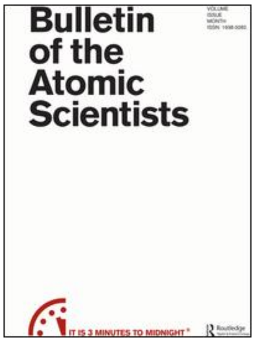

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Can North America's advanced nuclear reactor companies help save the planet?

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ABSTRACT
The advanced nuclear reactor industry in North America includes more than 50 companies and labs, which collectively have attracted some $1.3 billion in private capital, as well as government grants and other assistance. Proponents of advanced nuclear reactors say that they are essential to help humans stop heating the planet with carbon dioxide emissions, and that they can do so without the safety, security, and cost concerns posed by older nuclear technology. Detractors say the advanced nuclear industry will never take off, and particularly not without government action that puts a price on carbon dioxide emissions, helping low- and no-carbon energy sources compete economically with fossil fuels. The author interviews company leaders, academics, scientists, and regulators to determine which companies are most likely to succeed.

KEYWORDS
Advanced nuclear reactors; electricity; fusion; high-temperature gas-cooled reactor; molten salt reactor; nuclear; small modular reactor; sodium-cooled fast reactor

Brown curls bobbing, microphone clipped to her white shirt, Rachel Slaybaugh took the stage with a life-size image of Neil Armstrong on the moon projected behind her. "The space race was a fantastic scientific, political, and monetary challenge that captivated the world," the UC Berkeley assistant professor of nuclear engineering told a standing-room-only auditorium. She didn't get to participate, she lamented, because it began nearly 30 years before she was born. "Fortunately," she said, "there is a new race today that I would argue is even larger, and even more important: the energy race."

Slaybaugh was speaking at the Nuclear Innovation Bootcamp last August, to a room packed with students, professors, policy wonks, government officials, and entrepreneurs. She spearheaded the event to get top graduate students thinking entrepreneurially about advances in nuclear energy and have them rub shoulders with private-sector leaders in the field. The energy race she referred to is really two races that need to be won simultaneously. In one, humanity needs to limit climate change, ocean acidification, and the death toll from air pollution, which is about 6.5 million people per year. In the other, the goal is to end "energy poverty," which is the state of not being able to charge a phone, study by lamplight, or refrigerate a vaccine. Slaybaugh is not alone in deeming this dual goal a central challenge of our time; everyone from UN leaders to Barack Obama to Bill Gates has noted that access to clean energy is crucial for eradicating poverty. In fact, should the world succeed in ending energy poverty, the life improvements that directly result will be more obvious than those that came about from putting a man on the moon. Technological advances spun off from the space race – think satellite television and cordless power tools – aren't much use if you can't power up, and globally, some 1.2 billion people still lack access to electricity, according to the International Energy Agency (IEA 2016).

A subset of the scientists and entrepreneurs trying to solve the world energy problem has, like Slaybaugh, settled on nuclear energy as the path to salvation. There are good reasons for this choice: Nuclear power plants emit no carbon dioxide and are also capable of doing something that wind and solar energy cannot, which is provide baseload energy, a source that can operate around the clock regardless of the weather. Until major advances in energy storage occur, wind and solar power must operate in conjunction with baseload sources to provide predictable 24/7 electricity. That's why when a nuclear plant closes, its capacity is usually replaced with a carbon dioxide-emitting fossil fuel source. A recent report from the US Energy Information Administration found that as four US nuclear power plants were retired in 2013 and 2014, the power that three of them generated was replaced by either coal or natural gas (Energy Information Administration 2016a). Power from the fourth, Vermont Yankee, was replaced by energy imports from out of state, which in effect also meant mostly natural gas. In short, at least to date, less nuclear energy has meant more global warming.[1]

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Of course, nuclear power plants also have hazards of their own, like producing waste that remains radioactive for many thousands of years, poisoning the surrounding landscape when accidents occur, requiring the use of science and materials that can also be used to make weapons of mass destruction, and, more mundanely but probably most significantly, being extraordinarily expensive to build. Today in the United States, more nuclear power plants are closing than opening, and the most recent reactor to come online, the Watts Bar 2 in Tennessee, took 43 years between conception and completion (Blau 2016). Which is why young nuclear pioneers like Slaybaugh are not pushing for more of the water-cooled reactors with the cinch-waisted cooling towers that make up so much of today's fleet, but for variations on nuclear energy known collectively as "advanced" or "Generation IV" reactors.

The sell on this new technology is highly enthusiastic: Besides not emitting carbon dioxide, Gen IV reactors (mostly) don't melt down or explode when accidents occur, they produce much less radioactive waste, they are highly efficient, and they consume cheaper, safer fuels. Some are even designed to consume existing nuclear waste. For these reasons, proponents see advanced nuclear reactors as a critical tool for stopping climate change before its worst effects set in. Experts suggest that an 80 percent drop in global carbon emissions is needed by 2050 to avoid some of those effects, like catastrophic levels of drought and sea-level rise.

The companies involved in the new nuclear wave say that they will be able to deploy advanced reactors in the 2030s or even, in some cases, the 2020s. "If you can deploy reactors in the 2020s, you are absolutely responding to the policy needs for clean energy within a critical response horizon," said Simon Irish, chief executive of the advanced reactor company Terrestrial Energy. "The jackpot is awesome: Let's save the planet," said Michel Laberge, a plasma physicist who founded the advanced nuclear company General Fusion.

Their sense of urgency is palpable and understandable. Certainly, the energy race is more urgent than the space race, which was a case of one country trying to get to the moon before another. This time, a rising sea doesn't stop at national borders. But can the passionate advanced nuclear reactor industry actually help forestall the effects of global warming?

There are many members of the field's old guard who say it can't. But scientists like Slaybaugh, who is 32, are the Young Turks in a field that suffers from a weird generation gap. There are very few mid-career people in nuclear engineering, she told me, because from the mid-1980s, when the US stopped building nuclear power plants, until the early 2000s, when natural gas was still expensive and there was a resurgence of interest in nuclear energy as a carbon-free power source, few went into the field. "I do think that leaves an impact on what people see as possible," she said. "The influx of new things didn't happen in the same way in nuclear" as it might have in a field with no missing generation.

What is possible, though, depends on whether advanced nuclear reactors can thrive commercially, and whether they can do that depends not only on technology but also on the marketplace. Power consumers won't shift en masse to a source that isn't relatively cheap. A carbon tax or cap-and-trade system would help make nuclear energy more competitive, but the chances of seeing one implemented in the United States under the Trump administration seem slim. Without that kind of pricing assist, many experts don't believe that advanced nuclear can gain a foothold.

The industry is not monolithic, though; it includes some 50 companies pursuing a range of technologies. Some are more likely to succeed than others.

Seizing a moment

Promising designs, the pressures of climate change, and a generation of inventors not yet battle scarred by hard economic realities have converged in the last few years to draw significant attention – and money – to advanced nuclear reactors.

There are now around 50 companies developing nontraditional nuclear energy designs in North America, together attracting about $1.3 billion in private capital, according to Third Way, a think tank that published surveys of the industry in 2015 and 2016 (Third Way 2015). Many of the companies are young and relatively small start-ups, but the sector also includes well-known names like GE-Hitachi and Lockheed Martin. The US government is also helping the fledgling industry: The Obama administration's budget for fiscal year 2016 included more than $900 million for the nuclear energy sector to use in developing new technologies. In late 2015, the US Energy Department also promised another $12.5 billion in loan guarantees for advanced nuclear projects and launched the Gateway for Accelerated Innovation in Nuclear – GAIN – an initiative to help private companies move their advanced nuclear reactor designs toward commercialization by providing financial, regulatory, and technical support, including access to testing facilities in federally funded national research labs (White House 2015).

With both private and public money giving the industry a push, many advanced reactor proponents feel like their moment is now. "It shows a tremendous level of commitment to the broad group of advanced reactor technologies out there, that the Department of Energy wants to advance these designs and bring them to fruition," said Leslie Dewan, chief executive of the Cambridge, Mass. advanced reactor company Transatomic Power, which she cofounded in 2011 while still a PhD student in nuclear engineering at MIT. (She finished her degree in 2013.)

Not everyone is convinced that fruition will ever come. Many hype-weary scientists and policymakers who have studied the science and business of nuclear energy for years argue that new reactor designs notwithstanding, it's not actually different this time for the cost-plagued, reputationally challenged nuclear industry. They are not impressed with the press releases and social media posts that the new nuclear companies, hungry for capital and social acceptance, frequently issue. They point to the many traditional nuclear reactors that have struggled in the marketplace, as well billions of dollars and years of testing that have failed to bring an advanced reactor to the US electricity market. And they contend that even if myriad technical difficulties are solved and new safety levels achieved, with the price of renewable energy dropping and fossil fuel sources cheap, there's no evidence that the cost barrier can be overcome.

Writing in *Nature Energy* in January 2016, a group of 10 experts – including professors of chemistry, engineering, and physics – said of the advanced nuclear reactor industry that "no reactor design seems capable of simultaneously overcoming all the challenges confronting nuclear power. Besides economics and safety, these also include the generation of radioactive waste, the linkage to nuclear weapons, and the consequent public opposition" (Armstrong et al. 2016).

Reactor versus reactor

To understand the argument over whether advanced nuclear can succeed, it's important to know that none of the "new" nuclear technology is actually particularly new. While today's scientists are advancing and tweaking their respective designs, they are starting from blueprints that are many decades old, which have already been tried, in many countries and permutations.

Most advanced nuclear reactor designs are, like all nuclear reactors built to date, based on fission, a physical process that splits nuclei to generate heat. Every fission-based nuclear reactor needs a fuel and a coolant, and the choice of material for each has important implications. The two most widely used fuels are plutonium and enriched uranium. (Some advocate thorium as a fuel, but it must first be converted into a uranium isotope.) Plutonium is man-made, a radioactive by-product of nuclear reactions. Uranium is mined from the ground, and an enrichment process concentrates the amount of one isotope, uranium 235, so the material can sustain a nuclear reaction in a power reactor. If it is enriched enough, however, it can also be used in a nuclear weapon.

Because of this dual nature, some governments (and some international organizations) work hard to stop other governments from pursuing enrichment, even when those other governments say they only want to be able to enrich uranium to produce electricity. Some of the advanced nuclear reactors can consume very low-enriched uranium as fuel, which offers a security advantage because it means less overall global need to enrich uranium. Some of the advanced nuclear reactors can consume existing nuclear waste from other power plants, which not only eliminates some need for enrichment but also lowers the amount of waste that must be disposed of.

In traditional nuclear reactors, the coolant is typically water (either "light water," which is regular water, or "heavy water," which has a different isotopic composition). Water normally turns into a gas at high temperatures, but for it to cool a nuclear plant effectively, it must remain liquid. To make sure it does, traditional reactors keep it under high pressure. The new technologies, in contrast, use coolants like molten salt and liquid metal, which do not turn into gas at the temperatures the reactors reach. That means the reactors can operate at atmospheric pressure, which could reduce the risk of explosions and bring down costs, because not as much steel is required to build a pressurized vessel around the reactor core.

If ever brought to commercial scale, advanced nuclear reactors could have other advantages: They operate at higher temperatures than traditional reactors, which makes them more efficient at converting the heat they generate into electricity. And their designers say that unlike older reactors, the new advanced reactors have safety systems that do not require an active human presence in the event of an accident.

Beyond these general advantages, though, any assessment of advanced reactors has to consider them on a type-by-type basis. The companies developing them are pursuing distinct technologies, each with pros and cons.

Consider fusion, for instance, the one non-fission-based type of advanced reactor, which makes energy by fusing hydrogen nuclei together, the same process that powers stars and hydrogen bombs. The pro: Fusion would run on cheap, abundant fuel, making safe, carbon-free energy with a minimum of short-lived radioactive waste. The con: Practical fusion power has been the ever-receding holy grail of energy research for decades. Major scientific breakthroughs have to occur before fusion gets anywhere near powering your vacuum cleaner. As of 2016, there were 16 institutions in North America – seven of them private companies – working to develop fusion reactors, according to the latest survey by Third Way (2016). "In every portfolio, you look for a 'swing for the fences' kind of company," said William Lese, a managing partner of Braemar Energy Ventures, a venture capital company that has invested in General Fusion. Fusion may indeed be an important carbon-free energy source in the future, but it's safe to say that it will not be available in time to help seriously reduce carbon emissions by the middle of the century. True, Lockheed Martin released a 2014 video saying it was building a "compact fusion" device that could fit on an airplane or truck (Lockheed Martin 2014). The company said it could get to a prototype in 5 years, power military vehicles in 10 years, and "have clean power for the world" in 20 years. Outside scientists are skeptical, though. And one of the best known fusion efforts of the moment doesn't offer much reassurance. ITER, a collaboration between the European Union and seven other countries, including the United States, launched in 2006, aiming to build a fusion prototype by 2016 at a cost of around $5.3 billion. Now, ITER is not expected to achieve full power until 2035 or cost less than about $20 billion, if indeed it succeeds at all (Clery 2016).

Three fission-based technologies, on the other hand, stand a better chance. They are high-temperature gas-cooled, fast, and molten salt reactors.

Another category often lumped under the "advanced" label is the small modular reactor, but as the name suggests, it is defined by size and power output rather than technology. Proponents argue that radically shrinking nuclear reactors will make it possible to manufacture and ship them in parts, greatly reducing construction costs. Some of the advanced nuclear reactor designs are also small and modular. But the first small modular reactors to come to market, which could happen in the early 2020s, will likely use traditional water-cooled nuclear technology, making them more like the gasoline-powered Minis than the driverless Teslas of new nuclear power.

Three to watch

In the summer of 2016, the three US national nuclear laboratories – Idaho, Argonne, and Oak Ridge – issued a report comparing various advanced reactors on the bases of technical maturity and the ability to meet certain strategic objectives (Idaho National Laboratory 2016). The report, "The Advanced Demonstration and Test Reactor Options Study," found that two of the three technologies mentioned above, the high temperature gas-cooled reactor and the sodium-cooled fast reactor, "have high enough technology readiness levels to support a commercial demonstration in the near future."

The 2016 survey by Third Way found six North American institutions pursuing high-temperature gas-cooled reactors. One was a US Energy Department project and the rest were private companies ranging from small start-ups to a US-based branch of the French nuclear giant, Areva.

One of these companies is Maryland-based X Energy, which is developing a "pebble bed" reactor, so-named because its uranium oxide fuel is packed into "pebbles" the size of billiard balls. X Energy's design is smaller and more versatile than current nuclear reactors, and a plant would be unable to physically melt down, because the graphite used as coolant and moderator doesn't melt. These attributes could make it suitable for operation in urban areas, and the high temperatures at which it runs – up to 540 degrees Celsius – could make it especially useful for providing industrial process heat, such as is required in desalination, steelmaking, and shale oil recovery.[2] In January 2016, the US Energy Department awarded X Energy a grant of up to $40 million to develop its design, called the Xe-100.

The Xe-100 is based on an idea pioneered at Oak Ridge National Laboratory in 1944. The concept has been on the leading edge for 70 years, said Eben Mulder, X Energy's chief nuclear officer, and to him that is a good thing: Research dating that far back, with numerous plants built and decommissioned around the world in the seven-plus decades since, means a well-tested scientific foundation. To others, the fact that such "new" designs have been tried extensively without ever taking off is worrisome. "I do not see past experience pointing at a positive direction," said former Nuclear Regulatory Commission (NRC) Chairman Allison Macfarlane of pebble-bed high-temperature gas reactors.

In a study of several high-temperature gas-cooled reactors built over the years, M.V. Ramana, a theoretical physicist at the Nuclear Futures Laboratory at Princeton University, found that they "are prone to a wide variety of small failures, including graphite dust accumulation, ingress of water or oil, and fuel failures." These small problems do not always lead to bigger problems, but past experience of high-temperature gas-cooled reactors also suggests that they don't last long, all of those built having been shut down "well before the operating periods envisioned for them" (Ramana 2016). That affects their overall cost, particularly the cost per each kilowatt hour of electricity generated over the lifetime of the reactor.

The latest Third Way report found nine North American institutions – eight of them private companies – developing liquid-metal-cooled fast reactors,[3] of which the sodium-cooled fast reactors cited by the national laboratories report as nearing commercialization are a subset. (These are also sometimes called breeder reactors.) Many countries have pursued liquid-metal-cooled fast reactors, in part because they can create more fissile material than they consume, thus "breeding" their own fuel and allaying one-time fears about not having access to low-cost uranium. (Currently, uranium is cheap and abundant.) Two of the most prominent fast reactors being developed in the United States are the PRISM, by Wilmington, North Carolina-based GE-Hitachi, and the Traveling Wave Reactor, by TerraPower in Bellevue, Washington. The report by the national laboratories found that of a number of designs it looked at, the PRISM "best supports the extension of natural resources and reduction of the nuclear waste burden, as well as fulfilling the fundamental mission of efficient and reliable electricity production" (Idaho National Laboratory 2016).

Whereas a typical light water reactor generating 1000 megawatts electric produces about 20 metric tons per year of waste, TerraPower's Traveling Wave Reactor is designed to produce only 3.5 metric tons in the same amount of time, according to the Clean Air Task Force.[4] The Traveling Wave is so-called for a two-part reaction that occurs within its core. In parallel "waves" concentrated in the center of the core, it both creates more fissionable material – plutonium – and then immediately consumes it. Because the Traveling Wave is creating its own plutonium, once it is up and running, it can use depleted uranium for fuel. (It is designed to use low-enriched uranium to get going.) This means that no enrichment is required for continued operation. "If you have a bunch of Traveling Wave Reactors out there, you really don't have to build any more enrichment plants," said Kevan Weaver, director of technology integration at TerraPower.[5]

Expert reviews, though, have also found technical problems with fast reactors, in particular sodium leaks, which, while not deadly, have made past reactors prone to shutdowns, which increases the cost of electricity produced (Pillai and Ramana 2014). And though liquid sodium has some safety advantages as a coolant, it also reacts violently with water and burns if exposed to air; liquid-sodium-cooled fast reactors have been shut down for long periods by sodium fires (Cochran et al. 2010). The problems could get even more serious. The sodium that cools the core of fast reactors becomes intensely radioactive. To make sure a fire doesn't disperse radioactive sodium, designers have added an intermediate sodium loop, which solves the problem but at great extra expense. Perhaps most worrisomely, fast reactors are missing an important safety feature built into today's light water reactors. In current reactors, in which a water moderator slows down the neutrons and encourages the fission chain reaction, if the water is lost, the chain reaction ends. In a fast-neutron reactor – which is creating its own plutonium – the concentration of fissionable material is high enough that it can sustain a chain reaction even if it loses its coolant.

Nuclear physicist Thomas Cochran and five colleagues summarized this particular concern in a 2010 paper on the pitfalls of breeder reactors:

> if the core heats up to the point of collapse, it can assume a more critical configuration and blow itself apart in a small nuclear explosion. Whether such an explosive core disassembly could release enough energy to rupture a reactor containment and cause a Chernobyl-scale release of radioactivity into the environment is a major concern and subject of debate. (Cochran et al. 2010)

In their paper, they noted that though about $100 billion had been spent globally on breeder reactor research and development and demonstration projects, no one had yet produced a reactor that was economically competitive with a conventional light-water reactor. Japan is the most recent country to show signs of throwing in the towel: In October 2016, it announced that in 2020, it would start decommissioning its Monju fast reactor, which had a troubled history of accidents and cover-ups.

According to the latest Third Way survey, at least nine institutions including four private companies in North America are working on molten salt reactors, which generally use a molten salt mixture as both coolant and fuel.[6] (There also exist reactors that use molten salt as a coolant and a traditional solid fuel such as uranium rods.) The US national nuclear laboratories are not currently studying any liquid-fueled molten salt reactors.[7]

Molten salt reactors are designed to produce relatively little waste, with the Transatomic model producing about 10 metric tons for every 20 metric tons produced by a light water reactor with similar power output.[8] The waste itself is different, too. Whereas the waste from light water reactors has a half-life of 10,000 years or more, requiring a way to safely store it for that amount of time, most of Transatomic's waste would need to be stored only for a few hundred years, a much easier engineering challenge.

The Transatomic reactor is designed to be "walk-away safe" – in the event of a loss of power, the fuel – consisting of uranium dissolved in a liquid salt – drains from the reactor into a containment vessel and gradually cools and solidifies. It also is designed to use very low-enriched uranium as fuel, thus posing a relatively low risk of contributing to the spread of enrichment abilities.

In fact, the molten salt reactor's advantages have also attracted the attention of TerraPower, which started out pursuing its sodium-cooled fast reactor, the Traveling Wave. I asked Weaver why his company is doing both. "The Traveling Wave reactor is the flagship technology, and it's the one that we think is the nearest term," he said. "We don't leave out the fact that there are other technologies that are actually very good that ought to be pursued too." He pointed out that electricity accounts for only about a third of energy use, with the other two-thirds going to transportation and industrial uses. In molten salt reactors, which can operate at temperatures between 600 and 750 degrees Celsius, he sees the possibility of using nuclear power, instead of coal or gas, for industrial process heat, which could include purposes like desalination.

Last June, Transatomic won a $200,000 grant from GAIN to conduct work on its molten salt reactor at Oak Ridge National Laboratory. TerraPower, meanwhile, is developing its molten salt reactor in partnership with the Atlanta-based utility Southern Company, in a project for which they won a grant of up to $40 million from the US Energy Department.

One technical concern: Molten salt is highly corrosive and has to remain in the reactor for a long time as energy is extracted from the uranium, without damaging the surrounding materials. Molten salt reactors won't become viable until that challenge is overcome. Transatomic's Dewan, whose background is in nuclear materials, acknowledges that "the main technical challenge is component lifetime. It's solvable, but you want to make sure it's solvable while being economical, using materials that have a viable supply chain."

Regulatory challenges

When asked to name the biggest challenge in getting their products to market, none of the nine leaders at advanced fission reactor companies interviewed for this story cited the need for major scientific breakthroughs. Asked about problems like water ingress (in high-temperature gas-cooled reactors), sodium leaks (in sodium-cooled fast reactors), and component lifetime (in molten salt reactors), those company leaders said, basically, "We're on it." They didn't claim, necessarily, that the problems had been solved but expressed confidence that they could get there during the decade or two that they are giving themselves to arrive at a final product.

What many of them did mention as their main challenge was regulation. Nuclear companies seeking to operate in the United States must win approval from the NRC, which aims to ensure that plants are safe for people and the environment, in a multi-year process for which the companies pay. The problem, they say, is that the NRC, though highly esteemed as a safety regular of standard light water reactors, has little experience licensing new and unusual designs. So, its requirements are prescriptive, requiring elements that may not be applicable to the new designs or may increase operating costs.

For example, one company executive said that the NRC may require a certain number of operators in the control room, or a certain number of security personnel, even if the reactor is radically different than the one envisioned when the NRC rules were written.

Eben Mulder worked on major pebble-bed high-temperature gas-cooled projects in Germany and South Africa before coming to X Energy. He said that the US nuclear energy market

> is crazily regulated almost, to the point where it becomes very difficult to really get anything into the ground…. You don't know how long it's going to take, you don't know what the outcome is going to be, and you don't know how much it's going to cost. So you can imagine how tough it is to get private investment.

"The biggest challenge we face is getting through the licensing process," said Eric Loewen, chief consulting engineer at GE Hitachi in charge of leading efforts to deploy the PRISM. "The process to get through the licensing is a big risk for us, because it's kind of unbounded as far as the amount of resources you need and how much time it takes."

Companies applying for approval pay for the NRCs services at a rate of $258 per man hour, said Michael McGough, chief commercial officer of Oregon-based NuScale Power, which makes water-cooled – that is non-advanced – small modular reactors. His company officially entered the regulatory process in 2008. In the last 8.5 years, he said that NuScale has spent close to $10 million on NRC fees, and that's just getting started: In 2015, the General Accountability Office reported that it can cost $1 billion–$2 billion to design and certify a new type of nuclear reactor, with up to $75 million of that going to NRC fees for design certification (GAO 2015).

Peter Thiel, the billionaire Silicon Valley investor and partner in Founders Fund, which is an investor in Transatomic Power, wrote in a *New York Times* op-ed, "none of these new designs can benefit the real world without a path to regulatory approval, and today's regulations are tailored for traditional reactors, making it almost impossible to commercialize new ones" (Thiel 2015).

Not surprisingly, US regulators don't agree that they are the problem. Macfarlane, the former chair of the NRC (and a former chair of the *Bulletin*'s Science and Security Board), observed last August in the *MIT Technology Review*, "Some people blame the regulators for holding up the plants. Yet the NRC hasn't been presented with any applications for new reactors and probably won't be for years" (Macfarlane 2016). She points to lack of economic competitiveness as the chief culprit holding up new nuclear designs. "These people have to be able to produce viable designs, not only technically viable, but economically viable. Without a price on carbon, that's a heavy lift," she said.

And it's not as though the NRC is doing nothing. While no advanced reactor company has officially entered the approval process, the companies and the commission have been talking. "If the [advanced nuclear companies'] plans continue down the path they have been suggesting to us, we could see one or two of them starting some pre-application engagement in calendar year 2017," said Michael Mayfield, acting deputy director of the NRC's Office of New Reactors. (He would not name the companies, saying they had not yet gone public with their intent.) The NRC is working to "get our technical and regulatory processes lined up to be ready for when these folks show up," he said, to which end it has cosponsored two large public workshops on the subject, with a third planned for this spring. Mayfield says, in fact, that the NRC could license an advanced reactor today. "For aspects of the design where the regulations are simply not applicable, [the company] could request an exemption from the regulation. We don't require people to address things that are nonsensical."

But when NRC commissioners are asked to approve exemptions, GE-Hitachi's Loewen said, "that gives them discomfort."

Not made in the USA

On stage at the Nuclear Innovation Bootcamp, the projected image featured an American flag planted firmly on the lunar surface between Neil Armstrong and the landing module. Back on Earth, though, it seems pretty clear that the United States will not win the advanced nuclear race, if "win" is defined as "adopt advanced nuclear power first."

While numerous countries worked on and subsequently shut down liquid-metal-cooled fast neutron reactors, Russia persisted and recently connected the BN-800 at the Beloyarsk Nuclear Power Plant to the electrical grid, bringing it up to full power in the fall of 2016 (World Nuclear News 2016). China, which is investing heavily in nuclear and other clean-energy technologies, has said it will be able to deploy advanced reactors commercially by 2030 (Martin 2015). In early 2016, the director of the Institute of Nuclear and New Energy Technology at China's Tsinghua University claimed that the high-temperature gas-cooled reactor it had developed would go live in late 2017 and be on the world market by 2021 (Martin 2016a). China is also working on molten salt reactors and sodium-cooled fast reactors (Martin 2016b).

Prominent American advanced reactor companies, meanwhile, are not necessarily looking to establish themselves in the US market. In fact, among advanced reactor companies, only one in North America has begun the regulatory process. It is Ontario-based Terrestrial Energy, and it dodged the whole problem of perceived NRC bottleneck by seeking approval in Canada. It announced in February 2016 that it was submitting its molten salt design to the Canadian Nuclear Safety Commission for the first phase of its pre-licensing design review. While the US NRC is widely regarded as a gold standard in terms of safety worldwide, Canada's system is also respected. It had long experience approving and licensing the CANDU heavy water reactor, and some in the advanced reactor industry regard the Canadian Nuclear Safety Commission as more nimble and able to deal with new designs than the US system.

"The Canadian regulator has a framework which is supportive of private sector advanced reactor development," said Irish, Terrestrial's CEO. "It's graduated, so what you don't have to do is turn up on day one with 6000 pages of engineering evidencing your safety case." Those 6000 pages, he noted, cost a lot of money. "If the regulative philosophy is principles-based rather than prescriptive, you have the ability to make your case using a very different technology argument."

That different regulatory environment could make a big difference in bringing an advanced reactor to market. "If any of these small advanced reactor companies actually build something in the West, my guess is that it would be Terrestrial in Canada" said Jeff Terry, a physics professor at the Illinois Institute of Technology, a former staff scientist at Los Alamos National Laboratory, and a *Bulletin* columnist. With a population of only 35 million – little more than a tenth of the United States – Canada is a relatively small energy market. It wouldn't be surprising if Terrestrial hoped to use Canadian approval as a foothold that leads toward expanding into global markets.

Funded by Microsoft founder and mega-philanthropist Bill Gates, TerraPower also appears intent on bypassing the NRC. Advanced reactor companies have to ask themselves what the best use of their money is in terms of entering the regulatory process, Terry said, and some have clearly decided that Asia is the way to go. GE-Hitachi is looking for PRISM customers in China, Japan, and South Korea, Loewen said, and TerraPower cast its lot with Beijing in 2015, when it signed a memorandum of understanding with China National Nuclear Corporation to build its first Traveling Wave Reactor in China (Soper 2015). "It looks pretty clear that Bill Gates has decided it's not the NRC for his money. He'd rather do it in China and demonstrate that it works," Terry said.

Patient capital

It takes a special breed of investor to put money into advanced nuclear power. A messianic streak is helpful for getting through those dark years without any financially measurable return on investment.

"We're driven by financial return," said Lese, the partner in Braemar Energy Ventures, which owns a stake in General Fusion. "But we're looking to build great companies, that do things we hope will be important. There's an altruistic side of it for sure." General Fusion's investors also include Bezos Expeditions, the investment firm owned by Amazon founder Jeff Bezos. Transatomic Power's investors include the venture capital firm Founders Fund. Bezos Expeditions and Founders Fund also both happen to have stakes in space travel companies.

Investing in both saving the Earth and leaving it may represent some kind of ultimate hedge, but beyond that, there's a reason that advanced nuclear and space travel may attract the same kind of backer. When Dewan and her colleagues at Transatomic Power first started fundraising, they talked to venture capitalists who had primarily invested in software. "They'd say things like, 'This technology is great – can you get it built in six months?'" They learned and moved on. "It clicked for us when we realized we should be talking to people who had made aerospace investments in the past, because they understood the timeline," she said.

Kevan Weaver of TerraPower calls the money flowing into advanced nuclear "patient capital." It has to be, when the product under development may not come to fruition for 10 or 20 years. "We are a for-profit company, but … yes, there's the social mission for sure," he said. "We're not funded by philanthropists," he insists, although to be precise, Gates, one of TerraPower's two major funders, is also founder of one of the world's largest philanthropies and has made it his explicit personal mission to rid the world of energy poverty (Gates 2016). TerraPower's other major private backer is one-time Microsoft Chief Technology Officer Nathan Myhrvold. If anyone has capital patient enough to make advanced nuclear a serious carbon-reducing force, surely Gates and Myhrvold do.

Is there room for less patient investors in all this? Many advanced nuclear executives acknowledged that they won't succeed if they can't make the energy they produce cost-competitive. In a country where companies pay no price for emitting carbon, though, it's hard to see how the new nuclear firms will be able to do that. I asked Robert Rosner, a theoretical physicist at the University of Chicago, past director of the Argonne National Laboratory, and cochair of the *Bulletin*'s Science and Security Board, if the young advanced reactor companies are basically hoping for a legal change to come along and make their plans viable. "The ones who are hoping to sell these things in the United States, I think the answer is yes," he said. "I wouldn't invest in them if that's their strategy."

The source to beat

The best way to compare the cost of two power sources is by using the levelized cost of electricity, or LCOE, which factors in not only the cost of producing electricity in the moment but also costs like building and eventually decommissioning the power plant. Coal used to be the cheapest source of baseload electricity in the United States, but since the technological breakthroughs that led to fracking, natural gas has become the source to beat. The latest projections from the US Energy Information Administration suggest that for new plants entering service in 2022, the LCOE for conventional natural gas will be 56.4 dollars per megawatt hour, while for advanced nuclear reactors, the figure will be 99.7 dollars per megawatt hour (EIA 2016b). (The same projection places the estimated LCOE for solar power at 74.2, wind power at 58.5, and geothermal at 42.3, not including the effect of any tax credits.)

Players in the advanced nuclear reactor industry generally say that they will be able to produce energy as cheaply as fossil fuels. They make many assertions about how they will bring costs down: by building multiple reactors in one central factory using the same trained work force; through technology that makes it easier to achieve safety; by using cheaper fuel sources, including the waste generated by traditional reactors; and through lower financing costs made possible by smaller reactors. These approaches are all bound to help lower costs, but until an advanced nuclear reactor is actually built and operating, it's very hard to know if precise predictions about cost will bear out – and as skeptics point out, past efforts to produce nuclear energy with advanced reactors, sustainably and at a competitive price, have not worked out. Why, they want to know, should we throw good billions after bad?

If, as Macfarlane and Rosner suggest, advanced nuclear reactors won't succeed in the United States until Congress agrees to put a price on carbon, how likely is that? Very unlikely, it seems. Last November, voters in Washington State turned down a proposed carbon tax, which had it passed would have been the first of its kind in the country. And the incoming Trump administration seems averse to acknowledging that climate change exists, much less enacting taxes to deal with it.

Other countries and regions have adopted carbon taxes without much fuss; British Columbia, in Canada, is one of them, and the Canadian government recently gave the provinces until 2018 to enact their own carbon pricing plans or it would do it for them (Harris 2016) – perhaps another mark in favor of Ontario's Terrestrial getting a reactor to market. Many other countries, regions, and cities have either enacted carbon pricing or are considering it; even China, would-be future home of the first TerraPower reactor, has a carbon tax under consideration (Carbon Tax Center 2015).

If advanced nuclear reactor proponents seem starry-eyed, their belief that they can succeed is no more inherently illogical than skeptics' view that advanced nuclear will never succeed because it never has. No technology, after all, ever succeeded until it did. Moreover, as it seeks to deal with climate change, the United States will not choose between a bad energy source and a perfect one, but from a variety of sources, each of which has drawbacks, including a price tag that will be high. "Whatever we do to combat climate change, it's going to be very expensive," said Terry, the Illinois Institute of Technology physics professor. "When people say, 'Nuclear is going to cost too much' – well, everything is going to cost a lot of money, when it comes time to do it." How do you define "too expensive" when trillions were spent to achieve the technology that allows us to post selfies?

Slaybaugh acknowledged that given today's exact market conditions, the naysayers are probably correct that it would be very hard for advanced nuclear to compete. She also identified a potential alternate avenue for making it more viable: Policymakers needn't focus on taxing carbon but could try to incentivize clean electricity in other ways, for instance, by seeking to reduce the particulate matter in air pollution that causes childhood asthma. It's a practical outlook: If a swathe of the body politic cherry-picks its science, then focus on the cherries it has picked.

For some, there is no real choice: Something has to be done now. There are technologies besides nuclear that could reduce CO_2 emissions, including advanced batteries that would allow increased use of solar and wind power, and carbon capture and storage that could make natural gas – and perhaps even coal-fired power plants – into low- or no-carbon sources of electricity. There are laws and policies, including carbon taxes and markets, that could slow global warming. All of these potential solutions have some sort of drawback, technological, monetary, or political. So, some nuclear scientists, spying a glimmer of hope, are unwilling to stand still and argue over which to choose. "If we believe that nothing new can happen and everything is really hard, then it will be," Slaybaugh told me. "That's not to minimize the challenge, but it's to say, if you start out thinking something is impossible, it's very unlikely to happen."

Near the end of her talk at Berkeley, Slaybaugh told her audience:

> The bottom line is, no one else is coming to save our climate, or to rescue the nuclear sector. We are the people. This is our responsibility. And, like me going into this bootcamp, we aren't really prepared or ready, and that doesn't matter, we have to do it anyway. We have to do this with every tool that we have.

Notes

1. An agreement to close the Diablo Canyon nuclear power plant in California calls for its power to be replaced with renewable energy and energy conservation. Opponents of the closure dispute that this will occur. Following closure of the Fort Calhoun nuclear power plant in Nebraska in October 2016, officials say they will replace its capacity with a combination of wind, solar, and natural gas.
2. Currently, about 20% of US energy consumption goes into process heat applications, compared to about 35–40% into electricity. Traditional light water reactors produce heat at temperatures too low to be used in industrial process heat. Some advanced reactors operate at more than 700 degrees Celsius (World Nuclear Association 2016).
3. Broadly speaking, reactors fall into two categories, thermal, or low-energy, and fast, or high-energy. When fission releases a neutron, that neutron is high-energy, or "fast." In most of today's deployed reactors, which are thermal, a moderator – usually water – is used to slow down the neutrons, which makes it more likely that they will be captured by uranium-235 and cause it to fission. A fission event creates more neutrons, which cause more atoms to fission, creating a chain reaction.

   A "fast reactor" is designed to operate using fast neutrons, without the need to moderate them. The neutrons propagating the chain reaction remain energetic, or fast. Fast reactors are more flexible in the type of fuel they can consume and can, for example, use uranium-238 as fuel, which is 140 times more abundant than uranium-235 (Cochran et al. 2010).
4. Ashley Finan, a project director at the Clean Air Task Force, calculated this figure based on information released by TerraPower. The figure has been normalized to reflect the amount of waste the advanced reactor would produce if it was emitting the same amount of energy as a light water reactor over the same period of time.
5. Some experts have disputed that the Traveling Wave Reactor will reduce nuclear proliferation. For an exploration of the subject, see Makhijani (2013).
6. Liquid-fueled molten salt reactors are fueled by uranium dissolved in a liquid salt. Because the fuel is not surrounded by cladding, as in a solid-fueled reactor, the reactor can continuously remove the fission products. Companies like Transatomic say that the liquid fuel is much more resistant to structural damage from radiation than solid materials, and that with good filtration, a liquid fuel can remain in a molten salt reactor for decades. That would allow much more of its energy to be extracted and reduce proliferation concerns that arise during refueling.
7. The national laboratories are studying a solid-fueled molten-salt-cooled reactor. Their report (Idaho National Laboratory 2016) suggests that this design could launch in the 10–20 year time frame. The report says that they are not studying a liquid-fueled molten-salt design.
8. Ashley Finan, a project director at the Clean Air Task Force, calculated this figure based on information released by the company. It has been normalized to reflect the amount of waste the advanced reactor would produce if it was emitting the same amount of energy as a light water reactor over the same period of time. The reactor would produce only 0.5–1 metric ton of waste per year of operation, but a greater amount at decommissioning, averaging out to around 10 metric tons per year.

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