Office for Nuclear Regulation

ONR GUIDE			
GRAPHENE: THE OPPORTUNITIES AND THREATS OF EMERGING TECHNOLOGIES			
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1. INTRODUCTION

1.1 Since its discovery in 2004 the extensive range of properties that Graphene displays have been exploited in a variety of technologies and applications some of which are already in commercial products.[1,2,3]

1.2 Graphene is a transformative and disruptive technology, which has been identified within ONR as a material which may be used within the nuclear industry in a wide variety of applications. The nuclear industry is currently reviewing options for the use of graphene for a range of applications and a range of academic and commercial organisations are carrying out research in this area.[1]

1.3 Graphene is the first two-dimensional atomic crystal structure. It has characteristics and properties measured in experiments that exceed those obtained in other materials, with some reaching theoretically predicted limits. These properties include:

- Electrical conductivity greater than the theoretical limit
- Intrinsic strength – it is 200 times stronger than steel
- High thermal conductivity
- Complete impermeability to any gases
- Readily chemically functionalised
- Transparent
- High elasticity

1.4 Currently these properties have been achieved only for the highest-quality samples and for graphene deposited on special substrates such as the boron nitride. As yet, equivalent characteristics have not been observed on graphene prepared using other techniques, although the methods are rapidly improving. Graphene will be of even greater interest for industrial applications when mass-produced graphene demonstrates the same performance as the best samples obtained in research laboratories.

1.5 Graphene can take many forms, a single two-dimensional layer, multi-layers and functionalised graphene. Historically, it was considered that graphene is a perfect single layer, two-dimensional lattice of carbon atoms. However, research is now shifting towards understanding the properties and applications of deformed layers of graphene, graphene composites in addition a single layer of graphene. The size of the graphene flake has also been shown to have a large impact on its properties and the material characteristics. Furthermore, it has been found that different graphene based applications require different grades of graphene. This is a key driver towards widespread practical implementation of graphene based technologies.

1.6 Currently graphene utilisation is researched in two primary forms: Graphene Oxide flakes and Graphene Films.

1.7 The combination of properties in graphene makes it suitable for wide and varied applications in following main areas: electronics and photonics, energy generation and storage, bio-applications and composite materials, painting and coats.

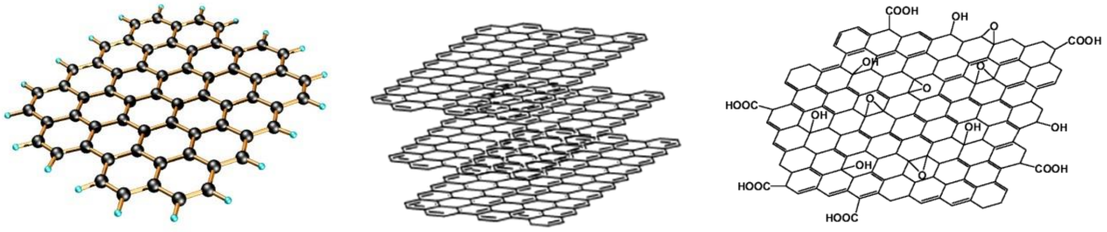

Figure 1. Single layer, multi-layer and functionalised graphene molecular structure

1.8 The UK nuclear industry is facing many technically complex challenges throughout the nuclear fuel cycle. It is therefore important to have an awareness of technological advances to ensure that the nuclear industry utilises these in a safe and efficient manner.

2. PURPOSE AND SCOPE

2.1 The purpose of this document is to review and collate research on technologies and applications that include graphene. Graphene based technologies offer many advantageous properties but the rapid growth in the sector poses a potential risk that the user may not know that they have graphene deployed technology. This potential risk may have safety implications within the nuclear industry from the inclusion into safety classified equipment without knowledge through to specific use for nuclear processes.

2.2 This research project will give clarity on the graphene landscape and study how graphene may be incorporated into technologies and their applications in the nuclear sector. In addition to this, the aim of this study is to gain an understanding of the safety implications of the inclusion of graphene products to allow ONR to efficiently and effectively regulate the nuclear industry.

2.3 It was recognised that within ONR there is currently very limited information within guidance documents on graphene and its derivatives. As a result it was recommended to propose a research project, for a PhD student to complete entitled ‘Graphene: An Investigation and Review of Nuclear Industry Opportunities and Threats’. This was accepted onto the 2015/2016 research register. As a result of a meeting with the National Graphene Institute (NGI) at the University of Manchester ONR decided that an internal project to maintain a current view on graphene based technologies would be a better fit for purpose. It is of the view that this project may allow a future PhD placement and allows ONR to engage with a wider range of research.

2.4 The Energy Act 2013 enables ONR to carry out or commission research in connection with its purposes and therefore supports delivery of its strategic goal of being an exemplary regulator.

2.5 It is important to recognise that ONR’s research needs are different from those of a nuclear licensee as they must support its independent regulatory decision making. This needs to be based on objective scientific and technical understanding of the safety issues.

2.6 The deployment of graphene technologies within the nuclear industry in all likelihood will become more common, therefore it is of interest to the ONR to understand the safety implications of graphene technologies and prepare appropriate regulatory guidance when assessing nuclear safety cases.

2.7 This research project was put forward and accepted onto the ONR Regulatory Research Register under the following criteria in 2015:

- Research into potential safety/security issues associated with new technologies before their application to new of existing facilities.

2.8 The scope of this document will be limited to publicly available research and commercial information on graphene based technologies and applications. The current graphene landscape is in the development and early scale-up stages and the research is heavily protected by intellectual property (IP) and commercial sensitivity, which limits the sharing of information on the technology.

3. PRODUCTION

3.1 The market of graphene applications is limited and driven by progress in the production of graphene with properties appropriate for the specific application, which is expected to be the situation for the next decade. There are currently in excess of 12 methods of graphene production and development to prepare graphene of various dimensions, shapes and quality. For the purpose of this document, the focus will be on the methods that are currently scalable.

3.2 Graphene has been successfully manufactured in two formats: a continuous lattice film, which can used as a film to adding to a surface, or a discontinuous lattice, which are platelets in bulk powder form for dispersion into a host medium. Different production methods are available for graphene. The USA has the most graphene producers at 27 companies and organisations, followed by China (20) and the UK (11).[1,2]

3.3 Depending on the type and the quality, the properties of the synthesized graphene may vary a great deal; in particular, the grain size, shape, thickness, and the density of defects change and thus affect the graphene's mechanical and tribological properties. The method of manufacture dictates which and how many imperfections the resultant graphene exhibits and its properties. [6]

3.4 Initially, graphene was produced by the so-called 'scotch-tape' or mechanical exfoliation method, where commercially available adhesive tape is used to peel multiple layers from highly ordered pyrolytic graphite (HOPG) and to transfer them by pressing the tape onto the desired substrate. Since then the number of methods for graphene production has significantly increased. Some of these include dry mechanical or chemical exfoliation; unrolling/unzipping of carbon nanotubes (CNTs) through a variety of ways such as electrochemical, chemical or physical methods; chemical vapour disposition (CVD) or epitaxial growth; arc discharge; the reduction of graphene oxide; and many other organic synthetic methods. [9]

3.5 Currently widely used CVD methods are able to synthesize high-quality graphene on the catalytic surface, such as nickel or copper, in the presence of a carbon supply such as hydrocarbon gases. Raman spectroscopy is used for analysing the synthesised graphene defects in the synthesized graphene, as well as the number of deposited graphene layers. However the lack of efficient etching and transfer methods limit the scale of production because the etching time for nickel layers increases exponentially with the size of graphene films. [1,6] The CVD method is advantageous for large-area growth of graphene; it requires a rigid substrate that can stand the high temperature (above 900 ºC) in addition to an etching process for removing catalyst layers. [9]

3.6 A method has been developed to produce wafer scale, high-quality graphene films as large as 3 inch wafer size on Nickle and Copper films under ambient-pressure and transfer onto arbitrary substrates through instantaneous etching of metal layers. This has demonstrated an increase in the yield and improved scalability, compared to CVD.[7]

3.7 Graphene can be synthesised on silicon carbide wafer by a process of sublimating silicon atoms resulting in a graphitized surface.[6] The crystalline layers orientation can be controlled to allow graphene to be synthesised to a high quality. However this is only at a small scale approaching hundreds of micrometres in size. In addition to this, the cost of the wafers is high and the high temperatures (above 1000 ºC) needed to sublime to silicon carbide can damage the technology by which the graphene will be built into. [9]

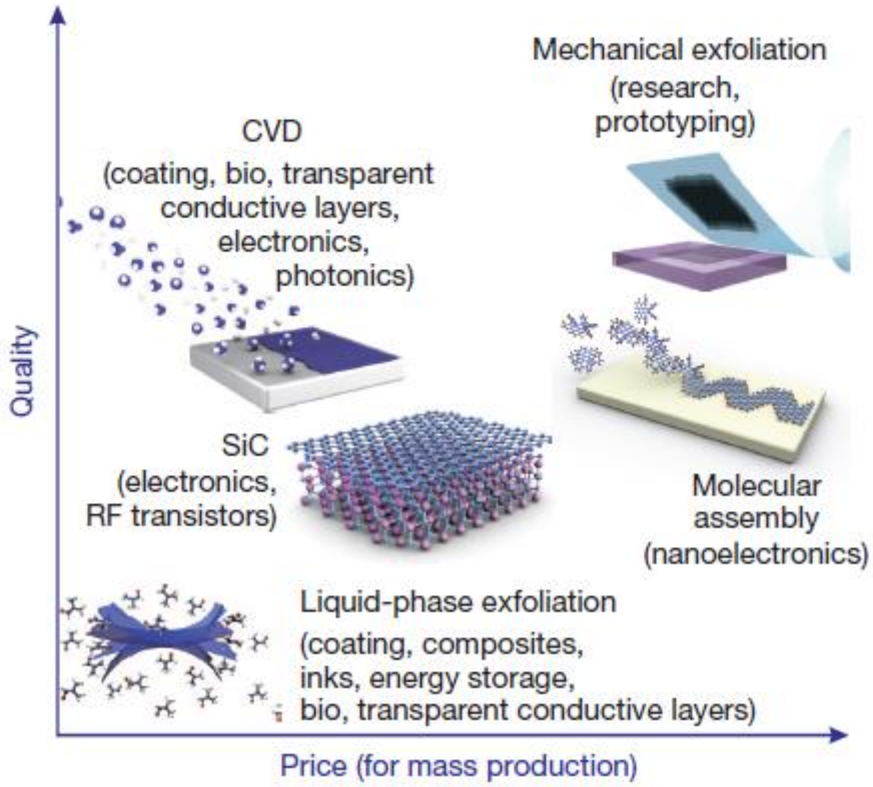

Figure 2. There are several methods of mass-production of graphene, which allow a wide choice in terms of size, quality and price for a particular application (Image reference 'A roadmap for graphene' K. S. Novoselov, V. L. Flanko, doi:10.1038/nature11458)

3.8 Thomas Swan is a company that focuses in performance and speciality chemicals, including high purity graphene, which the company began producing in 2014 through the liquid shear-exfoliation method to yield stabilised 2D dispersions and powders. [19]

3.9 It is important to establish a manufacturing infrastructure to ensure quality and environmental control with proven scale-up experience that is underpinned by recognised accreditations.

3.10 As seen in figure 2, currently there are few methods that have a high scalability factor and a high value. The lower graphene grades are more likely to meet the requirements of lower grade applications; therefore there must be significant development in manufacturing methods for high grade graphene technologies to be commercially viable. There are also technical difficulties in handling and dispersing free-form nanomaterials, which is a current barrier to mass production of graphene. The graphene nanotechnology intermediates, such as graphene paints and enhanced resin are more commercially favourable than nano-enabled products such as sensors and water filtration membranes.

4. LITRERATURE REVIEW

4.1 The major industry sectors for graphene applications are: polymer composites, construction materials, lubricants, coatings and inks, energy, electronics, water treatment and metals. However each of these graphene technologies is at differing levels of technological readiness. The following applications have been discussed as they have been identified that they have the potential to enter the nuclear fuel cycle.

5. BUILDING MATERIALS

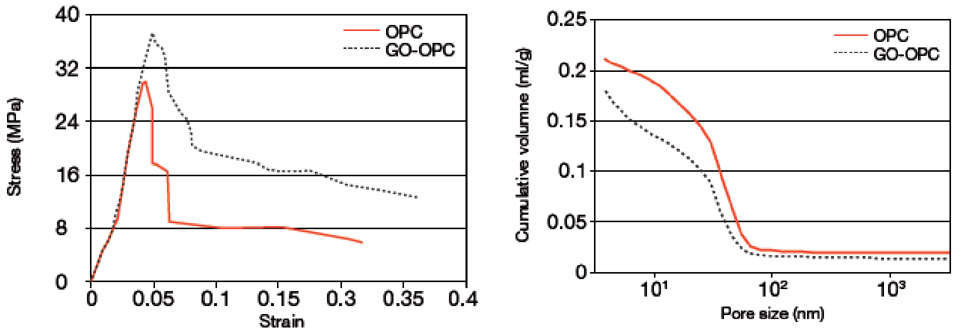

Figure 3. The graphs show the comparison of mechanical parameters of graphene oxide reinforced cement (GO-OPC) and OPC. On the left the compressive strength of cement is 46% higher with GO impregnation and on the right the graph shows that the microstructure of cement paste is finer and denser with the inclusion of GO sheets. (Image reference Rheological behaviours of graphene oxide reinforced cement composite W. Duan)

5.1 There have been many recent studies on nanomaterials in cement composites such as nano-silica and carbon nanotubes. Reinforcements in cement matrix materials are far more effective at the nano-scale than the conventional millimetre scale because they can mitigate the growth of nano-size cracks before they develop into micro-sized cracks. GO is a form of graphene which has been functionalised with oxygen bearing groups such as carboxyl, hydroxyl and epoxy. These functional groups significantly alter the Van der Waals forces between the graphitic sheets, which results in a more stable and homogeneous dispersion in water compared to graphene sheets. [15,16] Studies have shown that graphene oxide has superior adhesion properties in comparison to graphene, this is a result of the oxygen functional groups providing potential binder sites for chemical or physical interactions between the GO and cement paste. The 2D GO nano-sheets provide an extra dimension to interact with cement and concrete matrix. [17] Research by the West Pomeranian University of Technology in Szczecin studied the addition of 3 wt% of graphene oxide in cement and found that the additive had a significant enhancement of Young's modulus. Furthermore, it was reported that the GO flakes homogeneously dispersed in the cement matrix which is favourable to ensure an even distribution of properties. [14]

5.2 The University of Monash also studied the incorporation of graphene oxide (GO) into Ordinary Portland Cement (OPC) has a higher compressive and tensile strength as well as proving to be corrosion resistant and more durable than the current OPC that is widely used in the construction industry. Currently concrete must be reinforced with steel bars and various fibres to overcome its poor tensile properties and to delay the development of micro-cracks.[8]

5.3 When GO is impregnated in OPC, the composite matrix materials produced exhibit significantly improved mechanical and physical properties. This is demonstrated in the graphs in figure 3. Laboratory tests by the University of Monash show that as little as

0.05% of GO additive is needed to improve the flexural strength of a cement matrix form between 41% and 59% and compressive strength from between 15% to 33%.

5.4 Furthermore, the addition of GO has also been shown to improve the ductility and reduces the likelihood of sudden failure of concrete. This is seen in figure 3 with GO-OPC samples displaying a broader stress-strain curve in the post-peak zone.

5.5 When 0.05% of GO is added, research at the University of Monash shows a decrease in the total porosity of GO-OPC from 32.6% to 28.2%. This is rationalised as a result of an improved pore structure providing higher compressive strength and a more durable cement matrix. [8]

5.6 This technology was developed is patented by Monash University in Canada and it is currently seeking industry partners to further develop this technology with a view to licensing and commercialisation. [8]

6. COATINGS AND PAINTS

6.1 Graphene-based paints can be used for conductive inks, electromagnetic interference shielding and gas barrier applications. In principle, the production technology is simple and reasonably well developed through liquid-phase or thermally exfoliated graphene.

6.2 Graphene is highly inert, so can act as a corrosion barrier against water and oxygen diffusion. In addition to research that has demonstrated graphene can be grown directly on the surface of almost any metal under the right conditions, it has the potential to for a protective conformal layer on complex surfaces.

6.3 Graphene has the potential to be used as a high-performance barrier coating. Graphene is anti-oxidant and research has shown that coatings increase corrosive protection and improve anti-fouling properties via particulate lubricity.[9] The graphene can be impregnated into coatings to be applied as paints in industrial applications. Currently the Applied Graphene Materials Company is collaborating with two large companies (unknown due to commercial sensitivity reasons) to test and develop this into a commercial product.

6.4 The anti-fouling properties are currently being harnessed through the shipping industry, where paints and coatings with graphene technology can be applied to the underwater hull to control the fouling and corrosion of the sea water.

6.5 One recent study that is of particular interest is the addition of graphene coatings to improve the corrosion resistance of steel. In 2015, the Institute for Frontier Materials in Australia demonstrated for the first time the growth of 3D networks of graphene Nano-flakes across porous stainless steel substrates of micron sized metal fibres.[10] The presence of graphene was shown to enhance the specific surface area of the material and contribute to the increased corrosion resistance and electrical conductivity without compromising the properties or structure of the native stainless steel material. This new development is an advanced surface coating.

6.6 Printable inks are common throughout industry, however often unreliable in terms of performance and longevity. The introduction of graphene to the printed inks has the potential to impact on flexible circuitry. The University of Cambridge has developed graphene inkjet-printed circuit boards which could be printed on surfaces such as glass and plastic.

7. COMPOSITES

7.1 Currently the more near-term market adoption of graphene based technologies is through composites. This involves the addition of graphene into certain materials, which have different properties, to produce an end material with unique characteristics.

These materials do not blend or dissolve together but remain distinct within the final composite structure. Composite materials can be made to be stronger, lighter or more durable through the addition of graphene. [9] Most composites are made of two materials: the matrix, which surrounds a cluster of fibres or fragments of a stronger material or the reinforcement. By selection of a matrix and reinforcement material, in addition to the optimum manufacturing process, it is possible to create materials with properties tailored for specific needs. [18]

7.2 The mechanical, chemical, electronic and barrier properties of graphene are favourable within composite graphene applications. The graphene is the reinforcement within the matric material and effectively merges the advantageous graphene properties. [9]

7.3 Graphene composites also bring extra functionality including gas and moisture barrier properties, strain monitoring capability to the surrounding polymer matrix and electrical and thermal conductivity. As an additive to a composite matrix polymer graphene has the potential to increase the operating temperature level of composites, reduce moisture uptake, induce antistatic behaviour and improve composite compressive strength. [18]

7.4 There have been many commercial developments in the field of graphene composites:

- An example of a graphene composite product that is already in the commercial research stage is the use of graphene within polyester films, which Dyson and P&G have begun testing for injection moulded and extruded plastics.
- Fiat is part of a program to investigate graphene composites applications for the automotive industry.
- TBA Electro Conductive Products announced the release of a new sprayable transparent conductive coating based on graphene platelets and carbon nanotube hybrid material.
- Carbon fibre composite aircraft are currently covered with a copper mesh for protection against lightning strikes. The conductive properties of a graphene reinforced aluminium matrix is currently being researched jointly by the National Graphene Institute (NGI) and the Beijing Institute of Aeronautical Materials (BIAM) to accelerate the application of graphene in the aviation industry and other sectors. [9]

7.5 Research at Cardiff University has shown improvements of carbon fibre composites that have been reinforced with graphene nano-platelet technology. The results of this research show a 13% increase in the compression strength and 50% increase in compression after impact performance. This is significant because damage resistance in compression properties are extremely important in high performance structures. [20]

7.6 Imperial College has also shown that graphene could significantly enhance the functionality of materials, an example is mixing graphene with epoxy resins to carbon fibres would not only increase the strength and flexibility but also the reduce weight.

7.7 Graphene enhanced nano composite materials have been developed by the University of Manchester. The research shows that the graphene additive greatly improves the mechanical performance and reduces the weight of polymers used in 3D printing. 3D printing refers to a process in which a 3D printer is used for staking layers of material under computer control, following a 3D model resulting in a printed 3D object. There has been highly technical 3D printing of graphene impregnated filaments, which has been in commercial production since 2015. Future applications include the printing of

3D batteries based on graphene, which outperform current commercial batteries and can be tailored to match the design of specific devices.

8. ELECTRONICS

8.1 Graphene films are currently the closest to commercial use in the form of electron microscopy. Electron microscopy is the use of an electron microscope to capture high resolution images of things that would not normally be resolved. Graphene films have been tested in coating mammalian cells to provide a simpler method of preparing the cells for viewing. Usually the process would involve freeze drying the cells to prepare them for the near vacuum conditions within an electron microscope, however with the use of a graphene film it is possible to seal the cells while still making them observable.[4] Other research areas consist of sensing technologies.

8.2 Sensors are a promising area for graphene film integration as the electrochemical properties of graphene make it ideal for sensing changes in size, magnetic fields, gas density, etc. Currently the research into sensors is quite wide; Bosch announced in 2015 that they had developed a magnetic field sensor that is 100 times more sensitive than current market leaders. This sensor takes advantage of the unique conductive properties of graphene. Biomedical sensors are being developed by a company called ‘Graphene Frontiers’. These take advantage of graphene’s chemical properties to detect illnesses with multiple chemical markers, such as cancer. This is a new technology, known as ‘lab on a chip’ as the sensor itself is only around the size of a thumb. Photodetectors are being developed by AMO that have been shown to have a much higher transfer rate than current sensors. These would be used in fibre optic cables to allow for a higher frequency of data transfer. Another novel use of graphene films is to coat textiles, this is being researched by ETRI who have the vision or gas sensors woven into the clothing of firefighters. In general the sensing market is still in the applied research and development phases, this is due to the difficultly in mass producing graphene films.

8.3 An area of research that is much further progressed is that of thin, flexible, transparent conductors. Or touch screen films. These have been shown off by multiple phone companies as the future of smart phones; however the difficultly in mass producing graphene is hampering this technology also.[5]

8.4 Graphene Oxide flakes are another method of inserting graphene into current technologies. The most promising of these is inserting graphene oxide flakes into Lithium Ion batteries. It has been shown in research that this increasing the charging capacity, speed of charging, and longevity of the battery. The primary mode of failure for a Li-Ion battery is structure degradation due to thousands of deep charge cycles. By incorporating graphene oxide flakes into the substrate it is possible to reduce the damage cause and charge the batteries faster.

8.5 A similar product to the graphene infused Li-Ion batteries is the supercapacitor market. By incorporating graphene flakes into a supercapacitor in a similar manner to the batteries you can create a rapidly charging capacitor with superior structural integrity. The uses for these are in high speed circuitry for the purpose of timing and circuit protection. Figure 2 shows the many concepts and research projects that are being looked into currently.

9. FILTRATION MEMBRANES

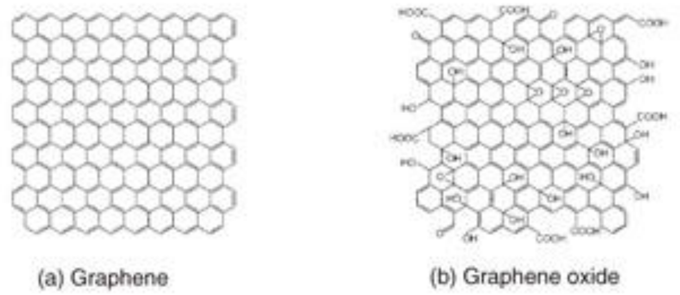

Figure 4. The structures of graphene and graphene oxide, which is functionalised with hydroxyl, carboxyl and epoxy groups.

9.1 There has been intense interest in filtration and separation properties of graphene-based materials. These materials have well-defined nano meter sized pores and exhibit low frictional water flow inside them. Graphene based materials have had particular attention in nano filtration and desalination applications. Research by the University of Manchester has shown fast permeation of water through carbon nanotubes and more recently graphene oxide (GO) laminates. The GO laminates are currently the more viable option because they are easy to fabricate, mechanically more robust and offer no principle obstacles towards industrial scale production. [18]

9.2 GO laminates are made of impermeable oxide functionalised graphene sheets that have space in between each layer to accommodate a mobile layer of water. The GO laminates are vacuum-tight in the dry state, but if immersed in water act as molecular sieves, blocking all solutes larger than water. The University of Manchester found that the GO laminates are impermeable to all liquids and gases except for water.[12] Smaller ions in solution such as K^+ permeate through membranes thousands of times faster than simple diffusion. The current research suggests that this behaviour is caused by a network of nano capillaries that open up in the hydrated state and accept species that can fit through. The fast permeation through the membrane is attributed the GO membrane that attract a high concentration of small ions into the membrane. [18]

9.3 Furthermore, the research shows that the GO structure does not allow inter-diffusion between two different solutions, one of which does not contain water, separated by the GO membrane. [12] The situation changes when the two solutions are filled with two water based solutions. It was observed that there was permeation through the GO membrane in the direction of flow given by osmosis. For example, container with a sucrose solution and water separated by a GO membrane the level of sucrose solution will rise as water moves by osmosis. [18]

10. FUNCTIONAL FLUIDS

10.1 In recent developments it has become increasingly important to reduce friction and wear-related mechanical failure in moving mechanical systems. This is due to friction’s adverse impacts on efficiency, durability and environmental compatibility. Graphene as a two-dimensional material offers ultra-low friction and wear properties that are not usually seen in conventional materials. [7] In addition to its well-researched range of properties, graphene can also serve as a solid or colloidal liquid lubricant. Graphene has an atomically smooth surface in addition to its high chemical inertness, extreme strength and easy shear capability give graphene tribological behaviour. [13]

10.2 The advantages of oil coatings and inclusion in fluids by preventing metal to metal contact, cooling components and carrying by-products in suspension have been used in throughout the nuclear industry and wider. The Applied Graphene Company are currently undergoing collaborations with Millers Oils to use graphene based technology for fuel and oil additives using the lubricating property of graphene to reducing friction and improve machine performance and reducing the engine wear. [9]

10.3 Graphene has an ultra-low friction between sheets of graphene and this has also been found to occur between graphene and other surfaces. The benefits of frictionless coatings through graphene based super-lubricants would reduce the energy loss between mechanical parts thus improving energy efficiency and extending the service life of equipment.[12]

11. DISCUSSION IN RELATION TO NUCLEAR INDUSTRY

11.1 There has currently been very limited UK research in graphene behaviour in radiation fields. There has been a SRIM simulation that has shown graphene to be radiation resistant, however the damage mechanisms to graphene are unexplored and it will require investigations to test the radiation resistance of graphene.[11] In addition, the thinness of graphene that results in a low electron to nucleus column density may be beneficial to resisting radiation damage because the radiation has less electrons or nuclei to interact with.

11.2 The nuclear industry has highlighted the need for sensors in a report commissioned by the Nuclear Decommissioning Authority (NDA), and small, light, low-cost replaceable reactors have the potential to play a key role in sensors in the nuclear sector, for example in spent fuel ponds. There is one report that states that graphene oxide (GO) can remove radioactive material from contaminated water, whilst the second report shows that GO changes structure during irradiation. These results contradict each other therefore the validity of each report is uncertain.[12]

11.3 The Dalton Cumbrian Facility of The University of Manchester proposed a research project to expose graphene to alpha, beta and gamma radiation. However this project did not have sufficient technical or commercial interest therefore was not continued. The proposal was a novel project with the following objectives:

- To test radiation resistance of graphene and functionalised graphene;
- To explore the effects of alpha, beta and gamma irradiation on graphene and graphene sensors;
- To compare the efficiency of beta and gamma radiation in reducing graphene oxide to graphene;
- To test graphene-based sensors in-situ under irradiation conditions to evaluate the feasibility of the technology.

11.4 One of the main challenges of the UK nuclear industry is the safe decommissioning of the First Generation Magnox Storage Pond (FGMSP), which poses a significant safety risk and a decommissioning priority. To assist with retrievals, a detailed knowledge of the facility’s inventory through visual inspection of the pond. Water samples are collected routinely for laboratory analysis, which poses a risk of radiation dose to personnel. Instrumentation has many challenges, as electrical instruments often fail in radioactive environments. Graphene based technologies in both sensors and batteries have the potential to be included within the water quality monitors that have been developed for remote, long-term monitoring applications.

12. TECHNOLOGICAL READINESS

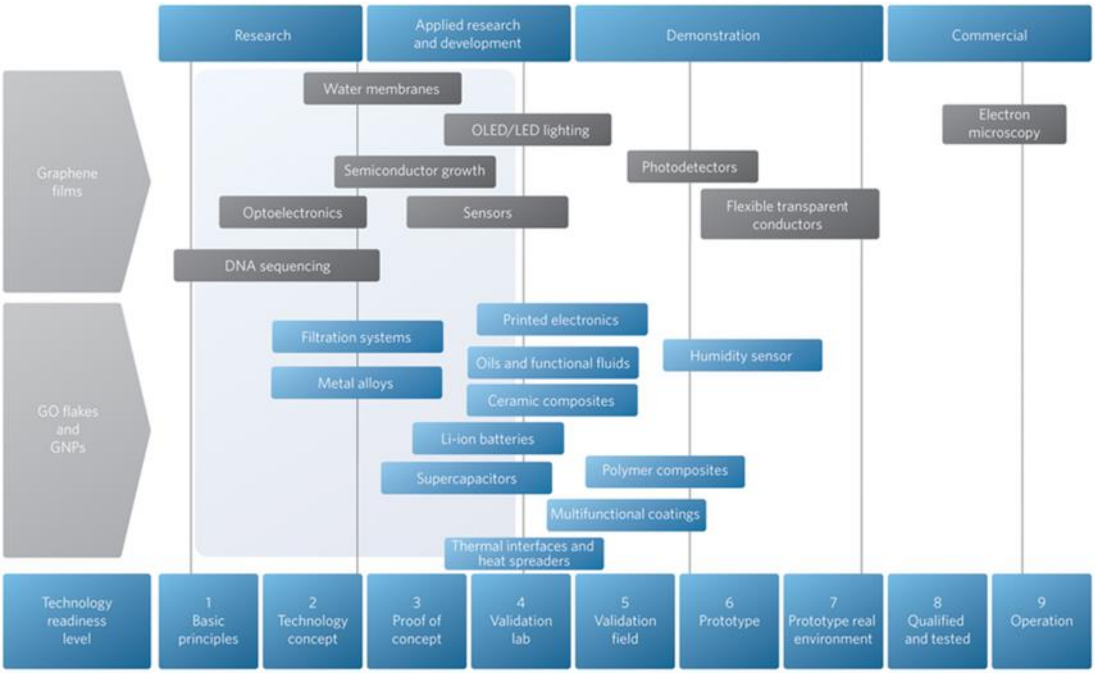

Figure 5. The technological readiness of graphene films and graphene oxide flakes (Image reference University of Manchester road map)

12.1 In the UK the National Graphene Institute (NGI) has researched new concepts and applications for graphene products. [11] It is currently developing low cost and scalable manufacturing methods for high quality graphene. In addition to this, the process to achieve reproducible quality graphene with high yields is a key barrier to commercialisation. The Graphene Engineering Innovation Centre (GEIC) is currently being built in Manchester to manufacture graphene and research graphene applications development in collaboration with research. [12]

12.2 Although some graphene based products have entered the commercial sector, the technologies are currently relatively premature in the route to commercialisation. The National Graphene Institute state that the current UK graphene market is in the concept development stage; this is defined by focusing on the concept development of graphene based technologies. [11] The GEIC will deliver technology and capability demonstration programmes and create value through delivery of graphene based products into end-user and supply chain applications. The time scales of this are speculative but the NGI predicts that it will be between 2015 and 2035 before the graphene based products enter the market, depending on each applications complexity and commercial drivers.

12.3 It must be taken into consideration the speculative nature of graphene based technologies. This document is current with the technologies available at present. However there could be potential emerging graphene technologies within the next 5-10 years that currently are not commercial products. In addition, as with any new technology, the initial cost is high and the companies within the nuclear industry may not justify the benefit to cost ratio. However it is recommended that the nuclear industry, including ONR, maintain an interest and understanding of these technologies to ensure the maximum benefits in nuclear safety.

12.4 The figure below identifies the technological readiness level of different graphene technologies. From the table it is clear that the majority of applications are currently in the research and development phases. Composites, multifunctional coatings, photodetectors, humidity sensors and flexible transparent conductors are all in the demonstration phase whereby prototypes are being developed.

13. REVIEW OF REGULATIONS

13.1 Currently there is no UK or international relevant good practice for graphene based technologies or clearly defined health and safety requirement for handling these. This poses a threat to the development of graphene technologies and the safety of both workers and the public. However the European Commission launched a public consultation regarding the benefits, risks, concerns and awareness of technology. It is important that there is an understanding and awareness of the safety implications of graphene technologies within the nuclear sector to efficiently regulate the industry.

13.2 Product standardisation is required to ensure clear product specifications and ensuring product safety. It is important that commercial companies and regulators understand good practice for the whole lifecycle of graphene based technologies. [7] This is particularly prominent in the nuclear industry.

13.3 For large scale commercialisation the materials standards, regulations, supply availability and fair price must be obtained. Currently there are no materials standards that companies must comply with. This is having a detrimental effect on the development of the sector as end-users, regulators and insurers cannot assess product quality nor obtain guidance on material safe usage. [10]

14. CONCLUSIONS

14.1 As the current market of graphene based technologies and applications is driven by the production of graphene, there is a hierarchy to how soon these applications will reach the end user and enter the nuclear fuel cycle. The applications that use the lowest grade, cheapest and most available form of graphene will be the first to appear and those which require the highest, electronic-quality grades may take decades to develop.

14.2 To ensure that graphene based technologies and applications are efficiently regulated, there must be national and international regulatory guidelines developed to manage the potential hazard and risk. In addition to this, regulations are necessary to standardise the production of graphene itself as well as the applications. This is particularly important because the structure of graphene has a significant impact on its characteristics and properties.

14.3 It is important for industry and the regulators to have an awareness and understanding of the current graphene landscape to ensure that future safety case assessments that include graphene based technologies are proportionately regulated. This is in-line with the ONR's strategy of enabling regulation to facilitate future technologies and applications, which utilise graphene's properties and characteristics that will bring potential benefits to the nuclear industry.

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