enrichment, the uranium goes through more chemical reactions to turn it back to uranium oxide, a black powder with a higher U-235 content (4-5%).

How concerned should I be about proliferation? I am much more concerned about the threat of cyberattack on our electric grid, driving after 11pm on a Friday night, and murder hornets than I am about the weaponization of nuclear power plant fuel. That said, uranium mining processes produce chemical waste and radiation that needs to be handled and disposed of very carefully. The US NRC manages and regulates these processes, described here.

Standard Nuclear Fuel (for Light Water Reactors)

This "standard assay low-enriched uranium" or SALEU is fabricated into fuel pellets. Fresh nuclear fuel isn't very radioactive — you can hold it in your (gloved) hand.[31] These pellets are loaded into long metal rods, which are sealed and bundled together into a "fuel assembly." (For more on how nuclear fuel is made, see this overview from the World Nuclear Association.)



"Nuclear fuel pellets" by NRCgov is licensed under CC BY 2.0

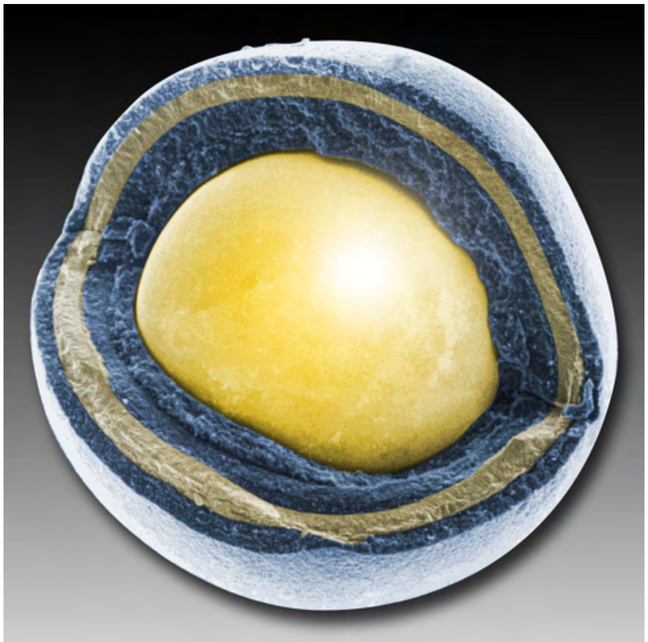
During operation, neutrons strike the U-235 within the fuel rods. If they hit with the right energy, a nuclear fission reaction occurs and U-235 splits into smaller atoms (+ more neutrons, radiation, and energy). These atoms and neutrons continue to fission into smaller atoms through several chain reactions, until they become a stable atom like lead (Pb-207). (For those curious, more physics here.)

At the end of a fuel pellet's life, it still contains about 1% uranium-235 and 95% uranium-238. The rest are heavy isotopes (plutonium, americium, neptunium, and curium) and other fission products. Of these, **Cesium-137** and **Strontium-90** are the most dangerous in terms of their long-term effects. Their half-lives are about 30 years — long enough to stick around, but short enough to pack a radiative punch. Iodine-131 with its 8-day half-life is worse in the short-term, particularly due to its volatility. Because of these, spent nuclear fuel is considered "high-level radioactive waste" and must be shielded (with water, metal or concrete) to prevent radiation exposure.

High Assay Low-Enrichment Uranium (HALEU) fuel contains up to 20% U-235, a higher fraction of U-235 than current fuels contain. HALEU fuel is needed for advanced fast reactors (such as Moltex, Oklo, and TerraPower's Natrium reactor) because the likelihood that a fast neutron will create a fission reaction is lower than for thermal neutrons.

HALEU's availability in the US is currently very limited - it has to come from the DOE's stockpile of weapons-grade uranium, or from the spent fuel of naval reactors. (We could also import it from the Russians, who are building out HALEU production capacity, if the powers-that-be are okay with that.) To begin addressing this, the US DOE has contracted Centrus Energy to build a domestic HALEU production facility, which is scheduled to come online in 2022.

TRISO is a specific type of HALEU fuel that is notably accident-tolerant and safe. (TRISO stands for TRi-structural ISOtropic particle fuel.) TRISO particles are engineered to not melt in a reactor. Each TRISO particle is made up of a uranium kernel, surrounded by three layers of carbon- and ceramic-based materials (think of a gobstopper). Because these outer layers are super heat resistant and cannot melt, radioactive fission products can't get out of the gobstopper even if there is an accident and cooling is lost (like what happened at the Fukushima plant in 2011). Each particle is effectively it's own containment structure.



Several advanced reactors will use TRISO fuel, which has a more enriched (20%) uranium-235 core surrounded by a carbide for containment. (Image by INL)

The individual gobstoppers like the one pictured above are incredibly small- about the size of a poppy seed. They can be fabricated into cylindrical pellets or baseball-sized spheres called "pebbles" for use in either high temperature gas or molten salt-cooled reactors. Both Kairos Power and X-Energy plan to use TRISO fuel in their advanced reactors. There are currently two facilities with the ability to fabricate TRISO fuel: X-Energy w/ GE Hitachi in Wilmington, NC; and BWXT at their site in Lynchburg, VA.

Thorium

Thorium cycle nuclear reactors have been proposed many times but have seen little practical use. For brevity I'm omitting them here (I'm sure I'll get a few emails about this.)

Nuclear Waste

Nuclear plants produce three distinct classes of radioactive waste:

1. High-level waste (3% by volume), almost entirely used uranium fuel (not glowing green sludge!)
2. Intermediate level waste (7%) — typically filters, steel, and reactor components.
3. Low-level waste (90%), which consists of lightly contaminated items like tools and work clothing

High-Level Waste

Most high-level nuclear waste is the used or "spent" nuclear fuel assemblies. After about 5 years of use, the spent fuel assemblies are removed from the reactor and stored in a spent fuel pool. The water in the spent fuel pool both cools the assemblies and provides shielding, so you can walk around the pool safely. (***What would happen if you swam in it?***) At this point, the fuel assemblies still produce some heat and radiation, which falls off exponentially with time. The fuel assemblies typically chill in the pool for at least ten years — currently, most of the US's spent fuel is stored in pools at the power plant.

While a few countries (notably Finland and Sweden) have plans and identified sites for long-term waste storage facilities, the US has not. For roughly the first 40 years that the US was creating nuclear waste (from the Manhattan project through the Cold War Era), there was no long-term plan for radioactive waste disposal. In the early 1980s, the US passed a law (The Nuclear Waste Policy Act) requiring the federal government to come up with a long-term solution. The government decided to focus efforts on assessing Yucca Mountain in Nevada as a geological repository (underground storage facility), and spent more than $10B studying the site and creating a proposal. However, by the time this proposal was submitted (over 20 years later in 2008), politics had changed and this proposal was effectively scuttled.

With Yucca Mountain out of the picture, the US's current storage plans rely on above ground "cask pads" or **independent spent fuel storage installations (ISFSIs)**. These are licensed for at least 20–40 years, and are usually adjacent to the nuclear power plant (NRC map of ISFSIs). The spent fuel assemblies can be placed in **dry casksu** once enough of the decay heat has been removed. These containers typically have a sealed metal cylinder to contain the spent fuel enclosed within a metal or concrete outer shell to provide radiation shielding, and are located all over the US. Dry casking is an expensive process, which encourages utilities to store spent fuel and other high- or intermediate-level waste in the pool if there is space.

Inspecting a dry cask storage facility (Image Credit: US NRC)

Low-Level Waste

In addition to nuclear reactor operations, low-level waste is produced from medical, academic, and other uses of radioactive materials. It is typically stored on site until its radioactivity has decayed and it can be disposed of as trash, or until there is a large enough shipment to a low level waste disposal facility. After processing, it can be permanently disposed of in standard facilities. (Much less exciting.)

How much nuclear waste is generated?

According to the World Nuclear Association, the waste from a reactor supplying a person's electricity needs for a year would be about the size of a brick. Only a small fraction, about 5 grams of that brick would be high-level waste. Per the Nuclear Energy Institute, the entire amount of nuclear waste ever created in the United States would fill one football field, 10 yards deep (from the first nuclear power plant in the 1950s through 2020). Looking ahead, the U.S. Nuclear Waste Technical Review Board estimates the quantity of spent fuel stored in 2048 will be double the 2012 volume. Substantial, but not orders of magnitude greater than what is managed today.

By comparison, coal plants in the US generated 130 million tons of solid waste (coal ash) in 2014 alone, most of which must be stored somewhere (a small fraction can be used in cement) . Coal plants also release more radiation to the environment — "ounce for ounce, coal ash released from a power plant delivers more radiation than nuclear waste shielded via water or dry cask storage." (Scientific American)

How do other countries handle nuclear waste? All are working through similar challenges. High-level waste disposal is always regulated and coordinated by the national government. Several countries have approved plans for long-term underground storage facilities, including France who plans to open theirs in 2025. Sweden is similarly planning to open a long-term facility in 2023. France, the UK, Russia, and Japan reprocess nuclear fuel, which reduces its volume by about 75%.

There has been significant research (and some work to commercialize) "fast reactor" concepts that could use high-level waste as fuel and therefore recycle it. Expect more on this and other advanced reactor technologies to come.

The [Saint-Laurent Nuclear Power Plant] in France, by [Nitot] under CC

My Personal View on Nuclear Waste: *I recognize that long-term storage of high level nuclear waste is currently an unanswered question. The (albeit small amounts of) fission products we create in nuclear reactors will stick around for centuries, even if we come up with a plan for burying them underground.*

I also respect that the nuclear industry reports and helps manage the waste it produces. I appreciate the culture of peer reviews, sharing best practices, and collaborating on technology development both within the US and with the broader international community. This certainly isn't true of all industries.

In my view, nuclear fission as an important bridge to power us through at least the next 30–50 years, until we can find a way to meet our energy needs with other sources (fast reactors, fusion, renewables and a futuristic electric grid?) Compared to other energy sources, nuclear power is cleaner and produces a fairly small volume of waste. Doubling or even tripling the volume of nuclear waste over the next few decades is relatively minor compared to other environmental challenges we face.

"NRC Commissioner visits Vogtle, GA Construction SIte" by *NRCgov*

Policy and Regulatory Considerations

Nothing screams EXCITING like regulations and licensing processes, I know. That said, getting approval from the US Nuclear Regulatory Commission (NRC), the Canadian Nuclear Safety Commission (CNSC), or another nation's regulatory body is a huge and very exciting milestone for aspiring advanced reactor startups and other nuclear technology companies.

US Regulatory Process

Companies wanting to build new nuclear plants in the US currently have two options for licensing. The first option is the O-G two-step licensing process, or "Part 50" license. Under Part 50, if I wanted to build a new nuclear power plant, I would first apply to the NRC for a construction permit. I would separately apply for an operating license once the power plant is built. Before 1989, this was the only option. A big challenge with the Part 50 licensing process is predictability — a huge amount of money and resources could be spent building a nuclear plant that never receives a license to operate. (This happened in the 1980s with the Shoreham Nuclear Power Plant outside of NYC, a situation that also highlighted the importance of community engagement.)

To make the licensing process more predictable, streamlined, and financially backable, the NRC created a second option, the Combined License (COL) or "Part 52" license in 1989. This process combines the application for a construction permit and an operating license, allowing the company and the NRC to resolve potential regulatory issues before construction begins. The challenge (particularly for new nuclear designs) is that once the license is issued and construction begins, the ability to make changes or adjust if needed is limited.

As a "bonus" option, a nuclear reactor company can apply for Design Certification before choosing a site and submitting a combined license application. As part of this very intense review process, the company provides an essentially complete nuclear plant design. An advantage is that any issues resolved during the design certification can't be reopened during the Part 52 application review, giving the applicant more certainty for a specific project.

"NuScale-Upper-One-Third-Mockup"
by Oregon State University under CC

Neither of these options is ideal — both the Part 50 and Part 52 licensing processes are very specific to large, light water reactors (the only type of commercial nuclear plants currently operating in the US). To fix this, Congress passed a law that requires the NRC to modernize the review process for advanced reactors, called NEIMA. This new process is tentatively being called "Part 53", with a final rule to be published by October 2024. In the meantime, nuclear reactor companies have had to find ways to work through the existing options. (One could argue that this has created a first-mover disadvantage.)

No advanced reactors have received Part 50 or 52 licenses yet, although NuScale's light water reactor received NRC design certification approval in August 2020. Micro-reactor company Oklo skipped the design certification and has submitted the first non-light water Part 52 application. (List of submitted Part 52 applications.) The other companies mentioned are in pre-application discussions with the NRC. Expect to see press releases when these NRC applications are finally filed and accepted and much more fanfare when the first company (which will likely be Oklo) receives a COL.[35]

International Regulatory Processes

Each country with operational nuclear plants has its own regulatory agency. Most of the startups relevant to us focus on the US, Canadian, and UK regulatory processes, as these are seen as the "gold standard.". These three regulatory agencies are the most likely to either support construction of an advanced nuclear reactor domestically, or to be seen as a strong enough proof point to license a design in certain other countries.

There are a few differences in how the regulatory processes are run. The Canadian Nuclear Safety Commission licensing process permits the nuclear reactor at a specific site. For their Chalk River demonstration in Ontario, USNC and Ontario Power Generation have taken the option to complete a Vendor Design Review to get feedback from the CNSC before submitting an application. X-energy also began a pre-licensing Vendor Design Review with the CNSC last year.

In the United Kingdom, the Office of Nuclear Regulation (ONR) is actually an independent public organization that regulates 36 nuclear power plant sites. In the UK, the approval process for a new power plant design is first a Generic Design Assessment (GDA), where the license application is based on the design of the reactor. (This isn't about hitting an approval level but the safety of every individual component.) Once the generic approval is granted, the company applies for a site specific approval for a specific site. The local site approval process is much quicker, and if the same design is built again and again just the local site assessment is required.

International Cooperation
The US requires "Section 123" agreements for nuclear cooperation with other countries. (CRS Primer). The US has signed agreements with several nations since 2010 (here is a list). There are also about 30 "Emerging Nuclear Energy Countries" that are considering, planning or starting nuclear power programmes.

Conclusion

At the end of the day, we don't get to decide whether someone half-way around the world builds a new nuclear plant, recycles used fuel, or buries it underground. We can decide as a nation to participate in developing safe, efficient, and responsible nuclear technologies and to have a seat at the table.

Notes

[1] The most up-to-date science around climate change is published HERE

[2] Top 5 bad things that will happen: 1) more wildfires; 2) more severe storms; 3) rising sea levels, affecting millions along the coasts; 4) dead coral reefs; 5) [Pick one more interesting one]

[3] A recent IPCC report found that to limit global temperature increases to 2°C, global greenhouse gas (GHG) emissions will by 2030 need to decline 10% to 30% below 2010 levels and between 2065 and 2080 fall to net negative. This great article discusses the ultimate carbon footprint of solar, wind and nuclear considering a full "life-cycle assessment" (LCA), which takes into account activities like constructing the power plant and manufacturing fuel in the case of nuclear.

[4] A terawatt-hour is a massive unit of energy, equal to providing one trillion watts of power for a full hour. Just one terawatt-hour is equal to the energy released by 57 atomic bombs.

[5] The rest of the electricity we use is mostly generated by hydro (15.8%, 4,330 TWh), nuclear power plants (10.2%, 2,660 TWh), wind (4.8%, 1,270 TWh), solar (2.1%, 554 TWh).

[6] From Carbon Brief's coal map. This assumes an average coal plant size of 279MW, which is fairly small.

[7] Replacing the electricity we currently generate from coal (10,200 TWh) would take about 1200 of today's nuclear power plants, 4 times as many as are currently operating.

[8] OECD stands for the Organization for Economic Cooperation and Development

[9] (Forbes) Why? A combination of factors including electrifying the transportation sector, increased domestic manufacturing, increased need for air conditioning, and increased population growth (the US adds 3 million each year on average)

[10] Comment on where these estimates come from

[11] One example is Marc Jacobson's group from Stanford. Their high-level assessment has prompted spirited back-and-forth discussions from the academic community.

[12] One fuel pellet weighs about 10 grams, and contains the same amount of energy as 17,000 scf of natural gas (5081 kilowatt-hours, kWh). The average US household used 10,649 kWh of electricity in 2019. That comes out to roughly 2 nuclear fuel pellets needed per household per year!

[13] The reactor manufacturer Rosatom is owned by the Russian state

[14] Per the World Nuclear Association, the preliminary plans outlined in May 2020 by S. Korea's government include increasing electricity generation from renewables to 40% by 2034, and reducing nuclear from 19% to 10%. The provisional plan assumes that power demand will grow at an average of 1% a year to 2034, which would require aggressive conservation measures.

[15] Examples of recent overnight construction costs: the Czech government is anticipating ~$7B for a 1200 MW unit (which can't go out for bidding until the EU approves)

[16] What's in the agreement: "over the next 18 months, the US and Poland will work together on a report delivering a design for implementing Poland's nuclear power program, as well as potential financing arrangements." (Source) Poland currently does not have any nuclear plants, and generates 70% of its power from coal. With stricter clean energy requirements in the EU on the horizon, nuclear power makes sense for several Eastern European countries with limited solar and wind resources.

[17] What's in the agreement: it allows the US and Romania to collaborate on building two new reactors at the Cernavoda nuclear power plant and refurbishing the oldest. Romania currently has two operating nuclear power reactors (Cernavoda 1 and 2) and plans to add two more at the same site. The agreement also calls for cooperation between the US and Romania in regulation, research & development, staff training, and the development of small modular reactors in Romania. (World Nuclear News) The Romanian state-owned nuclear power producer Nuclearelectrica had previously been in talks with China General Nuclear (CGN). (Reuters)

[18] The initial awards were $80 million to each company, with additional support of roughly $1 billion to each project as a 50% cost-share match. X-Energy and DOE officially entered a cooperative agreement to demonstrate X-Energy's high-temperature gas-cooled reactor at a site in Washington state in March 2021, with the DOE covering roughly half of the costs of the $2.5B project. The DOE announced its support for the demonstration of TerraPower's Natrium sodium-cooled fast reactor technology at a coal power plant in Wyoming in June 2021 (also expected to cost roughly $2B.)

[19] The DFC is the development finance institution of the United States federal government - its expansion can be seen as a strategy to counteract / provide an alternative to China's Belt and Road Initiative, which has built an incredible amount of infrastructure in developing nations. The U.S. International this week that it has changed its policy to fund nuclear power projects. (Source)

[20] Source: Rolls-Royce SMR Brochure, July 2017

[21] There were 427 coal power plants in 2015, capable of generating about 280,000 MW of electricity. By 2020, this dropped to less than 300 power plants with a total capacity of 218,000 MW. In some cases, coal power plants are replaced with, or converted to natural gas power plants (38% of coal plants closed from 2011–2019 were converted to or replaced by natural gas).

[22] For those looking to dive into the weeds, a full list of operational and planned nuclear plants around the world is available from the IAEA here

[23] The neutrons released from uranium fission initially have an energy distribution that peaks around 1 to 2 MeV —in the fast neutron range. For context, 1 MeV is equivalent to a speed of 14,000 km/s (31 million mph) — those neutrons are fast!

[24] Historical context: The US Navy drove development of first light water reactors in the 1950s. Nuclear-powered propulsion revolutionized naval warfare, freeing submarines from being limited by fuel (just the need for supplies and the crew's endurance). Today, over 85% of the world's nuclear electricity is generated by reactors whose designs originated from naval use, and all of the US Navy's submarines and aircraft carriers are powered by small light water reactors.

[25] Heavy water reactors also produce some plutonium (can be used to make bombs) and tritium. The proliferation risk of heavy vs light water reactors is complicated.

[26] This short IAEA report on the safety updates made after the Chernobyl accident 10 years after the accident does not inspire confidence. This LiveScience article does a nice job of explaining the cause of the accident, and also how water heating up makes it a better neutron quencher- a feature that graphite doesn't share.

[27] The US is on track to mostly skip building "Gen III" nuclear power plants, which are light water reactors with updated and simplified safety features vs the Gen IIs. The Westinghouse AP1000 units that are under construction at Vogtle, GA will be some of the few Gen III operational plants operating in the US. Outside of the US, the nuclear plants being built by China and Russia are Gen III designs.

[28] Sodium stays liquid over a huge range of temperatures — 98 degC to 883 degC. (Wikipedia) Because of this, even though sodium has a lower heat capacity than water, it can absorb a lot of heat. It's high thermal conductivity also helps prevent local overheating.

[29] To cut down on the amount of enriched uranium needed, the material from the breeder reactors would be processed to remove the extra plutonium. This would be mixed with uranium to make fuel for conventional reactors. A single fast breeder reactor could supply fuel for several light water reactors.

[30] In contrast to molten salt and sodium-cooled reactors, light water reactors typically operate at 75 to 150 times atmospheric pressure so that the water can get hotter before it boils.

[31] Uranium-235 and -238 aren't significantly radioactive (when they aren't getting hit by neutrons) — their half-lives are hundreds of millions of years. However, as a heavy metal uranium is chemically toxic.

[32] This has created serious problems, specifically at the Hanford nuclear weapons production site in Washington state. A multibillion dollar cleanup effort is still underway, as many of the 192 tanks containing liquid waste from weapons production in the 1940s and 1950s were found to be leaking. This is a very sad example of why the entire lifecycle of a facility needs to be considered from the beginning.

[33] The design certification process is exacting and involves a huge amount of engineering work. (NuScale reported spending over $500mm on the design certification process.) The scope and contents of the application are equivalent to the level of detail found in a Final Safety Analysis Report for a currently operating nuclear plant. The design certification process also includes a review during a public meeting and allows public comments to be submitted. A design certification is valid for 15 years.

[34] The existing NRC licensing pathways are very specific to large (~1000 MW) light water reactors. The prescriptive requirements include things like containment building specifications, the number of operators per reactor. I'd expect the operator staffing requirements for microreactors generating 1–20MW to be very different from light-water reactors producing over 200 MW! (Source: Clearpath)

[35] As a microreactor producing only 1.5 MW with the first plant, Oklo has a much easier safety case to make than the larger SMRs. In the event of an accident, there is much less fuel in the reactor, and much less heat to dissipate. Oklo has also been very thoughtful in engaging with the NRC from the get-go.