Small Modular Reactors

A Window on Nuclear Energy

An Energy Technology Distillate
from the Andlinger Center for Energy and the Environment at Princeton University

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Biographical sketches of contributors and their disclosures are available at http://acee.princeton.edu/distillates.

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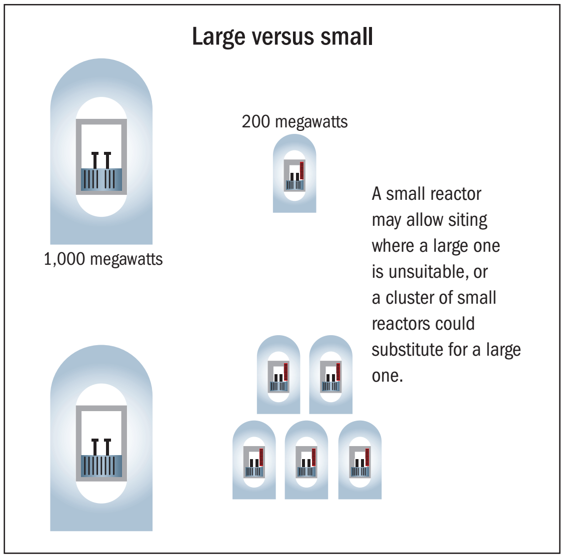
Article 1: Introduction

The future of nuclear power over the next few decades is murky. In the United States and other industrialized countries, a looming question is what will happen when the current nuclear power plants are retired. Of the 99 currently functioning U.S. nuclear power plants, all but four have been operating for a quarter century or more; the nuclear plants of France and Japan are only about a decade younger. Will these be replaced by new nuclear plants, or have new nuclear plants become too costly in these countries? Could the cost barrier be overcome by a new generation of nuclear plants? In China and some other industrializing countries, a central question is how much nuclear power the country will build. Today, nuclear power provides about 10 percent of the world's commercial electricity. This percentage has been falling; its historic maximum of 17.6 percent was in 1996. Some scenarios for the future mix of energy sources show a continuation of the current steady decline of global nuclear power, and some show an expansion, usually driven by rapid uptake in the developing world.

Two scenarios where nuclear power continues to grow, but that nonetheless are very different from each other, are presented in the International Energy Agency's *World Energy Outlook 2014*. The "Current Policies" scenario projects that by 2040 global production of nuclear electricity will have risen by 60 percent relative to 2012, but nuclear power's share of total electricity will have fallen to 9 percent. By contrast, the "450 Scenario" shows in 2040 an expansion in production by 160 percent and a growth of market share to 18 percent, driven by a seven-fold expansion of nuclear power, relative to 2012, in the developing world. As the appearance of "450" in its name indicates, the latter scenario involves a decrease in carbon dioxide emissions with the aim of stabilizing the concentration of carbon dioxide in the atmosphere at 450 parts per million in 2100, only 50 parts per million higher than today. Global carbon dioxide emissions in this low-carbon scenario fall from 32 billion tons in 2012 to 19 billion tons by 2040, whereas emissions rise to 46 billion tons in 2040 in the "Current Policies" scenario. An increasing role for nuclear power often appears in low-carbon scenarios, because nuclear fission produces no carbon dioxide, and fossil fuel emissions associated with nuclear power are limited to those associated with reactor construction and auxiliary functions like mining and enriching uranium. However, some low-carbon scenarios achieve their target while phasing out nuclear power, relying on other low-carbon energy strategies – notably, renewable energy, fossil fuel use without carbon dioxide emissions ("carbon dioxide capture and storage"), and energy demand reduction.

Alongside these questions about quantity and share of nuclear electricity are questions about reactor size and type. Two reactor types—the pressurized- and boiling-water reactors—have been the primary choice for the current global nuclear power fleet, constituting over 80 percent of all operating reactors. Their typical power capacity (the rate at which they can produce electricity) is approximately 1,000 megawatts, which is also roughly the size of most modern coal power plants, and global capacity is equivalent to 350 of these plants. Both of the dominant types are called "light-water reactors," using ordinary (light) water for removing the heat produced in the reactor and uranium for fuel. Alternatives have long been considered and the many contenders come in varied types and sizes. Until recently, the discussion has been largely about alternatives to the light-water reactor that keep the size at approximately 1,000 megawatts. More recently, the debate over the future of nuclear power has included greater attention to reactor size—specifically whether reactors with a substantially smaller power output are a better choice. This newer debate about size is the subject of this Energy Technology Distillate.


Large versus small

A small reactor may allow siting where a large one is unsuitable, or a cluster of small reactors could substitute for a large one.

Figure 1.1: Two possible deployments of small modular reactors.

Generally, for a reactor to qualify to be called “small,” its capacity must be less than 300 megawatts, that is less than one-third the capacity of the reactors that are common today. Two quite different deployments are being considered: 1) as single reactors in locations where a large reactor is unsuitable and 2) as groups, where several small reactors are intended as an alternative to one large one (see Figure 1.1).

The one-at-a-time deployment strategy could be credible for a country or region with limited total electricity capacity, where a single 1,000-megawatt plant would represent too large a fraction of total national or regional capacity and create systemic risk. A rule of thumb is that, to enhance the stability of an electrical grid, the capacity of no single power plant should be larger than 10 percent of the grid’s total capacity. Over 150 countries have a national installed electricity capacity of less than 10,000 megawatts, which would nominally lead them to avoid having any 1,000-megawatt reactors. Moreover, grids are often smaller than country-wide. Of course, a country will be less cautious about building a large reactor if it takes into account its expectations for growth of total domestic capacity and the option of a regional grid that includes several countries. For example, the West African Power Pool involves 14 countries in the region that have come together to establish a regional grid so as to be able to trade electricity. Although none of the individual countries have installed capacities in excess of 6,000 megawatts, with most having under 1,000 megawatts, together their combined installed capacity is close to 12,000 megawatts.

As for groups of small reactors being preferred over single large reactors, this trade-off involves two competing economic principles. The disadvantage of smallness is extra capital cost: five 200-megawatt power plants will generally cost more to build than one 1,000-megawatt plant built in the same way, because of what are called “scale economies.” On the other hand, if the numbers of small plants becomes large enough, unit costs can come down by virtue of “economies of serial production.” To bring down unit costs, large numbers of small reactors might be built more completely in a factory than large reactors could be, which is why the generic name for the size alternative to today’s dominant reactor is the “small modular reactor.”

In this distillate, Article 2 outlines a new typology that allows the more than 50 small modular reactor designs to be placed in four broad groups. We then consider small modular reactors from the perspectives of safety (Article 3), linkages to nuclear weapons (Article 4), siting flexibility (Article 5), and economics (Article 6). Article 7 concludes the main text with a brief discussion of policy issues and a table showing some of the small modular reactor designs that are being developed around the world. At the back is an Appendix, “Key Concepts and Vocabulary for Nuclear Energy,” which should be helpful background for any reader new to nuclear issues.

Article 2: Small Modular Reactor Families

Many small modular reactor designs with distinct characteristics have been proposed or are being developed. These designs vary in their power output, physical size, fuel type, refueling frequency, siting options, and status of development. To create some coherence out of this variety, we group these small modular reactors into four categories or "families." These categories are distinguished by the main objective that guides the design of the reactor, rather than, for example, by some feature of their technology like their fuel or coolant. Our four categories are:

1. *Ready to Build.*
2. *Succeeding the Second Time Around.*
3. *Reducing the Burden of Nuclear Waste.*
4. *Comes with Fuel for a Lifetime.*

As in many classification schemes, the distinctions can be blurry. Some small modular reactor concepts fit into more than one category, and a few others fit not very well in any category.

Family 1:

Ready to Build

The first family of small modular reactors involves reactor designs that are guided by the idea of demonstrating the feasibility of small modular reactors as soon as possible and leveraging the advantages they would accrue by being first-to-market. One reason these are considered close to being marketed is because they are pressurized-water reactors, the predominant type of currently deployed nuclear reactor technology. Reactors of the first family dominate the small modular reactor discussion today. The other three classes of reactors involve small modular reactors that have few if any counterparts among today's large commercial reactors.

Pressurized-water reactors were originally developed to power submarines, and since the 1950s they have done so. In fact, the first commercial power reactor in the United States (Shippingport, Pennsylvania) was based on the first submarine reactor used on the USS Nautilus. Shippingport fed 60 megawatts of electricity to the grid from 1957 until it was permanently shut down in 1982. Around the world, about 200 naval reactors (all using pressurized-water reactor technology) are in operation today. Given this long record of operation and the licensing experience, small modular reactors based on pressurized-water reactor technology have a substantial head start.

At the same time, there are significant differences. Submarine reactors are designed to operate under stressful conditions, and this has consequences for many of their components. Further, because of the greater difficulty of replacing fuel in a reactor located within a submarine in comparison with reactors at a power plant, the submarine reactors are often, though not always, fueled with highly enriched uranium, which permits significantly longer intervals between refueling. In contrast, pressurized-water reactors use low-enriched uranium.

As would be expected, many reactor components and materials envisioned for small modular reactors in this category are similar to those used in the existing large power reactors. The fuel proposed is almost identical to the fuel used in standard light-water reactors. The fuel rods are generally shorter, but they are loaded into similar tubes made of an alloy of zirconium ("cladding") and they are made of uranium enriched to around 5 percent in uranium-235. As a result, developers expect a more straightforward licensing process for the fuel and would work with established vendors of equipment and fuel.

One important difference found in many of the proposed small modular reactors that are pressurized-water reactors is the so-called "integral design"; such reactors are often dubbed integral pressurized-water reactors. In this design, the steam generators, which use the heat produced in fission reactions in the reactor core to convert water into steam, are located in the same reactor vessel as the reactor core, whereas in the conventional pressurized-water reactor the steam generator is located outside the reactor vessel. Integral designs can reduce the risks and the consequences of a break in a pipe carrying water at high pressure to the reactor core; such a break is considered a key initiating event for severe accidents in conventional reactors, because it would divert the water needed to remove the heat constantly produced within the core.

There would also be differences in fuel handling in this type of small modular reactor. The entire core of the small modular reactor is expected to be replaced as a “cassette” during each refueling, in contrast to the large pressurized-water reactors where typically only one-third of the fuel assemblies are replaced at each refueling, while the remaining two-thirds are “shuffled” to other locations within the core so that the fuel is more efficiently utilized. Replacing the entire core at once would simplify operations, but the fraction of uranium fissioned in different parts of the core would be more uneven and about 50 percent more uranium fuel would need to be sent through the reactor to produce the same amount of electricity.

Box 1 below lists four prominent examples of small modular reactors that are pressurized-water reactors. These are illustrative of efforts in different countries and are among the most technologically mature designs.

ACP-100, CNNC (China). The ACP-100 is a 100-megawatt integral pressurized-water reactor developed by the China National Nuclear Corporation (CNNC). Though the design predates the Fukushima accidents, CNNC started promoting the ACP-100 in earnest only after 2011. The design has not yet been approved for construction, but the site for the first demonstration project has been identified as Putian, a city on the east coast of China.

SMART, KAERI (South Korea). The SMART is a 100-megawatt integral pressurized-water reactor designed by the Korea Atomic Energy Research Institute (KAERI). It was approved in 2012 for construction by South Korea’s regulatory agency, the Nuclear Safety and Security Commission, and thus became the first licensed modern small modular reactor. In March 2015, KAERI entered into an agreement with Saudi Arabia's King Abdullah City for Atomic and Renewable Energy to review the feasibility of constructing SMART reactors in Saudi Arabia.

NuScale, NuScale Power (USA). The NuScale power plant consists of several 45-megawatt modules submerged in a common pool of water. Each module is a separate integral pressurized-water reactor, and the NuScale plant is expected to include six to 12 units. NuScale has been in the pre-application stage of getting its design certified by the U.S. Nuclear Regulatory Commission since 2008 and, in 2013, was selected by the U.S. Department of Energy to receive up to $217 million in matching funds over five years towards commercialization of its design.

mPower, Babcock & Wilcox (USA). The mPower is an integral pressurized-water reactor with a power output of 180 megawatts per unit. Babcock & Wilcox has been in the pre-application stage of getting its design certified by the U.S. Nuclear Regulatory Commission since 2009 and, in 2012, was selected by the U.S. Department of Energy (DOE) to receive up to $226 million in matching funds towards commercialization of its design. Since then, mPower has significantly cut its spending on the associated research and development because it foresees weak demand for its reactors. As a result, the U.S. DOE funding has diminished too.

CAREM-25, CNEA (Argentina). CAREM-25 is an integral pressurized-water reactor with a power output of 25 megawatts per unit. There is also a larger-scale version with an output of 300 megawatts. The design relies on water circulation through convection and does not need coolant circulation pumps. A prototype of the 25-megawatt design is under construction in Argentina, at a site where two reactors are already operating.

Box 1: Family 1 small modular reactor designs.

Family 2:

Succeeding the Second Time Around

A second class of small modular reactors is based on fundamentally different designs than those of light-water reactors but includes only reactors that were evaluated extensively in the past. These were not considered actively after the 1970s when the world largely converged on light-water reactors as a standard technology class. Two major reactor concepts in this category stand out: pebble-bed reactors and molten-salt reactors (Box 2); both are radically different from light-water reactors.

Pebble-bed reactors are designed to operate at much higher temperatures than pressurized-water reactors. (Typical operating temperatures are 300 degrees Celsius for pressurized-water reactors and 800 degrees Celsius for pebble-bed reactors.) Such a high operating temperature is made possible by the use of gases (typically helium rather than water) for cooling and by the use of a fuel that consists of small (6 centimeter diameter) uranium particles coated with several ceramic layers. As a result of their higher operating temperature, pebble-bed reactors convert the thermal energy produced from uranium fission into electricity substantially more efficiently. (Typical thermal efficiencies are 30–35 percent for pressurized-water reactors and 40–45 percent for pebble-bed reactors.) The higher operating temperature also enables certain non-electricity industrial applications.

In molten-salt reactors the nuclear fuel is dissolved in a liquid-carrier salt. Salt, in this context, is used in the more general sense of being a chemical compound formed by a positively charged ion bonded to a negatively charged ion; while common table salt (sodium chloride) melts to become a liquid only at around 800 degrees Celsius, other salts enter the liquid phase at much lower temperatures. In molten-salt reactors, the salts used involve fluorine, instead of chlorine, as the negative ion, and metals like lithium and beryllium, or some combination, as the positive ion. Boiling temperatures of salts can be very high, more than 1600 degrees Celsius in the case of lithium fluoride.

One of the distinctive features of molten-salt reactors is that the molten fuel is continuously cycled in and out of the reactor, and when it is outside the reactor, the unwanted fission products are removed and makeup fuel can be added. This is an advantage from the viewpoint of managing the reactor: without continuous (“online”) fuel processing, isotopes of various kinds would build up in the reactor and absorb neutrons needed to continue the fission process, thereby preventing the chain reaction from being sustained. Not all isotopes need to be removed, however, and different molten-salt reactor designs involve different levels of chemical processing.

Several technical challenges would have to be resolved before molten-salt reactors could be deployed commercially. These challenges include handling the highly radioactive molten-salt stream and ensuring that various structural components of the reactor core can tolerate high levels of irradiation as well as corrosion from the highly corrosive salts.

Both of these reactor concepts have had a long history. In the case of the pebble-bed reactors, a few prototype reactors were built in the 1960s and 1970s at the same few-hundred-megawatt capacity that would make them small modular reactors today. The expectation then, however, was that reactors of this type would be scaled up to the 600- to 1,000-megawatt range. But the relatively poor performance of these prototypes and the nuclear industry’s convergence on light-water reactors meant that this concept had to be reformulated as a small modular design before it could receive active

HTR-PM, Tsinghua (China). The HTR-PM consists of two 105-megawatt pebble-bed reactors connected to one 210-megawatt turbine. It is currently under construction in Shandong province in China and is expected to start operating in 2017. The reactor’s designers are now looking at other sites to build follow-on reactors as well as working on a scheme to connect six reactors to a single turbine. The HTR-PM builds on experience with a pilot plant about 30 times less powerful that has been operating since 2003 and that has undergone multiple stringent safety tests.

IMSR, Terrestrial Energy (Canada). The Integral Molten-Salt Reactor is currently proposed in multiple versions with different power outputs, ranging from 25 megawatts to 300 megawatts. The IMSR uses low-enriched uranium fuel and aims to minimize fuel processing. Current design information suggests that developers are aiming for a seven-year core life. The IMSR will be marketed as a reactor unit without onsite refueling to reduce the potential for diverting nuclear material for nuclear weapons. The developers of the IMSR are proposing that their reactor can be a source of high-temperature heat for use in extracting oil sands in the province of Alberta in Canada.

Box 2: Family 2 small modular reactor designs.

consideration. In the case of the molten-salt reactor, there has been experience only with pilot plants, tens of times smaller than full-scale reactors. Like the pebble-bed reactors, larger molten-salt reactors with outputs of up to 1,000 megawatts were proposed but never constructed.

Family 3:

Reducing the Burden of Nuclear Waste

Nuclear waste disposal remains one of the key issues affecting the discussion of nuclear power in the public and political debate. Several small modular reactor concepts put the nuclear waste issue front and center; they are presented as technologies that can generate energy while reducing the waste problem by “burning” (or “transmuting”) various isotopes in existing spent fuel.

To generate 1,000 megawatts of electric power, any type of nuclear reactor consumes (“fissions”) about one ton of material (generally, uranium or plutonium) per year. The resulting fission products are highly radioactive and must be safely isolated from the environment. Besides fission products, nuclear reactors also produce elements with higher atomic numbers (“transuranics”), many of which are highly radioactive and have half-lives much greater than those of nearly all fission products.

Not all of the uranium or plutonium loaded into a reactor undergoes fission and so all this radioactivity is embedded in a larger quantity of spent nuclear fuel (about 20 tons per year in the case of a 1,000-megawatt light-water reactor), the bulk of which consists of uranium that has not undergone fission. About 270,000 tons of spent nuclear fuel have been accumulated around the world today, and 8,000 tons are added each year. This spent fuel can be safely stored in dry casks at reactor sites for several decades, but ultimately a long-term disposal strategy is going to become essential.

Siting geologic repositories for spent nuclear fuel has proven extremely challenging for both technical and political reasons. If nuclear power were to continue at even its present level of global deployment, additional large repositories for nuclear waste would be needed on a regular basis. This prospect has led several developers of reactors—including those in this third category—to make waste minimization the main paradigm guiding their reactor designs and fueling policies.

The common feature underlying most reactors in this category is that they are based on “fast” neutrons as opposed to “slow,” or “thermal” neutrons. This is an important distinction in reactor design. Today’s reactors are based on thermal neutrons. When neutrons are produced during fission, they are moving fast. In pressurized-water reactors, neutrons are slowed down due to collisions with nuclei in the water (the “moderator”). Similarly, in pebble-bed reactors, the neutrons are slowed down by collisions with graphite (carbon) nuclei. The advantage with slow neutrons is that they have a much higher probability of inducing fission in uranium nuclei as compared to fast neutrons, which makes it easier to sustain a chain reaction. These reactors are called thermal-neutron reactors.

In fast-neutron reactors, by contrast, there is no moderator. A higher proportion of fissile materials is used in the reactor fuel to compensate for the lower probability of absorption; even though the absolute reaction probabilities are lower for fast neutrons, the relative probability for fission after absorption increases, which results in better fuel utilization in fast-neutron reactors. Another compensating factor is that, when uranium or plutonium undergoes fission after absorbing fast neutrons, the fission produces more neutrons on average when compared to fission events triggered by slow neutrons. Overall, fast neutrons are more efficient in consuming fuel that includes transuranic elements (e.g., recovered from spent fuel) than thermal neutrons are. This property can result in the reduction of long-lived radioactive elements in the spent fuel. Some assessments of this scheme to use fast-neutron reactors to deal with long-lived radioactive elements, including a major review in 1996 by the National Academy of Sciences, have concluded, however, that the benefits with regard to waste management would be small compared to the cost.

Four prominent candidate systems that follow this approach are listed in Box 3.

PRISM, GE-Hitachi (USA/Japan). The PRISM is a 311-megawatt integral fast reactor (IFR) based on a design that was originally developed by the U.S. Argonne National Laboratory and was based on experience with the Experimental Breeder Reactor II (EBR-II) that operated from 1963 to 1994. The PRISM uses metallic fuel: an alloy of zirconium, uranium, and plutonium. GE-Hitachi has been promoting the PRISM, especially in the United Kingdom, as a potential way to use existing stockpiles of plutonium to generate electricity.

EM2, General Atomics (USA). The Energy Multiplier Module (EM2) is a 240-megawatt fast high-temperature gas-cooled reactor, with a 30-year core, operated without refueling. The reactor uses 12-percent-enriched uranium starter fuel in its core and a “blanket” incorporating spent nuclear fuel. To achieve the desired lifetime, General Atomics proposes to develop a new kind of fuel that can withstand extended irradiation by neutrons.

Traveling Wave Reactor, Terrapower LLC (USA). The Traveling Wave Reactor (TWR) is being pursued by Terrapower LLC, a company founded in 2007 with strong support from former Microsoft executives Bill Gates and Nathan Myhrvold. It is sodium-cooled. Its proposed power level is usually cited as 600 megawatts, but it could be smaller. Its fuel would incorporate current "spent" fuel that has been irradiated in other reactors without reprocessing, with the objective of reducing its transuranic content.

WAMSR, Transatomic Power (USA). The Transatomic Power (TAP) reactor (also Waste Annihilating Molten-Salt Reactor, WAMSR) is a 520-megawatt thermal reactor that combines a (liquid) fuel salt with (solid) moderator pins. It is designed to operate with material recovered from light-water-reactor spent fuel.

Box 3: Family 3 small modular reactor designs.

Family 4:

Comes with Fuel for a Lifetime

Especially in the U.S. debate on the future of nuclear power, the vision of the “nuclear battery”—a reactor that would not require onsite refueling throughout its commercial life (perhaps 30 years)—provided an important motivation for government support for the small modular reactor concept in the early 2000s. At the time, there was much optimism with regard to a rapid global expansion of nuclear power; but there were also concerns about the coupling of nuclear power to nuclear weapons, exemplified by the discovery of Iran’s uranium enrichment program and the possibility that additional states without nuclear weapons would seek technologies that could enhance their capability to build nuclear weapons.

If small modular reactors with lifetime cores were to dominate the deployment of global nuclear power, the resulting landscape of suppliers and clients could resemble a hub-spoke architecture. In this landscape, a few international or regional vendors in the hubs would not only supply reactors to countries, but also offer front-end and back-end fuel cycle services. This could be compared with the civilian aircraft manufacturing industry, where very few suppliers (i.e., Boeing and Airbus) have essentially captured the global market after having absorbed most of their smaller competitors. Both companies manufacture their aircraft in very few assembly lines for all international customers and also provide extensive servicing.

The hub-spoke concept would seek to discourage countries from acquiring indigenous fuel cycle capabilities such as enrichment or reprocessing; overall, it may then also weaken the rationale and reduce opportunities for countries to develop research facilities and trained cadres of scientists and technicians that could later be reassigned to weapons activities. A hub-spoke architecture would require that client countries accept discriminatory practices (restrictions on their nuclear activities not accepted by the supplier countries), unless all countries, including the supplier countries, accept a high degree of international control over their nuclear energy programs. Today, with few exceptions, neither countries seeking nuclear power nor countries already possessing nuclear facilities are showing interest in a hub-spoke architecture.

The power output of battery-type reactors ranges from a few megawatts to about 100 megawatts. When such a reactor is marketed primarily as a power source for remote locations where there are no other power plants to generate electricity, a small modular reactor needs to possess the capability to adjust its output to respond to variations in electricity demand; this kind of operation is termed "load following."

4S, Toshiba (Japan). The 4S (super-safe, small, simple) is a 10-megawatt fast reactor cooled by molten sodium and fueled with a metallic alloy of zirconium and uranium, enriched to close to 20 percent, with a 30-year core. There is also a 50-megawatt design. The 4S is envisioned for "emerging markets" (remote locations) and, besides generating electricity, can have special applications such as water desalination and process heat. The 4S was proposed for deployment in Alaska in 2005, but the project has not moved forward. Currently, there are no licensing efforts underway.

G4M (Gen 4 Module, formerly known as Hyperion), Gen4 Energy (USA). The G4M is a 25-megawatt liquid-metal fast reactor based on work done by scientists at the U.S. Los Alamos National Laboratory, which has provided Gen4 Energy the commercialization rights to introduce, license, manufacture, market and distribute the technology. The Gen 4 Module envisions a 10-year sealed core, operated without refueling or reshuffling. The reactor uses 20-percent-enriched uranium (nitride) fuel and is lead-bismuth cooled. The module is primarily intended for off-grid electricity to power remote industrial operations and isolated island communities. In 2013, Gen4 Energy received a two-year grant from the U.S. Department of Energy for research and development relevant to this reactor.

AFPR-100, Pacific Northwest National Laboratory (USA). The AFPR-100 (the Atoms for Peace Reactor) is a 100-megawatt boiling-water reactor with pebble-bed-type fuel. The AFPR-100 uses cross-flow water-cooling and 10-percent enriched uranium fuel. The AFPR-100 has a lifetime (40-year) core and is one of the very few water-cooled designs in this category, but no development effort appears currently to be underway.

Box 4: Family 4 small modular reactor designs.

A variant of the long-lived battery is a small modular reactor located in one country but operated by another one. This approach also aims to minimize the host's involvement with the unit's operation and, in some cases, to restrict the host's access. (This mode of deployment is not peculiar to small modular reactors, and is also envisioned in some instances for current light-water reactors.) Addressing this objective, two small modular reactor concepts are being developed today, both located offshore near the coast of the host country: the Russian "floating nuclear power plant" and the French underwater (seabed) Flexblue reactor. Both use light-water reactor technology and require regular refueling. But given the deployment mode, the host country sees a "battery," since the refueling is done without any involvement of the customer.

KLT-40S, OKBM (Russia). KLT-40S involves two 35-megawatt pressurized-water reactors that are mounted on a ship called the floating power plant. It is based on the design of reactors used in the small fleet of nuclear-powered icebreakers that Russia has operated for decades. Refueling of the reactor is performed inside the floating power plant itself and the spent fuel discharged from the reactor is unloaded into a temporary storage location onboard. Deployment of the KLT-40S is linked to the completion of the Akademik Lomonosov ship, currently under construction but long-delayed, that would carry two KLT-40S units.

Flexblue, DCNS (France). Flexblue is a 50-megawatt to 250-megawatt pressurized-water reactor that builds on reactors used in French nuclear submarines. Reactor modules are sited underwater, moored on the seafloor at a depth of 60–100 meters a few kilometers off shore. Under routine operating conditions, they are controlled remotely from the shore. Electricity is delivered to the coast via transmission cables.

Box 5: Two more Family 4 small modular reactor designs.

Article 3: Safety

During regular operations, nearly all the radioactivity produced in a nuclear reactor remains within the reactor. As a result, the radiation dose to the public from routine operation of nuclear power plants is small, measured, for example, against the radiation received from radon gas in homes, cosmic rays from space, and medical procedures. The situation is dramatically different during severe accidents, such as those that occurred in March 2011 at multiple reactors at Fukushima in Japan. Radiation was released and dispersed widely, resulting in the evacuation of an estimated 160,000 people, the deliberate destruction of contaminated crops and food, and widespread anxiety and depression among survivors. One large direct cost came from shutting down 48 nuclear power plants in Japan; plants seeking permission to resume operation will need to install safety upgrades. Four years later, no reactor has resumed operations, work at the site to decommission the facility is still under way, and over 100,000 citizens still cannot return to their homes.

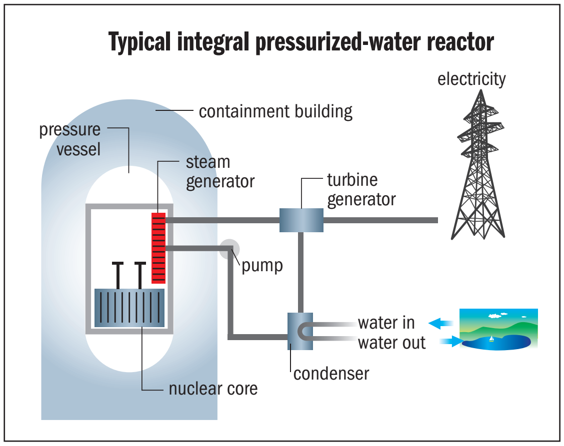


Figure 3.1: Schematic of integral pressurized-water reactor. In conventional, non-integral reactor designs, the steam generator (shown in red) is outside the pressure vessel.

The standard approach to lowering the risk of a catastrophic nuclear accident is to choose reactor designs that have a very low probability of undergoing certain kinds of accidents and to include multiple redundant safety features to prevent the release of radioactive materials. For example, the cladding surrounding the fuel would have to give way, the integrity of the pressure vessel would have to be lost, and the containment structure that surrounds the reactor would have to be breached before a radioactive release from the reactor core could occur. Safety is also enhanced through the establishment of emergency planning zones around the reactor, from which evacuation is pre-planned.

In some respects, small reactor size provides additional safety opportunities. Any accident at a single small reactor will have less impact than the same accident at a large reactor simply because the small reactor will generally have a smaller in-core inventory of radioactive material and less energy available for release during an accident.

Smallness also permits certain design modifications that could enhance safety. For example, for small pressurized-water reactors, Family 1 in our categorization system, it becomes feasible to place the high-pressure primary cooling loop entirely inside the pressure vessel, which means that a break in that loop should not result in a loss of cooling function for the reactor (see Figure 3.1). Doing the same in currently deployed large pressurized-water reactors would require substantial enlargement of the pressure vessel, which could impact its structural integrity. For larger pressurized-water reactors, such a “loss-of-cooling accident” resulting from a failure in the primary cooling loop has long been a focus of attention. The cooling water for the reactor comes in at high pressure, and if the pipe carrying this cooling water were to break, the water would blow out of the hole in the form of steam and the reactor would lose its cooling. The reactors in French submarines already incorporate a primary cooling loop entirely within the pressure vessel.

A second advantage of smallness arises for reactors that strive to be passively cooled in the event of an accident. Passively cooled reactors aim to operate without the need for external inputs, such as electricity for fans or pumps to drive water or air, after the plant shuts down; instead, the heat that builds up in the reactor in an accident might be cooled convectively by natural ventilation or there might be a large pool of water that boils off, carrying away heat from the reactor in the process. China is building a small modular reactor (210-megawatt capacity) whose fuel is in the form of small balls (pebbles) with special coatings (a “pebble-bed reactor”). The idea is to limit by passive means the maximum temperature that the pebbles can attain, even during an accident, to below the temperature at which the coatings fail and radioactive fission products can escape from the pebbles. A larger reactor of this kind could not be passively cooled without design modifications.

Even when a single small reactor has safety advantages over a single large reactor of the same kind, there is still the question of whether several small reactors are safer than a single large reactor when both have the same total capacity. Depending on the relative levels of safety, it is possible that the likelihood of an accident at one of the five small modular reactors may be larger than the likelihood of an accident at the large reactor, even if each individual small modular reactor is safer than the large reactor.

Further, an accident at one unit may make it harder to prevent an accident at a second one, for example, if the units have been put at risk for a common reason, like an earthquake. At Japan's multiple-reactor Fukushima Daiichi plant, explosions at one reactor damaged the spent fuel pool confinement building in a co-located reactor. Radiation leaks from one unit made it difficult for emergency workers to approach the other units.

Around each reactor site is an emergency planning zone whose size has an impact on reactor siting and operating costs. A typical emergency planning zone for a large nuclear plant in the United States extends to about 10 miles from the reactor. The analogous term used by the International Atomic Energy Agency and many other European countries is "urgent protective action planning zone," and this varies from a few miles to up to 15 miles, depending on the characteristics of the plant. Operating costs are affected by the size of the emergency planning zone because the reactor owner is required to pay to maintain the capability of the local government and local population within the emergency planning zone to respond to an accident. Typical costs include the costs of training emergency service providers so that they are prepared to implement protective actions such as the evacuation of citizens.

Substantial effort is being directed by small modular reactor vendors toward the objective of being allowed to have a smaller emergency planning zone than that of a large nuclear plant. Some of these vendors argue that the zone need not extend beyond the site boundaries of the small modular reactor power plant. An open question in the United States today is whether the Nuclear Regulatory Commission will allow such shrinkage of the emergency planning zone. Other countries, including China and South Korea, have seen less debate over this question, with the regulatory authorities and small modular reactor designers agreeing to continue with the same rules as for large reactors, at least initially.

The emergency planning zone discussion is one of many where the issue is how to distribute the safety advantages of small modular reactors between public and private interests. Another example where rules bearing on safety and security are under discussion addresses the number of units that can be managed from one control room. At one extreme, the entire safety benefit accrues to the public, which sees no dilution of the safety-related rules already established for large nuclear plants. At the other extreme, safety-related costs are reduced until small modular reactor operation is less safe than large-reactor operation, making the industry more profitable at the cost of increased public risk. More generally, shrinking the emergency planning zone and augmenting the tasks assigned to a single control room are examples of rule changes that may reduce operating costs but increase operating risks.

Article 4: Linkages to Nuclear Weapons

Small modular reactors have a distinctive geopolitics. The countries of the world today include: the nine with established nuclear weapons programs (United States, Russia, United Kingdom, France, China, Israel, India, Pakistan, North Korea); many countries that are capable of developing nuclear weapons but say that they do not wish to; and other nations that for now are not capable of developing nuclear weapons.

Small modular reactors provide what one might call a lower price of admission to the nuclear weapons club. This is a two-step argument: a) the small modular reactor option lowers the investment required to build a first nuclear power plant and b) acquiring a first reactor brings with it the training of scientists and engineers, the acquisition of relevant infrastructure and capabilities, and sometimes even associated fuel-cycle facilities with potential weapons-related uses. Therefore, largely independent of any particular reactor technology, small modular reactors could challenge the traditional “nonproliferation” regime, which seeks to prevent any increase in the number of nations with nuclear weapons.

When a country that does not yet have nuclear weapons chooses to develop or acquire small modular reactors, one must consider both what it says it will do and what it could do. A declaration that it will not develop nuclear weapons notwithstanding, if a country has the capability to make nuclear weapons, political and military planners in other countries will have to take into account the possibility that this capability could well translate into an actual, even if clandestine, nuclear arsenal. Countries are not the only concern: the use of weapons-usable plutonium or uranium tempts fate at the subnational level as well, by creating opportunities for malevolent actions by individuals and sub-national groups.

Highly enriched uranium and plutonium are the connectors that link nuclear power and nuclear weapons. Uranium exists in nature but not in the highly enriched form that makes it usable for weapons, and plutonium does not exist in nature at all. The development of nuclear weapons requires either enriching uranium or separating plutonium.

Enriching uranium means using technology to create uranium that contains more of the rare nucleus of natural uranium, uranium-235 (U-235), relative to uranium-238 (U-238), than in natural uranium. In nature, only seven of every 1,000 nuclei of uranium are U-235 and almost all of the remainder is U-238. Today’s fuel for large commercial pressurized-water reactors contains 30 to 50 U-235 atoms per 1,000 total uranium atoms; when it is above 200 per 1,000 (20 percent) U-235, the enriched fuel is considered “highly enriched” uranium. The level of uranium enrichment in today’s weapons and in the reactors that power U.S. and U.K. submarines is greater than 90 percent. In the small modular reactors currently under discussion, the amount of enrichment of the uranium fuel ranges widely, but it is always kept below 20 percent (sometimes, just below). Indeed, since the late 1970s, designers of commercial nuclear power reactors of all sizes have accepted this 20 percent constraint on fuel enrichment.

A uranium enrichment facility can be reconfigured to provide any enrichment of U-235, however. It is therefore possible for a uranium enrichment facility designed to produce fuel for a reactor to be reconfigured to produce fuel for a bomb. Thus, uranium enrichment at the “front end” of the nuclear power fuel cycle where the reactor fuel is produced provides one of the two dangerous potential linkages between nuclear power and nuclear weapons.

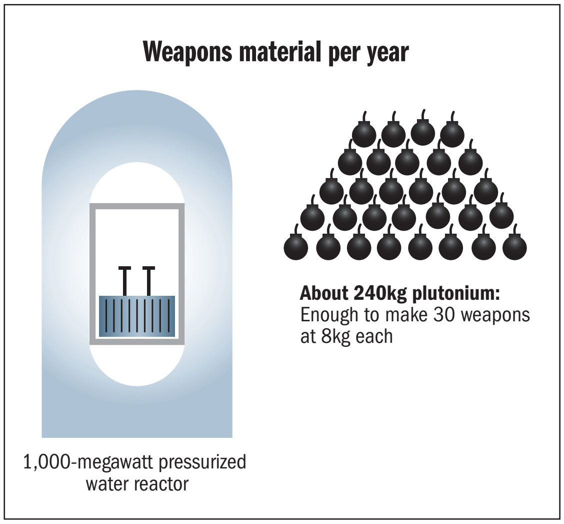


Figure 4.1: A nuclear reactor makes plutonium as it produces power. Plutonium that has been chemically separated from the spent fuel can be used to make bombs.

As for plutonium, it is created within the uranium fuel assemblies at all nuclear power plants, but there it is collocated with intensely radioactive materials (see Figure 4.1). Therefore, if the plutonium is to be used subsequently, further steps have to be taken at the "back end of the fuel cycle" to "reprocess" the spent fuel after it leaves the reactor. There are many methods to carry out such reprocessing, and all of them make plutonium much more accessible, whether for inclusion in new fuel or for use in weapons (see Figure 4.2).

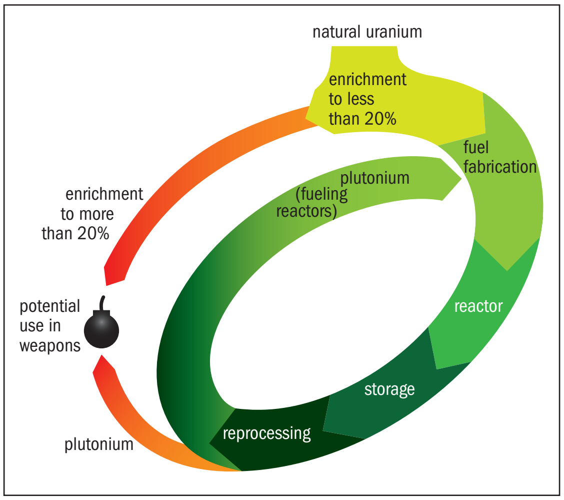


Figure 4.2: Two routes to bombs create risks for nuclear power.

In summary, the primary risks of nuclear power for creating the capacity to make weapons derive less from the design of the reactors themselves and more from the chain of activities associated with processing of the fuel, in particular, the enrichment of uranium at the front end and the treatment of spent fuel at the back end. A country wishing to have nuclear power plants could choose to forgo indigenous enrichment and reprocessing, either because it wants to ease the concerns of other countries that it might be developing nuclear weapons or simply to avoid the cost and trouble of enrichment and reprocessing. If it decides not to enrich, it has to arrange for another country to provide its low-enriched uranium. At the back end, there is no need for fuel to be reprocessed. It can be stored and eventually disposed of in a deep underground repository. However, even if a country commits to not reprocessing its spent fuel, the presence of nuclear reactors in the country provides what has been termed "breakout potential," the ability to withdraw from such a commitment and to produce weapons-usable plutonium from its fuel, potentially building a nuclear arsenal (see Figure 4.3).

Below, for each of the four categories of small modular reactors presented in Article 2, we briefly examine its nuclear weapons potential, considering both its fuel cycle and the geopolitical implications of its currently intended use.

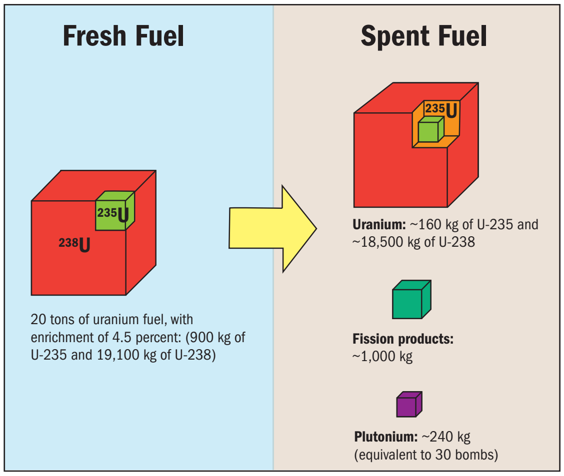


Figure 4.3: Annual flow of material through a 1,000-megawatt pressurized-water reactor. Figure adapted from http://www.laradioactivite.com/en/site/images/CompositionCUen.jpgimages/CompositionCUen.jpg

Family 1: Ready to Build. Today's light-water reactor technology can be relatively robust against use to produce material for nuclear weapons. Uranium is enriched only to 3 to 5 percent U-235, and reprocessing of spent fuel is optional. As a result, small modular reactors that copy the dominant fuel cycle of commercial large reactors, i.e., with no reprocessing of used fuel, will not create new linkages to nuclear weapons. Quantitatively, for the same amount of power production, small modular reactors belonging to Family 1 could require about 50 percent more fuel to move through the reactor, relative to today's large commercial light-water reactors, partly as a result of the small modular reactor fuel being replaced all at once and the large reactor fuel being replaced one-third at a time. Thus, for generating the same amount of electrical energy, small modular reactors may require more uranium to be mined, processed, and enriched.

Although today's light-water reactors and related technologies have no need for fuel reprocessing, France, Russia, India, Japan, and the United Kingdom have built reprocessing into the fuel cycle for their commercial reactors. (The United Kingdom, however, will be ending its reprocessing program over the next several years and is now focusing on how to dispose of its plutonium stockpile.) Fuel from small modular reactors based on today's pressurized-water reactors might be reprocessed as well.

Family 2: Succeeding the Second Time Around. Given the lack of operating experience, the risks of weapons couplings for high-temperature and molten-salt reactors, large and small, are poorly understood, but there are no obvious consequences of moving to smaller scale. (Having a larger number of individual reactors in place for the same power output, one could argue, creates more separate opportunities for mischief.) In comparison with light-water reactors, a much larger volume of used fuel from high-temperature reactors would need to be handled to obtain the same quantity of plutonium. However, the level of uranium enrichment used by various high-temperature reactors is higher (the uranium fuel is roughly 10 percent U-235) than in light-water reactors.

With molten-salt reactors, the most worrisome issue from the point of view of weapons linkage is the continuous processing of fuel, which is integral to reactor operation. Continuous processing facilitates the extraction of weapon-usable materials (plutonium or uranium-233) from the fuel. In contrast, reprocessing of spent fuel from pressurized-water reactors is optional.

Family 3: Reducing the Burden of Nuclear Waste. These reactors would be fueled by the spent fuel of (for example) pressurized-water reactors, from which most fission products have been removed. Even if separation of weapon-usable plutonium during fuel preparation were renounced initially, a country could add the relevant additional steps to acquire separated plutonium at a later time if desired. One of the small modular reactors in this category is a small version of the full-scale integral fast reactor, currently marketed as the PRISM; the continuous reprocessing integral to this reactor concept could produce nuclear weapons material (separated plutonium), even though that is not how the system is supposed to operate.

Family 4: Comes with Fuel for a Lifetime. In order to operate for decades, small modular reactors with lifetime cores must start with a higher loading of fissile material than reactors that are refueled periodically; generally, this means that the uranium enrichment level will be higher. To achieve lifetime cores, these reactors generate at least as much new fuel as the fuel they consume, which requires the amount of plutonium in the reactor to increase continually. One 200-megawatt lifetime-core reactor could contain on the order of 1,000 kilograms of plutonium after seven years and almost 3,000 kilograms of plutonium after 30 years (see Figure 4.4). By comparison, about 150 kilograms of plutonium would be contained in the spent fuel discharged periodically from a 200-megawatt pressurized-water reactor (typical refueling periods for small modular reactor designs range from 14 months to 48 months; see Table 7.1).

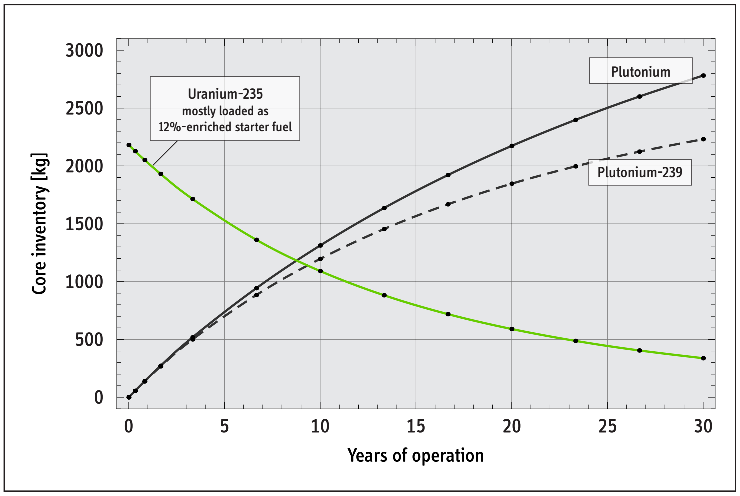


Figure 4.4: Build-up of plutonium in a 200-megawatt lifetime core-reactor (Family 4).

Article 5: Siting Flexibility

Choosing a suitable site for a nuclear power plant is a complex process that involves carefully balancing a multitude of variables and issues. The factors that need to be taken into account when reviewing the suitability of a site to host a nuclear power plant can be divided into three categories: physical, economic, and societal. First, with regard to physical siting requirements, the location of a nuclear power plant should have low seismic activity and low susceptibility to floods; the site should also be close to water sources for cooling during normal operation and during accidents. Second, the key economic determinants are the local cost of land and labor (for construction and operation); the geographical accessibility of the chosen site, which determines transportation costs (especially for heavy equipment); and the proximity to markets for the electrical energy generated, given that locating a power plant far from consumption centers induces economic penalties due to longer transmission lines and power losses on these lines. Third, there are societal issues such as the population density at the site: more people living near the reactor could result in greater impacts from accidents and greater difficulty evacuating the local population in the event of a plant emergency. Another societal factor is the local attitude toward nuclear power, which may strongly vary regionally, even within a country. Most siting challenges arise because of the tradeoffs among the various variables listed above. Clearly, building a nuclear reactor closer to densely populated areas reduces transmission costs and losses but increases the health impacts of a radiation release in an accident.

Small modular reactors raise different siting issues where there already is a power plant at the site versus where the site is undeveloped. In the first instance, packages of small modular reactors might replace today's large nuclear plants as they are retired in the United States, Japan, France, or elsewhere. There would be a four-way competition at each site: several small modular reactors, one large new nuclear plant, non-nuclear power production, or a site no longer producing power. If use of the site for nuclear power were discontinued (either of the last two options), the site would need to be "decommissioned," which is expensive. The construction of either small or large reactors at the site would postpone the need for decommissioning, although it might result eventually in greater cleanup costs because of its extended use.

Of course, small modular reactors could have other roles beyond replacing old nuclear plants as they are retired: they could also be constructed at sites that currently host coal-fired power plants if these were to be shut down. Such deployment would reduce the total cost of small modular reactors because they could use some of the infrastructure (transmission lines, cooling water, railroad access) already in place at these sites. In the United States, there are about 560 coal sites with almost 1,400 generators and an installed capacity of more than 300,000 megawatts. Many of these plants are small and old—and they will have to be closed down soon.

In the United States, 250 of these sites host coal plants that were built before 1980 and that have less than 500 megawatts of capacity. As seen in Figure 5.1 below, about 150 of these sites are potential candidates for replacement of aging coal plants by small modular reactors, because they have a population of less than 100,000 within 10 miles of the plant; the total capacity of the coal plants at these sites is 70,000 megawatts. About 60 of these sites have a population of less than 20,000 within 10 miles of the plant.

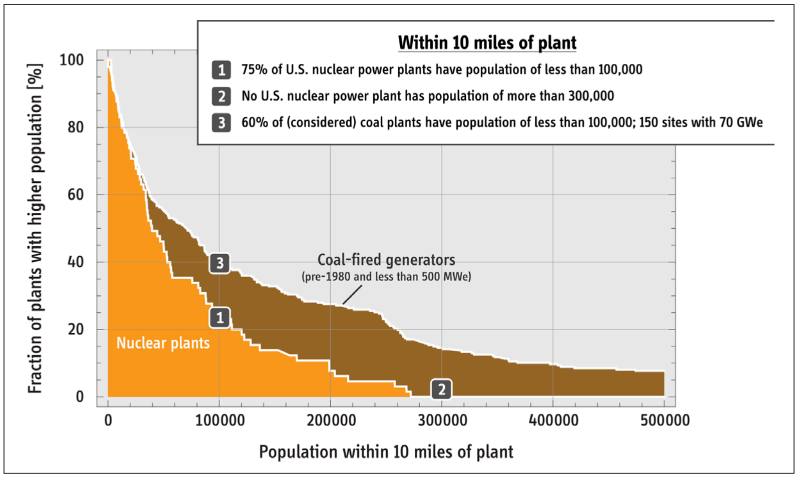


Figure 5.1: Populations within 10 miles of coal-fired and nuclear power plants in the United States. Note: MWe and GWe refer to megawatts and thousands of megawatts of electric capacity, respectively.

Article 6: Economics

Economic competitiveness is a challenge for nuclear power, particularly in liberalized electricity markets where utilities compete to meet a given demand by supplying power at the lowest cost. We address two related questions: 1) How competitive is nuclear power? 2) What will determine how well small modular reactors will compete against large nuclear reactors?

How competitive is nuclear power?

The main component of the cost of generating power at a nuclear plant, no matter what the size of the plant, is the capital cost of constructing the nuclear reactor. Many costs are proportional to the capital cost, including project financing costs, depreciation, insurance, taxes, and interest during construction. We combine these costs and annualize them by multiplying the capital cost by a constant levelized capital charge rate of 15 percent per year – a typical factor in power plant cost estimation. Cost components that are recurrent and not directly related to the capital cost include the costs of the fuel and operating costs. We obtain a total annualized cost for the power produced at the plant by combining the annualized capital-related cost and the annual recurrent capital-independent costs, and we obtain the cost of electricity by dividing this sum by the amount of power the plant produces in a year. Our estimate entails many simplifications, including neglecting two difficult-to-quantify costs associated with nuclear power: the cost of dealing with the radioactive waste products, and the cost of setting aside money to clean up the site after the reactor has been retired.

The construction cost for a new nuclear power plant is highly uncertain. The costs of plants constructed in the past have varied widely, and the variations can be explained only in part by the amount of previous experience, interest rates, land prices, site-specific factors, and regulatory stringency. One source of cost estimates for future plants is an "expert elicitation" conducted by Carnegie Mellon University in 2013. This elicitation presented a set of questions to 16 people with significant experience in nuclear reactor manufacture and made special efforts to control for bias and overconfidence. The elicitation focused on assessing the "overnight capital cost," defined as the sum of engineering, procurement, and construction costs, and excluding financing of construction, site work, transmission upgrades and other "owner's costs." Cost estimates were requested in 2012 dollars and were to be not for the first plant built but for a plant that "has recouped the cost of design engineering and licensing, has exploited technological learning, and has streamlined construction management." It was further specified that the plants were to be built in the southeastern United States "under a 'favorable' regulatory environment, overseen by a regulator such as the U.S. Nuclear Regulatory Commission (NRC)." With this guidance, for 13 of the 16 respondents the median estimate of the overnight construction cost was between $4,100 per kilowatt and $6,100 per kilowatt.

The estimates elicited from these experts must be balanced against the long history of construction costs and construction times ending up substantially higher than estimates in the pre-construction phase. An example is the Vogtle nuclear reactor under construction in the U.S. state of Georgia, where the project is already delayed by at least 18 months and estimated capital costs that initially were about $6,000 per kilowatt are now over $7,300 per kilowatt.

We invoke a rule of thumb, that when the cost of construction of a nuclear plant is $4,000 per kilowatt, the capital-related costs represent two-thirds of the cost of electricity and the capital-independent costs account for the remaining one-third. Thus, for such a plant, the annualized cost for capital-related costs, per kilowatt of capacity, is $600 per year (15 percent per year times $4000 per kilowatt of capacity) and the capital-independent costs are $300 per year. We assume that whether the cost of construction is more or less than $4,000 per kilowatt, the other costs per kilowatt are still $300 per year. We ask how well such a reactor can compete against alternative sources of electricity.

Today's nuclear power plants are operated at or close to full power for 80 to 95 percent of the time, with planned shutdowns typically once every 18-24 months for fuel replacement. Accordingly, the most obvious cost comparisons are with other systems that can operate at full power nearly all of the time – so called "baseload" power plants. It is more complicated to compare nuclear plants with wind power or solar power, which produce electricity intermittently.

We choose as our baseload alternative a natural gas plant that is designed to run nearly all of the time at high efficiency, a so-called “combined-cycle” natural gas power plant. We assume that its installed capital cost is $1,000 per kilowatt of capacity, or, annualized and per kilowatt, $150 per year. We also assume that the only significant cost for baseload electricity from natural gas, other than capital, is the cost of the natural gas itself. And we assume that the natural gas plant converts 50% of the energy in natural gas into electricity. The calculation requires some artful arithmetic, because the price of natural gas is usually reported in dollars per million British thermal units (Btu) of energy. The associated component of the cost of the electricity, per year per kilowatt, for the natural gas power plant is 60 times the cost of natural gas in Btu units. For example, if natural gas costs $5 per million Btu (somewhat higher than the current price of natural gas in the U.S.), the cost per year of one kilowatt of power from the natural gas plant is $450: $150 for the capital cost of construction (annualized) and $300 for the natural gas.

With these assumptions we can identify the construction cost for a nuclear power plant that produces electricity at the same cost as a natural gas power plant, for a given price of natural gas. For natural gas at $5 per million Btu, the breakeven capital cost of the nuclear power plant is $1,000 per kilowatt; at that cost, the cost per year for nuclear electricity is also $450: $150 for the annualized capital and $300 for the capital-independent costs. A capital cost of $1000 per kilowatt, the expert elicitation referred to above informs us, is far less than anticipated construction costs for nuclear power plants. However, if natural gas costs $15 per million Btu (approximately the cost today of liquefied natural gas delivered by ship in Japan), the breakeven capital cost for nuclear power is $5,000 per kilowatt, which is within the range of expected construction costs. For every increase of $5 per million Btu in the price of gas, the breakeven construction cost for the nuclear power plant increases by $2,000 per kilowatt.

A carbon tax would make nuclear power a stronger competitor with power from natural gas. It turns out that a carbon tax of $100 per metric ton of carbon dioxide will increase the price of natural gas by approximately $5 per million Btu. Thus, a tax of this magnitude would raise the breakeven construction cost for the nuclear power plant by $2,000 per kilowatt. If the price of natural gas is $10 per million Btu (approximately the price in Western Europe), the breakeven construction cost for nuclear power would be $3,000 per kilowatt in the absence of a carbon price, but $5,000 per kilowatt in the presence of a tax of $100 per metric ton of carbon dioxide. $3,000 per kilowatt is below the costs estimates from the expert elicitation, but $5,000 per kilowatt is not (see Figure 6.1).

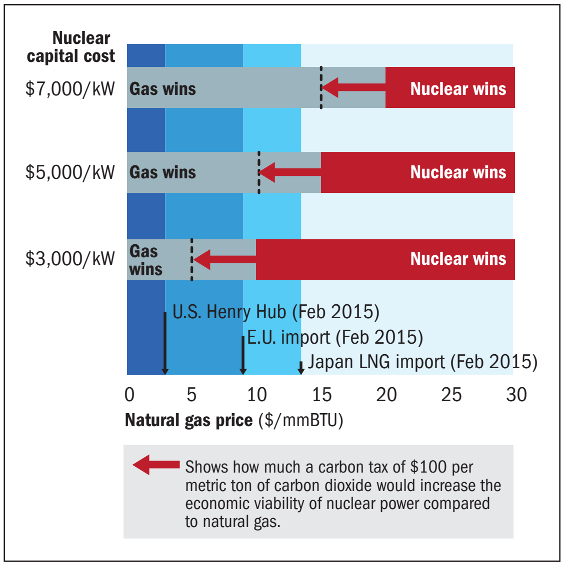


Figure 6.1: Nuclear power versus constant-power natural gas, for various gas prices and nuclear power capital costs, without and with a $100 per metric ton price of carbon dioxide.

What will determine how well small modular reactors will compete against large nuclear reactors?

A key economic challenge for small modular reactors is to compete with large nuclear reactors that provide the same capacity. Two effects influence the comparison in opposite ways: economies of scale and economies of serial production. For the same capacity, economies of scale can make a larger plant cheaper than a smaller plant. But economies of serial production can make a smaller plant cheaper, if small plants are produced in large numbers.

Economies of scale

The history of nuclear power can be understood as driven by the cost savings from bigness: in the 1950s and 1960s, nuclear reactors had power levels of 100 megawatts or less, but many of the reactors under construction today generate more than 1,000 megawatts, and some of the larger ones generate more than 1,500 megawatts. Economies of scale arise for both capital and operating costs. A 400-megawatt reactor does not need twice as much concrete or steel as a 200-megawatt reactor or require twice as many operating personnel. One way to visualize the scale economy is to compare the costs of transporting a group of 10 people: The cost of transporting the group in a large van is smaller than the cost of transporting each individual in a separate taxi, because a van does not cost 10 times as much as a car, nor does it need 10 drivers.

Such an analogy assumes that all 10 people need the transport services. The corresponding assumption is that all the electricity generated will be purchased. The market for electricity may be too small to justify a large reactor. The flexibility arising from phased construction of small modular reactors may outweigh a cost disadvantage when future demand for electricity is uncertain.

Since small modular reactors have an output electrical power of less than 300 megawatts, they are expected to suffer diseconomies of scale and therefore to have higher capital and operating costs per megawatt of capacity, when compared to the large reactors currently under construction or contemplated for construction.

Economies of serial production

Fewer large reactors than small reactors would need to be constructed to generate the same amount of electrical power. If many identical small modular reactors were constructed in a single factory, it is likely that unit costs would come down as a result of learning. Learning effects are well studied across many industries, including the nuclear industry. These effects are typically quantified by a "learning rate," the relative reduction in cost of construction, in percentage points, accompanying every doubling of the cumulative number of units. If a certain industry shows a learning rate of 10 percent for a technological product whose unit cost is $1,000 after construction of 3,000 units, it would be able to build its 6,000th unit for a price of $900.

A calculation displaying the trade-off between economies of scale and economies of serial production

It is by no means obvious that the methods used elsewhere in industry to quantify economies of scale and economies of serial production are appropriate for comparing small and large nuclear power plants. For one, there are significant differences in their designs: a small modular reactor is typically not just a scaled-down large reactor. Moreover, above some size, economies of scale are no longer realized: an airplane that has become too large to use existing runways, for example.

Similarly, there are reasons to doubt the usual models of economies of serial production. Below some number of production units, economies of serial production are not realized, because not enough experience has been gained to make further production routine. Furthermore, economies of serial production may not exhibit the same percentage cost reduction with doubled production for early doublings and late doublings (e.g., expanding from 300 to 600 units and later from 30,000 units to 60,000 units).

Nonetheless, existing tools can provide insights. Specifically, we calculate the number of small units that have to be built in order for the learning effects to cancel out the effects of diseconomies of scale.

All else being equal, the costs of two nuclear reactors with different power capacities but otherwise similar design will be related as the ratio of their power capacities raised to some exponent. Although there is no consensus in the literature regarding the appropriate exponents for economies of scale, an illustrative value for the exponent is 0.6. This relationship is a rule of thumb, not an exact estimate, but evidence for such scaling behavior is observed in many industries. To take a specific example, imagine that the capacities of the large and small reactors are 1,000 and 200 megawatts, respectively. Using 0.6 as the exponent in the rule, the cost of the 200 megawatt plant is not five times less but about 2.5 times less. As a result, the capital cost of producing 1,000 megawatts of power from five of the small plants is twice the cost of producing 1,000 megawatts from the large plant. Operations and maintenance costs also have a similar scaling behavior; that is, these costs too do not increase in linear proportion to the power output. Because the designs of many small modular reactors differ from the designs of their counterpart larger reactors in significant ways—for example, not using large pipes because steam generators are inside the pressure vessel (see Article 3)—scaling using an exponent of 0.6 must be considered only a crude approximation.

As for learning rates for nuclear power plants, analysts often use estimates in the range of 5 to 10 percent, even though in the two countries with the most reactors, the United States and France, learning has been negative and costs have increased with greater experience in construction. In the case of the United States, the cost escalation results in part from regulatory changes, in part from discovering more safety concerns, and in part from building custom-designed reactors, rather than reactors sharing the same design. How much learning will be possible with small modular reactors is difficult to predict in advance of extensive construction experience.

We work with an example. We combine a scale economy characterized by an exponent of 0.6 and a learning rate of either 10 percent or 5 percent for the small plants, a rate which comes into effect once 10 small plants have been produced. We further assume that there is no learning for the larger plants and that the capacities of the large and small plants are 1,000 and 200 megawatts, respectively. The result: with a learning rate of 10 percent, after 700 small plants have been produced they no longer cost more per kilowatt than a large plant: cost reductions from learning have overtaken cost penalties for smallness. With a slower learning rate of 5 percent and the other assumptions unchanged, the costs of large and small units cross only after 60,000 small units have been produced. This calculation illustrates the strong sensitivity of the crossover cost to the learning rate and the critical importance of fast learning for the competitiveness of small modular reactors. A slower learning rate for small modular reactors will result, for example, if several different reactor designs are deployed and none ends up dominating the marketplace.

Other considerations

Several considerations not yet discussed work to the advantage of a small reactor. The initial investment required to build a single small reactor will be considerably lower than that required to build a typical large reactor, possibly making it easier to borrow the necessary capital from financial markets. A lower construction cost also permits a utility to risk a smaller fraction of its capital on a single nuclear project. A shorter construction time reduces the costs of paying interest to lenders during the construction period. Longer construction periods have been a major factor responsible for cost escalation for nuclear reactors. The same expert elicitation described above estimates a shortening of the construction period from five years to three years. These experts, however, see substantial complications in any single facility that integrates several small units, because of complexities during the licensing phase, during construction, during routine operation, and during accidents.

Article 7: Policy

Several governments around the world are supporting the development and deployment of small modular reactors in a variety of ways (see Figure 7.1). In March 2012, the U.S. Department of Energy (DOE) established a cost-sharing program with the nuclear industry to support pre-construction activities for first-of-a-kind small modular reactors. The program was initially funded with $452 million to cover costs associated with research and development, design certification, and licensing. Although the program was open to any kind of small modular reactor, almost all the applications featured pressurized-water reactor designs from the first family described in Article 2.

Figure 7.1: Countries with small modular reactors under development.

In November 2012, the DOE selected the Babcock and Wilcox mPower reactor for cost-sharing. Babcock and Wilcox was to provide at least 50 percent of the total cost for the design, certification, and licensing of the mPower reactor; the maximum funding from the DOE was to be $226 million. A second award of up to $217 million over five years was provided to NuScale Power in December 2013. In early 2014, Babcock and Wilcox announced that it was significantly reducing its funding, by over three-quarters compared to the previous year, for research and development; subsequently, the DOE lowered its quarterly funding for the project as well.

In contrast to the United States, the first prototype small modular reactor construction occurring in China involves a reactor from the second family: a 210-megawatt pebble-bed reactor called the HTR-PM (High Temperature Reactor – Pebble-bed Module; see Box 2 in Article 2). The first reactor is being built in Shiadowan, in Shandong Province. The pebble-bed design was developed at Tsinghua University in Beijing on the basis of a design developed initially in Germany in the 1970s and considered seriously for a time in South Africa. Both Germany and South Africa, however, decided not to pursue the technology. But while the South African pebble-bed reactor design used helium to drive a turbine and generate electricity—a challenging technology—the Chinese design uses a more traditional steam generator that operates at a somewhat lower temperature. The China National Nuclear Corporation is also aggressively developing a light-water reactor design called ACP-100 (see Box 1 in Article 2). In April 2015, the China National Nuclear Corporation entered into an agreement with the International Atomic Energy Agency to have the design's safety reviewed by international experts.

Russia is developing two very different small modular reactors based on its marine reactors. The first 70-megawatt KLT-40S floating power plant is under construction (see Box 5 in Article 2), and a larger small modular reactor, the VBER-300, another pressurized-water reactor design, is in development. But Russia, like China, is also developing reactors that are not light-water reactors, such as a fast-neutron reactor cooled with molten lead, which is based on a reactor design used in a series of nuclear submarines built in the 1970s.

South Korea, France, India, and Argentina are also developing small modular reactor designs. In 2012, the South Korean regulatory agency, the Nuclear Safety and Security Commission, issued a Standard Design Approval, essentially a construction license without a specific site evaluation, for the SMART (100 megawatts; see Box 1 in Article 2), making it the first small modular reactor to be licensed that is based on pressurized-water technology (the first of our four families). France is drawing upon its experience with nuclear-powered submarines in developing the Flexblue reactor (see Box 5 in Article 2). In line with the traditional focus of its nuclear power program, India is developing an AHWR (advanced heavy-water reactor) that uses heavy water (water altered so that nearly all the hydrogen atoms are the heavier isotope of hydrogen, deuterium) to slow down neutrons. This reactor is fueled with a mixture of thorium and plutonium. While the design has received most regulatory approvals, no site has been selected, in part because the designers want to deploy it without an emergency planning zone. In 2014, Argentina started constructing CAREM-25, a prototype small modular reactor that belongs to the first family (see Box 1 in Article 2).

The International Atomic Energy Agency has initiated a series of programs aimed at promoting small modular reactors, especially for developing countries that are considering their first nuclear power plants. An important focus has been the evaluation of alternative technologies and the development of tools to facilitate national planning efforts.

Table 7.1 Small modular reactors discussed in Article 2

Name	Country	Family	Power Rating (mega-watts)	Moderator	Coolant	Fuel Type (uranium enrichment level)	Refueling period or lifetime
NuScale	USA	1	50	Water	Water	Enriched Uranium (4.95 %)	24 months
B&W mPower	USA	1	180	Water	Water	Enriched Uranium (4.95 %)	48 months
SMART	South Korea	1	90	Water	Water	Enriched Uranium (4.88 %)	36 months
ACP-100	China	1	100	Water	Water	Enriched Uranium (4.2 %)	24 months
CAREM-25	Argentina	1	25	Water	Water	Enriched Uranium (3.1 %)	14 months
HTR-PM	China	2	210	Graphite	Helium	Enriched Uranium (8.8 %)	Continuous refueling
IMSR	Canada	2	Variable	Graphite	Molten salts	Enriched Uranium	Continuous refueling
GE Hitachi PRISM	USA	3	311	None	Sodium	Plutonium (26 %)	18 months
General Atomics EM2	USA	3	240	None	Helium	Depleted Uranium plus Plutonium	30 years
Traveling Wave Reactor TWR	USA	3	600	None	Sodium	Depleted Uranium plus enriched Uranium as a seed	40 years
Waste-Annihilating Molten-Salt Reactor WAMSR	USA	3	520	Zirconium hydride	Molten salts	Enriched Uranium (2%)	Continuous refueling
Toshiba 4S	Japan	4	10	None	Sodium	Enriched Uranium (19.9 %)	30 years
G4M	USA	4	25	None	Lead Bismuth	Enriched Uranium (19.75 %)	10 years
AFPR-100	USA	4	100	Graphite	Water	Enriched Uranium (10 %)	40 years
KLT-40S	Russia	4	70	Water	Water	Enriched Uranium (14.1 %)	28 months
Flexblue	France	4	160	Water	Water	Enriched Uranium (5 %)	36 months

Note: Many of these designs are evolving, and the power levels and other characteristics keep changing. This table was constructed in May 2015. Blue-shaded designs are licensed while orange-shaded designs are currently under construction.

Appendix: Key Concepts and Vocabulary for Nuclear Energy

Power Plant

In most power plants around the world, heat, usually produced in the form of steam, is converted to electricity. The heat could come through the burning of coal or natural gas, in the case of fossil-fueled power plants, or the fission of uranium or plutonium nuclei. The rate of electrical power production in these power plants is usually measured in megawatts or millions of watts, and a typical large coal or nuclear power plant today produces electricity at a rate of about 1,000 megawatts. A much smaller physical unit, the kilowatt, is a thousand watts, and large household appliances use electricity at a rate of a few kilowatts when they are running. The reader will have heard about the “kilowatt-hour,” which is the amount of electricity consumed when electricity is used for an hour at a rate of one kilowatt, or for two hours at a rate of half a kilowatt.

Nuclear Fission

Nuclear fission is the process by which the nucleus of a very heavy atom, such as uranium or plutonium, absorbs a neutron and splits into two lighter nuclei (called fission products), releasing additional energy (see Figure A.1). Neutrons are uncharged subatomic particles that are present alongside protons inside the atomic nucleus. Being uncharged, neutrons can approach the positively charged nucleus without being repelled, and that enables them to induce nuclear reactions such as fission.

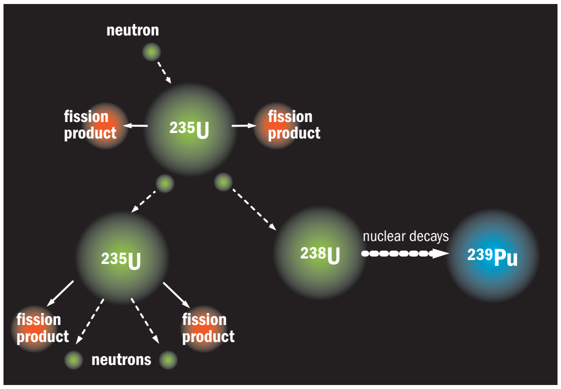


Figure A.1: A chain reaction produces steady power when the neutrons produced in every fission event produce exactly one further fission event. Plutonium is produced via neutrons that do not produce fission events.

The likelihood of fission depends on, among other things, the energy of the incoming neutron. Some nuclei can undergo fission even when hit by a low-energy neutron. Such elements are called fissile. The most important fissile nuclides are the uranium isotopes, uranium-235 and uranium-233, and the plutonium isotope, plutonium-239. Isotopes are variants of the same chemical element that have the same number of protons and electrons, but differ in the number of neutrons. Of these, only uranium-235 is found in nature, and it is found only in very low concentrations. Uranium in nature contains 0.7 percent uranium-235 and 99.3 percent uranium-238. This more abundant variety is an important example of a nucleus that can be split only by a high-energy neutron.

When a neutron comes close to any of these nuclei, it can not only fission them, it can also be absorbed by them. When a neutron is absorbed, the result is a different nucleus, often an unstable one that decays into yet another one. For example, after absorbing a neutron, uranium-238 becomes plutonium-239 through a series of nuclear decays. Analogously, when a neutron is absorbed by thorium-232, which is the only naturally occurring isotope of thorium, the result after two decays is uranium-233.

During fission, neutrons are released, typically two or three per fission. A chain reaction can result if enough of these neutrons can be absorbed by other heavy nuclei, causing these nuclei to split in turn, and so on. An important prerequisite is the presence of an adequate amount of fissile material in close physical proximity. In a nuclear reactor the chain reaction is tightly controlled, so that the number of fissions in one “generation” is exactly equal to that in the previous generation; the result is that energy (heat) is produced in a steady manner. By contrast, in a nuclear bomb, the fissions roughly double in each generation, leading to the release of a great deal of energy in a very short period of time, i.e., a nuclear explosion.

Nuclear Reactors

The region of the reactor where the self-sustaining chain reaction occurs and heat is produced from the slowing down of the fission products is called the nuclear core, or simply the core. A nuclear reactor includes not only the core, but also a heat exchanger where the heat from the coolant is transferred to either water (producing steam) or a gas. The steam or hot gas then drives a turbine that produces electricity. The size of a reactor can be quantified either by its rate of heat production in its core or the rate at which electricity is exported onto high-voltage transmission lines. Roughly, three units of heat produced at the core are converted into one unit of electricity and two units of degraded heat that is rejected to the local environment. In this distillate all sizes refer to its electricity production rate, measured in megawatts.

Small Modular Reactor

The International Atomic Energy Agency categorizes any reactor having an electrical output less than 300 megawatts as a small reactor. The term “small” is used in comparison with the average power delivered by currently operating reactors and the reactors under construction, which is just under 1,000 megawatts.

“Modular” means that the reactor is mostly constructed within a factory, with only limited assembly of factory-fabricated “modules” at the site of the power plant itself. Each module represents a portion of the finished plant. Depending on the reactor design, it may even be possible to manufacture the entire reactor in a factory and ship it to the reactor site. Modular construction has been increasingly incorporated into the building of nuclear reactors of all sizes, including large reactors. However, some components of a large reactor are so physically big and heavy that they cannot be transported and must be assembled on site. For example, the containment structure that envelops each of the AP1000 reactors being built in Georgia and South Carolina in the United States has four rings, the largest of which weighs over 650,000 kilograms. The word “modularity” also conveys the idea that rather than constructing one large reactor, the equivalent power output will be generated by multiple smaller reactors, thereby allowing greater tailoring of generation capacity to demand.

Reactor Types

Several nuclear reactor designs have been constructed, and many, many more have been proposed. These designs make very different choices for the kind of fuel used, the materials used to cool the reactor, and (if the neutrons are deliberately slowed down) for the materials used to slow down (or moderate) the neutrons.

Fuel

The fuel used in a reactor must contain one or more of the limited number of fissile isotopes. However, this fuel can take different forms—solid pellets of uranium oxide, a mixture of uranium and plutonium metals fashioned into thin rods, uranium tetrafluoride dissolved in a molten salt, thousands of small uranium oxide particles coated with multiple layers of different carbon compounds and embedded in graphite to form spheres roughly the size of a tennis ball, and so on.

Uranium Enrichment

Fuels also differ in the uranium-235 enrichment level in the uranium fuel, relative to its concentration in the uranium in the Earth’s crust (“natural uranium”). Natural uranium consists of about 99.3 percent uranium-238 and 0.7 percent uranium-235 (the fissile isotope of uranium). The process of increasing the fraction of uranium-235 is called enrichment. Enrichment can be done by various technologies, including gaseous diffusion (the favored choice in the early days of nuclear energy) and gas centrifuges (today’s technology of choice).

Uranium enrichment using centrifuge technology is achieved by feeding the uranium in the form of uranium hexafluoride gas to fast-spinning cylinders (up to 100,000 rotations per minute). Once inside the cylinder, the heavier uranium-238 nucleus drifts towards the outside wall of the cylinder, resulting in a gas enriched in uranium-235 at the center of the cylinder. The central gas molecules are then fed to the next centrifuge and so on, in a “cascade,” until the desired level of enrichment is achieved.

Uranium in which the percentage of uranium-235 nuclei is not more than 20 percent is called low-enriched uranium, and when the percentage is more than 20 percent, it is called highly enriched uranium.

Coolant

A typical fission event produces about 200 million electron volts of energy. (Individual chemical reactions, such as the oxidation of a single molecule of hydrogen by oxygen, typically produce at most only a few electron volts of energy.) Over 80 percent of the energy released in fission is in the form of the kinetic energy of fast-moving fission products.

The kinetic energy turns into heat in the fuel as the fission fragments slow down, and this heat is then transferred into the reactor's coolant. Coolants come in three primary forms: gases (usually helium or carbon dioxide), liquids (usually ordinary water or heavy water), or molten metals (usually liquid sodium or lead).

Moderator

Reactors are distinguished by whether a neutron produced by fission mostly creates another fission before being slowed down, or this neutron is slowed down first and then produces another fission. Those reactors where the neutrons are not slowed down are called fast-neutron reactors, and those where the neutrons are slowed down are called thermal-neutron reactors. Fast neutrons travel at around 5 percent of the speed of light while thermal neutrons travel at around eight-millionths of the speed of light. The slowing down is achieved by collisions with light nuclei, such as hydrogen in water or carbon in graphite. When a neutron collides with a light nucleus it slows down more than when it hits a heavy one, because the light nucleus recoils more and carries away more of the neutron's original kinetic energy.

A chain reaction can be sustained with slow neutrons and natural uranium. If the moderator is water, it must be "heavy water," where the common form of hydrogen in water is replaced with a heavier form, deuterium. The hydrogen in ordinary water ("light-water") absorbs too many neutrons for a chain reaction to be sustained in natural uranium. In light-water reactors, the fuel must be enriched in the uranium-235 component in order to sustain a chain reaction. Typically, a light-water reactor requires 3 to 5 percent uranium-235.

Spent Fuel and Nuclear Waste

The radioactive products resulting from fission are not the only radioactive nuclei in a nuclear reactor. There are also structural materials made radioactive by neutron bombardment and radioactive "transuranic" elements (elements whose nuclei have more protons than uranium: neptunium, plutonium, americium, curium), produced when uranium-238 nuclei in the fuel absorb one or more neutrons followed by further decay processes. The fission products, the activated structural material, and the transuranic elements contain a mix of nuclei with all sorts of half-lives, from seconds to millions of years. Radioactive waste management is therefore a complex and highly regulated undertaking.

The irradiated fuel that is discharged from a nuclear reactor is called spent or used fuel. Spent fuel consists mainly of the uranium that has not undergone fission, fission products, and transuranic elements, notably the plutonium that has been produced by neutron absorption and subsequent transformation. Because of the high levels of heat and radiation emitted by spent fuel, upon discharge it is stored in pools of water. After several years, the spent-fuel elements can become cool enough to be taken out of water and stored in large air-cooled ceramic casks. This dry storage method has become more common in recent years as spent-fuel pools have been filling up, including at U.S. nuclear reactor sites.

The transuranic nucleus produced in greatest quantity in nuclear reactors is plutonium-239, created after a neutron is absorbed by uranium-238, the common uranium nucleus. Plutonium-239 can also be used in reactor fuel. This opens up the possibility of extracting a much greater amount of energy from the original uranium and providing fuel for more reactors from the finite amount of uranium ore available. The presence of plutonium in spent fuel has led some countries to adopt a chemical treatment method called "reprocessing" to separate out the plutonium.

Reprocessing can be done using a variety of chemical processes. The conventional method is called the Plutonium Uranium Redox EXtraction process, or PUREX for short, and was originally developed to separate out the plutonium for weapons. The process starts with chopping up the spent fuel and adding it to a hot nitric acid solution which dissolves the uranium, plutonium, and fission fragments but not the fuel's metallic alloy cladding. Later, the plutonium and uranium are separated from the fission products and transuranic elements. Other forms of reprocessing result in a product where the plutonium remains mixed with other transuranic elements.

Reprocessing creates the possibility of diverting the separated plutonium for use in nuclear weapons. Direct disposal is the alternative to all forms of reprocessing, including ones where plutonium is in a mixed form. Direct disposal of spent fuel requires permanent storage in a geological or other final repository. In this alternative the plutonium left in the spent fuel is relatively inaccessible, because the fission products provide a radioactive barrier to its removal. At present, wherever there is reprocessing, it only is done once, and spent fuel from reactors that have used reprocessed fuel is not reprocessed a second time. This is mainly due to technical challenges of reprocessing such spent fuel using currently deployed chemical processes.

Nuclear Weapons

Nuclear weapons are either pure fission explosives, such as the Hiroshima and Nagasaki bombs, or two-stage thermonuclear weapons with a fission explosive as the first stage and a fusion explosive as the second stage. The former are easier to produce. In a fission weapon, a sufficient quantity of fissile material has to be brought into close proximity so that it can sustain a chain reaction for a brief period. The amount of fissile material required depends on a number of design details.

The bomb that was dropped over the Japanese city of Hiroshima in 1945 contained about 60 kilograms of uranium enriched to about 80 percent in fissile uranium-235. In that design, the uranium was initially in two pieces, and one was fired into the other to bring together enough material for a chain reaction to be set off. The resulting explosion released roughly the equivalent of 15,000 tons of chemical explosive.

The bomb that was dropped on Nagasaki, on the other hand, used plutonium rather than enriched uranium. It used the technique of implosion, where chemical explosives compress a sphere of plutonium. The compression reduces the spaces between the atomic nuclei and thereby the distance a neutron released in one fission has to travel before it causes another fission. Once the plutonium is sufficiently compressed, it becomes capable of sustaining a chain reaction. Practically any mixture of plutonium isotopes (plutonium-239, plutonium-240, plutonium-241, and even higher isotopes) can be used to make nuclear weapons.

The implosion technique is also used in modern nuclear weapons that use enriched uranium, because compression reduces the quantity of uranium required to set off a nuclear explosion. The uranium in modern nuclear weapons typically is enriched to a uranium-235 concentration of at least 90 percent.

The key metric that is used to measure the linkage between nuclear energy and nuclear weapons is called a “significant quantity”. The International Atomic Energy Agency defines a significant quantity as the approximate amount of fissile material “for which the possibility of manufacturing a nuclear explosive device cannot be excluded.” The significant quantities are 8 kilograms for plutonium and 25 kilograms of uranium-235 contained in highly enriched uranium, including losses during production. The definition is based on the Nagasaki design. More sophisticated nuclear weapon designs use smaller quantities of fissile materials.

A single 1,000-megawatt light-water reactor produces about 30 significant quantities of plutonium during each year of operation (see Figure 4.1). Although the purpose of the initial build-up of plutonium stockpiles globally was to manufacture weapons, since the end of the Cold War a second stockpile of plutonium from the reprocessing of civilian spent fuel has been growing rapidly. Roughly 30,000 significant quantities of plutonium were produced explicitly for nuclear weapon purposes. Reprocessing of spent fuel from civilian power reactors already has resulted in the separation of roughly 30,000 significant quantities of plutonium, approximately the same amount as what was produced for weapon purposes.

Until recently, those focused on the diversion of civilian nuclear materials to weapons use focused far more on plutonium than enriched uranium, because of the perceived difficulty of enriching uranium. In recent years, however, as centrifuge enrichment has become cheaper, the prospect of clandestine production of highly enriched uranium has resulted in the front and back ends of the fuel cycle receiving comparably intense attention.