THE LITTLE REACTORS THAT COULD

Billed as safe and cheap, NuScale's small reactors aim to revive the ailing nuclear industry and help save a warming planet

By **Adrian Cho,** *in Corvallis, Oregon*

To a world facing the existential threat of global warming, nuclear power would appear to be a lifeline. Advocates say nuclear reactors, compact and able to deliver steady, carbon-free power, are ideal replacements for fossil fuels and a way to slash greenhouse gas emissions. However, in most of the world, the nuclear industry is in retreat. The public continues to distrust it, especially after three reactors melted down in a 2011 accident at the Fukushima Daiichi Nuclear Power Plant in Japan. Nations also continue to dither over what to do with radioactive reactor waste. Most important, with new reactors costing $7 billion or more, the nuclear industry struggles to compete with cheaper forms of energy, such as natural gas. So even as global temperatures break one record after another, just one nuclear reactor has turned on in the United States in the past 20 years. Globally, nuclear power supplies just 11% of electrical power, down from a high of 17.6% in 1996.

Jose Reyes, a nuclear engineer and cofounder of NuScale Power, headquartered in Portland, Oregon, says he and his colleagues can revive nuclear by thinking small. Reyes and NuScale's 350 employees have designed a small modular reactor (SMR) that would take up 1% of the space of a conventional reactor. Whereas a typical commercial reactor cranks out a gigawatt of power, each NuScale SMR would generate just 60 megawatts. For about $3 billion, NuScale would stack up to 12 SMRs side by side, like beer cans in a six-pack, to form a power plant.

But size alone isn't a panacea. "If I just scale down a large reactor, I'll lose, no doubt," says Reyes, 63, a soft-spoken native of New York City and son of Honduran and Dominican immigrants. To make their reactors safer, NuScale engineers have simplified them, eliminating pumps, valves, and other moving parts while adding safeguards in a design they say would be virtually impervious to meltdown. To make their reactors cheaper, the engineers plan to fabricate them whole in a factory instead of assembling them at a construction site, cutting costs enough to compete with other forms of energy.

Spun out of nearby Oregon State University (OSU) here in 2007, NuScale has spent more than $800 million on its design—$288 million from the Department of Energy (DOE) and the rest mainly from NuScale's backer, the global engineering and construction firm Fluor. The design is now working its way through licensing with the Nuclear Regulatory Commission (NRC), and the company has lined up a first customer, a utility association that wants to start construction on a plant in Idaho in 2023.

NuScale is far from alone. With similar projects rising in China and Russia, the company is riding a global wave of interest in SMRs. "SMRs as a class have a potential to change the economics," says Robert Rosner, a physicist at the University of Chicago in Illinois who co-wrote a 2011 report on them. In the United States, NuScale is the only company seeking to license and build an SMR. Rosner is optimistic about its prospects. "NuScale has really made the case that they'll be able to pull it off," Rosner says.

For now, NuScale's reactors exist mostly as computer models. But in an industrial area north of town here, the company has built a full-size mock-up of the upper portion of a reactor. Festooned with pipes, the 8-meter-tall gray cylinder isn't exactly

PHOTO: NUSCALE POWER, LLC

NuScale researchers want to operate 12 small nuclear reactors from a single control room. They built a mock one in Corvallis, Oregon, to show they can do it.

small. It resembles the conning tower of a submarine, one that has somehow surfaced through the dusty ground. NuScale built it to see if workers could squeeze inside for inspections, says Ben Heald, a NuScale reactor designer. "It's a great marketing tool."

Not everyone thinks NuScale will make the transition from mock-up to reality, however. Dozens of advanced reactor designs have come and gone. And even if NuScale and other startups succeed, the nuclear industry won't build enough plants quickly enough to matter in the fight against climate change, says Allison Macfarlane, a professor of public policy and geologist at George Washington University in Washington, D.C., who chaired NRC from 2012 through 2014. "Nuclear does not do anything quickly," she says.

A NUCLEAR REACTOR is a glorified boiler. Within its core hang ranks of fuel rods, usually filled with pellets of uranium oxide. The radioactive uranium atoms spontaneously split, releasing energy and neutrons that go on to split more uranium atoms in a chain reaction called fission. Heat from the chain reaction ultimately boils water to drive steam turbines and generate electricity. Designs vary (see sidebar, p. 809), but 85% of the world's 452 power reactors circulate water through the core to cool it and ferry heat to a steam generator that drives a turbine.

The water plays a second safety role. Power reactors typically use a fuel with a small amount of the fissile isotope uranium-235. The dilute fuel sustains a chain reaction only if the neutrons are slowed to increase the probability that they'll split other atoms. The cooling water itself serves to slow, or moderate, the neutrons. If that water is lost in an accident, fission fizzles, preventing a runaway chain reaction like the one that blew up a graphite-moderated reactor in 1986 at the Chernobyl Nuclear Power Plant in Ukraine.

Even after the chain reaction dies, however, heat from the radioactive decay of nuclei created by fission can melt the core. That happened at Fukushima when a tsunami swamped the emergency generators needed to pump water through the plant's reactors.

NuScale's design would reduce such risks in multiple ways. First, in an accident the small cores would produce far less decay heat. NuScale engineers have also cut out the pumps that drive the cooling water through the core, relying instead on natural convection. That design eliminates moving parts that could fail and cause an accident in the first place, says Eric Young, a NuScale engineer. "If it's not there, it can't break," he says.

NuScale's new reactor housings offer further protection. A conventional reactor sits within a reinforced concrete containment vessel up to 40 meters in diameter. Each 3-meter-wide NuScale reactor nestles into its own 4.6-meter-wide steel containment vessel, which by virtue of its much smaller diameter can withstand pressures 15 times greater. The vessels sit submerged in a vast pool of water: NuScale's ultimate line of defense.

For example, in an emergency, operators can cool the core by diverting steam from the turbines to heat exchangers in the pool. During normal operations, the space between the reactor and the containment vessel is kept under vacuum, like a thermos, to insulate the core and allow it to heat up. But if the reactor overheats, relief valves would pop open to release steam and water into the vacuum space, where they would transfer heat to the pool. Such passive features ensure that in just about any conceivable accident, the core would remain intact, Reyes says.

To prove that the reactor will behave as predicted, NuScale engineers have constructed a one-third scale model. A 7-meter-tall tangle of pipes, valves, and wires lurks in the corner of a lab at OSU's department of nuclear engineering. The model aims not to run exactly like the real reactor, Young says, but rather to validate the computer models that NRC will use to evaluate the design's safety. The model's core heats water not with nuclear fuel but with 56 electric heaters like those in curling irons, Young says. "It's like a big percolator," he says. "We set up a test and watch coffee being made for 3 days."

Making a reactor smaller has a downside, says M. V. Ramana, a physicist at the University of British Columbia in Vancouver, Canada. A smaller reactor will extract less energy from every ton of fuel, he argues, driving up operating costs. "There's a reason reactors became larger," Ramana says. "Inherently, NuScale is giving up the advantages of economies of scale."

But small size pays off in versatility, Reyes says. One little reactor might power a plant to desalinate seawater or supply heat for an industrial process. A customized NuScale plant might support a developing country's smaller electrical grid. And in the developed world, where intermittent renewable sources are growing rapidly, a full 12-pack of reactors could provide steady power to make up for the fitful output of windmills and solar panels. By varying the number of reactors producing power, a NuScale plant could "load follow" and fill in the gaps, Reyes says.

SUCH VISIONS point to another key aspect of NuScale's plans: Designers want to dramatically change how nuclear plants are organized and run. Under NRC regulations, a control room can operate no more than two reactors, in which case it must have a staff of at least six operators. NuScale wants permission to run a dozen of their simpler, safer reactors from such a control room. "People have laughed at me when I said I could run this plant with six people," says NuScale senior operations engineer Ross Snuggerud.

To show that it's possible, NuScale engineers built a fully operational control room to run a virtual power plant. The control room, locked away on the second floor of NuScale's building in an industrial park along the Willamette River, has a wall of jumbo high-resolution monitors that display the 12 virtual reactors' performance. On a recent day, Snuggerud manipulates a touch screen to cook up a mock crisis. Reactivity spikes in one of the 12 virtual reactors. Graphite control rods, which should drop into the core to absorb neutrons and stop the reaction, fail to respond.

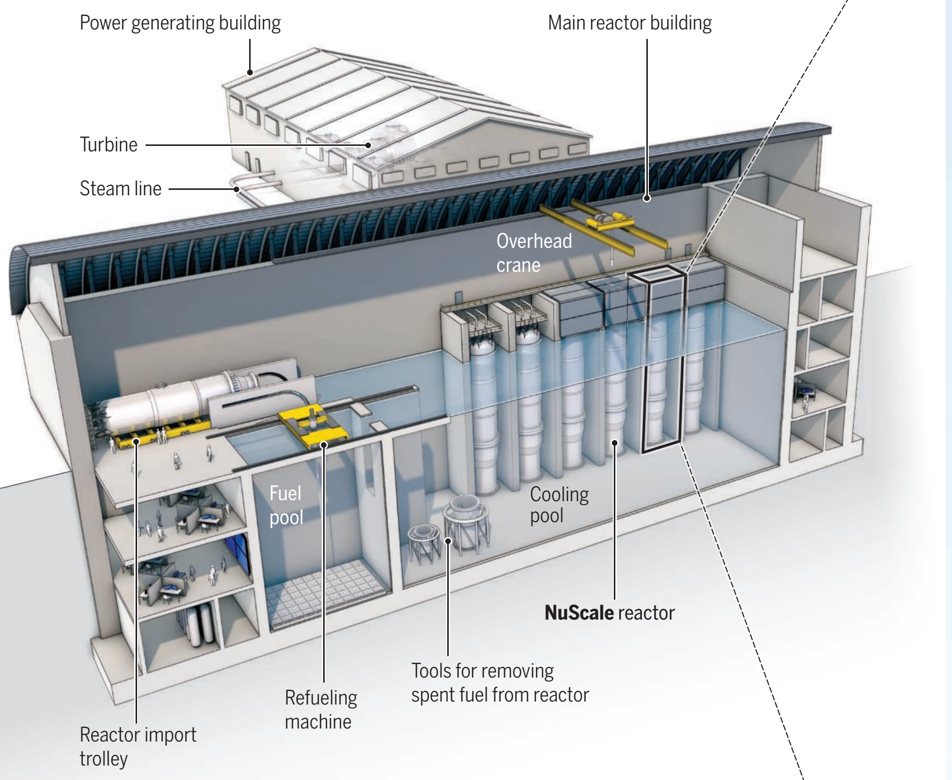
An alarm sounds. Lights flash. The core's temperature surges. But the NuScale reactor handles the crisis with ease. Within minutes, temperatures fall as the reactor automatically shunts heat into the pool. So is melting the core impossible? "No responsible engineer would say 'never,'" Snuggerud says. "But we've done a lot of things right to ensure the core's integrity."

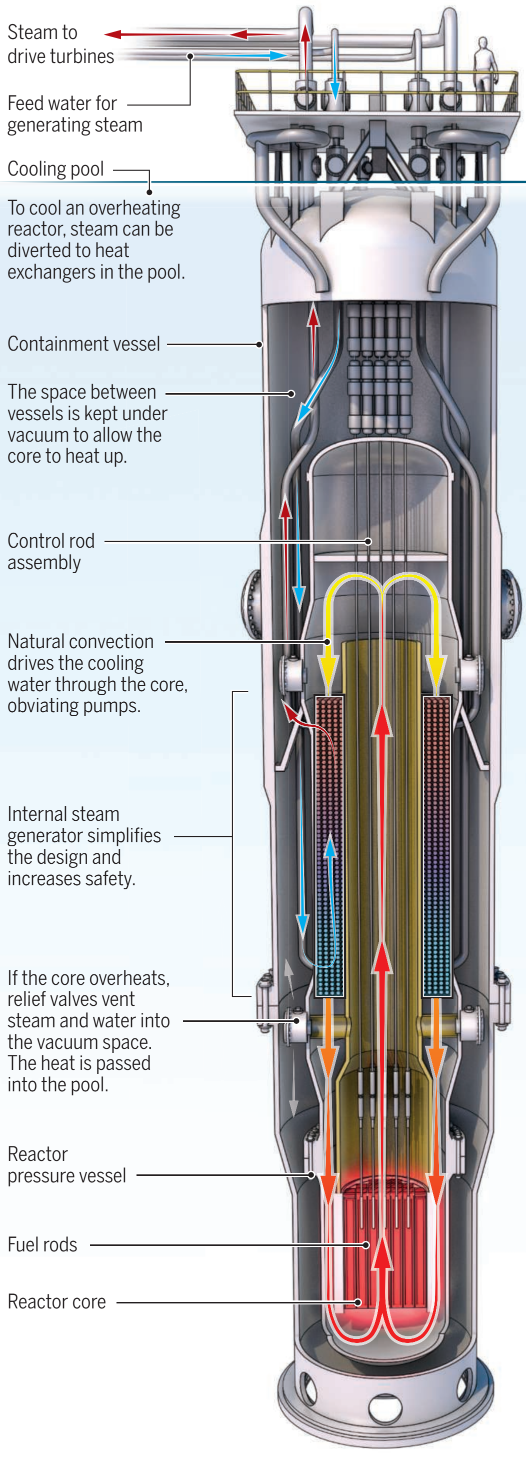
NuScale engineers must convince NRC that a real plant would run as placidly. Two years ago, the company submitted its 12,000-page application, and the review should conclude by September 2020. The NuScale team has plenty of experience with such reviews. While Reyes was at OSU, he helped NRC certify two conventional Westinghouse designs. If approved, NuScale's design would be the first that NRC has licensed since 2014.

NuScale has responded to more than 1500 formal requests for more information, about a third of the typical number, says Carrie Fosaaen, a licensing specialist at NuScale. "I think that speaks volumes about what we put together up front," she says. Still, Fosaaen says, "Our design is so different that it's a challenge even for people who have done a lot of licensing."

Twelve-pack of power

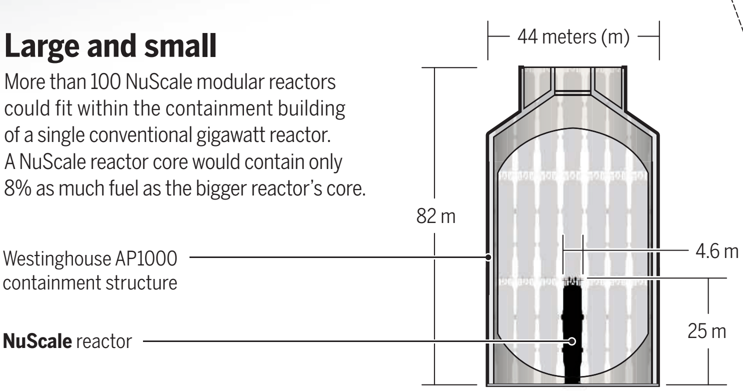
A NuScale plant would submerge 12 small modular reactors in a single pool of water. Each reactor has passive safety features that would help avoid a meltdown, and the simple design eliminates the pumps and pipes that could fail and cause an accident. To keep costs down, the factory-built reactors would be sent whole to a construction site.





Large and small

More than 100 NuScale modular reactors could fit within the containment building of a single conventional gigawatt reactor. A NuScale reactor core would contain only 8% as much fuel as the bigger reactor's core.



GRAPHIC: C. BICKEL/SCIENCE

If interpreted strictly, Fosaaen says, NRC regulations would push NuScale engineers toward building a miniature version of a conventional reactor—exactly what they don't want to do. So the task, she says, is to explain to regulators how the NuScale design is safe without having to add back layers of complexity.

Some of NuScale's requests are bold. The company has asked NRC to eliminate a requirement for backup electrical power because its reactors can shut down without power. Similarly, NuScale wants to avoid a requirement for an emergency evacuation zone 32 kilometers wide, arguing its reactors pose no risk of spreading radiation beyond the plant boundary. Such a rule change would enable a utility to replace an aging coal plant with a NuScale plant in a populated area. "That's something that utilities really want," Reyes says.

Such requests strike one prominent critic as hubris. Nuclear safety relies on layers of protection, says Edwin Lyman, a physicist with the Union of Concerned Scientists in Washington, D.C., and NuScale is peeling them away to cut costs. "To say that you know so well how a new reactor will work that you don't need an emergency evacuation zone, that's just dangerous and irresponsible," he says. However, Jacopo Buongiorno, a nuclear engineer at the Massachusetts Institute of Technology (MIT) in Cambridge, says NuScale's requests are reasonable and likely to win approval. "I would disagree that they're removing safety features," he says. "Quite the opposite."

NUSCALE ENGINEERS ARE ITCHING to build a real plant. The company has a tentative deal with Utah Associated Municipal Power Systems (UAMPS), a consortium of 46 public utilities in six western states, to build a 12-pack plant at DOE's Idaho National Laboratory near Idaho Falls as part of UAMPS's carbon-free power project. As DOE's lead nuclear energy lab, Idaho National Laboratory would use one module for research and another to supply the lab with power. The other 10 modules would feed the grid. UAMPS should decide this year about the plant, which would be built by 2027.

NuScale expects other customers to follow. "There are many companies that don't want to be first but would clearly like to be second in line," says Tom Mundy, NuScale's chief commercial officer. According to a 2014 report by the National Nuclear Laboratory in Sellafield, U.K., by 2035 SMRs could provide 65 to 85 gigawatts of power globally, a building spree worth between $320 billion and $510 billion. Engineers in Argentina, China, Russia, and South Korea have all developed SMR designs. However, because of the quality of its design, "internationally, NuScale is going to be a formidable competitor," Rosner predicts.

To succeed, NuScale will have to compete with cheap natural gas. The company aims to produce electricity at a total cost, including construction and operations, of $65 per megawatt-hour. That's about 20% higher than the current cost of energy from a gas-powered plant. However, Rosner says, "The price of gas isn't going to stay low forever." Countries also could put a price on carbon emissions, which would drive up the cost of fossil-fuel power. In fact, a September 2018 report from MIT indicated that a carbon tax could make nuclear competitive with gas.

Nuclear power could face even stiffer competition from renewable sources of energy such as wind and solar power, which are getting cheaper and cheaper, Ramana says. And given the numbers, Lyman says he expects NuScale will find few customers—and that's only if DOE subsidizes the deals, as it has for UAMPS. "I just don't see this tsunami of small reactors around the world," he says, "and it's because the economics is so bad." But like many experts, Reyes argues that an energy economy based on renewables will require some form of steady "baseload" power—and nuclear, unlike gas, can deliver it without carbon emissions.

Although NuScale is eager to break ground in the United States, an indicator of its prospects may come from across the Atlantic. To reduce carbon emissions, the United Kingdom has committed to shuttering its remaining seven coal-fired power plants by 2025. It could replace them with gas-fired plants, but NuScale is trying to persuade U.K. government officials to make a bolder choice and opt for its nuclear plants. "We are not a concept, we are not a technology that is still on the drawing board," Mundy says. "We're real." A few years should tell whether that's true. ■

The quest for boundless energy

For all their innovations, NuScale Power's small modular reactors remain conventional in one way: They would use ordinary commercial reactor fuel that's meant to be used once and safely disposed of. But for decades, nuclear engineers envisioned a world powered by "fast reactors" that can breed an essentially boundless supply of fuel as they operate while producing less long-lived radioactive waste to boot. The dream lives on today in dozens of designs for advanced fast reactors meant to be cheaper and safer than their predecessors.

The uranium fuel for a typical nuclear reactor contains less than 5% of the isotope uranium-235. Its nuclei can split, or fission, to release energy and neutrons. The dilute fuel sustains a chain reaction only if the neutrons are slowed by a moderator, typically the reactor's cooling water, to increase the probability that they'll split other nuclei. In contrast, a fast reactor runs without a moderator by using a fuel richer in uranium-235, or one containing plutonium. Both fuels produce copious neutrons. They enable a fast reactor to breed more fuel as neutrons shower nuclei of uranium-238, turning them into fissile plutonium-239, which can be recovered by reprocessing the fuel.

In the 1950s, early in the atomic age, experts believed nuclear energy would one day supply most of the world's power, raising the specter of uranium fuel shortage and boosting interest in fast breeder reactors.

However, those reactors are complex and hard to manage. They must be cooled with substances such as liquid sodium or molten salt. The chemically intensive recycling process produces plenty of its own hazardous waste. And the closed fuel cycle would establish a global market for plutonium, the stuff of atomic weapons, raising proliferation concerns. Just 19 fast reactors—most, small research reactors—have ever run. Today, only five are operating: three in Russia, one in China, and one in India.

Just as with conventional water-cooled reactors (see main story, p. 806), engineers are now emphasizing small modular designs for fast reactors. In some designs, the plutonium is bred and then "burned" in place, eliminating the need to reprocess the fuel.

But some experts doubt that fast reactors will ever become mainstream. "The waste issues are probably what's going to choke the life out of the fast-reactor designs," says Allison Macfarlane, a professor of public policy and geologist at George Washington University in Washington, D.C., and former chairman of the Nuclear Regulatory Commission.

Perhaps most important, nuclear energy supplies just 11% of global electrical power, and uranium reserves are larger than once expected. The world is in no danger of running out of uranium, says Jacopo Buongiorno, a nuclear engineer at the Massachusetts Institute of Technology in Cambridge. Fast reactors aren't needed, he says, "certainly not in the U.S. and probably not anywhere."—*Adrian Cho*

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The little reactors that could

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