The Forgotten History of Small Nuclear Reactors

Economics killed small nuclear power plants in the past—and probably will keep doing so

By M.V. Ramana
Posted 27 Apr 2015 | 19:00 GMT

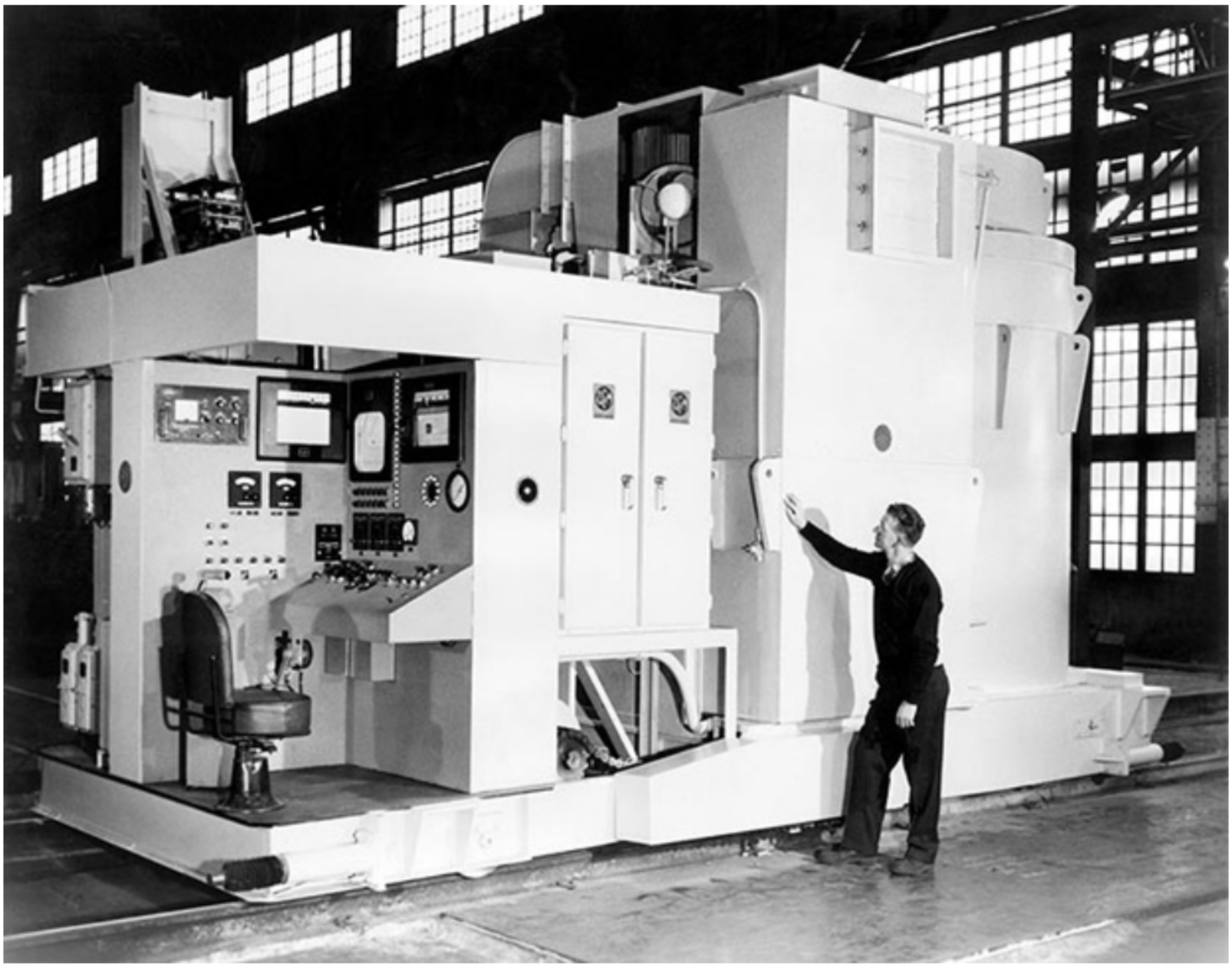


Photo: Everett Collection/Alamy

The Enrico Fermi Atomic Power Plant, Unit 1, in Newport, Mich. was an early small nuclear reactor constructed with funding from the U.S. Atomic Energy Commission. It reached criticality in 1963 and operated until 1972, despite suffering a partial meltdown in 1966.

A tantalizing proposition has taken hold again in the nuclear industry: that small nuclear reactors have economic and other advantages over the standard-size ones being built today. The idea is that by reducing the substantial financial risk of a full-scale nuclear project, small reactors are the best option for kick-starting a much-discussed revival of nuclear power.

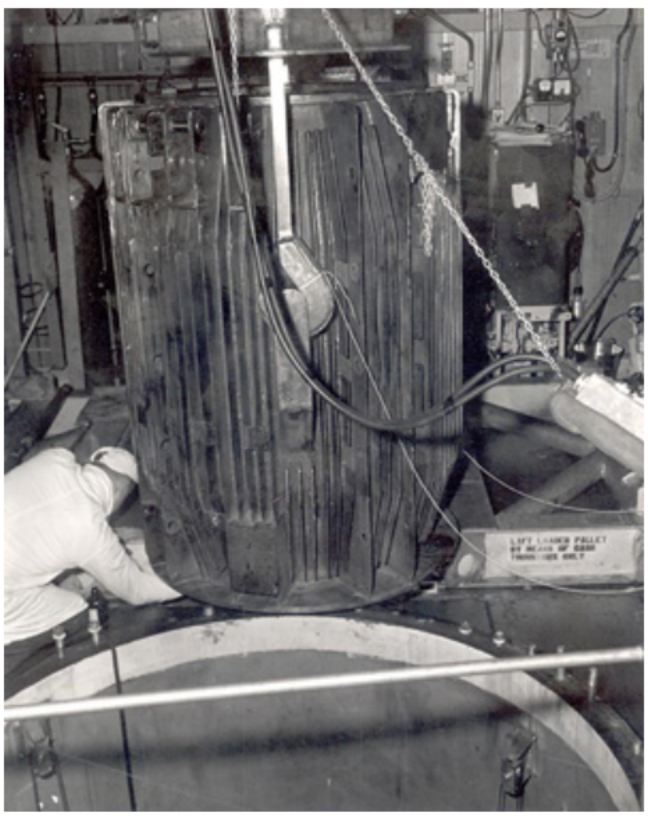
Although concerns about climate change have led energy planners to retain nuclear power as an option, the technology remains in stasis or decline throughout the Americas and Europe. Two new nuclear projects now under way in the United States were the first to be awarded construction licenses in the country since the late 1970s. Globally, nuclear power produced about 11 percent (http://www.worldnuclearreport.org/IMG/pdf/201408msc-worldnuclearreport2014-lr-v4.pdf) [PDF] of all electricity in 2013, down from its high of 17.6 percent in 1996, according to data from the *BP Statistical Review of World Energy 2014*. In the United States, the number of operating nuclear power plants has slipped below 100, with the recent shutdown of the Vermont Yankee plant. (http://www.vox.com/2014/12/30/7468263/vermont-yankee-shut-down)

A fundamental reason for this decline is indeed economic. Compared with other types of electricity generation, nuclear power is expensive. According to a 2014 report by the Wall Street advisory firm Lazard (http://www.lazard.com/PDF/Levelized%20Cost%20of%20Energy%20-%20Version%208.0.pdf), [PDF] the cost of generating a megawatt-hour of electricity from a new nuclear reactor (without considering government subsidies, including those for liability for severe accidents) is between US $92 and $132. Compare that with $61 to $87 for a natural-gas combined-cycle plant, $37 to $81 for wind turbines, and $72 to $86 for utility-scale solar. Nuclear's high costs result directly from the very high costs of building a reactor—estimated by Lazard at $5.4 million to $8.3 million for each megawatt. These per-megawatt costs translate into billions of dollars. For example, the latest estimate for one of the two U.S. projects mentioned above—a pair of 1,117-MW reactors being built near Jenkinsville, S.C. (http://www.thestate.com/news/business/article14658584.html)—is $11 billion.

These costs were acknowledged in a 2012 brochure (http://www.slideshare.net/etully/2nd-annual-small-modular-reactor-conference) for an industry conference devoted to what are called small modular reactors (SMRs). Noting the "huge billion dollar challenges" posed by traditional nuclear plants, the brochure declared that "Small Modular Reactors are the perfect solution to this problem by mitigating billions in financial risk, growing incrementally with power demand and offering shorter and easier construction schedules.... The SMR market is global and extremely vast.... In short the power industry is crying out for commercial SMR projects throughout the world."

If it is, the power industry is likely to be disappointed. Small reactors, in fact, date back to the earliest days of atomic power, and this long history shouldn't be overlooked as vendors tout new generations of the technology. As the history makes clear, small nuclear reactors would be neither as cheap nor as easy to build and operate as their modern proponents are claiming they would be.

SMRs have outputs of anywhere from 10 to 300 MW. Compare that with the 860-MW average of the most popular reactor types now operating around the world and the 980-MW average of the reactors under construction. Although some of the dozens of new small reactor designs (http://www.iaea.org/NuclearPower/Downloadable/News/2014-09-24-nptds/2_NPTDS_Subki_Advanced_Reactors-SMR_r5F.pdf) [PDF] take novel approaches, many of them, especially the ones most likely to be licensed for construction first, are just variations on the familiar light-water reactor. The cost of SMRs can be kept low, proponents say, in part by using factory-fabricated modules, which would require only limited assembly at the site of the power plant itself.



Photos: Top: U.S. Navy/National Science Foundation (2); Bottom: U.S. Navy Seabee Museum

The U.S. Navy's PM-3A Nuclear Power Plant at McMurdo Station was the first and only nuclear reactor in Antarctica. It

The basic idea actually dates to the 1940s, when the U.S. Air Force, Army, and Navy each initiated R&D on various types of small reactors. From 1946 to 1961, the Air Force spent more than $1 billion (http://www.military.com/Content/MoreContent1/?file=cw_atomicairpower) trying to build a reactor to power long-range bombers—to no avail. In canceling the program, President John F. Kennedy wrote, "The possibility of achieving a militarily useful aircraft in the foreseeable future is still very remote."

The Navy had better success with developing nuclear power for its aircraft carriers and submarines. But these have quite different requirements from today's SMR proposals. A submarine reactor is designed to operate under stressful conditions—to provide a burst of power when the vessel is accelerating, for example. And unlike civilian power plants, naval nuclear reactors don't have to compete economically with other sources of power production. Their overwhelming advantage is that they enable a submarine to remain at sea for long periods of time without refueling.

Of the U.S. military's early small reactors, the ones that are most comparable to what's being discussed today came from the Army Nuclear Power Program. It led to the construction of eight small reactors. Several of these were located in the same types of isolated spots that are now being proposed as potentially attractive sites for SMRs: Antarctica, Greenland, and remote Army bases. This vintage 1969 Army documentary highlights the program's perceived virtues:

The experience at these sites was not encouraging. The PM-3A at McMurdo Station in Antarctica, for example, "developed several malfunctions, including leaks in its primary system [and] cracks in the containment vessel that had to be welded," according to the official history of the program (http://www.amazon.com/Armys-Nuclear-Power-Program-Contributions/dp/0313272263) by Lawrence H. Suid. The leaks from the plant (which was owned and operated by the U.S. Navy) resulted in was shut down in 1972, after cracks and leaks developed in the containment vessel and coolant piping. Eventually, the contaminated components and 14,400 metric tons of soil were shipped to California for disposal.

significant contamination, and 14,400 metric tons of soil were removed and shipped to Port Hueneme, a naval base north of Los Angeles, for disposal.

Unlike the Navy's submarine reactors, the Army reactors could be displaced by conventional diesel generators, and in 1976 the Army canceled the program. As Suid writes, the Army concluded "that the development of complex, compact nuclear plants of advanced design was expensive and time consuming...that the costs of developing and producing such plants are in fact so high that they can be justified only if the reactor has a unique capability and fills a clearly defined objective backed by the Department of Defense...[and that] the Army and the Pentagon had to be prepared to furnish financial support commensurate with the AEC's [U.S. Atomic Energy Commission's] development effort on the nuclear side."

As it happened, the AEC (predecessor of the U.S. Department of Energy and the Nuclear Regulatory Commission) was keenly interested in small reactors. Starting in the 1950s, a number of civilian small reactors were proposed in the United States, and eventually 17 reactors (http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=US) with power outputs of less than 300 MW were commissioned. None of them are in operation today.

Many of these projects were supported by the AEC, which promoted nuclear power to U.S. utilities. Its first round of funding, announced in January 1955, went toward small units that could serve as "prototype reactors that would contribute to the development of large reactors," wrote Wendy Allen in her 1977 report *Nuclear Reactors for Generating Electricity: U.S. Development From 1946 to 1963* (http://www.rand.org/content/dam/rand/pubs/reports/2007/R2116.pdf) [PDF].

Of the four proposals submitted, the AEC funded three: the Yankee (http://www.yankeerowe.com/) (not to be confused with the later and much larger Vermont Yankee), Dresden-I (http://atomicpowerreview.blogspot.com/2011/06/atomic-history-dresden-1.html), and Fermi-I. (http://news.blogs.cnn.com/2011/03/29/u-s-nuclear-plant-had-partial-meltdown-years-before-three-mile-island/) Of these, Fermi is the best known, because it suffered a meltdown in 1966, which was colorfully described in John G. Fuller's 1975 book *We Almost Lost Detroit* (http://wsrl.org/pdfs/detroit.pdf) [PDF] and Gil Scott-Heron's song (https://www.youtube.com/watch?v=b54rB64fXY4) of the same title. The other two reactors were relatively successful in meeting the goals they aimed for. The 185-MW Yankee, also known as Yankee Rowe, operated for 31 years; its decommissioning, however, took 16 years and cost $608 million (http://www.recorder.com/news/nation/world/8235952-95/yankee-rowe-closing-took-15-years-608-million).

As mentioned, the AEC viewed these reactors as prototypes of bigger things to come. It preferred large reactors to small ones for a simple reason: economies of scale. Many of the expenses associated with constructing and operating a reactor do not change in linear proportion to the power generated. For instance, a 400-MW reactor requires less than twice the quantity of concrete and steel to construct as a 200-MW reactor, and it can be operated with fewer than twice as many people. Writing in *Science* in 1961, a senior member of the AEC worried that "competition [from fossil fuel plants] is indeed formidable" and suggested that "with current pressurized-water reactor technology, lower nuclear power costs can be achieved most readily with large plants."

Belief in scale economies was so strong within the electrical industry that in the early 1960s, some utilities banded together to absorb the output of a large nuclear power plant.

In the face of this prevailing wisdom, proponents of small reactors pinned their hopes on yet another popular commercial principle: “economies of mass production.” For instance, Samuel B. Morris, the general manager and chief engineer of Los Angeles’s Department of Water and Power, traveled all the way to Geneva in 1955 to attend the first International Conference on the Peaceful Uses of Atomic Energy. There, he made a case for small reactors, arguing that because the “number of small units...is many times the number of large units,” there could be “economy in development and repetitive manufacture” of the small units.

Meanwhile, representatives from the smaller electric utilities, including those in rural areas, argued that the AEC’s focus on large reactors effectively excluded them.

Photos: Nuclear Regulatory Commission (2)

Electricity from the short-lived 22-megawatt Elk River Power Reactor in Minnesota cost twice as much as that from a coal-fired plant. It operated for just three and a half years and was shut down for good in February 1968, after cracks appeared in the cooling system piping.

Confronted with such arguments and wanting to extend nuclear power to regions that could not support large reactors, the AEC announced in September 1955 a second round of funding. This time, small reactors were the goal, not a means to an end. The commission received seven proposals, of which it funded two: a 22-MW reactor in Elk River, Minn., (http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=596) about 50 kilometers northwest of Minneapolis, and a 12-MW reactor (http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=894) near the town of Piqua, Ohio. Two more reactors were later added to the program: the Boiling Nuclear Superheater (Bonus) reactor (http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=703) in Punta Higuera, Puerto Rico, and the La Crosse boiling water reactor (http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=710) in Genoa, Wis.

Elk River was heralded by its operator as "Rural America's First Atomic Power Plant." Much like the SMRs envisioned now, it was made from prefabricated components, and its reactor vessel was compact enough to be shipped to the site on a standard railroad flat car (http://ansnuclearcafe.org/2013/04/18/the-hook-ons/).

The reactor design was a variant of the boiling water reactor, which is the second most common reactor type today. But its fuel was unusual, consisting of a mixture of highly enriched uranium (which had more of the chain-reacting isotope uranium-235 than was typical for nuclear fuel) and thorium. Many experts considered thorium to be the hope for nuclear power in the long run, in part because they feared uranium would run out; to this day, some still believe thorium to be the answer (http://spectrum.ieee.org/tech-talk/energy/nuclear/is-thorium-the-nuclear-fuel-of-the-future) to all of nuclear energy's problems.

At the congressional hearings on the power demonstration program, O.N. Gravgaard, president of the Rural Cooperative Power Association, which was building the plant, stated, "We in rural power started out from scratch, out of necessity. Power was not available several years ago.... We in rural power will do everything to make this reactor a financial success."

Construction of Elk River began in January 1959, and the reactor reached criticality in November 1962. But it wasn't declared as operating commercially until July 1964 (http://www.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=596), three and a half years behind schedule. The lengthy delay resulted from various engineering problems, including cracks in some components. According to congressional hearings in 1967, Elk River's construction cost more than doubled, from $6.2 million to $16 million. To be sure, other reactors built then and later ended up costing at least three times their initial estimates; in comparison, Elk River looked pretty good.

For a reactor that took more than five years to complete, Elk River had a remarkably short operating life: just three and a half years. The reactor was shut down for good in February 1968 after cracks appeared in the cooling system piping. Faced with repair costs estimated at $1 million, the cooperative chose not to fix it. A spokesperson for the co-op told the *Chicago Tribune* that the group "didn't feel we wanted to spend the money, especially since the reactor has not been too economical because it is too small," adding that the reactor had produced power at twice the cost of power from coal-fired plants.

As noted by the nuclear physicist Walt Patterson (http://www.waltpatterson.org/nuclearpower.htm) in his 1976 book *Nuclear Power*, Elk River became the first demonstration power reactor to be decommissioned. Because the reactor vessel was quite radioactive, decommissioning required the development of new underwater torches that were manipulated remotely to cut up the thick steel structure. The process took three years and cost $6.15 million, which was almost the same figure as the initial estimate for construction.

Dealing with the irradiated uranium-thorium fuel proved difficult too. Eventually, the spent fuel was shipped to a reprocessing plant in southern Italy.

In 1968, the same year Elk River shut down, the last of the AEC's small reactors was connected to the grid: the 50-MW La Crosse boiling water reactor. That plant operated for 18 years; by the end, its electricity cost three times as much (http://lacrossetribune.com/news/local/a-nuclear-option-after-years-genoa-reactor-s-waste-gets/article_38fce0e2-ce37-11e1-8c0c-0019bb2963f4.html) as that from the coal plant next door, according to a 2012 news account about the disposal of the plant's spent fuel. In the article, a former plant manager was quoted as saying that the La Crosse plant "had a great design. The only problem was it was too small."

Since then, not a single small reactor has been commissioned in the United States. Indeed, reactor size in the United States ballooned, reaching the 800- to 1,300-MW level by the mid-1970s.

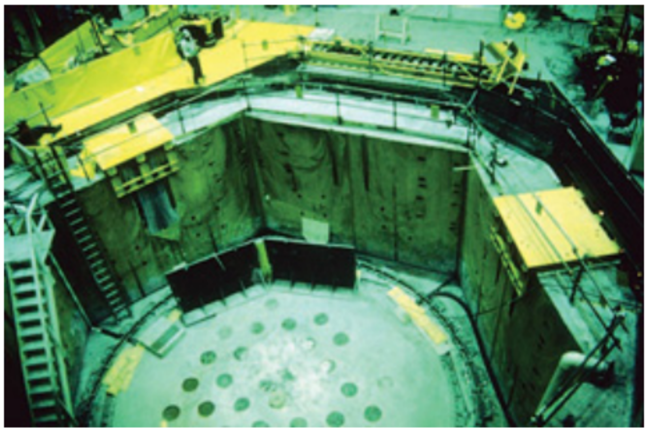


Photo: Nuclear Regulatory Commission

The 330-Megawatt Fort St. Vrain Nuclear Generating Station in Platteville, Colo. had a high-temperature gas-cooled reactor design deemed to be "ultrasafe." However, it rarely operated at full capacity and was shut down in 1989.

The one exception to this growth trend was an experimental 330-MW high-temperature gas-cooled reactor, the Fort St. Vrain plant in Platteville, Colo. It came on line in 1976, with a design promoted as being ultrasafe. But the reactor was a failure. A *New York Times* article about the 1988 decision to shut it down captured the gist of the problem: "Safest Reactor Is Closing Because It Rarely Runs. (http://www.nytimes.com/1988/12/08/us/safest-reactor-is-closing-because-it-rarely-runs.html)" Data from the International Atomic Energy Agency showed that the plant produced about 15 percent of the electricity it would have if it had run at full capacity.

Small reactors were constructed in many other countries too, but all of them served as stepping-stones to larger reactors. The country with the most recent experience with small reactors is India, which until recently was still constructing 220-MW heavy-water reactors. These fit many of the characteristics of today's SMRs as envisioned by proponents: modest size and a relatively standardized design that was manufactured and operated by a single utility and its partners. Nevertheless, the Indian atomic energy establishment decided to scale these up to generate 700 MW or more. The bottom line: Economies of scale were not peculiar to the United States.

What was and is peculiar to the United States and explains the country's greater interest in small reactors is that its nuclear plants are operated by private utilities; in most countries, government-controlled organizations run the nuclear reactors. Private utilities have more stringent budgets and face tighter capital constraints, hence the attraction of a potentially cheaper nuclear reactor. To the extent that other countries have been interested in developing small reactors, it is mostly with an eye toward the export market.

The dream of small nuclear reactors did not die with the 1960s. In the 1980s, the nuclear industry was reeling from high cost and schedule overruns in reactor construction that had begun in the previous decade. And so, proponents of nuclear power circled back to the idea of going small.

A 1983 paper in the journal *Energy* by analyst Joe Egan offered his vision of small, prefabricated reactors. "A novel, factory-based approach to manufacturing reactors under 400-MWe size may alleviate many of the pragmatic constraints on nuclear business," he wrote, suggesting that "prefabrication and standardization of major plant components could lower dollar-per-kilowatt capital costs to levels now boasted by 1,000-MW models." Such factory assembly could further reduce costs, he wrote, by reducing regulation, shortening construction times, and avoiding quality issues with components.

"The reactors, once assembled on barges (or even railroad cars, in one case), would be floated across oceans, up rivers, or be carted cross-country to operating sites," Egan added. "There, purchasers would anchor the plants and simply 'turn the key' for 200–400 MWe of instant power."

This vision never materialized. No turnkey reactors were carted cross-country or floated up rivers. Then, as earlier, they were deemed too expensive.

Sadly, the nuclear industry continues to practice selective remembrance and to push ideas that haven't worked. Once again, we see history repeating itself in today's claims for small reactors—that the demand will be large, that they will be cheap and quick to construct.

But nothing in the history of small nuclear reactors suggests that they would be more economical than full-size ones. In fact, the record is pretty clear: Without exception, small reactors cost too much for the little electricity they produced, the result of both their low output and their poor performance. In the end, as an analyst for General Electric pronounced in 1966, "Nuclear power is a big-plant business: it is most competitive in the large plant sizes." And if large nuclear reactors are not competitive, it is unlikely that small reactors will do any better. Worse, attempts to make them cheaper might end up exacerbating nuclear power's other problems (http://www.sciencedirect.com/science/article/pii/S2214629614000486): production of long-lived radioactive waste, linkage with nuclear weapons, and the occasional catastrophic accident.

About the Author

M.V. Ramana is a researcher with the Nuclear Futures Laboratory (http://nuclearfutures.princeton.edu/)and the Program on Science and Global Security (http://www.princeton.edu/sgs/) at Princeton University. In this article, he writes about small nuclear reactors of the past, many of which suffered from poor economics as well as technical problems. "There was a lot of hope attached to those reactors," Ramana says. "Given the claims being made about today's small reactor designs, the history of the earlier ones is worth revisiting."

To Probe Further

The World Nuclear Industry Status Report 2014 (http://www.worldnuclearreport.org/IMG/pdf/201408msc-worldnuclearreport2014-lr-v4.pdf) [pdf], by Mycle Schneider and Antony Froggatt, is part of a series published off and on since 1992 that reviews worldwide developments in nuclear energy. This latest report contains surveys of nuclear energy programs by country and region, as well as overviews of the economics of nuclear power, construction periods of reactors, the status of the Fukushima site in the aftermath of the multiple reactor accidents, and a comparison of how renewable energy and nuclear energy are performing.

Several papers coauthored by the author examine the potential of small nuclear reactors to overcome the main challenges of nuclear power: nuclear weapons proliferation, the potential for catastrophic accidents, the production of radioactive waste, and economic competitiveness. The articles are "Resource Requirements and Proliferation Risks Associated with Small Modular Reactors (http://www.ans.org/store/j_19873)," by Alexander Glaser, Laura Berzak Hopkins, and M.V. Ramana, in *Nuclear Technology* 184: 121–29, 2013; "Licensing Small Modular Reactors (http://www.princeton.edu/~ramana/EGY5388-SMR-Licensing-2013.pdf)"[pdf] by M.V. Ramana, Laura Berzak Hopkins, and Alexander Glaser, in *Energy* 61: 555–64, 2013; and "One Size Doesn't Fit All: Social Priorities and Technical Conflicts for Small Modular Reactors (http://www.sciencedirect.com/science/article/pii/S2214629614000486)," by M.V. Ramana and Zia Mian, in *Energy Research & Social Science* 2 (June): 115–24, 2014.

In *Power Plant Cost Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics* (http://www.komanoff.net/nuclear_power/Power_Plant_Cost_Escalation.pdf) [pdf], Charles Komanoff offers a detailed analysis of the escalating costs of nuclear reactors and coal plants in the 1970s in the United States. His study, published in 1981, shows that, contrary to what was then the conventional view, nuclear costs increased at roughly twice the rate of coal plants' costs, in real, inflation-adjusted terms. More than three decades later, these results still offer insights for understanding why nuclear costs keep increasing.

Journalist Stephanie Cooke has covered the nuclear beat since the 1980s. Her 2009 book *In Mortal Hands: A Cautionary History of the Nuclear Age* (http://inmortalhands.com/in_mortal_hands.html) (New York: Bloomsbury, 2009) is a compelling account of the development of nuclear power and of nuclear weapons and the close connections between the two pursuits. Particularly relevant to this article is the book's coverage of the hopes surrounding atomic energy and resultant policy actions promoting nuclear reactors in the 1950s and 1960s, as well as the various means used by proponents to make these early power plants seem economically competitive.

M.V. Ramana's *The Power of Promise: Examining Nuclear Energy in India* (http://www.amazon.com/The-Power-Promise-Examining-Nuclear/dp/0670081701)(New Delhi: Penguin India, 2012) recounts the history of India's adoption of nuclear energy, including the country's experience with constructing smaller 220-megawatt heavy-water reactors. Despite a standardized approach to designing, constructing, and operating these plants, many of them suffered lengthy delays and cost overruns, producing electricity at costs significantly higher than that from coal-based thermal power plants.