Nuclear Decommissioning Authority

The Potential Applications of Graphene (and Related Compounds) Relevant to the NDA's Decommissioning Mission

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Preface

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Glossary

AGH	Amidoxime GO Hydrogel
CNT	Carbon Nanotube
CPI	Centre for Process Innovation
CVD	Chemical Vapour Deposition
DOE	US Department of Energy
DRP	Direct Research Portfolio
EARP	Enhanced Actinide Removal Plant
GBM	Graphene-Based Material
GFET	Graphene Field Effect Transistors
GLEEP	Graphite Low Energy Experimental Pile
GO	Graphene Oxide
HAL	High Active Liquors
IEC	International Electrotechnical Commission
ISO	International Organization of Standardization
LP&S	Legacy Ponds and Silos
NDA	Nuclear Decommissioning Authority
NPL	National Physical Laboratory
NSF	US National Science Foundation
ONR	Office for Nuclear Regulation
OSTI	Office of Scientific and Technical Information
PNNL	Pacific Northwest National Laboratory
POCO	Post Operation Clean Out
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation & restriction of CHemicals
ROV	Remotely Operated Vehicle
SETP	Segregated Effluent Treatment Plant
SiC	Silicon Carbide
SIXEP	Site Ion Exchange Plant
STP	Solvent Treatment Plant
UoM	University of Manchester

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1 Introduction

Research and development (R&D) is fundamental to ensuring the cost-effective delivery of the Nuclear Decommissioning Authority (NDA) mission. Together with innovation and the sharing of national and international good practice, the intelligent application of R&D can reduce decommissioning costs and timescales, reduce environmental impact and improve safety.

Through the Direct Research Portfolio (DRP), the NDA supports early technical innovation to address identified needs, risks or opportunities across the NDA estate [1]. These multi-site needs, risks and opportunities are identified through engagement between the NDA and the nuclear estate, and summarised in the NDA Technical Baseline document [2].

The NDA has recently identified graphene technology as a potentially promising area that could offer some benefits to the NDA mission. The NDA is aware of some of the novel properties of graphene and its compounds that could enable the use of these new materials in a wide range of applications.

There is a broad range of research being undertaken by several research groups in the UK, e.g. University of Manchester (UoM), the National Physical Laboratory (NPL) and the University of Cambridge, as well as abroad which is developing a deeper understanding of the chemical and physical properties of graphene and its compounds, potential applications and manufacturing technologies. There are also some significant collaborative research programmes e.g. the EU funded Graphene Flagship which aims to take graphene from research laboratories into society by 2023. The EU Graphene Flagship has a budget of €1 billion and represents a joint, coordinated research approach on an unprecedented scale, forming Europe's biggest ever research initiative. The Graphene Flagship is tasked with bringing together academic and industrial researchers, to take graphene from the realm of academic laboratories into European society. The growing consortium now consists of over 150 academic and industrial research groups in 23 countries, with NPL and the UoM's National Graphene Institute participating and playing prominent roles in the project from its inception. Furthermore, the Flagship now includes associate-member institutions from outside Europe.

Innovate UK is a governmental funding body who work with people, companies and partner organisations to find and drive the science and technology innovations that will grow the UK economy. Within this remit, Innovate UK has been involved in the funding of graphene based research and represents a source of information for graphene research information. In 2014, The Centre for Process Innovation (CPI) was setup as the home of a £14 million Graphene Applications Innovation Centre, to provide facilities and expertise to help companies to develop, prove, prototype and scale up graphene based products and processes. Rapid progress Catapults such as the CPI are helping UK businesses accelerate the commercialisation of new and innovative technologies and provides another focal point for information on graphene based research development.

The Clarivate Analytics' Web of Science database [3] currently lists 90,414 research articles on various topics related to graphene. The extent of interest and research in this material has meant that keeping abreast of developments in this area and potential applications has been challenging, such that the knowledge of graphene technology and relevant applications is not very well known across the NDA estate. Therefore the NDA would like to raise awareness across its estate about the properties and potential opportunities for the use of graphene and its compounds in nuclear decommissioning. This will enable organisations engaged in decommissioning to better assess potential applications and allow better communication with the research community. This in turn could facilitate the identification and funding of further specific R&D in key areas.

1.1 Document Scope

This document follows on from the "Summary of Graphene (and Related Compounds) Chemical and Physical Properties" report [4], which was intended to be used as a reference point for the NDA and the NDA estate for graphene related information. This document reviews existing graphene research, both within academia and industry, and attempts to identify correlations between current graphene research and the NDA R&D requirements. Furthermore, any potential limitations in the use of graphene have also been highlighted.

This document includes the following sections:

- The properties of graphene relevant to the nuclear decommissioning industry;
- Graphene research areas;
- Correlations between the identified graphene research areas and NDA decommissioning research and development needs;
- The limitations of the use of graphene in nuclear decommissioning applications;
- Conclusions.

The term "graphene", as used in this document, has been used to describe a collection of graphene-based materials (GBMs) including, but not limited to, single-layer graphene, graphene nanoplatelets, graphene oxide (GO), reduced graphene oxide and functionalized/chemically modified graphene.

2 The Properties of Graphene of Relevance to the Nuclear Decommissioning Industry

The properties of graphene of relevance to the nuclear decommissioning and remediation are outlined in this section and directly follows on from the information presented in Reference [4].

Although the application of graphene in the nuclear decommissioning industry is still in its infancy, there have already been a number of early research projects and associated publications in this area. The Unity2 team comprising NSG, UoM and the NPL have reviewed the literature and identified a series of publications directly relevant to nuclear decommissioning and remediation that have demonstrated the use of graphene. These publications and key research areas are summarised below, and include:

- Water decontamination;

- Isotopic separation;
- Composite materials;
- Sensors.

The properties of graphene that make it attractive to nuclear applications have also been identified.

2.1 Water Decontamination

Aqueous effluents arise from a range of operational and decommissioning activities. The effluents can contain a complex mix of radioactive and non-radioactive species. Effluents are treated in dedicated plants, such as Sellafield's Site Ion Exchange Plant (SIXEP), Enhanced Actinide Removal Plant (EARP) and Solvent Treatment Plant (STP), to remove radionuclides in order to satisfy strict regulatory limits on, and progressively reduce radioactive discharges into the environment. Current treatment strategies rely on a mix of evaporation, precipitation, ion-exchange and filtration processes. In some cases these approaches suffer from poor selectivity in the presence of competing species and in the future the composition of the effluent stream is likely to change as operations cease. Improving the materials and processes used in effluent treatment may simultaneously reduce operating costs, help to comply with discharge regulations and reduce the total volume of waste for future disposal.

In some instances, radionuclides have already escaped into environmental water sources (e.g. due to past effluent discharges from Sellafield, the accidents at the Fukushima Daiichi power plant and the leaking waste tanks at the Hanford Site). Contaminated sites must be treated to prevent a direct radiation risk to the public and the environment as well as avoiding the undermining of confidence in future nuclear energy production. Environmental decontamination is still a costly and challenging process and although some approaches to decontamination have been demonstrated to be effective in the laboratory, they perform less well in the presence of competing ions and in realistic environmental conditions.

A recurring problem in both aqueous effluent treatment and environmental decontamination is poor selectivity and better, highly selective materials are required. GO is particularly appealing for these applications because it can be fabricated into a membrane material with relative ease and subsequently used for nano-filtration, or alternatively dispersed in water and used as an adsorbent for radionuclides. In addition, it is non-toxic and biodegradable so it is safe to introduce into the aqueous environment. Two specific research areas relating to GO in water decontamination are discussed below.

2.1.1 Nano-Filtration

GO membranes can be fabricated by vacuum filtration of an aqueous suspension of GO sheets. The resulting film has a layered structure of graphene sheets comprising oxygen-containing groups. The material swells when immersed in water, forming an array of uniform 2D nano-channels in between individual sheets. The extremely high water flux observed through the membrane [5] has opened up the possibility of GO being used in water purification applications for nano-filtration.

In the last few years, impressive progress has been made in the development of GO membranes as highly selective ionic/molecular filters [6]. The factor determining whether a given solute will pass through the membrane is its size, with only small solutes able to enter the GO channels and pass through the membrane. Although the experiments conducted to date did not focus on radioactive contaminants, many of those that were investigated can be considered as radioactive analogues. Recently, computer modelling has predicted that GO membranes could be used for the separation of the long-lived and extremely problematic isotope, Tc99, from competing species, such as sulphate and chloride ions, in contaminated water [7].

Instead of taking advantage of the nano-channels created by GO when suspended in water, an alternative approach could be to create size specific pores within the graphene or GO surface using an ion beam when suspended on a surface to generate a graphene/GO 'sieve'. The resulting material could be used to filter solutes of defined size.

This emerging research field is highly appealing for the diverse nature of effluent treatment and decontamination separation problems faced by the nuclear decommissioning industry. A nano-filtration process is amenable to miniaturisation and incorporation into a portable form that could be used for localised effluent treatment.

2.1.2 Adsorption

Many approaches used to remove radionuclides from the environment rely on adsorbents due to their simplicity and application at a large scale. Commonly used materials for aqueous radionuclides include clay minerals, metal oxides, biomaterials and activated carbons. However, in many cases these materials exhibit poor adsorption capacities, low efficiencies and often they do not work across a broad range of environmental conditions, such as at low pH.

Due to their high surface area and abundance of oxygen-containing groups, GO flakes can be used as adsorbents instead. Romanchuk et al. demonstrated that GO was an extremely effective adsorbent for many of the most toxic and radioactive long-lived radionuclides from contaminated water [8]. They observed effective adsorption of cationic contaminant radionuclides including the actinides (Am, Th, Pu, Np, U) and long-lived, high yield fission products (Sr, Eu) from a simulated nuclear effluent that contained both competing ions, such as sodium and calcium, and complexing agents, including acetate and citrate. However, poor adsorption was observed for the mainly anionic Tc species, due to the negative charge of GO in normal conditions. Many other research groups have reported GO as effective adsorbents for U [9, 10], Am and Pu [11], Eu and Cs [12], Sr [13] and Th [14].

GO typically displays rapid adsorption and much higher maximum adsorption capacities compared to traditional adsorbents, especially for the actinides. Experimental techniques (up to 300 mg per gram of GO), supported by density functional theory calculations, have shown that the radionuclides predominantly bind to the epoxy and hydroxyl sites. The 2D structure of GO maximizes the accessibility of the oxygen groups, contributing to the very high adsorption capacity. The uses of GO as an adsorbent for aqueous radionuclides has also been reviewed [15]. Although GO is relatively expensive compared to clay minerals and other carbon-based materials such as activated carbons, GOs may be synthesised at low price in the near future (see Section 5.2) and its high adsorption capacity means that comparatively less adsorbent is needed.

Alternatively, the oxygen-containing sites in GO can be functionalised by chemical grafting to enhance selectivity and adsorption capacity. These enhancements are due to a synergistic effect of the high chemical specificity of the functional groups combined with the high surface area and high density of oxygen groups in GO. Examples of GO functionalities that display enhanced radionuclide adsorption include Bayberry tannins for Sr [16], polyaniline for U, Eu, Sr, Cs [17], polydopamine for U [18] and an amidoxime GO hydrogel (AGH) for U [19]. In particular, AGH was found to have a high efficiency for U adsorption and a capacity of 400 mg/g, much higher even than those capacities observed in normal GO. In addition, this adsorbent material was able to remove U from simulated seawater, containing competing species, with U present only at ppb or ppm concentrations, ranking it amongst the most effective U adsorbents ever reported.

In the work of Romanchuk et al., GO dispersions readily coagulated following adsorption of radionuclides, facilitated by the adsorbed ions cross-linking between individual sheets. The resulting agglomeration could easily be filtered. It is easy to see how the combined adsorption and coagulation properties of GO could be followed by ultrafiltration of the resulting particles. Combined with the simplicity of industrial scale up of GO production, these properties make GO a promising new material for radionuclide separation and removal.

2.2 Isotopic Separations

Another separation application involves the use of monolayer graphene (created by Chemical Vapour Deposition (CVD)) to separate hydrogen and deuteron ions. This pioneering work by researchers at the UoM demonstrated a scalable and competitive way for hydrogen isotope enrichment and may also be of use for the removal of tritium from waste streams. Using electrical measurements and mass spectrometry, it was found that deuterons permeate through graphene much slower than hydrogen ions, resulting in a separation factor of ≈10 at room temperature. The hydrogen ion conductivity of graphene was comparable to commercially available Nafion films, potentially offering a competitive and scalable way for hydrogen isotope enrichment. Moreover, the scale-up potential of graphene using techniques such as CVD provides a realistic prospect of graphene being implemented in industry for hydrogen isotope separation [20]. Zhang et al. have performed quantum calculations to compute activation energies for isotopic hydrogen ion permeation through graphene. They demonstrated that the ratios between different isotopes were in close agreement with the experimental permeation velocity ratios [21].

Researchers at Pacific Northwest National Laboratory (PNNL) were also able to remove low concentrations of radioactive tritiated water from large volumes of contaminated aqueous effluent using GO membranes [22]. Three different membrane thicknesses were investigated, with enhanced separation potentially achievable using thicker membranes, at the expense of lower permeation rates. PNNL researchers observed a slightly different mechanism of separation, whereby normal, deuterated and tritiated water was transported through the oxygenated regions of the membrane at different rates, via a proton-hopping mechanism, and not transport through the membrane by simple diffusion.

The two isotopic approaches outlined above for separating hydrogen ions and tritiated water utilised graphene and GO respectively. The properties of these two materials are very different, with the graphene required for hydrogen isotope separations having minimal defects, whilst the separation of tritiated water requiring GO that has lots of defects in the form of oxygenated groups, which are required to facilitate the transport of water through the membrane.

2.3 Composite Materials for Waste Immobilisation and Disposal

2.3.1 Cement Composites

The ability to safely dispose of radioactivity and mitigate its migration into the environment over geological timescales is critical in underpinning nuclear waste management strategies. Typically, mobile radionuclides must be immobilised before potential transportation and final disposal in a long-term storage facility. For low and intermediate level waste this conventionally involves their immobilisation in Portland cement based grouts. However, Portland cement is brittle and has a weak tensile strength because of relatively large pores that may initiate microcracks. A portion of the cement can be replaced by some supplementary materials that may act to improve the mechanical properties, by delaying the development of microcracks and therefore improve the tensile strength of the cement.

There are examples of researchers using low-dimensional nanomaterials, such as carbon nanotubes (CNTs) [23], to enhance the mechanical properties of cement. The nanomaterials are able to fill cracks that develop in the cement during setting, bridging between the interfaces on either side of the crack. Materials with low aspect ratios (length to width ratios), excellent intrinsic strength and toughness are suitable. GO is particularly suitable as an additive because of its excellent mechanical properties, ease of dispersibility in water and abundance of reactive oxygen-containing groups that can bond within the cement matrix.

Gong et al. [24] made a GO-cement composite via a high shear mixture to improve the distribution of GO in the cement matrix with 0.03 wt.% of GO. They investigated the resulting change in porosity and influence on compressive tensile strength compared to the pure Portland cement. They observed that the composite exhibited 13.5% lower porosity, 27.7% fewer capillary pores and a 40% increase in 28-day compressive and tensile strength. The refinement in pore structure was attributed to an enhancement in the degree of hydration. Pan et al. [25] added 0.05 wt.% of GO and observed a 33% improvement in the compressive strength and observed the ability of GO to fill cracks in the cement. Sedeghat et al. [26] investigated the thermal diffusivity and electrical conductivity of a GO-cement composite and concluded that both increased relative to the pure cement. High thermal diffusivity is important to dissipate the heat generated by the hydration process. The main disadvantage to adding GO to cement is that the workability is significantly reduced.

Additives (e.g. zeolites or bentonite) can be used to reduce the mobility of radionuclides through the pores of cement based wasteforms. Since the adsorptive properties of GO have also been proven (Section 2.1.2), the addition of GO has the potential to simultaneously improve the mechanical, thermal and radionuclide mobility properties of the cement.

Although the work outlined above [23, 24, 25, 26] was specific to the civil engineering and building materials, the potential to enhance cement properties through the addition of GO may be useful for nuclear waste conditioning. The improvement in the cement's mechanical strength, enhanced thermal diffusivity and potentially improved radionuclide retention properties would all be beneficial for radioactive waste conditioning. The impact of reduced porosity (described in Reference [24]) on nuclear waste conditioning is not known and further research would be required to fully understand the short and long term impact of cement/GO composites on waste conditioning.

The defects found within GO membranes (i.e. the abundance of oxygen containing groups) make this material a good additive due to its ability to form chemical bonds with the matrix material. Graphene with few or minimal defects is unlikely to be as successful owing to its inert nature.

2.3.2 Polymer Composites

The conditioning of some radioactive waste types are incompatible with Portland cement. For example, aluminium, uranium and Magnox corrode in the alkaline cement matrix, with the corrosion products expanding and damaging the wasteform. High molecular weight polymeric encapsulants have been proposed as an alternative approach for these problematic waste types. The advantage of these materials is that they are generally stronger than cement with improved performance for leaching of radionuclides into the matrix. They are also resistant to acids, alkalis and organic solvents. A vinyl ester styrene is already in use at a waste treatment plant in Trawsfynydd in Wales to encapsulate ion-exchange resins, and other polymer-based waste forms are being considered. Graphite Low Energy Experimental Pile (GLEEP) fuel at Harwell has also been conditioned using polymers (epoxy resin) to isolate the waste and infill residual voidage [27]. However, polymers with additives display lower heat capacity and thermal conductivity compared to cements, leading to possible problems for large-scale polymer encapsulation, in the context of heat generation due to radioactive decay.

Rafiee et al. synthesized an epoxy-graphene nanocomposite and showed that the graphene flakes could be homogeneously dispersed [28]. With only 0.1 wt.% graphene flakes they demonstrated 31% greater Young's modulus (stress to strain ratio), 40% increase in tensile strength and 53% increase in fracture toughness than pristine epoxy. The improvements in mechanical properties were found to be similar to those with CNTs, but achieved with much lower weight fractions. The improved properties relative to CNTs are thought to be due to enhanced adhesion between the graphene and polymer matrix, high surface area and 2D geometry of graphene. Graphene-polymer nanocomposites have also demonstrated improved thermal properties with a shift in the glass transition temperature of 30°C [29]. Another group have demonstrated up to 70% and 57% increases in tensile strength and Young's modulus, respectively, upon addition of just 0.9 wt.% graphene [30]. Those researchers also observed that smaller graphene flakes improved dispersion in the polymer melt and reduced the likelihood of introducing free volume into the matrix. A useful review on the mechanical properties of epoxy/nanomaterial (graphene,

graphene oxide and carbon nanotubes) has recently been published by NPL and Kingston University London [31].

2.4 Sensors for Radiation/Molecular Adsorption

Graphene has excellent electronic properties (e.g. electrical conductivity) making it an attractive material for use in sensors. However, the 2D nature of graphene means that it is unable to absorb radiation, such that the structure has relatively poor radiation resistance despite its aromatic nature, being damaged by alpha, beta and gamma radiation [1]. Despite this perceived weakness, graphene and related compounds have been successfully incorporated into sensors and detectors by coupling the graphene to an absorber material. Specific examples are presented in Sections 2.4.1 and 2.4.2 below and relate to the use of graphene in radiation and molecular detection.

2.4.1 Radiation Detection

There is a need for inexpensive, low-power, size-scalable detection devices, which are exceptionally sensitive to X-rays, gamma-rays, and neutrons. Such high performance sensors could be used for detecting the presence of nuclear material and radionuclides. One major challenge in the development of sensors for the detection of ionising radiation is achieving high-energy resolution at room temperature. Due to its exceptional electronic properties (high charge carrier mobility, low noise and extreme sensitivity to changes in local electric fields) the use of graphene in sensor devices could help address these challenges.

Several groups have demonstrated the use of graphene field effect transistors (GFETs), for the detection of radiation [32, 33]. In these devices, graphene is mounted upon a radiation-absorbing semiconductor (such as SiC, CdTe and CaAs), separated by a thin buffer layer. When the radiation interacts with the underlying absorber material it deposits energy and perturbs the local electric field of the material. The detection mechanism relies heavily on the high sensitivity of graphene to detecting changes in the electric field due to this radiation-induced event. This can be interpreted from the measured current or resistance upon application of a gate voltage across the GFET. The decoupling of the absorber and detector in this manner also offers additional benefits via the flexibility in the choice of the absorber material. The detectors showed low noise, low power detection of radiation and operation at room temperature.

Zhang [34] noted the degradation of graphene (and corresponding performance as a sensor), mounted on a SiO_2 substrate, in the presence of X-ray irradiation and in the presence of reactive species such as oxygen or hydrogen. Sensor degradation needs to be considered when developing sensors for long-term use and increased radiation tolerance.

2.4.2 Molecular Detection

In addition to graphene based radiation detection, graphene based sensors can be used for the detection of molecular chemical species. Highly sensitive sensors have application in the detection of gaseous radionuclides present in extremely low concentrations, which could be used for monitoring discharges from effluent treatment plants or the escape of radionuclides from containment in a waste disposal facility. Past development of sensors capable of detecting a single atom or molecule has been limited by their sensitivity. This is because the intrinsic noise due, to fluctuations in thermal motion of charges and defects, exceeds the signal from individual molecules, usually by many orders of magnitude.

Schedin et al. showed that micron sized sensors made from graphene are capable of detecting individual events when a single gas molecule attaches to, or detaches from the graphene surface [35]. The adsorbed molecule changes the local carrier concentration in graphene one electron at a time, leading to step-like changes in resistance. Graphene is so suitable for the detection of single adsorption/desorption events due to the fact it has such a high conductivity and is an exceptionally low-noise electronic material. A review article recently highlighted the vast amount of research conducted on graphene-based gas detectors to date [36].

2.5 Properties Relevant to Nuclear Applications

The properties of graphene and related compounds that make it useful in the nuclear specific applications outlined above are summarised in Table 1. The properties have been grouped according to the particular applications.

Table 1: Graphene Properties of Relevance to the Nuclear Decommissioning Industry

Application	Properties Relevant to the Application
Water decontamination: Nano-filtration	• Structural functionalisation – incorporation of functional groups allowing nano-channels to form; • High surface area – high water flux through nano-channels; • Nano-channels only allow small solutes to filter through the material; • Biodegradable – potentially lessened negative impact on the environment; • Non-toxic (in this application) – again minimising impact on the environment and not contributing to water contamination.
Water decontamination: adsorption	• High surface area; • Abundance of oxygen containing groups (negative charge) facilitate in absorbing radionuclides cations; • 2D structure – maximises accessibility of the oxygen groups to give high adsorption capacity; • Structural functionalisation – oxygen groups can be readily functionalised to improve selectivity and adsorption capacity; • Dispersible in water; • Biodegradable – no negative impact on the environment;

Application	Properties Relevant to the Application
	• Non-toxic (in this application) – again minimising impact on the environment and not contributing to water contamination.
Isotopic separations	• Electronic structure – the strength of the electronic interactions between the graphene surface and hydrogen isotopes differ, allowing it to act as an isotopic sieve.
Composite materials: cement additives	• High strength; • Good mechanical properties; • Dispersible in water; • Structural functionalisation – oxygen containing groups form covalent bonds with the cement matrix; • High thermal diffusivity; • Binds to radionuclides to reduce the leaching properties of cement.
Composite materials: polymer composites	• High strength; • Good mechanical properties; • Dispersible; • Structural functionalisation – oxygen containing groups form bonds with the polymer matrix; • High thermal diffusivity.
Sensors: radiation detection	Exceptional electronic properties, which include; • Low noise; • Sensitive to changes in the local electric field created by a radiation induced event.
Sensors: molecular detection (e.g. monitor discharges)	Graphene-based sensors are capable of detecting events when a single gas molecule attaches or detaches from the graphene surface due to: • Changes in resistance due to adsorption of molecules; • High conductivity; • Low noise.

2.6 Summary

Nuclear specific applications for graphene and related compounds have already been identified and could be used to support decommissioning and remediation work. To date graphene and related compounds have been investigated for water decontamination (molecular filtration, adsorption and isotope separations), as additives in cement and polymer composites and use in sensors for radiation and molecular detection.

Some of the key properties of graphene and related compounds that make them useful in these applications are highlighted in Table 1 and include:

- Structural functionalisation – the incorporation of functional groups allows these compounds to form nano-channels, adsorb radionuclides and form covalent bonds with a range of materials. The latter allows graphene derivatives to be used an effective additive in composites;
- High surface area – the 2D structure means that accessibility of the functional groups is maximised, resulting in increased interaction with the surrounding environment which is required for applications involving adsorption and when incorporated into cement/polymer matrices;
- Dispersible in water – allowing graphene and related compounds to be used in water decontamination, as well as being readily dispersed within composite materials;
- Biodegradable and non-toxic – these compounds are potentially unlikely to cause additional problems to the environment and operatives, however this is also presented as a potential limitation to its use in Section 5.3;
- High strength – the favourable mechanical properties of these compounds could be used to enhance the mechanical properties of other materials when used as an additive;
- Electronic properties – these compounds are sensitive to changes in the local electric field, which could be created through interactions with the graphene surface and isotopes and molecules, or through a radiation induced event;
- Low noise – allowing graphene-based sensors to be used at room temperature, whilst displaying high resolution.

However, the properties of graphene and related compounds that are useful to the nuclear decommissioning industry are very application specific. Each application requires a unique set of properties that may not be favourable for other applications.

3 Graphene Research and Development Areas

Section 2 focussed on the known, nuclear specific graphene related research conducted to date. This section, however, presents a wider review of graphene research, including non-nuclear graphene research areas.

A desktop study was undertaken to identify research areas associated with graphene (and related compounds), and an assessment of their potential relevance to the nuclear decommissioning industry was made. The section provides an overview of the research teams, universities and research programmes worldwide that are undertaking graphene research, and their current and previous areas of interest.

This includes information compiled by the NPL and UoM that have specialist knowledge in current graphene research areas, conduct research as institutions themselves, and participate in large collaborative programmes in graphene research.

3.1 Methodology

The basis of the desktop study was to identify current graphene research from within the nuclear and non-nuclear research areas. This was achieved by reviewing published literature and funding awards. Various information sources were used as part of this review including:

- The Graphene Flagship;
- Interviews with researchers at UoM;
- Google Scholar and SciConnect;
- US Department of Energy (DOE) funding database;
- US National Science Foundation (NSF) database;
- US Office of Scientific and Technical Information database;
- Innovate UK;
- A wider international literature review, including Asian research activities.

As previously mentioned, The Graphene Flagship has brought together a large European consortium with about one hundred and fifty partners in twenty-three countries. The partners represent academia, research institutes and industries, which work closely together in fifteen technical work packages and five supporting work packages covering the entire value chain from materials to components and systems. NPL reviewed ninety tasks (covering fifteen technical work packages and five supporting work packages) to highlight projects that are of relevance to the nuclear decommissioning industry.

The UoM reviewed projects focussing on the key academic researchers in Asia, as well as reviewing the entire catalogue of Innovate UK awards and industrial collaborations and again identifying those projects relevant to the nuclear decommissioning industry.

Regarding the US, a review was undertaken to search currently funded projects that contain the word “graphene”, including new projects awarded and funding renewals, from the US DOE and the US NSF websites. In total, 68 grants were provided by the US DOE search and 346 grants were provided by the NSF search. Each of the US DOE project abstracts were analysed and judged as to their relevance to the nuclear decommissioning industry. Given the larger number of US NSF funded projects, the abstracts were filtered using various keywords; e.g. “glass”, “composite”, etc.; and subsequently analysed and judged for their relevance. It was observed that the all of the funding of these projects from the US DOE and US NSF are associated with US universities and associated spin-out companies. Hence, a separate search of SciTech connect—a scientific search engine developed by the Office of Scientific and Technical Information (OSTI) within the US DOE was used to identify research publications associated with the seventeen US national laboratories funded by the US DOE. This provided 1651 hits, and were subsequently filtered on a laboratory-by-laboratory basis. It is noted that a number of results had no relevance to graphene and were filtered out by pattern matching “graphene” in either the title or abstract of the work. This filtering process yielded 266 publications.

A complete list of unfiltered projects used in this literature review is contained in Reference [37], which contains a full list of research programmes from The Graphene Flagship, Innovate UK, US Doe, NSF and OSTI. This list was utilised for identifying the research areas of relevance, or potential relevance to the nuclear decommissioning industry.

Research projects that were deemed to be relevant to the nuclear decommissioning industry were categorised into specific research area categories. These categories will be used later in Section 4, where correlations to the NDA decommissioning R&D requirements are made.

A summary of the relevant and potentially relevant projects and publications from this review are presented in Table 2 in Section 3.2. Detailed results that provide a synopsis of each project/report are presented in Appendix A.

3.2 Summary

From the literature survey outlined in Section 3.1, it is evident that there are numerous programmes of research that are relevant or potentially relevant to the nuclear decommissioning industry. In total, 119 projects/publications have been identified from the sources searched (Graphene Catapult, The Graphene Flagship, InnovateUK, US DOE, US NSF, OSTI and a wider international search including Asia). Table 2 provides a summary of the search results. The majority of the relevant, or potentially relevant projects centre on:

- Membranes – essentially selective barriers composed of GBM's, with research often centred on desalination/waste water treatment and gas separation;
- Sensors – the use of GBM's within sensors, predominantly gas-sensors, to detect molecules including water, oxygen, ammonia and nitrogen dioxide, at very low concentrations;
- Radiation detectors – another form of sensor, detecting ionising radiation using GFETs;
- Gas storage – utilising functionalised GBM composites and their porous 3D architectures with high surface areas for optimised gas adsorption and storage ; and
- Advanced materials – including cements, polymers, glasses, ceramics and coatings. Research centres on the incorporation of GBM's into materials to form advanced composites with improved properties.

Table 2: Number of Graphene Projects and/or Publications from Research in the UK, US and Asia that are Relevant to the Nuclear Decommissioning Industry

Source	Number of Projects/Publications	
	Relevant to the Nuclear Decommissioning Industry	Potentially Relevant to the Nuclear Decommissioning Industry
Graphene Flagship Tasks	19	13
UoM Survey (Projects/ Publications)	13	22
US DOE Funded Projects	5	5
US NSF Funded Projects	7	14
US DOE Funded Publications	12	9

A more in depth presentation of the data is presented in Appendix A, while the full unfiltered output from the review is presented in Reference [37].

4 Correlation Between the Identified Graphene Research Areas and NDA Decommissioning Research and Development Needs

One of the key objectives of this project was to determine the potential applications of graphene (and its compounds) within the nuclear decommissioning industry. This section seeks to apply the knowledge acquired from previous sections which focussed on the useful properties of graphene and graphene research areas, to identify the correlations between the graphene research areas and the NDA estate decommissioning R&D needs. By identifying these synergies, further conclusions can be drawn as to the potential research gaps or areas of future opportunity for graphene research related within nuclear decommissioning.

4.1 Methodology

An assessment of the NDA estate's nuclear decommissioning R&D needs was undertaken by reviewing the NDA Technical Baseline document [2]. This document is based on the Site Licence Companies TBuRD submissions and discusses the NDA estate needs and opportunities for R&D in nuclear decommissioning. A summary of these R&D requirements and opportunities was then tabulated (Section 4.2 and Appendix B).

The needs and opportunities were then assessed against the graphene research areas that were reviewed in Section 3 (and presented in full in Appendix A), to identify correlations between the identified graphene research and the NDA estate decommissioning R&D needs.

4.2 NDA Decommissioning Research and Development Needs

The NDA estate decommissioning R&D needs are categorised by ‘Strategic Theme’ and then by ‘Strategic Topic’ to provide a flowing structure to their requirements. The tabulation of these R&D requirements has therefore adopted this structure and is presented in Appendix B.

Not all the R&D needs and opportunities are relevant to graphene research. R&D needs and opportunities deemed irrelevant include, “Technologies that would make NDAs uranics inventory more saleable” and “Improved statistical approach to monitoring programme”. These have been identified as needs and opportunities where the application of graphene technology would be unlikely to provide any feasible added benefit. Hence, some of the R&D needs listed in Appendix B have been struck-through and represent the NDA needs that were not deemed to be relevant to the scope of this project, or were repetitive from previous sections of the NDA Technical Baseline document [2].

4.3 Identification of Correlations

As described in Section 4.1, correlations between the NDA estate decommissioning R&D needs and opportunities, and current graphene research have been established and are presented in Table 3. This table lists all of the relevant NDA decommissioning R&D needs and opportunities that were identified in Reference [2] (and Appendix B). However, an additional column has been inserted into Table 3 showing the broad graphene research areas that could potentially be applicable to each of the NDA decommissioning R&D needs and opportunities. Further commentary with regards to the assignment of each correlation is provided in the following sub-sections. The NDA R&D needs that were deemed to be irrelevant (as indicated in Appendix B) have been removed from Table 3.

Table 3 also highlights where there are currently NDA decommissioning R&D needs or opportunities, which currently have no applications within current graphene research areas, or require extensive further research to be developed. These will be discussed further in Section 4.4.

The final column in Table 3 (Timescale for Application) gives the likely timescales for applying the identified graphene technology to each NDA R&D requirement. The timescales are denoted short, medium, or long term and are defined as follows:

- Short term: <5 years
- Medium term: 5 - 20 years
- Long term: >20 years.

For example, short term is applicable to graphene applications relating to Magnox reprocessing, where this is due to end in 2020. Long term application timescales generally relate to operational and decommissioning requirements, which could be >20 years from now. The timescales do not denote urgency, more the time in which the technology has to be developed for utilisation in these areas.

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Table 3: Identified Correlations Between NDA Estate Research and Development Needs and Graphene Research Areas

Strategic Theme	Strategic Topic	Research and Development Need	Graphene Research Industry/ Research Area	Timescale for Application
Spent Fuels – defines NDA approach to managing the diverse range of spent nuclear fuels for which we are responsible	Spent Magnox Fuel	Improved characterisation technologies that would provide Sellafield Ltd with a better understanding of the condition of the reprocessing facility could be required.	Sensors	Short-term
		Development of technologies to treat the small amounts of fuels left over once Magnox reprocessing operations cease.	No Direct Identification	N/A
		Further technologies to dry store and/or immobilise legacy Magnox fuels to manage materials held within Legacy Ponds and Silos (LP&S) at Sellafield.	Advanced Materials	Short-term
	Spent Oxide Fuel	Improved characterisation technologies that would provide Sellafield Ltd with a better understanding of the condition of the reprocessing facility could be required.	Sensors	Short-term
		Pond storage of spent oxide fuel is planned for a significant period. Therefore technologies that improve NDAs existing approach to treating pond water are of interest: • Technologies that monitor spent oxide fuel and associated pond furniture under wet storage conditions will be required.	Radionuclide Remediation; Membranes; Water Treatment; Adsorbents; Gas Storage Sensors	Short- to Long-term

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Strategic Theme	Strategic Topic	Research and Development Need	Graphene Research Industry/ Research Area	Timescale for Application
		• In situ technologies that monitor the precursors of spent oxide fuel corrosion are of particular interest.		
		In the longer term technologies associated with drying, storage and disposal of spent oxide fuel are of interest to NDA.	No Direct Identification (potentially Advanced Materials, for storage and disposal)	Medium- to Long-term
	Spent Exotic Fuel	Improved technical options for long-term storage of specific exotic fuels;	Advanced Materials	Medium- to Long-term
		Technologies associated with monitoring, storage, treatment and disposal of spent exotic fuels are therefore of interest.	Sensors; Radiation Detectors; Advanced Materials;	Medium- to Long-term
Nuclear Materials – defines NDA approach to dealing with the inventory of uranics and plutonium currently stored on some of our sites	Plutonium	Technologies for monitoring waste packages and stores that improve upon existing approaches are therefore of interest.	Sensors; Radiation detectors	Short- to Long-term
Integrated Waste Management – considers how	Radioactive Waste	*Reprocessing* There is a need to understand how the existing facilities will treat wastes from POCO of the		

Strategic Theme	Strategic Topic	Research and Development Need	Graphene Research Industry/ Research Area	Timescale for Application
NDA manage all forms of waste arising from operating and decommissioning NDA sites, including waste retrieved from legacy facilities		reprocessing facilities and how existing treatment facilities could be modified to manage new wastes. Some of the key areas of research include: • Wasteform development (e.g. glass formulation) for vitrification of POCO HAL feeds; • Options for treating effluents that allow decommissioning of existing facilities (e.g. SETP) to take place.	Advanced Materials Membranes; Advanced Coatings; Water Treatment; Radionuclide Remediation	Short- to Medium-term Medium- to Long-term
		There are also synergies with the interim storage of other packaged wastes (e.g. decommissioning waste). Some of the key areas of research include: • Remote monitoring of waste packages (e.g. corrosion); • Remote monitoring of stores (e.g. humidity).	Sensors; Energy/Energy Storage (hydrogen capture)	Short- to Long-term
		<u>Legacy Facilities</u> Some of the key areas of research include: • Remote monitoring of waste packages (e.g. corrosion, hydrogen evolution); • Remote monitoring of stores (e.g. humidity, temperature).	Sensors; Energy/Energy Storage (hydrogen capture)	Short- to Long-term

Strategic Theme	Strategic Topic	Research and Development Need	Graphene Research Industry/ Research Area	Timescale for Application
		<u>Operational and Decommissioning Wastes</u> Some of the key areas of research include: • Improved encapsulants (e.g. reduced cost, higher waste incorporation, increased security of supply, easier processability, increased compatibility with wastes).	Advanced Materials	Short- to Long-term
	Liquid and Gaseous Discharges	The liquid and gaseous discharges for decommissioning activities are more varied. Particularly at Sellafield, the variety can be challenging from a scheduling and compatibility viewpoint. Key areas of research include: • Modular and mobile effluent treatment facilities to allow the decommissioning of existing effluent facilities or to manage short-term effluent requirements; • In-line monitoring technologies to avoid the transport of samples and increase sampling interval.	Membranes; Advanced Coatings; Water Treatment; Radionuclide Remediation Radiation Detection; Sensors	Short- to Medium-term
Site Decommissioning & Remediation – defines NDA approach to decommissioning	Decommissioning	In situ characterisation to determine level of contamination: • Portable versions of existing characterisation techniques; • Non-destructive evaluation technologies.	Radiation Detectors; Sensors	Short- to Long-term

Strategic Theme	Strategic Topic	Research and Development Need	Graphene Research Industry/ Research Area	Timescale for Application
redundant facilities and managing land quality in order that each site can be released for its next planned use		Improved decontamination techniques: • Increased efficiency and effectiveness; • Reduction in secondary waste; • Removal of heels and residues from process vessels.	Membranes; Advanced Coatings; Water Treatment; Radionuclide Remediation	Short- to Long-term
		Remote or enhanced operation for extreme conditions (e.g. high dose, confined spaces): • Enhanced tools and techniques for air-fed suit decommissioning operations; • Enhanced tele-operation (e.g. virtual reality and haptics); • Robotics and autonomous systems.	Energy/Energy Storage; Gas Storage; Advanced Electronics	Short- to Long-term
	Land Quality Management; Site interim and End States; Land Use.	Improved groundwater monitoring: • Increased automation to increase frequency of monitoring and reduce cost; • Increased information (e.g. isotopic ratios, chemical speciation, improved limit of detection) to identify source of contamination; • Increased information (e.g. in situ groundwater flux measurement) to improve predictions of movement of contaminants.	Advanced Electronics; Advanced Materials; Sensors;	Short- to Long-term

Strategic Theme	Strategic Topic	Research and Development Need	Graphene Research Industry/ Research Area	Timescale for Application
		Technologies and approaches for monitoring facilities and their contents over extended periods of C&M/deferral.	Sensors	Medium- to Long-term
		Techniques for early detection of leaks from existing facilities.	Advanced Coatings; Sensors; Energy/Energy Storage	Short- to Medium-term
		In situ remediation of contaminated ground: ○ Techniques (e.g. bioremediation) that either reduce or limit the spread of contaminants and can be applied on sites with facilities still present.	Membranes; Advanced Coatings; Energy/Energy Storage	Medium- to Long-term

The main areas of graphene research that appear applicable to the overall NDA decommissioning R&D needs are:

- Sensors;
- Advanced Materials;
- Radionuclide Remediation;
- Water Treatment;
- Membranes;
- Adsorbents;
- Radiation Detectors;
- Advanced Coatings;

The areas of graphene research that are potentially less applicable, but could be relevant in some way are:

- Gas Storage;
- Energy/Energy Storage;
- Advanced Electronics.

Further justification for the assignment of the above graphene research areas to the NDA decommissioning R&D needs is provided in the following sub-sections, with reference to some of the properties of graphene that enable it to provide added benefit in such areas.

4.3.1 Spent Fuels

The NDA requirements for R&D for spent fuels centre on three main areas of graphene research/industry: Sensors; Advanced Materials and Membranes/Water treatment/Radionuclide Remediation. Projects referred to herein from Appendix A will be referred to by their project number, **#**, identifier. It is noted that there are potential limitations to the application of graphene technology/research identified to the NDA R&D requirements discussed below, including radiation tolerance, particularly in applications relating to spent fuel management. However, these limitations are discussed in Section 5.

Spent Magnox and spent oxide fuel streams require further research into improved characterisation technologies to enable SLCs to have a better understanding of reprocessing facility conditions, which graphene sensor technology could potentially provide. Section 2 highlights the exceptional electronic properties of graphene (particularly its high sensitivity to changes in the electric field), which are also discussed in Reference [4], providing excellent sensor based capabilities. Both radiation and molecular detection sensors have been developed utilising graphene technology, which could be utilised by SLCs for facility condition characterisation. Appendix A includes multiple research projects, such as **#3**, **#62** and **#75**, which describe sensors that can detect gases and achieve < ppm sensitivity for water, oxygen, ammonia and nitrogen dioxide, as well as other electrochemical type sensors. The gases may not be of direct relevance to SLCs facilities; however development of the technology could lead to the tuning of the materials to detect other gases with similar sensitivity. Magnox reprocessing will end in 2020, hence, the development of sensors for characterising and understanding the condition of Magnox reprocessing facilities would need to be undertaken in the near future.

These sensors could also have potential applications in the monitoring of spent exotic fuels, as well as monitoring spent oxide fuel and associated pond furniture under wet storage. Graphene sensor technology could also be developed and tuned to monitor the precursors of oxide fuel corrosion. Appendix A includes reference to a research project, **#102**, which is focused on the development of graphene and 2D remote sensors for pools or waste storage, which has could have direct relevance to the monitoring of fuel corrosion under wet storage. The timescales for implementing sensors for the monitoring of spent exotic and oxide fuels would be medium to long term (5 - 20 years).

The treatment of small amounts of fuels left over from Magnox reprocessing is not necessarily an area that current graphene research can be applied to. However the conditioning of such materials and development of materials to immobilise legacy Magnox fuels, could utilise graphene technology. Graphene has been shown to impart many beneficial properties to materials such as cements, polymers, ceramics and glasses, historically. The beneficial properties for some of these materials (particularly those for graphene doped polymers) are highlighted in Section 2.3. These graphene-based composites display high strength, good mechanical properties, and high thermal diffusivity. Graphene doped polymers have shown improved leaching performances over non-doped polymers, and due to the adsorptive properties of GO, the addition of GO has the potential to also improve the leaching properties of cements. Cements, polymers, ceramics and glasses have all been used previously in immobilisation and encapsulation of nuclear waste. Therefore graphene doped advanced composite materials with enhanced properties, may be ideal for use in such a role. Appendix A includes multiple research projects relating to graphene doped polymers (including **#26**, **#27**, **#46**, **#54**, **#55**, **#57**), cements (**#96**), ceramics (**#33** and **#42**) and glasses (**#58**), with many focussed on the beneficial properties for applications in the nuclear decommissioning industry. These materials also have potential applications in the conditioning and disposal of spent oxide and exotics fuels, and long-term storage of specific exotic fuels.

It is further recognised that the advanced cement material, for example, could be used for construction purposes, with application in future dry storage facilities for spent nuclear fuels and nuclear waste in general.

The NDA requirement for research into spent oxide fuel pond water treatment, and also the treatment of radioactively contaminated water or effluent in general, is likely to be an area where application of graphene technology could provide added benefit to the NDA. Graphene materials, particularly GO which can be fabricated into a membrane with relative ease or dispersed into water, possesses properties enabling it to perform nano-filtrations and isotopic separations and, adsorb target cations and also selectively filter/separate tritium. Sections 2.1 and 2.2 document these properties and include some of the research projects these materials have been currently involved in. For example, the potential removal of Tc99 through nano-filtration [7], adsorption and removal of toxic and radioactive long-lived radionuclides from water [8], and isotopic separation of hydrogen isotopes [20]. The deployment of such materials at Sellafield for the treatment of radioactively contaminated water could be highly beneficial in the removal of radionuclides, with the added benefit of being able to target specific radionuclides. It has been highlighted that a recurring problem in both aqueous effluent treatment and environmental decontamination is poor selectivity and that new highly selective materials are required.

Appendix A includes several further examples of research projects looking at Membranes, Water Treatment and Radionuclide Remediation (including **#2**, **#4**, **#25**, **#50**, **#56**, **#63**, **#85** *etc.*) showing the promising potential for the use of GBMs in this nuclear decommissioning application. Appendix A also includes examples of the use of GBMs for water desalination purposes, which have been highlighted as having relevance to nuclear decommissioning due to the similarity in the application to radionuclide remediation in contaminated waters, including projects **#80** and **#81**.

4.3.2 Nuclear Materials

The NDA decommissioning R&D requirements for nuclear materials, specifically plutonium are related to technologies for monitoring waste packages and stores. Again, it is noted that there are potential limitations to the application of graphene technology/research identified, such as radiation tolerance particularly in applications relating to nuclear material management and these limitations are discussed in Section 5.

The graphene research areas that correlate with this requirement are focussed on Sensors and Radiation Detection, which were discussed in Section 4.3.1. Graphene-based systems could offer potential benefits over current systems due their high sensitivity offering low limits of detection. Particularly radiation detectors, as previously, mentioned there is a need for inexpensive, low-power, size-scalable detection devices, which are exceptionally sensitive to X-rays, gamma-rays, and neutrons, which could be used for detecting the presence of nuclear material and radionuclides.

Further research may be required to tune the materials to detect the required chemical components or types of radiation or to provide in-line detection. Appendix A shows the extent of research being conducted in this field. The timescales for applying graphene based sensors and radiation detectors to this strategic topic span short term through to long term (<5 years to >20 years, Table 3).

4.3.3 Integrated Waste Management

The NDA integrated waste management R&D requirements for radioactive waste is split into “Reprocessing”, “Legacy Facilities” and “Operational and Decommissioning Wastes”.

The requirements for “Reprocessing”, again correlate well with the research areas of Advanced Materials and Water Treatment/Membranes/Radionuclide Remediation. The requirement for the development of vitrification wasteform for POCO HAL feeds could utilise the Advanced Materials graphene research, which was discussed in Section 4.3.1 and include the concept of deploying graphene based composite materials for waste conditioning. Appendix A includes a research project relating to the development of novel advanced glasses (**#58**), which could be directly relevant to vitrification of POCO HAL feeds. As indicated in Table 3, a short to medium timescale (5 – 20 years) would be applicable for the development of advanced graphene materials in vitrification.

Regarding options for the treatment of effluents highlighted in the "Reprocessing" section of Table 3, it is thought that the research discussed in Section 4.3.1, relating to graphene's applications in contaminated water and effluent treatment could be relevant. As previously mentioned, Appendix A includes many relevant research projects to this area. However, project **#107** which relates to researching smart filter membranes adopting advanced coatings may be of specific relevance to this requirement. The Smart filter membranes are based on graphene and have been tested in desalination trials in aqueous media and the project focus is to expand into applications within nuclear decommissioning/desalination. Applications involving water and effluent treatment have a longer application window, ranging from medium to long term (5 - >20years).

The NDA R&D requirements for both "Reprocessing" and "Legacy Facilities", for research into remote monitoring of waste packages and stores, is again applicable to the graphene research area of Sensors. As discussed previously, this graphene research area for the use in SLC monitoring applications has been discussed in Section 4.3.1. In addition, Appendix A contains research projects relating to hydrogen capture (**#70**) which could be applied to the monitoring of corrosion/hydrogen evolution of wastes. Moreover, sensors which monitor gaseous water (**#3**) could potentially be applied to monitoring humidity.

The NDA R&D requirements for "Operational and Decommissioning Wastes" involve research into improved encapsulants. The graphene research area of Advanced Materials has direct relevance for this requirement and is discussed in Section 4.3.1. Briefly, new graphene-based composites involving polymer and cement may have beneficial properties for waste conditioning and packaging.

The NDA R&D requirements for "Liquid and Gaseous Discharges" correlate well with the research areas of Water Treatment/Membranes/Radionuclide Remediation and Radiation Detectors/Sensors. The requirement for research into modular and mobile effluent treatment facilities could be complemented by the graphene research areas of Water Treatment/Membranes/Radionuclide Remediation, which was discussed in Section 4.3.1. The mobile aspect of these facilities could be complemented by the lightweight nature of graphene and ability to prepare GO membranes to a required size, suitable for a mobile device.

The requirement for research into in-line monitoring technologies correlates well with the graphene research area of Radiation Detector and Sensors, as discussed in Section 4.3.1. The use of graphene brings the benefits of a higher sensitivity, though the long-term ionising radiation tolerance of graphene should be considered further. This aspect is to be considered in depth as part of project **#39** in Appendix A.

4.3.4 Site Decommissioning and Remediation

The NDA site decommissioning and remediation R&D requirements are split into the strategic topics, "Decommissioning", "Land Quality Management", "Site Interim and End States" and "Land Use". The predominant graphene research areas that correlate well with these requirements are Sensors, Radiation Detectors, Membranes/Water Treatment/Radionuclide Remediation, Advanced Coatings, Energy/Energy Storage and Advanced Materials/Electronics.

The NDA requires further research into in situ characterisation to determine levels of contamination during site decommissioning, which correlates well with the graphene research area of Radiation Detectors and Sensors. Discussion surrounding these research areas has been documented in Section 4.3.1. However, it can be further embellished to consider the portability aspects that NDA require. As described in Section 2, graphene is a lightweight yet mechanically strong material which is ideal for manufacture of portable equipment, both for the actual sensor electronics required and potentially also for the casing of the device. A further more abstract link is to the graphene research area of Energy/Energy Storage, which could be applied to this role in the form of portable power supplies for these devices. However this is likely to require significantly more development. Research projects, such as project **#117** in Appendix A, are looking to combine graphene with materials such as steel, as a charge collecting material in batteries and other advanced energy storage devices. Successful utilisation of this technology could allow for improvements in performance as well as significant cost reduction in batteries and supercapacitors alike. Short to long timescales (<5 years to >20 years) would be applicable to the development and utilisation of these applications.

Research into improved decontamination techniques are also required which correlates well with the graphene research areas of Membranes, Advanced Coatings, Water Treatment and Radionuclide Remediation. The application of these graphene research areas for decontamination and removal of radionuclides from contaminated solutions has been documented in Section 4.3.1, with the increased effectiveness and efficiency due to the enhanced selectivity of the graphene materials. The NDA are also seeking to minimise secondary waste in these techniques, which the employment of advanced coatings for filters such as those being developed in Appendix A, project **#107**, can offer. As the radionuclides are trapped onto a graphene-based membrane, the filter could be used for longer rather, potentially reducing secondary waste generation.

Graphene-based research into Energy/Energy Storage and Gas Storage is currently one of the most prominent sectors for graphene research and could be applied in devices intended for remote or enhanced operation in extreme conditions. GBMs have shown the potential to be used in hydrogen cells (Appendix A, **#77**) and as charge collecting materials for use in batteries and other advanced storage devices (Appendix A, **#117**). This technology could be utilised in portable devices, such as handheld/portable monitoring devices (as discussed in Section 4.3.4) and also in equipment such as Remotely Operated Vehicles (ROVs). Applications for ROVs in decommissioning can vary greatly. However increased battery performance/power storage may be beneficial to ROVs with high energy consuming components (such as tooling for decommissioning, including dismantling and disrupting equipment). Such tooling may drain battery life, preventing the ROV from operating over long timescales. Similar to this area is the further development of the Advanced Electronics graphene research area.

The NDA also requires further research into improved groundwater monitoring for site remediation applications. In terms of groundwater monitoring, an increase in automation could be brought about by application of advanced graphene-based electronics and materials. Utilising graphene sensor technology to increase information obtained during monitoring, identifying contaminants and predicts their movements, is a promising area. Further to the previous discussion surrounding the use of graphene-based sensors (Section 4.3.1), graphene sensors could potentially be utilised in the future for the determination of chemical speciation. Appendix A contains a research project (**#75**) that is developing advanced electrochemical sensors, with applications in the nuclear decommissioning industry, which could determine information relating to contaminants based on their electric potential. The use of graphene sensor technology has also been previously discussed in Section 4.3.1 for use in monitoring of facilities and waste packages, and so could be applicable for waste package condition monitoring and inspection.

Techniques for early detection of leaks from existing facilities could also utilise the graphene research area of Sensors. This could also be complemented by the application of the graphene research area of Energy/Energy Storage and Advanced Coatings. Appendix A contains projects, such as **#77**, which discusses the use of GBMs tritium capture, which could be useful in detecting tritium permeation. Appendix A also highlights a project, **#91**, which is researching the use of reduced GO as a cheap coating sensor to measure radiation leaks, which again would be directly applicable.

Project **#77** in Appendix A, is also potentially relevant for applications intended to reduce or limit the spread of contaminants during in situ remediation of contaminated ground, particularly for tritium contamination. GBMs could be utilised to capture tritium being emanated and hence reducing or limiting the spread of tritium. Appendix A contains other projects looking at gas storage, particularly in the Energy/Energy Storage graphene research area, which could have cross-over applications in the trapping of radioactive gases. The graphene research area of Membranes and Advanced Coatings could correlate well with the application of reducing or limiting the spread of contaminants, particularly if the GBMs could be deployed around the perimeter of the contaminated ground. Section 4.3.1, discusses the ability for graphene membranes and coatings to remove Tc99 [7], remove toxic and radioactive long-lived radionuclides [8], and isotopic separation of hydrogen isotopes to potentially remove tritium [20], in aqueous systems. These could be potentially utilised in contaminated ground environments where the groundwater flow transports soluble contaminants, such as Tc99 as pertechnate.

4.4 Identification of Research Gaps and Opportunities

From reviewing Table 3, it can be seen that the vast majority of the NDA decommissioning research and requirements broadly correlate with the graphene research areas identified in Appendix A. However, some gaps in the NDA requirements were identified during the above assessment are discussed in Section 4.4.1.

Furthermore, a number of potential opportunities have been identified and will be discussed further in Section 4.4.2.

4.4.1 Potential Research Gaps

Two of the NDA requirements from Table 3 have been identified as potential gaps. A potential research gap is defined as an NDA R&D opportunity or need where the application of graphene technology could potentially provide feasible added benefit, but does not currently correlate with any of the research projects identified. Research gaps therefore differ from irrelevant research areas, which were discussed in Section 4.2. Irrelevant research areas are those where graphene technology is not thought to provide any benefits (e.g. making the uranics inventory more saleable and improving statistical approaches).

The two potential research gaps include:

Spent Fuels:
Development of technologies to treat the small amounts of fuels left over once Magnox reprocessing operations cease;

- There are currently no graphene research areas that have been reviewed that have potential applications in the treatment of fuels, *i.e.* in such roles as fuel reprocessing.

Spent Oxide Fuel – In the longer term technologies associated with drying, storage and disposal of spent oxide fuel are of interest to NDA;

- There are currently no graphene research areas that have been reviewed that have potential applications in the drying of fuels.
- However, Advanced Materials could be utilised in the future storage of spent oxide fuels, in the manufacture of waste containers or dry fuel storage casks.
- It has already been discussed that Advanced Materials may have a role in waste encapsulation/immobilisation, which could also be utilised for spent oxide fuel disposal.

Further research could be conducted into the application of graphene in these areas. However, this may not be necessary given the maturity of existing fuel treatment technologies. Therefore, graphene based research may not yield any significant benefits beyond those already provided by existing fuel treatment technologies.

4.4.2 Potential Opportunities

In addition to the research correlations identified in Section 4.3, opportunities for further graphene research have been identified that could provide benefit to the NDA estate in ways not considered previously. Many of these opportunities would need to be developed further with a nuclear decommissioning interest in mind.

As highlighted in Section 4.3, the graphene research area of Advanced Materials such as cements, polymers, ceramics and glasses, could be utilised in the conditioning and immobilisation of nuclear and radioactively contaminated wastes. Further research into this, specifically for the encapsulation and immobilisation of these wastes could be a great opportunity to explore. Furthermore, combining these immobilising/conditioning materials within waste containers lined with graphene membranes could be an opportunity for further research. Waste containers lined with GO membranes that can capture radionuclides and/or perform isotopic separations to prevent radioisotopes from migrating out of the waste container could be advantageous in a geological repository environment. This may be particularly relevant after ground water infiltration has occurred within the waste packages and could minimise the release of radionuclides into the environment. GBMs could also be used in the filters of vented waste containers, to again minimise radionuclide release, particularly of gaseous radionuclides. Such research could be complemented by the research project **#56** discussed in Appendix A, which aims to research GBMs and understand their impact on microbial populations used in wastewater treatment. This in turn may overlap with the interactions between water, microbes, and graphene-based wastes in a repository environment.

Research into graphene's long term radiation hardness and potential environmental effects should be also considered (examples of projects listed in Appendix A include **#68**, **#89**, **#93** and **#94**).

Graphene research has also been focused on the development of corrosion resistant coatings. Project **#111** in Appendix A aims to research the potential of graphene in fire retardant and protective coatings. This could certainly be beneficial to machinery and tooling employed in corrosive decommissioning environments, such as the caustic ponds used for wet storage of nuclear waste, or waste containers in a potentially high pH cementitious geological repository environment, where corrosion is a significant factor. Utilising a protective coating could prolong the life of machinery, tooling and waste containers. The latter potentially slowing the corrosion and failure of waste containers in a geological repository environment.

Graphene is also being researched for use in oil products, to provide enhanced lubrication and hence reduce the wear/extend the life of components. This could again be beneficial to the NDA estate, in improving the lifetime of machinery and tooling used in nuclear decommissioning and lowering secondary waste arisings.

5 The Potential Limitations of the Use of Graphene in Nuclear Decommissioning Applications

Although graphene and other GBMs could potentially provide benefits to the nuclear decommissioning industry, there are also limitations and barriers to the use of these materials. These are discussed in the following sub sections.

5.1 Cost

The cost of producing graphene for commercial applications varies greatly by mass, depending on its physical form (such as powder/film), its chemical form (pure graphene, GO or other functionalised material), or by its density. The price variation is brought about in part due to the method of manufacture (as discussed in Section 5.2).

Table 4 presents a comparison of some commercial prices for graphene and related compounds, with prices accurate as of February 2017.

Table 4: A Comparison of Commercial Prices for Graphene in Different Forms

Supplier	Form and Amount	Price
Graphenea	Graphene Oxide (0.5 mg/mL, Water Dispersion 250 mL)	£38.74
Graphenea	Graphene Oxide Powder (1 gram)	£82.64
Graphenea	Easy Transfer: Monolayer Graphene on Polymer Film (1 cm x 1 cm)	£61.98
Sigma-Aldrich	Graphene powder, bulk density 0.0215, weight 6 g, platelet planar size 0.3-5um	£485.00
Cambridge Nanosystems	CamGraph Graphene Powder (1 g)	£185.00 – £240.00 (depending on density)

The prices in Table 4 vary greatly, with graphene in its pure powdered form being the most expensive. This is due to its high manufacturing costs. The application and hence form of graphene required and the resulting benefits will determine whether the cost is prohibitive. Applications requiring pure powdered graphene will inherently cost more than those requiring less pure graphene. Cost as a limitation will also depend on the amount of graphene required in the application, for example the amount of graphene required to dope an advanced cement or polymer, will affect the cost for the production of the material.

Overall the cost of graphene is decreasing, this is due to the increasing number of manufacturing facilities and manufacturing processes becoming more scalable, specifically in CVD and epitaxial growth on silicon carbide (see Section 5.2).

5.2 Manufacturing Scale Up

The properties of graphene are strongly affected by its form and defect structure. The latter is dependent on the fabrication method, interactions with the substrate and environment. It should also be noted that many properties of graphene are not necessarily maintained as the material is scaled-up and is thus a limitation [4]. Table 5 presents the advantages and disadvantages of each graphene manufacture/scale up by method.

Table 5: Advantages and Disadvantage of Graphene Scale Up by Method

Graphene Manufacturing Method	Advantages	Disadvantages
Micro-mechanical exfoliation	• High quality, single crystals of monolayer graphene with micron sizes; • Method can be applied to other layered crystals.	• Not scalable.
Chemical Vapour Deposition	• Large area growth of single-layer graphene, >50 cm^2; • Roll-to-roll production of graphene.	• Polycrystalline, defects e.g. pin-holes created; • High costs; • High process temperatures (~1000 ℃).
Liquid phase exfoliation (includes ultrasonic, shear and electrochemical exfoliation)	• Scalable processes; • Easy to realise; • Moderate yields (dependent on method); • Nanometre to micron sizes; • Low costs.	• Non-uniformity of nanosheets; • Impurities; • Ultrasonic and shear typically yields low concentrations; • Requires multiple cycles.
Epitaxial Growth on silicon carbide	• High quality, thin films (several microns).	• Low yield; • High cost; • Requires high temperatures (1500 ℃).
Oxidation of Graphite to form GO	• High yield; • Scalable; • Material can be further functionalised; • Dispersed in water; • Insulating material.	• Hazardous reaction including strong acids and oxidants; • Requires excessive water washes; • Expensive.
Reduction of GO to form RGO	• High yield; • Scalable; • Variety of reducing methods.	• Until recently, difficult to effectively remove all oxygen groups; • Defects.

Table 5 shows that generally, methods that produce high quality, single crystals of pure graphene are not scalable [4]. This may be for technical reasons, or for financial considerations. However as discussed in Reference [4], pure graphene is not always required for materials with certain desired properties. Though applications where it is required, there are currently no available methods for large scale.

This could be a limitation to graphene's use in the nuclear decommissioning industry. For example the production of advanced sensors and detectors generally requires graphene that is synthesised by the manufacturing methods CVD and epitaxial growth on silicon carbide (SiC), which currently have high associated cost, though those are decreasing steadily. The cost of producing SiC wafers is not an obstacle anymore, however the cost of producing graphene layers from these wafers will remain relatively high until production is scaled up, which is possible in the future.

5.3 Environmental Safety Impacts

A number of literature reviews have been conducted into the environmental and safety impacts of GBMs. It is recognised however, that due to the relative immaturity of graphene and graphene technology, the long term effects of these materials on humans, wildlife and the environment are generally not yet known.

A review by Pinto et al assesses the biocompatibility of GBMs [38], which could be relevant to the nuclear decommissioning industry if GBMs become released into the environment, or come into contact with humans and wildlife. Studies have shown that mammalian cell viability decreases slightly after exposure to GBMs. The in vivo effect of GBMs were found to depend on the physical–chemical properties, concentration, time of exposure, and administration route, and also on the characteristics of the animals used. Most studies reported no occurrence of adult animal death. However, it is noted that there are some reports of GBMs accumulation and histological findings associated with inflammation, and, more rarely, fibrosis. The encapsulation of GBMs in a matrix has shown a potential reduction in toxicity and some reports show potential antibacterial properties of GBMs [38].

A paper by Zhao et al assesses the impacts of graphene in the aquatic environment [39], which again could be relevant if these materials are used in the nuclear decommissioning industry. Upon exposure in aquatic environments, GBMs have shown to have adverse impacts on aquatic organisms (e.g., bacteria, algae, plants, invertebrates, and fish). GBMs internalised in the cells of biota through direct penetration can cause oxidative stress, mitochondrial dysfunction, and DNA damage [39]. It is also seen that GBMs transform and/or degrade in the aquatic environment, such as the transformation of GO, to reduced GO and the degradation of GBMs upon exposure to UV irradiation and/or biota.

A review by Arvidsson et al [40] assessed the potential environmental and health risks of graphene. The results from this study indicated that graphene could exert a considerable toxicity and that considerable emission of graphene from electronic devices and composites are possible in the future. The effects include physical damage to cell membranes, attachment to cell membranes and also signs of cell apoptosis (non-programmed cell death) [40]. It was also suggested that graphene is persistent and has a long residence time in the environment. However, the report caveats this statements with the stance that further work needs to be undertaken into graphene's toxicity, particularly with a risk perspective taking into account aspects including:

- Workplace emissions and exposure;
- The fate of graphene in environmental media;
- The physical shape of graphene in environmental media.

From the above information it can be seen that graphene could pose a potential risk to humans, wildlife and to the environment. If utilised in an advanced material as a composite, it appears that this could be much less of a risk than applications of pure graphene [38]. Taking into account all of the information, it is seen that further work is required to fully assess the safety risks of graphene to humans, wildlife and the environment, and assessments into the degradation components of GBMs and their potential hazards is required.

5.4 Regulatory Concerns

The main limitations to the nuclear industry are related to how the material will be registered e.g. through the European Union regulation of Registration, Evaluation, Authorisation & restriction of CHemicals (REACH)[1], or an alternative registration route. Currently there are no UK or international regulations relevant to good practice for graphene based technologies, or clearly defined health and safety requirement for handling these materials [41]. This poses a threat to the development of graphene technologies and the safety of both workers and the public. Though recently the European Commission has launched a public consultation regarding the benefits, risks, concerns and awareness of technology. From a nuclear decommissioning perspective it is important that there is an understanding and awareness of the safety implications of graphene technologies within the nuclear sector to enable efficient regulation of the industry.

It is acknowledged that the nuclear industry may be indirectly exposed to graphene and related materials. For example, through introduction of GBMs in materials such as oils and steels doped with graphene. These materials may already be used, but the industry may be unaware of due to the commercial protection placed on the formulations sold by the suppliers.

It is further understood that the Office for Nuclear Regulation (ONR) is intending to develop a process for approving new materials and new technologies intended for use in the industry, which will be of relevance to implementation of graphene into the nuclear decommissioning sector.

5.5 Lack of Standardisation

Standardisation is required to ensure clear product specifications and product safety. For large scale commercialisation the materials standards, regulations, supply availability and fair price must be obtained [41]. There are no current materials standards that companies must comply with in relation to graphene. This results in an

[1] REACH aims to provide high level protection to human health and the environment. It also aims to make the people who place chemicals on the market (manufacturers and importers) responsible for understanding and managing the risks associated with their use.

adverse effect on the development of the sector as end-users, regulators and insurers cannot assess product quality of GBMs. Nor can they obtain guidance on material safe usage or adopt any Health and Safety standards [42].

International standardisation will be crucial for what could be a worldwide market, though no international standards have yet been published for graphene. There is currently activity in this area, in both the International Organization of Standardization (ISO) and the International Electrotechnical Commission (IEC), with several standards currently under development [42].

Standardisation will also ensure the properties of the materials produced are consistent, which is important to the application of GBMs in the nuclear decommissioning industry. This is in part due to the fact the properties that make a GBM attractive for one application may mean that it is unsuitable for another application. For example, whilst the electronic properties of pure graphene (low noise, high conductivity and highly sensitive to changes in the local electrical field) make it an attractive material for sensors and detectors, the inert nature of the material is unlikely to be as useful in radionuclide adsorption or composite materials. Therefore, the properties of graphene and related compounds that are useful to the nuclear decommissioning industry are very application specific and standards are required to ensure these properties are correct and consistent for each different application.
There is a notable program of R&D at NPL and the Graphene Flagship aiming at the development and validation of rapid, accurate, preferably in-line measurement protocols and instrumentation. These will be developed for structural, physical and chemical characterisation and quality control of 2D materials produced on an industrial scale, which will lead to new standards and measurement services.

5.6 Radiation Tolerance

As outlined in Reference [4], graphene has been shown to degrade when exposed to gamma, alpha and beta radiation [43, 44, 45], with severe lattice damage being observed at low energies (80 keV for beta particles and 1.5 MeV for alpha particles). However, encapsulation of graphene within devices has been shown to improve the radiation hardness, hence maintaining the performance and stability of the material. Such improvements in the radiation hardness have been demonstrated for graphene based semi-conductor devices [43, 46].

To be utilised in the nuclear industry graphene is likely to need to withstand exposure to ionising radiation, at least to an extent where its properties are unaffected, to allow it to fulfil its function. The application of graphene in Advanced Materials is likely to be effective in terms of radiation tolerance, due to graphene's improved radiation tolerance in composite materials. The use of pure graphene in Sensors could be affected by the materials lack of radiation tolerance. However it is likely the device that the pure graphene is constructed into will offer some protection/shielding, meaning the graphene may not be directly exposed to the radiation. Again, like most of the limitations discussed, further research into graphene's radiation tolerance is required. Appendix A documents a number of projects related to this area which will hopefully provide further information in the coming future.

6 Conclusions

This report has identified a number of key correlations between the NDA decommissioning R&D needs and graphene research areas. Hence, broader research programmes being undertaken in academia and industry, could provide added benefit to the NDA estate in the future of nuclear decommissioning.

The desktop review of the graphene research areas provided a comprehensive outlook of current graphene research. The categorisation of the research projects into different industry/research areas facilitated the high level correlation of the graphene research areas to the NDA decommissioning R&D requirements. The graphene research areas that formed the predominant links with the NDA R&D requirements included, Sensors/Radiation Detectors, Radionuclide Remediation/Water Treatment/ Membranes/Advanced Coatings.

The timescales for implementing the identified graphene research/technology varies depending on the intended application within the nuclear decommissioning industry (Table 3). For example, graphene applications related to fuel reprocessing (such as Magnox) would likely need to be implemented within the next 5 years. Applications relating to decommissioning may be less time constrained with the timescale for application being within 20 years, or longer.

Discussions and arguments have been put forward to explain the correlations between the graphene research areas and NDA requirements. Many of these discussions and arguments hypothesised using the knowledge acquired previously about graphene's properties, helping to illustrate the potential added benefit graphene could provide to the nuclear decommissioning industry. A few of the NDA requirements could not be synergised with a graphene research area, though this was very much the minority and were listed in Section 4.4.1.

The limitations to the use of graphene in the nuclear decommissioning industry were also assessed. It was identified however, that further research would be required to confirm the most significant limitations, especially regarding long term effects of graphene and GBMs to human/wildlife health and the degradation of the material. The cost and the scale up of manufacture is a limitation depending on the type of graphene material required, with pure graphene currently being harder to scale up and costing more to produce. Though as described, the purity of graphene does not always relate to its performance, as this is application dependent. The potential toxicity of graphene is a potential major limitation, especially in aqueous environments, and if graphene cannot be proven safe to use in such environments then this limits the applications it can be used for in the nuclear decommissioning industry. This would particularly affect its use in effluent treatment or being used in immobilisation/encapsulation in waste packages destined for a geological repository.

The regulation and standardisation of graphene are inherently linked, as standards need to be formed to ensure compliance with regulations, particularly those of the ONR, to enable graphene's use in the nuclear decommissioning industry. However, international standardisation is currently under development, which could prevent these factors from being major limitations. The last potential limitation considered was radiation tolerance. This aspect is important, as graphene research indicates that graphene is generally used in a composite form, reducing this factor as a limitation.

6.1 Key Synergies Identified

The key collations and opportunities with respect to the nuclear decommissioning industry are:

- Advanced Materials – These include advanced polymers, cements, ceramics and glasses. These could be utilised in the conditioning/immobilisation of nuclear wastes, as well as in construction of modern devices or buildings/facilities. The benefits of including GBMs in composite materials include enhanced mechanical and leaching properties. The use of graphene in a composite could also improve graphene's radiation tolerance and could potentially lower its toxicity by being chemically incorporated into the composite matrix and reducing its likelihood of migration into the surrounding environment. Graphene used in composites is unlikely to be required in its pure form, with GO being more applicable which has greater scale-up potential and lower costs.
- Membranes – These could be utilised in effluent treatment and potentially incorporated into future waste containers, to minimise radionuclide leaching. The major benefit to graphene in this role is its selectivity.
- Sensors/Radiation Detectors – These could be utilised in numerous roles as identified in Table 3. The impressive electronic properties of graphene potentially lend itself to the development of enhanced Sensors/Radiation Detectors for the use in the nuclear decommissioning industry. The radiation tolerance and costs for manufacture will need to be further considered, however, in terms of the sensitivity that could be offered these are worth further investigation.

7 Recommendations

1. Further consideration of the research gaps identified in Section 4.4.1, which relate to Magnox fuel (treatment of small amounts of fuels left over once Magnox operations cease) and spent oxide fuel (technologies associated with drying, storage and disposal). Initial assessment indicated that none of the existing graphene research areas correlated with these NDA requirements. However it should be considered whether graphene technology is needed to fulfil these requirements, when other technologies have been or are being developed to satisfy these requirements.

2. It is further recommended that the graphene research areas identified as being relevant to nuclear decommissioning applications (Section 4) are investigated further. This could be achieved through appropriate mechanisms to support early development, such as feasibility studies with Innovate UK, DRP projects or PhD projects, and could include:
    - Trials to assess the suitability of graphene doped advanced materials for nuclear waste immobilisation/encapsulation;
    - Trials to assess the incorporation of graphene membranes into RWM approved waste containers and assessment of their radionuclide retention;

- Manufacture of radiation resistant graphene materials for use as in-situ radiation detectors/leak monitors;
- Trials to assess the gas storage capabilities of graphene materials;
- Trials to assess the performance of graphene based energy storage devices and their ability to improve operations that require the use of remote surveillance equipment.

3. In addition to the technical applications noted above, the NDA could maintain a watching brief on the limitations relating to the use of graphene in the nuclear decommissioning industry. These limitations include cost, manufacturing scale-up, environmental and safety, regulation and standardisation (Section 5).

4. Finally it is recommended that the NDA proactively follow a number of journals, research groups, funding bodies and conferences (such as those suggested in Ref. [4]) to keep abreast of up to date graphene research and technology. Due to the rapid development of graphene research and technology, the content of this report has a lifetime. Therefore, it is recommended that this document is reviewed and updated biennially to ensure that the information represents the latest graphene research and technology. Conducting this review biennially would also coincide with the cycle of the Graphene Flagship, aligning well with the review and update process.

   Ultimately further advances in graphene and related materials, specifically targeting nuclear decommissioning, would require close interaction between the graphene researchers, nuclear engineers and regulatory authorities. This means targeted joint R&D projects involving multi-disciplinary teams.

Nuclear
Decommissioning
Authority

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Appendix A

Detailed Output from the Desktop Review of Graphene research areas

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
Research identified from The Graphene Flagship								
#1	University of Manchester	WP1 (Enabling Research) Task 1.2	Work Package Leader: Professor Vladimir Falko (University of Manchester)	R.R. Nair, at al. Science 335, 442 (2012). R.K. Joshi, et al. Science 343, 752 (2014). G. Algara-Siller, et al. Nature 519, 443-445 (2015	—	Investigation of nanocapillary properties of graphene- and hBN-based structures; development of intercalated graphene structures. Example: graphene laminate that would filter out >80% of salt ions from water over one pump cycle. Manchester University have recently found that graphene-based nanocapillaries with a size of »10 Å, made by a bottom-up technique using graphene oxide, provide practically no barrier for water vapour permeation and offer remarkable properties for water filtration. The latest research shows that water inside such graphene nanocapillaries forms square ice at room temperature. They work to develop top-down technologies for fabricating nanocapillaries from graphene, hBN and other 2D materials and investigate their properties in view of their applications in separation of gas mixtures and desalination of water.	Desalination	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#2	Friedrich-Schilleruniversitat Jena	WP3 (Enabling Materials) Task 3.1.2	Work Package Leader: Professor Mar Garcia-Hernandez, CSIC, Consejo Superior de Investigaciones Cientificas,	P. Angelova, et al. ACS Nano 7, 6489-6497 (2013)	—	The goal of this activity is to scale-up the technology for synthesis of graphene membranes. Growth of membranes and their heterostructures by electron beam crosslinking of self-assembled molecules. Structural, electrical, optical, mechanical characterisation. Permeation tests. Growth and characterisation of membranes of other 2D materials from LPE by vacuum filtering. Patterning with nanoimprint lithography. Potential use of advanced membranes to be used for various nuclear decommissioning projects	Membranes	Yes
#3	Friedrich-Alexanderuniversitaet Erlangen Nuernberg	WP3 (Enabling Materials) Task 3.1.6	Work Package Leader: Professor Mar Garcia-Hernandez, (CSIC)	S. Eigler and A. Hirsch, Angewandte Chemie International Edition 53, 7720-7738, (2014).	—	Chemical and physical modification of 2D materials for various applications. Achieve < ppm sensitivity for graphene-based gas sensors for H_2O, O_2, NH_3 and NO_2. Covalent coupling of bio and organic species on graphene for biosensors. Graphene-based devices respond to the presence of very small amounts of gases in the ambient atmosphere or to adsorption of molecules on its surface. However, specificity of this response can only be achieved by a combination of graphene sensor with functional molecular or atomic groups. The aim of this task is to develop methods to functionalise graphene for gas and bio applications.	Sensors	Yes
#4	CNM Technologies GmbH	WP3 (Enabling Materials) Task 3.2.3	Work Package Leader: Professor Mar Garcia-Hernandez, (CSIC)	—	—	Scale-up production of graphene membranes with transfer and their incorporation in standard filtration device structures, characterisation of their filtration properties. Device-scale engineering, integration and quality control of membranes. The participation of BASF is of particular note.	Membranes	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#5	Universidad de Castilla - La Mancha	WP4 (Health & Environment) Task 4.1	Work Package Leader: Professor Maurizio Prato, University of Trieste, Italy	WP Outputs: Wick P, 2014. Angew Chem Int Ed Engl. 53 (30): 7714-7718	—	Preparation of graphene enriched with stable and radioactive isotopes: Synthesis and characterisation of ^{14}C-labelled graphene and ^{13}C graphene and graphene oxide, instrumental to biodistribution routes studies. The aim of this task is to determine the kinetics and fate of graphene via aspiration route of exposure. It will include: 1) synthesis of graphene from ^{13}C-labelled methane ^{14}C-benzene precursor by CVD 2) in vivo administration of ^{14}C-labelled graphene suspensions to mice, 3) full-body radioimaging, and 4) extraction of graphene from target organs and characterization by high-resolution TEM. This work is of general H&S interest. It evaluates the risks to humans if graphene and related materials are to be used in practical applications.	Health and Safety/ Environment	Potentially
#6	Commissariat a l'Energie Atomique et Aux Energies Alternatives (CEA)	WP4 (Health & Environment) Task 4.9	Work Package Leader: Professor Maurizio Prato, University of Trieste, Italy	As (5)	—	Biodistribution of inhaled radiolabelled graphene: GRM bio-persistence beyond respiratory barriers. The aims and relevance to the nuclear industry for this Task is detailed in (5).	Health and Safety/ Environment	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#7	TU Delft	WP6 (Sensors) Task 6.1	Work Package Leader: Herre van der Zant, Technical University of Delft, The Netherlands	WP Outputs: Dolleman R. J., et al., Nano Lett., 16, 568 (2016)	—	Sensor fabrication and functionalization. Suspended graphene devices form the basis for four types of sensor applications pursued within WP6: pressure, gas and mass sensing and the translocation of DNA through nanopores. Large arrays of suspended CVD graphene membranes deposited on electrodes for electrical readout and actuation will be fabricated. Gas analysers in particular may be interesting for ND industry. In addition, calibrated nanopores can be used in other types of devices, e.g., for filtration.	Sensors	Yes
#8	TU Delft	WP6 (Sensors) Task 6.2	Work Package Leader: Herre van der Zant, Technical University of Delft, The Netherlands	—	—	Sensor fabrication and functionalization. Gas sensing will be pursued using different platforms. Resistive sensors are based on field-effect transistors functionalized by PLD or using nanopatterning; they respond to the presence of gases adsorbed on the surface by a measurable change in resistance due to doping or scattering effects. In resonant devices, graphene membranes are used as resonators and gas detection can be established through the adsorbed mass of the gas molecules and the accompanying change in resonant frequency or by a change of the dynamic properties in case nanoporous graphene is used. Optical read-out of gases using graphene plasmonics will also be examined. A major goal is to develop working principles for the miniature low-power sensors of the main pollutant gases (NOx, O_3, CO, SO_2, NH_3). The working principles can in the future be extended to other gases.	Sensors	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#9	TU Delft	WP6 (Sensors) Task 6.4	Work Package Leader: Herre van der Zant, Technical University of Delft, The Netherlands	—	—	Technology and feasibility assessment of GRM sensors. Feasibility and technology readiness assessment for application of graphene-related materials in sensor applications.	Sensors	Yes
#10	Politecnico di Milano	WP7 (Electronic Devices) Task 7.1	Work Package Leader: Dr Daniel Neumaier, AMO GmbH, Germany	—	—	This task is dedicated to the development of process technology for the fabrication of graphene and transition-metal-dichalcogenide (TMD) field-effect transistors (FETs) and passive multilayer devices. Ultrathin stable gate-stacks will be developed and optimized for graphene FETs (GFETs) fabricated from CVD-grown and hydrogen-intercalated epitaxial graphene and optimized for GFETs fabricated on quartz, high resistivity Si, SiO_2 and SiC. This work is relevant to the development of GFET radiation sensors.	Radiation Detectors	Yes
#11	TU-Wien	WP8 (Photonics & Optoelectronics) Task 8.1	Work Package Leader: Professor Frank Koppens, ICFO, Spain	—	—	Photo-detectors for visible, near-IR and shortwave IR, including waveguide-integrated PDs for the silicon-on-insulator platform, Ultra-sensitive PDs for low-intensity or single-photon detection, flexible photodetectors. The relevance of this work is in the potential to develop better, more sensitive and compact heat-sensitive detectors and cameras, or THz for non-destructive examination and testing.	Radiation Detectors	Yes
#12	Fondazione Bruno Kessler	WP8 (Photonics & Optoelectronics) Task 8.6	Work Package Leader: Frank Koppens, ICFO, Spain	—	—	Long-wavelength photo-detectors, such as high-response-speed THz field effect transistors, mid-IR detectors with pn-junctions and photodiodes. The aims and relevance to the nuclear industry for this Task is detailed in (11).	Sensors; Advanced Electronics	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#13	ST Microelectronics SRL	WP9 (Flexible Electronics) Task 9.3	Work Package Leader: Henrik Sandberg, VTT Technical Research Center of Finland Ltd., Finland	—	—	Flexible Sensing Modules including logic and, in some case, wireless connectivity, suitable for applications in 'Wearables' and 'Distributed Sensors Networks'. In summary, this work involves developing miniaturised sensors and associated wireless electronics.	Sensors; Advanced Electronics	Potentially
#14	Universite des Sciences et Technologies de Lille	WP9 (Flexible Electronics) Task 9.4	Work Package Leader: Henrik Sandberg, VTT Technical Research Center of Finland Ltd., Finland	—	—	Flexible Radio Modules: flexible connectivity modules, identifying possible key applications (wearables, etc.). In summary, this work involves developing miniaturised sensors and associated wireless electronics.	Sensors; Advanced Electronics	Potentially
#15	Flexenable Limited	WP9 (Flexible Electronics) Task 9.5	Work Package Leader: Henrik Sandberg, VTT Technical Research Center of Finland Ltd., Finland	—	—	Flexible user interface modules. In summary, this work involves developing miniaturised sensors and associated wireless electronics.	Sensors; Advanced Electronics	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#16	Nokia R&D	WP10 (Wafer-Scale System Integration) Task 10.4	Work Package Leader: Professor Marco Romagnoli, CNIT, Italy	—	—	Flexible electronics: Large-scale monolithic integration of GRM-based circuits, large-scale heterogeneous integration of multiple GRM-based components on flexible. In summary, this work involves developing miniaturised sensors and associated electronics with wireless.	Sensors; Advanced Electronics	Potentially
#17	Sabanci University	WP11 (Energy Generation) Task 11.2	Work Package Leader: Dr Gerard Gebel, CEA French Alternative Energies and Atomic Energy Commission, France.	WP Outputs: Quesnel E., et al., 2D Mater. 2, 030204 (2015) Konios D., et al., J. Mater. Chem. A, 4, 1612 (2016) Casalucci S., et al., Nanoscale (2016)	—	Fuel Cells: very low Pt content electrodes and hierarchical nanostructured electrocatalysts: towards Pt-free electrodes. Excess heat generated by the nuclear power stations can be directly converted into electric power using fuel cells. Lightweight portable autonomous power sources will be important in wireless sensor networks and robots.	Fuel Cells	Potentially
#18	Tor Vergata	WP11 (Energy Generation) Task 11.3	Work Package Leader: Dr Gerard Gebel, CEA French Alternative Energies and Atomic Energy Commission, France.	As (17)	—	Technology Up-scaling: PV and fuel cell demonstrators. The aims and relevance to the nuclear industry for this Task is detailed in (17).	Fuel Cells	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#19	Thales SA	WP12 (Energy Storage) Task 12.1	Work Package Leader: Dr Vittorio Pellegrini, IIT Graphene Labs, Istituto Italiano di Tecnologia, Italy.	WP Outputs: Liu T. et al., Science, 350, 6260, 530 (2015)	—	Supercapacitors: high-surface area and pseudocapacitive materials, graphene-based electrodes, EDLC and hybrid devices, flexible supercapacitors, spray-deposited supercapacitors. Lightweight portable autonomous power sources will be important in wireless sensor networks and robots. Gas storage applications of 3D porous graphene networks are of particular interest for nuclear decommissioning and energy generation industries (hydrogen storage).	Gas Storage	Potentially
#20	University of Cambridge	WP12 (Energy Storage) Task 12.2	Work Package Leader: Dr Vittorio Pellegrini, IIT Graphene Labs, Istituto Italiano di Tecnologia, Italy.	As (19)	—	Batteries: anodes and cathodes for Li-ion/Na-ion batteries, conformable and transparent batteries. The aims and relevance to the nuclear industry for this Task is detailed in (19).	Gas Storage	Potentially
#21	Umea Universitet	WP12 (Energy Storage) Task 12.3	Work Package Leader: Dr Vittorio Pellegrini, IIT Graphene Labs, Istituto Italiano di Tecnologia, Italy.	As (19)	—	Gas storage: porous 3D architectures with high surface area, adsorption optimisation. The aims and relevance to the nuclear industry for this Task is detailed in (19).	Gas Storage	Potentially

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#22	TU Dresden	WP13 (Functional Foams and Coatings) Task 13.1	Work Package Leader: Professor Xinliang Feng, TU Dresden, Germany	—	—	Functionalization and processing of nanocomposites for integration into functional composites, templated synthesis of 2D composites. The porous structures with well-developed surface areas may find applications in mopping spillage, filtration, chromatographic columns, gas storage, etc. In addition, graphene and related materials can be used as impermeable barrier coatings for metals and polymers, as well as functional coatings for catalysis.	Gas Storage	Yes
#23	TU Dresden	WP13 (Functional Foams and Coatings) Task 13.2	Work Package Leader: Professor Xinliang Feng, TU Dresden, Germany	—	—	Applications in foams and membranes: G/GRM and 2D-nanocomposite-based porous 3D structures for energy applications, light-weight thermally insulating and flame-retardant materials, functionalised porous structures. The aims and relevance to the nuclear industry for this Task is detailed in (22).	Membranes	Yes
#24	TU Dresden	WP13 (Functional Foams and Coatings) Task 13.3	Work Package Leader: Professor Xinliang Feng, TU Dresden, Germany	—	—	Coatings for electronics, energy storage and conversion, protection, photocatalysis, electrodes for desalination, EMI shielding. The aims and relevance to the nuclear industry for this Task is detailed in (22).	Advanced Coatings	Yes
#25	TU Dresden	WP13 (Functional Foams and Coatings) Task 13.4	Work Package Leader: Professor Xinliang Feng, TU Dresden, Germany	—	—	Characterization of nanocomposites and membranes. The aims and relevance to the nuclear industry for this Task is detailed in (22).	Membranes	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#26	National Research Council, Italy (CNR)	WP14 (Polymer Composites) Task 14.1	Work Package Leader: Dr Vincenzo Palermo, CNR National Research Council, Italy	Kawai S., et al., Science, 351, 6276, 957 (2016)	—	Composites processing and benchmarking, matrix interface control. The aim is to translate the exceptional properties of graphene from the nanoscale up to useful macroscopic materials, in particular bulk composites based on graphene related materials (GRM) and polymers. Strengthened and functionalised (in terms of their thermal, electrical and other properties) composites can find wide applications as engineering materials including nuclear industry.	Advanced Materials	Potentially
#27	Manchester University	WP14 (Polymer Composites) Task 14.2	Work Package Leader: Dr Vincenzo Palermo, CNR, Italy	Kawai S., et al., Science, 351, 6276, 957 (2016)	—	GRM-polymer composites with enhanced electrical charge percolation properties for EMI shielding and stealth coatings, high-power generation, transformation and distribution. The aims and relevance to the nuclear industry for this Task is detailed in (26).	Advanced Materials	Potentially
#28	Foundation for Research and Technology Hellas	WP14 (Polymer Composites) Task 14.3	Work Package Leader: Dr Vincenzo Palermo, CNR, Italy	—	—	GRM-polymer composites with enhanced mechanical, thermal and chemical stability for gas barriers, smart barriers for heat pipes, applications in aeronautics and automotive industry, such as for reduced flammability. The aims and relevance to the nuclear industry for this Task is detailed in (26).	Advanced Materials	Yes
#29	Fondazione Bruno Kessler	WP14 (Polymer Composites) Task 14.4	Work Package Leader: Dr Vincenzo Palermo, CNR, Italy	—	—	Modelling of GRM-polymer composites. The aims and relevance to the nuclear industry for this Task is detailed in (26).	Advanced Materials	Yes
#30	Avanzare Innovacion Tecnologica SL	WP15 (Production) Task 15.3	Work Package Leader: Dr Ken Teo, Aixtron Ltd., United Kingdom	—	—	The overall aim of the WP is to achieve economically viable volumes of graphene and GRM production, while maintaining the exceptional properties of these materials.	Advanced Manufacture	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#31	Universite de Montpellier	WP19 (Research Management) Task 19.4	Work Package Leader: Dr Katarina Boustedt, Chalmers University of Technology, Sweden	—	—	The relevance of these tasks is that the standards and reliable material, device and system validation instils confidence in the quality and performance of the novel technologies. Especially important for the nuclear industry, where reliability is paramount.	Standards	Yes
#32	Fraunhofer	WP19 (Research Management) Task 19.5	Work Package Leader: Dr Katarina Boustedt, Chalmers University of Technology, Sweden	—	—	Critical assessment of the state of the art and roadmapping of graphene/GRM research and industry.	Technology Policy	Yes
US DOE Funded Research Projects (currently funded in 2016): 68. Data taken from Abstract keyword search "graphene" from the US DOE Portfolio Analysis and Management System.								
#33	Brown University	Understanding and controlling toughening mechanisms in ceramic nanocomposites	Brian Sheldon	Award No: DE-SC0005242	2016	Work has focussed on using carbon nano-tubes to strengthen ceramics. Current work looks to expand this with graphene and reduced graphene oxide.	Advanced Materials	Yes
#34	Central Michigan University	Element specific atomic arrangement of nanosized catalysts in as prepared and active state	Valeri Petkov	Award No: DE-SC0006877	2016	Work focusses on nanocatalysts. Particular emphasis on the use of these in Li-batteries but also for the removal of pollutants such as CO.	Energy/ Energy Storage	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#35	Columbia University	Catalytic growth of molecular-scale wiring	Colin Nuckolls	Award No: DE-FG02-01ER15264	2016	Research focusses on fabricating catalysts out of low dimensional materials. Potential overlap with novel catalysts for use in nuclear waste management.	Advanced Manufacture/ Fabrication	Yes
#36	Massachusetts Institute of Technology	Development of scalable manufacturing process for high-selectivity single-layer nanoporous graphene membranes	Sean O'Hern (as part of GRoWater Inc.)	Award No: DE-SC0015175	2016	Research focussed on fabricating nanoporous graphene membranes. Particular emphasis is placed on the use of these materials in desalination, gas separation and organic solvents. Significantly likely that there could be overlap with nuclear waste management.	Membranes	Yes
#37	Technology Assessment & Transfer Inc.	Graphene reinforced glassy carbon particle beam windows	Jeffery Kutsch	Award No: DE-SC0015917	2016	Use of graphene for beam windows used in particle accelerators. Potential overlap with nuclear glasses.	Advanced Materials	Potentially
#38	Temple University	Center for the computational design of functional layered materials	John Perdew	Award No: DE-SC0012575	2016	Though mainly centred on computational research. Research focusses on (but not limited to) graphene-based catalysts. Of potential interest if catalysis research is in scope.	Catalysis	Potentially
#39	Texas A&M University	Radiation response of low dimensional carbon systems	Lin Shao	Award No: DE-SC0006725	2016	Work is focussed on looking at radiation damage of various low-dimensional materials including graphene. This work would have particular interest where low-dimensional materials are used in nuclear waste management.	Radiation Tolerance	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#40	University of Notre Dame	Radiation and photochemistry in the condensed phase and at interfaces	Ian Carmichael	Award No: DE-FC02-04ER15533	2016	Work centres on radiation chemistry. The laboratory has a long-standing research effort in nuclear chemistry. This research centres on solar cell and future energy technology development. Whilst solar photochemistry is not directly relevant to the nuclear industry, their characterisation at this facility might be in scope,	Energy/ Energy Storage; Radiation Tolerance	Potentially
#41	Virginia Commonwealth University	Elucidation of hydride interaction mechanisms with carbon nanostructures and the formation of novel nanocomposites	Puru Jena	Award No: DE-SC0007033	2016	Research on the using nanomaterials in hydrogen cells and hydrogen storage. Potential overlap with storing/trapping materials.	Energy/ Energy Storage	Potentially
#42	William Marsh Rice University	Understanding and controlling toughening mechanisms in ceramic nanocomposites	Jun Lou	Award No: DE-SC0010688	2016	Work focusses on nanocatalysts. Particular emphasis on the use of these in Li-batteries but also for the removal of pollutants such as CO.	Energy/ Energy Storage	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
NSF Funded Research Projects (currently funded in 2016): 346. Data taken from Abstract keyword search "graphene" from the NSF Awards website								
#43	Auburn University	GOALI/ Collaborative Research: Improving the performance of electrical connectors using extremely thin sheets of graphene sandwiched between metal layers	Robert Jackson	Award No: 1362126	2016	Research focusses on developing corrosion resistant electrical connectors. The work on the corrosion processes and characterisation may overlap with nuclear research.	Advanced Electronics	Potentially
#44	Case Western Reserve University	CAREER: Asymmetric functionalization of 2-d nanomaterials for tailored assemblies	Emily Pentzer	Award No: 1551943	2016	Research focusses on Janus nanosheets that have the potential to be used in advanced coatings. Such coatings may exhibit properties that could be used in treating nuclear waste materials.	Advanced Coatings	Yes
#45	City University of New York	COLLABORATIVE RESEARCH: Nano-engineered MOF-graphene materials: new perspectives for reactive adsorption and catalysis	Teresa Bandorz	Award No: 1133112	2016	Research focusses on developing of advanced absorbents for removing toxic gases (ammonia, hydrogen sulphide) that could possibly be applicable to the nuclear industry.	Adsorbents	Yes
#46	College of William and Mary	DMREF: Collaborative Research: Polymeric composites and foams based on two dimensional surfactants	Hannes Schneipp	Award No: 1534428	2016	Research focusses on developing graphene production that could potentially be used to develop advanced polymers. Such polymers may exhibit properties that could be used in treating nuclear waste materials.	Advanced Materials	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#47	Columbia University	GOALI/Collaborative Research: Improving the performance of electrical connectors using extremely thin sheets of graphene sandwiched between metal layers	Elon Terrell	Award No: 1363093	2016	Research focusses on developing corrosion resistant electrical connectors. The work on the corrosion processes and characterisation may overlap with nuclear research.	Advanced Electronics	Potentially
#48	Dartmouth College	DNP-enhanced NMR surface characterization	Chandrasekhar Ramanathan	Award No: 1410504	2016	Research focusses on studying surface interactions, with the potential to use graphene in advanced catalysts. Such surface interactions could form the bases of novel sensors that could be used in the nuclear industry.	Catalysis	Potentially
#49	Graphene Frontiers LLC	SBIR Phase II: Roll-to-roll production of uniform graphene films at atmospheric pressure and low temperature	Bruce Willner	Award No: 1330991	2016	Research focusses on the development of graphene fabrication. The products developed can potentially have further use in novel imaging technologies that can be used to assess irradiated nuclear material.	Advanced Manufacture/ Fabrication	Potentially
#50	Kansas State University	Investigating the structure and thermal damage resistance of molecular precursor derived ceramics for high power laser radiometry	Gurpreet Singh	Award No: 1335862	2016	Research focusses on developing advanced ceramic materials that are further resistant to heat damage which may ultimate be applicable to advanced ceramics for use in the nuclear industry.	Advanced Materials	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#51	Massacheusetts Institute of Technology	I-Corps: Application Development for graphene oxide nanofiltration membranes	Jeffrey Grossman	Award No: 1649058	2016	Research focusses on developing advanced membranes. Such membranes could be used in improved filters in wastewater treatment that could be used to treat nuclear wastes.	Membranes	Yes
#52	Nanomaterial Innovation Ltd,	SBIR Phase II: Carbide bonded graphene coating for enhanced glass molding	Jianfeng Yu	Award No: 1456921	2016	Research considers advanced coatings for plastics to improve their optical properties. Such coatings may also possibly have use in the nuclear industry.	Advanced Coatings	Potentially
#53	Rochester Institute of Tech.	Ultra high boiling performance on nano/microstructured surfaces through electrodeposition of copper and graphene	Satish Kandlikar	Award No: 1335927	2016	Research considers the study of heat transfer between graphene and copper that may potentially develop materials with improved heat transfer.	Heat Transfer	Potentially
#54	State University of New York at Binghamton	Collaborative Research: Experimental and computational nanomechanics of the load transfer mechanisms at the graphene polymer interface	Changhong Ke	Award No: 1537333	2016	Research considers the use of polymer nanocomposites, especially graphene, in advanced polymers and looks to study the graphene-polymer interface. Such advanced polymers may potentially be used to encapsulating nuclear waste.	Advanced Materials	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#55	University of Connecticut	DMREF: Collaborative Research: Polymeric composites and foams based on two dimensional surfactants	Douglas Adamson	Award No: 1535412	2016	Research focusses on developing graphene production that could potentially be used to develop advanced polymers. Such polymers may exhibit properties that could be used in treating nuclear waste materials.	Advanced Materials	Yes
#56	University of Houston	CAREER: Toxicology of graphene-based nanomaterials: A molecular biotechnology approach	Deborah Rodrigues	Award No: 1150255	2016	Research looks at graphene-based nanomaterials and their impact on microbial populations used in wastewater treatment. Such research may overlap with the interactions between water, microbes, and graphene-based wastes in a repository environment.	Water Treatment	Potentially
#57	University of Illinois at Urbana-Champaign	Collaborative Research: Experimental and computational nanomechanics of the load transfer mechanisms at the graphene polymer interface	Huck Beng Chew	Award No: 1538162	2016	Research considers the use of polymer nanocomposites, especially graphene, in advanced polymers and looks to study the graphene-polymer interface. Such advanced polymers may potentially be used to encapsulating nuclear waste.	Advanced Materials	Potentially
#58	University of Illinois at Urbana-Champaign	Imaging the surface dynamics of glasses and photoexcited molecules	Martin Gruebele	Award No: 1307002	2016	Research considers various advanced materials to probe the underlying theories on glasses. Developments in novel glasses could be used in the nuclear industry.	Advanced Materials	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#59	University of Massachusetts Amherst	Collaborative Research: Self-exfoliation as promising route to novel nanocomposite processing	H. Henning Winter	Award No: 1334460	2016	Research considers the use of graphene and clays to form advanced polymer matrices. Such advanced polymers may have better thermal characteristics that could potentially impact on novel encapsulants.	Advanced Materials	Potentially
#60	University of Massachusetts Dartmouth	Mechanics of multi-functional biocomposites	Vijaya Chalivendra	Award No: 1563040	2016	Research considers the use of applying graphene-based materials to natural fibres. This could potentially be used in novel construction materials.	Advanced Materials	Potentially
#61	University of North Carolina at Charlotte	Environment assisted cracking of graphene	Alireza Tabarrei	Award No: 1563224	2016	Research focusses on the potential for graphene to undergo stress-corrosion-cracking and to further understand the material property of graphene. Results of this research could indicate the viability of graphene-based materials in the nuclear industry.	Corrosion	Yes
#62	University of Toledo	I-Corps Teams: Customer discovery activity for microelectromechanical systems based gas sensors	Ahalapitiya Jayatissa	Award No: 1644894	2016	Research outlines the development of novel gas-detecting sensors. Such sensors may potentially be useful in novel detectors that are relevant to the nuclear industry.	Sensors	Potentially

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#63	Washington University	CAREER: Development and application of crumpled graphene oxide-based nanocomposites as a platform material for advanced water treatment	John Fortner	Award No: 1454656	2016	Research includes the use of graphene in novel water treatment facilities. Such techniques may be applicable to wastewater treatment in the nuclear industry.	Water Treatment	Potentially
Research Outputs and Patents from DOE funded research: 1656. Data taken from Abstract and Title keyword search "Graphene" from the OSTI website								
#64	Ames Lab. (AMES), Ames, IA (United States)	Adsorption and diffusion of Ru adatoms on Ru(0001)-supported graphene: Large-scale first-principles calculations	Yong Han	Journal Article DOI:10.1063/1.4934349	2015	Theoretical condensed matter. Normally out-of-scope; however, this research considers the adsorption processes of Ru atoms which may potentially have cross-over for the nuclear industry.	Fundamental Physics	Potentially
#65	Argonne National Lab. (ANL), Argonne, IL (United States)	Nanocarbon synthesis by high-temperature oxidation of nanoparticles	Ken-ichi Nomura	Journal Article 10.1038/srep24109	2016	Research focusses on potential use of silicon-carbide nanoparticles. Tenuously of interest due to its potential heat resistance.	Advanced Materials	Potentially
#66	Argonne National Laboratory (ANL), Argonne, IL (United States)	Nanoparticles for heat transfer and thermal energy storage	Dileep Singh	Patent Ref: 9,080,089	2015	Patent considers how nanoparticles can be used for heat transfer processes and storing thermal energy.	Advanced Materials	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#67	INL (Idaho National Laboratory (United States))	Charged particle detectors with active detector surface for partial energy deposition of the charged particles and related methods	David W. Gerts	Patent Ref: 8,378,308	2013	Patent discloses a radiation detector that uses graphene one or more layers at the active detector surface.	Radiation Detectors	Yes
#68	Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US)	Writable graphene: Breaking sp2 bonds with soft X-rays	S. Zhou	Journal Article LBNL-3487E	2010	Article considers the stability of graphene samples to soft x-rays. Could potentially overlap understanding the radiation hardness of graphene-based materials.	Advanced Materials	Potentially
#69	Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States)	Toughness and strength of nanocrystalline graphene	Ashivini Shekhawat	Journal Article DOI: 10.1038/ncomms 10546	2016	Work considers testing the mechanical strength of graphene, which may underpin its viability for specific applications	Advanced Materials	Potentially
#70	Lawrence Berkeley National Lab. (LBNL), Berkeley, CA (United States)	Graphene oxide/metal nanocrystal multilaminates as the atomic limit for safe and selective hydrogen storage	Eun Seon Cho	Journal Article DOI: 10.1038/ncomms 10804	2016	Though considered here for energy storage, the potential use of graphene to trap hydrogen may be of interest in the field of nuclear decommissioning.	Energy/ Energy Storage	Yes
#71	Lawrence Livermore National Laboratory (LLNL), Livermore, CA	Water confined in nanotubes and between graphene sheets: A first principle study	G. Cicero	Journal Article DOI: 10.1021/ja07441 8+	2008	Though this theoretical work is in the field of nanotechnology and nanobiology, the study focusses on the confinement of water.	Fundamental Physics	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#72	Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States)	Highly compressible 3D periodic graphene aerogel microlattices	Cheng Zhu	Journal Article DOI: 10.1038/ncomms 7962	2015	Work on the development of graphene-based aerogel which may potentially be used as a thermal insulating material.	Advanced Materials	Potentially
#73	Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States)	Graphene aerogels	Peter J Pauzauskie	Patent	2015	Work on the development of graphene-based aerogel which may potentially be used as a thermal insulating material.	Advanced Materials	Potentially
#74	Los Alamos National Laboratory (LANL)	Carbon nanomaterials in silica aerogel matrices	Christopher E Hamilton	Journal Article DOI: 10.1557/PROC-1258-R05-11	2010	Work on the development of graphene-based aerogel which may potentially be used as a thermal insulating material.	Advanced Materials	Potentially
#75	Los Alamos National Laboratory (LANL), Los Alamos, NM (United States)	Electrocatalytic interface based on novel carbon nanomaterials for advanced electrochemical sensors	Ming Zhou	Journal Article DOI: 10.1002/cctc.201 500198	2015	Development of advanced electrochemical sensors that may potentially have applications for the nuclear industry.	Sensors	Potentially
#76	National Energy Technology Lab., Pittsburgh, PA (US); National Energy Technology Lab., Morgantown, WV (US)	Optimization of char for NOx removal	J. Phillips	Technical Report DOI: 10.2172/769859	1999	Studies surrounding the gas treatment using activated carbon containing NOx, Could have potential overlap on the treatment of gaseous nitrogen-based wastes	Gas Separation	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#77	Oak Ridge National Laboratory	DOE Hydrogen Sorption Center of Excellence: Synthesis and processing of single-walled carbon nanohorns for hydrogen storage and catalyst supports	David B. Geohegan	Technical Report DOI: 10.2172/1024604	2011	Development of novel carbon structures with the potential use in hydrogen cells, which may have cross-over in capturing tritium	Advanced Materials	Yes
#78	Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States)	Selectivity trend of gas separation through nanoporous graphene	Hongjun Liu	Journal Article DOI: 10.1016/j.jssc.2014.01.030	2014	This work covers theoretical molecular dynamics calculations to underpin how gas separation occurs in graphene. Results of this study impact on the gas separation uses for graphene.	Fundamental Physics	Yes
#79	Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States)	Translational diffusion of water inside hydrophobic carbon micropores studied by neutron spectroscopy and molecular dynamics simulation	S.O. Diallo	Journal Article DOI: 10.1103/PhysRevE.91.022124	2015	Experimental work that considers external factors that affect the diffusion of water. Potential overlap into novel membranes	Fundamental Physics	Potentially
#80	Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States). Center for Nanophase Materials Sciences (CNMS)	Water desalination using nanoporous single-layer graphene with tunable pore size	Sumedh P. Surwade	Journal Article DOI: 10.1038/nnano.2015.37	2015	Details the development of advanced graphene-based membranes which although planned for desalination may be used in treating nuclear waste water.	Membranes	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#81	Pacific Northwest National Laboratory (PNNL), Richland, WA (United States)	Separation of tritiated water using graphene oxide membrane	Gary J. Sevigny	Technical Report DOI: 10.2172/1222908	2015	Details the development of advanced graphene-based membranes for the use of isolation tritiated waste.	Membranes	Yes
#82	Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States)	Exploring graphene field effect transistor devices to improve spectral resolution of semiconductor radiation detectors	Richard Karl Harrison	Technical Report DOI: 10.2172/1200672	2013	Development of advanced graphene-based electronics in developing novel radiation detector systems.	Radiation Detectors	Yes
#83	Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States)	New radiological material detection technologies for nuclear forensics: Remote optical imaging and graphene-based sensors	Richard Karl Harrison	Technical Report DOI:10.2172/1214453	2015	Development of advanced graphene-based radiation detectors.	Radiation Detectors	Yes
#84	Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States)	Gas permeability of graphene oxide membranes	Laura Butler Biedermann	Conference SAND2012-10172C	2012	No abstract provided, gas permeability though the potential for advanced graphene-based membranes to be used in the nuclear industry.	Membranes	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
Wider International Literature Review								
Graphene Radionuclide Removal – Broad Area: Graphene Oxide for Radionuclide Removal and/or Heavy Metal Sorption								
#85	Chinese Academy of Science	Highly Efficient Enrichment of Radionuclides on GO Supported Polyaniline	Xiangke Wang	Environmental Science & Technology	2013	Graphene oxide-supported polyaniline (PANI@GO) composites for the sorption of U(VI), Eu(III), Sr(II), and Cs(I) from aqueous solutions as a function of pH . The maximum sorption capacities of U(VI), Eu(III), Sr(II), and Cs(I) on the PANI@GO composites at pH 3.0 and T = 298 K calculated from the Langmuir model were 1.03, 1.65, 1.68, and 1.39 $mmol \cdot g^{-1}$, respectively.	Water Treatment; Radionuclide Remediation	Yes
#86	Rice University, USA Lomonosov Moscow State University, Russia	Graphene oxide for effective radionuclide removal	Prof. James Tour	PCCP	2013	Graphene oxide (GO) for rapid removal of some of the most toxic and Radioactive long-lived human-made radionuclides from contaminated water, even from acidic solutions. The interaction of GO with actinides including Am(III), Th(IV), Pu(IV), Np(V), U(VI) and typical fission products Sr(II), Eu(III) and Tc(VII) were studied, along with their sorption kinetics. Cation/GO coagulation occurs with the formation of nanoparticle aggregates of GO sheets, facilitating their removal. GO is far more effective in removal of transuranium elements from simulated nuclear waste solutions than other routinely used sorbents such as bentonite clays and activated carbon.	Water Treatment; Radionuclide Remediation	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#87	The University of Manchester	Selective removal of technetium from water using graphene oxide membranes	Christopher Williams and Paola Carbone	Environmental Science & Technology	2016	Molecular dynamic simulations on the ability for graphene oxide membranes to remove 99Tc present in the form of pertechnetate (TcO4-) from water Results indicate high selectivity for the ion	Water Treatment; Radionuclide Remediation	Yes
Graphene Radiation/Irradiation Tolerance, Irradiation Damage, Coatings								
#88	Nanjing University, Jiangsu Key Laboratory of Nuclear Energy Equipment Materials Engineering, China	Radiation damage resistance and interface stability of copper-graphene nanolayered composite	Da Chen	Journal of Nuclear Materials (note: only three papers relating to graphene have been published in this journal)	2015	The radiation damage resistance and interface stability of copper–graphene nanolayered composite are studied by atomistic simulations. Results show that the number of surviving point defects in bulk region is always less than that of pure copper at 100 K, when the range of initial distance d between a primary knock-on atom (PKA) with 3 keV and copper–graphene interface is less than 4 nm. The above phenomenon also occurs at 300, 500, and 700 K when d is ~15.4 Å, thereby implying that the composite resulting from copper–graphene interfaces exhibits excellent ability to resist radiation damage. A higher PKA energy corresponds to worse radiation damage of graphene in the composite. The damage may impair interface stability and eventually weaken the radiation damage resistance of the composite.	Advanced Materials; Advanced Coatings	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#89	University of Zaragoza Centro Universitaro de la Defensa de Zaragoza, Spain	The effect of gamma-irradiation on few/layered graphene	M. T. Martinez	Journal of Applied Surface Science	2014	Investigating γ-irradiation on the structure and composition of chemically synthesized few-layered graphene materials. Fully oxidized graphene oxide and graphene nanoribbons, as well as their respective chemically post-reduced forms, were treated under γ-irradiation in an air-sealed environment. Three different irradiation doses of 60, 90 and 150 kGy were applied. The XRD patterns were not affected by γ-irradiation, and small changes were observed in the FTIR and TGA results. However, significant modifications were detected by Raman spectroscopy and XPS, particularly in the Raman G/D band intensity ratios and in the C 1s XPS profiles. Comparatively, the changes in Raman and XPS spectra after γ-irradiation were even greater than those occurring during the chemical reduction of graphene oxides. Results indicate that the graphene carbon lattice was strongly affected by γ-irradiation, but the materials experienced small variations in their oxygen content.	Advanced Materials	Potentially
#90	Inter University Accelerator Centre, India	Radiation stability of graphene under extreme conditions	D. K. Avasthi	Applied Physics Letters	2014	Radiation stability of graphene under extreme conditions of high energy density generated by 150 MeV Au ion irradiation. Results indicate that graphene is radiation resistant for irradiation at 1014ions/cm2 of 150 MeV Au ions. Annealing effects are observed at lower fluences whereas defect production occurs at higher fluences: however crystallinity is still retained.	Radiation Tolerance	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#91	Kodak Technology Center, USA	Characterisation of X-ray irradiated graphene oxide coatings using X-ray diffraction, X-ray photoelectron spectroscopy and AFM	D. Majumdar	https://www.cambridge.org/core/services/aop-cambridge-core/content/view/S0885715613000109	2013	GO coatings are reduced to RGO upon exposure to high energy X-rays. RGO coating is conductivity and could be used as a cheap coating sensor to measure radiation leaks.	Advanced Coatings; Sensors	Potentially
#92	University of Manchester	Control of Radiation Damage in MoS_2 by Graphene Encapsulation	K. Novoselov	ACS Nano	2013	Investigation into effect of 60 KeV beam on bare monolayer MoS_2 with and without graphene sandwich layers Ionization effects can be prevented on MoS_2 when encapsulated between graphene monolayers	Advanced Coatings	Potentially
				Graphene-based Composites				
#93	Korea Advanced Institute of Science and Technology, Korea	Radiation Resistant Vanadium-Graphene Nanolayered Composite	Seung Min Han	Scientific Reports	2016	Investigation of the effect of radiation tolerance on V-graphene nanolayers Radiation induced hardening, evaluated via nanopillar compressions before and after He+ irradiation, is significantly reduced with the inclusion of graphene layers; the flow stresses of V-graphene nanolayers with 110 nm repeat layer spacing showed an increase of 25% while pure V showed an increase of 88% after He+ dosage of 13.5 dpa. Impermeability of He gas through the graphene resulted in suppression of He bubble agglomerations that in turn reduced embrittlement. In-situ SEM compression also showed the ability of graphene to hinder crack propagation that suppressed the failure.	Advanced Materials; Radiation Tolerance	Potentially

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#94	East China University of Science and Technology	Fabrication of Natural Rubber/Chemically Reduced Graphene Oxide Nanocomposites and Nuclear Radiation Resistant Behaviour	Luan Weiling	Chemical Journal of Chinese Universities	2016	Investigation into the effect of γ-radiation on natural rubber/chemically reduced graphene oxide. After a dose of 200 kGy, the tensile strength of the pure rubbers are decreased by 75 % compared to 56 % for the graphene/rubber composite.	Advanced Materials; Radiation Tolerance	Potentially
#95	Nanjing University of Aeronautics and Astronautics, China	Functionalized graphene serving as free radical scavenger and corrosion protection in gramma-irradiated epoxy composites	Jianping He	Carbon	2016	Synthesis of a novel functionalised graphene oxide/epoxide nanocomposite. ESR analysis on 0.25 wt % functionalised graphene/epoxy composite after γ-radiation indicates that the graphene behaves as a free radical scavenger. Increase in the oxidative stability of the composite due to the reduction of irradiation ageing speed. Additional improvements in anti-corrosion effects	Advanced Coatings; Radiation Tolerance	Yes
#96	Monash University, Australia	Reinforcing Effect of Graphene Oxide on Portland Cement Paste	Wen Hui Duan	Journal of Materials in Civil Engineering Patents also filed.	2015	Investigating the reinforcing effects of graphene oxide on Portland cement paste. Addition of 0.03 wt % GO into the cement can increase the compressive strength and tensile strength of the cement by more than 40 %. Moreover, GO sheets enhances the degree of hydration of the cement. Note: no reports on the effect of radioactive nuclei storage or radiation effects on graphene-based cements. This could be interesting area to pursue.	Civil Engineering/ Construction; Radiation Tolerance	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
Hydrogen Isotope Separation								
#97	The University of Manchester	Sieving hydrogen isotopes through two-dimensional crystals	Andre Geim	Science	2016	Demonstrated that monolayers of graphene and boron nitride can be used to separate hydrogen ion isotopes. Deuterons permeate through the monolayer crystals much slower than protons, resulting in a separation factor of ca. 10 at room temperature. This is ongoing work.	Radionuclide Remediation	Yes
Graphene-based Electronics								
#98	Columbia University Brookhaven National laboratory	Improving the radiation hardness of graphene field effect transistors (GFETs)	Ioannis Kymissis	Applied Physics Letters	2016	Investigation into the effects of γ-radiation on graphene-GFETs. Devised a method to protect GFETs i.e. radiation-hardened devices which exhibit minimal performance degradation and improved stability.	Sensors; Radiation Tolerance	Yes
#99	Pennsylvania State University & Purdue University	GFETs on undoped semiconductor substrates for radiation detection	Michael Foxe	IEEE Transactions on Nanotechnology	2012	Simulations of the interaction of γ-radiation on GFETs. Overall, the paper shows several advantages of using graphene FETs compared to traditional Si based FETs. The group from Purdue have published at least another 2 papers on the subject including using GFETs as a neutron sensor.	Sensors; Radiation Tolerance	Yes
Related Research Programs Ongoing at the University of Manchester								

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#100	The University of Manchester	EPSRC Funded Project: "Radiation Damage in Inorganic 2D Materials"	Prof. Cinzia Casiraghi & Dr. Aliaksandr Baidak	EPSRC Project	Ongoing	This project will be focused on the synthesis and post-irradiation characterisation of a number of 2D transition metal dichalcogenides (TMDCs) and hexagonal boron nitride (h-BN) in order to elucidate the radiation damage mechanisms in these materials. It is expected that the radiation damage in inorganic 2D materials will be quite different from graphene due to more complex layered structure and multi-element chemical composition of these compounds. The Co60 irradiator and the 5MV tandem ion accelerator at the Dalton Cumbrian Facility (DCF) will be deployed to produce lattice damaged specimen by gamma rays and by heavy ion bombardment, respectively. Radiolytic changes in inorganic 2D materials will be examined using Raman Spectroscopy, Fourier Transform Infrared Spectroscopy, Atomic Force Microscopy, Scanning Electron Microscopy and Transmission Electron Microscopy. Proposed extensive characterisation of irradiated two-dimensional materials will allow to quantify the extent of lattice damage and to gain a better understanding of the mechanisms of radiation-induced degradation. The proposed studies will make an important contribution to the fundamental understanding of radiation hardness (or instability) of the inorganic 2D materials.	Sensors; Radiation Tolerance	Yes (although the research focus is on non-graphene 2D materials)

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#101	The University of Manchester	EPSRC applied for funding: "Gamma Radiolysis as a Tool for Covalent Functionalisation of Graphene"	Prof. Cinzia Casiraghi & Dr. Aliaksandr Baidak	EPSRC Bid	Bid pending	This proposal involves the synthesis of novel functionalised graphene-based materials by gamma-radiolytic modification of exfoliated graphene in various organic solvents. We suggest that gamma radiolysis in liquid media can be used as a highly efficient and simple synthetic tool to accomplish covalent functionalisation of graphene. The proposed radiolytic approach offers the following advantages: (1) the covalent modification will be performed directly in solutions on liquid-phase exfoliated graphene sheets, i. e. in a scalable process suitable for mass production; (2) there is a wide selection of organic solvents with surface energies matching that of graphene, making them deployable for liquid-phase exfoliation technique; (3) each organic solvent has a characteristic radiolysis mechanism, i.e. there is a wide choice of various radical species available for radiolytic functionalisation of graphene; (4) since the exfoliated graphene is transferred to solution at relatively low concentrations (typically at ~ 1 wt%), most of the electromagnetic radiation of a gamma-ray will be absorbed by a solvent; therefore, we expect that the radiation damage to the exfoliated graphene to be negligible, whereas radical production due to radiolytic decomposition of a solvent will be the dominant process; (5) during gamma radiolysis radicals are produced uniformly in solution and the rate of the radical formation can be easily altered by modifying the dose rate of a radiation source.	Advanced Materials	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#102	The University of Manchester	Unfunded project "Graphene and 2D remote sensors for pools or waste storage"	Prof. Cinzia Casriaghi and Prof. Kostya Novoselov	N/A	N/A	Graphene and 2D remote sensors for pools or waste storage. No more details as of yet.	Sensors	Yes
#103	The University of Manchester	Unfunded project "Super-hydrophobic coatings"	Prof. Cinzia Casriaghi and IEEE team	N/A	N/A	Super-hydrophobic coatings. No more details as of yet.	Advanced Coatings	Potentially
#104	The University of Manchester	Radiolytic Modification of Graphene Oxide Nanoflakes for Selective Extraction of Radionuclides	Prof. Simon Pimblott & Dr. Aliaksandr Baidak	NDA Bursary Scholarship	Bid pending	Overall aim of this project is to develop and to test graphene oxide based nanomaterials exhibiting high selectivity and efficiency in removal of radioactive technetium from water. Our hypothesis is that this goal can be achieved by deploying a radiolytic approach to enable the fine-tuned modification of graphene oxide matrix. The proposed project will pursue the following objectives: (1) To test feasibility of radiolytic modification of the graphene oxide to produce derivatives with fine-tuned selectivity of removal of technetium-99 from water; (2) To determine which of the radiolytically modified products exhibit the highest adsorption capacity for the pertechnetate by performing batch studies with the perchlorate and the pertechnate anions to mimic Tc-99 extraction; (3) To establish the preparation protocol producing the lead nanomaterial for Tc-99 extraction and understand the mechanisms responsible for its high performance.	Radionuclide Remediation	Yes
Industry Funded Projects Relating to "Graphene" from Innovate UK/TSB: Duration 2015-2017								

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#105	KW Special Projects Limited, Nquiringminds Ltd., Cedar Metals Ltd., Carr's Welding Technologies Ltd., Tiscs Ltd., Brunel University London, Innovative Technology and Science Ltd., Cambridge Nanomaterials Technology Ltd.	Power ultrasound as a generic tool for micro/nanoscale processing of materials (Competition Title: Materials and Manufacturing over 12 months or over £100k)	N/A	Innovate UK/TSB: Duration 2015-2017	2016/2017	The project goal is a novel generic technology (UltraMAT) for materials processing of fluid and semi fluid phases that are widespread in manufacturing e.g. in the welding and adhesive joining of components, the manufacture of bulk composite components and in traditional, PM (HIP) and semi solid casting. The key purpose of UltraMAT is to enable production of manufactured components with step improvements in specific strength (yield/ fatigue/ impact) and modulus, fatigue life and thus lightweighting; driven by economic and environmental needs to reduce energy consumption and emissions in manufacture and transport. The enabling tool is power ultrasound with purpose shaped force fields for controlled movement and size creation of uniform nano structures to enable: (1) Production of homogeneously distributed and shaped nanoscale particulates, fibres or grains). (2) Enhancement of interlayer and filler-matrix adhesion bonds. UltraMAT will be validated through the fabrication and testing of samples of a number of key structure/joint types of growing importance especially in aerospace or automotive bodies/engines: (i) Ti/Al fibre laminates (ii) Ti/Al metal matrix composites with fibre/ particulate (ceramic TiC/SiC), Ti/Al laser welding and (iv) Al semi solid casting. Homogenisation performance will be studied using graphene (G) and carbon nanotubes (CNT) because the strong agglomeration tendencies of G and NT is impeding their ability to realise commercially, components of ultra-high specific strength. In short pulse echo mode, UltraMAT will self-evaluate its performance on line aided by predictive big analytics.	Advanced Materials; Advanced Manufacture/ Fabrication	Potentially

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#106	DZP Technologies Ltd., L.V.H Coatings Ltd, University of Warwick	Scalable electrophoretic manufacture of high density 2-dimensional materials for energy storage applications (Competition Title: Manufacturing over 12 months or over £100k)	N/A	Innovate UK/TSB: Duration 2015-2017	2016/2017	This is a collaborative project between two industrial partners, DZP Technologies Ltd and LVH Coatings Ltd, and one academic partner, the University of Warwick. The project will investigate the feasibility of using electrophoretic deposition to manufacture electrochemical energy storage of improved performance and new form factors. Additionally, our technology will make use of new, graphene-related materials which have the potential to produce a transformational step change in the performance of electro-chemical power devices. In this way, the project is involved with innovation in both manufacturing technology, and materials development. The new and improved power devices enabled by our technology can be used across different power sectors, including the national grid, distributed power networks and low-carbon vehicles, in addition to the constantly evolving consumer electronics sector. Further to energy storage applications, EPD manufacturing itself can produce novel 2D material coatings with anti-corrosion and self-lubricating properties for the automotive, aerospace, and advanced surface engineering sectors.	Energy/ Energy Storage; Advanced Coating	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#107	Centre for Process Innovation Ltd., Haydale Ltd.	Smart Filter Membrane (Competition Title: Creating Smart Products from Smart Materials)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	Membrane filters can be applied for a variety of industrial liquid and gas separations applications such as water desalination, water/oil separation during oil drilling and industrial waste water treatment. A major operational issue with filter membranes is their tendency to foul with use over time, which results in lowering through put, increasing energy consumption and the need for costly maintenance. The aim of this project is to develop a low-cost self-cleaning coating technology based on functionalised graphene, which once applied to industrial membranes makes them resistant to fouling. The technology has already been demonstrated successfully in lab-scale tests. Led by G2O Water Limited, this project will translate the lab-scale work into a working robust, reliable manufacturing process which can be scaled-up to enhance the performance of existing filter membranes. The coating will be formulated and validated by the consortium for deployment in a number of different applications, in order to ensure the resulting smart product can be taken to market and be readily applied to improve the performance of a broad range of industrial processes. The system is currently being transferred for applications in aqueous systems with desalination applications, with the ability to trap radionuclides onto membranes selectively. As the radionuclides are trapped onto the membrane, the filter can be used for longer.	Membrane; Advanced Coatings; Water Treatment	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#108	Cranfield University, Exergy Ltd., Solaris Photonics Ltd., Applied Materials Technology Ltd.	Low Cost Copper Transparent Electrode Material (LOCUST) (Competition Title: Energy Catalyst Rnd 2.)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	Transparent conductive electrode (TCE) is an essential component for solar cells and other devices such as displays, currently indium tin oxide (ITO) and silver are the prevailing choices. ITO and silver are however expensive. ITO has limited supply, and tends to degrade in performance under stress, so ITO-replacement TCEs have attracted extensive interests in the past years. Promising possible replacements include less expensive transparent conductive oxides, carbon nanotubes (CNT) or graphene-based thin films, conductive polymers, and metal grids based TCEs. This consortium aims to develop low cost and superior, sustainable Cu nanowires based TCE for solar cells, and explore its application to other devices.	Advanced Materials; Advanced Coatings	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#109	Precision Varionic Internation Ltd., Dycotec Materials Ltd., University College London	Endurance - Graphene-based coatings for durable wear resistant low cost position sensors (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	In recent years there has been an exponential increase in embedded electronics within cars as OEMs strive to satisfy consumer demand for greater comfort, safety, convenience, reliability, fuel efficiency, infotainment and fun, and stringent legislative targets for automotive emissions. Position sensors represent a key enabling technology used for monitoring and control of systems throughout the car, from engine management through to pedal position monitoring. Consumers demand intelligence as standard and at no extra cost. The state of the art provides two sensor types: i) contact based devices (low performance at low cost); and ii) non-contact devices (high performance at high cost). Utilising the unique properties of graphene-based coatings (wear resistance combined with customised conductivity and barrier) the ENDURANCE consortium will assess the feasibility for development of a low cost high performance linear and encoder position sensors enabling realisation of disruptive solutions meeting well defined user needs. The ENDURANCE technology has the potential to extend far beyond the automotive market (£770m) to secondary markets worth >£7.4 billion.	Sensors; Advanced Electronics; Advanced Coatings	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#110	Thomas Swan & Co. Ltd., Plessey Semiconductors Ltd., Nano Products Ltd., University of Strathclyde, Nottingham Trent University	FlexiLEDs with printed graphene-based thermal management (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	A new UK based mass manufacturing technology will create flexible plastic sheets with embedded electronics and microscopic light emitting devices. High compressed graphene flakes connected to the devices will allow heat to be drawn away from the devices so they carry on working efficiently. Formed into many shapes and sizes the devices could be placed anywhere. They could form part of the exterior of cars and vans to provide advertising or indicator and brakes lights. On the inside they could provide efficient video displays for passenger. In the home the devices could be built into the walls, ceilings and floors to allow endless opportunities for lighting the home. By using graphene to remove the heat these devices will use less energy and last for longer.	Advanced Electronics; Heat Transfer	Potentially
#111	Applied Graphene Materials Ltd., TWI Ltd., Sherwin-Williams Protective & Marine Coatings	GRAphene protective Coatings – GRACe (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	Each year, it is estimated that corrosion costs the economy £10 billion per annum in the repair, maintenance and replacement of structures in Britain. Organic coatings loaded with hazardous or environmentally unfriendly metals such as zinc and chromates are commonly used to protect such structures and so it is desirable to find improved green alternative solutions. Graphene has been identified as a suitable green anti-corrosive additive and Project GRACe will investigate and develop the potential of graphene-based anti-corrosive coatings. In addition, graphene has been identified with the ability to mitigate risks of fires, so GRACe will also explore the potential for using graphene in fire retardant, protective coatings.	Advanced Coatings; Corrosion	Yes

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#112	Marshall of Cambridge Aerospace Ltd., University of Sheffield, Emyrus Ltd., Netcomposites Ltd.	Inkjet Printing of Plasma Functionalised Graphene to Deliver Multifunctional Polymer Composites for Aerospace Applications (PlasmaGraph) (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	The objective of the PlasmaGraph project is to develop a method by which plasma functionalised graphene can be selectively deposited onto fibre reinforced composites to deliver multi-functionality to aerospace structures. There are three main elements to deliver to meet this overall objective:- Plasma functionalised graphene; to prevent the re-agglomeration of the graphene in a dispersion and the re-agglomeration of the graphene can both reduce the inherent properties of the graphene and, for inkjet printing, prevents use of graphene dispersions as the re-agglomerated material can block print heads;- Inkjet printing of graphene dispersions onto fabric preforms; this allows the selective placement of graphene into structural composites and will deliver multifunctional benefits;- Manufacturing of graphene functionalised composite components; this requires the inkjet-printed graphene to remain in-situ when the final composite part is manufactured so that the benefits are retained, but also so that there is no release of the graphene to the environment during processing.	Advanced Coatings	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#113	NPL Management Ltd., Oxford Instruments Nanotechnology Tools Ltd., University of Manchester	Industrial feasibility test of a graphene-enabled turnkey quantum resistance system (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	Graphene enabled Quantum resistance system will provide the high-end electronics instrumentation industry with a primary resistance standard which can be used directly on the factory floor dramatically reducing the calibration traceability chain and improving the precision of electronic instrumentation. The quantum Hall effect (QHE) is one of the most fundamental phenomena in solid-state physics. Its observation in graphene was the litmus test that proved that this material is a true 2-dimensional crystal of the highest quality. The QHE is also the cornerstone of electrical metrology as it is the primary realisation of the unit for resistance, the ohm. The proposed turnkey system will be cryogen free and operating at low magnetic fields. It will enable resistance calibration with unprecedented accuracy to industrial companies and reduce the cost and time from design to product.	Advanced Electronics	Potentially
#114	Meggit Aerospace Ltd. Haydale Composite Solutions Ltd.	The effect of graphene additions on carbon-carbon composite materials (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	Project Creosote investigates the potential of graphene additives to Carbon/Carboncomposites in a range of thermal management applications.	Advanced Materials; Heat Transfer	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#115	Haydale Composite Solutions Ltd., University of Warwick	INdustrial PRocessing Of Nano Epoxies (INPRONE) (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	The aim of this interesting project is to prove the feasibility of upscaling the manufacture (using industrially relevant processes) of Graphene enhanced epoxy masterbatch. In doing so we will prove that we can impart radical improvements in thermal properties of epoxy resins that have previously only been shown at academic and lab scale level. Additional improvements may also be seen such as material durability, resistance to wear and improvements in thermal cycling.	Advanced Materials	Potentially
#116	University of Bradford, Thomas Swan & Co. Ltd, DelStar International Ltd., Haydale Ltd.	GraNet - Graphene / Polypropylene Composite Nets for Filtration (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	This project uses graphene to produce composites with polyolefins to give a step change in performance for lightweight extruded oriented products used in specialist applications. The project team will; gain an understanding of how graphene can enhance the performance of polymer composites, especially in relation to physical strength and operating temperature develop techniques to achieve dispersion of graphene into a polymer matrix at production scale without damaging the platelet structure and reducing the benefits of addition. understand what impact graphene has on polymer processability and rheological properties, including trial sat production scale (processing up to 2.5kg of graphene to produce 250kg of composite) model the impact that addition of graphene has on product cost at predicted volumes. develop a value proposition for prototype products and gain feedback from customers in the target markets	Advanced Materials	Yes

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#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#117	University of Cambridge, Tata Steel UK Ltd.	Graphene coatings on steel for large scale energy storage applications (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	From burning firewood to oil, the ability to store energy and use it at our command has been responsible for the biggest transformations of humanity in the course of history. Today, electrochemical devices, namely batteries and supercapacitors which are predominantly used for portable energy, are probably the biggest limitation to the fast development of portable electrical appliances from mobile phones to cars, and significant improvements in these technologies are urgently required. This project aims to combine graphene with steel as a charge collecting material in batteries and other advanced energy storage devices. Graphene is a good conductor as well as a good barrier providing electrochemical stability of the steel. Success on this project would allow improvements in performance as well as significant cost reduction in batteries and supercapacitors alike.	Energy/Energy Storage;	Potentially
#118	Haydale Ltd., University of Bath	Multi-functional skins incorporating carbon (MuSIC) (Competition Title: Advancing the commercial applications of graphene)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	The aim of the project is to assess the feasibility of employing graphene-based polymer skins for sensing and deicing applications. There are major issues associated with deicing are in aircraft, at airports, transmission power lines, instrumentation, antenna masks, wind turbines and the exploration of cold environments (e.g. oil and gas). Such a sensing surface can be integrated with thermally active (shape changing) structures to achieve structural deflection for combined thermal-mechanical de-icing. The opportunity to limit the extent of ice build-up on structures has broad application opportunities and enable light weight structures with reduced material costs and fuel saving for mobile applications and improved performance for instrumentation.	Advanced Coatings; Sensors	Potentially

#	Institution/ Research Group/ Organisation	Title	Author/Lead Researcher	Source	Year	Research/ Project Summary	Research Area	Relevant?
#119	NPL Management Ltd., DZP Technologies Ltd.	Two-Dimensional graphene-related TRansition metal dichalcogenides for ultracapacitor ENergy storage Devices (2D TREND) (Competition Title: Energy Catalyst R3)	N/A	Innovate UK/TSB: Duration 2015-2017	2015/2016	The discovery of graphene inspired exciting new research in to other two-dimensional (2D) materials, most notably the 2D transition metal dichalcogenides (TMDs) which similarly to graphene can be exfoliated into atomically thin nano-sheets with unusual electronic and optical properties. To date, most research on TMDs has remained in the laboratory, in contrast to graphene which is already applied in new commercial products. This project, entitled Two-Dimensional TRansition metal dichalcogenides for ultra-capacitor ENergy storage Devices(2D TREND), aims to establish the feasibility of 2D-TMD materials for scale up and use in ultra-capacitor energy storage for the smart grid. The project will develop methods to exfoliate 2D-TMD materials to nano-sheets and integrate them into supercapacitor electrodes. This will be complemented by advanced structural and chemical characterisation to develop understanding of the material properties. The project will demonstrate electrochemical cells which will enable the evaluation of the 2D-TMD materials for real-life energy storage.	Energy/ Energy Storage	Potentially

Appendix B

The NDA Estate's Research and Development Needs

Strategic Theme	Strategic Topic	Research and Development Need	Explanation for Rejecting R&D Need
Spent Fuels – defines NDA approach to managing the diverse range of spent nuclear fuels for which we are responsible	Spent Magnox Fuel	• Improved characterisation technologies that would provide Sellafield Ltd with a better understanding of the condition of the reprocessing facility could be required; • Development of technologies to treat the small amounts of fuels left over once Magnox reprocessing operations cease; • Further technologies to dry store and/or immobilise legacy Magnox fuels to manage materials held within Legacy Ponds and Silos (LP&S) at Sellafield.	N/A

	Spent Oxide Fuel	• Improved characterisation technologies that would provide Sellafield Ltd with a better understanding of the condition of the reprocessing facility could be required;
		• Pond storage of spent oxide fuel is planned for a significant period. Therefore technologies that improve NDAs existing approach to treating pond water are of interest:
		    ○ Technologies that monitor spent oxide fuel and associated pond furniture under wet storage conditions will be required;
		    ○ In situ technologies that monitor the precursors of spent oxide fuel corrosion are of particular interest;
		• In the longer term technologies associated with drying, storage and disposal of spent oxide fuel are of interest to NDA.
			N/A

Strategic Theme	Strategic Topic	Research and Development Need	Explanation for Rejecting R&D Need
	Spent Exotic Fuel	• Improved technical options for long-term storage of specific exotic fuels; • ~~Improving NDAs understanding of potential long-term behaviours of additive materials and exotic fuel claddings under wet or dry storage conditions;~~ • ~~Identifying functional requirements and treatment technologies to facilitate storage and final disposition (e.g. disposal) of exotic fuels;~~ • Technologies associated with monitoring, storage, treatment and disposal of spent exotic fuels are therefore of interest.	• Not relevant to new material/technology development
Nuclear Materials – defines NDA approach to dealing with the inventory of uranics and plutonium currently stored on some of our sites	Plutonium	• Technologies for monitoring waste packages and stores that improve upon existing approaches are therefore of interest; • ~~Development work to underpin the treatment process operating conditions for the full range of materials that must be treated;~~ • ~~Research into technologies to extend the amount of plutonium that is suitable for reuse.~~	• Not relevant to new material development
	Uranics	• ~~Technologies that would make NDAs uranics inventory more saleable.~~	• Not relevant to new material/ development
Integrated Waste Management – considers how NDA manage all forms of waste arising from operating and	Radioactive Waste	_Reprocessing_ • ~~Understanding, maintaining and extending the lifetime of existing infrastructure is ongoing;~~ • There is however a need to understand how the existing facilities will treat wastes from POCO of the reprocessing facilities and how existing treatment facilities could be modified to manage new wastes.	• Not relevant to new material/technology development

Strategic Theme	Strategic Topic	Research and Development Need	Explanation for Rejecting R&D Need
decommissioning NDA sites, including waste retrieved from legacy facilities		Some of the key areas of research include: o ~~Understanding the benefits of co-processing reprocessing wastes with POCO wastes;~~ o ~~Understanding the impact of solids (formation, transport and treatment) on POCO of HAL treatment process;~~ o Wasteform development (e.g. glass formulation) for vitrification of POCO HAL feeds; o Options for treating effluents that allow decommissioning of existing facilities (e.g. SETP) to take place. • There are also synergies with the interim storage of other packaged wastes (e.g. decommissioning waste). Some of the key areas of research include: o Remote monitoring of waste packages (e.g. corrosion); o Remote monitoring of stores (e.g. humidity); • ~~Research into the disposal of HAW is on-going and being led by RWM [[2]]. Key areas of research include:~~ o ~~Role and evolution of barriers (package evolution; engineered barrier system; geosphere);~~ o ~~Release and movement of contaminants through the multi-barrier system (radionuclide behaviour; gas generation and migration; biosphere);~~ o ~~Control of low probability events and their outcome (criticality~~	• Not relevant to new material/technology development • Not relevant to new material/technology development

[2] Radioactive Waste Management. Geological Disposal – Science and Technology Plan (NDA/RWM/121). 2016

Strategic Theme	Strategic Topic	Research and Development Need	Explanation for Rejecting R&D Need

		~~safety; waste package accident performance);~~
		• ~~RWM also has projects investigating specific technical topics:~~
		  ○ ~~Disposal of wastes containing carbon-14;~~
		  ○ ~~Disposal of high-heat-generating wastes;~~
		  ○ ~~Disposal of uranium (depleted, natural and low enriched);~~
		  ○ ~~Maintaining and developing the range of geological disposal concepts;~~
		These disposal R&D requirements are common across radioactive wastes from reprocessing, legacy facilities and operational and decommissioning wastes.	

		<u>Legacy Facilities</u>
		• ~~For approaches that involve containerisation of waste, there may be opportunities to optimise future treatment of these packages through better understanding of the evolution of the waste and waste package or the development of new treatment technologies (e.g. thermal);~~
		• Some of the key areas of research include:
		  ○ ~~Reduced cost waste packages~~;
		  ○ Remote monitoring of waste packages (e.g. corrosion, hydrogen evolution);
		  ○ Remote monitoring of stores (e.g. humidity, temperature).
			• Not relevant to new material/technology development

		<u>Operational and Decommissioning Wastes</u> • Some of the key areas of research include:	

Strategic Theme	Strategic Topic	Research and Development Need	Explanation for Rejecting R&D Need
		○ Improved encapsulants (e.g. reduced cost, higher waste incorporation, increased security of supply, easier processability, increased compatibility with wastes); ~~○ Improved treatment technologies (e.g. thermal).~~	• Not relevant to new material development
	Liquid and Gaseous Discharges	• The liquid and gaseous discharges for decommissioning activities are more varied. Particularly at Sellafield, the variety can be challenging from a scheduling and compatibility viewpoint. Key areas of research include: ○ Modular and mobile effluent treatment facilities to allow the decommissioning of existing effluent facilities or to manage short-term effluent requirements; ○ In-line monitoring technologies to avoid the transport of samples and increase sampling interval.	N/A
	Non-Radioactive Waste	~~The 'Operational and Decommissioning Wastes' section of the NDA Technical Baseline document [2] covers both radioactive and non-radioactive wastes generated by both the operation and decommissioning of NDA facilities. Therefore any non-radioactive waste R&D needs will have been highlighted within this section above.~~	• Repetition of other requirements within other Strategic Topics
Site Decommissioning & Remediation – defines NDA approach to decommissioning redundant facilities and managing land quality in order that	Decommissioning	Whilst the approach to Site Decommissioning is often facility specific there are however some common technical challenges: ~~• Improved data visualisation tools to assist decision making;~~ • In situ characterisation to determine level of contamination: ○ Portable versions of existing characterisation techniques; ○ Non-destructive evaluation technologies;	• Not relevant to new material development

Nuclear Decommissioning Authority

Strategic Theme	Strategic Topic	Research and Development Need	Explanation for Rejecting R&D Need

each site can be released for its next planned use		• Improved decontamination techniques:
		  ○ Increased efficiency and effectiveness;
		  ○ Reduction in secondary waste;
		  ○ Removal of heels and residues from process vessels;
		• Remote or enhanced operation for extreme conditions (e.g. high dose, confined spaces):
		  ○ Enhanced tools and techniques for air-fed suit decommissioning operations;
		  ○ Enhanced tele-operation (e.g. virtual reality and haptics);
		  ○ Robotics and autonomous systems;
		• Technologies and approaches for monitoring facilities and their contents over extended periods of C&M/deferral;
		• ~~Waste treatment technologies for decommissioning wastes:~~
		  ○ ~~Sort and segregation approaches;~~
		Similarly whilst the approach to Site Remediation is often site specific, there are however some common technical challenges:
		• Improved groundwater monitoring:
		  ○ Increased automation to increase frequency of monitoring and reduce cost;
		  ○ Increased information (e.g. isotopic ratios, chemical speciation, improved limit of detection) to identify source of contamination;
			• Not relevant to new material development

Strategic Theme	Strategic Topic	Research and Development Need	Explanation for Rejecting R&D Need
		○ Increased information (e.g. in situ groundwater flux measurement) to improve predictions of movement of contaminants; ○ ~~Improved statistical approach to monitoring programme;~~ • ~~Improved data visualisation tools to assist decision making;~~ • ~~Improved knowledge regarding interactions of radionuclides with the environment:~~ ○ ~~Refine or eliminate assumptions in conceptual and predictive models;~~ • Techniques for early detection of leaks from existing facilities; • In situ remediation of contaminated ground: ○ Techniques (e.g. bioremediation) that either reduce or limit the spread of contaminants and can be applied on sites with facilities still present; • ~~Ex situ remediation of contaminated ground:~~ ○ ~~Techniques (e.g. sort and segregation; thermal treatment) that reduce the volume of contaminated ground that requires further long-term management.~~	• Not relevant to new material/technology development • Not relevant to new material/technology development