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.