Submission to the Federal Parliament's Standing Committee on Environment and Energy
'Inquiry into the prerequisites for nuclear energy in Australia'

Friends of the Earth Australia
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SMALL MODULAR REACTORS

1. Introduction to this submission

Friends of the Earth Australia (FoEA) welcomes the opportunity to provide a submission to this inquiry and we would welcome the opportunity to appear before a public hearing of the Committee.

At a later date, FoEA and other NGOs will provide the Committee with a joint submission comprehensively addressing all terms of reference. This submission focuses exclusively on 'small modular reactors' (SMRs) and has been written by FoEA's national nuclear campaigner Dr Jim Green.

In addition to the information provided in this submission, we encourage the Committee and the Secretariat to read the following important report on SMRs, published in July 2019:

Steve Thomas, Paul Dorfman, Sean Morris & M.V. Ramana, July 2019, 'Prospects for Small Modular Reactors in the UK & Worldwide', https://www.nuclearconsult.com/wp/wp-content/uploads/2019/07/Prospects-for-SMRs-report-2.pdf

We also encourage the Committee and the Secretariat to read the following article on the failure of small reactor projects historically:
M.V. Ramana, 27 April 2015, 'The Forgotten History of Small Nuclear Reactors', IEEE Spectrum, https://spectrum.ieee.org/tech-history/heroic-failures/the-forgotten-history-of-small-nuclear-reactors

2. Small modular reactors: an introduction and an obituary

Small modular reactors (SMRs) are generally defined as those with a capacity under 300 megawatts (MW). They can be considered a sub-set of 'advanced' or Generation IV nuclear technology. But the terminology isn't helpful: most interest in SMRs involves scaled-down and redesigned versions of conventional light-water reactors, not Generation IV concepts. Many Generation IV concepts might also be described as failed Generation I technology … and that description fits SMRs as well.

'Modular' means that SMRs are to be assembled from parts or "modules" mass-produced in factories (and the term sometimes also refers to the concept of having multiple SMRs on the same site to better match electricity generation capacity with demand). This brings us to the next important point to be made about SMRs – they don't have any meaningful existence. Some small reactors exist, and there are hopes and dreams of mass factory production of SMRs. But currently there is no such SMR mass manufacturing capacity.

Small reactors: past and present

There's nothing in the history of small power reactors that would inspire any confidence in the likelihood of a significant SMR industry developing now (for details see M.V. Ramana, 27 April 2015, 'The Forgotten History of Small Nuclear Reactors', https://spectrum.ieee.org/tech-history/heroic-failures/the-forgotten-history-of-small-nuclear-reactors). The Soviet Union built eight reactors with a capacity of less than < 300 MW[1] – four have been permanently shut down and the remaining four will soon be shut down and replaced by a floating nuclear power plant.[2] The US Army built and operated eight small power reactors beginning in the 1950s, but they proved unreliable and expensive and the program was shut down in 1977.[3] Small Magnox reactors in the UK have all been shut down and no more will be built.

Nothing came of a flurry of interest in SMRs in the 1980s and into the '90s. A 1990 article about SMRs by Australian anti-nuclear campaigner John Hallam could have been written this year with scarcely any changes – and perhaps it will be just as fresh 30 years from now.[4] Little has changed and it would be no surprise if the current flurry of interest – already a decade old, with little to show for itself – is no more fruitful than the one 30 years ago.

The World Nuclear Association provides the following information on operating small reactors:[5]

- China's CNP-300 pressurized water reactors: 300 MW capacity, one reactor in China and four in Pakistan.
- India's pressurized heavy water reactors (PHWRs), 16 of which meet the SMR definition of <300 MW capacity.
- Russia's four EGP-6 reactors, each with 11 MW capacity ('soon to retire' according to the WNA). A scaled-down version of the infamous RBMK (Chernobyl) reactor design.

None of those reactors are of significance to SMR debates.
- China's CNP-300 reactors are of little or no interest outside of Pakistan.
- The construction rate of India's small PHWRs was underwhelming (about 100 MW of installed capacity per annum – the equivalent of one large reactor per decade) and India has no plans to build any more. Despite a standardized approach to designing, constructing, and operating these reactors, many suffered cost overruns and lengthy delays.[6]
- Russia's EGP-6 reactors came online in the mid-1970s and will likely be taken offline soon.

Likewise, the list of small reactors under construction is underwhelming. There are currently just four SMRs under construction according to the International Atomic Energy Agency (IAEA) – in Argentina, China and Russia.[7] The number is a little higher according to the World Nuclear Association's list of small reactors under construction:[5]
- Russia's floating power plant with twin ice-breaker-type reactors (2 x 35 MW). The primary purpose of the plant is to power fossil fuel mining operations in the Arctic.[9]
- Russia's RITM-200 icebreaker ships powered by twin reactors (2 x 50 MW). Two such ships are operating and a third is under construction. The vessels are intended for the Northern Sea Route along the Russian Arctic coast.
- Argentina's 32-MW CAREM PWR reactor (Argentina's national atomic energy agency claimed in 2014 that it was the first SMR in the world to be officially under construction).
- China's high-temperature gas-cooled reactors (2 x 250 MW).
- China's ACPR50S demonstration reactor (1 x 50–60 MW). According to China's CGN: "The ACPR50S, designed for the marine environment as a floating nuclear power plant, will be used to provide stable, economical and green resources, such as electricity, heat and fresh water, for China's oilfield exploitation in the Bohai Sea and deep-water oil and gas development in the South China Sea."[10]

Thus the current real-world enthusiasm for small-reactor construction has little to do with climate-friendly environmentalism (or even the peculiar form of faux environmentalism practised by the nuclear industry and its lobbyists) and lots to do with fossil fuel mining. Another example comes from Canada, where one potential application of SMRs under consideration is providing power and heat for the extraction of hydrocarbons from oil sands.[11]

There are also multifaceted military links (discussed in sections 6–8 of this submission). Argentina's experience and expertise with small reactors derives from its historical weapons program. China's interest extends beyond fossil fuel mining and includes powering the construction and operation of artificial islands in its attempt to secure claim to a vast area of the South China Sea.[12] Saudi Arabia's interest in SMRs is likely connected to its interest in developing nuclear weapons or a latent weapons capability.

The World Nuclear Association lists nine SMR projects "for near-term deployment – development well advanced"[5] although most of those projects will probably never see the light of day. The projects include a number of proposed PWRs (VBER-300, NuScale, SMR-160, ACP100, SMART), sodium-cooled fast reactors (PRISM, ARC-100), a molten salt reactor (Terrestrial Energy's MSR) and Russia's lead-cooled BREST fast reactor. The class of SMRs called "integral pressurized water reactors" (iPWRs) is regarded as being closer to deployment than more innovative designs. iPWRs are based on conventional light-water reactor technology but they nevertheless have unique attributes, and challenges arising from the placement of components such as steam generators and control rod drive mechanisms within the reactor pressure vessel containing the nuclear fuel.

There has certainly been a proliferation of paper (or computer) designs. According to the IAEA: "There are about 50 SMR designs and concepts globally. Most of them are in various developmental stages and some are claimed as being near-term deployable."[7]

Why the hype?

Why the hype about SMRs? Much of the interest stems from what SMRs are not – hopelessly over-budget, behind-schedule large reactors under construction in various countries. One SMR enthusiast puts the case this way:[13]

"Over time, the technology could introduce new levels of predictability, reliability, and economies of scale to an industry that's become synonymous with billion-dollar cost overruns and years of delays. It also opens the possibility that nuclear power could serve smaller markets, and even military or industrial applications, where a full-scale reactor wouldn't make economic sense. The most immediate advantage, however, is that they might be cheap enough to get built at all. Raising the massive up-front capital to construct new full-scale reactors has become increasingly difficult in the United States, particularly after ballooning budgets for two plants in Georgia and South Carolina ended up tipping Westinghouse Electric into bankruptcy, nearly taking its parent company with it."

The hype surrounding SMRs also derives from their non-existence. They are just designs on paper (or computer screens) and thus any conceivable problem or objection can easily be solved … with words. The term 'proliferation resistant' or 'proliferation proof' resolves concerns about proliferation. The term 'meltdown proof' does away with any safety concerns. The word 'cheap' neatly solves any concerns that diseconomies of scale will make power from SMRs even more expensive than conventional nuclear power. To date, nothing has been demonstrated other than an industry insider's aphorism that "the paper-moderated, ink-cooled reactor is the safest of all".[14] Yet untested and implausible claims about SMRs are routinely regurgitated as demonstrated truths.

There's nothing new about SMRs or proposed SMR sub-types, and there's nothing new about the rhetoric. Admiral Hyman Rickover, a pioneer of the nuclear industry in the US, told members of Congress in 1957: "Any plant you haven't built yet is always more efficient than the one you have built. This is obvious. They are all efficient when you haven't done anything on them, in the talking stage. Then they are all efficient, they are all cheap. They are all easy to build, and none have any problems."[15]

In the real world, things are more complicated. M.V. Ramana and Zia Mian state in their detailed analysis of SMRs:[16]

"Proponents of the development and large scale deployment of small modular reactors suggest that this approach to nuclear power technology and fuel cycles can resolve the four key problems facing nuclear power today: costs, safety, waste, and proliferation. Nuclear developers and vendors seek to encode as many if not all of these priorities into the designs of their specific nuclear reactor. The technical reality, however, is that each of these priorities can drive the requirements on the reactor design in different, sometimes opposing, directions. Of the different major SMR designs under development, it seems none meets all four of these challenges simultaneously. In most, if not all designs, it is likely that addressing one of the four problems will involve choices that make one or more of the other problems worse."

Until such time as construction projects provide a reality check, anything is possible. In mid-2018, NuScale demonstrated yet again why the company "is one of the most influential and innovative energy disruptors the world has ever seen".[17] The company worked out a way to make its non-existent SMRs almost 20% cheaper – by making them almost 20% bigger!

And until such time as actual SMR construction projects provide a reality check, self-styled energy experts such as James Conca will continue serving up this sort of tosh: "This [NuScale] nuclear reactor is something that we've never seen before – a small modular reactor that is economic, factory built and shippable, flexible enough to desalinate seawater, refine oil, load-follow wind, produce hydrogen, modular to any size, and that provides something we've all been waiting for – a reactor that cannot meltdown."[18]

Skepticism

Failed technologies (SMRs and most of their proposed sub-types – fast reactors, molten salt reactors, HTGRs, etc.) … the near-certainty that SMRs will be even more uneconomic than large reactors … what could possibly go wrong? Alongside the hype there is a significant body of skepticism about the potential of SMRs.

A 2014 report produced by *Nuclear Energy Insider*, drawing on interviews with more than 50 "leading specialists and decision makers", noted a "pervasive sense of pessimism" resulting from abandoned and scaled-back SMR programs.[19] Kerr Jeferies, the report's lead author, opted for a positive spin: "From the outside it will seem that SMR development has hit a brick wall, but to lump the sector's difficulties together with the death of the so-called nuclear renaissance would be missing the point."[20] The report argued that "we believe a more accurate picture is that 2014 has been a teething year, and that the SMR story hasn't even really begun."[19] But that simply highlights the problem − the SMR story hasn't begun: no factories churning out identical reactor components, no supply chains, and precious few customers.

Thomas W. Overton, associate editor of POWER magazine, wrote in 2014: "At the graveyard wherein resides the "nuclear renaissance" of the 2000s, a new occupant appears to be moving in: the small modular reactor (SMR). ... Over the past year, the SMR industry has been bumping up against an uncomfortable and not-entirely-unpredictable problem: It appears that no one actually wants to buy one."[21]

The prevailing skepticism was evident in a February 2017 Lloyd's Register report based on "insights and opinions of leaders across the sector" and the views of almost 600 professionals and experts from utilities, distributors, operators and equipment manufacturers.[22] The report stated that the potential contribution of SMRs "is unclear at this stage, although its impact will most likely apply to smaller grids and isolated markets." Respondents predicted that SMRs have a "low likelihood of eventual take-up, and will have a minimal impact when they do arrive".[23]

The UK's National Infrastructure Commission was somewhere between skeptical and dismissive of SMRs in its 2018 report: "Large scale projects have long construction timelines and often face delays. Smaller reactors are still at an early stage of development and their benefits remain speculative. It is estimated that the end-to-end deployment process will take 12-14 years for the first small modular reactor."[24]

World Finance reported in October 2018:[25]

"But while SMRs are purported to be the key to transforming the nuclear sector, history has painted a troubling picture: SMR designs have been in the works for decades, but none have reached commercial success. In fact, Westinghouse worked on an SMR design for about a decade, but the project was abandoned in 2014. At the time, then-CEO Danny Roderick said: "The problem I have with SMRs is not the technology, it's not the deployment – it's that there's no customers." ...

"Although SMRs have been talked about for decades, the progress made so far has been tiny. New technologies in the nuclear sector take a huge amount of time to develop – just look at the struggle to build EPRs in Europe. Plus, opting for a small design cuts out the economies of scale, or the cost advantages that come about due to increasing the size of a project. This is something nuclear projects often rely on."

Former World Nuclear Association executive Steve Kidd wrote about some of the nuclear industry's self-serving "myths" in 2015.[26] He wrote: "Examining the agendas at nuclear conferences and the speeches of key leaders shows that many people in the industry are somewhat deluded. They either don't think carefully about the key issues or else simply choose to ignore many years of evidence that fails to support their beliefs."

On SMR myths, Kidd wrote:[26]

"Assuming they are technically viable, the smaller capital expenditure needed to build a largely factory-built smaller unit and the shorter construction period are certainly attractive features. ... Lower cost, however, doesn't necessarily mean better economics. ... The jury is

still out on SMRs, but unless the regulatory system in potential markets can be adapted to make their construction and operation much cheaper than for large LWRs, they are unlikely to become more than a niche product. Even if the costs of construction can be cut with series production, the potential O&M [operating and maintenance] costs are a concern. A substantial part of these are fixed, irrespective of the size of reactor."

William Von Hoene, senior vice president at Exelon, said last year that no more large nuclear plants will be built in the US due to their high costs and he also expressed skepticism about SMRs and Generation IV designs.[27] "Right now, the costs on the SMRs, in part because of the size and in part because of the security that's associated with any nuclear plant, are prohibitive," he said. "It's possible that that would evolve over time, and we're involved in looking at that technology. Right now they're prohibitively expensive."

The SMR 'hype cycle'

Dr Mark Cooper, senior research fellow for economic analysis at the Institute for Energy and the Environment at Vermont Law School, describes the SMR 'hype cycle' which shares many features with the hype that drove the 'nuclear renaissance' – the short-lived upsurge of interest in large reactors a decade ago.

Cooper writes:[28]

"At the start of the "nuclear renaissance" nuclear advocates argued that streamlining the regulatory process would allow advanced nuclear reactors with more passive safety design and standardized production processes in the third generation of commercial technology to be built quickly and deliver electricity at much lower cost. In less than a decade, the nuclear industry was force to admit that scaling up already huge gigawatt scale reactors in the "nuclear renaissance" had failed to make them cost competitive.

"The industry changed direction, hypothesizing that learning and standardization applied to the production of larger numbers of smaller units, rather than very small numbers of very large units, would do the trick. Under all circumstance, the key, constant demand they make is for a relaxation of licensing and safety requirements.

"The vendors and academic institutions that were among the most avid enthusiasts in propagating the early, extremely optimistic cost estimates of the "nuclear renaissance" are the same entities now producing extremely optimistic cost estimates for the next nuclear technology. We are now in the midst of the SMR hype cycle.

- *Vendors produce low-cost estimates.*
- *Advocates offer theoretical explanations as to why the new nuclear technology will be cost competitive.*
- *Government authorities then bless the estimates by funding studies from friendly academics."*

Cooper argues that the nuclear industry is becoming even more deluded:[28]

"Has the nuclear industry been cured of its myopia? Not at all. In fact, there is a sense that the disease is getting worse, not better, since the characteristics that are said to make small modular technologies attractive are precisely the characteristics that make other alternatives more attractive. In the past, the refusal to look at alternatives could be explained by the fact that the advocates were looking at different characteristics – claiming that huge baseload facilities are indispensable. They dismissed the alternatives because they are too small or too variable. Today, they emphasize small size and speed to market, characteristics on which the alternatives are vastly superior. At the same time they ignore the innovation that has sharply increased renewable load factors and the dramatic advances in information and control technologies that have improved the ability to forecast and integrate renewables."

An obituary

There's nothing in the history of small reactors that would inspire any confidence in the likelihood of a significant SMR industry developing now. The history of SMRs has largely been a history of failure. The history of a number of proposed SMR sub-types also fails to inspire any confidence:

- The history of fast neutron reactors has largely been a history of failure.[29]
- Nothing in the history of high-temperature gas-cooled reactors (HTGRs) suggests that they are likely to progress beyond the experimental stage.[30] China is building two 250-MW HTGR reactors, but plans for 18 additional HTGR reactors at the same site as the demonstration plant have been "dropped" according to the World Nuclear Association.[31]
- The history of molten salt reactors is uninspiring, and a great deal of R&D needs to be done. The French Institute for Radiological Protection and Nuclear Safety said in a 2015 report that there "is no likelihood of even an experimental or prototype MSR … being built during the first half of this century" let alone a factory-based production chain churning out MSRs by the dozen.[32] In 2013, Transatomic Power was promising that its 'Waste-Annihilating Molten-Salt Reactor' would deliver safer nuclear power at half the price of power from conventional, large reactors.[33] By the end of 2018, the company had given up on its 'waste-annihilating' claims, run out of money, and gone bust.[34]

The small list of small reactors under construction is uninspiring. Roughly half the reactors are designed to facilitate access to fossil fuel resources in the Arctic, the South China Sea and elsewhere. Argentina claims that it was the first country to begin construction of an SMR with its CAREM reactor – but it is ridiculously expensive and has been in gestation since the 1980s. China's high-temperature gas-cooled reactors might or might not be economic: no credible, independent information is available, and in any case there is no reason to believe that costs in China can be replicated elsewhere.

The nascent SMR industry has suffered one set-back after another. Babcock & Wilcox abandoned its mPower SMR project in the US despite receiving government funding of US$111 million. Transatomic Power gave up on its molten salt reactor R&D last year. Westinghouse sharply reduced its investment in SMRs after failing to secure US government funding. MidAmerican Energy gave up on its plans for SMRs in Iowa after failing to secure legislation that would force rate-payers to part-pay construction costs. Rolls-Royce sharply reduced its SMR investment in the UK.

It seems highly unlikely that SMRs will be economically competitive (see section 4 in this submission – 'SMR cost estimates, and costs of SMRs under construction'). Private-sector investment in SMRs has been orders of magnitude lower than the level of investment that would be required to kick-start an SMR industry. Governments in the US, the UK and Canada are subsidizing SMR projects … but again the level of investment is orders of magnitude short of that required. A recent US Department of Energy report states that to make a "meaningful" impact, about $10 billion of government subsidies would be needed to deploy 6 gigawatts of SMR capacity by 2035.[35] And the pro-nuclear authors of a 2018 article in the *Proceedings of the National Academy of Science* argue that for SMRs to make a significant contribution to US energy supply, "several hundred billion dollars of direct and indirect subsidies would be needed to support their development and deployment over the next several decades".[36]

State-run SMR programs – such as those in Argentina, China, Russia, and South Korea – might have a better chance of steady, significant funding, but to date the investments in SMRs have been minuscule compared to investments in other energy programs. And again, wherever you look there's nothing to justify the high hopes (and hype) of SMR enthusiasts. South Korea, for example, won't build any of its domestically-designed SMART SMRs in South Korea ("this is not practical or economic" according to the World Nuclear Association[37]). South Korea's plan to export SMART technology to Saudi Arabia is problematic and may in any case be in trouble.[38]

Westinghouse's experience illustrates what a miserable decade the nuclear industry has had. The company's efforts to develop small, medium and large reactors have all been unsuccessful:

- Westinghouse abandoned its SMR R&D in the US in 2014 when it failed to secure government funding. Its interest was revived when UK government funding became a possibility – but that funding is very modest.
- Westinghouse bet on a 600-MW medium-sized design, the AP600, which was granted Design Certification by the US Nuclear Regulatory Commission in 1999. But no orders were received and Westinghouse "recognized" that its cost estimate for the AP600 was "not competitive in the U.S. market".[39]
- Westinghouse decided to focus on large AP1000 reactors. Then the company decided to focus on survival and restructuring after its March 2017 bankruptcy filing, due largely to catastrophic cost overruns and delays with its AP1000 projects in South Carolina (abandoned after the expenditure of at least US$9 billion) and Georgia (where the latest cost estimates are about 10 times higher than Westinghouse's 2006 estimate of the cost of AP1000 reactors).[40]

Westinghouse has learned the lesson from its unhappy experiences: that planning to build reactors (of any size) is a waste of money and actually building reactors can lead to bankruptcy. Resuscitated, restructured and sold by Toshiba to Canadian company Brookfield Business Partners, Westinghouse will no longer take the lead role in large-reactor construction projects such as those that bankrupted it. And its involvement in SMRs is low-level and largely limited to sniffing around for government R&D funding.

Smart money left the building without suffering Westinghouse's humiliations. Warren Buffet's MidAmerican Energy considered building SMRs in Iowa for four years. The company was promoting SMRs as late as February 2013[41] but the project was put on ice in June 2013. In 2010, the state legislature allowed MidAmerican to charge ratepayers an estimated US$15 million for a feasibility study (some of which was later returned to ratepayers).[42] The company's efforts to convince the state legislature to allow it to tap ratepayers for much greater sums had not been successful by the time the project was abandoned.[43-45] MidAmerican has invested over US$10 billion in renewables (especially wind power) in Iowa and is now working towards its vision "to generate renewable energy equal to 100 percent of its customers' usage on an annual basis."[46] From 2008 to 2017, power generation from coal in Iowa declined from 76% to 45% while wind's share increased to 38%.[46]

References:

1. https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=RU
2. Scott L. Montgomery, 8 June 2018, 'The nuclear industry is making a big bet on small power plants', https://theconversation.com/the-nuclear-industry-is-making-a-big-bet-on-small-power-plants-94795
3. Edwin Lyman, 22 Feb 2019, 'The Pentagon wants to boldly go where no nuclear reactor has gone before. It won't work.', https://thebulletin.org/2019/02/the-pentagon-wants-to-boldly-go-where-no-nuclear-reactor-has-gone-before-it-wont-work/
4. John Hallam, July 1990, 'New clear technology – is it the answer?', Chain Reaction #61, http://www.reasoninrevolt.net.au/objects/pdf/d2017.pdf
5. World Nuclear Association, Jan 2019, 'Small Nuclear Power Reactors', http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx
6. M.V. Ramana, 2012, 'The Power of Promise: Examining Nuclear Energy in India', New Delhi: Penguin India.
7. IAEA, Small Modular Reactors, accessed 13 Feb 2019, https://www.iaea.org/topics/small-modular-reactors
9. Jan Haverkamp, 28 May 2018, World's first purpose-built floating nuclear plant Akademik Lomonosov reaches Murmansk, Nuclear Monitor #861, https://www.wiseinternational.org/nuclear-monitor/861/worlds-first-purpose-built-floating-nuclear-plant-akademik-lomonosov-reaches
10. CGN, 'Small Modular Reactor', accessed 13 Feb 2019, http://en.cgnpc.com.cn/encgn/c100050/business_tt.shtml
11. Canadian Small Modular Reactor Roadmap Steering Committee, 2018, 'A Call to Action: A Canadian Roadmap for Small Modular Reactors. Ottawa, Ontario, Canada', https://smrroadmap.ca/wp-content/uploads/2018/11/SMRroadmap_EN_nov6_Web-1.pdf
12. Dawn Stover, 1 June 2016, 'Floating nuclear power plants: China is far from first', http://thebulletin.org/floating-nuclear-power-plants-china-far-first9522
13. James Temple, 17 July 2017, 'Small Reactors Could Kick-Start the Stalled Nuclear Sector', https://www.technologyreview.com/s/608271/small-reactors-could-kick-start-the-stalled-nuclear-sector/
14. Helmut Hirsch, Oda Becker, Mycle Schneider and Antony Froggatt, April 2005, "Nuclear Reactor Hazards: Ongoing Dangers of Operating Nuclear Technology in the 21st Century", Report prepared for Greenpeace International.

15. Quoted in: Michael Shellenberger, 18 July 2018, 'If Radical Innovation Makes Nuclear Power Expensive, Why Do We Think It Will Make Nuclear Cheap?', https://www.forbes.com/sites/michaelshellenberger/2018/07/18/if-radical-innovation-makes-nuclear-power-expensive-why-do-we-think-it-will-make-nuclear-cheap/
16. M.V. Ramana and Zia Mian, 4 Sept 2014, 'Too much to ask: why small modular reactors may not be able to solve the problems confronting nuclear power', Nuclear Monitor #790, www.wiseinternational.org/nuclear-monitor/790/too-much-ask-why-small-modular-reactors-may-not-be-able-solve-problems
17. Russell Ray, 13 June 2018, 'Can SMR Technology Revitalize the Business of Nuclear Power?', https://www.power-eng.com/articles/2018/06/can-smr-technology-revitalize-the-business-of-nuclear-power.html
18. James Conca, 16 March 2017, 'NuScale's Small Modular Nuclear Reactor Keeps Moving Forward', https://www.forbes.com/sites/jamesconca/2017/03/16/nuscales-small-modular-nuclear-reactor-keeps-moving-forward/
19. Nuclear Energy Insider, 2014, "Small Modular Reactors: An industry in terminal decline or on the brink of a comeback?", http://1.nuclearenergyinsider.com/LP=362
20. 27 February 2015, 'SMRs "back on the agenda next year", says new report by Nuclear Energy Insider', www.prweb.com/releases/2015/03/prweb12549421.htm
21. Thomas W. Overton, 1 Sept 2014, 'What Went Wrong with SMRs?', https://www.powermag.com/what-went-wrong-with-smrs/
22. Lloyd's Register, February 2017, 'Technology Radar – A Nuclear Perspective: Executive summary', https://www.lr.org/en/latest-news/technology-radar-low-carbon/
23. World Nuclear News, 9 Feb 2017, Nuclear more competitive than fossil fuels: report', http://www.world-nuclear-news.org/EE-Nuclear-more-competitive-than-fossil-fuels-report-09021702.html
24. National Infrastructure Commission, July 2018, 'National Infrastructure Assessment', www.nic.org.uk/wp-content/uploads/CCS001_CCS0618917350-001_NIC-NIA_Accessible.pdf
25. Courtney Goldsmith, 15 Oct 2018, 'Nuclear power continues its decline as renewable alternatives steam ahead', https://www.worldfinance.com/markets/nuclear-power-continues-its-decline-as-renewable-alternatives-steam-ahead
26. Steve Kidd, 11 June 2015, 'Nuclear myths – is the industry also guilty?', www.neimagazine.com/opinion/opinionnuclear-myths-is-the-industry-also-guilty-4598343/
27. Steven Dolley, 12 April 2018, 'No new nuclear units will be built in US due to high cost: Exelon official', https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/041218-no-new-nuclear-units-will-be-built-in-us-due-to-high-cost-exelon-official
28. Mark Cooper, May 2014, 'The Economic Failure of Nuclear Power and the Development of a Low-Carbon Electricity Future: Why Small Modular Reactors Are Part of the Problem, Not the Solution', https://www.nirs.org/wp-content/uploads/reactorwatch/newreactors/cooper-smrsaretheproblemnotthesolution.pdf
29. Nuclear Monitor #831, 5 Oct 2016, 'The slow death of fast reactors', https://www.wiseinternational.org/nuclear-monitor/831/slow-death-fast-reactors
30. Nuclear Monitor #823, 4 May 2016, 'The checkered history of high-temperature gas-cooled reactors', https://www.wiseinternational.org/nuclear-monitor/823/nuclear-news-nuclear-monitor-823-4-may-2016
31. World Nuclear Association, 21 March 2016, 'First vessel installed in China's HTR-PM unit', http://www.world-nuclear-news.org/NN-First-vessel-installed-in-Chinas-HTR-PM-unit-2103164.html

32. IRSN, 2015, 'Review of Generation IV Nuclear Energy Systems', https://www.irsn.fr/EN/newsroom/News/Documents/IRSN_Report-GenIV_04-2015.pdf
33. Kevin Bullis, 12 March 2013, 'Safer Nuclear Power, at Half the Price', http://www.technologyreview.com/news/512321/safer-nuclear-power-at-half-the-price/
34. Nuclear Monitor #867, 15 Oct 2018, 'Transatomic Gen IV startup shuts down', https://wiseinternational.org/nuclear-monitor/867/nuclear-news-nuclear-monitor-867-15-october-2018
35. Kutak Rock and Scully Capital for DOE's Office of Nuclear Energy, Oct 2018, 'Examination of Federal Financial Assistance in the Renewable Energy Market: Implications and Opportunities for Commercial Deployment of Small Modular Reactors', https://www.energy.gov/ne/downloads/report-examination-federal-financial-assistance-renewable-energy-market or https://www.energy.gov/sites/prod/files/2018/11/f57/Examination%20of%20Federal%20Financial%20Assistance%20in%20the%20Renewable%20Energy%20Mark..._1.pdf
36. M. Granger Morgan, Ahmed Abdulla, Michael J. Ford, and Michael Rath, July 2018 'US nuclear power: The vanishing low-carbon wedge', Proceedings of the National Academy of Science, https://www.pnas.org/content/115/28/7184
37. World Nuclear Association, Feb 2019, 'Nuclear Power in South Korea', http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx
38. Jung Suk-yee, 16 Nov 2018, 'Small Modular Reactor Export from S. Korea in Jeopardy', http://www.businesskorea.co.kr/news/articleView.html?idxno=26628
39. W.E. Cummins, M.M. Corletti, T.L. Schulz / Westinghouse Electric Company, 2003, 'Westinghouse AP1000 Advanced Passive Plant', http://nuclearinfo.net/twiki/pub/Nuclearpower/WebHomeCostOfNuclearPower/AP1000Reactor.pdf
40. Nuclear Monitor #867, 15 Oct 2018, 'Vogtle's reprieve: snatching defeat from the jaws of defeat', https://www.wiseinternational.org/nuclear-monitor/867/vogtles-reprieve-snatching-defeat-jaws-defeat
41. NERA Economic Consulting, Feb 2013, 'A Comprehensive Financial and Economic Assessment of Future Iowa Baseload Generation in a Carbon-Constrained Environment', prepared for MidAmerican Energy Company, https://www.nera.com/content/dam/nera/publications/archive2/PUB_NERA_MidAmerican_Final_0213.pdf
42. Neila Seaman, 8 April 2012, 'Iowans deserve honest answers from MidAmerican', https://www.thegazette.com/2012/04/08/iowans-deserve-honest-answers-from-midamerican
43. Joe Gardyasz, 20 April 2012, 'Iowa's nuclear decision', https://businessrecord.com/Content/Energy-Environment/Energy-Environment/Article/Iowa-s-nuclear-decision/183/930/54774
44. Bob Shively, 11 July 2013, 'Should Utilities Consider Small Modular Nuclear Reactors?', https://blog.enerdynamics.com/2013/07/11/should-utilities-consider-small-modular-nuclear-reactors/
45. Paul Deaton, 4 June 2013, Iowa Pulls the Plug on Nuclear Power, https://pauldeaton.com/2013/06/04/iowa-pulls-the-plug-on-nuclear-power/
46. Donnelle Eller, 7 Aug 2018, 'Groups question MidAmerican's 100% renewable energy plan, given coal reliance',

https://www.desmoinesregister.com/story/money/business/2018/08/07/midamerican-renewable-energy-plan-coal-reliance-environmental-groups-wind-energy/913170002/

3. SMR economics: an overview

Small modular reactors (SMRs) only exist as theoretical constructs. No SMRs exist if a strict definition is applied (modular, factory production of numerous, identical components). Only a few are under construction … or none if a strict definition is applied. Thus meaningful information about SMR economics is nearly non-existent.

The void is filled by propagandists … the SMR market is in the hundreds of billions and SMRs are reviving nuclear power's hope of becoming too cheap to meter. The more-digestible size of small reactors, combined with factory-based modular construction techniques, will solve all of nuclear power's problems at once … which rather begs the question as to why so few small reactors have been or are being built. It also begs the question as to why there is a deep reluctance on the part of SMR developers, the finance sector and governments to finance SMRs.

Fundamental problems

M. V. Ramana summarizes some of the fundamental economic challenges facing SMR developers:[1]

"As the name suggests, SMRs produce smaller amounts of electricity compared to currently common nuclear power reactors. A smaller reactor is expected to cost less to build. This allows, in principle, smaller private utilities and countries with smaller GDPs to invest in nuclear power. While this may help deal with the first problem, it actually worsens the second problem because small reactors lose out on economies of scale. Larger reactors are cheaper on a per megawatt basis because their material and work requirements do not scale linearly with generation capacity.

"SMR proponents argue that they can make up for the lost economies of scale by savings through mass manufacture in factories and resultant learning. But, to achieve such savings, these reactors have to be manufactured by the thousands, even under very optimistic assumptions about rates of learning. Rates of learning in nuclear power plant manufacturing have been extremely low; indeed, in both the United States and France, the two countries with the highest number of nuclear plants, costs rose with construction experience.

"For high learning rates to be achieved, there must be a standardized reactor built in large quantities. Currently dozens of SMR designs are at various stages of development; it is very unlikely that one, or even a few designs, will be chosen by different countries and private entities, discarding the vast majority of designs that are currently being invested in. All of these unlikely occurrences must materialize if small reactors are to become competitive with large nuclear power plants, which are themselves not competitive.

"There is a further hurdle to be overcome before these large numbers of SMRs can be built. For a company to invest in a factory to manufacture reactors, it would have to be confident

that there is a market for them. This has not been the case and hence no company has invested large sums of its own money to commercialize SMRs. …

"Given this state of affairs, it should not be surprising that no SMR has been commercialized. Timelines have been routinely set back. In 2001, for example, a DOE report on prevalent SMR designs concluded that "the most technically mature small modular reactor (SMR) designs and concepts have the potential to be economical and could be made available for deployment before the end of the decade provided that certain technical and licensing issues are addressed". Nothing of that sort happened; there is no SMR design available for deployment in the United States so far."

None of this is new. Ramana quotes a General Electric analyst who said in 1966: "Nuclear power is a big-plant business: it is most competitive in the large plant sizes."[2] Ramana goes on to say: "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: production of long-lived radioactive waste, linkage with nuclear weapons, and the occasional catastrophic accident."[2]

Market size

Here are some examples of industry hype about the SMR market:

- *Nuclear Energy Insider* estimates a global SMR market size of US$500 billion by 2035[3] (for comparison, global clean energy investment totaled US$332 billion in 2018 alone[4]).
- The Small Modular Reactor Research and Education Consortium estimates that the potential economic benefits from the establishment of an SMR construction business in the US could range from US$34−250 billion or more.[5]
- A 2014 report by the UK National Nuclear Laboratory estimates 65–85 GW of installed SMR capacity by 2035, valued at £250–400 billion.[6]
- British companies are urging the government to support the development of an SMR industry that "could create 40,000 skilled jobs, contribute £100bn to the economy and open up a potential £400bn global export market."[7]
- According to the SMR Smart consortium, if the US captures "just" one-third of the global market of 65–85 GW, SMRs would create tens of thousands of high-paying American jobs in addition to generating billions of dollars in domestic economic activity and tax revenues.[8]
- Elsewhere, SMR Start claims that US exporters of SMR technologies would only need to capture 10% of the global market in order to create tens of thousands of jobs and billions of dollars in tax revenues.[9]
- The global SMR market could be valued at US$1 trillion by 2035 according to the *Power Engineering* magazine.[10]
- According to NuScale: "Conservative estimates predict approximately 55-75 GW of global electricity will come from SMRs by 2035, equivalent to over 1,000 NuScale Power Modules."[11]

The OECD's Nuclear Energy Agency is more circumspect: it estimates up to 21 GW of installed SMR capacity by 2035 while its low-case scenario has less than 1 GW installed by 2035.[12]

With such riches on offer, numerous companies and countries – including the US, Russia, China, South Korea and Argentina – are said to be in a "race to be the first to market".[13] If so, they are making haste slowly.

NuScale Chief Technology Officer Jose Reyes said last year: "If NuScale only gets 10-20 percent of that global SMR market, we would have to be manufacturing three to six modules a month. That's $3-6 billion annually, just for the manufacturing of it. There's tremendous opportunity for SMRs globally, and that's only if you get a small percentage of the market."[14] But Reyes is talking about a market that only exists in the imagination of SMR enthusiasts.

In truth, there is virtually no market for SMRs – hence the reluctance of industry and government to make the multi-billion-dollar investments that would kick-start an SMR industry. These are heady times for conference organizers jumping on the SMR bandwagon, and for graphic artists generating images of non-existent SMR designs … but there is virtually no market for actual SMRs.

Will Davis, a consultant to the American Nuclear Society, said in 2014 that the SMR "universe [is] rife with press releases, but devoid of new concrete."[15] The same year, *POWER* magazine noted that "air seems to be leaking out of the SMR balloon lately."[16] Gordon Edwards from the Canadian Coalition for Nuclear Responsibility states: "SMR stands for "Small Modular Reactor(s)". It also stands for the Second Make-Believe Renaissance, for it is the latest effort by an increasingly desperate nuclear industry to create a "Nuclear Renaissance". They have already failed once before."[17]

In early 2019, Kevin Anderson, North American Project Director for *Nuclear Energy Insider*, said that there "is unprecedented growth in companies proposing design alternatives for the future of nuclear, but precious little progress in terms of market-ready solutions."[18] Anderson argued that it is time to convince investors that the SMR sector is ready for scale-up financing but that it will not be easy: "Even for those sympathetic, the collapse of projects such as V.C Summer does little to convince financiers that this sector is mature and competent enough to deliver investable projects on time and at cost."[18]

Thomas W. Overton, associate editor of POWER magazine, wrote in 2014: "At the graveyard wherein resides the "nuclear renaissance" of the 2000s, a new occupant appears to be moving in: the small modular reactor (SMR). ... Over the past year, the SMR industry has been bumping up against an uncomfortable and not-entirely-unpredictable problem: It appears that no one actually wants to buy one."[19]

Overton explained:[19]

"The problem has really been lurking in the idea behind SMRs all along. The reason conventional nuclear plants are built so large is the economies of scale: Big plants can produce power less expensively per kilowatt-hour than smaller ones. The SMR concept disdains those economies of scale in favor of others: large-scale standardized manufacturing that will churn out dozens, if not hundreds, of identical plants, each of which would

ultimately produce cheaper kilowatt-hours than large one-off designs. It's an attractive idea. But it's also one that depends on someone building that massive supply chain, since none of it currently exists. ... That money would presumably come from customer orders − if there were any. Unfortunately, the SMR "market" doesn't exist in a vacuum. SMRs must compete with cheap natural gas, renewables that continue to decline in cost, and storage options that are rapidly becoming competitive. Worse, those options are available for delivery now, not at the end of a long, uncertain process that still lacks NRC approval."

Danny Roderick, then president and CEO of Westinghouse, said in 2014: "The problem I have with SMRs is not the technology, it's not the deployment – it's that there's no customers. ... The worst thing to do is get ahead of the market".[20] It would be difficult to justify the economics of SMRs at this point, Roderick said, especially without government subsidies. Westinghouse twice missed out on US government funding to pursue its SMR program, and decided to give up on SMRs in favor of its AP1000 reactors and pursuing its aim of tripling its decommissioning business to reach US$1 billion per year. Westinghouse's enthusiasm for SMRs – and its confidence in the growth of a market – was later revived when the UK government announced that funding would be made available for SMR projects.

So, how many orders would a manufacturer need to go to the financial markets to get funding to build a supply chain to build lots of SMRs? Westinghouse's Danny Roderick said in 2014: "Unless you're going to build 30 to 50 of them [SMRs], you're not going to make your money back."[20] Pro-nuclear commentator Dan Yurman wrote in 2016: "The answer, according to David Orr, head of nuclear business development for Rolls-Royce in the UK, ... is a minimum of about four dozen units and six dozen would be better. Those are high numbers which make some proponents of SMRs unhappy. The reason is this estimate means that turning out the first 50 or so SMRs for any firm in the business could be a high wire act."[21]

Costs per MWh

A 2016 report by the South Australian Nuclear Fuel Cycle Royal Commission estimated levelized costs of electricity (LCOE) of US$161/MWh based on the US NuScale SMR design.[22] A 2015 NuScale report estimated a LCOE of $98-$108/MWh.[23] And in June 2018, NuScale said it is targeting a cost of just US$65/MWh for its first plant.[24] No doubt NuScale's cost estimates will continue to drop precipitously … unless and until it actually builds an SMR plant.

NuScale Chief Technology Officer Jose Reyes said last year: "We're already competitive with natural gas in the UK – it's already the lowest cost next to coal."[14] He meant to say that if NuScale ever develops the ability to churn out large numbers of SMRs (it hasn't yet built one), and if its absurd cost estimates are proven correct, NuScale SMRs will be competitive with gas. Nuscale's construction cost estimate – "about" US$3 billion for a 12-unit plant with a total capacity of 684 MW – is as implausible as its $/MWh claims.[25]

A 2017 report published by the US-based Energy Innovation Reform Project (EIRP) provides another example of idiotic SMR hype.[26] The report crunched the numbers on eight advanced reactor concepts, four of them meeting the SMR criterion of <300 MW capacity. The report found an average LCOE of US$60/MWh, well below the US$99/MWh expected by the US Energy Information Agency for large PWR nuclear plants entering service in the early 2020s.

This finding "has important strategic implications for the industry and the nation", the EIRP report states, and the cost estimates "suggest that these technologies could revolutionize the way we think about the cost, availability, and environmental consequences of energy generation." With one exception, even the upper estimates were below the US$99/MWh benchmark, reinforcing the revolutionary potential and strategic importance of Generation IV concepts.

But to estimate the costs of Generation IV nuclear concepts, the researchers simply asked vendors (or would-be vendors) to supply the information! The EIRP report did at least have the decency to qualify its useless findings: "There is inherent and significant uncertainty in projecting NOAK [nth-of-a-kind] costs from a group of companies that have not yet built a single commercial-scale demonstration reactor, let alone a first commercial plant. Without a commercial-scale plant as a reference, it is difficult to reliably estimate the costs of building out the manufacturing capacity needed to achieve the NOAK costs being reported; many questions still remain unanswered – what scale of investments will be needed to launch the supply chain; what type of capacity building will be needed for the supply chain, and so forth."[26]

Lazard's most recent levelized-cost-of-energy analysis gives figures of US$112–189/MWh for new, large reactors; $29–56 for wind power; and $36–46 for utility-scale solar.[27] If figures of US$60–65/MWh could be achieved with SMRs, the electricity they generate would be 2–3 times cheaper than that from large reactors but still more expensive than wind power and utility-scale solar.

Rolls-Royce claims that its SMRs, if built, will generate power at a cost of £60/MWh (US$77.70/MWh).[28] That's highly competitive compared to Lazard's figure for large nuclear … but the estimate is implausible and Rolls-Royce is demanding significant UK government funding to pursue its SMR project and threatening to abandon the project in the absence of government largesse.

Learning curve

Claims the SMRs will be economic rest on unlikely estimates of capital costs and costs per unit of electricity generated. Such claims also rest on purported learning curves and cost reductions as more and more units are built.

But nuclear power is the one and only energy source with a negative learning curve – in some countries, at least.[29] Thus if SMRs enjoy a faster (negative) learning curve than large reactors, first-of-a-kind SMRs will be uneconomic and nth-of-a-kind SMRs will become more and more uneconomic at an even faster rate than large-reactor boondoggles like French EPR reactors or the AP1000 projects in the US that bankrupted Westinghouse and nearly bankrupted its parent company Toshiba.

M.V. Ramana writes:[30]

"SMR proponents argue that they can make up for the lost economies of scale two ways: by savings through mass manufacture in factories, and by moving from a steep learning curve early on to gaining rich knowledge about how to achieve efficiencies as more and more reactors are designed and built. But, to achieve such savings, these reactors have to be manufactured by the thousands, even under very optimistic assumptions about rates of learning. Rates of learning in nuclear power plant manufacturing have been extremely low. Indeed, in both the United States and France, the two countries with the highest number of nuclear plants, costs went up, not down, with construction experience."

Mark Cooper, senior research fellow for economic analysis at the Institute for Energy and the Environment at Vermont Law School, compares the learning curves of nuclear and renewables:[31]

"Renewable technologies have been exhibiting declining costs for a couple of decades and these trends are expected to continue, while nuclear costs have increased and are not expected to fall. Renewables have been able to move rapidly along their learning curves because they actually do possess the characteristics that allow for the capture of economies of mass production and stimulate innovation. They involve the production of large numbers of units under conditions of competition. They afford the opportunity for a great deal of real world development and demonstration work before they are deployed on a wide scale. These are the antithesis of how nuclear development has played out in the past, and the push for small modular reactors does not appear to solve the problem."

SMRs as 'affordable luxuries', diseconomies of scale

Edwin Lyman, a senior scientist at the Union of Concerned Scientists, wrote in a 2013 report:[32]

"Unless the negative economies of scale can be overcome, SMRs could well become affordable luxuries: more utilities may be in a financial position to buy an SMR without "betting the farm," but still lose money by producing high-cost electricity. In any event, it would take many years of industrial experience, and the production of many units, before the potential for manufacturing cost savings could be demonstrated.

"In the meantime, as the Secretary of Energy Advisory Board's SMR subcommittee stated in a November 2012 report, "first of a kind costs in U.S. practice will likely make the early [SMR] units considerably more expensive than alternative sources of power. If the U.S. is to create a potential SMR market for US vendors, it will need to do something to help out with such costs". The report pointed out that if the government decided to provide such help, it would have a "panoply of direct and indirect tools available to support the development of an SMR industry" ranging from "funding SMR demonstration plants, perhaps on U.S. government sites (the DOE is a particularly large user of electricity) to a variety of financial incentives" including "continued cost sharing with selected SMR vendors beyond design certification,"

"loan guarantees," and "production tax credits or feed-in tariffs for those utility generators that are early users of SMR power purchase contracts." …

"DOE officials have referred to this situation as a "Catch-22." The economics of mass production of SMRs cannot be proven until hundreds of units have been produced. But that can't happen unless there are hundreds of orders, and there will be few takers unless the price can be brought down. This is why the industry believes significant government assistance would be needed to get an SMR industry off the ground. …

"In addition to imposing a penalty on the capital cost of SMRs, economies of scale would also negatively affect operations and maintenance (O&M) costs (excluding costs for nuclear fuel, which scale proportionately with capacity). Labor costs are a significant fraction of nuclear plant O&M costs, and they do not typically scale linearly with the capacity of the plant: after all, a minimum number of personnel are required to maintain safety and security regardless of the size."

Standardized modular rhetoric

The M in SMR refers to plans for the manufacture and construction of SMR components (modules) primarily in dedicated factories, with the components then shipped to site for installation. According to the International Atomic Energy Agency, "the modularity of SMRs that enables the centralized fabrication of major components of the power unit has several advantages, including the standardization of both components and design, creating significant economies of mass production. Scale economies from modularization are anticipated to stem not only from mass manufacturing of component modules, but also from increases in productivity and efficiency gains as the production of successive modules continues over time."[33]

Whether those benefits would be realized in practice is doubtful. Experts interviewed during the preparation of a report published in the *Proceedings of the National Academy of Science* were skeptical about the impact of modular construction on SMR economics: "We challenged experts to identify potential economies of scale in modular construction and the economies of volume associated with factory fabrication that might be exploited in smaller reactors. … However, most experts were skeptical that such economies would completely offset the diseconomies of scale in reactor size."[34]

A 2014 report produced by *Nuclear Energy Insider*, drawing on interviews with more than 50 "leading specialists and decision makers", noted that modular factory construction methods don't obviate the need for careful, skilled construction at the reactor destination site: "[I]n order to ensure a smooth transition from the drawing board to the construction site there are key questions to be faced in separating the expertise held in a reactor factory and the expertise required to install an SMR when it arrives on site. For an effective SMR supply chain to be developed it will need to be localized − despite the reactors being built off site, a great amount of the on-site infrastructure and materials will still require precision assembly."[35]

Transport issues arising from the modular construction model are too often glossed over. Dr David Lowry notes that the UK's so-called Expert Finance Working Group on Small Nuclear Reactors (EFWG)[36] "makes no attempt to provide an analysis of how to provide market-based insurance for SMRs, against accidents and terrorist attack on modules in transit to site and in situ; nor how to privately fund SMR radioactive waste management: yet these are real risks for nuclear power, SMRs included. For example, the EFWG (p.11) talks of "road transportable modules which are easily installed on site" but makes no calculation of the exposure to disruption or indeed destruction of such an SMR module being transported on public roads from fabrication facility to operating site, possible hundreds of miles distant."[37]

The logic (or rhetoric) of modular factory construction vanishes if the factories producing reactor components are systematically underperforming. The Creusot Forge foundry in France is a topical example. Systemic sub-standard processes combined with corruption and cover-ups resulted in an ever-widening scandal. The saga is covered in some detail in the September 2018 World Nuclear Industry Status Report (WNISR).[38]

This brief excerpt from the WNISR report gives some indication as to the scale of the problem: "On 17 July 2018, EDF sent its assessment of the manufacturing dossiers of 1,142 parts to ASN [France's nuclear regulator] concerning a total of 46 reactors. Examination of these dossiers by ASN is expected to last until the end of 2018. The information released on EDF's website covers, however, only 42 reactors and there is no information on the nature of the 1,142 affected parts. EDF found a total of 1,775 violations of regulatory or contractual requirements, ranging from 16 to 55 per reactor, plus 449 violations of the manufacturer's internal guidelines."[38]

Reflecting on the failure of Generation III reactor construction projects, the 2015 World Nuclear Industry Status Report states: "The reality may be that nuclear technology is simply not mature enough to standardize yet and there is still a continuing flow of design changes driven by experience of operating plants and technical change that it would be foolish to ignore. The rate of ordering may also be too low for standardization to be feasible. If vendors are receiving only a handful of orders per decade, it seems to make little sense to standardize."[39]

The same arguments can be applied to SMRs. The report further states that the "attempt to reduce sitework by shifting the workload to factories through modularized design also does not seem to have had the desired effect, and seems to simply have shifted the quality issues from site to module factories."[39]

Nuclear industry rhetoric about standardized modular construction also extends to large reactors. Michael Shellenberger noted in a 2018 article:[40]

"You might have heard about a new kind of nuclear reactor that promises far greater safety at a much lower cost. How?

- *It is much simpler and thus requires "half as many safety-related valves, 83 percent less safety-related pipe and one-third fewer pumps;"*
- *Its components can be manufactured in a factory and assembled on-site at lower cost rather than built from scratch;*

- *Its cooling and passive safety features rely on "natural forces, like gravity… rather than relying on mechanical pumps powered by electricity."*
- *These features mean it will have a very low cost. How low? "Somewhere between $1.4 billion and $1.9 billion" per reactor."*

Shellenberger notes that the rhetoric doesn't concern SMRs but Westinghouse's AP1000 reactors, and he goes on to note that AP1000 projects in the US were long-delayed, subject to massive cost overruns, and that one of the two projects was abandoned altogether.

Modular construction models contributed to cost overruns and delays with the AP1000 projects in the US, the doubling of cost estimates for both projects, the abandonment of the VC Summer project in South Carolina, and the near-collapse of the Vogtle project in Georgia (which is 5.5 years behind schedule).[41-44]

The kindest thing that could be said about standardized, modular construction techniques is that the promise might yet be realized, to some extent, even if history suggests otherwise. A Southern Co. executive involved in the AP1000 project in Georgia told *Associated Press* that building in modules might still work despite the problems with the AP1000 projects. "Has it for the first units resulted in a lot of time savings? No. But does it have promise? Yes," he said.[43]

References:

1. M. V. Ramana, 14 Feb 2018, 'Small Modular Reactors for Nuclear Power: Hope or Mirage?' Nuclear Monitor #857, https://www.wiseinternational.org/nuclear-monitor/857/small-modular-reactors-nuclear-power-hope-or-mirage
2. M.V. Ramana, 27 April 2015, 'The Forgotten History of Small Nuclear Reactors', https://spectrum.ieee.org/tech-history/heroic-failures/the-forgotten-history-of-small-nuclear-reactors
3. Nuclear Energy Insider, 2019, 'Expert Global Analysis on SMRs from 80+ Sources', https://eloqua.nuclearenergyinsider.com/LP=23195
4. BloombergNEF, 16 Jan 2019, 'Clean Energy Investment Exceeded $300 Billion Once Again in 2018', https://about.bnef.com/blog/clean-energy-investment-exceeded-300-billion-2018/
5. James Conca, 16 Feb 2015, 'Can SMRs Lead The U.S. Into A Clean Energy Future?', https://www.forbes.com/sites/jamesconca/2015/02/16/can-smrs-lead-the-u-s-into-a-clean-energy-future/
6. UK National Nuclear Laboratory, December 2014, 'Small Modular Reactors (SMR) Feasibility Study', http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf
7. Rolls-Royce, 12 Sept 2017, 'British small nuclear plants can deliver low cost, low carbon electricity – report issued today', https://www.rolls-royce.com/media/press-releases/2017/12-09-2017-rr-british-small-nuclear-plants-can-deliver-low-cost-low-carbon-electricity.aspx
8. SMR Start, September 2017, 'The Economics of Small Modular Reactors', http://smrstart.org/wp-content/uploads/2017/09/SMR-Start-Economic-Analysis-APPROVED-2017-09-14.pdf

9. SMR Start, 14 Feb 2017, 'Policy Statement on U.S. Public-Private Partnerships for Small Modular Reactors', http://smrstart.org/wp-content/uploads/2017/02/SMR-Start-Public-Policy-on-Federal-Public-Private-Partnership.pdf
10. Russell Ray, 13 June 2018, 'Can SMR Technology Revitalize the Business of Nuclear Power?', https://www.power-eng.com/articles/2018/06/can-smr-technology-revitalize-the-business-of-nuclear-power.html
11. NuScale, 12 Jan 2017, 'NuScale Submits First Ever Small Modular Reactor Design Certification Application (DCA)', https://newsroom.nuscalepower.com/press-release/company/nuscale-submits-first-ever-small-modular-reactor-design-certification-applicat
12. OECD Nuclear Energy Agency, 2016, 'Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment', https://www.oecd-nea.org/ndd/pubs/2016/7213-smrs.pdf
13. Russell Ray, 13 June 2018, 'Can SMR Technology Revitalize the Business of Nuclear Power?', https://www.power-eng.com/articles/2018/06/can-smr-technology-revitalize-the-business-of-nuclear-power.html
14. Alan Neuhauser, 23 May 2018, 'Small Nuclear Passes a Milestone – But Does it Have a Future?', https://www.usnews.com/news/national-news/articles/2018-05-22/small-nuclear-passes-a-milestone-but-does-it-have-a-future
15. Will Davis, 13 Feb 2014, 'Argentina carries torch for SMR construction', http://ansnuclearcafe.org/2014/02/13/carem-25-carries-torch-for-smr-construction/
16. Kennedy Maize, 1 April 2014, 'Worldwide Nuclear Commerce: Good News and Bad News', www.powermag.com/worldwide-nuclear-commerce-good-news-and-bad-news/
17. Gordon Edwards, 12 Sept 2018, 'SMR – The Second Make-Believe Renaissance', http://www.ccnr.org/SMR_Second_Make-Believe_Renaissance_2018.pdf
18. Nuclear Energy Insider, 2019, 'The time is now – build the investment case to scale SMR', https://www.nuclearenergyinsider.com/international-smr-advanced-reactor
19. Thomas W. Overton, 1 Sept 2014, 'What Went Wrong with SMRs?', https://www.powermag.com/what-went-wrong-with-smrs/
20. Anya Litvak, 1 Feb 2014, 'Westinghouse Backs off Small Nuclear Plants', www.post-gazette.com/business/2014/02/02/Westinghouse-backs-off-small-nuclear-plants/stories/201402020074
21. Dan Yurman, 21 Jan 2016, 'The UK plans to become a global center for small nuclear reactors. Can it succeed?', https://neutronbytes.com/2016/01/21/the-uk-plans-to-become-a-global-center-for-small-nuclear-reactors-can-it-succeed/
22. WSP / Parsons Brinckerhoff, Feb 2016, 'Quantitative analysis and initial business case – establishing a nuclear power plant and systems in South Australia', http://nuclearrc.sa.gov.au/app/uploads/2016/05/WSP-Parsons-Brinckerhoff-Report.pdf
23. Jay Surina (NuScale Chief Financial Officer), 20-21 August 2015, 'NuScale Plant Market: Competitiveness & Financeability', https://newsroom.nuscalepower.com/sites/nuscalepower.newshq.businesswire.com/files/press_release/additional/Jay_Surina_-_NuScale_Financial_Breakout_Session_0.pdf
24. Sonal Patel, 6 June 2018, 'NuScale Boosts SMR Capacity, Making it Cost Competitive with Other Technologies', https://www.powermag.com/nuscale-boosts-smr-capacity-making-it-cost-competitive-with-other-technologies/?printmode=1
25. NuScale, accessed 20 February 2019, 'A cost competitive nuclear option for multiple applications', https://www.nuscalepower.com/benefits/cost-competitive

26. Energy Innovation Reform Project, 2017, 'What Will Advanced Nuclear Power Plants Cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development', report prepared by the Energy Options Network, https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Reactors-Cost-Study.pdf
27. Lazard, Nov 2018, 'Lazard's Levelized Cost of Energy Analysis – Version 12.0', https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf
28. Neil Ford, 7 March 2018, 'Rolls-Royce SMR to use on-site 'factories' to hit 60 pounds/MWh', https://analysis.nuclearenergyinsider.com/rolls-royce-smr-use-site-factories-hit-60-poundsmwh
29. Mark Cooper, Sept 2010, 'Policy challenges of nuclear reactor construction, cost escalation and crowding out alternatives: Lessons from the U.S. and France for the effort to revive the U.S. industry with loan guarantees and tax subsidies', http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.175.2423&rep=rep1&type=pdf
30. M.V. Ramana, 7 Nov 2018, "Are thousands of new nuclear generators in Canada's future?", https://thetyee.ca/Opinion/2018/11/07/Nuclear-Generators-Canada-Future/
31. Mark Cooper, Sept. 2014, 'Small modular reactors and the future of nuclear power in the United States', Energy Research & Social Science, Vol.3, pp.161–177, https://www.sciencedirect.com/science/article/pii/S2214629614000929
32. Edwin Lyman, Sept 2013, 'Small Isn't Always Beautiful: Safety, Security, and Cost Concerns about Small Modular Reactors', https://www.ucsusa.org/sites/default/files/legacy/assets/documents/nuclear_power/small-isnt-always-beautiful.pdf
33. International Atomic Energy Agency, 2018, 'Deployment Indicators for Small Modular Reactors Methodology, Analysis of Key Factors and Case Studies', IAEA-TECDOC-1854, https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1854web.pdf
34. Ahmed Abdulla, Inês Lima Azevedo, and M. Granger Morgan, 2013, 'Expert assessments of the cost of light water small modular reactors', Proceedings of the National Academy of Science, https://www.pnas.org/content/110/24/9686
35. Nuclear Energy Insider, 2014, "Small Modular Reactors: An industry in terminal decline or on the brink of a comeback?", http://1.nuclearenergyinsider.com/
36. Expert Finance Working Group on Small Nuclear Reactors, March 2018, 'Market framework for financing small nuclear', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/732220/DBEIS_11_-_Market_Framework_for_Financing_Small_Nuclear_EFWG_Final_Report_.pdf
37. David Lowry, 7 Aug 2018, 'Panglossian puffery for mini reactors in new report from UK Government advisors that avoids addressing security and nuclear waste problems of small modular reactors', http://drdavidlowry.blogspot.com/2018/08/panglossian-puffery-for-mini-reactors.html
38. Mycle Schneider, Antony Froggatt et al., Sept 2018, 'The World Nuclear Industry Status Report 2018', www.worldnuclearreport.org/Nuclear-Power-Strategic-Asset-Liability-or-Increasingly-Irrelevant.html
39. Mycle Schneider, Antony Froggatt et al., July 2015, 'World Nuclear Industry Status Report 2015', www.worldnuclearreport.org/-2015-.html

40. Michael Shellenberger, 18 July 2018, 'If Radical Innovation Makes Nuclear Power Expensive, Why Do We Think It Will Make Nuclear Cheap?', www.forbes.com/sites/michaelshellenberger/2018/07/18/if-radical-innovation-makes-nuclear-power-expensive-why-do-we-think-it-will-make-nuclear-cheap
41. Richard Korman, 1 Nov 2017 'Witness to the Origins of a Huge Nuclear Construction Flop', Engineering News-Record, https://www.enr.com/articles/43325-witness-to-the-origins-of-a-huge-nuclear-construction-flop
42. SCANA and Santee Cooper, 6 May 2014, Letter to CB&I and Westinghouse Electric Corporation, https://bloximages.newyork1.vip.townnews.com/postandcourier.com/content/tncms/assets/v3/editorial/9/81/981c2f5a-a52e-11e7-a8b9-bb32b93afb23/59ce6d9b7e835.pdf.pdf
43. Ray Henry / Associated Press, 26 July 2014, 'Promises of Easier Nuclear Construction Fall Short', http://abcnews.go.com/US/wireStory/promises-easier-nuclear-construction-fall-short-24725848
44. Andrew Brown, 27 Aug 2017, 'Early signs of 'incompetence at every level' went unheeded as South Carolina rushed toward 'sexy' nuclear future', http://www.postandcourier.com/business/early-signs-of-incompetence-at-every-level-went-unheeded-as/article_b47acd2c-89a5-11e7-830a-9364c7e7b71b.html

4. SMR cost estimates, and costs of SMRs under construction

Costs of SMRs under construction

Estimated construction costs for Russia's floating nuclear power plant (with two 35-MW ice-breaker-type reactors) have increased more than four-fold and now equate to over US$10 billion / gigawatt (GW) (US$740 million / 70 MW).[1] A 2016 OECD Nuclear Energy Agency report said that electricity produced by the plant is expected to cost about US$200/MWh, with the high cost due to large staffing requirements, high fuel costs, and resources required to maintain the barge and coastal infrastructure.[2]

Little credible information is available on the cost of China's demonstration 2x250 MW high-temperature gas-cooled reactor (HTGR). If the demonstration reactor is completed and successfully operated, China reportedly plans to upscale the design to 655 MW (three modules feeding one turbine, total 655 MW) and to build these reactors in pairs with a total capacity of about 1,200 MW (so much for the small-is-beautiful SMR rhetoric). According to the World Nuclear Association, China's Institute of Nuclear and New Energy Technology at Tsinghua University expects the cost of a 655 MWe HTGR to be 15-20% more than the cost of a conventional 600 MWe PWR.[3]

A 2016 report said that the estimated construction cost of China's demonstration HTGR is about US$5,000/kW – about twice the initial cost estimates.[4] Cost increases have arisen from higher material and component costs, increases in labor costs, and increased costs associated with project delays.[4] The World Nuclear Association states that the cost of the demonstration HTGR is US$6,000/kW.[5]

The CAREM (Central Argentina de Elementos Modulares) SMR under construction in Argentina illustrates the gap between SMR rhetoric and reality. Argentina's Undersecretary of Nuclear Energy, Julián Gadano, said in 2016 that the world market for SMRs is in the tens of billions of dollars and that Argentina could capture 20% of the market with its CAREM technology.[6] But cost estimates have ballooned:

- In 2004, when the CAREM reactor was in the planning stage, Argentina's Bariloche Atomic Center estimated an overnight cost of US$1 billion / GW for an integrated 300-MW plant (while acknowledging that to achieve such a cost would be a "very difficult task").[7]
- When construction began in 2014, the estimated cost was US$17.8 billion / GW (US$446 million for a 25-MW reactor).[8]
- By April 2017, the cost estimate had increased to US$21.9 billion / GW (US$700 million with the capacity uprated from 25 MW to 32 MW).[9]

The CAREM project is years behind schedule and costs will likely increase further. In 2014, first fuel loading was expected in 2017[8] but completion is now anticipated in November 2021.[10]

Credible assessments of SMR economics

International Energy Agency (IEA) and the OECD Nuclear Energy Agency (NEA): A 2015 report by the IEA and the OECD NEA predicts that electricity costs from SMRs will typically be 50−100% higher than for current large reactors, although it holds out some hope that large volume production of SMRs could help reduce costs − if that large volume production is comprised of "a sufficiently large number of identical SMR designs ... built and replicated in factory assembly workshops."[11]

The agencies were even more underwhelmed by Generation IV concepts: "In terms of generation costs, generation IV technologies aim to be at least as competitive as generation III technologies ... though the additional complexity of these designs, the need to develop a specific supply chain for these reactors and the development of the associated fuel cycles will make this a challenging task."[11]

European Commission: The European Commission released its 'Communication on a Nuclear Illustrative Programme' (PINC) in 2016[12], along with a Staff Working Document which informs the main report.[13] The Staff Working Document noted that the nuclear industry has been considering the deployment of commercial SMRs since the 1950s, but little has come of it and only a few SMRs are under construction around the world. The Document notes that the cost of investment per kW is likely to be higher for SMRs compared to larger reactors. It notes that claims supporting SMR economics – which emphasize standardization, learning effects, cost sharing and modularization – "are difficult to quantify due to the lack of existing examples". The Staff Working Document further states: "Due to the loss of economies of scale, the decommissioning and waste management unit costs of SMR will probably be higher than those of a large reactor (some analyses state that between two and three times higher)."

Atkins Report: A report by the consultancy firm Atkins for the UK Department for Business, Energy and Industrial Strategy found that electricity from the first SMR in the UK would be 30% more expensive than power from large reactors, because of reduced economies of scale and the costs of deploying first-of-a-kind technology.[14]

The Atkins report said there is "a great deal of uncertainty with regards to the economics" of the smaller reactors. The report estimates that the levelized cost of electricity for an SMR based on a pressurized water reactor design would be £86–124/MWh with a central estimate of £101/MWh, and adds this caveat: "However it is recognised that SMR is a new technology and there is a substantial risk that these costs will be higher than this if costs accumulate during development or if financing costs are initially higher than they are for large nuclear."[14]

South Australian Nuclear Fuel Cycle Royal Commission: The Royal Commission was stridently pro-nuclear but was nevertheless unimpressed by the economic case for nuclear power in South Australia.[15] In its May 2016 Final Report, the Commission stated: "Taking into account the South Australian energy market characteristics and the cost of building and operating a range of nuclear power plants, the Commission has found it would not be commercially viable to develop a nuclear power plant in South Australia beyond 2030 under current market rules."

The Royal Commission identified hurdles and uncertainties facing development and commercial deployment of SMRs including the following:[15]

- SMRs have a relatively small electrical output, yet some costs including staffing may not decrease in proportion to the decreased output.
- SMRs have lower thermal efficiency than large reactors, which generally translates to higher fuel consumption and spent fuel volumes over the life of a reactor.
- SMR-specific safety analyses need to be undertaken to demonstrate their robustness, for example during seismic events.
- It is claimed that much of the SMR plant can be fabricated in a factory environment and transported to site for construction. However, it would be expensive to set up this facility and it would require multiple customers to commit to purchasing SMR plants to justify the investment.
- Reduced safety exclusion zones for small reactors have yet to be confirmed by regulators.
- Timescales and costs associated with the licensing process are still to be established.
- SMR designers need to raise the necessary funds to complete the development before a commercial trial of the developing designs can take place.
- Customers who are willing to take on first-of-a-kind technology risks must be secured.

A report by WSP / Parsons Brinckerhoff, commissioned by the Royal Commission, estimated levelized costs of electricity of A$225/MWh (US$161/MWh) based on the NuScale SMR design (and slightly lower costs based on the abandoned mPower design).[16] That's 2.5 times higher than the implausible figures being promoted by NuScale Power: the company's "target" for its first project is US$65/MWh.[17] Costs per MWh for NuScale are estimated by WSP / Parsons Brinckerhoff to be 22% higher than large PWRs (A$184 or US$132).

WSP / Parsons Brinckerhoff concluded:[16]

"Analysis of the economic viability measures for the scenarios under consideration suggests that nuclear power plants in South Australia are not likely to be economically viable, unless:
- *capital and operating costs of nuclear power plants are reduced to or below the lowest extreme of the plausible range of costs considered by this study; and/or*
- *the cost of capital (debt and equity) is reduced to a level that is unlikely to be commercially available from the open market; and*
- *electricity prices increase dramatically as a result of strong climate action, such as 100% reduction in emissions relative to 2000 levels by 2040 to 2050."*

Mark Cooper: A September 2014 journal article by Dr Mark Cooper, senior research fellow for economic analysis at the Institute for Energy and the Environment at Vermont Law School, assesses the prospects for SMR technology from three perspectives:[18]
- the implications of the history of cost escalation in nuclear reactor construction for learning, economies of scale and other process that SMR advocates claim will lower cost;
- the challenges SMR technology faces in terms of high costs resulting from lost economies of scale, long lead time needed to develop a new design, the size of the task to create assembly lines for modular reactors and intense concern about safety;
- and the cost and other characteristics – e.g. scalability, speed to market, flexibility, etc. – of available alternatives compared SMR technology.

Cooper concluded that the recent (in 2014) decisions of major vendors Westinghouse and B&W to dramatically reduce SMR development efforts "reflects the severe disadvantages that SMR technology faces in the next several decades. … Westinghouse and B&W are big names in the nuclear space, had thrown a great deal of weight and money into advancing SMRs as the next big thing and the savior of the nuclear industry, but they failed."[18]

In a separate 2014 paper, Cooper argues that the economic potential of SMRs is weak for the following reasons:[19]

"First, the viability of SMRs is dependent on the very economic processes that have eluded the industry in the past. The ability of the small modular reactor technology to reverse the cost trajectory of the industry is subject to considerable doubt. … SMR technology will need massive subsidies in the early stages to get off the ground and take a significant amount of time to achieve the modest economic goal set for it.

"Second, even if these economic processes work as hoped, nuclear power will still be more costly than many alternatives. Over the past two decades wind and solar have been experiencing the cost reducing processes of innovation, learning and economies of scale that nuclear advocate hoped would benefit the "Renaissance" technology and claim will affect the small modular technology. Nuclear cost curves are so far behind the other technologies that they will never catch up, even if the small modular technology performs as hoped.

"Third, the extreme relaxation of safety margins and other changes in safety oversight is likely to receive a very skeptical response from policymakers.

"Fourth, the type of massive effort that would be necessary to drive nuclear costs down over the next couple of decades would be an extremely large bet on a highly risky technology that would foreclose alternatives that are much more attractive at present. Even if the technology could be deployed at scale at the currently projected costs, without undermining safety, it would be an unnecessarily expensive solution to the problem that would waste a great deal of time and resources, given past experience.

"Finally, giving nuclear power a central role in climate change policy would not only drain away resources from the more promising alternatives, it would undermine the effort to create the physical and institutional infrastructure needed to support the emerging electricity systems based on renewables, distributed generation and intensive system and demand management."

Energy and Power Engineering: A 2014 study published in *Energy and Power Engineering* concluded that fuel costs for integral pressurized water reactors are 15% to 70% higher than for large light water reactors, and points to research indicating similar comparisons for construction costs.[20]

International Atomic Energy Agency: The IAEA can usually be relied upon to parrot nuclear industry propaganda, but it states that "although SMRs require less upfront capital per unit, their electricity generating cost will probably be higher than that of large reactors".[21]

Massachusetts Institute of Technology: A 2018 MIT report states:[22]

"The main economic question is whether an SMR can be built at a substantially lower unit capital cost (i.e., per kW of capacity) and therefore generate baseload electricity at lower total unit cost (i.e., per MWh). NuScale advertises a capital cost of less than $5,100/kWe, which is only a modest improvement over the advertised cost of certain Gen-III+ systems and still not competitive against natural gas-fired generation under current circumstances. A 2016 study performed by Atkins for the U.K. government estimates the FOAK cost of power from integral PWR SMR designs to be about 30% above the NOAK cost of a traditional, large LWR. The Atkins study scales up companies' own capital cost estimates to correct for the 'optimism bias' discussed earlier, while also noting both the potential for sharp cost declines with volume production of factory builds and the enormous uncertainties involved in attempting to estimate this decline.

"Proponents of many small reactor designs also advertise other advantages besides lower capital costs. Some focus on the advantages of smaller total plant size. They point out that this opens up sections of the market that are unsuited to large LWRs of 1 gigawatt (GW) capacity or more. They also point out that buyers will be better able to finance capacity purchases in smaller bites.

"A note of caution is in order when evaluating claims concerning the ancillary advantages of small size. The challenge facing the nuclear industry is to reduce unit capital cost (i.e., cost per kWe) to be more competitive in generating the lowest unit cost electricity. If the size of a small plant also happens to be the size that offers the lowest unit capital cost, then the

ancillary benefits of a smaller plant are an extra bonus. However, the extra advantages of small plant size are unlikely to make up for a failure to radically reduce unit capital cost.

"The problem is that, with respect to size, there is often a tradeoff between the technically optimal design and the needs of some customers. This is an age-old issue for the nuclear industry, as it is in many other industries. The optimally-sized reactor suits some segments of the market, but not all. Therefore, many reactor vendors size their technically optimal reactor first, and later produce smaller versions to serve segments of the market to which the most efficient design is not suited. Among LWR designs, examples of this approach include the Russian VBER-300, Holtec's SMR-160, and China's ACP1000.

"The industry's problem is not that it has overlooked valuable market segments that need smaller reactors. The problem is that even its optimally scaled reactors are too expensive on a per-unit-power basis. A focus on serving the market segments that need smaller reactor sizes will be of no use unless the smaller design first accomplishes the task of radically reducing per-unit capital cost. If nuclear technology cannot be competitive at its optimal scale of generation, whether large or small, it is difficult to see how it will succeed by scaling plants below the optimal size. If, on the other hand, smaller designs are optimal and can radically reduce unit capital costs, then the ancillary advantages of accessing a larger market will be a nice bonus."

Studies published in the *Proceedings of the National Academy of Science*

An article by four current and former researchers from Carnegie Mellon University's Department of Engineering and Public Policy, published in 2018 in the *Proceedings of the National Academy of Science*, argues that it is most unlikely that any new large nuclear power plants will be built over the next several decades in the US.[23] "There is no reason to believe that any utility in the United States will build a new large reactor in the foreseeable future. These reactors have proven unaffordable and economically uncompetitive. In the few markets with the will to build them, they have proven to be unconstructible," M. Granger Morgan and his pro-nuclear colleagues state. "[T]here is virtually no chance that the United States will be able to undertake the construction of additional large LWR power plants in the next several decades," they add.

The authors further argue that no US advanced reactor design will be commercialized before mid-century and that the purported advantages of advanced reactor concepts "remain speculative". That leaves light-water SMRs as the only option that might be deployed at significant scale over the next few decades. They conclude: "We have systematically investigated how a domestic market could develop to support that [SMR] industry over the next several decades and, in the absence of a dramatic change in the policy environment, have been unable to make a convincing case."

On the use of SMRs for electricity generation (alone), the authors state:

"Our results reveal that while one light water SMR module would indeed cost much less than a large LWR, it is highly likely that the cost per unit of power will be higher. In other words, light water SMRs do make nuclear power more affordable but not necessarily more

economically competitive for power generation. That vision of the dramatic cost reduction that SMR proponents describe is unlikely to materialize with this first generation of light water SMRs, even at nth-of-a-kind deployment.

"Because light water SMRs incur both this economic premium and the considerable regulatory burden associated with any nuclear reactor, we do not see a clear path forward for the United States to deploy sufficient numbers of SMRs in the electric power sector to make a significant contribution to greenhouse gas mitigation by the middle of this century."

The authors also systematically investigated how a domestic market could develop to support a SMR industry across a range of applications – producing process heat for industrial applications; switching SMRs back and forth between electricity generation and water desalination to complement intermittent generation from renewable energy sources; and deploying SMRs as a source of electrical and thermal energy for US military bases. But none of those options show promise.

The authors state that subsidies amounting to several hundred billion dollars would be required to kick-start an SMR industry:

"Because the United States will probably not build any new large LWRs, and there is no practical way to bring advanced reactor designs to achieve widespread commercial viability in the United States in less than several decades, we have argued that only factory-manufactured SMRs could contribute a significant new nuclear carbon-free wedge on that time scale. For that to happen, several hundred billion dollars of direct and indirect subsidies would be needed to support their development and deployment over the next several decades, since present competitive energy markets will not induce their development and adoption."

A separate article published in the *Proceedings of the National Academy of Science* (with two of the same co-authors) points to dramatic variations in expert assessments of overnight constructions costs for integral light-water SMRs (overnight costs comprising the sum of engineering, procurement, and construction costs but excluding site-work, transmission up-grades and other "owner's costs", and the cost of financing).[24] Further, the analysis considered a nth-of-a-kind plant and thus "assumed that the vendor has recouped the cost of design engineering and licensing, has exploited technological learning, and has streamlined construction management."

The authors concluded: "Consistent with the uncertainty introduced by past cost overruns and construction delays, median estimates of the cost of new large plants vary by more than a factor of 2.5. Expert judgments about likely SMR costs display an even wider range. Median estimates for a 45 megawatts-electric (MWe) SMR range from $4,000 to $16,300/kWe and from $3,200 to $7,100/kWe for a 225-MWe SMR."[24]

For a single 45 MWe reactor, 11 experts gave median costs between $4,000 and $7,700/kWe while five experts (four of them working for nuclear technology vendors) provided estimates as much as a factor of two to three higher. The authors state: "These five experts argued that costs rise rapidly as reactors become smaller, with the result that the 45-MWe reactor is especially disadvantaged."[24]

The article was published in 2013 and thus its conclusions can be reassessed in light of intervening events. In their 2013 article, the authors state that median estimates of the overnight cost of a 1,000-MWe reactor range from US$2,600 to US$6,600/kW.[24] Yet in the 2018 article published in the *Proceedings of the National Academy of Science*, the authors note that the cost of the Vogtle AP1000 project in the US state of Georgia amounts to "a staggering $11,000 per kWe, and these costs are expected to rise".[23]

SMR projects won't be immune from the major cost overruns that have beset large reactors. Indeed cost overruns have already become the norm for SMR projects:

- estimated construction costs for Russia's floating SMRs increased more than four-fold;
- the estimated construction cost of China's demonstration HTGR is about twice the initial estimate; and
- recent construction cost estimates for Argentina's CAREM SMR are 22 times greater than the number being floated in 2004 and the current estimate is a hopelessly uneconomic US$21,900 / kW (well outside the range suggested by the above-mentioned experts).

References:

1. Charles Digges, 25 May 2015, 'New documents show cost of Russian floating nuclear power plant skyrockets', http://bellona.org/news/nuclear-issues/2015-05-new-documents-show-cost-russian-nuclear-power-plant-skyrockets
2. OECD Nuclear Energy Agency, 2016, 'Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment', https://www.oecd-nea.org/ndd/pubs/2016/7213-smrs.pdf
3. World Nuclear Association, Feb 2019, 'Nuclear Power in China', http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
4. 1 Dec 2016, 'China's plans to begin converting coal plants to walk away safe pebble bed nuclear starting in the 2020s', http://www.nextbigfuture.com/2016/12/chinas-plans-to-begin-converting-coal.html
5. World Nuclear Association, Feb 2019, 'Nuclear Power in China', http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx
6. 7 Oct 2016, 'Gadano affirmed that 2,000 million pesos will be invested in the development of CAREM', http://u-238.com.ar/gadano-afirmo-se-invertiran-2-000-millones-pesos-desarrollo-del-carem/
7. Darío Delmastro, Marcelo Oscar Giménez et al., January 2004, 'CAREM concept: A competitive SMR', Conference Paper, Argentina's Bariloche Atomic Center, https://www.researchgate.net/publication/267579277_CAREM_concept_A_competitive_SMR
8. World Nuclear News, 10 Feb 2014, 'Construction of CAREM underway', http://www.world-nuclear-news.org/NN-Construction-of-CAREM-underway-1002144.html
9. Andrew Baker, 17 April, 'Argentine nuclear reactor due to start up in 2020', https://www.bnamericas.com/en/news/electricpower/argentine-nuclear-reactor-due-to-start-up-in-2020/

10. World Nuclear Association, January 2019, 'Nuclear Power in Argentina', http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/argentina.aspx
11. International Energy Agency (IEA) and OECD Nuclear Energy Agency (NEA), 2015, 'Projected Costs of Generating Electricity':
Media release: https://www.iea.org/newsroom/news/2015/august/joint-iea-nea-report-details-plunge-in-costs-of-producing-electricity-from-renew.html
Executive Summary: https://www.iea.org/Textbase/npsum/ElecCost2015SUM.pdf
Full report: https://webstore.iea.org/projected-costs-of-generating-electricity-2015
12. European Commission, 4 April 2016, 'Nuclear Illustrative Programme', http://ec.europa.eu/transparency/regdoc/rep/1/2016/EN/1-2016-177-EN-F1-1.PDF
13. European Commission, 4 April 2016, 'Commission Staff Working Document, Accompanying the document: Communication from the Commission, Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty', https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v10.pdf
14. Atkins, 21 July 2016, 'SMR Techno-Economic Assessment Project 1: Comprehensive Analysis and Assessment Techno-Economic Assessment, Final Report, Volume 1, For The Department of Energy and Climate Change', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665197/TEA_Project_1_Vol_1_-_Comprehensive_Analysis_and_Assessment_SMRs.pdf
15. South Australian Nuclear Fuel Cycle Royal Commission Report, May 2016, http://yoursay.sa.gov.au/system/NFCRC_Final_Report_Web.pdf
16. WSP / Parsons Brinckerhoff, Feb 2016, 'Quantitative analysis and initial business case – establishing a nuclear power plant and systems in South Australia', http://nuclearrc.sa.gov.au/app/uploads/2016/05/WSP-Parsons-Brinckerhoff-Report.pdf
17. Sonal Patel, 6 June 2018, 'NuScale Boosts SMR Capacity, Making it Cost Competitive with Other Technologies', https://www.powermag.com/nuscale-boosts-smr-capacity-making-it-cost-competitive-with-other-technologies/?printmode=1
18. Mark Cooper, Sept. 2014, 'Small modular reactors and the future of nuclear power in the United States', Energy Research & Social Science, Vol.3, pp.161–177, https://www.sciencedirect.com/science/article/pii/S2214629614000929
19. Mark Cooper, May 2014, 'The Economic Failure of Nuclear Power and the Development of a Low-Carbon Electricity Future: Why Small Modular Reactors Are Part of the Problem, Not the Solution', https://www.nirs.org/wp-content/uploads/reactorwatch/newreactors/cooper-smrsaretheproblemnotthesolution.pdf
20. Christopher P. Pannier and Radek Skoda, 2014, 'Comparison of Small Modular Reactor and Large Nuclear Reactor Fuel Cost', Energy and Power Engineering, 6, 82-94, https://www.scirp.org/journal/PaperInformation.aspx?PaperID=45669
21. IAEA, 16 Feb 2018, 'IAEA Expands International Cooperation on Small, Medium Sized or Modular Nuclear Reactors', https://www.iaea.org/newscenter/pressreleases/iaea-expands-international-cooperation-on-small-medium-sized-or-modular-nuclear-reactors
22. Massachusetts Institute of Technology, 2018, 'The Future of Nuclear Energy in a Carbon-Constrained World: An Interdisciplinary MIT Study, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf

23. M. Granger Morgan, Ahmed Abdulla, Michael J. Ford, and Michael Rath, July 2018, 'US nuclear power: The vanishing low-carbon wedge', Proceedings of the National Academy of Science, https://www.pnas.org/content/115/28/7184
24. Ahmed Abdulla, Inês Lima Azevedo, and M. Granger Morgan, 2013, 'Expert assessments of the cost of light water small modular reactors', Proceedings of the National Academy of Science, https://www.pnas.org/content/110/24/9686

5. No-one wants to pay for SMRs: US and UK case studies

No company, utility, consortium or national government is seriously considering building the massive supply chain that is at the very essence of the concept of SMRs – mass, modular construction. Yet without that supply chain, SMRs will be expensive curiosities.

All or almost all SMR projects are either dependent on government handouts or they are run by state-owned agencies. The private sector won't bet shareholders' money on SMRs to any significant degree but governments have "a once in a lifetime opportunity" to bet taxpayers' money on private-sector SMR frolics and to offer SMR developers "full and ongoing Government support".[1] But government funding has generally been modest (in the US and UK, for example) and well below that required to kick-start or sustain an SMR industry. The Chinese and Argentinian governments hope to develop a large export market for their high-temperature gas-cooled reactors and small PWRs, respectively, but so far all they can point to are partially-built demonstration reactors that have been subject to significant cost overruns.

Government funding for SMRs in the UK is currently of the order of tens of millions of pounds – three orders of magnitude less than the largesse showered on the Hinkley Point C large-reactor project (lifetime subsidies of several tens of billions of pounds). In the US, government SMR funding of several hundred million dollars is an order of magnitude lower than subsidies for large reactors (several billion dollars for the AP1000 projects).

Of course, it could be argued that government funding for SMR programs is excessive given the strong likelihood of failure. A case in point is the mPower project in the US, which was abandoned despite receiving government funding of US$111 million.[2]

And of course, just because government funding is currently a small fraction of that required to kick-start an SMR industry, it is still possible that government funding will be dramatically increased.

United States

A 2018 article in the *Proceedings of the National Academy of Science* discusses the funding provided by the US Department of Energy's (DOE) Office of Nuclear Energy (NE) for advanced reactor designs:[3]

"[W]e recently analyzed the DOE's efforts to commercialize advanced reactor designs. NE has spent $2 billion on this effort since the late 1990s, with very little to show for it. This is unsurprising: Even by its own assessment, this amount is less than half what is necessary to

demonstrate even one non-light water technology. Moreover, NE's spending portfolio conflicts with much of the wisdom regarding the execution of innovative research and development programs: Annual funding varies fourfold, priorities are erratic, and spending on existing infrastructure (some of which is obsolete or ill-suited to support testing of new designs) consumes more than half of the budget.

"Moreover, the funds dedicated to advanced reactors have been spread across a number of different designs and fuel types, not because a conscious choice has been made to further these technologies based on their technical, economic, and institutional benefits but because they are the favored projects of different national laboratories. In interviews with leaders across the enterprise, those associated with the DOE and the national laboratories expressed either alarm or despair at the trajectory of advanced fission innovation in the United States."

SMR Smart, a US consortium of companies and utilities, said in a 2017 "policy statement":[4]

"The total cost to obtain regulatory approvals and perform first-of-a-kind final design engineering for two or more SMR designs and the initial SMR facilities is expected to be $2 billion to $2.5 billion. To date, four designers have invested a total of more than $1 billion dollars to develop their SMR designs.

"Potential owners of SMR facilities have also invested tens of millions of dollars in preparing their sites for possible deployment of SMRs. The U.S. Department of Energy's (DOE's) SMR Licensing Technical Support (LTS) program, envisioned to provide initial funding of $452 million on a cost share basis, is much appreciated but not sufficient in the current business environment to achieve large-scale SMR commercialization.

"The SMR LTS program is scheduled to end in fiscal year 2017, just as the first design and facility applications are being submitted for review by the NRC. DOE's LTS program should be expanded to cover design finalization in addition to licensing under the multiple available regulatory processes …, with a commensurate increase in funding and extension through FY2025."

SMR Start's "policy statement" is nothing more than a wish-list for additional government subsidies including commercial deployment partnerships (production tax credits, power purchase agreements, loan guarantee program), technology development partnerships (grid security and reliability programs, national laboratory support), and manufacturing and supply chain partnerships.[4]

NuScale has submitted an application to the US Nuclear Regulatory Commission for its small PWR design. The company has spent more than US$800 million on its design – including US$288 million from the Department of Energy.[5] NuScale estimates that by the time it gets through the NRC licensing process, it will have spent US$1 billion overall (including government contributions).[6] That's US$1 billion (possibly more) before the first concrete pour. NuScale will then face the problem that there is a long way from NRC certification to the completion of its first SMR, and further still from the first reactor to mass production for a mass market. One of many reality checks will be the eventual, inevitable acknowledgement that NuScale's estimate of "around $3 billion" for its first 684 MWe plant is ridiculous.[7]

The 2018 article in the *Proceedings of the National Academy of Science* states:[3]

"Often, proponents of nuclear power note that private enterprise is faring better than the government at advancing non-light water reactor concepts. Indeed, more than $1.3 billion has been secured by close to four dozen such companies. However, a dozen of these are working not on advanced fission reactors but on fusion reactors or nuclear fuels. Another dozen reactors either belong to bankrupt companies (e.g., Westinghouse) or are proceeding at a very low level of activity (e.g., the DOE's Next Generation Nuclear Plant and various university ventures that are very much in the conceptual design phase). Moreover, while $1.3 billion sounds impressive, that sum is dominated by one firm, TerraPower, which has found it remarkably challenging to build or secure access to the range of equipment, materials, and technology required to successfully commercialize its innovative design. As a result, it is teaming with China in its development efforts."

Since that article was published, Terrapower's plan to build a demonstration fast reactor in China has been abandoned and the company is now focused on fundraising in the US. Dan Yurman takes up the story: "When Bill Gates came to DC offering to match his billions to an equal stake from the government, the most polite way to describe the response is "don't let the screen door hit you on the way back home." Gates, who was investing his own money in TerraPower's collaboration with Chinese state owned enterprises, got the door slammed in his face by Trump's ill-advised trade war with China."[8]

The 2018 *Proceedings* article concluded that the development of an SMR industry in the US would require "several hundred billion dollars of direct and indirect subsidies" over the next several decades "since present competitive energy markets will not induce their development and adoption."[3]

SMR developers are keen to get their hands on taxpayers' money and electricity ratepayers' money – but not so keen to invest their own money. Dan Yurman surveyed the SMR scene in the US in 2015, noting that "three potential customers ran into financial and regulatory headwinds which are no different than for plans to build the 1000MW units."[9]

- Babcock & Wilcox had scaled down its spending on mPower (and abandoned the project in 2017 despite receiving US$111 million of government funding). B&W CEO Jim Ferland said that he sees the future of SMRS as "still being up in the air." B&W had no customer, hence its unwillingness to invest more money, the unwillingness of the finance sector to invest, and the unwillingness of the US government to throw good money after bad.
- First Energy was "nominally" still interested in SMRs, Yurman states. But First Energy subsidiaries, including FirstEnergy Nuclear Operating Company, filed for bankruptcy protection in March 2018.[10]
- Westinghouse attempted to develop a 225 MW SMR in partnership with Ameren in Missouri. Westinghouse abandoned its efforts after it missed out on funding from the US Department of Energy.
- Ameren twice failed twice to win legislative approval for CWIP financing for either a large French EPR reactor or an SMR. CWIP – Construction Work in Progress – is

legislation in a handful of US states that allows a utility to charge ratepayers higher rates to cover future costs of a yet-to-be-constructed reactor, even if that reactor is never built. CWIP has always been controversial, all the more so after the collapse of the AP1000 project in South Carolina and the doubling of cost estimates for the two AP1000 reactors still under construction in Georgia.

- Warren Buffet's MidAmerican Energy tried but failed to secure CWIP funding for an SMR in Iowa … and then gave up on the project.

NuScale was "the sole survivor of the US SMR shakeout", Yurman noted in his 2015 article.[9]

A November 2018 US Department of Energy (DOE) report states that to make a "meaningful" impact, about US$10 billion of government subsidies would be needed to deploy 6 GW of SMR capacity by 2035.[11] (For comparison, about 12.5 GW of new renewable energy capacity was installed in 2017 alone in the US, in addition to 3.5 GW of small-scale solar capacity.[12])

The DOE report, prepared for the Department by Kutak Rock and Scully Capital, cites claims by SMR Start that costs of SMR-generated power could be reduced by 22% by milking any and every subsidy that might be made available at local, state and federal levels: Production Tax Credits, credit incentives (loan guarantees), and state and local tax incentives such as sales and use tax exemptions and property tax abatements.

The DOE report promotes the case for SMR subsidies yet it suggests some strong reasons not to bet on SMRs. It notes that the development and construction of SMRs "represents a highly uncertain endeavor" and it further states: "SMRs face significant challenges in commercial deployment, including the need to develop a manufacturing ecosystem for a new technology, significant work remaining to license and develop a working generation facility, and costs which may be high relative to other energy sources in the competitive and quickly evolving power markets."[11]

Canadian Nuclear Laboratories has set the goal of siting a new demonstration SMR at its Chalk River site by 2026. But serious discussions about paying for a demonstration SMR – let alone a fleet of SMRs – have not yet begun. The Canadian SMR Roadmap website simply states: "Appropriate risk sharing among governments, power utilities and industry will be necessary for SMR demonstration and deployment in Canada."[13] The CEO of Terrestrial Energy said in early 2019 that the Canadian government "must … provide financial products which minimize commercial risks", with options including loan guarantees, production tax credits, grants and offtake agreements.[14]

United Kingdom

Government funding made available in the UK to kick-start an SMR industry is trivial compared to the amount required. In 2018, the UK government agreed to provide £56 million towards the development and licensing of advanced (non-LWR) modular reactor designs and £32 million towards advanced manufacturing research.[15,16]

Industry sources told the *Guardian* in 2017 that government funding is relatively small and they are unsure whether it will be enough to make a difference. "It's a pretty half-hearted, incredibly British, not-quite-good-enough approach," one said.[17] An energy industry source questioned how credible most of the SMR developers were: "Almost none of them have got more than a back of a fag packet design drawn with a felt tip."[17]

Andy Dawson, author of a 2018 Global Warming Policy Foundation briefing paper on SMRs[18], argues that "three years have been wasted, and the window for a meaningful UK participation in SMR delivery has narrowed almost to the point of closure."[19] Dawson suggests several possible reasons: a loss of commitment at ministerial level, loss of Treasury support, civil service inertia and technical incompetence.[19]

Rolls-Royce missed out on government funding for its SMR design but continues to lobby. *Nuclear Energy Insider* reported in January 2019 that the Rolls-Royce SMR consortium has asked for over £200 million pounds of UK government funding to develop and license its light-water SMR design.[20] In mid-2018, Rolls-Royce scaled back its SMR investment significantly, from several millions to simply paying for "a handful of salaries".[21] David Orr, executive vice-president of Rolls-Royce's SMR program, said that without government funding the project "will not fly. We are coming to crunch time."[21]

The Guardian reported in October 2018:[22]

"Backers of mini nuclear power stations have asked for billions of pounds of taxpayers' money to build their first UK projects, according to an official document. … But the nuclear industry's claims that the mini plants would be a cheap option for producing low-carbon power appear to be undermined by the significant sums it has been asking of ministers.

"Some firms have been calling for as much as £3.6bn to fund construction costs, according to a government-commissioned report, released under freedom of information rules. Companies also wanted up to £480m of public money to help steer their reactor designs through the regulatory approval process, which is a cost usually paid by nuclear companies. ...

"David Lowry, a nuclear policy consultant who obtained the document, said: "SMRs are either old, discredited designs repackaged when companies see governments prepared to throw taxpayers' subsidies to support them, or are exotic new technologies, with decades of research needed before they reach commercial maturity.""

The so-called Expert Finance Working Group on Small Nuclear Reactors in the UK laments "the financing sectors potential misunderstanding of nuclear specific risks and how such risks can be mitigated, and that nuclear specific risks aside, nuclear energy projects are no different to any other energy project."[23] The finance sector might be in need of education on nuclear-specific risks, but its disinterest in SMRs suggests a clear understanding of the likelihood that they would be uneconomic.

References:

1. Rolls-Royce, 12 Sept 2017, 'British small nuclear plants can deliver low cost, low carbon electricity – report issued today', https://www.rolls-royce.com/media/press-releases/2017/12-09-2017-rr-british-small-nuclear-plants-can-deliver-low-cost-low-carbon-electricity.aspx
2. Nuclear Monitor #840, 21 March 2017, 'U.S. small reactor project just got smaller', https://wiseinternational.org/nuclear-monitor/840/us-small-reactor-project-just-got-smaller
3. M. Granger Morgan, Ahmed Abdulla, Michael J. Ford, and Michael Rath, July 2018 'US nuclear power: The vanishing low-carbon wedge', Proceedings of the National Academy of Science, https://www.pnas.org/content/115/28/7184
4. SMR Start, 14 Feb 2017, 'Policy Statement on U.S. Public-Private Partnerships for Small Modular Reactors', http://smrstart.org/wp-content/uploads/2017/02/SMR-Start-Public-Policy-on-Federal-Public-Private-Partnership.pdf
5. Adrian Cho, 21 Feb 2019, 'Smaller, safer, cheaper: One company aims to reinvent the nuclear reactor and save a warming planet', https://www.sciencemag.org/news/2019/02/smaller-safer-cheaper-one-company-aims-reinvent-nuclear-reactor-and-save-warming-planet
6. Dan Yurman, 4 May 2016, 'NuScale announces roadmap for SMR operation at Idaho site by 2024', https://neutronbytes.com/2016/05/04/nuscale-announces-roadmap-to-smr-operation-at-idaho-site-by-2024/
7. NuScale, accessed 26 February 2019, 'A cost competitive nuclear option for multiple applications', https://www.nuscalepower.com/benefits/cost-competitive
8. Dan Yurman, 10 Feb 2019, 'Why are so many firms investing in new uranium fuel projects?', https://neutronbytes.com/2019/02/10/why-are-so-many-firms-investing-in-new-uranium-fuel-projects/
See also: Steven Mufson, 28 Jan 2019, 'The Energy 202: Bill Gates is selling Washington on the promise of nuclear power', https://www.washingtonpost.com/news/powerpost/paloma/the-energy-202/2019/01/28/the-energy-202-bill-gates-is-selling-washington-on-the-promise-of-nuclear-power/5c4e33e71b326b29c3778ce0/
9. Dan Yurman, 1 March 2015, 'Be careful about rose colored glasses when viewing the future of SMRs', http://neutronbytes.com/2015/03/01/be-careful-about-rose-colored-glasses-when-viewing-the-future-of-smrs/
10. First Energy, 31 March 2018, 'FirstEnergy's Transformation to Fully Regulated Utility Company with Stronger Financials and Customer-Focused Growth Moves Ahead', https://www.firstenergycorp.com/content/fecorp/newsroom/news_articles/firstenergy-s-transformation-to-fully-regulated-utility-company-.html
11. Kutak Rock and Scully Capital for DOE's Office of Nuclear Energy, Oct 2018, 'Examination of Federal Financial Assistance in the Renewable Energy Market: Implications and Opportunities for Commercial Deployment of Small Modular Reactors', https://www.energy.gov/ne/downloads/report-examination-federal-financial-assistance-renewable-energy-market or https://www.energy.gov/sites/prod/files/2018/11/f57/Examination%20of%20Federal%20Financial%20Assistance%20in%20the%20Renewable%20Energy%20Mark..._1.pdf

12. US Energy Information Administration, 10 Jan 2018, 'Nearly half of utility-scale capacity installed in 2017 came from renewables', https://www.eia.gov/todayinenergy/detail.php?id=34472#
13. https://smrroadmap.ca/
14. Nuclear Energy Insider, 16 Jan 2019, 'Canadian utilities build SMR alliances as developers tackle licensing', https://analysis.nuclearenergyinsider.com/canadian-utilities-build-smr-alliances-developers-tackle-licensing
15. Neil Ford, 18 July 2018, 'UK funding spurs advanced reactor R&D but application outlook needed', https://analysis.nuclearenergyinsider.com/uk-funding-spurs-advanced-reactor-rd-application-outlook-needed
16. NucNet, 21 Feb 2019, 'UK Announces Feasibility Studies For Small Modular Reactor Development', https://www.nucnet.org/all-the-news/2018/09/13/uk-announces-feasibility-studies-for-small-modular-reactor-development/print
17. Adam Vaughan, 4 Dec 2017, 'UK government to release funding for mini nuclear power stations', https://www.theguardian.com/business/2017/dec/03/mini-nuclear-power-stations-uk-government-funding
18. Andy Dawson, 2018, 'Small Modular Nuclear: Crushed at birth', Global Warming Policy Foundation, https://www.thegwpf.org/content/uploads/2018/09/Dawson2.pdf
19. Andy Dawson, 17 Sept 2018, 'Who Killed the Small Modular Reactor Programme?', http://euanmearns.com/who-killed-the-small-modular-reactor-programme/
20. Nuclear Energy Insider, 30 Jan 2019, 'Rolls-Royce seeks UK SMR funding as market gaps open; NRC delays Seabrook license verdict', https://analysis.nuclearenergyinsider.com/rolls-royce-seeks-uk-smr-funding-market-gaps-open-nrc-delays-seabrook-license-verdict
21. NucNet, 23 July 2018, 'Rolls-Royce 'Planning To Shut Down SMR Project Without Government Support', https://www.nucnet.org/all-the-news/2018/07/23/rolls-royce-planning-to-shut-down-smr-project-without-government-support
22. Adam Vaughan, 1 Oct 2018, 'Energy firms demand billions from UK taxpayer for mini reactors', https://www.theguardian.com/environment/2018/sep/30/energy-firms-demand-billions-from-uk-taxpayer-for-mini-reactors
23. Expert Finance Working Group on Small Nuclear Reactors, March 2018, 'Market framework for financing small nuclear', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/732220/DBEIS_11_-_Market_Framework_for_Financing_Small_Nuclear_EFWG_Final_Report_.pdf

6. Small modular reactors and nuclear weapons proliferation

Power/weapons connections

First, a refresher on the broad patterns of intersection between (ostensibly) peaceful nuclear programs and weapons proliferation … the world into which an SMR industry might be born. These were neatly summarized last year by Michael Shellenberger from the Environmental Progress pro-nuclear lobby group.[1-3] Shellenberger is notorious for peddling misinformation[4] and his promotion of nuclear weapons proliferation is stupid and dangerous[5-6], but his analysis of the civil/military proliferation problem is sound (and his critique of Generation IV nuclear hype is perceptive[7]).

Patterns connecting the pursuit of power and weapons stretch back across the 60 years of civilian nuclear power. Shellenberger noted that "at least 20 nations sought nuclear power at least in part to give themselves the option of creating a nuclear weapon".[1]

"[N]ational security, having a weapons option, is often the most important factor in a state pursuing peaceful nuclear energy", Shellenberger wrote.[3] An analysis by Environmental Progress found that of the 26 nations that are building or are committed to build nuclear power plants, 23 have nuclear weapons, had weapons, or have shown interest in acquiring weapons.[8] "While those 23 nations clearly have motives other than national security for pursuing nuclear energy," Shellenberger wrote, "gaining weapons latency appears to be the difference-maker."[1]

Shellenberger pointed to research by Fuhrmann and Tkach which found that 31 nations had the capacity to enrich uranium or reprocess plutonium, and that 71% of them created that capacity to give themselves weapons latency.[9]

The military origins of SMR programs

Kennedy Maize wrote in *POWER* magazine in 2015:[10]

"Small reactors are familiar to the nuclear industry, which began with small machines that bulked up over the years to take advantage of economies of scale. The legendary Shippingport nuclear plant in western Pennsylvania, the first fully commercial pressurized-water nuclear plant, entered service in 1957 and was rated at 60 MW. The U.S. military and the Soviet Union spent considerable sums in the 1950s and 1960s on designs for small, transportable, remote reactors and for reactors to be used in ship propulsion.

"Many of today's SMR plans have their roots in naval reactor technology, as did Shippingport. Its technology was based on Westinghouse reactors that powered the first U.S. nuclear submarines. Argentina's CAREM 25 reactor design came from the Argentine navy. The country unveiled the design at a 1984 IAEA conference. The project then got shelved, but was revived in 2006 as Argentina moved to revitalize its nuclear power program in the face of limited supplies and high prices for imported natural gas. Argentina has few easily accessible indigenous energy resources.

"Russia's floating nukes also rely on maritime technology, reactors developed for its successful fleet of nuclear icebreakers, dating back well into the days of the Soviet Union. The nation's first nuclear icebreaker, the NS Lenin, was launched in 1957, the same year that Shippingport went into commercial service.

"In the U.S., two of the major SMR industrial developers, Babcock & Wilcox and Westinghouse, both have extensive experience with naval reactors."

Small reactors and proliferation

Small power reactors have been used to produce fissile material for weapons. Examples include:

- Magnox reactors in the UK which were used to generate power and to produce plutonium for weapons.[11]
- North Korea has tested weapons using plutonium produced in its 'Experimental Power Reactor' – a Magnox clone.[12]
- India refuses to place numerous power reactors (including some of its small PHWR reactors) under safeguards[13] and presumably uses (or plans to use) them for weapons production.

Based on historical experience, there's every reason to be concerned about the weapons proliferation risks associated with a proliferation of SMRs. It can be anticipated that countries with an interest in developing weapons – or a latent weapons capability – will be more interested in acquiring SMRs than countries with no such interest ("nations that lack a need for weapons latency often decide not to build nuclear power plants", Shellenberger states[1]).

Saudi Arabia's interest in acquiring a South Korean-designed SMART SMR may be a topical case study, and South Korea may have found a model to unlock the potential of SMRs: collaboration with a repressive Middle Eastern state that has a clear interest in developing a nuclear weapons capability, with extensive technology transfer thrown in.[15]

A subsidiary of Holtec International has actively sought a military role, inviting the National Nuclear Security Administration to consider the feasibility of using a proposed SMR to produce tritium, used to boost the explosive yield of the US nuclear weapons arsenal.[16]

NuScale Power, on the other hand, claims to be taking the high moral ground. NuScale's chief commercial officer said in 2013 that the company is not in business to sell reactors to politically unstable countries.[17] Yet in early 2019, NuScale participated in a White House meeting which discussed, among other issues, the possibility of selling nuclear power technology to Saudi Arabia – a known nuclear weapons wannabe in a volatile region.[18]

The CAREM SMR under construction in Argentina was originally a Navy project with the aim of building nuclear-powered submarines and ships.[19,20] Those ambitions resurfaced in 2010. The World Nuclear Association reported: "The Ministry of Defence in Argentina has said it is reviewing the idea of using nuclear reactors to power some of its naval vessels. … One potential supplier of reactors to meet these kinds of requirements would be the nuclear technology firm Invap, which has exported several research reactors and developed the Carem power plant design."[21]

SMRs as the proliferator's technology of choice

Power reactors (and associated infrastructure) have been used in support of weapons programs[22], as have research reactors.[23] There is a long-running debate about whether (large) power reactors or research reactors are the proliferators' technology of choice.[24-26] Research reactors are relatively cheap (typically several hundred million dollars) but the plutonium production rate is typically low. Power reactors are expensive but produce large amounts of plutonium (and can be run on a shortened irradiation cycle to produce large amounts of weapons-grade plutonium).

SMRs could become the technology of choice for proliferators: reactors that produce significant amounts of plutonium each year without the expense of a gigawatt-scale nuclear power program. In the early 1990s, the director of the Turkish Atomic Energy Authority said Argentina's 25-MW CAREM SMR design "was too small for electricity generation and too big for research or training, however, very suitable for plutonium production".[27]

The proliferation risks associated with different SMR designs

The IAEA estimates there are around 50 SMR designs. Since they are paper designs, let's assume there are, say, five possible configurations of each design (fast vs. thermal neutrons, different fuels, closed vs. open fuel cycles, etc.) Now let's run through those 250 configurations and consider the proliferation risks associated with each. Or, on second thoughts, let's not. Suffice it to make a few general points.

By far the most important point to make is that any configuration of any SMR design will pose proliferation risks. As the UK Royal Society notes: "There is no proliferation proof nuclear fuel cycle. The dual use risk of nuclear materials and technology and in civil and military applications cannot be eliminated."[28]

Ramana and Mian state in a 2014 article:[29]

"Proliferation risk … depends on both technical and non-technical factors. While the non-technical factors are largely not dependent on choice of reactor type, SMRs and their intrinsic features do affect the technical component of proliferation risk. In the case of both iPWRs [integral Pressurized Water Reactors] and fast reactors, the proliferation risk is enhanced relative to current generation light water reactors primarily because greater quantities of plutonium are produced per unit of electricity generated. In the case of HTRs [high temperature gas-cooled reactors], proliferation risk is increased because of the use of fuel with higher levels of uranium enrichment, but is diminished because the spent fuel is in a form that is difficult to reprocess."

Glaser, Hopkins and Ramana compare the proliferation risks of standard light-water reactors, proposed integral pressurized water SMRs (iPWRs) and proposed SMRs with long-lived cores (LLCs) that would not require refueling for two or more decades (typically fast-spectrum designs cooled by helium, sodium, or other liquid metals such as lead and lead-bismuth eutectics).[30]

The authors state:[30]

"iPWRs are likely to have higher requirements for uranium ore and enrichment services compared to gigawatt-scale reactors. This is because of the lower burnup of fuel in iPWRs, which is difficult to avoid because of smaller core size and all-in-all-out core management. These characteristics also translate into an increased proliferation risk unless they are offset

by technical innovations in reactor and safeguards design and institutional innovations in the nuclear fuel cycle.

"Uranium and uranium enrichment requirements are reduced for fast-spectrum SMRs with LLCs, but in this case strong incentives for spent-fuel reprocessing are likely to result from the high fissile content of the spent fuel. This same characteristic also increases the probability of proliferation success in a diversion scenario …"

A report by the UK Parliamentary Office of Science & Technology offers these generalizations:[31]

"There is uncertainty over the extent to which widespread SMR use might increase or decrease non-proliferation risk. Some SMRs require less frequent refuelling than conventional nuclear, reducing high risk periods. However, more integrated designs may be more challenging to inspect, and some designs use more highly enriched uranium than conventional nuclear. Both of these aspects could increase proliferation risk."

Uranium enrichment

Ramana and Mian note that attempts to reduce one proliferation risk can worsen another:[29]

"Proliferation resistance is another characteristic that imposes sometimes contradictory requirements. One way to lower the risk of diversion of fuel from nuclear reactors is to minimize the frequency of refueling because these are the periods when the fuel is out of the reactor and most vulnerable to diversion, and so many SMR designers seek longer periods between refueling. However, in order for the reactor to maintain reactivity for the longer period between refuelings, it would require starting with fresh fuel with higher uranium enrichment or mixing in plutonium.

"Some designs even call for going to an enrichment level beyond 20 percent uranium-235, the threshold used by the International Atomic Energy for classifying material as being of "direct use" for making a weapon. All else being equal, the use of fuel with higher levels of uranium enrichment or plutonium would be a greater proliferation risk, and is the reason why so much international attention has been given to highly enriched uranium fueled research reactors and converting them to low enriched uranium fuel or shutting them down.

"Moreover, an SMR design relying on highly enriched uranium fuel creates new proliferation risks – the need for production of fresh highly enriched uranium and the possibility of diversion at the enrichment plant and during transport. Any reduction of proliferation risk at the reactor site by reducing refueling frequency, it turns out, may be accompanied by an increase in the proliferation risk elsewhere."

In January 2019, the US government allocated US$115 million to kick-start a domestic uranium enrichment project in Piketown, Ohio.[32] The HALEU Demonstration Program will aim to produce 19.75%-enriched 'high assay low enriched uranium' (HALEU) using US-designed and operated centrifuge technology.[33] The project is being sold as a step towards domestic production of enriched uranium for 'advanced reactors' (including SMRs) but there is also a military agenda. Republican Senator Rob Portman said: "Getting Piketon back to its full potential benefits the skilled workforce here, the surrounding local economy, and strengthens national energy and defense security."[32] The Department of Energy said that Centrus subsidiary American Centrifuge Operating was the only firm that qualified for the project, noting that the company is US-owned and controlled, a requirement for enrichment contracts to supply the military.[32]

Nationalistic military hawks have been lobbying furiously (and evidently successfully) to re-establish domestic uranium enrichment in the US to accommodate the Navy's long-term 'need' for additional highly enriched uranium to fuel its reactors for long intervals between refueling, and the 'need' for a domestic source of low enriched uranium to fuel reactors used to produce tritium for weapons.[34]

It might be the case that very few if any SMRs are ever built in the US, yet the promise of an SMR industry is already providing cover for military projects.

Plutonium reactors

The US Department of Energy is working on a plan to establish a 'versatile test reactor' as a source of high-energy neutrons to help researchers develop fuels and materials for fast reactors, including SMRs.[35] The Department plans to make a decision in 2020 as to whether to proceed with the project.

Edwin Lyman from the Union of Concerned Scientists wrote: "What may not be clear from the name is that this facility itself would be an experimental fast reactor, likely fueled with weapon-usable plutonium. Compared to conventional light-water reactors, fast reactors are less safe, more expensive, and more difficult to operate and repair. But the biggest problem with this technology is that it typically requires the use of such weapon-usable fuels as plutonium, increasing the risk of nuclear terrorism."[36]

Safeguards and security

Some claim that up to 85 GW of SMR capacity could be installed by 2035, comprising perhaps 1,000 small reactors. How would the IAEA safeguards system cope with the additional workload? The IAEA safeguards system has been chronically underfunded[37] and it is implausible that any increased funding made available to the IAEA to safeguard an SMR industry would be commensurate with the increased workload. On the other hand, it is entirely plausible than an SMR industry will fail to materialize and that the safeguards system will therefore not face additional stresses.

The Union of Concerned Scientists discussed SMR security issues in a 2013 paper.[38] Some key excerpts are reproduced here but the paper is worth reading in its entirety:

"Fukushima Daiichi demonstrated how rapidly a nuclear reactor accident can progress to a core meltdown if multiple safety systems are disabled. A well-planned and -executed terrorist attack could cause damage comparable to or even worse than the earthquake and tsunami that initiated the Fukushima crisis, potentially in even less time. For these reasons,

the NRC requires nuclear plant owners to implement robust security programs to protect their plants against sabotage.

"Despite these concerns, SMR proponents argue for reducing security requirements – in particular, security staffing – to reduce the cost of electricity produced by small modular reactors. In 2011, Christofer Mowry, president of Babcock & Wilcox mPower, Inc., said, "Whether SMRs get deployed in large numbers or not is going to come down to O&M [operations and maintenance]. And the biggest variable that we can attack directly, the single biggest one, is the security issue".

"His position was echoed by the NEI [Nuclear Energy Institute], which submitted a position paper to the NRC in July 2012 on the issue of physical security for SMRs. It clearly laid out the industry view: "The regulatory issue of primary importance related to physical security of SMRs is security staffing. The issue has the potential to adversely affect the viability of SMR development in the U.S. Security staffing directly impacts annual operations and maintenance (O&M) costs and as such constitutes a significant financial burden over the life of the facility. … For this reason, evaluation of security staffing requirements for SMRs has become a key focal point." …

"The NRC staff appears to be open to suggestions for alternative measures that take into account design features of SMRs that may make them less vulnerable to attack. The primary feature that mPower and other SMR vendors appear to credit in seeking relief from security regulations is underground siting. Underground siting would enhance protection against some attack scenarios, but not all. A direct jet impact on the reactor containment is less likely for an underground reactor, but the ensuing explosions and fire could cause a crisis. Certain systems, such as steam turbines, condensers, electrical switchyards, and cooling towers, will need to remain aboveground, where they will be vulnerable. Plants will require adequate access and egress for both routine and emergency personnel. Ventilation shafts and portals for equipment access also provide potential means of entry for intruders. In addition, if SMR sites have smaller footprints, as vendors are claiming, the site boundary will be closer to the reactor, and thus there will be less warning time in the event of an intrusion and potentially insufficient spatial separation of redundant and diverse safety systems.

"In short, knowledgeable and determined adversaries will likely be able to develop attack scenarios that could circumvent measures such as underground siting. In situations such as hostage scenarios, terrorists may even be able to utilize the additional defense afforded by an underground site against off-site police and emergency response. Thus, a robust and flexible operational security response will be required no matter what intrinsic safeguards are added to reactor design."

References:

1. Michael Shellenberger, 29 Aug 2018, 'For Nations Seeking Nuclear Energy, The Option To Build A Weapon Remains A Feature Not A Bug', https://www.forbes.com/sites/michaelshellenberger/2018/08/29/for-nations-seeking-nuclear-energy-the-option-to-build-a-weapon-remains-a-feature-not-a-bug/
2. Michael Shellenberger, 6 Aug 2018, 'Who Are We To Deny Weak Nations The Nuclear Weapons They Need For Self-Defense?',

https://www.forbes.com/sites/michaelshellenberger/2018/08/06/who-are-we-to-deny-weak-nations-the-nuclear-weapons-they-need-for-self-defense/
3. Michael Shellenberger, 28 Aug 2018, 'How Nations Go Nuclear: An Interview With M.I.T.'s Vipin Narang', http://environmentalprogress.org/big-news/2018/8/28/vipin-narang-interview
4. Nuclear Monitor #852, 30 Oct 2017, 'Exposing the misinformation of Michael Shellenberger and 'Environmental Progress'', https://www.wiseinternational.org/nuclear-monitor/853/exposing-misinformation-michael-shellenberger-and-environmental-progress
5. Nuclear Monitor #865, 6 Sept 2018, 'Nuclear lobbyist Michael Shellenberger learns to love the bomb, goes down a rabbit hole', https://www.wiseinternational.org/nuclear-monitor/865/nuclear-lobbyist-michael-shellenberger-learns-love-bomb-goes-down-rabbit-hole
6. Nuclear Monitor #865, 6 Sept 2018, ''Almost Trumpian in its incoherence': Critical responses to Michael Shellenberger's promotion of nuclear weapons proliferation', https://www.wiseinternational.org/nuclear-monitor/865/almost-trumpian-its-incoherence-critical-responses-michael-shellenbergers
7. Michael Shellenberger, 18 July 2018, 'If Radical Innovation Makes Nuclear Power Expensive, Why Do We Think It Will Make Nuclear Cheap?', https://www.forbes.com/sites/michaelshellenberger/2018/07/18/if-radical-innovation-makes-nuclear-power-expensive-why-do-we-think-it-will-make-nuclear-cheap
8. Environmental Progress, 2018, Nations Building Nuclear – Proliferation Analysis, https://docs.google.com/spreadsheets/d/1YA4gLOekXNXiwpggCEx3uUpeu_STBlN_gHD60B5QG1E/edit#gid=0
9. Matthew Fuhrmann and Benjamin Tkach, 8 Jan 2015, 'Almost nuclear: Introducing the Nuclear Latency dataset', Conflict Management and Peace Science, https://doi.org/10.1177/0738894214559672
http://journals.sagepub.com/doi/abs/10.1177/0738894214559672
10. Kennedy Maize, 1 May 2015, 'Small Modular Reactors Speaking in Foreign Tongues', http://www.powermag.com/small-modular-reactors-speaking-in-foreign-tongues/?printmode=1
11. 'Magnox', accessed 26 Feb 2019, http://en.wikipedia.org/wiki/Magnox#Reactors_built
12. Yongbyon Nuclear Scientific Research Center, accessed 26 February 2019, https://en.wikipedia.org/wiki/Yongbyon_Nuclear_Scientific_Research_Center
13. John Carlson, 15 April 2015, submission to Joint Standing Committee on Treaties, Parliament of Australia, http://www.aph.gov.au/DocumentStore.ashx?id=8c00f0a2-c00e-4885-99cb-a2894564d3f6&subId=301365
14. Michael Shellenberger, 29 Aug 2018, 'For Nations Seeking Nuclear Energy, The Option To Build A Weapon Remains A Feature Not A Bug', https://www.forbes.com/sites/michaelshellenberger/2018/08/29/for-nations-seeking-nuclear-energy-the-option-to-build-a-weapon-remains-a-feature-not-a-bug/
15. Nuclear Monitor #800, 19 March 2015, 'Small modular reactors: a chicken-and-egg situation', https://www.wiseinternational.org/nuclear-monitor/800/small-modular-reactors-chicken-and-egg-situation
16. Thomas Clements, 2012, 'Documents Reveal Time-line and Plans for "Small Modular Reactors" (SMRs) at the Savannah River Site (SRS) Unrealistic and Promise no Funding', http://aikenleader.villagesoup.com/p/documents-reveal-time-line-and-plans-for-small-modular-reactors-smrs-at-the-savannah-river-site-sr/840884

17. Bennett Hall, 9 Aug 2013, 'NuScale refutes SMR critics', Corvallis Gazette-Times, https://www.gazettetimes.com/news/local/nuscale-refutes-smr-critics/article_01366a1e-0097-11e3-9416-0019bb2963f4.html
18. World Nuclear Association, 14 Feb 2019, 'US nuclear industry seeks presidential support', http://www.world-nuclear-news.org/Articles/US-nuclear-industry-seeks-presidential-support
19. https://en.wikipedia.org/wiki/List_of_submarines_of_Submarine_Force_Command
20. https://www.cnea.gob.ar/es/proyectos/carem/sintesis-historica/
21. World Nuclear Association, 8 June 2010, 'Nuclear propulsion an option for Argentina', http://www.world-nuclear-news.org/Articles/Nuclear-propulsion-an-option-for-Argentina
22. See section 7 in: Nuclear Monitor #804, 28 May 2015, 'The myth of the peaceful atom', https://www.wiseinternational.org/nuclear-monitor/804/myth-peaceful-atom
23. Friends of the Earth Australia, 'Research reactors and weapons proliferation', https://nuclear.foe.org.au/research-reactors-nuclear-weapons/
24. John Holdren, 1983, "Nuclear power and nuclear weapons: the connection is dangerous", Bulletin of Atomic Scientists, January, pp.40-45, http://fissilematerials.org/library/hol83.pdf or https://www.tandfonline.com/doi/abs/10.1080/00963402.1983.11458937
25. Anthony Fainberg, 1983, "The connection is dangerous", Bulletin of the Atomic Scientists, May, p.60, http://tinyurl.com/fainberg
26. John Holdren, 1983, "Response to Anthony Fainberg, 1983, 'The connection is dangerous'", Bulletin of the Atomic Scientists, May, pp.61-62.
27. Mustafa Kibaroglu, Spring-Summer 1997, 'Turkey's quest for peaceful nuclear power', The Nonproliferation Review, https://www.nonproliferation.org/wp-content/uploads/npr/kibaro43.pdf
28. Royal Society, Oct 2011, 'Fuel Cycle Stewardship in a Nuclear Renaissance', https://royalsociety.org/topics-policy/projects/nuclear-non-proliferation/report/
29. M.V. Ramana and Zia Mian, 4 Sept 2014, 'Too much to ask: why small modular reactors may not be able to solve the problems confronting nuclear power', Nuclear Monitor #790, https://www.wiseinternational.org/nuclear-monitor/790/too-much-ask-why-small-modular-reactors-may-not-be-able-solve-problems
30. Alexander Glaser, Laura Berzak Hopkins and M. V. Ramana, March 2017, 'Resource Requirements and Proliferation Risks Associated with Small Modular Reactors', Nuclear Technology, Vol.184, Issue 1, https://www.tandfonline.com/doi/abs/10.13182/NT13-A19873
31. UK Houses of Parliament, Parliamentary Office of Science & Technology, July 2018, 'Small Modular Nuclear Reactors', No. 580, http://researchbriefings.files.parliament.uk/documents/POST-PN-0580/POST-PN-0580.pdf
32. James Osborne, 25 Jan 2019, '$115 million nuclear contract draws scrutiny on Perry', Houston Chronicle, https://www.chron.com/business/energy/article/115-million-nuclear-contract-draws-scrutiny-on-13562022.php
33. Neil Ford, 27 Feb 2019, 'DOE funding propels US towards first advanced fuel factory by 2023', https://analysis.nuclearenergyinsider.com/doe-funding-propels-us-towards-first-advanced-fuel-factory-2023
34. Nuclear Monitor #850, 'Nuclear power, weapons and 'national security'', 7 Sept 2017, https://www.wiseinternational.org/nuclear-monitor/850/nuclear-power-weapons-and-national-security

35. World Nuclear Association, 15 November 2018, 'PRISM selected for US test reactor programme', http://www.world-nuclear-news.org/Articles/PRISM-selected-for-US-test-reactor-programme
36. Ed Lyman, 15 Feb 2018, 'The "Versatile Fast Neutron Source": A Misguided Nuclear Reactor Project', https://allthingsnuclear.org/elyman/a-misguided-nuclear-reactor-project
37. John Carlson, Nov 2018, 'Future Directions in IAEA Safeguards', https://www.belfercenter.org/publication/future-directions-iaea-safeguards
38. Edwin Lyman, Sept 2013, 'Small Isn't Always Beautiful: Safety, Security, and Cost Concerns about Small Modular Reactors', https://www.ucsusa.org/sites/default/files/legacy/assets/documents/nuclear_power/small-isnt-always-beautiful.pdf

7. A military bromance: SMRs to support and cross-subsidize the UK nuclear weapons program

Industry and government in the UK openly promote SMRs on the grounds that an SMR industry would support the nuclear weapons program (in particular the submarine program) by providing a pool of trained nuclear experts, and that in so doing an SMR industry will cross-subsidize the weapons program. Such arguments are problematic for several reasons. Firstly, the weapons program is problematic and the UK's compliance with its Nuclear Non-Proliferation Treaty obligations is questionable. Secondly, why subsidize an SMR industry to subsidize the weapons program – why not simply invest more in the weapons program directly? Thirdly, there are strong reasons to firewall civil nuclear programs from military programs yet there is no longer any pretense of a firewall.

The arguments are clearly stated in a 2017 report by Rolls-Royce.[1] The company trumpets its role in powering and maintaining the UK Royal Navy submarine fleet. But its recent interest in civil SMRs isn't a case of swords-to-ploughshares … it's ploughshares-supporting-swords. The report states:[1]

"The indigenous UK supply chain that supports defence nuclear programmes requires significant ongoing support to retain talent and develop and maintain capability between major programmes. Opportunities for the supply chain to invest in new capability are restricted by the limited size and scope of the defence nuclear programme. A UK SMR programme would increase the security, size and scope of opportunities for the UK supply chain significantly, enabling long-term sustainable investment in people, technology and capability.

"Expanding the talent pool from which defence nuclear programmes can draw from would bring a double benefit. First, additional talent means more competition for senior technical and managerial positions, driving excellence and performance. Second, the expansion of a nuclear-capable skilled workforce through a civil nuclear UK SMR programme would relieve the Ministry of Defence of the burden of developing and retaining skills and capability. This would free up valuable resources for other investments."

So SMRs will relieve the Ministry of Defence of the "burden" of paying for its own WMD programs!

Andy Stirling and Phil Johnstone have carefully studied the links between the UK's nuclear power program and the weapons program.[2] They wrote in *The Guardian* in March 2018:[3]

"Their [National Audit Office] 2008 costing of military nuclear activities states: "One assumption of the future deterrent programme is that the United Kingdom submarine industry will be sustainable and that the costs of supporting it will not fall directly on the future deterrent programme." If the costs of keeping the national nuclear submarine industry in business must fall elsewhere, what could that other budget be?

"Although unstated, by far the most likely source for such support is a continuing national civil nuclear programme. And this where the burgeoning hype around UK development of SMRs comes in. Leading designs for these reactors are derived directly from submarine propulsion. British nuclear submarine reactor manufacturer Rolls-Royce is their most enthusiastic champion. But, amid intense media choreography, links between SMRs and submarines remain (aside from reports of our own work) barely discussed in the UK press.

"This neglect is odd, because the issues are very clear. Regretting that military programmes are no longer underwritten by civil nuclear research, a heavily redacted 2014 MoD report expresses serious concerns over the continued viability of the UK nuclear submarine industry. And Rolls-Royce itself is clear that success in securing government investment for SMRs would "relieve the Ministry of Defence of the burden of developing and retaining skills and capability" for the UK's military nuclear sector. Other defence sources are also unambiguous that survival of the British nuclear submarine industry depends on continuation of UK civil nuclear power. Many new government initiatives focus intently on realising the military and civil synergies.

"Some nuclear enthusiasts have called this analysis a conspiracy theory, but these links are now becoming visible. In response to our own recent evidence to the UK Public Accounts Committee, a senior civil servant briefly acknowledged the connections. And with US civil nuclear programmes collapsing, the submarine links are also strongly emphasised by a former US energy secretary. Nuclear submarines are evidently crucial to Britain's cherished identity as a "global power". It seems that Whitehall's infatuation with civil nuclear energy is in fact a military romance."

References:
1. Rolls-Royce, 2017, 'UK SMR: A National Endeavour', https://www.uknuclearsmr.org/wp-content/uploads/2017/09/V2088-Rolls-Royce-SMR-Report-Artwork-Web.pdf
2. Andy Stirling and Phil Johnstone, 23 Oct 2018, 'A global picture of industrial interdependencies between civil and military nuclear infrastructures', Nuclear Monitor #868, https://www.wiseinternational.org/nuclear-monitor/868/global-picture-industrial-interdependencies-between-civil-and-military-nuclear
3. Andy Stirling and Phil Johnstone, 29 March 2018, 'Why is the UK government so infatuated with nuclear power?', https://www.theguardian.com/science/political-

science/2018/mar/29/why-is-uk-government-so-infatuated-nuclear-power Against a worldwide background

8. SMRs to power military installations and forward bases in the United States

The US military experimented with small reactors in remote locations beginning 1954.[1,2] Dr Edwin Lyman, a senior scientist at the Union of Concerned Scientists, summarizes the early experiments:[3]

"The Army Nuclear Power Program was initiated in 1954, in the heady early days of the atomic power era, to develop ground-based nuclear power plants for military use – a mission distinct from the Navy's submarine nuclear propulsion program already well underway. Over two decades, the US Army built and operated eight small power reactors, ranging from less than one megawatt to ten megawatts of electricity, with limited success. The worst outcome was the 1961 core meltdown and explosion at the SL-1 reactor in Idaho, which killed three operators. Five of the reactors were designed to be portable to some degree, and three were deployed at remote military bases in Greenland, Alaska, and Antarctica. Although these reactors didn't explode, they proved unreliable and expensive to operate. Based on that experience, the program was shut down in 1977."

Efforts to renew the US military's interest in SMRs – including microreactors in the range of 1–10 MW – have been underway for some time.[4] Industry bodies such as the Nuclear Energy Institute have been proactive, and the Pentagon, with the support of Congress, is exploring the potential for the deployment of SMRs at defense installations for power generation, desalinating water and generating hydrogen for fuel. It is potentially a significant market: the Department of Defense manages more than 500 fixed installations and is the single largest energy consumer in the US.

Marc Nichol, the Nuclear Energy Institute's director of new reactor deployment, said in October 2018: "Small reactors are one of the most promising new nuclear technologies to emerge in decades. Energy is important to our national security; it must be reliable and resilient so that it's there when our men and women in uniform need it. Micro-reactors can enhance our capabilities by providing that resilient, 24/7 energy."[5]

However the plan is improbable and problematic. An article by current and former researchers from Carnegie Mellon University's Department of Engineering and Public Policy, published in the *Proceedings of the National Academy of Science* in July 2018, discusses the looming problems:[6]

"Because it is unlikely that further and substantial DOE funding will be dedicated to reinvigorating civilian nuclear power, and because the nuclear enterprise is unlikely to rebound on its own, some have advanced national security arguments to stem and reverse the perceived decline in US standing by assigning this task to the Department of Defense (DoD). Given the current political climate, which supports American primacy in areas of strategic importance, supporters in Congress, think tanks, the Army, and the Navy have

floated the possibility of diverting large sums of money through the DoD to catalyze the development and deployment of SMR technologies.

"While we share the fears about the future of nuclear science and nuclear power in the United States, we believe that the proposal to try to address the problem through DoD leadership in development is both unwise and unlikely to succeed. There are several practical challenges. Any SMR that is designed to primarily serve the DoD would likely be too expensive for a commercial utility to deploy. The design specifications upon which the DoD would insist would likely render commercial variants infeasible (because, to minimize or avoid frequent refueling, it would likely need to use fuel that is enriched more than the current operating fleet standard of ~5% U-235, and perhaps even greater than 20%) and economically uncompetitive in most of today's markets.

"Moreover, SMRs designed to serve a US base would face the same economic challenges as current commercial reactors, and there is no guarantee that a nuclear design would win the day in a competition for US military base power supply. Even siting, a purported advantage of having the military deploy SMRs, would be difficult. The DoD follows state environmental guidelines when they do not compromise the defense mission. The siting of SMRs would likely still become an issue for the DoD in a range of locations, and not just those that reject nuclear power outright. Finally, having the DoD take the lead in development risks creating several large, expensive, "too-big-to-fail" fiefdoms, which would detract from more pressing warfighting needs.

"In addition to the practical challenges, there are compelling normative arguments to be made against relying on the DoD to revivify the nuclear enterprise. These revolve around the role of the US military in American economic and civic life.

"First, the military develops new technologies when they are the only available solution to a problem. Scenarios proposed for military leadership in SMR design and development do not convincingly make the cut when balanced with alternatives, such as power purchase agreements. Second, we endorse the firebreak between the civilian and military nuclear programs because it has substantial normative value. Third, at a time when American civic and political norms rest on precarious ground, using the military to rescue a commercial industry degrades the social fabric from which it derives legitimacy. It also undercuts the DOE by underscoring its failure to enable the development of advanced reactors.

"Most troublingly, adopting this model would amount to an admission of failure on the nuclear industry's part. Defaulting to the national security argument in an effort to salvage the US commercial nuclear industry concedes the failure of the technical and economic arguments in favor of the technology. It also does little to drive commitment from industry that would generate broader deployment. Other options, including long-term power purchase agreements, coordination in human capital development, and research into grid security, constitute avenues for DoD involvement that are more politically credible and economically sound. However, it is unclear that any of these could have more than a modest impact on the development of a domestic SMR industry in the next few decades."

Project Dilithium

In January 2019, the US Department of Defense issued a call for information in support of its interest in acquiring small (1–10 MW) power reactors for use at forward operating bases.

Edwin Lyman argues that the "inherently safe reactor" sought by the military is a myth:[7]

"All it really means is that in certain idealized scenarios, a reactor, after shutdown, could be adequately cooled by passive mechanisms, such as convective airflow. But passive safety cannot eliminate every pathway by which the reactor fuel could be damaged and release radioactivity. If a severe accident or sabotage attack were to induce more extreme conditions than the reactor was designed to withstand, all bets are off. How long would passive airflow keep nuclear fuel safely cool if, say, an adversary threw an insulating blanket over a small reactor? Or if the reactor were buried under a pile of debris? Moreover, it is hard to imagine that a direct explosive breach of the reactor core would not result in dispersal of some radioactive contamination. ... At best a release of radioactivity would be a costly disruption, and at worst it would cause immediate harm to personnel, render the base unusable for years, and alienate the host country."

Lyman notes that reactors deployed at forward operating bases or shipped through war zones would be prime targets of the enemy, and if commanders need to expend significant resources to protect them from military strikes, such reactors could become burdens rather than assets.[7]

Lyman commented on the proliferation risks:[7]

"The original RFI [request for information] stipulated that the reactor fuel had to be high-assay low-enriched uranium (HALEU), which is uranium enriched to levels above the 5 percent uranium-235 concentration of conventional power reactors, but still below the 20 percent that marks the lower limit for highly enriched uranium (HEU), which is usable in nuclear weapons. Although HALEU is considered highly impractical for direct nuclear weapons use, it has greater proliferation potential than fuel with uranium-235 concentrations below 5% because of the reduced effort needed to enrich it to a weapon-usable level – which is why the international community saw Iran's stockpiling of HALEU as a threat. If the Defense Department goes forward with Project Dilithium, other nations, including US adversaries, may be prompted to start producing HALEU and building their own military power reactors.

"An even more worrisome problem is that the revised RFI issued on January 22 no longer includes the HALEU requirement. That opens the door for reactors fueled with HEU – a major proliferation threat. The Defense Department may be envious of NASA, which is moving forward with development of a tiny HEU-fueled reactor to power deep space missions while turning a blind eye to the proliferation risks. Or it may have decided that the current lack of availability of a sufficient quantity of HALEU for a demonstration reactor would cause an unacceptable delay. Or the omission may simply be a mistake. As of this writing, the contracting officer at Defense has not responded to a request to clarify whether this was an innocuous oversight or a deliberate gesture.

"Given the dubious strategic value, low chance of success, and potential for sparking a HALEU-fueled international arms race, what can explain the Defense Department's renewed interest in small reactors after decades of dormancy? To be sure, Project Dilithium didn't just spring out of nowhere. It is the culmination of a patient, decade-long effort by nuclear lobbyists to interest Defense and its congressional overseers in a costly product – small nuclear reactors – that few in the private sector seem to want. The Pentagon is precisely the savior small nuclear reactor vendors need: deep-pocketed and unbeholden to return-seeking investors. But this coup by the nuclear industry will do little to enhance US national security and could expose fighting forces to undue risk. Hopefully, pragmatists at the Defense Department will realize this and pull the plug on this misguided effort before billions of dollars are wasted on a fruitless search for a reactor as rare as a dilithium crystal."

References:
1. Peter Rejcek, 25 June 2010, 'Powerful Reminder', https://antarcticsun.usap.gov/features/contenthandler.cfm?id=2175
2. Hanne E.F. Nielsen, 23 July 2019, 'Remembering Antarctica's nuclear past with 'Nukey Poo'', https://theconversation.com/remembering-antarcticas-nuclear-past-with-nukey-poo-99934
3. Edwin Lyman, 22 Feb 2019, 'The Pentagon wants to boldly go where no nuclear reactor has gone before. It won't work.', https://thebulletin.org/2019/02/the-pentagon-wants-to-boldly-go-where-no-nuclear-reactor-has-gone-before-it-wont-work/
4. Dan Yurman, 6 Oct 2018, 'DOD Seeks SMRs for Tactical Readiness at Military Bases', http://neutronbytes.com/2018/10/06/dod-seeks-smrs-for-tactical-readiness-at-military-bases/
5. Nuclear Energy Institute, 9 Oct 2018, 'A Big Move Toward Small: Micro-reactors and the Pentagon', https://electricenergyonline.com/article/energy/organisation/nuclear-energy-institute/21270/724762/nuclear-energy-institutea-big-move-toward-small-micro-reactors-and-the-pentagon.html
6. M. Granger Morgan, Ahmed Abdulla, Michael J. Ford, and Michael Rath, July 2018 'US nuclear power: The vanishing low-carbon wedge', Proceedings of the National Academy of Science, https://www.pnas.org/content/115/28/7184
7. Edwin Lyman, 22 Feb 2019, 'The Pentagon wants to boldly go where no nuclear reactor has gone before. It won't work.', https://thebulletin.org/2019/02/the-pentagon-wants-to-boldly-go-where-no-nuclear-reactor-has-gone-before-it-wont-work/

9. SMR safety issues

'Can we make a nuclear reactor that won't melt down?' That the opening question in a *Forbes* article written by self-styled energy expert James Conca. His answer: "Yes we can. It's called a small modular nuclear reactor (SMR) and NuScale Power is the company that will build the first one in America."[1]

Conca continued his January 2018 article:[1]

"Last year, they submitted to the U.S. Nuclear Regulatory Commission the first design certification application (DCA) for any SMR in the United States. Just two months later, NRC

accepted their design certification application. By accepting the DCA for review, the NRC staff confirmed that NuScale's submission addresses all of NRC's initial concerns and requirements.

"Now, less than a year later, the NRC approved NuScale's walk-away-safe concept. That means just what it sounds like – the reactor doesn't need the complex back-up power systems that traditional reactors require and which traditionally add a lot of cost as well as some uncertainty. This is a big deal. It means the reactor just won't melt down or otherwise cause any of the nightmares people think about when imagining the worse for nuclear power. It just shuts down and cools off. ...

"The small size and large surface area-to-volume ratio of NuScale's reactor core, that sits below ground in a super seismic-resistant heat sink, allows natural processes to cool it indefinitely in the case of complete power blackout. No humans or computers are needed to intervene, no AC or DC power, no pumps, and no additional water for cooling. ...

"This nuclear reactor is something that we've never seen before – a small modular reactor that is economic, factory built and shippable, flexible enough to desalinate seawater, refine oil, load-follow wind, produce hydrogen, modular to any size, and that provides something we've all been waiting for – a reactor that cannot meltdown."

Dr Ed Lyman from the Union of Concerned Scientists (UCS) provides a reality check:[2]

"As discussed in detail in my September 2013 report "Small Isn't Always Beautiful,"[3] UCS has safety and security concerns about small modular reactors in general and about the NuScale design in particular. SMR vendors are pushing the Nuclear Regulatory Commission (NRC) to weaken its regulations regarding operator staffing, security staffing, and emergency planning, based on highly optimistic assertions that their reactors will be significantly safer than larger reactors.

"NuScale raises issues because of its fundamental design: up to 12 reactor modules packed together in a swimming-pool type structure. The Fukushima disaster has shown the world the complexity of trying to manage multiple nuclear reactor accidents when crisis strikes, and it is far from obvious that the NuScale concept addresses this issue adequately. UCS also does not have confidence that the NRC's licensing processes will give appropriate weight to multi-unit safety issues. Unfortunately, earlier this month the NRC staff concluded that safety concerns associated with "multiunit core damage events" did not warrant further evaluation in its "Generic Issues" program, which could have resulted in additional regulatory requirements.

"Many of the safety concerns described in the UCS report have now been validated by a Powerpoint presentation that was recently included, perhaps inadvertently, in the many thousands of pages of documents that the NRC has released under a Freedom of Information Act request for documents related to the Fukushima accident. The Powerpoint presentation, entitled "Center for Nuclear Waste Regulatory Analyses: Support to the U.S. Nuclear Regulatory Commission Office of New Reactors"[4] (p. 479-529) and dated March 24, 2011, describes safety issues for SMRs such as

- *Potential fire and explosion hazards: below-grade facilities present unique challenges, such as smoke/fire behavior; life safety; design and operation of the HVAC system and removal of waste water.*
- *Potential flooding hazards: below-grade reactors and subsystems raise concerns with regard to hurricane storm surges, tsunami run-up and water infiltration into structures.*
- *Limited access for conducting inspections of pressure vessels and components that are crucial for containing radiation, such as welds, steam generators, bolted connections and valves.*

"The document also spells out safety concerns particular to the NuScale design, observing that the reactors and spent fuel are stored in the same structure and depend on the same pool for cooling; that the bioshield covering the reactors or even the reactors themselves could be displaced in a flood; that the cooling pool could become contaminated with debris or other substances during a flood; and that operation under both normal and accident conditions depends highly on proper operation of valves around the pressure vessel.

"This document underscores the fact that SMRs are novel designs that raise new safety issues, and much analysis and testing will be required in order to verify the vendors' safety claims. There is therefore no basis at the present time for the NRC to grant SMRs any special exemptions to its regulatory requirements, and the Department of Energy should take steps to ensure that its Technical Licensing Support program does not use taxpayer funds to endanger public health by undermining nuclear safety and security standards."

PRISM propaganda

To give another example of disingenuous SMR safety hype, non-existent 'integral fast reactors' (IFR) are said to be meltdown-proof in addition to their other purported benefits. The best-known variant of the non-existent IFR is the non-existent Power Reactor Innovative Small Module (PRISM). Once again Ed Lyman provides a reality check in an article discussing the *Pandora's Promise* propaganda film:[5]

"In the IFR concept, which was never actually realized in practice, reactor-spent fuel would be reprocessed using a technology called pyroprocessing, and the extracted plutonium would be fabricated into new fuel. IFR advocates have long asserted that pyroprocessing is not a proliferation risk because the plutonium it separates is not completely purified.

"But a 2008 U.S. Department of Energy review – which confirmed many previous studies – concluded that pyroprocessing and similar technologies would "greatly reduce barriers to theft, misuse or further processing, even without separation of pure plutonium."

"Other Department of Energy studies showed that pyroprocessing, by generating large quantities of low-level nuclear waste and contaminated uranium, greatly increases the volume of nuclear waste requiring disposal, contradicting "Pandora's Promise's" claim it would reduce the amount of waste.

"And what about [Charles] Till's claim that the IFR can't melt down? It's false. "Pandora's Promise" referenced two successful safety tests conducted in 1986 at a small demonstration

fast reactor in Idaho called the Experimental Breeder Reactor-II (EBR-II). But EBR-II operators scripted these tests to ensure the desired outcome, a luxury not available in the real world. Meanwhile, the EBR-II's predecessor, the EBR-I, had a partial fuel meltdown in 1955, and a similar reactor, Fermi 1 near Detroit, had a partial fuel meltdown in 1966.

"Moreover, fast reactors have inherent instabilities that make them far more dangerous than light-water reactors under certain accident conditions, conditions that were studiously avoided in the 1986 dog-and-pony show at EBR-II.

"Perhaps the biggest myth in the film is the notion that all U.S. research on fast reactors was terminated. In fact, the IFR program's demise was a shutdown in name only. The Department of Energy has continued to fund research and development on fast reactor technology to the tune of tens of millions to hundreds of millions of dollars a year. The IFR Fuel Reprocessing Facility in Idaho shown in the film – in reality, a plant called the Fuel Conditioning Facility – has been operating for decades, essentially as a jobs program, to reprocess spent fuel from the now-defunct EBR-II, despite the system's serious problems. In 2000, the Department of Energy promised that all the fuel would be processed by around 2007. Three years later, it delayed the projected completion date to 2030.

"Till's assertion in "Pandora's Promise" that "we know how to do these things" does not square with the difficulties the Department of Energy has encountered in trying to operate this troubled plant."

The one true meltdown-proof SMR

First prize for SMR safety idiocy and dishonesty goes to molten salt reactor (MSR) enthusiasts who claim that MSRs are meltdown-proof. MSRs are in fact meltdown-proof, twice over. First, fuel meltdown in MSRs is impossible because MSRs don't exist. Secondly, if MSRs did exist, the fuel couldn't possibly melt because it is liquid.

As with solid-fueled reactors, dispersal of radionuclides via fire or chemical explosion is possible … but fuel melting is not. That's not an advantage of MSRs – it could be a liability.

The UK National Nuclear Laboratory noted in a 2016 report that constructing a safety case for MSRs will necessarily be very different compared to a conventional reactor:[6]

"This is dictated by the fact that in an MSR the normal operating condition is with the fuel melted and therefore some of the barriers to release of fission products, actinides and activation products in a solid fuel reactor no longer apply. Although MSR designs are typically characterised by strong negative temperature feedback coefficients, un-pressurised systems, tolerance of high temperatures and passive decay heat removal, these features per se may not necessarily make the safety case easy to demonstrate. There will need to be extensive experimental test data available that will substantiate all aspects of the safety case. At present this database does not exist …"

References:
1. James Conca, 24 Jan 2018, 'Can We Make A Nuclear Reactor That Won't Melt Down?', https://www.forbes.com/sites/jamesconca/2018/01/24/can-we-make-a-nuclear-reactor-that-wont-melt-down/
2. Ed Lyman, 17 Dec 2013, 'Safety and Security Concerns about Small Modular Reactors: NuScale's Design', https://allthingsnuclear.org/elyman/safety-and-security-concerns-about-small-modular-reactors-nuscales-design
3. Edwin Lyman, Sept 2013, 'Small Isn't Always Beautiful: Safety, Security, and Cost Concerns about Small Modular Reactors', https://www.ucsusa.org/sites/default/files/legacy/assets/documents/nuclear_power/small-isnt-always-beautiful.pdf
4. Southwest Research Institute, 'Center for Nuclear Waste Regulatory Analyses: Support to the U.S. Nuclear Regulatory Commission Office of New Reactors', http://pbadupws.nrc.gov/docs/ML1327/ML13270A404.pdf
5. Edwin Lyman, 7 Nov 2013, 'Scientist: Film hypes the promise of advanced nuclear technology', https://edition.cnn.com/2013/11/07/opinion/lyman-nuclear-pandora/index.html
6. National Nuclear Laboratory, 15 March 2016, 'SMR Techno-Economic Assessment, Project 3: SMRs Emerging Technology, Assessment of Emerging SMR Technologies, Summary Report For The Department of Energy and Climate Change', https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665274/TEA_Project_3_-_Assessment_of_Emerging_SMR_Technologies.pdf

10. Generation IV nuclear waste claims debunked

Lindsay Krall and Allison Macfarlane have written an important article in the *Bulletin of the Atomic Scientists* debunking claims that certain Generation IV reactor concepts promise major advantages with respect to nuclear waste management.[1] Krall is a post-doctoral fellow at the George Washington University. Macfarlane is a professor at the same university, a former chair of the US Nuclear Regulatory Commission from July 2012 to December 2014, and a member of the Blue Ribbon Commission on America's Nuclear Future from 2010 to 2012.

Krall and Macfarlane focus on molten salt reactors and sodium-cooled fast reactors, and draw on the experiences of the US Experimental Breeder Reactor II and the US Molten Salt Reactor Experiment.

The article abstract notes that Generation IV developers and advocates "are receiving substantial funding on the pretense that extraordinary waste management benefits can be reaped through adoption of these technologies" yet "molten salt reactors and sodium-cooled fast reactors – due to the unusual chemical compositions of their fuels – will actually exacerbate spent fuel storage and disposal issues."

Here is the concluding section of the article:

"The core propositions of non-traditional reactor proponents – improved economics, proliferation resistance, safety margins, and waste management – should be re-evaluated.

The metrics used to support the waste management claims – i.e. reduced actinide mass and total radiotoxicity beyond 300 years – are insufficient to critically assess the short- and long-term safety, economics, and proliferation resistance of the proposed fuel cycles.

"Furthermore, the promised (albeit irrelevant) actinide reductions are only attainable given exceptional technological requirements, including commercial-scale spent fuel treatment, reprocessing, and conditioning facilities. These will create low- and intermediate-level waste streams destined for geologic disposal, in addition to the intrinsic high-level fission product waste that will also require conditioning and disposal.

"Before construction of non-traditional reactors begins, the economic implications of the back end of these non-traditional fuel cycles must be analyzed in detail; disposal costs may be unpalatable. The reprocessing/treatment and conditioning of the spent fuel will entail costs, as will storage and transportation of the chemically reactive fuels. These are in addition to the cost of managing high-activity operational wastes, e.g. those originating from molten salt reactor filter systems. Finally, decommissioning the reactors and processing their chemically reactive coolants represents a substantial undertaking and another source of non-traditional waste. ...

"Issues of spent fuel management (beyond temporary storage in cooling pools, aka "wet storage") fall outside the scope of the NRC's reactor design certification process, which is regularly denounced by nuclear advocates as narrowly applicable to light water reactor technology and insufficiently responsive to new reactor designs. Nevertheless, new reactor licensing is contingent on broader policies, including the Nuclear Waste Policy Act and the Continued Storage Rule. Those policies are based on the results of radionuclide dispersion models described in environmental impact statements. But the fuel and barrier degradation mechanisms tested in these models were specific to oxide-based spent fuels, which are inert, compared to the compounds that non-traditional reactors will discharge.

"The Continued Storage Rule explicitly excludes most non-oxide fuels, including those from sodium-cooled fast reactors, from the environmental impact statement. Clearly, storage and disposal of non-oxide commercial fuels should require updated assessments and adjudication.

"Finally, treatment of spent fuels from non-traditional reactors, which by Energy Department precedent is only feasible through their respective (re)processing technologies, raises concerns over proliferation and fissile material diversion. Pyroprocessing and fluoride volatility-reductive extraction systems optimized for spent fuel treatment can – through minor changes to the chemical conditions – also extract plutonium (or uranium 233 bred from thorium). Separation from lethal fission products would eliminate the radiological barriers protecting the fuel from intruders seeking to obtain and purify fissile material. Accordingly, cost and risk assessments of predisposal spent fuel treatments must also account for proliferation safeguards.

"Radioactive waste cannot be "burned"; fission of actinides, the source of nuclear heat, inevitably generates fission products. Since some of these will be radiotoxic for thousands of years, these high-level wastes should be disposed of in stable waste forms and geologic

repositories. But the waste estimates propagated by nuclear advocates account only for the bare mass of fission products, rather than that of the conditioned waste form and associated repository requirements.

"These estimates further assume that the efficiency of actinide fission will surge, but this actually relies on several rounds of recycling using immature reprocessing technologies. The low- and intermediate-level wastes that will be generated by these activities will also be destined for geologic disposal but have been neglected in the waste estimates. More important, reprocessing remains a security liability of dubious economic benefit, so the apparent need to adopt these technologies simply to prepare non-traditional spent fuels for storage and disposal is a major disadvantage relative to light water reactors. Theoretical burnups for fast and molten salt reactors are too low to justify the inflated back-end costs and risks, the latter of which may include a commercial path to proliferation.

"Reductions in spent fuel volume, longevity, and total radiotoxicity may be realized by breeding and burning fissile material in non-traditional reactors. But those relatively small reductions are of little value in repository planning, so utilization of these metrics is misleading to policy-makers and the general public. We urge policy-makers to critically assess non-traditional fuel cycles, including the feasibility of managing their unusual waste streams, any loopholes that could commit the American public to financing quasi-reprocessing operations, and the motivation to rapidly deploy these technologies. If decarbonization of the economy by 2050 is the end-goal, a more pragmatic path to success involves improvements to light water reactor technologies, adoption of Blue Ribbon Commission recommendations on spent fuel management, and strong incentives for commercially mature, carbon-free energy technologies."

Pyroprocessing: the integral fast reactor waste fiasco

In theory, integral fast reactors (IFRs) would gobble up nuclear waste and convert it into low-carbon electricity. In practice, the IFR R&D program in Idaho has left a legacy of troublesome waste. This saga is detailed in a 2017 article[2] and a longer report[3] by the Union of Concerned Scientists' senior scientist Ed Lyman. This will be of particular relevance if the US Department of Energy proceeds with its plan to support the construction of a 'versatile test reactor' based on GE-Hitachi's 'Power Reactor Innovative Small Module' (PRISM) design, which is based on IFR designs.[4]

Lyman notes that the IFR concept "has attracted numerous staunch advocates" but their "interest has been driven largely by idealized studies on paper and not by facts derived from actual experience."[2] He discusses the IFR prototype built at Idaho – the Experimental Breeder Reactor-II (EBR-II), which ceased operation in 1994 – and subsequent efforts by the Department of Energy (DOE) to treat 26 metric tons of sodium-bonded metallic spent fuel from the EBR-II reactor with pyroprocessing, ostensibly to convert the waste to forms that would be safer for disposal in a geological repository. A secondary goal was to demonstrate the viability of pyroprocessing – but the program has instead demonstrated the serious shortcomings of this technology.

Lyman writes:[2]

"Pyroprocessing is a form of spent fuel reprocessing that dissolves metal-based spent fuel in a molten salt bath (as distinguished from conventional reprocessing, which dissolves spent fuel in water-based acid solutions). Understandably, given all its problems, DOE has been reluctant to release public information on this program, which has largely operated under the radar since 2000.

"The FOIA [Freedom of Information Act] documents we obtained have revealed yet another DOE tale of vast sums of public money being wasted on an unproven technology that has fallen far short of the unrealistic projections that DOE used to sell the project to Congress, the state of Idaho and the public. However, it is not too late to pull the plug on this program, and potentially save taxpayers hundreds of millions of dollars. …

"Pyroprocessing was billed as a simpler, cheaper and more compact alternative to the conventional aqueous reprocessing plants that have been operated in France, the United Kingdom, Japan and other countries.

"Although DOE shut down the EBR-II in 1994 (the reactor part of the IFR program), it allowed work at the pyroprocessing facility to proceed. It justified this by asserting that the leftover spent fuel from the EBR-II could not be directly disposed of in the planned Yucca Mountain repository because of the potential safety issues associated with presence of metallic sodium in the spent fuel elements, which was used to "bond" the fuel to the metallic cladding that encased it. (Metallic sodium reacts violently with water and air.)

"Pyroprocessing would separate the sodium from other spent fuel constituents and neutralize it. DOE decided in 2000 to use pyroprocessing for the entire inventory of leftover EBR-II spent fuel – both "driver" and "blanket" fuel – even though it acknowledged that there were simpler methods to remove the sodium from the lightly irradiated blanket fuel, which constituted nearly 90% of the inventory.

"However, as the FOIA documents reveal in detail, the pyroprocessing technology simply has not worked well and has fallen far short of initial predictions. Although DOE initially claimed that the entire inventory would be processed by 2007, as of the end of Fiscal Year 2016, only about 15% of the roughly 26 metric tons of spent fuel had been processed. Over $210 million has been spent, at an average cost of over $60,000 per kilogram of fuel treated. At this rate, it will take until the end of the century to complete pyroprocessing of the entire inventory, at an additional cost of over $1 billion.

"But even that assumes, unrealistically, that the equipment will continue to be usable for this extended time period. Moreover, there is a significant fraction of spent fuel in storage that has degraded and may not be a candidate for pyroprocessing in any event. …

"What exactly is the pyroprocessing of this fuel accomplishing? Instead of making management and disposal of the spent fuel simpler and safer, it has created an even bigger mess. …

"[P]yroprocessing has taken one potentially difficult form of nuclear waste and converted it into multiple challenging forms of nuclear waste. DOE has spent hundreds of millions of dollars only to magnify, rather than simplify, the waste problem. This is especially outrageous in light of other FOIA documents that indicate that DOE never definitively concluded that the sodium-bonded spent fuel was unsafe to directly dispose of in the first place. But it insisted on pursuing pyroprocessing rather than conducting studies that might have shown it was unnecessary.

"Everyone with an interest in pyroprocessing should reassess their views given the real-world problems experienced in implementing the technology over the last 20 years at INL. They should also note that the variant of the process being used to treat the EBR-II spent fuel is less complex than the process that would be needed to extract plutonium and other actinides to produce fresh fuel for fast reactors. In other words, the technology is a long way from being demonstrated as a practical approach for electricity production."

References:
1. Lindsay Krall and Allison Macfarlane, 2018, 'Burning waste or playing with fire? Waste management considerations for non-traditional reactors', Bulletin of the Atomic Scientists, 74:5, pp.326-334, https://tandfonline.com/doi/10.1080/00963402.2018.1507791
2. Ed Lyman / Union of Concerned Scientists, 12 Aug 2017, 'The Pyroprocessing Files', http://allthingsnuclear.org/elyman/the-pyroprocessing-files
3. Edwin Lyman, 2017, 'External Assessment of the U.S. Sodium-Bonded Spent Fuel Treatment Program', https://s3.amazonaws.com/ucs-documents/nuclear-power/Pyroprocessing/IAEA-CN-245-492%2Blyman%2Bfinal.pdf
4. World Nuclear Association, 15 Nov 2018, 'PRISM selected for US test reactor programme', http://www.world-nuclear-news.org/Articles/PRISM-selected-for-US-test-reactor-programme

11. High-temperature, gas-cooled zombie SMRs

High-temperature gas-cooled reactors (HTGR) and their pebble-bed modular reactor (PBMR) sub-type have a long and troubled history. But the zombie HTGR concept refuses to die: each failure is followed by another attempt and another failure.

Here is an excerpt from Nuclear Monitor's 2010 report on the failure of South Africa's PBMR project:[1]

The Pebble Bed Modular Reactor. Remember? It was globally heralded as the perfect nuclear reactor: small, safe and cheap. Dozens would be built in South Africa alone and in 1999 the company expected to sell 30 reactors annually from 2004 on.

Now, the South African government announced it is expected to close operations at PBMR (Pty) Ltd. finally 'within a few weeks' (that is August). The company once planned to build up to 24 165-MW high-temperature gas-cooled reactor modules for state-owned utility Eskom and export the modular HTR worldwide, but hasn't built even the demonstration model.

The government has invested an estimated South Africa Rand 9 billion (US$1.23 billion at current rates) in PBMR Ltd. over the 11 years since it was founded as an Eskom subsidiary. PBMR Ltd. is formally owned by Eskom, the Industrial Development Corp. and Westinghouse, but they have put no equity in the company for several years.

In a July statement, the Department of Public Enterprises, which has responsibility for the PBMR company, said PBMR "has not been able to acquire additional investment in the project since government's last funding allocation in 2007, nor has it been able to acquire an anchor customer despite revising its business model in 2008/09."

The company is operating on funds that were left over from the 2007 allocation and has downsized from about 800 staff to about 25. Although the PBMR website doesn't show anything about the current situation, it says there are "no career opportunities at the moment."

The company was set up in 1999 as Pebble Bed Modular Reactor (Pty) Ltd. to develop and deploy German technology it had acquired for small HTRs with coated pebble-shaped fuel elements. Besides British Nuclear Fuels plc (BNFL), Exelon, the largest nuclear fleet operator in the US, also made an early equity investment, and the company was broadly touted as the herald of a new nuclear age for the developing world based on small reactors that could be set up quickly under various site conditions. BNFL's stake was transferred to Westinghouse when the latter was sold to Toshiba.

But the PBMR partners never agreed on a new equity structure and the company remained the property of the South African government. The Department of Public Enterprises believes the R9-billion spent on the PBMR project has not been lost, as the skills developed "will contribute significantly in any future nuclear programs and save the country huge amounts of money in the process".

One of the critics, Stephen Thomas, professor of energy policy at the University of Greenwich in the UK, told the Cape Times that it was clear at least six years ago that the PBMR project was "going badly wrong. Yet the government continued to pour public money into it, indeed about 80 percent of all the money spent on the pebble bed was spent in the past six years."

Tristen Taylor, of Earthlife Africa, said "We hope that this will also mark the end of the South African government's love affair with nuclear energy and that taxpayer funds can now be spent on clean, proven and reliable forms of renewable energy".

The demise of PBMRs ... and China's attempted revival

Steve Thomas, Professor of Energy Policy at the University of Greenwich, wrote about the demise of PBMRs in the *Bulletin of the Atomic Scientists* in 2009.[2] Thomas covers the failure of PBMR projects in Germany and South Africa. He notes that the cost of the proposed PBMR demonstration plant in South Africa was initially US$223 million but the estimate had escalated eight-fold to at least US$1.8 billion by the time the project was abandoned.

Thomas concluded:[2]

"All the major countries involved in designing reactors, including the United States, Germany, France, Japan, and Britain, have put major time and effort into developing high-temperature, gas-cooled reactors such as the PBMR. Despite more than 50 years of trying, however, no commercial-scale design has yet been produced. Yet China and South Africa have found the allure of pebble bed technology irresistible, as if it were an "unpolished gem" waiting to be developed, regardless of the consistent engineering problems it has had since the beginning.

"South Africa took a particularly aggressive approach, believing that it could develop a commercial-size PBMR design without even operating a prototype. If the PBMR is proved to be fundamentally flawed, as indicated in the Jülich report[3], South Africa's $980 million investment in the project will be seen in hindsight as wasteful, one that the country, plagued with many more pressing and basic problems, could ill afford."

The Jülich report mentioned by Thomas is the Jülich Center's 2008 review of its previous PBMR work.[3] It was Jülich's design – specifically the prototype PBMR – which South Africa had taken as the basis for its PBMR. It seems that one after another nuclear nation is destined to find out for themselves that HTGR/PBMR designs are technically challenging and are best avoided.

China is building one demonstration HTGR/PBMR: twin reactors driving a single 210 MWe turbine.[4] Further HTGR feasibility studies are underway in China[5], but plans for 18 additional HTGR/PBMRs (with total capacity of 3,800 MW) at the same site as the demonstration plant have been "dropped" according to the World Nuclear Association.[4] In 2016, completion of the demonstration reactor was anticipated the following year, and China's HTGRs would be on the world market within five years.[6,7] But the demonstration reactor has not been completed as of February 2019, construction of larger HTGRs in China has not yet begun, and the world will simply have to wait for Chinese HTGRs … or find alternative power sources. Construction cost estimates of the demonstration HTGR have approximately doubled.[8]

The checkered history of HTGRs

University of British Columbia academic M.V. Ramana has written a summary of the troubled history of HTGR / PBMR projects.[9] An excerpt from Ramana's article is reproduced here:

"Proponents of HTGRs often claim that their designs have a long pedigree. ... But if one examines that very same experience more closely – looking in particular at the HTGRs that were constructed in Western Europe and the United States to feed power into the electric grid – then one comes to other conclusions. This history suggests that while HTGRs may look attractive on paper, their performance leaves much to be desired. The technology may be something that looks better on paper than in the real world ...

"Although Germany abandoned this technology, it did migrate to other countries, including China and South Africa. Of these, the latter case is instructive: South Africa pursued the

construction of a pebble-bed reactor for a decade, and spent over a billion dollars, only to abandon it in 2009 because it just did not make sense economically. Although sold by its proponents as innovative and economically competitive until its cancellation, the South African pebble-bed reactor project is now being cited as a case study in failure. How good the Chinese experience with the HTGR will be remains to be seen. ...

"From these experiences in operating HTGRs, we can take away several lessons – the most important being that HTGRs are prone to a wide variety of small failures, including graphite dust accumulation, ingress of water or oil, and fuel failures. Some of these could be the trigger for larger failures or accidents, with more severe consequences. ... Other problems could make the consequences of a severe accident worse: For example, pebble compaction and breakage could lead to accelerated diffusion of fission products such as radioactive cesium and strontium outside the pebbles, and a potentially larger radioactive release in the event of a severe accident. ...

"Discussions of the commercial viability of HTGRs almost invariably focus on the expected higher capital costs per unit of generation capacity (dollars per kilowatts) in comparison with light water reactors, and potential ways for lowering those. In other words, the main challenge they foresee is that of building these reactors cheaply enough. But what they implicitly or explicitly assume is that HTGRs would operate as well as current light water reactors – which is simply not the case, if history is any guide. ...

"Although there has been much positive promotional hype associated with high-temperature reactors, the decades of experience that researchers have acquired in operating HTGRs has seldom been considered. Press releases from the many companies developing or selling HTGRs or project plans in countries seeking to purchase or construct HTGRs neither tell you that not a single HTGR-termed "commercial" has proven financially viable nor do they mention that all the HTGRs were shut down well before the operating periods envisioned for them. This is typical of the nuclear industry, which practices selective remembrance, choosing to forget or underplay earlier failures."

References:

1. Nuclear Monitor #714, 20 Aug 2010, 'The end is near for the PBMR', https://www.wiseinternational.org/nuclear-monitor/714/end-near-pbmr
2. Steve Thomas, 22 June 2009, 'The demise of the pebble bed modular reactor', http://thebulletin.org/demise-pebble-bed-modular-reactor
3. R. Moormann, "A Safety Re-evaluation of the AVR Pebble Bed Reactor Operation and Its Consequences for Future HTR Concepts," Forschungszentrum Jülich, 2008, https://inis.iaea.org/collection/NCLCollectionStore/_Public/39/099/39099096.pdf?r=1&r=1
4. World Nuclear Association, 21 March 2016, 'First vessel installed in China's HTR-PM unit', http://www.world-nuclear-news.org/NN-First-vessel-installed-in-Chinas-HTR-PM-unit-2103164.html
5. World Nuclear Association, 19 Sept 2017, 'China plans further high temperature reactor innovation', http://www.world-nuclear-news.org/NN-China-plans-further-high-temperature-reactor-innovation-1909171.html
6. Dan Yurman, 13 Feb 2016, 'Nuclear News Roundup for 2/14/16', http://neutronbytes.com/2016/02/13/nuclear-news-roundup-for-21416/

7. Richard Martin, 11 Feb 2016, 'Two high-temperature, gas-cooled reactors under construction in Shandong will make up the first commercial-scale plant of its type in the world', https://www.technologyreview.com/s/600757/china-could-have-a-meltdown-proof-nuclear-reactor-next-year/
8. 1 Dec 2016, 'China's plans to begin converting coal plants to walk away safe pebble bed nuclear starting in the 2020s', http://www.nextbigfuture.com/2016/12/chinas-plans-to-begin-converting-coal.html
9. M. V. Ramana, April 2016, 'The checkered operational history of high-temperature gas-cooled reactors', Bulletin of the Atomic Scientists, http://dx.doi.org/10.1080/00963402.2016.1170395