Why SMRs with Supporting Fuel Cycle Facilities Represent a Golden Opportunity for UK Business

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Executive Summary

The Government's recent decision to proceed with the Hinkley Point C Nuclear Power Plant has been an essential step on the road to nuclear renaissance in the UK, and this project is most likely to be followed by others. Although Hinkley Point C is a large nuclear plant, there is also renewed interest in smaller designs for the future, such as Small Modular Reactors (SMRs) due to the possibility of automated pre-fabrication and data exchange, permitting efficient factory construction, and hence shorter deployment times. The UK Government's interest in the potential benefits offered by SMRs was first set out in the Nuclear Industrial Strategy, published in 2013 and more recently has been confirmed by announcement of a competition to identify the best value small modular reactor (SMR) design for the UK. The UK has unique history, capabilities, facilities and nuclear materials as a result of its nuclear research, development and operations over the last half century. In alignment with advances in digital technology and its strategic level alignment and implementation, this experience can be used to place the UK in a strong position for deployment of SMRs.

These advantages offer an exciting opportunity to:

- Enable nuclear power to work in harness with renewables for carbon free energy
- Enable a much larger proportion of the world's population to access nuclear power
- Implement a sustainable solution to the problems of nuclear waste

Introduction

There has been a break in the development of nuclear power in the UK since the most active period from the late 1940's to the early 1980's. That time has now firmly come to an end with the go-ahead for construction of the Hinkley Point C Nuclear Power Plant. The reasons for Hinkley Point C were based on converting to carbon-free energy and the need for a reliable base-load electricity supply to back up renewable energy sources which are inherently diffuse and intermittent. Hinkley Point C has been an essential step on the road to nuclear renaissance, without which the talent and infrastructure of the nuclear industry in the UK may have declined to sub-critical levels. This first step is likely to pave the way for other plants at sites such as Wylfa, Oldbury, Moorside, Bradwell and Sizewell.

The future for nuclear power in the UK is brighter than it has been for a long time.

Economies of scale have normally resulted in very large nuclear reactor designs of about 1,000 MWe. However, smaller designs would allow transportability of constructed modules to site (hence the potential for cheaper and more efficient factory production and shorter deployment times). There is also a need for geographically diverse sources of electricity supply located close to centres of consumption, also thereby mitigating risk in regard to faults or interruptions.

All new projects must allow for decommissioning at the end of life, and the smaller size of SMRs provides an important advantage when it comes to the removal of the nuclear components from site at the end of their useful life, a process which the UK are able to deliver through digital platforms and the commitment to the Governments Directive on Building Information Modelling (BIM) Level 2.

The UK Government's interest in the potential benefits offered by SMRs was first set out in the Nuclear Industrial Strategy, published in 2013 [1]. In particular, the government recognized that SMRs may have the potential to enable shorter deployment times, reduce the costs of nuclear power for energy consumers, and present a possible area of high value opportunity for UK industry.

In March 2016 the Government announced that it will invest £250m in an ambitious nuclear research and development programme, enabling the UK to be a global leader in innovative nuclear technologies. This includes a competition to identify the best value small modular reactor (SMR) design for the UK [2].The foregoing discussion is all well known, but there are certain other advantages of SMRs, and most particularly the potential for their exploitation by the UK with our unique nuclear history and capabilities, together with our facilities and materials. The UK has for many years produced and fueled its own SMRs, made by Rolls Royce, for the Royal Navy's fleet of nuclear submarines. UK companies such as Moltex are developing new designs of reactors for the future. This provides an excellent springboard for the deployment of SMRs, initially within the United Kingdom, but then through export to other countries. The export to other countries is likely to be limited in the first instance to those countries which have an established nuclear power generation network. These first two steps are a pre-requisite for the final step, which would be to supply SMRs to countries which do not currently have nuclear power. This represents a much larger potential market. The way this might be done is now explored.

SMRs

SMRs are typically defined as nuclear reactors with less than 300 MWe output, in contrast to the typical full scale reactors greater than 1,000 MWe. The UK already has experience with constructing SMRs for its fleet of nuclear submarines. The world's very first nuclear submarine, Nautilus, had a power output of just 10MW, whereas the largest submarine and marine reactors now have an output of up to 500MW thermal (approx. 150MW shaft power) [3]. The current reactors are all based on the pressurized water reactor (PWR) concept, which uses uranium fuel and light[1] water as the coolant and neutron moderator. Very high power density (and hence compact size) is achievable with this design, which is particularly favourable for mobile reactors.

Several countries are now developing SMR concepts for land-based duty and these are designed to take advantage of the features of factory build, easy transport to site (e.g. by ship) and hence short deployment time in order to reduce costs. It is natural that the majority of these proposals are based on the tried-and-tested PWR. In the longer term, however, the relatively poor neutron economy of a light water coolant and the low temperature (and hence low thermal efficiencies) of the PWR are likely to drive towards other designs.

Despite the preponderance of PWRs there is already a significant proportion of SMR proposals based on high temperature reactors and helium coolant [4]. There is also interest in the molten salt cooled reactor system (first pioneered in the USA in the early days of nuclear power), of which the Moltex Energy Stable Salt Reactor (SSR) is an important UK-based example.

Relationship between SMRs and the Fuel Cycle

The majority of the world's large nuclear plants operate an open (once-through) fuel cycle. The lightly enriched uranium fuel is replenished during operation and the discharged spent fuel is stored in ponds or casks pending ultimate disposal. Usually the spent fuel remains on the reactor site because of the complexities and costs of transporting it away and the lack of economic options for dealing with it immediately. Only about 1% of the uranium originally mined for the fuel is actually used, the remaining 99% being discarded either as depleted uranium during the enrichment process, or as unburnt uranium in the discharged spent fuel. The much-publicised longevity of nuclear waste ("dangerous for hundreds of thousands of years") is also primarily an issue of extra waste products arising from the once-through fuel cycle. Fission products, which are the truly irreducible waste products of the nuclear fission process, become essentially harmless by radioactive decay within a few centuries and certainly within the timescale of robust and secure management by containment and burial.

The open fuel cycle as widely practiced today was never envisaged as anything other than a stepping stone at the outset of the nuclear age - the goal was to achieve far greater

[1] "Light" Water refers to ordinary natural water. Water is made up of hydrogen and oxygen, and natural hydrogen can be processed to separate out the small proportion of the heavier isotope, deuterium. If this is done the resulting water is referred to as "Heavy" water. Nuclear fission is more efficient if heavy rather than light water is used, but the production and use of heavy water causes additional complications.

efficiency through reprocessing and recycle of the fuel (including use of the depleted uranium arising from the enrichment process). That goal was technically achievable and indeed has in part been achieved commercially, particularly in the UK and France. In China, there is a clear commitment to moving towards a closed fuel cycle and there are plans to achieve that by the middle of the century [5].

There is an obvious need for nuclear power to be able to come and ultimately to go without leaving any trace. It is also obvious that SMRs provide the potential for exactly that. A simple example would be a nuclear powered submarine or ship sailing up to an isolated community, docking and coupling its reactor to a steam turbine on-shore, generating power for that community for a period and then sailing away. It should be remembered that a nuclear submarine's reactor could supply electricity sufficient for a community of about 100,000 people. There is no new or unestablished technology needed for this option. The community would pay to have power for the appropriate period, but (other than in the event of a major nuclear accident) would have no long term consequences or waste to deal with. The reactor would be the responsibility of its progenitor nation, which would be paid to provide the reactor and the fuel (and possibly to operate it), to transport the reactor to and from the site and deal with the resulting waste. In the example quoted it is particularly convenient that the reactor system is self-propelled, but it doesn't have to be like that – the reactor, fuel and attendant radiation shielding could be transported by conventional means. With this general concept nuclear power could be supplied to a far wider proportion of the world's population than at present. It could also be used not just for electricity generation but for other purposes such as water desalination and district heating.

In order to minimise transport operations the reactor should be able to operate without refueling for as long as possible - ideally at least a few years. Nuclear submarines can already operate for life on a single charge of fuel (up to 50 years operation in extreme cases), but that requires highly enriched fuel which might involve difficult security implications for a civilian operation. Nevertheless, with lower enrichment but good neutron economy in advanced SMR designs, fuel burn-ups towards 300,000MWd/Te (equivalent to about 30% burnup of the fuel atoms) would ultimately be possible compared with conventional PWR cores of around 50,000 MWd/Te. This would extend time between refueling from the typical PWR interval (about 1.5 years) towards 10 years and possibly longer.

For the countries supplying the fuel and reactors, and taking back the waste, there needs to be a better end-point than storage of all the spent fuel in ponds and casks. The concept as a whole would only really work if there is a closed fuel cycle where the fuel is recycled and resupplied in the replacement reactors. Of course the UK has for decades been a world leader in nuclear fuel reprocessing, which would give the country a good start even though the fuel recycle for this concept is unlikely to involve traditional PUREX-type reprocessing.

It makes sense for a small number (rather than all) of the nations to take the responsibility for the nuclear facilities – the amounts of material involved in nuclear operations are physically quite small and there is no need to replicate complex fuel reprocessing and waste management facilities in lots of different places. Provided the operations are properly designed and regulated the risks to a community hosting such facilities should be very small, and not significantly greater because they are undertaking the operations on behalf of other nations as well. Some nations have particular advantages, for example they might have dry geology and remote unpopulated areas which are advantageous for sub-surface nuclear waste storage or disposal.

From the foregoing it can be seen that the UK's long experience with the fuel cycle would be a prime advantage for a business based on leasing SMRs.

Nuclear Materials

The past legacy of the UK's operations has built up a stock of unique nuclear materials. For the purpose of this article the two most important materials are uranium and plutonium, stored respectively at Capenhurst (principally) and Sellafield. The amount of uranium in store at Capenhurst is stated as 46,500 tonnes consisting of depleted uranium hexafluoride "tails" from the uranium enrichment process, and uranium trioxide recovered from the Magnox reprocessing operations. If all that uranium were subjected to nuclear fission in power stations it has an energy value sufficient to supply all of the UK with all its electricity for about 1,000 years at the current rate of consumption [6]. There is no shortage of fuel for this option – the UK already has plenty. The depleted uranium on its own is not a suitable fuel for SMRs, but there is a stock of some 100 tonnes of separated plutonium at Sellafield, which when mixed with the uranium in the right proportions would provide an appropriate fuel for new SMR reactors. Mixed Oxide (MOX) fuel of this type is well established even though the UK's recent experience of producing it has not been an entirely happy one. If the UK were to provide fueled SMRs as a business, the returning reactors would in due course provide recycled materials to extend the life of the materials in store, and the materials could in any cases be supplemented as required by small quantities derived from more conventional sources (e.g. enriched uranium).

Waste

As far as waste is concerned in this scenario the normal possibilities of deep geological disposal with engineered barriers would be available, but a totally new approach might also be possible. The heat generated by nuclear waste is currently seen as a grave disadvantage for its disposal, but so long as the waste is properly immobilized and contains only fission products, it could be placed in a location where the heat produced could be usefully used until it effectively runs out (a few decades later). The waste needs to be placed in a sub-surface location where it is safe from external impact and from which its clandestine extraction would be very difficult to achieve. The heat would be brought to the surface by a heat exchange system and that process would go on until it becomes uneconomic to extract the heat any longer, after which the waste can then be isolated and left where it is since the long term hazard will be small and diminishing within a few hundred years to levels equivalent to uranium ore. The extracted heat would, of course, be low grade and possible uses include the provision of domestic heating in remote communities, or heating for enhancing agricultural production (greenhouses, fish farms etc.). Typical initial output of a one tonne waste canister would be about 25kW, falling by about a factor of 10 over 100 years.

There will of course be low-level waste arising from operations as well as the high level waste arising from the fuel referred to above, but there are well established conventional methods for handling the relatively small quantities of materials involved, which in any case only constitute a fraction of the total hazard.

Partnership

This article is looking at the UK's natural strengths for instigating a business based upon supply of SMR reactors. There is nothing, however, to stop the UK from joining with other countries to develop this business. The best partners may be nations such as China, USA, South Korea, Japan and France who all have the greatest global nuclear power generation ambitions. It may also be that the best potential partners are those which have particular characteristics which would support and enhance the proposal. In recent times South Australia has shown interest in developing the nuclear fuel cycle and waste management, and this has been examined in a Royal Commission report in that state [7]. South Australia has many advantages such as availability of uranium and suitable places for waste disposal. The nuclear experience of the UK and its nuclear materials might suit a partnership with South Australia.

The Importance of "Digital" BIM Technology and Enterprise Life Cycle Management (ELM)

The construction of nuclear plants has sometimes suffered from problems of poor quality and schedule delays, and these problems have in some cases caused significant detriment to the economics of the projects. Because of the massive size and longevity of operation of traditional nuclear power plants it is almost inevitable that these complex construction projects are undertaken very infrequently, and each project is usually undertaken in a new location with a new team. Each project is effectively "first of a kind" and this does not offer the possibilities of improvement through replication. The SMR concept can change that, because the units can be produced in exact replica many times by the same organisation. Applying automation and data exchange in their manufacturing technologies. Another huge benefit of such replication is that it affords the possibility of high quality through the application of digital technology. The importance of this latter point can hardly be overstated, since the highest possible quality of construction and operation is obviously essential for the safety of the plants, as well as for the economics.

A fully BIM based solution allows the possibility in the future of an 8D Virtual Reactor solution where one could potentially model the asset performance inclusive of the process which could facilitate quicker licensing, more efficient optimized operations, life-time extension and decommissioning scenarios. In other words, a "Digital Twin" is the future.

The development and production of SMRs in the UK affords an enormous opportunity for export worldwide as described in this article and can employ automated pre-fabrication, modular construction and manufacture using the latest digital BIM and ELM solutions and their strategic level implementation for which Waldeck are at the forefront.

Licensing

The concepts described in this article will potentially involve interactions between different licensing and regulatory regimes, and, as stated above, it would be obviously desirable to test out the licensing aspects of all parts of this proposal by undertaking the concept entirely within the UK to start with so that there is only one national regulatory regime to deal with.

Conclusion

With new nuclear power firmly back on the agenda for production of carbon free electricity in the UK, the government has expressed its interest in new developments based on SMRs. At the moment the interest is focusing on comparing the various designs of SMRs for possible application in the UK, but equally important is the potential business opportunity for exploiting the UK's strong history, facilities and experience, and nuclear materials stocks. This article argues that the combination of these factors places the UK in a strong position to supply fueled SMR reactors to generate power in other countries and to take back the reactors and manage the waste at the end of life. Digital design, capture and validation will be fundamental to ensure high quality and safety, and this can be assured by employing automated pre-fabrication, modular construction and manufacture using the latest digital BIM and ELM solutions and their strategic level implementation for which Waldeck is at the forefront, affording an enormous opportunity for UK export worldwide.

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