On a December afternoon in Chicago during the middle of World War II, scientists cracked open the nucleus at the center of the uranium atom and turned nuclear mass into energy over and over again. They did this by creating for the first time a chain reaction inside a new engineering marvel: the nuclear reactor. Since then, the ability to mine great amounts of energy from uranium nuclei has led some to bill nuclear power as a plentiful utopian source of electricity.

A modern nuclear reactor generates enough electricity from one kilogram of fuel to power an average American household for nearly 34 years.
But rather than dominate the global electricity market, nuclear power has declined from an all-time high of 18% in 1996 to 11% today. And it's expected to drop further in the coming decades. What happened to the great promise of this technology? It turns out nuclear power faces many hurdles, including high construction costs and public opposition. And behind these problems lie a series of unique engineering challenges.

Nuclear power relies on the fission of uranium nuclei and a controlled chain reaction that reproduces this splitting in many more nuclei. The atomic nucleus is densely packed with protons and neutrons bound by a powerful nuclear force. Most uranium atoms have a total of 238 protons and neutrons, but roughly one in every 140 lacks three neutrons, and this lighter isotope is less tightly bound. Compared to its more abundant cousin, a strike by a neutron easily splits the U-235 nuclei into lighter, radioactive elements called fission products, in addition to two to three neutrons, gamma rays, and a few neutrinos.

During fission, some nuclear mass transforms into energy. A fraction of the newfound energy powers the fast-moving neutrons, and if some of them strike uranium nuclei, fission results in a second larger generation of neutrons. If this second generation of neutrons strike more uranium nuclei, more fission results in an even larger third generation, and so on. But inside a nuclear reactor, this spiralling chain reaction is tamed using control rods made of elements that capture excess neutrons and keep their number in check. With a controlled chain reaction, a reactor draws power steadily and stably for years.

The neutron-led chain reaction is a potent process driving nuclear power, but there's a catch that can result in unique demands on the production of its fuel. It turns out, most of the neutrons emitted from fission have too much kinetic energy to be captured by uranium nuclei. The fission rate is too low and the chain reaction fizzles out. The first nuclear reactor built in Chicago used graphite as a moderator to scatter and slow down neutrons just enough to increase their capture by uranium and raise the rate of fission. Modern reactors commonly use purified water as a moderator, but the scattered neutrons are still a little too fast. To compensate and keep up the chain reaction, the concentration of U-235 is enriched to four to seven times its natural abundance. Today, enrichment is often done by passing a gaseous uranium compound through centrifuges to separate lighter U-235 from heavier U-238. But the same process can be continued to highly enrich U-235 up to 130 times its natural abundance and create an explosive chain reaction in a bomb. Methods like centrifuge processing must be carefully regulated to limit the spread of bomb-grade fuel. Remember, only a fraction of the released fission energy goes into speeding up neutrons.

Most of the nuclear power goes into the kinetic energy of the fission products. Those are captured inside the reactor as heat by a coolant, usually purified water. This heat is eventually used to drive an electric turbine generator by steam just outside the reactor. Water flow is critical not only to create electricity, but also to guard against the most dreaded type of reactor accident, the meltdown. If water flow stops because a pipe carrying it breaks, or the pumps that push it fail, the uranium heats up very quickly and melts. During a nuclear meltdown, radioactive vapors escape into the reactor, and if the reactor fails to hold them, a steel and concrete containment building is the last line of defense. But if the radioactive gas pressure is too high, containment fails and the gasses escape into the air, spreading as far and wide as the wind blows. The radioactive fission products in these vapors eventually decay into stable elements. While some decay in a few seconds, others take hundreds of thousands of years.

The greatest challenge for a nuclear reactor is to safely contain these products and keep them from harming humans or the environment. Containment doesn't stop mattering once the fuel is used up. In fact, it becomes an even greater storage problem. Every one to two years, some spent fuel is removed from reactors and stored in pools of water that cool the waste and block its radioactive emissions. The irradiated fuel is a mix of uranium that failed to fission, fission products, and plutonium, a radioactive material not found in nature. This mix must be isolated from the environment until it has all safely decayed. Many countries propose deep time storage in tunnels drilled far underground, but none have been built, and there's great uncertainty about their long-term security. How can a nation that has existed for only a few hundred years plan to guard plutonium through its radioactive half-life of 24,000 years?

Today, many nuclear power plants sit on their waste, instead, storing them indefinitely on site. Apart from radioactivity, there's an even greater danger with spent fuel. Plutonium can sustain a chain reaction and can be mined from the waste to make bombs. Storing spent fuel is thus not only a safety risk for the environment, but also a security risk for nations. Who should be the watchmen to guard it?

Visionary scientists from the early years of the nuclear age pioneered how to reliably tap the tremendous amount of energy inside an atom - as an explosive bomb and as a controlled power source with incredible potential. But their successors have learned humbling insights about the technology's not-so-utopian industrial limits. Mining the subatomic realm makes for complex, expensive, and risky engineering.

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