# Small Modular Reactors

## Their potential role in the UK

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National Nuclear Laboratory

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With the growth of nuclear energy world-wide, there has been a resurgence of interest in new reactor designs. These include a substantial number of Small Modular Reactor (SMR) concepts for a range of applications including electricity production, district heating, desalination and plutonium management.

This paper introduces some of the potential SMR designs and technologies and provides an insight into the benefits and potential role of SMRs in the UK. The paper only considers land-based SMRs, although there is potential for their use in maritime propulsion.

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## Introduction

Conditions for a "Nuclear Renaissance" are falling into place in many countries including the United Kingdom (UK) where new nuclear build appears to be on the verge of the first orders being placed. Reasons for this are numerous and include the continued safe operation of the existing fleet of nuclear plants, reductions in operating costs of current plants, nuclear's contribution to low carbon emissions is now more widely recognised and appreciated, volatility of natural gas prices is becoming an ever greater concern and energy security is now a real worry, particularly with the closure of not just nuclear, but other power plants in the UK too e.g. coal stations closures as Government strives to achieve its $CO_2$ targets and commitments.

Nevertheless, there remain a number of key challenges to the successful deployment of a new nuclear fleet, particularly if a large fleet is being considered, as is the case for certain scenarios proposed for the UK[1]. The remaining challenges are not insurmountable, but the risk associated with any uncertainty (whether in financing, regulation, or technology) will affect the UK's new build programme. Even if the impact is merely a delay, the effect could be significant as the price of electricity drives more people into fuel poverty, the Government continues to fall short of its $CO_2$ commitments and as power stations close and are not replaced, the UK faces potential brown/blackouts.

Much is made of the technology choices available to the new build operators of today; whether they will choose Westinghouse's AP1000 or AREVA's EPR, or whether in the long term, the UK will need to adopt fast reactors if nuclear is to be sustainable. But one option that is often overlooked for the UK is the potential use of so-called "Small Modular Reactors" (SMRs). This paper introduces some of the potential SMR designs and technologies and provides an insight into the benefits and potential role of SMRs in the UK; economic benefit, grid demand smoothing, dedicated fuel cycle management (e.g. plutonium), supply chain advantages, enhanced safety and more flexible siting.

## Remaining Challenges for New Nuclear Build

The UK's energy policy review culminated in January 2008 with the production of the White Paper on nuclear power[2]. The major conclusions identified in that paper were that nuclear energy is:

- **Low-carbon** – helping to minimise damaging climate change
- **Affordable** – nuclear is currently one of the cheapest low-carbon electricity generation technologies, so could help us deliver our goals cost effectively
- **Dependable** – a proven technology with modern reactors capable of producing electricity reliably
- **Safe** – backed up by a highly effective regulatory framework
- **Capable of increasing diversity** and reducing our dependence on any one technology or country for our energy or fuel supplies.

This announcement laid the ground for the "requesting parties" (the reactor vendors and operators) to begin their assessments and undertake the preliminary steps towards licensing the technologies with the nuclear regulators, as well as begin the detailed economic assessments and contract negotiations and since 2008, there has been some notable progress.

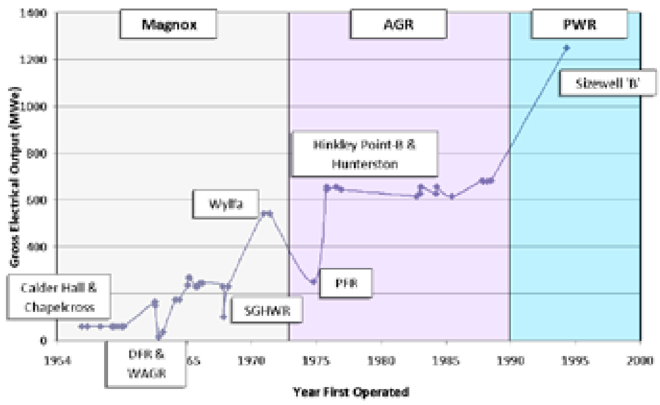



**Figure 1: UK Deployment of Reactors Over the Decades, Starting with Small Reactors**

Nevertheless, even though it appears inevitable that the UK will build new nuclear plants over the next few years, some key challenges remain. In many ways, the challenges that remain today are the same as those of the last few years; even though many believed that the argument for new nuclear build was compelling, there were many good reasons why none had been built for so long:

- With the high capital cost of the large, complex nuclear plants and the associated long build times, there was simply no driver for new nuclear build, especially when considering the uncertainty in the markets. The financing and need to raise the high levels of capital appear to be one of the remaining major hurdles for potential investors.
- The need for lower capital cost (via simpler designs, fewer components, or greater electrical output for same size plant) and lower operating cost (including higher plant reliability, less maintenance and shorter outages) are at the heart of the new designs being considered today.
- Financing a programme of nuclear reactors of several billion pounds results in a limited number of operators being able to afford to build and those that can afford to finance

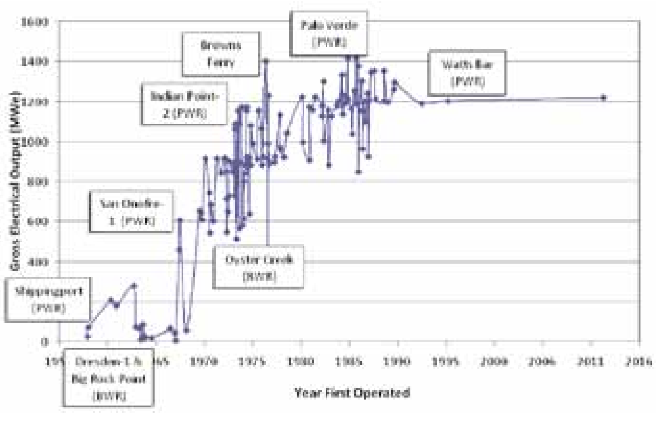



**Figure 2: US Deployment of Historic Fleet**

1 A range of between 16 and 90 GWe has been proposed: "UK Nuclear Fission Technology Roadmap: Preliminary Report", Energy Research Partnership, February 2012

2 "Meeting the Energy Challenge: A White Paper on Nuclear Power", Department for Business Enterprise and Regulatory Reform, January 2008

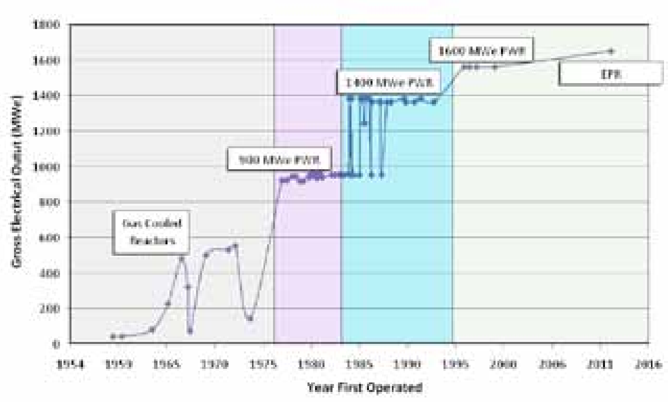



**Figure 3: French Deployment of Historic Fleet**

Data for Figures 1-3 taken from the IAEA Power Reactor Information System (PRIS) Database, September 2012)

such an undertaking need to be assured that all risks are understood and mitigated where possible.

- Government clarity and consistency in the energy market, in particular the work of the energy market reform, will reduce the perceived risk and uncertainty for potential investors.
- The low cost of other electricity generation, in particular gas, and no immediate capacity shortage meant that there was no urgency/need for new nuclear build over the last couple of decades.
- Post-Chernobyl and more recently post-Fukushima, the public concern over nuclear energy had been heightened. However, despite a dip in public support for the few months immediately after the Fukushima disaster, several months later the UK support for nuclear reached an all time high for new nuclear power stations to replace those being phased out. Furthermore, there has been an increasing trend in favour of nuclear energy in the UK over the last decade.
- Clearer transparency from the nuclear industry, an agreed long-term solution for the nuclear waste and assurance that nuclear energy will not be subsidised by UK Government/taxpayers, as well as the safety concerns, remains high on the public agenda.
- Streamlining of the licensing and approvals process (including the adoption of the GDA process etc) assists in removing the national energy/nuclear policy issues from the local planning requirements and as such, removes unnecessary delays.
- Particularly in the event of a larger nuclear capacity (way beyond the currently planned 16 GWe), siting and impact on the existing grid infrastructure becomes ever more paramount.

Although many of these issues are currently being addressed, the question remains as to whether the choice of nuclear reactor technology, specifically the use of SMRs, can either remove some/all of these issues completely or at least reduce the risks to the investors, the public and/or other stakeholders? Indeed, the role of SMRs could well be as part of a fleet of reactors that includes the larger plants such as AP1000 and EPR being considered today; it is not a choice of "either" / "or".

## How are Small Modular Reactors Different?

It is first worth defining what a "Small Modular Reactor" (SMR) is. Small reactors are defined by the International Atomic Energy Agency (IAEA) as those with an electricity output of less than 300 MWe, although general opinion is that anything with an output of less than 500 MWe counts as a small reactor[3]. Modular reactors are manufactured at a plant and brought to the site fully constructed. They allow for less on-site construction, increased containment efficiency and heightened nuclear materials security. The combination of these three facets in SMRs is intended to provide a flexible, cost effective energy alternative. However, not all SMRs are necessarily completely factory built. The SMRs do manage to provide some economies of scale, but by the number of units produced rather than their physical size. The philosophy is to then add an incremental number of these smaller units at the same site (sharing common facilities etc) as and when the electricity demand is there, or as and when the revenue from the previous units is such that another unit can afford to be built by the owners.

The concept of Small Modular Reactors (SMRs) is not new. Several design concepts emerged in the 1970s and early 1980s, initially motivated by optimism for the growth of nuclear energy around the world and potential future roles for nuclear e.g. desalination, district heating etc. An additional, later motivation came about from the lessons learnt from operating the larger Generation II Light Water Reactors (LWRs). For example, after the accident at Three Mile Island (TMI) in the USA in 1979, a new design intent introduced the principle of "inherent safety", which later became known as "passive safety". A significant study by Alvin Weinberg[4] stated "No new nuclear reactors have been ordered [in the USA] since 1978. The reason for this moratorium is that the safe operation of nuclear energy plants has been in doubt since the Three Mile Island crisis". The other main conclusions from that report included:

- Large light-water reactors pose very low risk to the public but high risk to the investor
- Large reactors are difficult to operate: complex and finicky
- Small inherently safe (highly forgiving) designs are possible if they can be made economically

These conclusions are still as equally valid today, although with the adoption of passive safety into the modern Generation III LWRs along with substantially more operating experience and other lessons learnt from TMI (for example, greater operator training), the second bullet point has been addressed to a large extent.

It is worth noting that the first commercial reactors built and operated in the UK were ***Small*** in energy output, if not always ***Modular***! For example, Figure 1 shows the historic trend in the UK, starting with small reactors of a few tens of MWe to today's much larger systems. The UK embarked on a new build programme in the 1950s with the Magnox reactors that were small in electrical output with a mission originally and primarily to do with plutonium production for the UK weapons programme. However, these reactors were never modular; the reactors cores are a cube of side approximately 12m and as such had to be constructed in-situ, plus every single Magnox station was unique in design! A similar evolutionary trend in reactor size can be seen in both the USA (Figure 2) and France (Figure 3).

3 "Status of Small Reactor Designs Without On-Site Refuelling", IAEA-TECDOC-1536, 2007

4 "The Second Nuclear Era: A New Start for Nuclear Power", A.M. Weinberg et al, Praeger Publishers, 1985

The trend to much larger plants was driven by a number of issues, including economies of scale, technology evolution and political/regulatory considerations (it takes about the same amount of time, effort and cost to gain approval for a small reactor as a large one, so on that basis, a large one may as well be built). So why has the trend potentially reversed to the re-consideration of SMRs around the world?

The SMR designs being proposed today are offering a similar philosophy to the original designs of the 1970s and 80s, but now enabled by excellent performance of the existing fleet of large nuclear plants, in particular the LWRs. The motivation in their design and potential implementation remains the same as the large nuclear plants (i.e., reduced $CO_2$ emissions, energy security and economics), but with additional proposed benefits, including safer new plant designs that require less investment:

**Reduced Capital Cost**: Clearly by building a smaller reactor, the capital cost will be smaller than for a large plant. However, per GWe, the capital cost of an SMR is likely to be higher as there are no economies of scale for the smaller plants, on a single plant basis. However, the benefit of several modules on one site (to achieve the same power output as a single or twin large unit) is that there is a notable reduction in cost through increased learning experience[5] and procurement strategy at a single site. The economy of scale is replaced here with the economy of serial production of many small and simple components and prefabricated sections, hence the "modularisation" part is key.

However, the major advantage that SMRs have regarding capital expenditure is that it allows more operators and/or investors the opportunity to consider a nuclear programme. For example, the level of investment for a single or twin large plant (of the order of several billion pounds) is not affordable to many companies, even in the richer parts of the world. Even with substantial consortia being established (such as the RWE nPower and E.On consortium, Horizon Nuclear Power in the UK), the ability of the companies to find the capital or the finance is often challenging or unpalatable. In smaller nations, such as in eastern Europe, South America, such a multi-billion investment would represent a large proportion of their Gross Domestic Product (GDP) and thus make it unfeasible as an option.

By use of a staggered build programme and the ability to build smaller units more quickly (for example three compared with five or six years for SMRs and large plants respectively), the total cumulative cash flow for an equivalent several-module unit on a single site has been shown to be of the order of one-fifth that of a single large plant[6]. As one module is finished and starts producing electricity, it will generate positive cash flow for the next module to be built.

**Competitive Electricity Generation Costs**: The benefits on the capital investment are not the only potential economic advantage for SMRs. Simpler, smaller designs with a reduced number of components (using passive safety features, for example) also have the potential for lower operating and maintenance costs as well as more flexible operating strategies e.g. easier to load follow using multiple, small plants than one large plant. Despite these potential economic advantages, the overall generating cost of SMRs are generally expected to be higher than those of large scale plants, because of the scaling effects noted earlier.

However, it should be noted that SMRs do not have to necessarily be as competitive as large nuclear plants. Instead, the comparison with the non-nuclear electricity generation types is the more relevant argument to make e.g., how competitive are SMRs compared with gas, coal and renewables? Furthermore, in certain instances (e.g., remote locations), the cost of electricity generation can be very large and therefore competitiveness of SMRs compared with large plants becomes irrelevant.

**Smaller Incremental Capacity Addition and Matched Power Demand and Growth Rate**: When the Pebble Bed Modular Reactor (PBMR), a high temperature gas SMR, was proposed, the major selling point was the ability to match the load demands and electricity growth needs of South Africa, as well as the additional benefit of not requiring a large national grid infrastructure to distribute the several GWe of large plants around the country; the PBMR module sites were to be positioned near the city that needed the electricity.

Large, fully industrialised countries have traditionally chosen reactors of $>1$ GWe as their market size and growth demands as well as grid infrastructure is able to support the large investment and plant size.

**Domestic Supply Chain**: There has been a great deal of discussion in recent years regarding the ability of the supply chain to provide the necessary components and expertise for new nuclear build. In particular, there remains concern over the large forgings such as the reactor pressure vessel (RPV) and the very limited number of factories in the world where these could be made. For SMRs, the major components are the same as for the large plants (RPV, steam generators, pumps, fuel etc), but the components are generally smaller, or at least fewer of them per unit. This is likely to mean that a greater number of domestic manufacturers will be able to supply a much greater number of components. In addition, the modular, factory build philosophy behind SMRs will mean that a much more substantial manufacturing base will have to be created in each country or region.

**Enhanced Safety from Simplified Designs**: As noted above, the SMR designs have taken the lessons learnt from operational experience of the large LWRs, including the likes of the accident at TMI. The resulting designs added additional levels of "robustness and resilience"[7]. These additional features not only enhance safety, but also assist in mitigating risk over investor and public concerns.

5 "IRIS – Economics Review", K Miller, ICAPP '05, Seoul, Korea, May 2005

6 "IRIS – Progress in Licensing and Toward Deployment", B. Petrovic et al, Nuclear Energy for New Europe 2006, September 2006

7 "An Overview of the Safety Case for Small Modular Reactors", D Ingersoll, ASME 2011 Small Reactors Symposium, Washington D.C., USA, September 2011

Despite a large variety of SMR designs, they tend to share a common set of design principles to enhance plant safety; (i) Eliminate potential accident initiators if possible (e.g., avoid loss of coolant accident (LOCA)), (ii) Reduce probability of an accident occurring (e.g., reducing vessel dose during operations reduces likelihood of RPV failure), (iii) Mitigate consequences of potential accidents (e.g., increased volume of primary coolant slow down potential heat-up accidents). Some of the typical features that enhance the safety, include[8],[9]:

- Incorporation of primary system components into a single vessel
- Increased relative coolant inventory in the primary reactor vessel
- Increased relative pressuriser volume (PWR specific)
- Smaller radionuclide inventory per reactor
- Vessel and component layouts that facilitate natural convection cooling of the core and vessel
- More effective decay heat removal
- Smaller decay heat per reactor
- Enhanced resistance to seismic events

**Enhanced Security from Siting Below Ground**: Since the reactor footprint is so much smaller, it makes it more economically viable than for large plants to locate the major reactor systems below ground. This significantly reduces the potential impact of external events such as aircraft collision or natural disasters. Locating the reactor below ground also reduces the number of paths for fission product release following an accident.

**More Flexible Siting**: There are a number of key criteria when determining if a given site is suitable for a nuclear reactor. For example, in the siting assessment report issued as part of the selection process for potential UK sites[10], the criteria included seismic, flooding, access to cooling water as well as the size of the site to accommodate works (including decommissioning of the existing facilities). As highlighted above, with SMRs often being located underground, sites that may have been excluded for larger plants due to seismic or other similar events, may well now be viable sites. Similarly, because the footprints of SMRs are smaller than larger plants and they need less cooling (as they have lower heat outputs per plant), they can be accommodated on sites that would otherwise have been excluded. This can most easily be seen in a recent US study that has shown that the use of SMRs (compared with large 1600 MWe plants) increases the percentage of US land that is viable for new nuclear build, from 13% to 24%.

**Adaptable to a broader range of energy needs**: The range of technologies proposed for SMRs is extensive and this has resulted in the potential of SMRs to fulfil a much broader range of roles, not just electricity generation. SMRs are a preferred option for non-electric applications that require a proximity to the customer such as seawater desalination, district heating and other process heat applications. The specifics of these do come down to technology choices, particularly if high temperature process heat is required.

Similarly, SMRs are proposed to have more flexible fuel cycle options, whether that is an "open" fuel cycle (i.e., direct disposal) or a "closed" fuel cycle (i.e., reprocessing and recycle). For example, a fast reactor SMR fleet could be envisaged as a dedicated reactor concept to manage plutonium stocks and minor actinide incineration. LWR SMRs could equally be used for plutonium management, as proposed for the IRIS (International Reactor Innovative and Secure) design[11] and with the potential of these designs to have a reduced or even avoid the need for an Emergency Planning Zone (EPZ), the designs could be ideally suited for such a mission.

**Decommissioning**: The modular nature of the reactor components not only assists in the construction of the plant, but will also ease the decommissioning timescales. With smaller modules, the ability to dispose of the entire unit could be feasible, including in the case of the cartridge type spent fuel. In addition, with many of the SMRs being based underground, there is the potential to back fill the site as is, simply removing the outer shell and buildings.

In summary, there are a range of key features, regardless of the specific technology, that makes SMRs attractive in certain energy markets:

- Ability to be accommodated into small electricity grids, including an option of autonomous operation
- Lower absolute overnight capital costs compared with large plants
- An option of incremental capacity increase that could perfectly meet the incremental increase of demand and minimise financial risk to the investor
- Reduced design complexity, use of passive safety and reduced operation and maintenance requirements
- More flexible range of roles for nuclear energy including energy production, district heating, desalination, plutonium management

In contrast, there also remain not just technical, but also institutional, regulatory and financial challenges that SMRs will need to overcome before the UK (or other countries) can expect to see any being built or operated. These are discussed in more detail later in this paper.

**"SMR technologies with a dedicated role and as part of a nuclear energy mix could prove to be advantageous to the UK."**

8 "An Overview of the Safety Case for Small Modular Reactors", D Ingersoll, ASME 2011 Small Reactors Symposium, Washington D.C., USA, September 2011

9 "Small and Medium Reactors: Status and Prospects", OECD-NEA Expert Group, OECD-NEA Publication, 1991

10 "Consultation on the Strategic Siting Assessment Process and Siting Criteria for New Nuclear Power Stations in the UK", Department for Business Enterprise and Regulatory Reform (BERR), July 2008

11 "Innovative Features and Fuel Design Approach in the IRIS Reactor", Carelli et al, OECD-NEA Advanced Reactors with Innovative Fuels (ARWIF) workshop, Chester, UK, October 2001

## Examples of SMR Technology

There are tens of SMR concepts and designs at various stages of development around the world today. Some are being developed by universities as pure research and teaching projects, others by private investors looking to break into the new build market and several by the large international reactor vendors. The list is too exhaustive to cover in this position paper, plus there is a huge amount of information readily retrievable from the internet and other sources. Therefore, the purpose of this section is to simply introduce the categories of design and a few of the designs in order to demonstrate the breadth in concepts. An attempt is also made to identify some of the remaining challenges facing the deployment of SMRs later in the paper.

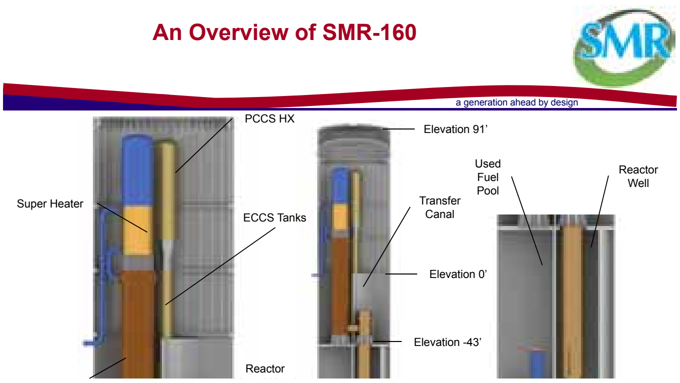
There are many ways to categorise nuclear reactors. They can be categorised by being "fast" or "thermal" reactors, by their coolant, open or closed fuel cycles etc. For consistency with the categories used by the IAEA, the OECD-NEA and the most recent US initiative on SMRs, the following categories, along with a few brief examples are described below:

- Light Water Reactors
- Gas Cooled Reactors
- Fast Spectrum Reactors
- Molten Salt Reactors

### Light Water Reactors

The LWR concepts are the most mature as they are based in one way or another on existing technology, operational experience and lessons learnt. The LWR designs are also where most of the significant investment money has been spent to date and work is still extremely active in this area, with tens of millions of Dollars currently looking to move these designs from concepts, through licensing and eventually to contracts being placed. This means that the LWR-based SMRs have the lowest technical risk.

The development of these options has progressed to the stage where they are starting the licensing submissions in the USA and a Memorandum of Agreement has been signed between the US Department of Energy (DoE) and three reactor vendors, two of which are PWRs (HI-SMUR and NuScale). One of the main themes in these designs is to have the key primary systems internally integrated e.g. steam generators, pumps, control rod drive mechanisms. In addition to electricity production, the




**An Overview of SMR-160**

LWR concepts have potential application primarily to district heating and desalination, as well as potential role in plutonium management.

Examples of LWR SMRs include:

- **SMR-160**: Holtec Inherently-Safe Modular Underground Reactor (HI-SMUR) is a 160 MWe reactor developed by Holtec International
- **mPower**: 180 MWe PWR from Babcock and Wilcox
- **NuScale**: 45 MWe PWR from NuScale
- Westinghouse SMR: 225 MWe PWR from Westinghouse

### Gas Cooled Reactors

After the operating experience of LWRs, gas cooled reactors have the next most operating experience, with a number of more advanced designs being looked at in the 1960s and 1970s e.g., the AVR in Germany and DRAGON in the UK. These developments have continued in recent years, in particular in China (with the HTR-PM) project and in the USA with the Next Generation Nuclear Plant (NGNP), in which the project is looking to develop, construct and operate a prototype high-temperature gas-cooled reactor (HTR) and associated electricity or hydrogen production facilities. The new designs could potentially generate high temperature helium either for industrial application as part of an indirect cycle via a heat exchanger or to make steam conventionally via a steam generator, or via a direct cycle to drive a turbine directly to increase thermal efficiency.

Examples of gas cooled SMRs include:

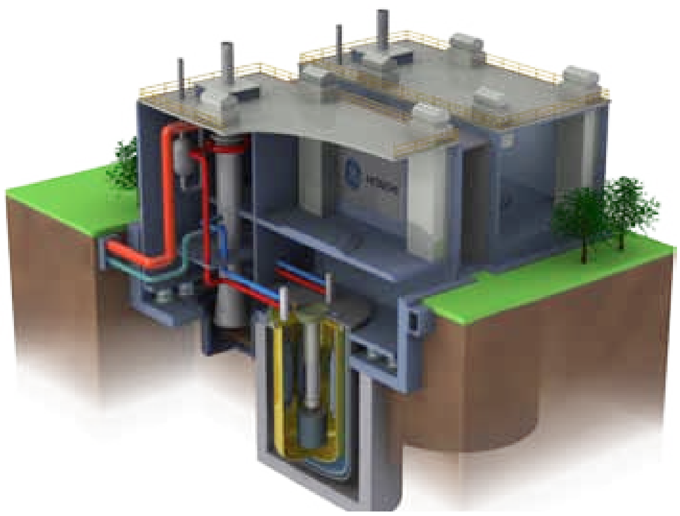
- **ANTARES**: 250 MWe HTR from AREVA that uses prismatic fuel
- **GT-MHR**: 285 MWe HTR from General Atomics that uses prismatic fuel
- **PBMR**: 80 MWe HTR from PBMR Ltd that uses pebble fuel

### Fast Spectrum Reactors

There have been a number of test/demonstration fast reactors around the world, including the Dounreay Fast Reactor (DFR) and Prototype Fast Reactor (PFR) in the UK; others include designs in France, Russia, Japan and the USA. The major difference with fast reactors compared with LWRs, is that they are designed to use the full energy potential of uranium via a full reprocessing recycle route i.e., closing the nuclear fuel cycle with the management of plutonium and consumption of minor actinides, which also means that any reactor technology development has to be in association with a similarly large programme on the fuel cycle technology. Typical coolants include liquid metal such as sodium, lead, or lead-bismuth, with high conductivity and boiling point, each of which carries its own challenges. They operate at or near atmospheric pressure and have passive safety features (most have convection circulating the primary coolant).

Examples of fast spectrum SMRs include:

- **4S**: 10 MWe Super-Safe, Small & Simple (4S) system by Toshiba and the Central Research Institute of Electric Power Industry (CRIEPI)
- **Gen4 Module (Hyperion)**: 25 MWe lead-bismuth cooled reactor from Gen4 Energy (formerly Hyperion)
- **PRISM**: Power Reactor Innovative Small Module (PRISM) by General Electric-Hitachi, each module is 311 MWe



**PRISM reactor cutaway**

### Molten Salt Reactors

The molten salt reactor technology comes into two distinct forms that need to be noted; one uses the molten salt solely as the coolant (the fuel is then in block form) and the other has the fuel integrally mixed with the coolant, as part of the molten salt (the fuel is a molten mixture of lithium and beryllium fluoride salts with dissolved enriched uranium, plutonium, thorium or U-233 fluorides). The fission products dissolve in the salt and are removed continuously in an on-line reprocessing plant and replaced with new fuel or fertile material. Actinides remain in the reactor until they fission or are converted to higher actinides, which also then fission. A demonstration design was run at the Oak Ridge National Laboratory in the 1960s (Molten Salt Reactor Experiment (MSRE)), but there has been relatively little development or investment in the MSR technology since then. Potential roles for MSRs, in addition to electricity production include minor actinide and plutonium consumption and for those designs that can use higher temperature salts, then process heat applications, including hydrogen production could be feasible.

Examples of MSR SMRs include:

- **AHTR**: based on the GT-MHR from General Atomics
- **Fuji MSR**: 100 MWe design from Fuji as an international consortium with Japan, US and Russia
- **LFTR**: 100 MWe design concept, Liquid Fluoride Thorium Reactor (LFTR)

## Potential Role in the UK

The full potential role for SMRs in the UK can not be fully realised until the role of nuclear energy for the UK is fully evaluated and developed. There is clear benefit and incentive in using nuclear energy for the UK to achieve its objectives of security of supply and $CO_2$ emission targets, whether that is purely for electricity production or indeed for transport, (via the use of electric vehicles). However, other roles for nuclear including district heating and industrial process heat have been considered, if not yet fully evaluated. In the event that there is an expansion in the use of nuclear energy beyond the current foreseen 16 GWe, then SMR technologies with a dedicated role and as part of a nuclear energy mix (e.g., larger plants dedicated to base load electricity supply, SMRs to more specific/niche application) could prove to be advantageous for the UK.

The ability for any organisation to raise the several billions of pounds finance for large nuclear programmes in the UK is challenging. Other mechanisms will need to be found if Government is to ensure that nuclear remains part of the UK's plans on the energy mix (whether that is part of the electricity market reforms, or the price of carbon etc), but as highlighted above, SMRs carry the distinct advantage of requiring less capital and provide a much faster return to the investors, thus exposing them to much lesser risks. In a relatively small market such as the UK and with a limited number of potential investors, a means by which more players can be brought to the nuclear energy market in the UK is required and SMRs could fulfil that requirement. It is unlikely that SMRs will be as competitive as the large nuclear plants in terms of p/kWh due to the loss of economy of scale, but in order to be economically viable, it is more important that SMRs are competitive with all of the non-nuclear electricity generation types, including gas, coal and renewables. A full economic assessment of SMRs in the UK context needs to be completed.

Following the public consultation on the management of the UK historic plutonium stocks, the Government recently announced that it will pursue a preliminary policy view that reuse of plutonium as MOX fuel is the best available option to manage the UK's plutonium stocks and any remaining plutonium that cannot be converted into MOX will be immobilised and treated as waste for disposal. Some of the SMR designs could be configured with a dedicated mission of plutonium management in mind. However, the Government's has yet to finalise its view on whether the mission goal for the UK is reduction or destruction of the plutonium stocks as quickly as possible, or construction of an integrated fuel cycle and use of the plutonium as a potential valuable resource in the future, (e.g., in fast reactors). Advantages of SMRs in any case would include:

- minimised capital investment to achieve the reactor re-use strategy
- with the potential reduction (or removal) of the emergency planning zone, the SMRs are a better fit for location at or near Sellafield where the plutonium bearing fuels would be manufactured. Similarly, the SMR electrical output is more compatible with the existing grid infrastructure at Sellafield.
- long lived cores to assist with proliferation resistance
- dedicated designs to enhance safe operations

In relation to specific siting issues, SMRs could also be of specific advantage to the UK. Given the limited existing nuclear sites in the UK that have been judged to be suitable for new build and given the limited land mass, the available land needs to be used efficiently and effectively. The current outline plan in the UK is for 16 GWe of nuclear as the minimum; EdF-Energy to host 6.4 GWe between Sizewell and Hinkley sites and Horizon Nuclear Power to host 6 GWe between Wylfa and Oldbury and NuGeneration to host 3.6 GWe near Sellafield. This means that of the 8 suitable sites identified by UK Government, 5 of these sites are already occupied. This would therefore leave enough sites for a further approximate 10 GWe, assuming large plants such as EPR or AP1000. Given that some of the estimates for nuclear energy demand would be of the order of 40-80 GWe, it is clear that either more sites need to be identified, or those existing sites need to be evaluated to see if they could accommodate additional capacity and SMRs could be the ideal way of achieving this, as highlighted above.

In addition, the existing UK sites will also be undertaking decommissioning of the old existing facilities over the next 10 to 20 years and so the available space on the sites will be limited for laying down new construction projects. The SMRs have the distinct advantage of having smaller footprints of each unit and faster construction times (estimated to be typically 3 compared with 5 or 6 years) and so it is likely that they could be more easily accommodated on the existing sites, even where decommissioning is taking place at the same time.

The use of SMRs on the old Magnox sites could also be advantageous as the number of units built could be matched to the electrical output capacity of the Magnox site, thus minimising the extent of any grid or interconnector upgrades required, particularly in the short terms. In addition, the tertiary cooling systems already in place for the Magnox stations would match that needed for the SMRs as they need less cooling water and this would minimise the additional works and costs at those sites.

A detailed assessment of the demands for new nuclear build in terms of capacity matching is also required in the UK. As nuclear and other energy forms go off the bars, a return of 2.5 to 3 GWe being put onto the grid may be too excessive, either causing impact on the grid infrastructure or on the electricity supply market and prices. SMR construction and operations could be more readily matched to these needs.

The Nuclear Industry Association assessed the UK capability for new nuclear build and it was found that UK nuclear supply chain could currently supply over 70% of a new nuclear plant, and with investment in resources and facilities, this proportion would be increased to over 80%[12]. The components that couldn't be sourced in the UK were primarily the large forgings e.g., reactor pressure vessel etc. For SMRs, it is highly likely that this proportion could increase further as the large forgings for SMRs are notably smaller than for the large plants like AP1000 and EPR. In addition to the individual components, the factory build concept of SMRs provides an additional opportunity for the UK supply chain. The reduced design complexity and reduced operation and maintenance requirements together could make SMRs a perfect vehicle to support local manufacturing and constructing industries in the UK. The factories could be based relatively nearby to the reactor sites such that the modules can be easily transported by road and rail over relatively short distances, unlike the large reactors where the components have to be brought in by sea barge.

**"Since none of the proposed SMRs are yet currently operating, or indeed being built, there still remain not just technical, but also financial, institutional and regulatory challenges to overcome before the UK (or other countries) can expect to see any being built or operated."**

## Remaining Challenges for SMRs

Since none of the proposed SMRs are yet currently operating, or indeed being built, there still remain not just technical, but also financial, institutional and regulatory challenges to overcome before the UK (or other countries) can expect to see any being built or operated. These are most easily summarised as follows:

### Technical

Even the LWR SMRs have some degree of innovation and therefore research and development is still needed. For example, many of the LWR SMRs are integral reactors and so the configuration of the primary systems needs optimising and then testing. Similarly, the internal control rod drive mechanisms and pumps will need designing and testing too, particularly in the case where the reactor is based along way underground. Use of natural circulation in some of the LWRs requires demonstration too in the final configurations and as importantly, the development of modelling and simulation tools to accurately predict these phenomena will be required.

Several of the LWR SMRs also have long-lived cores e.g., the "cartridge" fuel loadings for 2 to 4 years without refuelling. These carry their own development needs, including looking at the performance of the fuels under either increased control rod movements or higher burnups. With ever increasing asymmetry in the fuels, the ability to accurately predict the neutronics, thermal hydraulics and fuel rod thermo-mechanical performance could also be an issue. Similarly, the ability to manufacture these fuels and complete associated irradiation trials and post irradiation examination may be required. The use of long lived, single burn cores also carries with it a fuel cost penalty as the fuel is burnt inefficiently. As such, solutions to improve the fuel efficiency is also required. This would include the consideration as to whether single burn cores were suitable for reprocessing and recycle of spent fuel, if such a fuel cycle was judged to be relevant to the future UK scenarios.

For the non-LWR SMRs, it is clear that further R&D will be required. Typically this will include developments of high burnup fuels with high fissile and/or minor actinide loadings and their associated fuel manufacturing routes. With the higher burnups and more demanding environments (higher fluxes, temperatures and demanding chemical environments) comes the need for the development and testing of new resilient materials. The need for new inspection techniques goes hand in hand with these new materials.

Overall, there will also be developments required in the modular construction techniques used to ensure high quality of the products and a high volume of throughputs from the SMR factories.

### Financial

The major obstacle for new nuclear build is the investment levels required and the resulting number of utilities that have the appetite for nuclear construction, even if only for SMR levels of investment. The true capital costs for SMRs therefore still needs to be demonstrated and until designs are finalised, contracts are placed, and the first of a kind (FOAK) costs and the learning benefits for subsequent units are known, there remains a significant amount of financial risk.

### Institutional

The UK is still evaluating and coming to grips with the full potential of nuclear energy, not only in terms of electricity generation, but nuclear's potential to de-carbonise transport, its role in district heating and/or industrial heat needs. The timescales for SMRs are not in the short term and as such, it appears that perhaps these decisions do not need to be taken now? But this short sightedness of the potential of any new technology to solve future issues is not a sensible approach. Evaluating the most appropriate role for nuclear, followed by the appropriate technologies will help determine where the UK could/should invest time and effort to either better understand the technology and solutions, or to develop new UK technology. SMRs would fit into this category.

However, since the 1980s and 90s, the decline of the UK's nuclear research and development base, particularly that associated with reactor technology, has meant that the UK no longer takes the lead in civil nuclear reactor development, although there is still a strong capability in naval propulsion in Rolls Royce. There is still limited involvement as partners in collaborations (such as those in the European Union as part of the Euratom Framework Programmes), but the UK plays a relatively small role in these programmes and has very little activity in the development of SMRs today. Similarly, the UK has become a buyer of existing reactor technology, buying only that technology that has already been constructed elsewhere. It is likely that this would be the same for SMRs and as such, the timescales for the deployment for SMRs in the UK is still some time away.

There is also a current mindset that "big is beautiful" as the earlier trends from the UK, US and France have shown. With the nuclear "hassle factor" to gain approvals for siting, licensing etc, irrespective of the size of the reactor output (i.e., same process regardless of whether its 100 MWe or 1000 MWe), this trend is likely to continue unless the proposed SMR advantages can be demonstrated.

### Regulatory

Many of the proposed SMRs use new technology, some more so than others, but above all, the SMRs tend to be more revolutionary than evolutionary and as such requires a different approach and consideration by the regulators. This inevitably carries regulatory risk and potential delay as additional testing of components may be required, ability to accurately predict operational and safety performance has to be demonstrated etc. In the case of fast reactors, high temperature gas reactors or molten salt technology, their low technology readiness levels will mean greater level of demonstration than the LWR SMR technology.

Similarly, these reactors are less familiar to the regulators and indeed the level of expertise in a given technology or phenomena associated with that technology may be lacking or limited in a regulatory authority. Therefore, it is vital that any new SMR being even considered for market in the UK needs to engage with the regulators early. Similarly, the UK also needs to ensure that the appropriate level of expertise as well as a future "skills pipeline" is in place in order to develop knowledge base in the UK for intelligent customer and regulatory roles in the future. Licensing of LWR SMRs using even the likes of natural circulation themselves carry risk and will require greater level of demonstration of ability to cool, accurately predict flow rates etc.

All of this means that the regulators need to retain an open mind to new technologies, new phenomena and even a paradigm shift in acceptability of risk e.g., the potential of some SMRs to have no emergency planning zone and hence can be located near/next to high population densities or key industrial facilities. Other issues that need to be considered include control room operations and licensing and management of 10 modules concurrently (rather than 1 unit) and monitoring of several reactor constructions on one site.

## Conclusions

There are a substantial number of Small Module Reactor (SMR) concepts and designs at various stages of development around the world today. Some are being developed by Universities as pure research and teaching projects, others by private investors looking to break into the new build market and several by the large international reactor vendors.

Small reactors are defined by the International Atomic Energy Agency (IAEA) as those with an electricity output of less than 300 MWe, although general opinion is that anything with an output of less than 500 MWe counts as a small reactor[13]. Modular reactors are manufactured at a plant and brought to the site fully constructed. They allow for less on-site construction, increased containment efficiency, and heightened nuclear materials security. The combination of these two facets in SMRs is intended to provide a flexible, cost effective energy alternative that makes SMRs attractive in certain energy markets:

- Ability to be accommodated into small electricity grids, including an option of autonomous operation
- Lower absolute overnight capital costs compared with large plants
- An option of incremental capacity increase that could perfectly meet the incremental increase of demand and minimise financial risk to the investor
- Reduced design complexity, use of passive safety and reduced operation and maintenance requirements
- More flexible range of roles for nuclear energy including energy production, district heating, desalination, plutonium management, all potentially operating on either an "open" fuel cycle (i.e., direct disposal) or a "closed" fuel cycle (i.e., reprocessing and recycle)

It is clear that the capital investment required for new nuclear build in the UK is extremely challenging, particularly in the current economic climate. The ability to raise several billions of pounds for a twin unit is only possible by a few utilities in Europe and has seen the formation of consortia in the UK to look to address this issue e.g., Horizon Nuclear Power, NuGeneration. However, the major advantage that SMRs have regarding capital expenditure is that it allows more operators and/or investors the opportunity to consider a nuclear programme. With a cumulative cash flow for a fleet of SMRs being a fraction of that of large nuclear plants due to less capital outlay per unit, faster construction time and staggered build where as one module is finished and starts producing electricity, it will generate positive cash flow for the next module to be built.

This is not to say that the generating costs of SMRs will be less than large nuclear plants and in fact it is likely that they will be slightly higher. However, the issue is not over SMRs being competitive with other nuclear technology, but moreover, does

13 "Status of Small Reactor Designs Without On-Site Refuelling", IAEA-TECDOC-1536, 2007

this allow a nuclear programme to be undertaken in the first instance and is the SMR generating cost competitive with the likes of renewables and fossil?

Furthermore, the full potential role for SMRs in the UK can not be fully realised until the role of nuclear energy for the UK is fully evaluated and developed. There is clear benefit and incentive in using nuclear energy for the UK to achieve its objectives of security of supply and $CO_2$ emission targets. However, other roles for nuclear including district heating and industrial process heat have been considered, if not yet fully evaluated. SMR technologies with a dedicated role and as part of a nuclear energy mix (e.g., larger plants dedicated to base load electricity supply, SMRs to more specific/niche application) could prove to be advantageous for the UK.

There are a variety of SMR technologies that could be proposed for the UK in the next few years, not just for electricity generation, but with specific missions in mind e.g., the GE-Hitachi PRISM reactor for plutonium management. With this in mind, Regulators need to be engaged with early if SMRs are being considered for the UK, particularly for non-LWR technology. Therefore, the UK also needs expertise and/or a sustainable "skills pipeline" to develop and maintain an appropriate knowledge base in the UK to fulfil an intelligent customer AND regulator role. It is clear that the LWR concepts are the most mature at this time (as they are based on existing, operating technology) and are currently the designs with the most investment backing behind them, as well as being the closest to market.

If the UK is to undertake a large growth in nuclear energy (up to 80 GWe has been speculated), then in addition to the finances, one of the limiting factors for the UK will be availability of suitable sites. SMRs have specific advantages because their small footprint allows a number of them to be sited into smaller areas and as such the use of the existing sites in the UK can be optimised further. In addition, it will be easier to construct SMRs on the same sites as those reactor sites where decommissioning is taking place in parallel.

This paper has attempted to provide an insight into the benefits and potential role of SMRs in the UK; economic benefit, grid demand smoothing, dedicated fuel cycle management (e.g. plutonium), supply chain advantages, enhanced safety and more flexible siting. The designs are varied and are several years from being ordered or indeed constructed with some technical, financial, institutional and regulatory challenges remaining. Nevertheless, it is clear that there are potential benefits to the UK nuclear growth agenda whether that is from the perspective of opening up nuclear to more prospective participants (as the capital cost is so much lower), from the role that SMRs can play in the UK or the advantages with regard to the siting. However, more work is still required to confirm these potential benefits.

Once the UK has determined its future nuclear strategy and future scenarios and if this conclusion calls for the greater role of nuclear energy (for example, greater than the envisaged 16 GWe of new nuclear capacity foreseen today), then there are several recommended activities that need completing:

- An assessment of the economics of SMRs is undertaken in the UK including the potential financial models. An understanding is needed to mitigate the risk of not only First of a Kind (FOAK) engineering, but also FOAK business and financial models.
- A siting study should be completed for SMRs in the UK to determine if there are any advantages to be gained over larger nuclear plants, both in terms of total generating capacity that is possible to site on existing sites and what the size of the construction area would be for SMRs on existing sites.
- An assessment of SMR technologies for a range of roles in the UK should be complete, including district heating, industrial heat supply and plutonium management. The findings of such a study could drive the potential nuclear choices in the future, including SMRs.
- The UK skills and manufacturing base should be reassessed for SMRs, including the potential for factories in the UK to manufacture the full required modules for SMRs. This activity should be linked into the Nuclear Advanced Manufacturing Research Centre in Sheffield.

## Glossary

| | |
|---|---|
| **DFR** | Dounreay Fast Reactor |
| **DOE** | Department of Energy |
| **EPR** | European Pressurised Water Reactor |
| **EPZ** | Emergency Planning Zone |
| **FOAK** | First of a Kind |
| **GDA** | Generic Design Approval |
| **GDP** | Gross Domestic Product |
| **GT-MHR** | Gas Turbine Modular Helium Reactor |
| **GWe** | Gigawatt electrical |
| **HISMUR** | Holtec Inherently-Safe Modular Underground Reactor |
| **HTR** | High Temperature Reactor |
| **IAEA** | International Atomic Energy Agency |
| **INPRO** | IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles |
| **INS** | Innovative Nuclear Systems |
| **JAEA** | Japan Atomic Energy Agency |
| **KAERI** | Korea Atomic Energy Research Institute |
| **LFTR** | Liquid Fluoride Thorium Reactor |
| **LWR** | Light Water Reactor |
| **MOX** | Mixed Oxide |
| **MSR** | Molten Salt Reactor |
| **MSRE** | Molten Salt Reactor Experiment (Oak Ridge) |
| **MWe** | Megawatt electrical |
| **NGNP** | Next Generation Nuclear Plant |
| **NNL** | National Nuclear Laboratory |
| **PFR** | Prototype Fast Reactor |
| **PBMR** | Pebble Bed Modular Reactor |
| **PRIS** | Power Reactor Information System (IAEA) |
| **PRISM** | Power Reactor Innovative Small Module (General Electric) |
| **PWR** | Pressurised Water Reactor |
| **RPV** | Reactor Pressure Vessel |
| **SMR** | Small Modular Reactor |

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