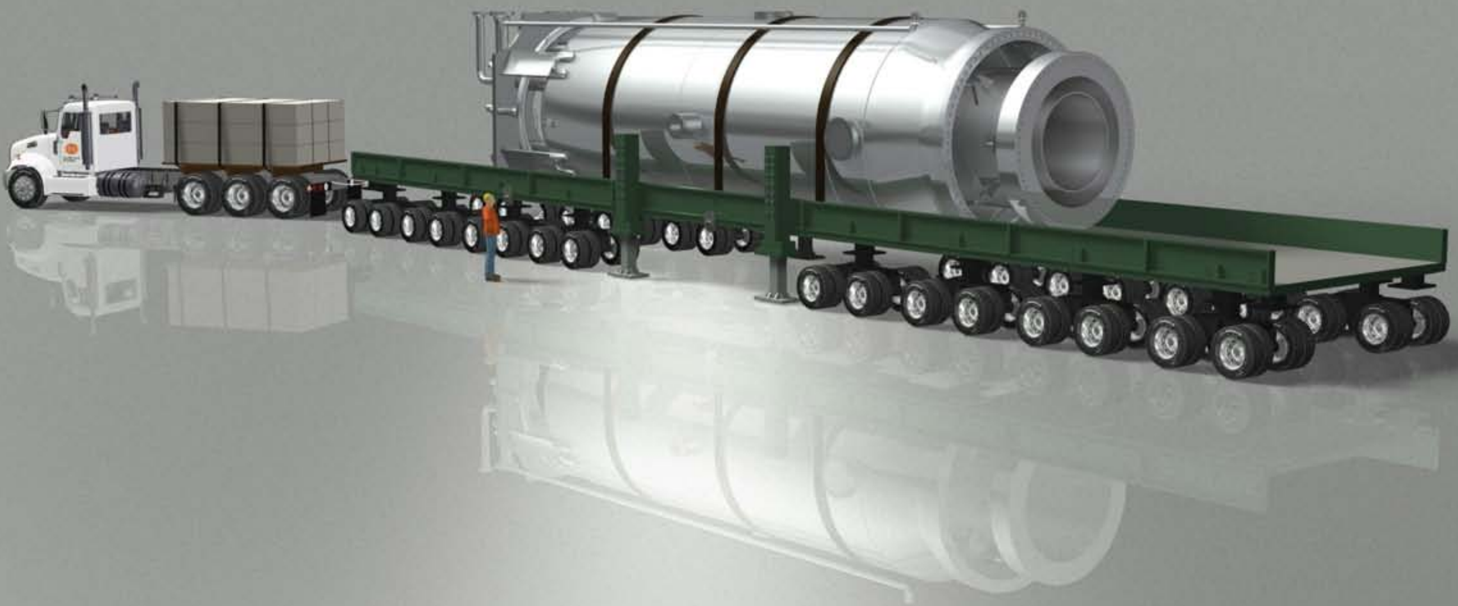
SMALL MODULAR NUCLEAR
Crushed at birth

Andy Dawson



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About the author

Andy Dawson originally graduated with a BSc in Nuclear Engineering from the University of Manchester in the early 1980s, joining the National Nuclear Corporation and working on a variety of aspects of the design and construction of the Heysham II and Torness advanced gas-cooled reactors.

He subsequently studied as a postgraduate specialising in operational aspects of reliability engineering before moving on to a career in the delivery of solutions for managing complex capital plant in a variety of sectors, before moving into IT. He has worked for a variety of technology and management consulting companies, and completed an MBA. His clients have included oil and gas majors, power generation, transmission and distribution firms, and energy retailers.

He has retained a close interest in the development of the nuclear sector, and published essays on the topic on a number of online blogs.

1 Introduction

In his Autumn Statement of 2015, the then Chancellor, George Osborne, made an announcement that surprised and enthused many; he said that the UK was to spend up to £250 million on support to nuclear innovation, including a competition to spur the development of small modular reactors (SMRs), a novel approach to delivering nuclear generating capacity:

> [T]he Spending Review and Autumn Statement invests at least £250 million over the next 5 years in an ambitious nuclear research and development programme that will revive the UK's nuclear expertise and position the UK as a global leader in innovative nuclear technologies. This will include a competition to identify the best value small modular reactor design for the UK. This will pave the way towards building one of the world's first small modular reactors in the UK in the 2020s. Detailed plans for the competition will be brought forward early next year.[1]

The announcement was greeted with an almost universally positive reaction – even the reliably anti-nuclear 'Guardian' ran the story under the headline 'George Osborne puts UK at the heart of global race for mini-nuclear reactors'.[2] Initially, progress appeared good – in particular, the response from the global nuclear industry was strong, with 38 organisations submitting responses to the call for competition. However, since then, it has become apparent that the early momentum has dissipated, to the extent that it appears unlikely any substantive progress has been made in nearly three years; certainly there is no sign that design selection has been progressed to the point that there is any real possibility of a technology being taken into the nuclear certification process within timescales compatible with a reactor operating before the end of the 2020s.

This paper will attempt to understand the actual state of progress in the competition, infer reasons for the apparent lack thereof, and to make suggestions as to how this situation can be rectified.

2 What are SMRs, and what benefits might they bring?

Throughout the history of nuclear development, there has been an underlying assumption that increases in unit size would bring economies of scale. This logic has developed to the point that units of up to 1750 MWe (megawatts electric – the measure of power output) are now in operation, almost three times the size of the UK's advanced gas-cooled reactors of the 1970s. Nor has the logic run its course. China's SNPTC holds a license for the 'passively safe' US AP1000 1100 MWe design, and is pursuing its upscaling to 1400 MWe and potentially to 1700 MWe or even 2100 MWe. Increased size, however, brings challenges: larger units become harder to integrate operationally into anything but the largest grids, and if accompanied with increased complexity can make for extended and risky builds. In practice, these putative gains have often been offset by loss of learning curve benefits, and regulatory demands for ever greater safety-related redundancy. Increased size also tends to require a higher ratio of siteworks to factory works (although not necessarily so). Furthermore, a larger core can mean additional difficulty in post-accident 'decay heat' removal, which is the key determinant in reactor safety (decay heat is the ongoing production of heat from fission products in fuel, even after shutdown; although it drops with time in the days and weeks immediately after a large reactor is shut down it can amount to tens of megawatts).

In contrast, the intention of SMR developers is to build large numbers of much smaller units. The accepted definition of an SMR is a unit of 300 MWe or less.[3] This potentially brings significant efficiencies, because an increased proportion of the effort can be undertaken in a controlled factory environment, and because frequent replication of identical units will allow for an improved learning curve effect (the general assumption in engineering development is that a doubling of the population of a given design will give around a 15% reduction in unit cost). In addition:

- grid integration is made easier;
- financial risk is moderated;
- smaller sized units are easier to cool passively in accident situations (a manifestation of the cube:square law, where smaller units have a larger surface area through which to lose heat relative to core volume).

It should be said that this logic is not universally supported: for the learning curve effect to apply, production volumes will have to be significant (and some conventional designs will also achieve significant volumes). Similarly, the 'factory build' concept already applies in significant measure to designs such as the Hitachi advanced boiling water reactor proposed for Wylfa and Oldbury: the entire 'Nuclear Steam Supply System' arrives on site in the form of the main reactor vessel, a single module of some 600 tons.

Other benefits have been claimed for SMRs, including that they offer potential for greater flexibility in grids with a large proportion of intermittent renewables, or that SMRs can be sited close to conurbations and supply heat to district heating schemes.

Beyond the basic concept of a small, volume-produced unit, however, there is no single consistent reactor technology used in SMR proposals to date. A brief review of the variety of technologies proposed is set out in Appendix 1.

3 The background to Osborne's announcement

The competition announced by George Osborne was not the first UK government activity aimed at giving the UK a leading role in the development of SMRs. In fact, in could be argued that the majority of the necessary work to select a viable design offer had already been undertaken.

In 2013/14, the then government had requested the National Nuclear Laboratory (NNL) to undertake a feasibility study concerning UK involvement in SMR development and production.[4] The stated objectives were to determine:

- whether SMRs are viable
- the potential UK industry role
- the possible role that Government might play in that process.

NNL is a globally respected nuclear research organisation – certainly possessing more technical expertise than is available within Whitehall – and was partnered in this exercise by other highly competent organisations such as Atkins, AMEC and KPMG. The study evaluated available designs on the basis of a number of key criteria:

- technical maturity and viability
- maturity of safety case and certification
- key strengths and areas for development
- programmes to address development needs

- available resources – people, capability, facilities and funding
- economic viability.

A shortlist of six reactor design technologies from US, French, Chinese and one multinational entity were identified, reduced to five when the work on the French design was discontinued by the vendor. The NNL study also noted that one technology (the Urenco 'U-Battery') was aimed at a notably different niche, being a 'nuclear battery'. Nuclear batteries are small (less than 10 MWe) 'sealed for life' units usually aimed at providing heat and power for remote 'off grid' sites.

With this sole exception, all of the designs considered were integral pressurised water reactors (IPWRs). The study concluded:

> There is a clear need for deeper investigation into the individual technologies and the capability required to deliver them to market, further financial analysis to clarify the economics case, and a testing of the possible engagement models for the UK to partner with a selected SMR technology vendor. Overall however, on initial review, this study concludes that there could be a significant market for SMRs and the UK has a narrow window of opportunity to participate in a joint development with a partner country, which could offer the UK a position as a market leader in nuclear low-carbon generation.

As can be seen, the conclusion appears to suggest proceeding on the basis of the four IPWR designs (from Westinghouse, Babcock and Wilcox/Bechtel, NuScale/Fluor and also the China National Nuclear Corporation), specifically stating that all were at a stage of development such that they were 'viable within the ten year time scale'. In addition, all had expressed openness to collaboration with the UK on bringing the designs to the worldwide market, but that this was subject to a limited timescale in which the UK could earn a significant share of intellectual property in order to benefit from design royalties.

At this stage – December 2014 – the Government would appear to have been presented with a clear forward path, based around a particular technology, a strong commercial upside and a time-limited opportunity. The Government reacted by commissioning a structured and rigorous 'techno-economic assessment' (TEA) from Atkins, even ahead of formal delivery of the NNL report.

4 The 2015 competition

Within a few months of Osborne's announcement, the Department of Energy and Climate Change had swung into action – but not necessarily in the way that the NNL authors had intended. In March 2017, rather than building directly on the NNL study, DECC instead announced an open 'call to competition',[5] – thus opening up the process to a large number of players beyond the four 'viable vendors', and inevitably introducing significant delay.

The stated objective of the call for competition was to 'gauge market interest among technology developers, utilities, potential investors, funders and other interested parties in developing, commercialising and financing SMRs in the UK'. What was not made clear at the time (or subsequently) is how the results of this exercise and the TEA would be integrated, or what the roadmap beyond that point would be – that was to be determined, and announced at the end of the competition phase. Integral to the exercise was the *Expression of Interest Questionnaire*,[6] setting out eight questions addressing relevant reactor building experience, cost and time estimates to take the design to completion of UK Generic Design

Approval (GDA, the UK's mechanism for safety approval of standard reactor designs), and the financial and technical resources available. On this basis, most observers (this author included) assumed that this was meant to be a highly targeted activity aimed at making progress beyond the NNL study.

However, it rapidly became apparent that this was not the approach being taken. By August 2016, responsibility for the competition had passed from DECC to the new Department for Business, Energy and Industrial Strategy (BEIS), who announced that of the 38 responses accepted, no fewer than 33 had been 'shortlisted'.[7] Worse, on examination of the list, it became apparent the BEIS had very definitely not applied near-term viability (or even relevance) as a selection criterion. The list can be seen in Appendix 2 – as can be seen, not only were many not from organisations with an apparent offer per se, but in fact many were not even marginally credible. Accepted responses included a proposed fusion reactor, several from companies so financially weak they were non-functional, and others used designs that would be viable only in timescales of 2030 and beyond.

A charitable interpretation would be that BEIS was attempting to ensure total transparency and fairness, or to maintain a public perception of progress while the serious work was proceeding under the aegis of the TEA; a less charitable interpretation was that this was an exercise in kicking the whole issue into the 'long grass', in the context of George Osborne having left office by this time. This apparent loss of sponsorship and purpose would become more apparent with time.

5 The techno-economic assessment

In parallel to the Call for Competition, Atkins (with support from Ernst and Young) were quietly proceeding with the TEA. This was a somewhat longer task than the Call for Competition, and the resulting report was published in December 2017, more than two years after the initial announcement of the project.

The report is a major publication,[8] consisting of a main document and a number of supporting analyses, the most important of which is the *Assessment of Emerging SMR Technologies*.[9] This document is very largely a validation of the NNL work; in fact, the stated aim was to:

> …inform UK Government as to whether SMRs have the potential to provide the economic, financial, technical and commercial opportunities that have been claimed, whilst identifying the risks to achieving these. In particular, to ascertain whether SMR technology has the potential to contribute to the generation of low carbon electricity at affordable prices, but also what the impact on the economy would be if the UK were to pursue a strategy to become a manufacturer and exporter of SMR technology.

The methodology was a mixture of literature review and direct engagement with vendors where possible. Rather than engaging with just the NNL-identified potential vendors, Atkins cast the net wider, in terms of both geography and technology. Instead of the primary focus being on IPWRs (as might have been logical following the NNL work), other designs considered included sodium- and lead-cooled fast reactors (SFRs and LFRs respectively), high-temperature gas-cooled reactors (HTRs), molten-salt reactors (MSRs) and non-integral PWRs. Considerable effort was also applied to understanding the economic and industrial possibilities, along with issues such as grid integration.

The technical conclusions were less than startling. It concluded that the only viable technologies for potential deployment in the 2020s were PWR (integral or non-integral). SFR, LFR, HTR and, in particular, MSR all suffered from a lack of R&D required for the safety case, and a lack of regulatory experience, as well as the need for an extended cycle of technology demonstrators and prototypes. It further concluded that first of a kind (FOAK) units would be more expensive than non-SMR designs, and that the potential for cost reductions was dependent on volume production. It noted (without apparent irony) that:

> SMR design development and licensing is proceeding in a number of countries. It is likely that first of a kind (FOAK) SMRs will be deployed in some of these countries in the next decade.

The detailed economic conclusions were more interesting. For mature IPWR designs, a levelized cost for a FOAK unit of £86–124 was forecast, excluding GDA costs, and with a central forecast of £101/MWh (for comparison, gas-fired units are forecast to generate at a cost in the range of £100–120/MWh, dependent on the level of carbon taxation, and offshore wind at around £97/MWh including system costs). On the central case and on the basis of a larger programme (8 GW globally out to 2035 – some 25–40 units for the more credible IPWR designs) levelized cost will sit in the range £60–100/MWh, with a central figure of around £80/MWh. This is almost identical to BEIS's longer term forecast for large nuclear, and in fact somewhat higher than the strike price currently anticipated for the Wylfa ABWR plant. For costs to reduce further, either an extremely large global programme (some tens of gigawatts), or an extremely high 'learning rate' has to be assumed. Nor does the report suggest that SMRs will have any inherent design advantage in terms of flexibility for grid integration – large nuclear can already attain high rates of change in power output, and the obstacles to using it in load-following mode are those of economics rather than of inherent technical flexibility.

So, slightly over three years from Osborne's announcement, a set of technical conclusions essentially identical to those of the NNL report, and (to anyone with any understanding of the technology) which were utterly predictable was produced. The economic case seems to have been significantly weakened, or at least identified a dependence on extremely large deployment. Little or no progress appears to have been made towards selecting one or more vendors with whom the UK government might collaborate in bringing an SMR to market.

6 The current status

Roughly coincident with the release of the Atkins report, the Government announced the release of just £4 million for 'Feasibility Studies' and £7 million to enhance regulatory capacities (although what form the latter might take is totally unclear).[10] Contingent on the results of the feasibility work, up to £40 million more may be released in 2020.

In these three years, the international landscape has changed:

- The Chinese have committed to construct SMRs and deploy them as part of floating power plants for use in the Pacific.
- NuScale has entered the US equivalent of GDA, with the intent of constructing a demonstrator SMR at the Idaho National Laboratory site.
- Westinghouse is emerging from bankruptcy, although it may or may not be keen to realise the value of its SMR investment to date.

A further complication appears to have been caused by Rolls-Royce's technology submission. Rolls has, for some reason (probably manufacturing capability), lobbied heavily against

IPWRs, and submitted its own non-integral PWR design. However, in an effort to overcome the disadvantageous economics of a non-integral design, it has increased the proposed capacity to 440 MWe, almost 50% larger than the commonly accepted SMR definition.

In June 2018, in the immediate aftermath of the announcement that support would not be available for the Swansea tidal lagoon, the £11m of funding was re-announced (in the broader context of the UK 'Nuclear Sector Deal'), and a list of eight companies eligible for next-phase funding was outlined. In September 2018 the government clarifed the nature of the designs accepted into the feasibility study exercise There are shifts in terminology which suggest that the Government is now primarily focused on longer-term developments (the term employed is now 'advanced modular reactors'); more worryingly, the list of companies found to be eligible for further feasibility study funding suggests a total abandonment of the near-term objective, and certainly flies in the face of the conclusions of the Atkins report concerning near-term viability:[11]

- Four (ARC, Hydromine, LeadCold and Westinghouse) are offering liquid-metal-cooled fast reactors (ARC sodium-cooled, the others lead-cooled).
- One (Moltex) is a molten salt design.
- Three (Urenco, DBD and Ultrasafe) are high-temperature reactors; DBD are 'fronting; the Chinese HTR design currently under construction at Shiadowan.
- Three are nuclear batteries (<10 MWe), and so are not relevant to a major power generation initiative.
- One (Tokamak Energy) is not even a fission design, but a novel approach to fusion reactors.

Crucially, Rolls-Royce, NuScale and Westinghouse do not appear on the list. Westinghouse and NuScale are the most credible and well-developed designs. Rolls-Royce has expressed frustration and called into question the continuance of its investment in the development of the technology without an explicit government commitment.[12] On a more positive note, BEIS's Expert Finance Working Group on Small Reactors has reported that they believe that commercial development of SMRs remains a viable objective *if* the government focuses on designs that are viable in the near term.

The programme has obviously been redirected from its clear original purpose; technologies that are clearly non-viable in the context of the original timescales are now at the heart of the programme, which currently bears all the hallmarks of an initiative which will be feasibility studied into paralysis. The reasons for this can only be speculated upon; a loss of commitment at ministerial level, loss of Treasury support, civil service inertia and technical incompetence all seem likely to have played a role. That seven of the eight selected firms could not reasonably support anything more than small-scale study work suggests that there is an intention to delay significant expenditure.

Despite optimistic responses from industry to the Nuclear Sector Deal as a whole, it is clear that the SMR programme, at least in the format originally implied by George Osborne, is dead. There is no possibility of bringing a design to deployable status, even by the mid-2020s. Even an IPWR or PWR would require some four years to complete GDA; assuming another year for site licensing and three years for FOAK construction, the design would have to be 'shovel ready' by 2022–23 at the latest. No shortlisted proposal is even potentially capable of meeting the 2020s timescale.

Potentially significantly, there have been developments around conventional nuclear projects. Hitachi and the UK and Japanese governments appear close to agreement on funding for the Wylfa development; details remain 'commercial in confidence', but most commentators appear to expect a strike price of around £75/ MWh and that the UK and Japanese governments will take equity stakes of up to 25% each.[13]

Note that this is of a similar order to what might be available as an equity share in an SMR design, and with lower technical risk. BEIS has also suggested that it will put in place a new model for funding future nuclear developments which could have the potential for significant reductions in their cost of capital (the key driver of nuclear costs).[14]

More tellingly, China General Nuclear (CGN), the lead developer of the proposed Bradwell B plant in Essex, have confirmed that they will not seek UK government support for the project. Bradwell is based around the company's HPR1000 design (also known as 'Hualong 1'),[15] a derivative of the Framatome 900-MW PWR, the backbone of the French fleet, and is currently about 18 months into the GDA process. The first HPR1000 at Fuqing has (as of early August 2018) completed the construction phase and is being moved into commissioning in the remarkably short time of approximately 3½ years from 'first concrete'; this suggests that the unit will be brought online within 54 months – a remarkable achievement. This means that any UK development will have the benefit of a learning curve of similar scale to that envisaged in the largest of the credible SMR rollouts; counting overseas sales and Chinese plants, the Bradwell units will be something like the 15th HPR1000 built, and potentially as much as the 50th. CGN is aiming for a capital cost of around $2,500/kW of capacity in Chinese build; even allowing for that increasing by 50% due to UK site conditions, that would still be around half the cost of Hinkley Point C. This suggests that a UK HPR1000 ought to be viable at a strike price of the order of £55–65/MWh, even at the inflated cost of capital allowed to Hinkley. At a more reasonable 5–7% that would be around £45/MWh.

7 Recovering the initiative

Government must decide if the original intention of SMR deployment in the 2020s (or now, the early 2030s) remains the plan. Assuming for the moment that is the case, BEIS must restore drive and clarity to the programme. This can only be achieved by the following:

- Confirm acceptance of the Atkins and NNL analysis around the technologies which offer potential for an early entry to the GDA process, which means a PWR of one form or another, preferably integral. Then declare if the delay has squandered the opportunity to develop a successful IPWR/PWR programme
- Confirm commitment to a near-term project, and select a shortlist of vendors with mature designs using this IPWR/PWR technology.
- Commence discussion with the shortlisted vendors to identify those willing to cede a minority stake in the intellectual property rights in return for Osborne's promised £250 million, and with the aim of announcing a preferred partner before the end of 2018.
- Make a commitment to facilitate the design passing through GDA.
- Confirm a choice of site for the demonstration plant (probably Trawsfynnydd or Heysham), to be offered to the selected vendor at zero cost.

If no such commitment exists, then it is time to call a halt to this project, and to confirm a focus on large-scale nuclear development; there are worrying signs that government indecision is causing overseas investors to question their commitment to UK projects.[16] The resources currently dedicated to SMR development should be redeployed to commercial models for new-build large-scale units, and to seeking supply chain and services opportunities for UK players in alliance with Chinese developers.

Three years have been wasted, and the window for a meaningful UK participation in SMR delivery has narrowed almost to the point of closure. With sufficient intent and clarity of purpose, it is not yet entirely too late – although continuance of the current approach will certainly make it so.

Appendix 1: Technologies proposed by SMR vendors

Pressurised water reactors

The starting point for the SMR proposals of most established nuclear technology companies has tended to be the pressurised water reactor (PWR). PWRs have been the backbone of the world's nuclear fleet for decades. PWRs scale readily. In power station units they exist in sizes ranging from around 500 MWe to 1750 MWe; they also power the world's nuclear naval units, in sizes equivalent to perhaps 15 MWe. They use a 'thermal' neutron spectrum, which requires a moderator – the light water coolant also provides moderation (i.e. slowing of the neutrons).

PWRs require a robust primary circuit, conventionally consisting of reactor vessel, steam generator(s), pressuriser, pumps and associated pipework. This is because they operate at significant pressure – typically about 160 bar. This complex primary circuit almost inevitably implies large-scale site works for assembly and complicates the safety case, which has led most potential SMR vendors to adopt a variant, outlined next.

The integral PWR

Integral PWRs (IPWRs) take the basic PWR concept, and then attempt to simplify the primary circuit. Instead of using separate steam generators and pressurisers, the entire steam-raising system is fitted into a single vessel containing those components and the core. This assembly can then be shipped to site in just one or two loads (typically, the upper parts will be removable to allow access for refuelling, and can thus be transported separately). This radically reduces the volume of the primary circuit and removes a large proportion of the need for on-site assembly.

There are several additional challenges introduced by the integral concept, however. For example, having steam-raising equipment occupying the space above the core means the control rods – which constrain the rate of nuclear fission – either have to enter from below (as is done in boiling water reactors) or submerged control rod drives (as used in AP1000) have to be used.

IPWRs have another potential major advantage. The relatively shorter pipework runs between the core and the steam generators (their primary heat sink) mean there is greater potential for the use of natural circulation of coolant – if not in full power operation, then at least in post-shutdown cooling.

IPWRs are generally not such a radical leap that nuclear regulators will struggle with safety evaluation and licensing; there is some operational experience (French naval units have used an integral concept). However, this is not the case for other, more radical designs, as outlined next.

Liquid-metal-cooled fast reactors

Nuclear designers have been attempting to utilise 'fast spectrum' reactors since the earliest days of the technology. In these reactors, no neutron-slowing moderator is needed, meaning that there is potential for the 'breeding' of new fuel, and the destruction of certain isotopes that make reprocessing and disposal of conventional fuel difficult.

These reactors produce a great deal of energy in a very small core, which means they need extremely efficient heat transfer; this leads to the use of liquid metals as coolants. Sodium and lead are the primary choices; neither absorbs fast neutrons to any significant degree. Sodium has particularly good heat-transfer characteristics, but must be kept well separated from water; lead is not quite so good, and poses challenges in chemical terms, but will allow even higher temperatures and is massively effective at shielding against gamma rays. With both, there is some operational experience to draw on, but in general there is little manufacturing or regulatory experience available in the West.

Molten salt reactors

Molten salt reactors (MSRs) have been the subject of a good deal of discussion in recent years. They are based on a concept trialled (at small scale) in the US's Oak Ridge National Laboratory in the late 1950s. Instead of being in solid form in sealed rods, the fuel is dissolved in a halide salt, thus acting as both fuel and heat-transfer medium.

There has been a huge proliferation of MSR concepts – ranging from those with discrete fuel and molten salt coolant (which, contrary to popular belief, is the nature of the ongoing Chinese work), to those operating with fuel dissolved in coolant, to breeder concepts based on either uranium or thorium. It should however be clearly understood that there are no thorium-fuelled designs. The thorium is 'bred' into fissionable uranium in order to be used.

All MSR designs are immature (most are best described as conceptual), and many of the companies proposing them are under-resourced and lack nuclear sector experience. On that ground, bringing a design to readiness for build will be a major undertaking. Assuming a design can be brought to maturity, MSR can have design advantages – lack of pressurisation, high temperatures, etc. On the downside, there are needs to demonstrate the durability of structural materials, radiolytic problems with moderators (or the need to validate assumptions about core-replacement options), handling of fission products that are outgassed or extracted from fuel salt, and so on. A particular issue is that the whole of the primary circuit, as opposed to just the core itself is intensely radioactive.

High-temperature reactors

High-temperature reactors (HTRs) are usually – but not exclusively – thermal in spectrum. They are designed to operate at more than 800°C, using helium coolant. In many ways they can be regarded as a descendant of the Magnox-AGR design concepts, using graphite moderators and gas coolant. However, the fuel concept is very different, being based on a concept called 'TRISO' (TRIstructural iSOtropic): a ceramic – typically pellets of uranium carbide – embedded in a matrix of pyrolitic carbon, and the whole element enrobed in a layer of silicon carbide, making it extremely tough and tolerant of very high temperatures. Fuel and moderator are therefore integrated, in either a single prismatic block or in 'pebbles'.

HTRs do operate at pressure, albeit not overly high – 40 bar would be typical. Although a number of prototypes were built in the 1960s and 1970s, the field has been pretty much moribund in recent years, with the exception of China, where 250 MWe prototypes are under construction. Probably the biggest downside to HTRs (beyond immaturity) is that the fuel is just about completely un-reprocessable. That can be argued as a virtue, for proliferation reasons, but it may hurt plant economics in the long run.

'Nuclear batteries'

In more than one sense, so-called 'nuclear batteries' do not represent a distinctive technology. In fact, the various designs that have been announced cover a range of technologies: fast and thermal, various coolants, unusual control mechanisms and so on.

They are typically small – the largest design that legitimately falls into the category would have about a 10 MWe capacity. They're designed to be 'sealed for life', installed at remote sites or as local power sources and swapped out when the fuel is exhausted. They're designed for zero operator intervention in normal operation, and extremely high levels of inherent safety. At this scale, it's unlikely they can perform a serious role in an advanced grid in supplying electricity at significant scale.

Appendix 2: ‘Shortlisted’ organisations for Phase 1 of the SMR competition

Vendor, *offer*	Country of origin	Technology	Unit size (MWe)	Description
		(NI, no information)		
Algometrics *Advanced Hybrid SMR*	UK	NI	NI	Cambridge-based engineering consultancy; accounts filed at Companies House appear to show no income in 2016–17; potentially no longer trading?
Amec-Foster Wheeler	UK	—	—	Large and highly capable engineering consultancy; does not appear to have made a specific technology offer and has subsequently been awarded a £2.9 million BEIS contract to develop improved digital design processes for reactors.
Advanced Reactor Concepts *ARC-100 advanced SMR*	Canada	Sodium-cooled fast reactor	100	Appears to be a downscaled version of the ‘PRISM’ concept, itself a derivative of the US EBR-II prototype.
Atkins	UK	—	—	Large and highly capable engineering consultancy; does not appear to have made a specific technology offer.
Bechtel *Generation mPower SMR*	US	IPWR	180	Bechtel - the world’s premier engineering management and project management company; Bechtel were ‘fronting’ the offer of the B&W mPower SMR. The mPower project appears to have been terminated in March 2017.
China National Nuclear Corporation *ACP100 SMR*	PRC	IPWR	100	Little known beyond technology type; however, appears to be the same unit as is proposed for floating units for deployment in the Pacific.
China National Nuclear Corporation *ACP100+ SMR*	PRC	IPWR	100	See above.

Costain	UK	—	—	Civil engineers; do not appear to have made a specific technology offer.
Critical Path Energy	UK	NI	NI	Dormant company according to Companies House filing April 2018.
EDF Energy *EDF Energy SMR*	France	—	—	No technical details appear to be available.
Empresarios Agrupados Internacional	Argentina	IPWR	25/ 100	This offer is based on the ‘CAREM’ SMR, the prototype of which is currently under construction near Buenos Aires.
Ernst & Young	UK	—	—	Management consultancy firm: does not appear to have made a specific technology offer, but is positioning for economic assessment work in the broader programme.
Frazer-Nash Consultancy	UK	—	—	Frazer-Nash describes itself as a ‘systems and engineering consultancy’, and appears to have particular strength in nuclear safety case work; no obvious single technology offering.
GE-Hitachi Nuclear Energy International *PRISM SMR*	US/Japan	Sodium-cooled fast reactor	300	PRISM is on offer to BEIS as a plutonium burner for reduction of the current stockpiles at Sellafield (stalled?). The design is a derivative of the successful US EBR-II sodium fast reactor design, and is almost certainly the most mature/developed of the various liquid-metal-cooled designs.
GF Nuclear Limited/ Korea Atomic Energy Research Institute	UK/South Korea	IPWR	100	KAERI Smart is a well developed SMR IPWR design which would appear to be close to ‘shovel ready’.
Holtec International *SMR-160*	US	IPWR	160	HOLTEC is a US engineering company with involvement in most parts of the nuclear supply chain; the SMR-160 is the subject of cooperation agreements with both GE-Hitachi and SMC-Lavalin, and hence must be regarded as a credible contender.

Hydromine Nuclear Energy *LFR-AS-200*	—	Lead-cooled fast reactor	—	Conceptual design only, attempting to extrapolate existing sodium-cooled reactor to use lead as coolant.
LeadCold Reactors *SEALER-UK*	Sweden	Lead-cooled fast reactor	<10	Appears to be an early-stage conceptual development of a very small lead-cooled fast reactor.
Moltex Energy *Stable Salt Reactor*	UK	Molten salt reactor	—	Moltex is the most developed UK proposal in the MSR space, and is distinguished from most MSRs as it uses discrete fuel 'rods' consisting of fuel-salt mixture in cans, immersed in a molten salt coolant. However, there still appear to be significant uncertainties as to what the design actually is; for example, their public website appears to imply that both thermal and fast neutron spectrum designs are options.
National Nuclear Laboratory	UK	—	—	The UK's primary nuclear R&D organisation. Does not appear to have made a specific technology offer.
Nuclear Advanced Manufacturing Research Centre	UK	—	—	R&D organisation based at Sheffield University. Known to be in close cooperaton with NuScale, Westinghouse and Rolls-Royce.
Nuclear Cogeneration Industrial Initiative *GEMINI*	—	—	—	EU R&D initiative to research potential process heat/cogeneration projects; HTR-based, but no actual design proposed.
NuScale Power	US/UK	IPWR	50	Small IPWR; currently undergoing US NRC certification with a view to construction of a prototype unit at Oak Ridge National Laboratory. Many novel design features, uncluding all-natural circulation operation and close-fitting submerged containment.
Nuvia	UK	NI	NI	Appears to be a medium-scale technology company specialising in nuclear instrumentation and decommissioning services.

Penultimate Power UK	US	—	—	Appears to be small, north-east based consultancy. CEO’s degree is in ‘rural development’; net current assets as of March 2017 of £128.
Rolls-Royce PLC, UK SMR	UK	PWR (non-integral)	220–440	Rolls-Royce’s participation is based on its position as the builder of the UK’s submarine reactors. Has proposed a relatively conventional PWR with up to four separate steam generators and a conventional primary circuit design.
Sainc Energy *Innovative SMR*	UK	NI	NI	Technical details do not appear to be publicly available, and the website appears to be a ‘shell’ giving no useful information.
Sheffield Forgemasters International	UK	—	—	Heavy engineering company specialising in large castings/forgings; known to be seeking work as component manufacturer for SMR vendors. No technology offer per se.
Terrestrial Energy *Integral Molten Salt Reactor*	Canada	Molten salt reactor	—	Terrestrial is probably the world’s most developed MSR offer; it has raised funding to enter a design approval process in its native Canada, including development of non-nuclear heat transfer test simulators.
Tokamak Energy *Small Modular Fusion Power*	UK	Fusion reactor	NI	Tokamak is a UK-based company which claims to have developed a novel approach to containment of fusion plasma; it intends to work through several generations of test rigs before attempting a ‘breakeven’ fusion reaction and a subsequent energy-positive design.
TWI	UK	—	—	TWI is The Welding Institute; presumably entrant seeking funds for study work rather than actual technology proposal.
Urenco Ltd *U-Battery*	UK/NL/DE	High-temperature reactor	<10	U-Battery is a small self-contained unit designed primarily for power and heating supply in remote ‘off-grid’ locations.

Westinghouse *Westinghouse SMR*	US	IPWR	220	Probably the most mature design in the market. The design makes heavy use of technology derived from the AP1000 full-sized PWR, which is has completed the GDA process and was planned for the Moorside site before Westinghouse entered Chapter 11 bankruptcy, from which it is now emerging. One of the larger designs, which is a good match for 'off the shelf' steam turbines used in the back-end of CCGT units.
Westinghouse Lead-cooled fast reactor	US	Lead-cooled fast reactor	400	Advanced lead-cooled concept

Notes

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About the Global Warming Policy Foundation

The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

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1	Andrew Turnbull	The Really Inconvenient Truth or 'It Ain't Necessarily So'
2	Philipp Mueller	The Greening of the Sahel
3	William Happer	The Truth about Greenhouse Gases
4	Gordon Hughes	The Impact of Wind Power on Household Energy Bills
5	Matt Ridley	The Perils of Confirmation Bias
6	Philipp Mueller	The Abundance of Fossil Fuels
7	Indur Goklany	Is Global Warming the Number One Threat to Humanity?
8	Andrew Montford	The Climate Model and the Public Purse
9	Philipp Mueller	UK Energy Security: Myth and Reality
10	Andrew Montford	Precipitation, Deluge and Flood
11	Susan Crockford	On the Beach
12	Madhav Khandekar	Floods and Droughts in the Indian Monsoon
13	Indur Goklany	Unhealthy Exaggeration
14	Susan Crockford	Twenty Good Reasons not to Worry about Polar Bears
15	Various	The Small Print
16	Susan Crockford	The Arctic Fallacy
17	Indur Goklany	The Many Benefits of Carbon Dioxide
18	Judith Curry	The Climate Debate in the USA
19	Indur Goklany	The Papal Academies' Broken Moral Compass
20	Donoughue and Forster	The Papal Encyclical: a Critical Christian Response
21	Andrew Montford	Parched Earth Policy: Drought, Heatwave and Conflict
22	David Campbell	The Paris Agreement and the Fifth Carbon Budget
23	Various	The Stern Review: Ten Years of Harm
24	Judith Curry	Climate Models for the Layman
25	Fritz Vahrenholt	Germany's *Energiewende*: a Disaster in the Making
26	Hughes, Aris, Constable	Offshore Wind Strike Prices
27	Michael Miersch	Truly Green?
28	Susan Crockford	20 Good Reasons not to Worry About Polar Bears: Update
29	Mikko Paunio	Sacrificing the Poor: *The Lancet* on 'pollution'
30	Mikko Paunio	Kicking Away the Energy Ladder
31	Bill Gray	Flaws in Applying Greenhouse Warming to Climate Variability
32	Mikko Paunio	Save the Oceans: Stop Recycling Plastic
33	Andy Dawson	Small Modular Nuclear: Crushed at Birth