SMALL MODULAR REACTORS
AND 'ADVANCED' OR 'GENERATION IV' REACTOR CONCEPTS

Briefing Paper

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This paper, and further information on SMRs, is posted at nuclear.foe.org.au/smr

Further information on 'advanced' or 'Generation IV' reactor concepts is posted at nuclear.foe.org.au/power/#gen4

Author and contact: Jim Green B.Med.Sci.(Hons), PhD, jim.green@foe.org.au

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1. Introduction to SMRs

'Small modular reactors' (SMRs) would have a capacity of under 300 megawatts (MW), whereas large reactors typically have a capacity of about 1,000 MW. Construction at reactor sites would be replaced with standardised factory production of reactor components (or 'modules') then installation at the reactor site. The term 'modular' also refers to the option of building clusters of small reactors at the same site.

SMRs 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, and no company, consortium, utility or national government is seriously considering betting billions building an SMR mass manufacturing capacity.

With near-zero prospects for new large nuclear power reactors in Western countries, SMRs are being promoted to rescue an industry that even nuclear lobbyists acknowledge is in crisis.[1] In essence, the nuclear industry's solution to its expensive and uncompetitive large reactors is to offer up even more expensive power from SMRs.

Previous attempts to build SMRs have failed and there is no reason to expect success now. M.V. Ramana concludes an analysis of the history of SMRs:[2]

> *"Once again, we see history repeating itself in today's claims for small reactors – that the demand will be large, that they will be cheap and quick to construct. But nothing in the history of small nuclear reactors suggests that they would be more economical than full-size ones. In fact, the record is pretty clear: Without exception, small reactors cost too much for the little electricity they produced, the result of both their low output and their poor performance."*

No private sector SMR projects have reached the construction stage. A small number of SMRs are under construction, by state nuclear agencies in Russia, China and Argentina. Most or all of them are over-budget and behind schedule. None are factory built (the essence of the concept of modular reactors).

Alarmingly, about half of the SMRs under construction are intended to facilitate the exploitation of fossil fuel reserves in the Arctic, the South China Sea and elsewhere. The primary purpose of the Russian floating plant is to power fossil fuel mining operations in the Arctic.[3] Russia's pursuit of nuclear-powered icebreaker ships (nine such ships are planned by 2035) is closely connected to its agenda of establishing military and economic control of the Northern Sea Route – a route that owes its existence to climate change.[4] China General Nuclear Power Group plans to use floating nuclear power plants for oilfield exploitation in the Bohai Sea and deep-water oil and gas development in the South China Sea.[5]

There are disturbing, multifaceted connections between SMR projects and nuclear weapons proliferation and militarism more generally:[6]

[1] https://www.wiseinternational.org/nuclear-monitor/839/nuclear-power-crisis-or-it-merely-end
[2] https://spectrum.ieee.org/the-forgotten-history-of-small-nuclear-reactors
[3] https://www.wiseinternational.org/nuclear-monitor/861/worlds-first-purpose-built-floating-nuclear-plant-akademik-lomonosov-reaches
[4] https://www.popularmechanics.com/military/navy-ships/a27615565/ural-russia-icebreaker/
[5] http://en.cgnpc.com.cn/encgn/c100050/business_tt.shtml
[6] https://wiseinternational.org/nuclear-monitor/872-873/small-modular-reactors-and-nuclear-weapons-proliferation
https://wiseinternational.org/nuclear-monitor/872-873/military-bromance-smrs-support-and-cross-subsidize-uk-nuclear-weapons
https://wiseinternational.org/nuclear-monitor/872-873/smrs-power-military-installations-and-forward-bases-united-states

- Argentina's experience and expertise with small reactors derives from its historic weapons program, and its interest in SMRs is interconnected with its interest in small reactors for naval propulsion.
- China's interest in SMRs 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.
- Saudi Arabia's interest in SMRs is likely connected to its interest in developing nuclear weapons or a latent weapons capability.
- A subsidiary of Holtec International has actively sought a military role, inviting the US National Nuclear Security Administration to consider the feasibility of using a proposed SMR to produce tritium, used to boost the explosive yield of nuclear weapons.
- Proposals are under consideration in the US to build SMRs at military bases and perhaps even to use them to power forward operating bases.
- In the UK, Rolls-Royce is promoting SMRs on the grounds that "a civil nuclear UK SMR programme would relieve the Ministry of Defence of the burden of developing and retaining skills and capability".

2. Widespread scepticism about SMRs

The prevailing scepticism about SMRs is evident in a 2017 Lloyd's Register report based on the insights of almost 600 professionals and experts from utilities, distributors, operators and equipment manufacturers.[7] They predict that SMRs have a "low likelihood of eventual take-up and will have a minimal impact when they do arrive".[8]

Likewise, American Nuclear Society consultant Will Davis said in 2014 that the SMR "universe is rife with press releases, but devoid of new concrete."[9]

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.[10]

Dr. Ziggy Switkowski – who headed the Australian Government's nuclear review in 2006 – noted in 2019 that "nobody's putting their money up'' to build SMRs and "it is largely a debate for intellects and advocates because neither generators nor investors are interested because of the risk."[11] Moreover "the window for gigawatt-scale nuclear has closed", Dr. Switkowski said[12], and nuclear power is no longer cheaper than renewables with costs rapidly shifting in favour of renewables.[13]

World Finance reported in October 2018 that "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."[14]

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[7] http://info.lr.org/techradarlowcarbon
[8] http://www.world-nuclear-news.org/EE-Nuclear-more-competitive-than-fossil-fuels-report-09021702.html
[9] http://ansnuclearcafe.org/2014/02/13/carem-25-carries-torch-for-smr-construction/
[10] http://1.nuclearenergyinsider.com/LP=362
[11] https://www.afr.com/politics/federal/no-investment-appetite-for-nuclear-switkowski-20190805-p52dwv
[12] https://www.theage.com.au/business/the-economy/australia-has-missed-the-boat-on-nuclear-power-20180111-p4yyeg.html
[13] http://www.smh.com.au/business/the-economy/safety-risks-stall-nuclear-role-in-australia-s-energy-mix-20180125-p4yyvj.html
[14] https://www.worldfinance.com/markets/nuclear-power-continues-its-decline-as-renewable-alternatives-steam-ahead

Former World Nuclear Association executive Steve Kidd wrote about SMR "myths" in 2015:[15]

> *"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 [light-water reactors], 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."*

The South Australian Nuclear Fuel Cycle Royal Commission's final report in 2016 identified numerous hurdles and uncertainties facing SMRs, including:[16]

- 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.

In 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."[17]

The business plan for SMRs also face a fuel supply issue. The fuel needed for some proposed SMRs is high-assay low enriched uranium (HALEU) which is limited in availability (due to limited demand). SMR developers in the US need security of fuel supply and potential fuel manufacturers need security of demand to invest in the technology.[18]

3. Operating and under-construction SMRs

The November 2022 edition of the World Nuclear Industry Status Report provides the following summary of operating SMRs, under-construction SMRs, and a few of the most important SMR projects in the design or planning stage:

> *“**Argentina.** The CAREM-25 project has been under construction since 2014. Following numerous delays, the latest estimated date for startup is 2027. The lower end of cost estimates per installed kilowatt correspond to roughly twice the cost estimates for the most expensive Generation-III reactors.*

[15] https://www.neimagazine.com/opinion/opinionnuclear-myths-is-the-industry-also-guilty-4598343/
[16] https://nuclear.foe.org.au/wp-content/uploads/NFCRC_Final_Report_Web_5MB.pdf
[17] https://www.nuclearenergyinsider.com/international-smr-advanced-reactor
[18] https://www.reuters.com/business/energy/americas-new-nuclear-power-industry-has-russian-problem-2022-10-20/

Canada. *There is continuous strong federal and provincial government support for the promotion of SMRs. While several grants to the value of tens of millions of dollars have been awarded to different design developers, the amounts remain small when compared to what would be required to advance one of these designs to the point of being licensed for construction. No design has yet been transmitted to the safety authority for review, leave alone for certification.*
China. *Construction on two high-temperature reactor modules started in 2012. The first module was connected to the grid for a few days in December 2021, almost five years behind schedule. Reportedly, neither unit has generated power since. The reasons are unknown. Construction started on a second design, the ACP100 or Linglong One, in July 2021, six years later than planned. It is scheduled to be completed by early 2026.*
France. *In February 2022, President Macron announced a US$1.1 billion contribution until 2030 to the financing of the development of the Nuward SMR design. However, EDF made it clear that the project is not high amongst its priorities.*
India. *An Advanced Heavy Water Reactor (AHWR) design has been under development since the 1990s, but its construction has been continuously delayed. Earlier in 2022, the government announced that a "Pre-Licensing Design Safety appraisal of the reactor has been completed".*
Russia. *Russia operates two SMRs on a barge called the Akademik Lomonosov. Both reactors were connected to the grid in December 2019, nine years later than planned. Since then, their performance has been mediocre. A second SMR project, a lead-cooled fast reactor design, was launched in June 2021.*
South Korea. *The System-Integrated Modular Advanced Reactor (SMART) has been under development since 1997. In 2012, the design received approval by the safety authority, but there have been no orders. Reportedly, several other designs are in very early stages of development.*
United Kingdom. *Since 2014, Rolls Royce has been developing the "UK SMR", a 470 MW reactor (exceeding the size-limit of 300 MW for the usual SMR definition). In November 2021, Rolls Royce announced it had received US$281 million in government funding and US$261 million from private sources (including company funding), far short of its earlier calls for US$2.8 billion in support. In March 2022, the regulator accepted the design for a Generic Design Assessment (GDA).*
(We note recent statements from Rolls Royce around options for the siting of a facility planned to manufacture SMR components. Any advance on this is contingent on agreement with the UK government on future SMR deployment and remains highly uncertain).
United States. *The Department of Energy (DOE) has already spent more than US$1.2 billion on SMRs and has announced further awards over the next decade that could amount to an additional US$5.5 billion. However, there is still not a single reactor under construction. Only one design, NuScale, has received a final safety evaluation report. However, since then, the design capacity has been increased from 50 MW to 77 MW per module, and many issues remain unsolved. In October 2021, eight municipalities withdrew from the only investment project in Utah, leaving the 6-module 462 MW project with subscriptions amounting to just 101 MW. Cost estimates (including financing) have ballooned to US$5.3 billion."*

See also the June 2023 summary of SMR projects published in nuClear News.[19]

[19] https://www.no2nuclearpower.org.uk/wp/wp-content/uploads/2023/06/nuClearNewsNo142.pdf

Operating SMRs

Just two SMRs are said to be operating – neither meeting the 'modular' definition of serial factory production of reactor components. The two operational SMRs – one each in Russia and China – exhibit familiar problems of massive cost blowouts and multi-year delays. SMR reality doesn't come close to matching SMR rhetoric.

Russia's has a floating nuclear power plant with two 35 MW reactors. The construction cost increased six-fold from 6 billion rubles to 37 billion rubles (A$785 million)[20], equivalent to A$10.1 billion / gigawatt (GW).

According to the OECD's Nuclear Energy Agency, electricity produced by the Russian floating plant costs an estimated US$200 (A$288) / megawatt-hour (MWh), with the high cost due to large staffing requirements, high fuel costs, and resources required to maintain the barge and coastal infrastructure.[21] To put that in perspective, the Minerals Council of Australia states that SMRs won't find a market in Australia unless they can produce power at a cost of A$60–80 / MWh[22] – about one-quarter of the cost of electricity produced by the Russian plant.

Rapid construction timelines are said to be a feature of SMRs, but the Russian floating plant took 12 years to build.[23] Shortly before construction began in 2007, Rosatom announced that the plant would begin operating in October 2010, but it was not completed until 2019.[24] A three-year construction project became a 12-year project. Russia's plan to have seven floating nuclear power plants by 2015 was not realised.[25]

The performance of Russia's floating nuclear power plant appears to be mediocre: the lifetime load factors for the two reactors stand at 38.8% and 17.2%.[26]

The other operating SMR (loosely defined) is China's demonstration 210 MW (2 x 105 MW) high-temperature gas-cooled reactor (HTGR). A 2016 report said that the estimated construction cost was about US$5 billion (A$7.2 billion) / GW – about twice the initial cost estimates – and that cost increases arose from higher material and component costs, increases in labour costs, and project delays.[27] The World Nuclear Association states that the cost of the demonstration HTGR is US$6 billion (A$8.6 billion) / GW[28], roughly twice the cost of larger Chinese 'Hualong' reactors (US$2.6–3.5 billion / GW).[29] Those figures (US$5–6 billion / GW) are 2–3 times higher than the US$2 billion (A$2.88 billion) / GW estimate in a 2009 paper by Tsinghua University researchers.[30]

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[20] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2021-HTML.html#_idTextAnchor013
http://bellona.org/news/nuclear-issues/2015-05-new-documents-show-cost-russian-nuclear-power-plant-skyrockets

[21] https://www.oecd-nea.org/jcms/pl_14924

[22] https://www.parliament.vic.gov.au/images/stories/committees/SCEP/Inquiry_into_Nuclear_Prohibition_Inquiry_/Transcripts/25_June_2020/5._FINAL_-_Minerals_Council_Aust.pdf

[23] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2021-HTML.html#_idTextAnchor013

[24] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html

[25] https://en.wikipedia.org/wiki/Russian_floating_nuclear_power_station

[26] https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=895,
https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=896

[27] http://www.nextbigfuture.com/2016/12/chinas-plans-to-begin-converting-coal.html
See also https://www.nextbigfuture.com/2017/08/china-small-modular-pebble-beds-will-be-400-million-for-200-mw-and-1-2-billion-for-600-mw.html

[28] https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

[29] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor147

[30] https://www.researchgate.net/publication/245194953_Current_status_and_technical_description_of_Chinese_2_250_MW_th_HTR-PM_demonstration_plant

Wang Yingsu, secretary general of the nuclear power branch of the China Electric Power Promotion Council, said in 2021 that HTGRs would never be as cheap as conventional light-water reactors.[31]

In 2004, the CEO of Chinergy said construction of the first HTGR would begin in 2007 and it would be completed by the end of the decade.[32] However, construction of the demonstration HTGR did not begin until 2012 (with an estimated construction time of 50 months[33]) and it was completed in 2021 after repeated delays. This nine-year construction project – more than double the construction time estimate in 2012 – undermines claims that SMRs could be built in as little as 2–3 years.

China's HTGR is said to be operational but the November 2022 edition of the World Nuclear Industry Status Report indicates that problems have arisen:[34]
"The first of two High Temperature Gas Cooled Reactor (HTGR) units at Shidao Bay (Shidao Bay 1-1 and 1-2) – IAEA-PRIS considers these as one plant – was connected to the grid on 20 December 2021. As of the time of this writing, there is no public announcement that the second unit has been connected. Further, between January and June 2022, there was no power fed to the grid from this site, according to China Nuclear Energy Industry Association (CNEIA). No information has been published about the reasons for the additional delays in commissioning the second unit and for the shutdown of the first unit in the first half-year of 2022."

However a December 2022 World Nuclear Association article was more upbeat, citing Chinese project partners stating that the HTGR reached "initial full power" on 9 December 2022, thus "laying the foundation for the project to be put into operation".[35]

Neutron Bytes reported in June 2020: "It has been reported by several sources that the high cost of manufacturing the HTGR reactor components and building it are caused, in part, by the need for specialty materials to deal with the high heat it generates, and by the usual first-of-a-kind costs of a new design which have contributed to the schedule delay. In any case, China's ambitious plans to make Shandong Province a showcase for advanced nuclear reactors have been put on hold."[36]

NucNet reported in 2020 that China's State Nuclear Power Technology Corp. dropped plans to manufacture 20 HTGRs after levelised cost of electricity estimates rose to levels higher than a conventional pressurised water reactor such as China's Hualong One.[37] Likewise, the World Nuclear Association states that plans for 18 additional HTGRs at the same site as the demonstration HTGR have been "dropped".[38]

Multiple nations have tried to develop high-temperature gas-cooled reactors but then abandoned those efforts.[39]

SMRs under construction and NuScale's SMR plans

Three SMRs are under construction – again with the qualification that they don't involve serial factory production of reactor components so don't meet the 'modular' part of the definition of SMRs.

[31] https://www.scmp.com/news/china/science/article/3159945/china-revives-abandoned-htgr-nuclear-technology-safe-power-drive
[32] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor147
[33] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor147
[34] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor030
[35] https://www.world-nuclear-news.org/Articles/China-s-demonstration-HTR-PM-reaches-full-power
[36] https://neutronbytes.com/2020/06/14/china-nuclear-energy-news-for-06-14-20/
[37] https://www.nucnet.org/news/progress-and-status-in-the-race-for-commercialisation-2-4-2020
[38] https://www.world-nuclear-news.org/NN-First-vessel-installed-in-Chinas-HTR-PM-unit-2103164.html
[39] https://ucsusa.org/sites/default/files/2021-03/advanced-isnt-always-better-full.pdf
https://wiseinternational.org/nuclear-monitor/872-873/high-temperature-gas-cooled-zombie-smrs

Cost estimates for the CAREM SMR under construction in Argentina 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").[40] In 2005, Argentina's National Atomic Energy Commission CNEA estimated a cost about US$105 million (US$4.2 billion / GW).[41] When construction began in 2014, the estimated cost was US$17.8 billion / GW (US$446 million for a 25-MW reactor).[42] In 2021, the cost estimate increased to US$23.4 billion / GW (US$750 million (A$1.1 billion) with the capacity uprated from 25 MW to 32 MW).[43] That's over one billion Australian dollars for a plant with the capacity of a handful of large wind turbines.

The CAREM project is years behind schedule and costs will likely increase further. The project was launched by CNEA in 1984.[44] When construction began in 2014, 30 years later – completion was expected in 2017.[45] But progress has been slow, work was suspended on several occasions[46] and completion was pushed back to 2024. Further delays pushed the estimated completion date back to late 2027.[47] A three-year construction project has become, at best, a 13-year construction project. Thirty-eight years after the project was launched, the first prototype remains incomplete.

In July 2021, China National Nuclear Corporation (CNNC) New Energy Corporation began construction of the 125 MW pressurised water reactor ACP100 at Hainan[48] with an estimated construction time of just under five years (58 months).[49] CNNC says it will be the world's first land-based commercial SMR.[50] The ACP100 has been under development since 2010.[51] Construction was supposed to begin as early as 2013 (and, later, 2015 … and 2016 … and 2017) but did not begin until 2021.[52] According to CNNC, construction costs per kilowatt will be twice the cost of large reactors, and the levelised cost of electricity will be 50% higher than large reactors.[53]

In June 2021, construction of the 300 MW demonstration lead-cooled BREST fast neutron reactor began in Russia. Plans for a lead-cooled fast reactor in Russia date from the 1990s but construction has been repeatedly delayed.[54] In 2016, construction of BREST was expected to begin in 2017 and completion was expected in 2020[55] – but construction hadn't even begun in 2020. Completion is now expected in 2026. In 2012, the estimated cost for the reactor and associated facilities was 42 billion rubles (A$891 million)[56]; now, the estimate has more than doubled to 100 billion rubles (A$2.1 billion).[57]

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[40] https://www.researchgate.net/publication/267579277_CAREM_concept_A_competitive_SMR
[41] IAEA, Aug 2021, 'Technology Roadmap for Small Modular Reactor Deployment', https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1944_web.pdf
[42] http://www.world-nuclear-news.org/NN-Construction-of-CAREM-underway-1002144.html
[43] https://www.gihub.org/resources/showcase-projects/carem-25-prototype/, https://www.gihub.org/quality-infrastructure-database/case-studies/carem-25-prototype/
[44] https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1944_web.pdf
[45] https://www.world-nuclear-news.org/NN-Construction-of-CAREM-underway-1002144.html
[46] https://www.world-nuclear-news.org/Articles/Construction-of-Argentinas-small-CAREM-25-unit-to
[47] https://world-nuclear.org/information-library/country-profiles/countries-a-f/argentina.aspx
[48] https://world-nuclear-news.org/Articles/Installation-of-containment-starts-at-Chinese-SMR
[49] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor147
[50] https://world-nuclear-news.org/Articles/Installation-of-containment-starts-at-Chinese-SMR
[51] https://world-nuclear-news.org/Articles/Installation-of-containment-starts-at-Chinese-SMR, https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor147
[52] https://www.worldnuclearreport.org/The-World-Nuclear-Industry-Status-Report-2022-HTML.html#_idTextAnchor147
[53] https://nucleus.iaea.org/sites/INPRO/df17/IV.1.-DanrongSong-ACP100.pdf
[54] https://www.neimagazine.com/features/featurebrest-is-best/
https://www.powermag.com/nuclear-first-work-starts-on-russian-fast-neutron-reactor/
[55] https://www.nsenergybusiness.com/news/newsconstruction-of-russias-brest-reactor-to-start-next-year-4974446/
https://www.nsenergybusiness.com/news/newsbreakthrough-project-continues-as-brest-reactor-is-postponed-5718901/
https://bellona.org/news/nuclear-issues/2015-05-perpetual-search-perpetuum-mobile
[56] https://bellona.org/news/nuclear-issues/2015-05-perpetual-search-perpetuum-mobile
[57] https://tass.com/economy/1300401

NuScale Power

The SMR plans of US company NuScale Power are heavily promoted.[58] Development of NuScale SMR technology dates from 2003 – 20 years ago – yet the company has not even begun construction of a single reactor.[59] A study by WSP / Parsons Brinckerhoff, commissioned by the South Australian Nuclear Fuel Cycle Royal Commission, estimated costs of A$225 / MWh for power from SMRs based on the NuScale design.[60] As noted above, the Minerals Council of Australia states that SMRs won't find a market unless they can produce power at a cost of A$60–80 / MWh[61] – about one-third of the WSP / Parsons Brinckerhoff estimate for NuScale technology.

In January 2023, NuScale announced a massive increase in its cost estimates for its proposed SMR plant in the US state of Idaho. According to NuScale, the new estimate was "influenced by external factors such as inflationary pressures and increases in the price of steel, electrical equipment and other construction commodities not seen for more than 40 years."[62] The latest US$89 / MWh estimate is 53% higher than the previous estimate of US$58 / MWh – an "eye-popping" increase according to the Institute for Energy Economics and Financial Analysis.[63] The 53% increase in costs-per-MWH reflects a 75% increase in the estimated construction cost, from US$5.3 billion to US$9.3 billion (A$13.3 billion) for a 462 MW plant with six reactors.[64] That equates to US$20.1 billion (A$28.8 billion) per GW – far more expensive than the wildly over-budget Vogtle project (US$34 billion / 2.2 GW = US$15.5 billion / GW). It should also be considered that pre-construction cost estimates for other SMR projects have dramatically underestimated true costs – e.g. the doubling of cost estimates for China's HTGR, and a six-fold cost increase for Russia's floating plant – and the same should be expected with NuScale.

Twenty-six UAMPS municipalities remain involved in the plan to finance the first NuScale SMR in Idaho (down from the original 30 municipalities).[65] UAMPS is a Utah-based group of 50 municipal utilities in six states. Despite their ongoing involvement, NuScale Power still requires considerable additional support to proceed. UAMPS municipalities have agreed to purchase just one-quarter of the plant's expected power generation (in capacity terms, 116 MW of a total of 462 MW).[66] "We're going to have to see measured improvement off the current subscription to keep moving forward with the project," UAMPS Chief Executive Mason Baker said in November 2022.[67] Another UAMPS spokesperson said the entire 462 MW of capacity must be fully subscribed for the project to go forward.[68]

The Institute for Energy Economics and Financial Analysis notes that NuScale's cost estimates would be "much higher" if not for government subsidies.[69] The *Portland Business Journal* noted in January 2023: "The U.S. Department of Energy has approved $1.4 billion to support the project, and the recently

[58] For further information on NuScale see:
Institute for Energy Economics and Financial Analysis, Feb. 2022, 'NuScale's Small Modular Reactor: Risks of Rising Costs, Likely Delays, and Increasing Competition Cast Doubt on Long-Running Development Effort'. Too late, too expensive, too risky and too uncertain. http://ieefa.org/wp-content/uploads/2022/02/NuScales-Small-Modular-Reactor_February-2022.pdf
M.V. Ramana, 2020, 'Eyes Wide Shut: Problems with the Utah Associated Municipal Power Systems Proposal to Construct NuScale Small Modular Nuclear Reactors'. https://d3n8a8pro7vhmx.cloudfront.net/oregonpsrorg/pages/21/attachments/original/1600287829/EyesWideShutReport_Final-30August2020.pdf
[59] https://d3n8a8pro7vhmx.cloudfront.net/oregonpsrorg/pages/21/attachments/original/1600287829/EyesWideShutReport_Final-30August2020.pdf
[60] http://nuclearrc.sa.gov.au/app/uploads/2016/05/WSP-Parsons-Brinckerhoff-Report.pdf
[61] https://www.parliament.vic.gov.au/images/stories/committees/SCEP/Inquiry_into_Nuclear_Prohibition_Inquiry_/Transcripts/25_June_2020/5._FINAL_-_Minerals_Council_Aust.pdf
[62] https://www.nuscalepower.com/en/news/press-releases/2023/nuscale-reaches-key-milestone-in-the-development-of-the-carbon-free-power-project
[63] https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor
[64] https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor
[65] https://www.bizjournals.com/portland/news/2023/01/09/nuscale-uamps-costs-surge.html
[66] https://www.eenews.net/articles/rising-costs-imperil-nations-leading-small-reactor-project/
[67] https://www.eenews.net/articles/rising-costs-imperil-nations-leading-small-reactor-project/
[68] https://www.eenews.net/articles/rising-costs-imperil-nations-leading-small-reactor-project/
[69] https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor

adopted Inflation Reduction Act allows for a production tax credit of $25 per megawatt-hour for 10 years or an investment tax credit of 30%."[70] Total committed subsidies are estimated at US$4 billion in a January 2023 *Seeking Alpha* article.[71]

NuScale received licensing approvals in the US – in particular, a Final Safety Evaluation Report in September 2020 – but that approval referred to NuScale's planned 50 MW reactor modules and further approvals are required due to the company's decision to increase the module size to 77 MW.[72] NuScale has submitted an application for Standard Design Approval of the updated design, based on a 6 x 77 MW (462 MW) plant configuration. In preliminary correspondence, NRC staff raised concerns about the new design, saying it raised "several challenging and/or significant issues."[73] Physicist Dr. Edwin Lyman from the Union of Concerned Scientists said: "The NRC's assessment clearly shows that NuScale's standard design approval draft application for the 77 MWe module is not ready for prime time. Of most concern, there is no evidence that NuScale has done the hard work yet to fully evaluate the major safety impacts" of its uprated design.[74]

The 2015/16 South Australian Nuclear Fuel Cycle Royal Commission commissioned research[75] on the economic potential of two SMR designs: Generation mPower (abandoned in 2017[76]) and NuScale (which may be abandoned and is far from building let alone operating its first reactor).

4. Failed SMR projects

Numerous SMR projects have been cancelled over the past decade including the following:
- The French government abandoned the planned 100–200 MW ASTRID demonstration fast reactor in 2019.[77]
- Babcock & Wilcox abandoned its Generation mPower SMR project in the US despite receiving government funding of US$111 million (A$160 million).[78]
- Transatomic Power gave up on its molten salt reactor R&D in 2018.[79]
- MidAmerican Energy gave up on its plans for SMRs in Iowa in 2013 after failing to secure legislation that would require ratepayers to partially fund construction costs.[80]
- TerraPower abandoned its plan for a prototype fast neutron reactor in China due to restrictions placed on nuclear trade with China by the Trump administration.[81]
- The US government abandoned consideration of 'integral fast reactors' for plutonium disposition in 2015[82]
- The UK government abandoned consideration of 'integral fast reactors' for plutonium disposition in 2019.[83]

[70] https://www.bizjournals.com/portland/news/2023/01/09/nuscale-uamps-costs-surge.html
[71] https://seekingalpha.com/article/4569771-nuscale-smr-technology-costs-problematic
[72] https://www.world-nuclear-news.org/Articles/Further-cost-refinements-announced-for-first-US-SM
See also https://www.reuters.com/business/energy/western-us-cities-vote-move-ahead-with-novel-nuclear-power-plant-2023-02-28/
[73] https://www.eenews.net/articles/rising-costs-imperil-nations-leading-small-reactor-project/
https://www.utilitydive.com/news/nrc-nuscale-smr-small-modular-application-utah-uamps/637456/
[74] https://www.utilitydive.com/news/nrc-nuscale-smr-small-modular-application-utah-uamps/637456/
[75] http://nuclearrc.sa.gov.au/app/uploads/2016/05/WSP-Parsons-Brinckerhoff-Report.pdf
[76] https://wiseinternational.org/nuclear-monitor/872-873/mpower-obituary
[77] https://www.reuters.com/article/us-france-nuclearpower-astrid/france-drops-plans-to-build-sodium-cooled-nuclear-reactor-idUSKCN1VK0MC
[78] https://wiseinternational.org/nuclear-monitor/872-873/mpower-obituary
[79] https://wiseinternational.org/nuclear-monitor/867/nuclear-news-nuclear-monitor-867-15-october-2018
[80] https://pauldeaton.com/2013/06/04/iowa-pulls-the-plug-on-nuclear-power/
[81] https://www.reuters.com/article/us-terrapower-china/bill-gates-nuclear-venture-hits-snag-amid-us-restrictions-on-china-deals-wsj-idUSKCN1OV1S5
[82] https://nuclear.foe.org.au/wp-content/uploads/2019-Federal-Nuclear-Inquiry-Joint-ENGO-Submission-Final.pdf
[83] Appendix 3, https://nuclear.foe.org.au/wp-content/uploads/2019-Federal-Nuclear-Inquiry-Joint-ENGO-Submission-Final.pdf

5. Nuclear waste generated by small modular reactors and Generation IV reactors

Small modular reactors

Claims that small modular reactors (SMRs) based on conventional light-water reactor technology are advantageous with respect to nuclear waste have no logical or evidentiary basis.

A *Nuclear Technology* journal article notes that integral pressurised water SMRs (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."[84] Thus radioactive waste streams across the nuclear fuel cycle – from uranium mining t enrichment to spent nuclear fuel – would be greater than large reactors per unit of electricity produced.

A study published in the *Proceedings of the National Academy of Sciences* in 2022 concludes that SMRs will produce more voluminous and chemically/physically reactive waste than conventional large reactors due to the use of neutron reflectors and/or of chemically reactive fuels and coolants in SMR designs.[85] The study finds that water, molten salt, and sodium cooled SMR designs will significantly increase the volume of nuclear waste.

The South Australian Nuclear Fuel Cycle Royal Commission said in its Final Report in 2016 that "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."[86]

A 2017 article by Princeton University researchers concludes: "Of the different major SMR designs under development, it seems none meets simultaneously the key challenges of costs, safety, waste, and proliferation facing nuclear power today and constraining its future growth. In most, if not all designs, it is likely that addressing one or more of these four problems will involve choices that make one or more of the other problems worse."[87]

One of the authors of the above-mentioned article, M.V. Ramana, notes in a different article that "a smaller reactor, at least the water-cooled reactors that are most likely to be built earliest, will produce more, not less, nuclear waste per unit of electricity they generate because of lower efficiencies."[88]

A 2016 European Commission document states:[89]
"At the current stage of development it cannot be assessed whether the decommissioning and waste management costs of SMRs will significantly differ from those of larger reactors. 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)."

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[84] https://www.tandfonline.com/doi/abs/10.13182/NT13-A19873
[85] https://www.pnas.org/doi/10.1073/pnas.2111833119
[86] https://nuclear.foe.org.au/wp-content/uploads/NFCRC_Final_Report_Web_5MB.pdf
[87] M.V. Ramana and Zia Mian, Jan 2017, 'Small Modular Reactors and the Challenges of Nuclear Power', https://www.aps.org/units/fps/newsletters/201701/reactors.cfm
[88] M.V. Ramana, 23 June 2018, 'The future of nuclear power in the US is bleak', http://thehill.com/opinion/energy-environment/393717-the-future-of-nuclear-power-in-the-us-is-bleak
[89] 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 for, the opinion of the European Economic and Social Committee', https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_autre_document_travail_service_part1_v10.pdf

Generation IV concepts and nuclear waste

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.[90] 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."

Krall and Macfarlane further state:

> *"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. ...*
>
> *"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.*

[90] 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

"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."

Pyroprocessing: the integral fast reactor waste fiasco

In theory, integral fast reactors (IFRs) would consume nuclear waste and convert it into low-carbon electricity. In practice, the EBR-II (IFR) R&D program in Idaho has left a legacy of troublesome waste. This saga is detailed in a 2017 article[91] and a longer report[92] by the Union of Concerned Scientists' senior scientist Dr. Edwin Lyman, drawing on documents obtained under Freedom of Information legislation.

Lyman writes:[93]

"[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. …

"The FOIA 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 …

"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."

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[91] Ed Lyman / Union of Concerned Scientists, 12 Aug 2017, 'The Pyroprocessing Files', http://allthingsnuclear.org/elyman/the-pyroprocessing-files

[92] 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

[93] Ed Lyman / Union of Concerned Scientists, 12 Aug 2017, 'The Pyroprocessing Files', http://allthingsnuclear.org/elyman/the-pyroprocessing-files

6. Diseconomies of scale and independent economic assessments of SMRs

Power produced by SMRs will be more expensive than large reactors.[94] SMRs will inevitably suffer diseconomies of scale: a 250 MW SMR will generate 25% as much power as a 1,000 MW reactor, but it will require more than 25% of the material inputs and staffing, and other costs including waste management and decommissioning will be proportionally higher. It is highly unlikely that potential savings arising from standardised factory production will make up for those diseconomies of scale.

Cost *reductions* arising from mass production of SMRs are entirely speculative. Cost *increases* arising from diseconomies of scale are certain – they are built into the very concept of SMRs.

Every independent economic assessment finds that electricity from SMRs will be more expensive than that from large reactors.[95]

As noted previously, A study by WSP / Parsons Brinckerhoff, commissioned by the South Australian Nuclear Fuel Cycle Royal Commission, estimated costs of A$180–184 / MWh for large pressurised water reactors and boiling water reactors, and A$225 / MWh for SMRs based on the NuScale design (and a slightly lower figure for the mPower design that was abandoned in 2017).[96]

The South Australian Nuclear Fuel Cycle Royal Commission stated in its 2016 report:[97]

> *"Advanced fast reactors and other innovative reactor designs are unlikely to be feasible or viable in the foreseeable future. The development of such a first-of-a-kind project in South Australia would have high commercial and technical risk. Although prototype and demonstration reactors are operating, there is no licensed, commercially proven design. Development to that point would require substantial capital investment."*

A 2015 report by the International Energy Agency and the OECD Nuclear Energy Agency predicts that electricity costs from SMRs will typically be 50−100% higher than for current large reactors.[98]

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 (assuming one is ever built) would be 30% more expensive than power from large reactors, because of diseconomies of scale and the costs of deploying first-of-a-kind technology.[99]

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*, considered options for the development of an SMR market in the US. They concluded that it would not be viable unless the industry received "several hundred billion dollars of direct and indirect subsidies"

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[94] https://wiseinternational.org/nuclear-monitor/872-873/smr-economics-overview
[95] https://wiseinternational.org/nuclear-monitor/872-873/smr-economics-overview
[96] http://nuclearrc.sa.gov.au/app/uploads/2016/05/WSP-Parsons-Brinckerhoff-Report.pdf
[97] https://nuclear.foe.org.au/wp-content/uploads/NFCRC_Final_Report_Web_5MB.pdf
[98] https://www.oecd-nea.org/jcms/pl_14756
[99] 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

over the next several decades "since present competitive energy markets will not induce their development and adoption."[100]

A 2014 study published in *Energy and Power Engineering* concluded that fuel costs for integral pressurized water SMRs are estimated to be 15% to 70% higher than for large light water reactors, and points to research indicating similar comparisons for construction costs.[101]

The Institute for Energy Economics and Financial Analysis states:[102]

> *"For all the hype in certain quarters, commercial deployment of small modular reactors (SMRs) have to-date been as successful as hypothesized cold fusion – that is, not at all. Even assuming massive ongoing taxpayer subsidies, SMR proponents do not expect to make a commercial deployment at scale any time soon, if at all, and more likely in a decade from now if historic delays to proposed timetables are acknowledged."*

A 2018 US Department of Energy 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. But there's no indication or likelihood that the US government will subsidise the industry to that extent.[103]

William Von Hoene, senior vice-president at US energy and nuclear giant Exelon, has expressed scepticism about SMRs, saying they are "prohibitively expensive".[104]

A 2018 article in the Proceedings of the National Academy of Science summarised private-sector investment in SMRs and other 'advanced' nuclear concepts:[105]

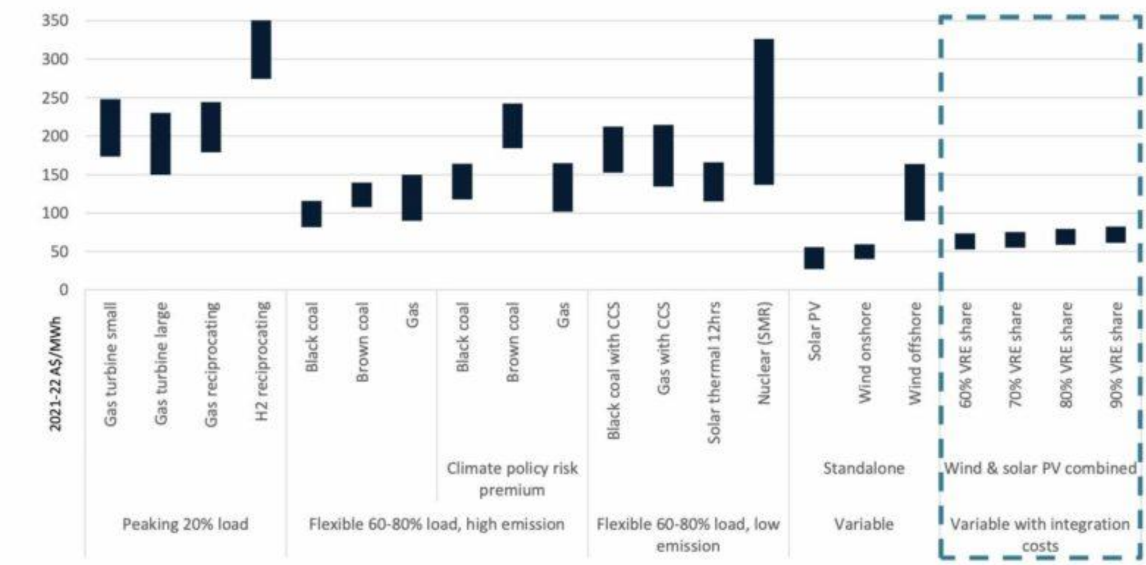
> *"Often, proponents of nuclear power note that private enterprise is faring better than the government at advancing non-light water reactor concepts. Indeed, more than $1.3 billion has been secured by close to four dozen such companies. However, a dozen of these are working not on advanced fission 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."*

[100] https://www.pnas.org/content/115/28/7184
[101] https://www.scirp.org/journal/PaperInformation.aspx?PaperID=45669
[102] https://www.aph.gov.au/DocumentStore.ashx?id=8297e6ba-e3d4-478e-ac62-a97d75660248&subId=669740
[103] https://www.energy.gov/ne/downloads/report-examination-federal-financial-assistance-renewable-energy-market
[104] 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
[105] https://www.pnas.org/content/115/28/7184

7. CSIRO / Australian Energy Market Operator SMR economic studies

In its July 2022 *GenCost* report, CSIRO provides these 2030 cost estimates for Australia:[106]
* Nuclear (small modular): A$136-326 / MWh
* 90% wind and solar PV with integration costs (transmission, storage and synchronous condensers) necessary to allow these variable renewables to provide 90% of electricity in the National Electricity Market: A$61-82 / MWh.

Nuclear power from SMRs is estimated to cost at least twice as much – and up to five times as much – as "firmed" wind and solar PV including storage and transmission costs.[107]



ES Figure 0-1 Calculated LCOE by technology and category for 2030

Source: GenCost 2022.

Some nuclear advocates have questioned the 2030 SMR cost estimate of A$136-326 / MWh. The upper figure is based on widely-available figures on the cost of power from large reactors, adjusted upwards to reflect the acknowledgement from the International Energy Agency and the OECD's Nuclear Energy Agency that SMR power costs could be up to 100% more expensive than power from large reactors.[108] Only two operational SMRs exist and cost-per-MWh data is only available for one of these: the OECD Nuclear Energy Agency's estimate of US$200 (A$288) / MWh for the Russian SMR.[109]

The low SMR estimate of A$136 / MWh is based on heroic and implausible assumptions about SMR learning rates and cost reductions, yet it is still far more expensive than firmed renewables.[110] Lower SMR cost estimates are based on an even greater degree of wishful thinking. For example, a Minerals Council of Australia report asserts that "robust estimates" using "conservative assumptions" suggest

[106] https://www.csiro.au/-/media/News-releases/2022/GenCost-2022/GenCost2021-22Final_20220708.pdf
[107] For discussion see: https://reneweconomy.com.au/slow-expensive-and-no-good-for-1-5-target-csiro-crushes-coalition-nuclear-fantasy/
[108] See pp.14-15 in the GenCost report.
[109] https://www.oecd-nea.org/jcms/pl_14924
[110] For discussion see: https://reneweconomy.com.au/small-modular-reactor-rhetoric-hits-a-hurdle-62196/

that SMRs will produce power at a cost of A$64-77 / MWh by 2030.[111] In fact, the estimate is not based on "robust estimates" using "conservative assumptions", but is based more on wishful thinking from those seeking taxpayer subsidies to develop SMRs.[112] The A$64-77 / MWh figure is three times lower than the Lazard estimate for power from conventional, large reactors (A$193–300 / MWh) despite the inevitable diseconomies of scale for SMRs. The A$64-77 / MWh figure is far lower than the only real-world figure available for SMRs (A$288 / MWh for the Russian SMR). In short, the Minerals Council's estimate is deeply implausible and the Council's claim that it is based on "robust estimates" using "conservative assumptions" is demonstrably false.

The Minerals Council of Australia said in 2020 that SMRs won't find a market unless they can produce power at a cost of A$60–80 / MWh.[113] The likelihood of SMRs producing power in that cost range in the foreseeable future is negligible.

8. Funding for state-run SMR programs

Funding for state-run SMR programs – such as those in Argentina, China, Russia, and South Korea – has been minuscule compared to investments in other energy programs.

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[114]). South Korea's plan to export SMART technology to Saudi Arabia is problematic[115] and may in any case be in trouble.[116]

China and Argentina hope to develop a large export market for their high-temperature gas-cooled reactors and small pressurised water reactors, but so far all they can point to are demonstration reactors (the completed HTGR in China and the incomplete SMR in Argentina) that have been subject to major cost overruns and delays.

Russia planned to have seven floating nuclear power plants by 2015, but only recently began operation of its first plant.

9. Creative accounting

As noted above (section 3.7), the Minerals Council of Australia's estimate that SMRs will produce power at a cost of A$64-77 / MWh by 2030 is implausible as is the Council's claim that the estimate is based on "robust estimates" using "conservative assumptions".

The Energy Information Reform Project (EIRP) purports to have conducted a 'standardized cost analysis of advanced nuclear technologies in commercial development'.[117] But the EIRP doesn't have any credible cost data or estimates for the 'advanced nuclear technologies' it considers (none of which are in commercial development). Indeed, the EIRP just uses estimates provided by companies involved in

[111] https://www.minerals.org.au/sites/default/files/Small%20Modular%20Reactors%20in%20the%20Australian%20Context%202021.pdf

[112] For discussion see: https://reneweconomy.com.au/small-nuclear-reactors-huge-costs/ and https://reneweconomy.com.au/small-modular-reactor-rhetoric-hits-a-hurdle-62196/

[113] https://www.parliament.vic.gov.au/images/stories/committees/SCEP/Inquiry_into_Nuclear_Prohibition_Inquiry_/Transcripts/25_June_2020/5._FINAL_-_Minerals_Council_Aust.pdf

[114] https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx

[115] https://www.wiseinternational.org/nuclear-monitor/800/small-modular-reactors-chicken-and-egg-situation

[116] http://www.businesskorea.co.kr/news/articleView.html?idxno=26628

[117] https://www.innovationreform.org/wp-content/uploads/2018/01/Advanced-Nuclear-Reactors-Cost-Study.pdf

R&D, despite their obvious interest in providing low estimates. The EIRP researchers heavily qualified their 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."

In support of its claim that "it is likely that SMRs will be Australia's lowest-cost generation source", SMR Nuclear Technology Pty Ltd cites[118] the EIRP report. SMR Nuclear Technology's claim is no more credible than the company estimates used in the EIRP paper. Based on that faulty premise, SMR Nuclear Technology further claims that failing to repeal federal legislative bans against nuclear power would come at "great cost to the economy". However, the introduction of nuclear power to Australia would most likely have resulted in the major cost overruns and delays that have crippled every reactor construction project in the US and western Europe over the past decade.

The Minerals Council of Australia claimed in its submission to the federal nuclear inquiry that SMRs could generate electricity for as little as $60 / MWh.[119] That claim was based on a report by the Economic and Finance Working Group (EFWG) of the Canadian government-industry 'SMR Roadmap' initiative.[120] Yet the EFWG paper takes a made-up, ridiculously-high learning rate and subjects SMR cost estimates to eight 'cumulative doublings' based on the learning rate. That is creative accounting and one can only wonder why the Minerals Council would present it as a credible estimate.

Here are the first-of-a-kind SMR cost estimates from the EFWG paper, all of them far higher than the figure cited by the Minerals Council:

300-megawatt (MW) on-grid SMR:	C$162.67 / MWh (A$175 / MWh)
125-MW off-grid heavy industry:	C$178.01 / MWh
20-MW off-grid remote mining:	C$344.62 / MWh
3-MW off-grid remote community:	C$894.05 / MWh (A$960/MWh)

The EFWG paper used a range of estimates from the literature and vendors. It notes problems with its inputs, such as the fact that many of the vendor estimates have not been independently vetted, and "the wide variation in costs provided by expert analysts". Thus, the EFWG qualifies its findings by noting that "actual costs could be higher or lower depending on a number of eventualities".

The 'Bright New World' nuclear lobby group (disbanded in 2021) promoted a 2016 study in support of its claims about nuclear construction costs, but the study was widely criticised for cherry-picking[121] including by a former World Nuclear Association executive.[122]

10. More information on SMRs

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

M.V. Ramana, 27 April 2015, 'The Forgotten History of Small Nuclear Reactors', IEEE Spectrum, https://spectrum.ieee.org/the-forgotten-history-of-small-nuclear-reactors

118 www.parliament.nsw.gov.au/lcdocs/submissions/63873/0004%20SMR%20Nuclear%20Technology%20Pty%20Ltd.pdf
119 https://www.afr.com/companies/energy/mining-industry-predicts-nuclear-will-be-cheapest-power-20190913-p52r29
120 https://smrroadmap.ca/wp-content/uploads/2018/12/Economics-Finance-WG.pdf
121 https://www.wiseinternational.org/nuclear-monitor/840/nuclear-economics-critical-responses-breakthrough-institute-propaganda
122 https://www.neimagazine.com/opinion/opinionachieving-better-nuclear-economics-new-designs-and-industry-structure-4848005/

WISE Nuclear Monitor 2019 report, https://wiseinternational.org/nuclear-monitor/872-873/nuclear-monitor-872-873-7-march-2019

Wrong reaction: Why 'next-generation' nuclear is not a credible energy solution, Australian Conservation Foundation, October 2022

Institute for Energy Economics and Financial Analysis, Feb. 2022, 'NuScale's Small Modular Reactor: Risks of Rising Costs, Likely Delays, and Increasing Competition Cast Doubt on Long-Running Development Effort'. Too late, too expensive, too risky and too uncertain. http://ieefa.org/wp-content/uploads/2022/02/NuScales-Small-Modular-Reactor_February-2022.pdf

M.V. Ramana, 2020, 'Eyes Wide Shut: Problems with the Utah Associated Municipal Power Systems Proposal to Construct NuScale Small Modular Nuclear Reactors'. https://d3n8a8pro7vhmx.cloudfront.net/oregonpsrorg/pages/21/attachments/original/1600287829/EyesWideShutReport_Final-30August2020.pdf

'The 'advanced' nuclear power sector is fuelling climate change, and WMD proliferation', 11 Sept 2019, https://reneweconomy.com.au/the-advanced-nuclear-power-sector-is-fuelling-climate-change-and-wmds-40205/

'Nuclear power exits Australia's energy debate, enters culture wars', 13 June 2019, https://reneweconomy.com.au/nuclear-power-exits-australias-energy-debate-enters-culture-wars-47702/

11. 'Advanced' or 'Generation IV' reactor concepts

Please also see relevant appendices in the joint NGO submission to the 2019 federal nuclear inquiry:[123]
Appendix 2: Fast neutron reactors (a.k.a. fast spectrum or fast breeder reactors)
Appendix 3: Integral fast reactors (IFRs)
Appendix 4: Fusion scientist debunks fusion power
Appendix 5: Thorium
Appendix 6: High-temperature gas-cooled zombie reactors

Overview

Conventional (or 'light water') reactors are fueled by uranium and cooled by ordinary ('light') water, which also slows (or 'moderates') the neutrons that maintain the nuclear chain reaction. 'Advanced' nuclear power generally refers to reactors – large or small – with different fuels, moderators and coolants.

'Advanced' or 'Generation IV' nuclear power concepts are generally not new and not promising, and most might best be described as failed Generation I concepts.

So-called Generation IV reactor concepts are diverse. Some are far from new – indeed most have been investigated for decades and have a troubled history. David Elliott – who previously worked with the

[123] https://www.aph.gov.au/DocumentStore.ashx?id=9eee9d5f-4362-4b30-b0b8-3b65ff98215f&subId=670271

UK Atomic Energy Authority – has written a book about this troubled history.[124] In an article[125] discussing some themes taken up in his book, Elliot writes:

> *"While some nuclear enthusiasts hope that these Generation III reactors, like the EPR or its rivals, will be successful, there is also pressure to move on to new technology and so-called Generation IV options, including liquid sodium-cooled fast neutron breeder reactors, helium-cooled high temperature reactors and thorium-fuelled molten salt reactors, at various scales. As I describe in my new book Nuclear Power: Past, Present and Future, many of them are in fact old ideas that were looked at in the early days and mostly abandoned. There were certainly problems with some of these early experimental reactors, some of them quite dramatic.*
>
> *"Examples include the fire at the Simi Valley Sodium Reactor in 1959, and the explosion at the 3MW experimental SL-1 reactor at the US National Reactor Testing Site in Idaho in 1961, which killed three operators. Better known perhaps was and the core melt down of the Fermi Breeder reactor near Detroit in 1966. Sodium fires have been a major problem with many of the subsequent fast neutron reactor projects around the world, for example in France, Japan and Russia.*
>
> *"For good or ill, ideas like this are back on the agenda, albeit in revised forms. … Fast neutron breeder reactors can produce new plutonium fuel from otherwise unused uranium-238 and may also be able to burn up some wastes, as in the Integral Fast Reactor concept and also the Traveling Wave Reactor variant. Molten Salt Reactors using thorium may be able to do this without producing plutonium or using liquid metals for cooling. Both approaches are being promoted, but both have problems, as was found in the early days. Certainly fast breeder reactors were subsequently mostly sidelined as expensive and unreliable. And as heightening nuclear weapons proliferation risks. The US gave up on them in the 1970s, France and the UK in the 1990s. Japan soldiered on but has now abandoned its troubled Monju plant. For the moment it's mainly Russia that has continued, including with a molten lead cooled reactor, although India also has a fast reactor programme, linked to its thorium reactors plans.*
>
> *"Thorium was used as a fuel for some reactors in some early experiments and is now being promoted again – there is more of it available globally than uranium. But there are problems. It isn't fissile, but neutrons, fast or slow, provided by uranium 235 or plutonium fission, can convert Thorium 232 into fissile U233. However, on the way to that, a very radioactive isotope, U232, is produced, which makes working with the fuel hard. Another isotope, U234 is also produced by neutron absorption. Ideally, to maximise U233 production, that should be avoided, but experts are apparently divided on whether this can be done effectively.*
>
> *"The use of molten salts may help with some of these problems, perhaps making it easier to play with the nuclear chemistry and tap off unwanted by-products, but it is far from proven technically or economically. The economics is certainly challenging."*

In the US, even if all the private-sector Generation IV R&D funding (an estimated US$1.3 billion[126]) was pooled, it is unlikely that it would suffice to build a single prototype reactor. An article by pro-nuclear

[124] David Elliott, May 2017, 'Nuclear Power: Past, Present and Future', Morgan & Claypool Publishers, http://bit.ly/2pIIX9Q
[125] David Elliott, 25 May 2017, 'Back to the future: old nukes for new', Nuclear Monitor #844, https://www.wiseinternational.org/nuclear-monitor/844/back-future-old-nukes-new

researchers from Carnegie Mellon University's Department of Engineering and Public Policy, published in the *Proceedings of the National Academy of Science* in 2018, argues that no US advanced reactor design will be commercialised before mid-century and that purported benefits remain "speculative".[127]

The US government has spent US$2 billion on Generation IV reactor R&D since the late 1990s "with very little to show for it" according to the Carnegie Mellon University researchers.[128]

The South Australian Nuclear Fuel Cycle Royal Commission investigated claims made about Generation IV concepts and concluded in its May 2016 Final Report:[129]

> *"[A]dvanced fast reactors and other innovative reactor designs are unlikely to be feasible or viable in the foreseeable future. The development of such a first-of-a-kind project in South Australia would have high commercial and technical risk. Although prototype and demonstration reactors are operating, there is no licensed, commercially proven design. Development to that point would require substantial capital investment. Moreover, electricity generated from such reactors has not been demonstrated to be cost competitive with current light water reactor designs."*

Little has changed since then – except the collapse of numerous Generation IV and SMR R&D projects.

Always decades away

Notwithstanding the history of (mostly failed) R&D projects, much work would need to be done to bring Generation IV concepts to commercial deployment. The World Nuclear Association noted in 2009 that "progress is seen as slow, and several potential designs have been undergoing evaluation on paper for many years."[130] The same could be said in 2022.

The Generation IV International Forum states: "It will take at least two or three decades before the deployment of commercial Gen IV systems. In the meantime, a number of prototypes will need to be built and operated. The Gen IV concepts currently under investigation are not all on the same timeline and some might not even reach the stage of commercial exploitation."[131] It could be argued that most or all of them are unlikely to reach commercial-scale deployment.

It should not be understood from the above statement that Generation IV systems will be commercialised in 2–3 decades. The point is that they are *always* 2–3 decades away. In general, R&D has not been promising and has been abandoned (either in the early stages or following the failure of prototype reactors). R&D budgets are far too small to commercialise the concepts and the pursuit of alternative energy sources has rightly been prioritised.

A 2015 report[132] by the French government's Institute for Radiological Protection and Nuclear Safety (IRSN) is of particular significance as it comes from a government which has invested heavily in nuclear

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[126] 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, http://www.pnas.org/content/early/2018/06/26/1804655115

[127] ibid.

[128] 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, http://www.pnas.org/content/early/2018/06/26/1804655115
Media release, 2 July 2018, 'The vanishing nuclear industry', www.eurekalert.org/pub_releases/2018-07/coec-tvn062918.php

[129] https://nuclear.foe.org.au/wp-content/uploads/NFCRC_Final_Report_Web_5MB.pdf

[130] World Nuclear Association, 15 Dec 2009, 'Fast moves? Not exactly...', www.world-nuclear-news.org/NN_France_puts_into_future_nuclear_1512091.html

[131] www.gen-4.org/gif/jcms/c_41890/faq-2

[132] Institute for Radiological Protection and Nuclear Safety, 2015, 'Review of Generation IV Nuclear Energy Systems', www.irsn.fr/EN/newsroom/News/Pages/20150427_Generation-IV-nuclear-energy-systems-safety-potential-overview.aspx
Direct download: www.irsn.fr/EN/newsroom/News/Documents/IRSN_Report-GenIV_04-2015.pdf

technology. IRSN is a government authority with approximately 1,790 staff under the joint authority of the Ministries of Defense, the Environment, Industry, Research, and Health. The IRSN report states: *"There is still much R&D to be done to develop the Generation IV nuclear reactors, as well as for the fuel cycle and the associated waste management which depends on the system chosen."*[133] *The report says that for lead-cooled fast reactors and gas-cooled fast reactors systems, small prototypes might be built by mid-century. For molten salt reactors (MSR) and SuperCritical Water Reactors (SCWR) systems, there "is no likelihood of even an experimental or prototype MSR or SCWR being built during the first half of this century" and "it seems hard to imagine any reactor being built before the end of the century".*

Purported benefits

It is doubtful whether the purported benefits of Generation IV reactors will be realised.

Physicist Dr. Edwin Lyman has written an important report for the Union of Concerned Scientists debunking claims that 'advanced' nuclear power concepts offer significant advantages over conventional nuclear power. The report considers sodium-cooled fast reactors, high-temperature gas–cooled reactors, and molten salt reactors.

Dr. Lyman writes:[134]

> *"Based on the available evidence, we found that the designs we analyzed are not likely to be significantly safer than today's nuclear plants. In fact, certain alternative reactor designs pose even more safety, proliferation, and environmental risks than the current fleet. Developing new designs that are clearly superior to LWRs [light water reactors] overall is a formidable challenge, as improvements in one respect can create or exacerbate problems in others. For example, increasing the physical size of a reactor core while keeping its power generation rate constant could make the reactor easier to cool in an accident, but it could also increase cost."*

The French government's Institute for Radiological Protection and Nuclear Safety (IRSN) reviewed the six concepts prioritised by the Generation IV International Forum and concluded:[135]

> *"At the present stage of development, IRSN does not notice evidence that leads to conclude that the systems under review are likely to offer a significantly improved level of safety compared with Generation III reactors, except perhaps for the VHTR [Very High Temperature Reactor] ..."*

The IRSN further states that the VHTR system could bring about significant safety improvements "but only by significantly limiting unit power".[136] The IRSN notes that it is difficult to thoroughly evaluate safety and radiation protection standards of Generation IV systems as some concepts have been partially tried and tested while others are still in the early stages of development.

The IRSN is unenthusiastic about research into transmutation of minor actinides (long-lived waste products in spent fuel), saying that "this option offers only a very slight advantage in terms of inventory reduction and geological waste repository volume when set against the induced safety and radiation protection constraints for fuel cycle facilities, reactors and transport." The IRSN notes that ASN, the French nuclear safety authority, has announced that minor actinide transmutation would not be a deciding factor in the choice of a future reactor system. Those factors partly explain the French

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[133] ibid.
[134] https://ucsusa.org/resources/advanced-isnt-always-better
[135] ibid.
[136] ibid.

government's recent decision to abandon the 100–200 MW ASTRID demonstration fast neutron reactor project.

Some Generation IV concepts promise major advantages such as the potential to use long-lived nuclear waste and weapons-usable material (esp. plutonium) as reactor fuel. However, fast neutron reactor technology might more accurately be described as failed Generation I technology. The history of fast reactors has largely been one of extremely expensive, underperforming, and accident-prone reactors which have contributed more to WMD proliferation problems than to their resolution. The troubled history of fast reactors is detailed in a report by the International Panel on Fissile Materials[137] and in two appendices to the joint NGO submission to the 2019 federal nuclear inquiry (Appendix 2. Fast Neutron Reactors; Appendix 3. Integral Fast Reactors).[138] Most of the countries that invested in fast reactor R&D have abandoned those efforts.

Most importantly, whether Generation IV concepts deliver on their potential depends on a myriad of factors − not just the resolution of technical challenges. India's fast reactor / thorium program illustrates how badly things can go wrong, and it illustrates problems that cannot be solved with technical innovation. John Carlson, former Director-General of the Australian Safeguards and Non-proliferation Office, writes:[139]

> *"India has a plan to produce [weapons-grade] plutonium in fast breeder reactors for use as driver fuel in thorium reactors. This is problematic on non-proliferation and nuclear security grounds. Pakistan believes the real purpose of the fast breeder program is to produce plutonium for weapons (so this plan raises tensions between the two countries); and transport and use of weapons-grade plutonium in civil reactors presents a serious terrorism risk (weapons-grade material would be a priority target for seizure by terrorists)."*

There is nothing 'advanced' about India's 'advanced' breeder / thorium reactor program. On the contrary, it is dangerous and irresponsible, even more so since India refuses to allow IAEA safeguards inspections of its fast reactor / thorium program.

US Government Accountability Office Report

In 2015, the US Government Accountability Office (GAO) released a report on the status of small modular reactors (SMRs) and other new reactor concepts in the US that concluded:[140]

> *"While light water SMRs and advanced reactors may provide some benefits, their development and deployment face a number of challenges. Both SMRs and advanced reactors require additional technical and engineering work to demonstrate reactor safety and economics, although light water SMRs generally face fewer technical challenges than advanced reactors because of their similarities to the existing large LWR [light water] reactors. Depending on how they are resolved, these technical challenges may result in*

[137] International Panel on Fissile Materials, Feb 2010, 'Fast Breeder Reactor Programs: History and Status', www.ipfmlibrary.org/rr08.pdf
On the use of fast reactors in support of weapons production, see also Mycle Schneider, 2009, 'Fast Breeder Reactors in France', *Science and Global Security*, 17:36–53, www.princeton.edu/sgs/publications/sgs/archive/17-1-Schneider-FBR-France.pdf

[138] https://www.aph.gov.au/DocumentStore.ashx?id=9eee9d5f-4362-4b30-b0b8-3b65ff98215f&subId=670271

[139] John Carlson, 2014, first submission to Joint Standing Committee on Treaties, inquiry into Australia–India Nuclear Cooperation Agreement, Parliament of Australia, https://www.aph.gov.au/DocumentStore.ashx?id=79a1a29e-5691-4299-8923-06e633780d4b&subId=301365
See also: John Carlson, 2015, supplementary submission to Joint Standing Committee on Treaties, 'Suggested revisions to the text of 5 September 2014, as requested by JSCOT at the hearing of 9 February 2015', https://www.aph.gov.au/DocumentStore.ashx?id=242f5715-24fd-4b3e-8a4f-4c30651d1dc4&subId=301365

[140] US Government Accountability Office, July 2015, 'Nuclear Reactors: Status and challenges in development and deployment of new commercial concepts', GAO-15-652, www.gao.gov/assets/680/671686.pdf

higher-cost reactors than anticipated, making them less competitive with large LWRs or power plants using other fuels. ...

"Both light water SMRs and advanced reactors face additional challenges related to the time, cost, and uncertainty associated with developing, certifying or licensing, and deploying new reactor technology, with advanced reactor designs generally facing greater challenges than light water SMR designs. It is a multi-decade process, with costs up to $1 billion to $2 billion, to design and certify or license the reactor design, and there is an additional construction cost of several billion dollars more per power plant.

"Furthermore, the licensing process can have uncertainties associated with it, particularly for advanced reactor designs. A reactor designer would need to obtain investors or otherwise commit to this development cost years in advance of when the reactor design would be certified or available for licensing and construction, making demand (and customers) for the reactor uncertain. For example, the price of competing power production facilities may make a nuclear plant unattractive without favorable rates set by a public authority or long term prior purchase agreements, and accidents such as Fukushima as well as the ongoing need for a long-term solution for spent nuclear fuel may affect the public perception of reactor safety. These challenges will need to be addressed if the capabilities and diversification of energy sources that light water SMRs and advanced reactors can provide are to be realized."

Many of the same reasons explain the failure of the Next Generation Nuclear Plant (NGNP) Project. Under the Energy Policy Act of 2005, the US Department of Energy (DOE) was to deploy a prototype 'next generation' reactor using advanced technology to generate electricity and/or hydrogen by the end of fiscal year 2021. The project was initiated in 2005 but the DOE decided not to proceed with it in 2011, citing an impasse between the DOE and the NGNP Industry Alliance regarding cost-sharing arrangements.[141]

According to the GAO report, SMRs and new reactor concepts "face some common challenges such as long time frames and high costs associated with the shift from development to deployment − that is, in the construction of the first commercial reactors of a particular type."

Advanced reactor designers told the GAO that they have been challenged to find investors due to the lengthy timeframe, high costs, and uncertainty. Advanced reactor concepts face greater technical challenges than light water SMRs because of fundamental design differences.

Generation IV concepts and nuclear weapons proliferation

Advocates of every conceivable type of reactor claim that their preferred reactor type is proliferation-proof or proliferation-resistant.

A thorium enthusiast claims that thorium is "thoroughly useless for making nuclear weapons."[142] But the proliferation risks associated with thorium fuel cycles can be as bad as the risks associated with conventional uranium reactor technology.[143]

[141] Nuclear Regulatory Commission, accessed 20 May 2019, 'Next Generation Nuclear Plant (NGNP)', https://www.nrc.gov/reactors/new-reactors/advanced/ngnp.html
[142] Tim Dean, 16 March 2011, 'The greener nuclear alternative', https://www.abc.net.au/news/2011-03-16/thoriumdean/45178
[143] 'Thor-bores and uro-sceptics: thorium's friendly fire', Nuclear Monitor #801, 9 April 2015, https://www.wiseinternational.org/nuclear-monitor/801/thor-bores-and-uro-sceptics-thoriums-friendly-fire

An enthusiast of integral fast reactors (IFR) claims they "cannot be used to generate weapons-grade material."[144] But IFRs *can* be used to produce plutonium for weapons – or at least they could be used to produce plutonium for weapons if they existed. Dr. George Stanford, who worked on an IFR R&D program in the US, notes that proliferators "could do [with IFRs] what they could do with any other reactor − operate it on a special cycle to produce good quality weapons material."[145]

Fusion has yet to generate a single Watt of useful electricity, but it has already contributed to proliferation problems. According to Khidhir Hamza, a senior nuclear scientist involved in Iraq's weapons program in the 1980s: "Iraq took full advantage of the IAEA's recommendation in the mid-1980s to start a plasma physics program for "peaceful" fusion research. We thought that buying a plasma focus device ... would provide an excellent cover for buying and learning about fast electronics technology, which could be used to trigger atomic bombs."[146]

Fusion scientist Dr. Daniel Jassby discusses the proliferation risks associated with fusion concepts in a 2017 article in the *Bulletin of the Atomic Scientists*.[147]

All existing and proposed reactor types and nuclear fuel cycles pose proliferation risks. 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."[148] Likewise, John Carlson, former Director-General of the Australian Safeguards and Non-Proliferation Office, notes that "no presently known nuclear fuel cycle is completely proliferation proof".[149]

Thorium

There is a great deal of rhetoric regarding thorium. This, for example:[150]

> *"Thorium is a superior nuclear fuel to uranium in almost every conceivable way ... If there is such a thing as green nuclear power, thorium is it. ... For one, a thorium-powered nuclear reactor can never undergo a meltdown. It just can't. ... Thorium is also thoroughly useless for making nuclear weapons. ... But wait, there's more. Thorium doesn't only produce less waste, it can be used to consume existing waste."*

Those claims do not stand up to scrutiny.

Readiness

The World Nuclear Association (WNA) notes that the commercialisation of thorium fuels faces some "significant hurdles in terms of building an economic case to undertake the necessary development work." The WNA states:[151]

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144 Barry Brook, 9 June 2009, 'An inconvenient solution', The Australian, http://bravenewclimate.com/2009/06/11/an-inconvenient-solution/
145 George Stanford, 18 Sep 2010, 'IFR FaD 7 – Q&A on Integral Fast Reactors', http://bravenewclimate.com/2010/09/18/ifr-fad-7/
146 Khidhir Hamza, Sep/Oct 1998, 'Inside Saddam's Secret Nuclear Program', Bulletin of the Atomic Scientists, Vol. 54, No. 5, https://books.google.com.au/books?id=rwsAAAAAMBAJ
147 Daniel Jassby, 19 April 2017, 'Fusion reactors: Not what they're cracked up to be', Bulletin of the Atomic Scientists, https://thebulletin.org/2017/04/fusion-reactors-not-what-theyre-cracked-up-to-be/
148 UK Royal Society, 13 Oct 2011, 'Fuel cycle stewardship in a nuclear renaissance', http://royalsociety.org/policy/projects/nuclear-non-proliferation/report
149 John Carlson, 2009, 'Introduction to the Concept of Proliferation Resistance', www.foe.org.au/sites/default/files/Carlson%20ASNO%20ICNND%20Prolif%20Resistance.doc or http://archive.foe.org.au/sites/default/files/Carlson%20ASNO%20ICNND%20Prolif%20Resistance.doc
150 Tim Dean, 16 March 2011, 'The greener nuclear alternative', https://www.abc.net.au/news/2011-03-16/thoriumdean/45178
151 www.world-nuclear.org/info/Current-and-Future-Generation/Thorium/

"A great deal of testing, analysis and licensing and qualification work is required before any thorium fuel can enter into service. This is expensive and will not eventuate without a clear business case and government support. Also, uranium is abundant and cheap and forms only a small part of the cost of nuclear electricity generation, so there are no real incentives for investment in a new fuel type that may save uranium resources.

"Other impediments to the development of thorium fuel cycle are the higher cost of fuel fabrication and the cost of reprocessing to provide the fissile plutonium driver material. The high cost of fuel fabrication (for solid fuel) is due partly to the high level of radioactivity that builds up in U-233 chemically separated from the irradiated thorium fuel. Separated U-233 is always contaminated with traces of U-232 which decays (with a 69-year half-life) to daughter nuclides such as thallium-208 that are high-energy gamma emitters. Although this confers proliferation resistance to the fuel cycle by making U-233 hard to handle and easy to detect, it results in increased costs. There are similar problems in recycling thorium itself due to highly radioactive Th-228 (an alpha emitter with two-year half life) present."

A 2012 report by the UK National Nuclear Laboratory states:[152]

"NNL has assessed the Technology Readiness Levels (TRLs) of the thorium fuel cycle. For all of the system options more work is needed at the fundamental level to establish the basic knowledge and understanding. Thorium reprocessing and waste management are poorly understood. The thorium fuel cycle cannot be considered to be mature in any area."

Fiona Rayment from the UK National Nuclear Laboratory stated:[153]

"It is conceivable that thorium could be introduced in current generation reactors within about 15 years, if there was a clear economic benefit to utilities. This would be a once-through fuel cycle that would partly realise the strategic benefits of thorium.

"To obtain the full strategic benefit of the thorium fuel cycle would require recycle, for which the technological development timescale is longer, probably 25 to 30 years.

"To develop radical new reactor designs, specifically designed around thorium, would take at least 30 years. It will therefore be some time before the thorium fuel cycle can realistically be expected to make a significant contribution to emissions reductions targets."

Kirk Sorensen, founder of a US firm which aims to build a demonstration 'liquid fluoride thorium reactor' (a type of molten salt reactor − MSR), notes that "several technical hurdles" confront thorium-fueled MSRs, including materials corrosion, reactor control and in-line processing of the fuel.[154]

Nuclear physicist Prof. George Dracoulis writes:[155]

"MSRs are not currently available at an industrial scale, but test reactors with different configurations have operated for extended periods in the past. But there are a number of technical challenges that have been encountered along the way. One such challenge is that the hot beryllium and lithium "salts" – in which the fuel and heavy wastes are dissolved – are highly reactive and corrosive. Building a large-scale system that can operate reliably for

[152] UK National Nuclear Laboratory Ltd., 5 March 2012, 'Comparison of thorium and uranium fuel cycles', www.decc.gov.uk/assets/decc/11/meeting-energy-demand/nuclear/6300-comparison-fuel-cycles.pdf

[153] Stephen Harris, 9 Jan 2014, 'Your questions answered: thorium-powered nuclear', www.theengineer.co.uk/energy-and-environment/in-depth/your-questions-answered-thorium-powered-nuclear/1017776.article

[154] Stephen Harris, 9 Jan 2014, 'Your questions answered: thorium-powered nuclear', www.theengineer.co.uk/energy-and-environment/in-depth/your-questions-answered-thorium-powered-nuclear/1017776.article

[155] George Dracoulis, 19 Dec 2011, 'Thoughts from a thorium 'symposium'', http://theconversation.com/thoughts-from-a-thorium-symposium-4545

decades is non-trivial. That said, many of the components have been the subject of extensive research programs."

The 2015 report[156] by the French government's Institute for Radiological Protection and Nuclear Safety states that for molten salt reactors (MSR) and SuperCritical Water Reactors (SCWR) systems, there "is no likelihood of even an experimental or prototype MSR or SCWR being built during the first half of this century" and "it seems hard to imagine any reactor being built before the end of the century".

Thorium is no 'silver bullet'

Do thorium reactors potentially offer significant advantages compared to conventional uranium reactors?

Prof. George Dracoulis states: "Some of the rhetoric associated with thorium gives the impression that thorium is, somehow, magical. In reality it isn't."[157]

The UK National Nuclear Laboratory report argues that thorium has "theoretical advantages regarding sustainability, reducing radiotoxicity and reducing proliferation risk" but that "while there is some justification for these benefits, they are often overstated."[158] The report further states that the purported benefits "have yet to be demonstrated or substantiated, particularly in a commercial or regulatory environment." The report further states: "Thorium fuelled reactors have already been advocated as being inherently safer than LWRs [light water reactors], but the basis of these claims is not sufficiently substantiated and will not be for many years, if at all."

Thorium and weapons proliferation

Claims that thorium reactors would be proliferation-resistant or proliferation-proof do not stand up to scrutiny.[159] Irradiation of thorium-232 produces uranium-233, which can be and has been used in nuclear weapons.

The World Nuclear Association states:[160]

> *"The USA produced about 2 tonnes of U-233 from thorium during the 'Cold War', at various levels of chemical and isotopic purity, in plutonium production reactors. It is possible to use U-233 in a nuclear weapon, and in 1955 the USA detonated a device with a plutonium-U-233 composite pit, in Operation Teapot. The explosive yield was less than anticipated, at 22 kilotons. In 1998 India detonated a very small device based on U-233 called Shakti V."*

According to Assoc. Prof. Nigel Marks, both the US and the USSR tested uranium-233 bombs in 1955.[161]

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[156] Institute for Radiological Protection and Nuclear Safety, 2015, 'Review of Generation IV Nuclear Energy Systems', www.irsn.fr/EN/newsroom/News/Pages/20150427_Generation-IV-nuclear-energy-systems-safety-potential-overview.aspx
Direct download: www.irsn.fr/EN/newsroom/News/Documents/IRSN_Report-GenIV_04-2015.pdf

[157] George Dracoulis, 5 Aug 2011, 'Thorium is no silver bullet when it comes to nuclear energy, but it could play a role', http://theconversation.com/thorium-is-no-silver-bullet-when-it-comes-to-nuclear-energy-but-it-could-play-a-role-1842

[158] UK National Nuclear Laboratory Ltd., 5 March 2012, 'Comparison of thorium and uranium fuel cycles', www.decc.gov.uk/assets/decc/11/meeting-energy-demand/nuclear/6300-comparison-fuel-cycles.pdf

[159] 'Thor-bores and uro-sceptics: thorium's friendly fire', Nuclear Monitor #801, 9 April 2015, https://www.wiseinternational.org/nuclear-monitor/801/thor-bores-and-uro-sceptics-thoriums-friendly-fire

[160] www.world-nuclear.org/info/Current-and-Future-Generation/Thorium/

[161] Nigel Marks, 2 March 2015, 'Should Australia consider thorium nuclear power?', http://theconversation.com/should-australia-consider-thorium-nuclear-power-37850

Uranium-233 is contaminated with uranium-232 but there are ways around that problem. Kang and von Hippel note:[162]

> *"[J]ust as it is possible to produce weapon-grade plutonium in low-burnup fuel, it is also practical to use heavy-water reactors to produce U-233 containing only a few ppm of U-232 if the thorium is segregated in "target" channels and discharged a few times more frequently than the natural-uranium "driver" fuel."*

John Carlson, former Director-General of the Australian Safeguards and Non-proliferation Office, discusses the proliferation risks associated with thorium:[163]

> *"The thorium fuel cycle has similarities to the fast neutron fuel cycle – it depends on breeding fissile material (U-233) in the reactor, and reprocessing to recover this fissile material for recycle. ...*
>
> *"Proponents argue that the thorium fuel cycle is proliferation resistant because it does not produce plutonium. Proponents claim that it is not practicable to use U-233 for nuclear weapons.*
>
> *"There is no doubt that use of U-233 for nuclear weapons would present significant technical difficulties, due to the high gamma radiation and heat output arising from decay of U-232 which is unavoidably produced with U-233. Heat levels would become excessive within a few weeks, degrading the high explosive and electronic components of a weapon and making use of U-233 impracticable for stockpiled weapons. However, it would be possible to develop strategies to deal with these drawbacks, e.g. designing weapons where the fissile "pit" (the core of the nuclear weapon) is not inserted until required, and where ongoing production and treatment of U-233 allows for pits to be continually replaced. This might not be practical for a large arsenal, but could certainly be done on a small scale.*
>
> *"In addition, there are other considerations. A thorium reactor requires initial core fuel – LEU or plutonium – until it reaches the point where it is producing sufficient U-233 for self-sustainability, so the cycle is not entirely free of issues applying to the uranium fuel cycle (i.e. requirement for enrichment or reprocessing). Further, while the thorium cycle can be self-sustaining on produced U-233, it is much more efficient if the U-233 is supplemented by additional "driver" fuel, such as LEU or plutonium. For example, India, which has spent some decades developing a comprehensive thorium fuel cycle concept, is proposing production of weapons grade plutonium in fast breeder reactors specifically for use as driver fuel for thorium reactors. This approach has obvious problems in terms of proliferation and terrorism risks.*
>
> *"A concept for a liquid fuel thorium reactor is under consideration (in which the thorium/uranium fuel would be dissolved in molten fluoride salts), which would avoid the need for reprocessing to separate U-233. If it proceeds, this concept would have non-proliferation advantages.*

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[162] Jungmin Kang and Frank N. von Hippel, 2001, "U-232 and the Proliferation-Resistance of U-233 in Spent Fuel", *Science & Global Security*, Volume 9, pp.1-32, www.princeton.edu/sgs/publications/sgs/pdf/9_1kang.pdf

[163] John Carlson, 2009, 'Introduction to the Concept of Proliferation Resistance', www.foe.org.au/sites/default/files/Carlson%20ASNO%20ICNND%20Prolif%20Resistance.doc or http://archive.foe.org.au/sites/default/files/Carlson%20ASNO%20ICNND%20Prolif%20Resistance.doc

"Finally, it cannot be excluded that a thorium reactor – as in the case of other reactors – could be used for plutonium production through irradiation of uranium targets. "Arguments that the thorium fuel cycle is inherently proliferation resistant are overstated. In some circumstances the thorium cycle could involve significant proliferation risks."

False distinctions between thorium and uranium

Some thorium advocates posit a sharp distinction between thorium and uranium. But there is little to distinguish the two. A much more important distinction is between conventional reactor technology and some 'Generation IV' concepts − in particular, those based on repeated (or continuous) fuel recycling and the 'breeding' of fissile isotopes from fertile isotopes (Thorium-232>Uranium-233 or Uranium-238>Plutonium-239).

A report by the Idaho National Laboratory states:[164]

"For fuel type, either uranium-based or thorium-based, it is only in the case of continuous recycle where these two fuel types exhibit different characteristics, and it is important to emphasize that this difference only exists for a fissile breeder strategy. The comparison between the thorium/U-233 and uranium/Pu-239 option shows that the thorium option would have lower, but probably not significantly lower, TRU [transuranic waste] inventory and disposal requirements, both having essentially equivalent proliferation risks.

"For these reasons, the choice between uranium-based fuel and thorium-based fuels is seen basically as one of preference, with no fundamental difference in addressing the nuclear power issues.

"Since no infrastructure currently exists in the U.S. for thorium-based fuels, and processing of thorium-based fuels is at a lower level of technical maturity when compared to processing of uranium-based fuels, costs and RD&D requirements for using thorium are anticipated to be higher."

Prof. George Dracoulis takes issue with the "particularly silly claim" by a science journalist (and others) that almost all the thorium is usable as fuel compared to just 0.7% of uranium (i.e. uranium-235), and that thorium can therefore power civilization for millennia. Prof. Dracoulis states:[165]

"In fact, in that sense, none of the thorium is usable since it is not fissile. The comparison should be with the analogous fertile isotope uranium-238, which makes up nearly 100% of natural uranium. If you wanted to go that way (breeding that is), there is already enough uranium-238 to 'power civilization for millennia'."

Some Generation IV concepts promise major advantages, such as the potential to use long-lived nuclear waste and weapons-usable material (esp. plutonium) as reactor fuel using breeding and continuous recycling. But those concepts are generally those that face the greatest technical challenges. Moreover, uranium/plutonium fast reactor technology might more accurately be described as failed Generation I technology: the history of fast reactors has largely been one of extremely expensive, underperforming and accident-prone reactors which have contributed more to WMD proliferation problems than to the resolution of those problems.[166]

[164] Idaho National Laboratory, Sept 2009, 'AFCI Options Study', INL/EXT-10-17639, https://www.researchgate.net/publication/255214351_AFCI_Options_Study or https://inldigitallibrary.inl.gov/sites/sti/sti/4480296.pdf

[165] George Dracoulis, 5 Aug 2011, 'Thorium is no silver bullet when it comes to nuclear energy, but it could play a role', http://theconversation.com/thorium-is-no-silver-bullet-when-it-comes-to-nuclear-energy-but-it-could-play-a-role-1842

[166] 'The slow death of fast reactors', 2 Nov 2016, https://energypost.eu/slow-death-fast-reactors/

Most importantly, whether Generation IV concepts deliver on their potential depends on a myriad of factors − not just the resolution of technical challenges. India's fast reactor / thorium program illustrates how badly things can go wrong, and it illustrates problems that can't be solved with technical innovation. John Carlson writes:

> *"India has a plan to produce [weapons-grade] plutonium in fast breeder reactors for use as driver fuel in thorium reactors. This is problematic on non-proliferation and nuclear security grounds. Pakistan believes the real purpose of the fast breeder program is to produce plutonium for weapons (so this plan raises tensions between the two countries); and transport and use of weapons-grade plutonium in civil reactors presents a serious terrorism risk (weapons-grade material would be a priority target for seizure by terrorists)."*[167]

Generation IV thorium concepts such as molten salt reactors (MSR) have a lengthy, uncertain R&D road ahead of them − notwithstanding the fact that there is some previous R&D to build upon.[168] Kirk Sorensen, founder of a US firm which aims to build a demonstration 'liquid fluoride thorium reactor' (a type of MSR), notes that "several technical hurdles" confront thorium-fuelled MSRs, including materials corrosion, reactor control and in-line processing of the fuel.[169]

Prof. George Dracoulis writes:[170]

> *"MSRs are not currently available at an industrial scale, but test reactors with different configurations have operated for extended periods in the past. But there are a number of technical challenges that have been encountered along the way. One such challenge is that the hot beryllium and lithium "salts" – in which the fuel and heavy wastes are dissolved – are highly reactive and corrosive. Building a large-scale system that can operate reliably for decades is non-trivial. That said, many of the components have been the subject of extensive research programs."*

Further information on thorium

The following report provides useful information:
Dr. Rainer Moormann, 2018, 'Thorium – a better fuel for nuclear technology?', Nuclear Monitor #858, https://www.wiseinternational.org/nuclear-monitor/858/thorium-%E2%80%92-better-fuel-nuclear-technology

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[167] John Carlson, 2014, submission to Joint Standing Committee on Treaties, Parliament of Australia, www.aph.gov.au/DocumentStore.ashx?id=79a1a29e-5691-4299-8923-06e633780d4b&subId=301365

[168] Stephen Harris, 9 Jan 2014, 'Your questions answered: thorium-powered nuclear', www.theengineer.co.uk/energy-and-environment/in-depth/your-questions-answered-thorium-powered-nuclear/1017776.article
See also: Oliver Tickell, August/September 2012, 'Thorium: Not 'green', not 'viable', and not likely', www.no2nuclearpower.org.uk/nuclearnews/NuClearNewsNo43.pdf

[169] Stephen Harris, 9 Jan 2014, 'Your questions answered: thorium-powered nuclear', The Engineer (UK). Article available from jim.green@foe.org.au

[170] George Dracoulis, 19 Dec 2011, 'Thoughts from a thorium 'symposium'', http://theconversation.com/thoughts-from-a-thorium-symposium-4545