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Author for correspondence:
Sue Ion
e-mail: s.ion@ic.ac.uk

Challenges to deployment of twenty-first century nuclear reactor systems

Sue Ion

Department of Materials, Imperial College, Exhibition Road, London SW7 2AZ, UK

SI, 0000-0002-1527-0199

The science and engineering of materials have always been fundamental to the success of nuclear power to date. They are also the key to the successful deployment and operation of a new generation of nuclear reactor systems and their associated fuel cycles. This article reflects on some of the historical issues, the challenges still prevalent today and the requirement for significant ongoing materials R&D and discusses the potential role of small modular reactors.

1. Introduction

The first commercial nuclear power stations started operation in the 1950s. At the start of January 2016, there were about 440 commercial nuclear power reactors operable in 31 countries. Sixty-five more reactors were under construction, 173 are on order or planned, a further 337 are proposed (http://world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx). Currently, some 56 countries operate a total of about 240 research reactors and a further 180 nuclear reactors power some 140 ships and submarines; so as it stands today around just under 11% of global electricity is provided by reliable, baseload, low carbon, nuclear power. The bulk is still provided by fossil fuels of one sort or another. As we seek to try to curb carbon emissions, nuclear power along with renewable sources of energy will be increasingly important [1]. In regions of the world with significant state intervention e.g. in China and India, construction of new nuclear power plants continue apace. But in areas where the free market prevails, the economic construct for nuclear energy is stalling the necessary investment.

The cost of nuclear energy is dominated by the cost of capital and its financing through to the point of generation. This is why plants such as Hinkley

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Point with its very large capital outlay and long construction duration are proving so difficult to get off the ground. In deregulated markets like the UK's, there is increasing support for the concept of much smaller reactors which have a lower capital outlay and a much speedier construction schedule largely within a factory rather than at site [2]. The generating cost benefits of large-scale plants and the well-developed nature of the grid have never made them attractive. This is changing for a number of reasons but in particular the increase in the proportion of electricity generation from renewable and dispersed generation. The need for flexibility, rotational inertia (large turbo-generators) and load following capability is also a contributory factor. Research initiatives targeted to take even modest amounts off the capital cost and increase speed of deployment are likely to have a very significant impact on the overall cost of generating electricity and hence are the focus of recent and future Innovate UK and BEIS calls for proposals.

2. Reactor systems in operation and planned for early deployment in the UK

Contrary to many beliefs, nuclear reactor technology is not mature. Although over 11 000 reactor-years of experience has been gained to date and there are over 400 reactors operating worldwide, the vast majority of the currently deployed reactor systems are only second generation systems. Given the life cycle of these reactor systems, this means that bringing new innovations to market can take many years. It also means that while extending the lives of existing nuclear power plants can be demonstrably the right thing to do, there are many challenges more often than not associated with materials understanding and performance. For example, the continued safe operation of the UK's 14 advanced gas-cooled reactors is underpinned by detailed study of the evolution and behaviour of the graphite moderator material. In this type of reactor, the graphite acts as a structural component as well as a moderator for neutrons. A typical core has over 300 fuel channels and 12 layers of graphite bricks each one being 830 mm high and 460 mm in diameter and linked together by a keying system, which allows the structure to move. Radiolytic oxidation during operation results in weight loss and changes in density, physical and elastic properties and fast neutron irradiation causes changes in dimension and in physical and mechanical properties. Relatively new techniques such as three-dimensional X-ray tomography are providing new insights into the three-dimensional structure of nuclear graphite and enabling a more accurate analysis of physical and mechanical properties [3].

Third generation systems are now being offered in the market, notably for the pressurized water reactor (PWR) variant, Westinghouse's Advanced Passive 1000 (AP1000) system and Areva's Evolutionary Pressurized Water Reactor (EPR) system. Both of these are the culmination of developments over the past decade or so and offer evolutionary improvements on light water systems. For example, the AP1000 offers some very novel passive safety features that rely on natural processes such as gravity and convection, which eliminates the need for active safety systems or operator invention in the event of an accident scenario. Likewise, the EPR reactor offers novel features such as molten core catcher and improved performance characteristics, systems layout and safety control systems. This approach is based on using the experience gained to date in improving the overall safety of systems while making them simpler and more economic. Likewise the developments made in boiling water reactor technology with the Advanced Boiling Water Reactor offered by Hitachi-GE. All three of these systems will be deployed in the UK over the coming decade.

For light water reactors (LWRs) where the original design intent was for a lifetime of 30–40 years, the long-term behaviour of material could not be accurately determined at the outset. Designers did not necessarily know the fine points of the materials the fabricators were installing or sufficiently appreciate the effects of residual stresses and strains. Although new techniques allow us to predict and measure phenomena which were not even known in the early days of nuclear power, long term now means 60–80 years not 40 and a global supply chain determines choice of fabricators. Understanding material properties and quantifying and validating both the materials themselves and the processing route they have experienced, in extended conditions of temperature, environment and time, is vital. This means that fundamental and applied materials research coupled with advanced manufacturing research form a key bedrock of R&D proposals to underpin the UK's nuclear industry strategy and build on the start made by the research councils in 2012 in the NNUMAN New Nuclear Manufacturing initiative to drive step changes in manufacturing science and technologies that will enable improved efficiency manufacturing for next generation civil nuclear reactors [4–6].

The programme targeted the adaption of manufacturing methods that, while deployed in other manufacturing segments, have not been applied to nuclear systems because of regulatory and long life related risks. These processes, that are 'New to Nuclear', must be aimed at demonstrating proof of performance (e.g. for 60-year plant life) in order to provide products that meet the industry's very stringent performance needs. Considerable success has been achieved to date through R&D carried out at the Nuclear Advanced Manufacturing Research Centre (NAMRC), in welding and joining technologies and machining surfacing and gradient structures [7] and in exploring the effects of oxygen control in hot isostatically pressed stainless steel as a means for near net shape manufacturing to reduce the number of welds present in primary pipe work [8,9].

3. Developments in fuel technology

In terms of studying fuel cladding, new tools and techniques not available to the original developers such as synchrotron radiation are now being used to study the reaction of zircaloy cladding with hydrogen. This will allow its performance in reactor, in storage and in disposal conditions to be better understood and predicted [10,11].

The fuel technology in use today is largely an evolution of that developed over 50 years ago in the early days of nuclear power but with very significant steps towards the aim of achieving high burnup. Fine tuning in both fabrication technology and the introduction of zirconium alloys containing small additions of niobium has served the industry very well. Fuel is rarely an issue in LWR nuclear power plant performance statistics and fuel is performing far more reliably compared with early days. The goal now is to achieve even greater reliability (it is already better than 10^{-5}) in combination with increased burnup. Development continues to be evolutionary but operators and fuel manufacturers increasingly recognize that in order to achieve substantially higher burnup there is a need to develop a more mechanistic understanding of how alloy chemistry, microstructure and other materials aspects affect performance.

For advanced fuel development, e.g. for high-temperature reactor (HTR) systems, coated particle fuel originally developed in the early days of nuclear power is being re-examined [12]. Other initiatives aimed at increasing tolerance to fault conditions, so-called 'accident tolerant fuels' (ATFs) are also being progressed, e.g. SiC-SiC composite cladding [13,14].

4. Materials issues in reactor systems

When it comes to materials issues and choices for the reactor system itself, many of the challenges faced by the designers and operators of the Generation III+ and Generation IV plants are common to those faced in today's Generation II and Generation III plants.

The 'new 'plant designs use validated materials performance currently applied in existing plants to continue to meet better than 90% capacity factor operations. Nickel alloys, especially a variant known as Alloy 600, have been employed as corrosion-resistant heat transfer surfaces (e.g. steam generator tubing) or ferritic steel compatible reactor pressure vessel penetrations (e.g. control rod drive mechanism (CDRM) housings) from the industry's inception. But as early as 1959, some French researchers had spotted stress corrosion cracking (SCC) problems, which were not properly recognized until some years later and still can cause problems today if operational vigilance is not sustained [15].

It is now known that all product forms of Alloy 600 are susceptible to SCC possibly due to an internal oxidation mechanism [16–18]. Machining processes can increase the susceptibility as can the practices adopted by the material supplier in the melting and mechanical processes used.

R&D on Alloy 600 (SCC-susceptible) and Alloy 690 (improved SCC-resistance) has focused on SCC crack growth rates, but the vast majority of the in-service exposure is spent in the SCC 'initiation' regime; SCC propagation requires the existence of a viable crack, generally a hundred micrometres in extent. Recent work by Bertali, Scenini and Burke at the University of Manchester deals with understanding the precursor reactions and incubation phenomena involved with SCC initiation in Alloy 600 used in LWRs (PWRs); it is important because the mechanistic understanding can then be used to explore 'factors-of-improvement' for more SCC-resistant alloys (such as Alloy 690—now used for PWRs)—as the operating 'lifetimes' are proposed for more than 60 years (approx. 80 years) [19,20].

Work undertaken by the University of Manchester in collaboration with the Universities of Birmingham and Oxford has examined the addition of platinum group metals to enhance the corrosion resistance of stainless steel [21,22].

Development and application of novel *in situ* analytical transmission electron microscope techniques in both gaseous and liquid environments to assess localized environment–alloy interactions, particularly with respect to these important 'precursor' reactions that can precede the initiation of environmentally assisted cracks in order to develop optimized materials and microstructures for improved performance in these environments represents one of the new innovative approaches being used [23].

The goals to further extend the life of existing plants and to reduce the number of safety systems required in the post Fukushima era has led to a new focus on the development of ATFs. These are fuels which would be able to tolerate the loss of active cooling of the core for a longer period than existing fuels and also maintain or improve the fuel performance. Progress is being made in the development of ATF cladding-candidate coating materials with the necessary strength; SiC is one example of a potential advanced clad which would retain its strength to 1500°C and beyond but there are still many challenges to be overcome to enable it to be fabricated probably as a composite of radiation-resistant tough fibres.

All of the next generation of nuclear reactors (Generation-IV systems) have been previously studied to some extent and in many (although not all) cases experimental or prototype systems have been operated. However, even for those systems which have enjoyed the most extensive development, many of the Generation-IV goals cannot be met by systems which employ currently available technology. Materials science, complex modelling of systems on a holistic basis and early detailed consideration of the science underpinning future waste management are essential components of the evolving international R&D programmes as is engineering demonstration of key parts of each system. For example, iron oxides are important controls on radioelement behaviour in effluent treatment plants, the environment and geological disposal and the behaviour of neptunium can be predicted by understanding how it interacts with iron oxide particles [24].

High-temperature gas-cooled reactors (HTRs), which have seen a resurgence of interest globally, in fact had their genesis in the UK at Winfrith in Dorset with a reactor under OECD sponsorship called Dragon, these reactors have significant potential to be dual in mission as both electricity generators and providers of high-temperature heat to assist key chemical processes including electrolysis of hydrogen. Here, the materials challenges are associated with coupling a complex chemical process with the reactor—a challenge not dissimilar to that, yet remaining for pre or post combustion carbon capture and sequestration (CCS) systems. China is investing significantly in HTRs as part of a future technology platform and it is fair to say that the investments made may well bring this technology to commercial realization internationally faster than originally foreseen.

One new development in HTRs, which is likely to reach commercial reality on an earlier timescale is the so-called U-battery (TM), a 5 MW micro reactor under development by URENCO, AMEC-FW, Atkins, Cammell Laird and Laing O'Rourke, targeted at remote communities and as an alternative to diesel back up for military and other secure installations. U-Battery is a concept which has been in development since 2008.

Its creation followed a challenge set by URENCO, which addressed the changing market demand for energy, to design an economically viable, modular nuclear power generation system, which is intrinsically safe. Putting this into context, as highlighted in the early part of the paper, large-scale nuclear reactors require high capital investment and heavily rely on the infrastructure of nuclear sites. Designers were therefore motivated to develop smaller scale reactors, especially for developing countries and remote areas off main power grids. Over a 3-year period, the University of Manchester (UK) and Delft University of Technology (NL) collaborated in an effort to design a unit that would work like a battery. This would allow the modules to be manufactured in series and transported to the customer's site by rail, barge, truck, etc. and the upfront costs of the reactor would be significantly lower than a traditional large-sized reactor. The universities completed a feasibility study in 2011 for the design of such a small, safe modular nuclear power generation system—culminating in the U-Battery. The study concluded that there were opportunities to design a reactor for large industries or small towns, with those opportunities arising from modularity and standardization, simple design, serial fabrication of components and building multiple units at one site [25]. The U-Battery® has been developed based on currently mature HTR fuel blocks using standard TRISO particles as fuel. The reactor core of the U-Battery® is composed of hexagonal fuel blocks with reflectors. HTR fuel has been successfully demonstrated in various prototype or demonstration systems over the past 40 years including the OECD's Dragon project in the UK, Fort St Vrain in the USA, Japan's high-temperature test reactor at Tokai-mura, China's pebble bed HTR at Tsinghua and the HTR MODUL and Thorium HTR pebble bed type reactors in Germany.

5. Materials challenges in recycling

For the long term and looking at sustainability in a world where fast neutron reactors play a significant role, much has been done on the development of the reactor systems themselves internationally, but for fast reactors to succeed, recycling is also essential. Materials issues remain significant but not insurmountable, just challenging! For the future, it will be necessary to address the manufacturing needs of the next generation, 'Closing the Fuel Cycle' plants that will use new materials for which no proven manufacturing methods exist or where the only international experience has been gained in prototype and demonstration facilities in some cases decades ago. Commercial nuclear fuel reprocessing is carried out in nitric acid solutions but the extreme radioactivity leads to unexpected chemical effects, which can be explained by better understanding of the interactions of radiation with nitric acid. [26,27]. Seventy years after their discovery, the complexity and subtlety of the transuranium elements is still being revealed, partly due to the technical challenges of working with these radioactive materials, and partly due to the complexity of their physics and chemistry [28,29]. The need to ensure we have a good understanding will be fundamental not only for successful development of advanced recycling technologies but also building confidence as we approach selection of a site for a geological disposal facility. In geological disposal conditions, the cement backfill will raise the pH and, in these conditions, uranium can form stable nanoparticles which substantially alter its behaviour.

Understanding radiation effects on a much wider range of materials; corrosion performance of process plants e.g. stainless steel corrosion [30]; manufacture and validation of advanced fuels with novel matrices containing minor actinides (MAs) are just a few of the areas for future targeted research. The fabrication of fuels containing high quantities of MAs and possibly long-lived fission products, which will necessitate remote procedures in heavily shielded facilities, poses many technical and economic challenges. Moreover, the waste forms arising from these new processes are not well characterized and new methods for managing these wastes will need to be developed. All of these activities will need to be developed within the context of improving the economic performance of recycling, which will call for significant improvements in materials and components reliability in order to improve plant reliability and reduce downtime. This will require strong links to the activities in advanced materials development and to the advanced modelling and simulation capabilities.

There is the potential for a large amount of cross-cutting research on fast reactor fuels. Most of the generation IV fast reactor fuels use plutonium in higher concentrations than previous fast reactors, typically around 30% and there is a need to produce a new catalogue of both non-irradiated and irradiated mixed oxide fuel properties for Pu contents ranging from about 25 to 30%. Carbide and nitride and metal fuels are all potential candidates which offer improved thermal conductivity and hence lower fuel operating temperatures. Advanced metal cladding materials such as oxide dispersion strengthened steels still require much development, evaluation and qualification. Currently developed ceramic cladding materials, for application as ATFs in LWRs, are a prerequisite for gas-cooled fast reactors and these may offer significant safety advantages also for the liquid metal-cooled fast reactors. Ceramic cladding is also the route for lead-cooled fast reactors to operate at higher temperatures while avoiding the corrosion issues associated with operating metal-clad much above 500°C.

Leading nuclear nations internationally are engaged in R&D programmes to evaluate, develop and potentially deploy advanced closed cycles in the timeframe 2030–2060. Specifically, outside Europe there are programmes in USA, Republic of Korea (ROK), Japan, China, India and Russia. While fuel cycle R&D has fallen back in Japan following Fukushima, the other Asian countries are investing heavily and within the next two decades they will become global leaders in fuel recycling. China, India and Russia have multi-track programmes, that is: looking across thermal and fast reactor recycling; covering aqueous and pyrochemical technologies for nearer and longer term applications; integrating reprocessing and fuel re-manufacturing and building new facilities [31]. ROK is unusual in that, mainly because of non-technical reasons, they are focused solely on applying pyrochemical recycling technology. The USA also maintains a significant programme of fuel cycle research and development that includes advanced separations and waste forms for future closed cycles. Mostly, this is focused on aqueous separations but the Idaho National Laboratory continues to process historic metal fast reactor fuel through a small-scale pyro-processing plant and they have a bilateral arrangement with ROK on pyro-processing. Conventional reprocessing involves the separation of just the reprocessed uranium (Rep U) and plutonium for recycle. The fission products and residual transuranics (including uranium and plutonium impurities—although the amount of U & Pu sent to wastes from separations in reprocessing is very small indeed. TRansUranic in high-level waste are dominated by Np, Am, Cm) are sent to the vitrified high-level waste (VHLW) stream for interim storage and eventual geological disposal. Partitioning and transmutation involves the separation of MA species, usually Np, Am and Cm for recycle [32]. The MAs can be recycled homogeneously as a minor component of nuclear fuel or heterogeneously in the form of target fuels. Np and Am can be transmuted very effectively in thermal or fast neutron spectrum systems, either by an initial neutron capture event, followed by a second neutron capture event that causes fission, or by direct fission following the initial neutron capture. Cm is more difficult to transmute effectively and is also more difficult to handle in fuel fabrication. Overall P&T consists of four steps all of which are rich areas for research going forward: separation of the MA content at reprocessing either as individual products or as co-products; fabrication of MA bearing homogeneous or heterogeneous fuels [33,34]; transmutation of MA bearing fuels in a fission system and potentially, multi-cycle reprocessing of MA bearing fuels. P&T reduces the inventory of MAs in VHLW and can lead to reduced heat load and radiotoxicity of the VHLW stream [35].

6. Thorium-based fuels and fuel cycle

The past 50 years of the nuclear industry have been dominated heavily by the uranium fuel cycle, virtually without exception other than for several test programmes. The uranium fuel cycle now represents a commercially demonstrated fuel route, deployed worldwide with all of the commercial power stations using uranium as its source of fuel. Therefore, any future alternative to this technically mature, proven, commercial fuel cycle would need to demonstrate clear notable benefits over the existing options in order for it to be adopted e.g. benefits associated with the technology, economics, safety and security, environmental performance and sustainability. The thorium cycle is often cited as such an option but the benefits are often overstated and the challenges underestimated [36].

The thorium fuel cycle can be deployed in both, a once-through fuel cycle or fuel recycling. The once-through fuel cycle is simpler technologically, but only offers very limited benefits in terms of uranium utilization. Full recycle with Th-232/U-233 offers an unlimited resource, but also poses many technological challenges, especially reprocessing and fuel manufacture.

In 1996, the Euratom Science and Technology Committee provided a formal Opinion STC(96)D18, in the context of the use of Th in the accelerator based Energy Amplifier proposed by Professor Carlo Rubbia [37].

An extensive annex (included as Annex A to this opinion) was provided to the main STC Opinion STC(96)D18 which detailed all the issues and challenges which needed to be addressed before the Th based fuel cycle could be brought to industrial scale deployment.

Since then only modest investment has been undertaken in the EU. Most developments have occurred as a result of individual Member States research funding within the University sector. Internationally however extensive initiatives have been undertaken particularly in India and China. In the former case because of the availability in India of extensive Th reserves and in the latter case because of their determination to significantly advance Molten Salt systems in which Th may play a significant role. The World Nuclear Association routinely reports on developments internationally (http://www.world-nuclear.org/info/Current-and-Future-Generation/Thorium). However, the paradigm shift that could occur with deployment of molten salt reactors (MSRs) using in-cycle recycle means that Th should be considered in this light from an R&D perspective.

7. Molten salt systems

Significant international activity has taken place over the last decade on revisiting the potential of MSRs for the future and has culminated recently in major initiatives in China, India and Russia with smaller initiatives in a number of European countries led by both University teams and by groups sponsored by high net worth individuals convinced of the potential of MSRs. Within the MSR technology platform (there are a multiplicity of designs), there is also a significant Th component.

In common with other generic MSR systems in which the fuel is incorporated in the molten salt coolant, molten salt fast reactor has theoretical advantages over conventional solid fuel reactors. These include the removal of any requirement to fabricate solid fuel elements and meet all the associated mechanical quality requirements; the obviation of fuel endurance issues that allows the fuel salt to remain in core indefinitely; the relaxation of fuel thermal limits; the elimination of the conventional out-of-core fissile inventory and the possibility of online fuel processing.

Unresolved issues include: the control of corrosion in primary circuit components, including core vessel, pipework, heat exchangers, pumps and other in-core components in the high-temperature salt environment; the control of fission products and transuranics within the primary circuit fuel salt and the avoidance of active crud build-up on primary circuit components; development of a satisfactory system for processing fuel salt and extracting fission products; the immobilization of fission products extracted from the primary circuit in an adequately safe form and its eventual immobilization for transport and disposal; demonstration of safe transient characteristics of cores with very low effective delayed neutron fractions; development of a safety case for a very unconventional system and addressing the unique safeguarding challenges.

There are R&D activities on MSR in the EU, Switzerland, Russian Federation, the USA and Asia, especially China, although the latter two are targeting their initial efforts on molten salt-cooled reactors rather than on molten salt fuelled. The MSR has also attracted many small start-up companies usually sponsored by high net worth individuals and there are competing designs in Canada, USA and UK which are still at the conceptual development stage and which are attempting to secure government support. However, it is likely that activities in China will overtake any others as they are pressing ahead with an MSR demonstrator.

The long term then presents a long and challenging journey to deployment of advanced next generation reactor systems and fuel cycles; so returning to the near term and the particular issues associated with small modular reactors where we may see deployment in the UK in the next decade alongside the first wave of large Generation III LWRs. In choosing the design(s) which may be deployed it will be essential to define exactly what the most important attributes should be, whether it is first to grid, maximum opportunities for UK manufacturing jobs, cheapest electricity price or maximum possible generating capacity for the sites available particularly in the shorter term. Different attributes are likely to lead to very different system choices. There are many ideas being advocated: some with more substance behind them than others. To ensure success, any system in the pipeline for serious consideration will have to have a wealth of verification and validation data and evidence from extensive analysis of materials properties and performance underpinning novel manufacturing processes. Welding technology not used to date for large components is just one of the many aspects receiving significant attention at the NAMRC.

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Author profile

Sue Ion is Chairman of the Nuclear Innovation Research Advisory Board set up in January 2014 and a member of the ONR Independent Advisory Panel. She represents the UK on a number of international review and oversight committees for the nuclear sector including the Euratom Science and Technology Committee, which she chairs, having been reappointed in April 2014 for a second term. She is the only non-US member of the US Department of Energy's Nuclear Energy Advisory Committee on which she has served since 2005. She was the UK's representative on the IAEA Standing Advisory Group on Nuclear Energy 2000–2007.

Sue Ion holds a Visiting Professorship in the Department of Materials at Imperial College and is Deputy Chair of the Board of Governors of the University of Manchester.

She was a member of the UK Council for Science and Technology from 2004 to 2011. She was a member of the Particle Physics and Astronomy Research Council from 1994 to 2001, a member of Council for EPSRC between 2005 and 2010 and chaired the Fusion Advisory Board for the Research Councils from 2006 to 2012. She served on the DECC Scientific Advisory Group 2010–2014.

Sue Ion was Vice President and Member of Council of the Royal Academy of Engineering between 2002 and 2008 and has chaired a number of the Academy's key standing committees. Sue Ion has been involved in energy matters generally since 2004 and chaired the steering group which oversaw the Research Councils' International Review of Energy Research 2010–2011.

Dr Ion was BNFL's Group Director of Technology 1992–2006 responsible for approximately 1000 staff in five UK locations including the active laboratories at Sellafield, Springfields and Berkley. During the period the company owned Westinghouse from 1997, she was responsible for functional oversight of the Group's technology portfolio including all R&D investment in new reactor systems.

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