FROM CORE TO CAPTURE: GRAPHITE MANAGEMENT BY GASIFICATION AND CARBON CAPTURE & STORAGE (CCS)

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ABSTRACT

Radioactive graphite waste arises principally from the moderators of graphite/gas-cooled reactors at the end of life of the reactors. Commercial power producing reactors (for example, Magnox, AGR and RBMK) have graphite moderators, each containing several thousand tonnes of graphite, with the UK having the largest inventory of over 90,000 tonnes. Additionally, there are smaller quantities of graphite arising from other sources such as fuel element components. The current long term strategy for management of reactor graphite in the UK is for these wastes to be conditioned for disposal followed by transfer to a geological disposal facility (GDF). With this baseline position, these wastes will account for about 30% of the ILW inventory in a GDF. As the volume of the graphite waste is so large, it is not currently economic to retrieve and process the graphite in advance of the availability of a geological disposal facility. Recent work by the NDA has ascribed a much smaller "incremental" volume of 2% due to graphite, calculated on the basis that the GDF has to be a certain size anyway in order to dissipate the decay heat from high level waste.

Graphite is densely packed in the reactor core, hence any retrieval and packaging of the graphite constitutes a volume increase (unless the graphite is processed in some way for volume reduction), and hence this tends to be uneconomic in the absence of appropriate disposal facilities. The absence of a practical and available route for management of graphite waste thus prevents completion of dismantling of the reactor cores and hence prevents early final site clearance of the reactor sites. It is recognised that graphite is not the only technical obstacle to early final site clearance, but it is perhaps the most difficult one, and other problems are capable of solution by other waste volume reduction technologies [1].

Alternative options for the management of radioactive graphite waste are now receiving considerable international attention. The principal alternatives to the baseline are:

- packaging and disposing of graphite waste in a "shallow" facility - either in an existing Low Level Waste (LLW) repository or a specially constructed one, or possibly even on the site where the graphite arises – or
- "gasifying" the graphite, *i.e.* converting it to carbon dioxide to manage the resulting gas and residual solid secondary waste by appropriate routes.

It is this latter option which is the topic of this report. If applied to the UK alone, this approach would have the potential to reduce the volume of graphite-origin intermediate level waste by 95% and save up to £2.4bn in graphite management costs.

The organisations which have come together for the production of this report have a strong track record of previous work in the field of graphite gasification. The team has agreed what is deemed to be a process, as outlined in this report, which could be substantiated as applicable on a full scale. This process has four elements:

- Retrieval, using a novel retrieval methodology based on breaking up the graphite in situ and vacuuming it out of the reactor core;
- Gasification using established technology to convert graphite to carbon dioxide gas and a small volume of residual secondary waste containing the majority of the radioactivity;
- CO_2 Liquefaction and Transport;
- "Potential Exposure Reduction" (PER), as defined below, and Sequestration of carbon dioxide in a Carbon Capture and Storage (CCS) scheme.

Our proposal for gasification of graphite allows a totally different concept for radiological safety in which the two principal problem isotopes ^{14}C and ^{36}Cl are mixed with stable isotopes. The pure radioactive isotopes are relatively low in specific activity (Bq/g) in the first place due to their long half-lives, but admixture with stable isotopes renders the specific activity lower still. Because normal processes in nature are incapable of re-concentrating isotopes, the procedure will ensure insignificant radiological consequences from these isotopes from any pathway at any time in the future. This is not "dilute and disperse", because it can be accompanied by continuing isolation from the biosphere in a CCS scheme. We refer to the process of rigorously mixing radioactive and non-radioactive isotopes of a chemical element in the same chemical form as "Potential Exposure Reduction" (PER) because this will reduce the potential for future radiation exposure. It will also be argued in this report that if the PER process is done properly, the radiological hazard is effectively neutralised at that point and there is then no need for further radiological regulatory control. There is an increasing, but not universal, acceptance that land or materials which have concentrations of radioactive material below a certain level constitute an insignificant hazard and should fall outside the scope of radiological controls. These levels can be used as a guide to determine the levels of isotopes in Bq/g which would be appropriate to release. The guidance as it currently stands cannot simply be applied to the proposed process, however, because a central principle of such clearance procedures and levels is that material must never be deliberately diluted in order to achieve the necessary clearance level. A requirement for proper rigour in the PER process (ensuring the irreversibility of mixing) would be an important pre-condition for any request for dispensation from the usual "no deliberate dilution" provision.

The baseline method of graphite management is normally considered advantageous because it retains the graphite in the form of large monolithic blocks right through from the reactor core to the disposal site. However, only lightly irradiated graphite has been retrieved to date and it is argued in this report that there may be significant difficulties in retrieving graphite as intact blocks from reactors, particularly when the graphite is highly irradiated and hence brittle and subject to significant dimensional changes and weight loss. If the graphite cannot be retrieved as intact blocks, the "form factor" advantage of the baseline will be lost, suggesting that other methods of management (such as the one proposed in this report) may be preferable.

The primary aim of developing and then implementing gasification management of graphite as per this report is thus to provide a means to permit early final site clearance of the fleet of graphite moderated reactors internationally, in advance of the development of long term storage infrastructure (e.g. Geological Disposal Facility). While the early final site clearance may have financial and other benefits in its own right, the volume reduction may also allow savings in the GDF itself, particularly its footprint and associated costs.

The process may also have value in managing smaller quantities of graphite waste that are in more urgent need of a satisfactory solution than the reactor moderators. The need for this may be based on concerns over long term safety "in-situ" (e.g. Windscale Pile 1) or the financial or environmental value of land which could be released from restriction by virtue of graphite removal followed by site clearance as mentioned above. The solving of some of these smaller problems may act as a pilot and feasibility demonstration for future management of commercial reactor moderators, but would not commit the UK irrevocably to using that route in future.
We therefore strongly believe that there is a powerful case for demonstrating some significant dismantling and waste-management progress. Development of the process described in this report appears to be a timely and valuable contribution to the armoury of dismantling procedures for graphite-moderated reactors, especially as international R&D work on gasification routes for graphite management is steadily increasing and there is commercial experience with gasification of similar types of radwaste (as with Studsvik's THOR plant). It would also provide a firm demonstration of a way to 'de-couple' final site clearance from the GDF availability.

There are a number of potential projects in the UK which could act as forerunners to full scale processing; these are listed here with some brief comments:

1) BEPO. This was one of the first reactors in the UK, built at Harwell. Its clearance could potentially release a significant quantity of valuable land;
2) DRAGON. This is the HTR reactor at Winfrith. There is an urgent need to clear the graphite because of plans to complete Early Final Site Clearance at Winfrith [2];
3) Windscale Piles. The motivation for an early project here is not release of land, but the need to stabilise these reactors;
4) Chapelcross and Hunterston Graphite. Longer-term target but which by adoption of this process could support the current Scottish position with respect to radwaste management strategy;

5) AGR Fuel Sleeves. This is an AGR project which might attract funding from AGR related sources, such as the Nuclear Liabilities Fund (NLF). Demonstration of management of these sleeves could open the possibility of Early Final Site Clearance in decommissioning of the AGR's, which in turn could reduce liabilities.

It should be noted that the main focus of the report concerns the UK situation, as UK is the majority holder of irradiated graphite wastes arising from nuclear power generation. Parallels between the UK situation can be drawn with many other international graphite owners, although each will have aspects which are unique to their country and which may require slightly modified approaches, resulting from aspects such as their national policies and legislation. If the UK develops a capability for graphite management along the lines suggested in this report, there is a possibility that the UK suppliers can supply those same services to other countries which need them. This is a distinct advantage compared with the NDA's baseline case, because if the UK instead follows a strategy of long in-situ delay before any graphite management takes place, there will be no short term market for such services. Studsvik is concurrently working on some of these concepts with other European utility providers which are participants in an IAEA Collaborative Research Programme (CRP). Should these other programmes progress forward, the UK work programme (if funded) will focus on the total gasification concept as described in this report, to avoid duplication of effort or potential future infringement of rights.

This report provides an overview of the various elements which when combined define this new and innovative 'From Core to Capture' approach to graphite management. It also provides a high level business case study focused on the UK situation to provide a means of demonstrating the potential cost savings which graphite management by gasification can afford when compared to the current UK baseline approach of encapsulation and storage within a Geological Disposal Facility (GDF). The purpose of the report is not only to provide information about this novel approach, but also to prompt a debate about the underlying principles of radiological safety that it implies. The authors hold the view that the PER process output has particular merit for radiological safety. While direct burial of graphite might be made adequately safe by appropriate underpinning work, direct burial of graphite cannot match the "a priori" radiological safety of our alternative for the radionuclides carbon-14 (^{14}C) and chlorine-36 (^{36}Cl). For the other radionuclides we propose the equivalent conventional burial route anyway.

The nuclear industry has learnt over recent years to avoid what is sometimes referred to as "decide, announce and defend", i.e. deciding on a way forward, announcing it and then defending the plan against hostile criticism. The usual outcome of this type of approach in a modern democratic society is failure. The authors believe that the new potential method of graphite management described in this report has technical and financial merit, but they wish to seek the opinion of others first before seeking to commit to any major project. The various steps so far taken include engagement with the international scientific community through the IAEA CRP and the structuring of a "Users' Group" through a UK Technology Strategy Board (TSB) project. The Users Group provides the platform for early-stage engagement with regulators and other stakeholders to seek views, and to modify and adapt the proposals in response to those views or to meet particular needs.

1. INTRODUCTION

1.1. Background to Irradiated Graphite Management Baseline Options

Graphite is used extensively as a neutron moderator and as a structural and reflector material in nuclear reactors, particularly in the gas-cooled reactor designs used for power production in the UK. The graphite materials used in reactors consist almost entirely of the element carbon, with only very small amounts of impurities being present. Because the graphite is exposed to the neutron flux in the reactors, it becomes radioactive due to slow-neutron activation of carbon and other minor impurities. Eventually, therefore, the graphite becomes radioactive waste.

Radioactive graphite contains radionuclides arising from impurities in the graphite, from entrained material moved by reactor coolants and from the coolant itself, and from the 1.1% naturally-occurring 13C in the carbon, which is an important source of the isotope 14C. This isotope, along with tritium (3H) and 36Cl, are potentially volatile. Likely non-volatile and semi-volatile radionuclides include

60Co, 134Cs, 137Cs, 90Sr, 239Pu, 63Ni, 55Fe and small amounts of uranium isotopes. The reactor core graphite in some of the experimental and plutonium production reactors may also contain fission products from failed fuel elements, whilst low-temperature reactor graphite may contain a considerable amount of stored Wigner energy. Wigner energy accumulation may occur in graphite under fast-neutron irradiation because atoms are displaced from their normal lattice positions into a configuration of higher potential energy. This is effectively manifested as a reduction in the specific heat capacity of the material.

The higher the irradiation temperature, the lower is the amount of Wigner energy because of thermal annealing. In certain cases, arguments about the release of Wigner energy may be required to satisfy safety cases for safe storage and disposal. Wigner energy can be released if the graphite is heated approximately 50K above its irradiation temperature, although a temperature in excess of 2000°C is required before all the energy can be released. The Wigner energy is however released upon gasification.

The majority of irradiated graphite wastes in the world originate from the United Kingdom, France, and the countries of the former Soviet Union, with the UK being the major source. The United States also had a significant programme of early production reactors; additionally there are lesser quantities of irradiated nuclear graphite in a number of countries which include China, Germany, Spain, Italy, Japan and North Korea. For reactors built in the late 1940s and the 1950s, little or no thought was given to the ultimate destiny of the reactor components, and there was little improvement in this position over the next decades. The issues relating to dealing with a cumulative world total in the order of 250,000 tonnes of irradiated graphite, of which approximately 90,000 tonnes are present in the UK, are only now being fully addressed.

Radioactive graphite waste arises principally from the moderators and reflectors of graphite/gas-cooled reactors at the end of their operational lifetimes. Such commercial power producing reactors (such as Magnox, AGR, and UNGG) have graphite moderators which can each amount to several thousand tonnes of graphite in the largest (Magnox) examples. Graphite reactors with air or carbon monoxide coolants lose some material (and therefore component strength) during operation due to radiolytic oxidation. The Soviet designed RBMK reactors and their predecessors, as well as the Hanford production reactors in the USA, are water-cooled (the fuel resides inside the water tubes which pass through the graphite stack) but, in other respects, the graphite behaves similarly under the irradiation. In addition, various experimental reactors with graphite moderators or reflectors exist internationally, which are no longer in operation.

Reactor moderators and reflectors are not the only source of graphite waste. Certain reactor designs incorporate graphite components in the fuel elements such as sleeves and struts, and graphite forms part of the fuel materials of High Temperature Reactors (HTR's) such as the Dragon reactor at Winfrith, UK. Fuel graphite materials are removed from the reactor during operation or at the end of life and are currently stored in appropriate storage facilities pending availability of suitable waste management routes. Irradiated, or at least radioactively-contaminated, graphite also arises from a number of minor sources, such as the moulds used for pre-forming weapons material.

All of this graphite material has particular characteristics that make it a special radioactive waste form. Some examples include:

- the phenomenon of stored 'Wigner energy': this is an important issue for the Windscale piles, where it contributed to the 1957 accident; smaller amounts are present in the lower regions of Magnox-reactor graphite stacks, but not in sufficient quantity to present a release hazard because of the higher irradiation temperatures employed;

- a perception, arising out of the Windscale and Chernobyl accidents, that graphite wastes may present both a combustion hazard (oxidation) and a dust-explosion (deflagration) risk;
- its high purity and unique chemical nature;
- problems associated with the potential release over geological timescales of labile isotopes such as ^{14}C and ^{36}Cl with half-lives of 5,760y and 301,000y respectively;
- the presence of these isotopes together with shorter-lived isotopes such as 3H and 60Co may require the treatment of much of the graphite as intermediate-level waste (ILW);
- the "baseline" destiny of graphite (in the UK at least) is retrieval, encapsulation, containment, and deep storage of a very large volume of treated material. This option may be expensive, and there is currently no disposal facility available at present for the acceptance of the graphite waste in the UK. Similar situations currently apply in other graphite owning countries (e.g. France);
- microbial degradation could cause release of radioisotopes from structures in storage for long periods. Because radioactivity is not distributed homogeneously in graphite, the radioisotopes *e.g.* ^{14}C might be released without significant degradation of the graphite itself. This is a potential consequence of not applying PER.

Because the graphite is densely packed in the reactor core, any retrieval and packaging of the graphite constitutes a volume increase (unless the graphite is processed in some way for volume reduction), and hence this tends to be uneconomic in the absence of appropriate disposal facilities. The absence of a practical and available route for management of graphite waste thus prevents completion of dismantling of the reactor cores and hence prevents early final site clearance of the reactor sites.

Because of these issues, the UK has tended to leave graphite where it is in the reactor cores – despite some of the reactors having been shut down for several decades. The feasibility of retrieval of graphite from reactor cores has, however, been well demonstrated in two cases in the UK: the Windscale AGR and the low-irradiated graphite stack GLEEP at Harwell. In the USA, graphite has been removed from the prototype HTR at Fort St Vrain and, more recently, from the Brookhaven Graphite Research Reactor (BGRR). Despite perceived concerns such as fire and dust explosion (for which strong technical arguments against the risk have been established, as will be demonstrated later within this report) it has been demonstrated that the existing graphite-moderated reactors present no special hazard for dismantling as a consequence of graphite properties, other than for some very specific exceptions. These exceptions relate to reactors in which serious incidents have occurred (e.g. Windscale Pile 1) or in which the graphite has been consistently irradiated at temperatures below around 160°C with the consequent accumulation of significant amounts of Wigner energy which is capable of release at temperatures potentially accessible in handling or vault storage. The otherwise generally benign state of the graphite during dismantling also extends to any dusts generated during the process, even when high-temperature cutting equipment is used in the vicinity (provided appropriate precautions are taken).

An excellent example of this was the BGRR, where a remotely-operated mechanical shovel system was used to break up and remove the core in a reactor in which significant Wigner-energy accumulation had occurred [3]. The BGRR was an air-cooled graphite moderated reactor that operated from 1950 through to 1968. The graphite pile was approximately 25ft (7.62m) on each side, consisted of ~60,000 rectangular graphite blocks, which in total weighed approximately 700 metric tonnes. The retrieval of the graphite from the BGRR was undertaken by remotely operated means, thereby negating the dose implications associated with man access. It utilised standard demolition techniques, modified and applied remotely to address essentially a demolition exercise in a nuclear environment. The reactor was encased within a sealed negative-pressure containment, with HEPA

filters and ventilation system, as well as a camera system to support the remote operations. The approach required the shearing of both the alignment and control rods and their subsequent removal, undertaken in parallel to the size reduction of the graphite moderator (by hammering), and the collection of the broken graphite by conventional excavator shovel. The moderator was sprayed with a fixative to minimise the potential for dust liberation during decommissioning activities. The graphite was then placed into flexible bags for loading into containers for on-going transport and long term storage. The approach demonstrates that a graphite moderated reactor does not need to be 'reversed engineered': instead, standard approaches to demolition adapted for the nuclear environment provide cost, time and dose effective options.

The current UK long term strategy for management of reactor graphite is for these wastes to be placed uncemented/ungrouted (unless waste stream is subject to significant particulate content) into stainless-steel containers followed by transfer to a geological disposal facility (GDF). With this baseline position, these wastes will account for about 30% of the ILW inventory of waste in a GDF [4]. Recent work by the NDA has ascribed a much smaller "incremental" volume of 2% due to graphite, calculated on the basis that the GDF has to be a certain size anyway in order to dissipate the decay heat from high level waste. However, an alternative long-term management solution is being sought, largely because of the effect that the large volume of UK reactor graphite would have on a repository footprint[1] [5]. The search for alternative radioactive graphite waste management strategies is underpinned by Government policy, as indicated by a statement in the Managing Radioactive Waste Safely (MRWS) White Paper of June 2008 [6]:

> *"In practice, there may also be some types of waste – for example, the graphite cores from MAGNOX nuclear reactors – where alternative management options could alter the inventory of waste destined for geological disposal. NDA competitions will introduce international expertise in decommissioning and waste management that could lead to other options being proposed and implemented in due course."*

Alternative options for the management of radioactive graphite waste are receiving considerable attention at present by, for example, the NDA [7] and strategic option assessments are on-going. The NDA's approved strategy, for example, includes the following statement:

> *"Graphite wastes - We will explore the management/treatment options for graphite waste, taking account of worldwide developments and best practice. Finding an innovative solution to graphite wastes would inform a business case for accelerated decommissioning Magnox reactor sites."*

There are many possible routes for management of graphite waste in addition to the deep geological disposal option which currently forms the UK's baseline. Significant international effort is being made to examine these alternatives, including some options for reuse and recycle of graphite. However, the principal alternatives to the current baseline are:

a) packaging and disposing of graphite waste in a "shallow" facility - either in an existing Low Level Waste (LLW) repository or a specially constructed one, or possibly even on the site where the graphite arises – or

b) "gasifying" the graphite, i.e. converting it to carbon dioxide and to manage the resulting gas and residual solid secondary waste by appropriate routes. It is this latter option which is the topic of this report.

[1] Co-location of Higher-Activity Waste (HAW) would reduce the footprint of the graphite to a much lower figure

When considering shallow burial it is quite possible that a robust case could eventually be made to satisfy regulatory and public concern because the radionuclides concerned do not have particularly high radiotoxicity and the models which have predicted concern contain considerable pessimisms which can probably be overcome by further work. However, the physical precautions required to satisfy public and regulatory concern may in the end prove costly for this option. Another consideration is the public reaction to proposals for the new and special radioactive waste disposal facilities almost certainly required by this option, however logical and appropriate these might be. It is this type of non-technical problem which appears to be hampering the development of a suitable facility in France at the present time.

In view of the costs and timescales of the baseline option and the uncertainties of the shallow burial option it would therefore appear prudent to investigate the option of gasification management of graphite.

The organisations which have come together for the production of this report have a strong track record of previous work in the field of graphite management and gasification. Bradtec and Studsvik have been collaborating on graphite gasification management since the 1990's and Studsvik has extensive experience with industrial scale gasification of various radioactive wastes as referred to elsewhere in this report. Studsvik is concurrently working on some of these concepts with European utility providers, which includes members of the current IAEA CRP. Should these other programmes progress forward, the UK work programme (if funded) will focus on the total gasification concept as described in this report, to avoid duplication of effort or potential future infringement of rights.

Costain has significant experience in the field of Carbon Capture and Storage (CCS). Costain also collaborated with Hyder, Studsvik and Bradtec to make various previous proposals to the NDA in the last three years, particularly in relation to the treatment of Hunterston graphite Fuel Element Debris. Although those proposals were not accepted, the work which was done to prepare the proposals has significantly advanced and refined the ideas for graphite gasification management.

The nuclear industry has learnt over recent years to avoid what is sometimes referred to as "decide, announce and defend", i.e. deciding on a way forward, announcing it and then defending the plan against hostile criticism. The usual outcome of this type of approach in a modern democratic society is failure. The authors believe that the new potential method of graphite management described in this report has technical and financial merit, but they wish to seek the opinion of others first before seeking to commit to any major project. The various steps taken thus far include engagement with the international scientific community through the current IAEA CRP and the structuring of a "Users' Group" through a UK TSB project. The Users Group provides the platform for early-stage engagement with regulators and other stakeholders to seek views, and to modify and adapt the proposals in response to those views or to meet particular needs.

1.2. Current Plans / Practices Internationally

The UK is holder of the largest quantity of graphite waste in the world and it is therefore appropriate that the UK should be in the forefront of international efforts to find a solution for management of graphite waste. There are developments taking place in other countries, and a brief review of some relevant developments follows. This is not intended to be a comprehensive review of the international scene.

1.2.1. France

French plans for management of graphite waste are rather more advanced than in the UK because of a policy decision to undertake early dismantling of the six UNGG graphite moderated reactors in France. There is also a technical reason for early dismantling in France relating to the design of the UNGG reactors – unlike Magnox, the graphite core in UNGG reactors is often above the steam-raising plant, making the reactor less stable for long term in-situ storage over decades.

At an early stage (1990s), incineration of graphite was proposed and an experimental programme was undertaken by Framatome whereby a prototype plant was constructed at Le Creusot and successfully demonstrated [8]. This plant required granulation of the graphite in order to enable a sufficient oxidation rate of the graphite to occur even under the fluidised-bed conditions and with an initially enhanced supply of oxygen in the air. Concerns about dust deflagrations were successfully addressed with a thorough analysis of the risks. This issue was further addressed successfully (again, albeit, with unirradiated material) both by extensive theoretical and practical studies at the University of Leeds (UK) in support of future dismantling of the Windscale piles [9] and (for UNGG dismantling) by a comprehensive study in France utilising high ignition energies [10]. It was, however, concerns about discharges of ^{14}C to the atmosphere from such a plant which finally determined that incineration would not be the adopted route for irradiated graphite disposal in France at that time. Such concerns are addressed later in this report.

France instead opted for shallow burial as the preferred method of dealing with the graphite waste. A French Law, 2006-739, on management of nuclear wastes mandated the drawing up of solutions for disposing of wastes contaminated with radium and of graphite wastes in order that a disposal centre for them be put into operation in 2013. The Commission Nationale d'Evaluation (CNE) and ANDRA's scientific committee pointed out to the government that this date left insufficient time to prepare for a centre. As a result the government asked ANDRA to draw up a plan whereby authorisation for the centre would be sought in 2013 with the commencement of operations in 2019 [11].

The traditional objections to shallow burial of graphite, *e.g.* arising from work by NDA RWMD (formerly UK NIREX), concerned local doses to population from ^{14}C and ^{36}Cl in the evolution of the repository. RWMD's baseline objective is the concentration and containment of radioactivity. France has always expressed confidence that their proposals were robust, but the proposals have changed over recent years to incorporate a greater depth than the original 15m and now involve a different concept of tunnelling into the side of a hill in order to encase the waste with a more extensive barrier than would be afforded by a traditional shallow site. The primary issue of contention in France appears to be concern over the migration of ^{36}Cl.

In a press release dated June 24, 2009 ANDRA announced that the French government had selected two communities as potential locations for a disposal facility for the wastes: Auxon and Pars-lès-Chavanges in Aube. They were chosen from the forty-two communities that had offered themselves as sites, nine of which withdrew. According to ANDRA, they are the most promising locations from the point of view of geography, environment, and local support. The intention was that they would be investigated in 2009 and 2010. Then, after a public debate in 2011, the government anticipated choosing between them. Shortly after ANDRA announced the selection of the two sites, the municipal council of Pars-lès-Chavanges voted to remove the community from consideration. Then the municipal council of Auxon voted to withdraw the candidacy of Auxon. In the current circumstances there is therefore some uncertainty about the way forward [12].

Perhaps because of these challenges with the shallow burial option, France, along with other countries is supporting renewed trial work on gasification of graphite, adopting a variant of the technology which is now described in detail in this report Sections (1.4.1 and 2.4).

1.2.2. Japan

Japan has experimented with incineration technologies for graphite management, but their major contribution has proven to be in the area of radioisotope recovery from the combustion gases, notably the initial development of the "Pressure Swing Absorption (PSA)" carbon isotope separation method. It is still the declared intention to incinerate fuel sleeves from the Tokai 1 MAGNOX reactor, with consideration also being given to the incineration of the reflector region of the core. The proposals again involve the use of oxygen enriched air (30%) [13].

Development of Pressure Swing Absorption seems to have ceased in Japan, and without this it seems unlikely that the more radioactive graphite could be treated in the same way.

1.2.3. Russia

At present, 15 water-cooled graphite-moderated reactors (11 RBMK and 4 EGP-6 reactors) are being operated in Russia and generate more than one half of the country's nuclear power generation. Three first-generation water-cooled graphite-moderated reactors (AM reactor in Obninsk and 2 AMB reactors at Beloyarsk NPP) are permanently shut down for decommissioning. There were also 13 uranium-graphite production reactors designed for plutonium generation. These reactors except for one are now shut down.

Russian work on preparing for graphite management consists of investigating methods to establish engineering barriers for the long-term storage of graphite in the form of solid radwaste, and investigating methods of graphite chemical transformation for the purpose of the separation of the relevant isotopes and the reduction of the volumes for the further storage. In particular the Russians are developing molten salt technology for the treatment of graphite containing fuel spills, which is particularly valuable for converting the radioactive fuel contamination into a stable vitrified product in a single process operation [14].

This process has been developed primarily for fuel contaminated graphite waste, which is different from the UK situation.

An alternative Russian proposal involves chemical treatment of the contaminated graphite waste admixed with aluminium and titanium dioxide to form a vitreous matrix. This process is jointly developed between RADON in Moscow and the UK University of Sheffield [15] but has the disadvantage of increasing overall the waste volume destined for repository disposal significantly, albeit with a major reduction in the potential hazard from leaching of fission isotopes.

We may also note that there is renewed interest in incineration of irradiated graphite in Russia, and a pilot plant has been developed by VNIINM in Moscow and then transported to the Siberian Nuclear Combinat near Seversk, and its performance is presently being evaluated following some issues with the off-gas cleaning system [V. Kascheev, personal communication]. Again, concerns about 14C have been expressed, but the remoteness of the proposed processing site and the previously published analyses of global-dose effects [16] give persuasive arguments that there will be only minimal issues with local doses.

1.2.4. Other Activities

In addition to these major initiatives, we note for completeness that work on alternative glasses for immobilised graphite waste is in progress at The University of Sheffield [17] whilst Swiss colleagues, dealing with a very small amount of graphite from two research reactors, are in the process of

incorporating the powdered graphite into a concrete matrix which is utilised for embedding other radwaste items [18].

1.2.5. International Collaborative Activities

International deliberations about the future disposal of irradiated graphite commenced under the auspices of the Commission of the European Communities (later European Union) with a report in 1984 which assessed a number of potential 'management modes' for graphite disposal using the UK MAGNOX and AGR reactor materials as examples [19]. At that time, options such as sea burial were still contemplated, and the perceived risks and uncertainties associated with that route were assessed alongside two alternative forms of deep geologic disposal – in deep clay and coastal shale, in a number of different packaged forms. Incineration was also considered, and the report was quick to recognise the situation which still exists, namely that individual nations have different issues and constraints in all aspects of irradiated graphite management, and there is no 'one case fits all' scenario.

The international collaborations were taken up by the International Atomic Energy Agency (IAEA) in a number of consultancies and conferences [20-22], and this continues at the present time with a Collaborative Research Programme entitled 'Treatment of Irradiated Graphite Wastes to meet Acceptance Criteria for Waste Disposal" in which nine Member States are participating: this collaboration covers the development of numerous material-characterisation and disposal options, a number of which have been mentioned above, and also the present work.

'CARBOWASTE' is a more recent EU project which was launched in April 2008 under the 7th EURATOM Framework Programme (FP7-211333), with a duration of five years , addressing the 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste" [23].

The objective of this project was the development of best practices in the retrieval, treatment and disposal of irradiated graphite, but specifically including other carbonaceous waste like structural material made of graphite or non-graphitised carbon bricks and fuel coatings (pyrocarbon, silicon carbide). It addressed both existing legacy waste as well as waste from graphite-based nuclear fuel resulting from a new generation of nuclear reactors (High-Temperature Reactors (HTR) and the projected Very High-Temperature Reactors (VHTR)). After defining the various targets (end points) for an integrated waste management approach, analysis of the key stages of the road map (i.e. from in-reactor storage to final disposal) has then been undertaken with regard to the most economic, environmental and sustainable options. The project unites organisations from most EU Member States faced with a need for graphite and carbonaceous waste management, along with participation from certain non-EU countries such as South Africa.

The CARBOWASTE project, along with the current IAEA CRP, continue the efforts to address the present unsatisfactory status in this waste disposal area, giving opportunities to build upon previous work, to review technological advances, and to develop innovative ideas which have arisen in more recent years, and thus to identify the most technologically appropriate, environmentally sustainable, and cost-effective procedures, at all stages in the treatment and disposal of all types of carbonaceous wastes.

Finally, a very recent development has been the initial work undertaken between Bradtec, EdF and FZJ to develop an international collaborative project (CarboSOLUTIONS) which aims to confederate the national and industrial activities on i-graphite management around a `Programme-related R&D approach' targeting near-term national and industrial solutions at the pilot scale:

- addressing the open R&D issues left after the CARBOWASTE project;

- providing scientific support for the adaptation of the treatment processes to industrial needs;
- treating different i-graphite grades in the pilot scale;
- designing a full process line including secondary waste management;
- testing alternate treatment options;
- leaching of pre-treated *i*-graphite as proof-of-concept test;
- optimizing waste package concepts;
- improving alternate waste matrices manufacture in relevant scale (e.g. Impermeable Graphite Matrix);
- establishing reuse options;
- evaluating alternate disposal routes, etc.

The CarboSOLUTIONS project is relevant for the management of existing legacy waste and also for closing the 'I-Graphite Cycle' of Generation IV reactors such as Very High Temperatures Reactors (VHTR) and Molten-Salt Reactors.

1.3. Background to Novel Retrieval Methodology "Nibble and Vacuum"

The current baseline option for the removal of graphite from nuclear reactors is to remove the blocks intact, one at a time. This technique has been successful in a number of projects. The baseline method of graphite management is normally considered advantageous because it retains the graphite in the form of large monolithic blocks right through from the reactor core to the disposal site. However, only lightly irradiated graphite has been retrieved to date and there may be significant difficulties in retrieving graphite as intact blocks from reactors, particularly when the graphite is highly irradiated and hence brittle and subject to significant dimensional changes and weight loss. The block-by-block method may be unable to deal with broken or clamped blocks, or where the graphite blocks have been extensively keyed together during construction. If the graphite cannot be retrieved as intact blocks, the "form factor" advantage of the baseline will be lost, suggesting that other methods of retrieval and management may be preferable.

The concept of the "nibble-and-vacuum" technique addresses these issues through in-situ size reduction and extraction of the graphite from the reactor via vacuum transfer, therefore eliminating the need to remove the blocks individually in an intact form. The reluctance hitherto to use destructive methods in-situ for retrieving graphite may have been based on concern over excessive dust formation. While this is indeed a genuine concern which must be addressed, there are now examples of "destructive" retrieval which have been accomplished without serious dust problems, which at least gives some confidence that the problems can be handled. In particular, the BGRR dismantling team employed a gel spray to limit dust for reasons of visibility (direct viewing and CCTV). Initial testing work on a block of virgin nuclear grade graphite from Bradwell Magnox stock, has shown that dust generation can be minimized through reducing the down force applied on application of the size reduction tool.

Another important advantage of this method is concerned with the transfer of highly radioactive material from the reactor core. The traditional approach to such transfers is to build "heavy engineering" shielded structures and facilities (shield walls, gates, transfer flasks etc.), concentrating on achieving radiological protection through "shielding". As is widely recognized, protection from penetrating ionising radiation can be achieved by a combination of minimising time of exposure,

increasing distance from the source and applying shielding – "time, distance and shielding". A completely different method of retrieval and transfer involves achieving radiation protection during the transfer phase by the "time" and "distance" components rather than by provision of heavy and expensive shielding. Vacuum or hydraulic transfer can be completed very quickly (the radioactive material travels at the rate of several metres per second), and the "distance" component is achieved by excluding personnel from the transfer pathway during the short period of the transfer. This approach has been used extensively in the nuclear industry in the past (e.g. so-called "rabbit" transfer systems) and in the transfer of highly radioactive ion exchange resin from LWR primary containments to waste transfer vehicles during chemical decontamination operations.

The benefits of utilising this type of approach for use in the retrieval of moderator graphite from a reactor setting have been accepted by various parties, both in the UK and internationally, including by the NDA, who have stated [4]:

> *"size reduction techniques such as "nibble and vacuum" could be employed during retrieval if necessitated by the physical and mechanical characteristics of the irradiated core"*

The nibble-and-vacuum process requires further development and testing to become a viable alternative for graphite retrieval. The initial stage includes undertaking a trial to demonstrate that this process is workable and safe, and to gain crucial information that researchers can use to further develop it for application in nuclear power plant decommissioning. Through utilisation of this new concept for graphite retrieval, the potential exists for significant cost savings as well as substantial reductions in radiological dose.

The team proposes development work using both irradiated and non-irradiated nuclear grade graphite to both understand the correlations between these materials and to refine the process parameters to ensure that all aspects of its application within a nuclear environment (*e.g.* reactor vessel) are understood and taken into account.

1.4. Background to Gasification / Thermal Treatment of Radioactive Wastes, Relevance to and Experience with Graphite

Gasification is a two-stage process of first converting carbonaceous materials, such as graphite, into carbon monoxide and hydrogen by reacting the materials at high temperatures with a controlled amount of oxygen or steam, and then converting the gases to carbon dioxide and water (steam). The overall chemical reaction involves the oxidation of carbon by oxygen to form carbon dioxide.

In a gasifier, carbonaceous material undergoes several different processes including both pyrolysis, which is the spontaneous chemical decomposition of organic (carbonaceous) materials that occurs at high temperatures, and steam reforming, which is the reaction of the pyrolysis synthesis gases ('syngas') with steam to form carbon dioxide and water. Such gasification is often undertaken in a fluidised bed reaction vessel, but the conditions are much different from those utilised in the incineration processes already referred to.

Gasification, pyrolysis and fluidised bed steam reforming are processes which are in widespread use in the chemical process / waste management industries. Applications include biomass gasification, syngas production, metal reduction, chemical processes, petroleum refinery applications, and organic liquor destruction / energy recovery in the pulp and paper industry.

These treatment techniques have been further developed for specific use with radioactive wastes because of their inherent capability to reduce the volume of waste requiring disposal and to form an inert, safe waste form suitable for disposal.

The most advanced steam reforming process for the gasification of graphite is Studsviks THOR pyrolysis/steam reforming process. Studsvik has developed a family of non-incineration thermal treatment technologies referred to as THOR that are deployed in the US commercial nuclear waste processing marketplace and are currently being deployed within the US DoE sector for the processing of a wide variety of radioactive waste streams. Through the development and deployment of this process, Studsvik has gained experience in the processing of graphite and other carbon bearing materials.

The THOR technology provides for the maximum volume reduction of both organic and inorganic carbon bearing waste. The technology and its deployment systems are robust and can process waste with a wide variety of characteristics including liquids, sludges, gases, and solids with high organic content, high nitrate, and with inorganic content including alkali metals, to produce a dry, volume-reduced, inert waste product suitable for stabilisation. Likewise, the application equipment is configured to address specific input waste characteristics and desired final products. For certain waste streams, such as high sodium nitrate reprocessing wastes, chemical additives can be used to directly produce a stabilised product.

The key advantages of gasification steam reforming are:

- waste volume reduction;
- passivation and stabilisation of wastes, reducing reactive components which can cause product quality problems for disposability;
- robust and flexible with regard to waste inputs;
- temperatures are low enough that key nuclides of concern, such as 137Cs, are not volatised, but retained in the residue;
- a commercially proven and deployed technology;
- low capital cost compared with other techniques.

Furthermore, the system is passively safe – only very small amounts of material are in process at any one time and the system operates at low pressures (primarily vacuum). All process reactions terminate within seconds of a manual or automatic system shutdown should a process upset occur.

1.4.1. Operational Facilities / Facilities in Development

Fluidised-bed steam reforming of organic-based radioactive wastes has been successfully deployed on a commercial scale at the Studsvik Processing Facility (SPF) in Erwin, Tennessee (Figure 1). This small-footprint establishment processes commercial radioactive waste such as ion exchange resins with contact dose rates up to 6.5 Sv/hr. (dependent upon the density and form of the waste). The waste streams processed at this facility contain large amounts of water and organics. The SPF also treats combustible wastes such as plastic, oil, paper and wood. The SPF can receive and remotely process liquid and solid waste at feed rates of over 500 kg/hr. Plant operations have proven safe and efficient over the past nine years of operations while treating over 9570 m3 of highly radioactive waste from numerous US sources (*n.b.* in the USA, high levels of radioactivity of short-lived isotopes may be classified as LLW).

An additional plant has been constructed at the US DoE's Idaho National Laboratory to treat an inventory of sodium-bearing waste that is currently stored in underground tanks. The Idaho

installation is in the commissioning phase and is due to start radioactive operations in early 2014. Other project-development work, consisting primarily of bench-scale and pilot-scale testing, and conceptual and preliminary design work, continues for both US DoE and international commercial customers.

FIG. 1: The Studsvik Processing Facility (SPF)

The THOR process is used on a commercial basis to process intermediate level wastes and the process has been thoroughly evaluated and accepted for intermediate and high level waste applications within the US DoE. For those applications, it is a mature technology. The gasification of graphite in a fluidised bed steam reforming process is straightforward. Carbon materials including coal and charcoal, which are used as additives for many applications, are routinely gasified in the THOR process along with organic wastes. However, at this stage, the THOR process has not been deployed for the treatment of irradiated graphite in full scale.

A testing programme using active graphite samples from utility companies in Europe has been undertaken. Samples of sleeve graphite have been transported from Europe to the SPF at Erwin. There, the samples are prepared for testing before being transported to a specialist radiochemical laboratory in Knoxville, where the samples are roasted and gasified. Further testing and development work is being conducted concurrently with the graphite-gasification concept which is the focus of this document.

The THOR process benefits for treatment of graphite include:

- dissipates Wigner energy contained in the graphite;
- achieves gasification for maximum volume reduction leaving a small (<0.5%) ash volume that can be stabilized for disposal;
- the process uses steam and oxygen so that only small gas volumes are generated: consequently the size of the plant is small and capital costs are minimized, especially compared with incineration;
- the small gas volumes simplify the collection and separation of radioactive isotopes, if required, from the gas stream;
- converts reactive metals such as fuel fragments to an inert state (oxides);

- has high throughput in small footprint and has a number of flexible and scalable deployment options that could be adapted for the needs of reactor site decommissioning.

1.5. Introduction to Carbon Capture and Storage (CCS) and its Relevance to Graphite Management

Increased industrialisation, particularly fossil-fired power generation has led to steadily increasing levels of CO_2 in the atmosphere and the effect of this on climate change is a well-known global concern.

Carbon Capture and Storage (CCS) is under development to enable the continued use of fossil fuels, including oil, gas and coal, with greatly reduced emission of CO_2 into the atmosphere, critical in the transition to renewable energy sources and nuclear power to meet long-term goals for reduction in greenhouse gas emissions. The UK government recently announced funding for the implementation of two commercial-scale CCS schemes. The development of CCS is discussed in detail in Sections 6.3 and 7.

The proposed method of managing the CO_2 from gasification of the graphite involves mixing the 'natural' isotopes of carbon arising from combustion of fossil fuels with the radioactive 14C isotope arising from graphite. We refer to the process of rigorously mixing radioactive and non-radioactive isotopes of a chemical element in the same chemical form as "Potential Exposure Reduction" (PER) because it will reduce the potential future radiation exposure.

The fossil-fuel sources are in fact depleted in ^{14}C compared with the natural background because of radioactive decay since the original plant matter died (Suess effect [24]): thus, the suggested mixing of the CO2 from the irradiated graphite with this large source of 'depleted' CO_2 can be engineered so as to result in a mixture in which the final ^{14}C content of the mixed gas remains below the natural background level, ensuring low future radiological risk, prior to its long term storage in the geological formations being considered in current plans for CCS.

The opportunity for co-disposal of two wastes in the manner described, besides offering unique radiological safety benefits, allows access to the planned CCS infrastructure, either in prototype or fully mature stages.

1.6. Experience of Gasification without CCS in "Low Inventory" Cases

There are already a number of cases where graphite has been gasified in relatively small quantities that have a low inventory of radionuclides. In the cases to date the resulting carbon dioxide gas has been emitted to the atmosphere.

Perhaps the most important example to date has been the graphite from "GLEEP" - the prototype zero energy reactor at Harwell. The graphite moderator in this reactor was dismantled manually, the graphite was crushed, stored and then sent for "calcination" at an industrial facility operated by 'Tradebe' near Fawley, Hampshire. A large proportion of the ^{14}C and ^{3}H present were released during this process, in which only a small amount of the graphite itself was consumed to form carbon dioxide. This release of radioactivity was deliberate, and indeed the objective of the operation [25], this being permissible because the quantities were tiny, as a consequence of the very low irradiation received by the graphite, and thus it was easy to demonstrate that the releases would be well within the limits allowed in this (non-nuclear) facility. The resulting calcined graphite was also effectively 'free release' material after the process, formally non-radioactive.

This is a perfectly acceptable practice so long as the inventory of radionuclides present is very low. There is more graphite with similar properties in the legacy inventory for which this solution is probably the best available technology (BAT).

Later in this report we will consider the potential to extend this type of concept by mixing the carbon dioxide resulting from gasification with non-radioactive carbon dioxide arising from combustion of fossil fuels.

1.7. Timing Issues

1.7.1. Why Hasn't This Been Done Before?

Gasification as a route for management of radioactive graphite waste has been considered for a very long time, but it is only recently that the idea has gained any momentum. Originally the proposals for gasification of graphite involved incineration with minimal off-gas treatment - indeed a CEGB study in the 1980's [16] examined the radiological consequences of releasing the ^{14}C inventory of graphite moderators into the atmosphere in the form of carbon dioxide (at the rate of one complete Magnox-reactor graphite stack per year for twenty years) and found these consequences to be negligible, albeit there was a caveat that local population doses should be more carefully studied. Despite this, the idea of graphite incineration has remained internationally moribund because of concerns over the public reaction to release of aerial discharges. Only in the late 1990's did alternatives start to emerge which would avoid significant aerial discharges by using steam reformation technology [26].

Even in the last decade, where the technology of gasification has improved sufficiently to make it a potentially viable option for graphite management, it has still not yet been possible to gain much international momentum behind the idea for commercial application. The reasons for this are mainly non-technical. In the UK the baseline methodology for graphite management required a geological disposal facility which was not currently available. This in turn prevented retrieval of graphite from reactors, for reasons described above, which then led to a "care and maintenance" philosophy for handling the reactors themselves. The care and maintenance approach removed the urgency to do anything at all with graphite, and hence any further technical development of alternatives was unsupported. The perverse result was that the unavailability of the baseline option for graphite management prevented the development of any alternatives.

If the UK was moving too slowly to allow development of alternatives, France was maybe moving too quickly. The French national decision to decommission the UNGG reactors rapidly required an immediate definition of a firm and available solution to the problem of graphite waste. Any proposal which was deemed below the highest "Technical Readiness Level (TRL)" could not be considered. France therefore chose what they considered at the time to be the technically reliable and tested option for graphite management, namely encapsulation and burial.

Other countries with more minor quantities of graphite have naturally looked to UK and France to take the lead; hence there has been no progress.

1.7.2. Why Do It Now?

Despite nearly three decades of international work on the topic there has been no final disposal of commercial quantities of graphite waste by encapsulation and burial. Progress towards the construction of a geological disposal facility in the UK has been dogged by repeated setbacks (the original intention was to have an operational facility by the year 2000).

Due to negative public and political reaction to the original proposals for a GDF, the UK government established a Committee on Radioactive Waste Management (CoRWM) including representatives for both the technical, industrial and socio-economic aspects of the issue. While the careful deliberations of CoRWM have supported the concept of a GDF, the resulting action by appropriate authorities has led to different policies for Scotland versus England and Wales. Incidentally CoRWM specifically singled out graphite as a waste stream which might require special treatment.

In the UK, the current policy for the shutdown Magnox reactors is a 'Care and Maintenance' period (during which all obvious and easy dismantling of structures external to the pressure vessel and shielding is performed), followed by a lengthy period of 'Safe Storage', planned for a total of up to the 130 years. During 'Care and Maintenance', some monitoring of the core behaviour (temperature, moisture content of the surrounding air atmosphere) is taking place, with the internal atmosphere allowed to equilibrate with the external air through a primary filter through which some measure of activity transfer is recorded.

This strategy was derived partly on the basis of a lack of any obvious alternative, but also to allow the decay of short-lived isotopes, particularly the 60Co present in the graphite and surrounding steel structures. It was felt that this significant reduction in the radiation dose rate would simplify (and reduce the cost of) subsequent dismantling, for which 'new and improved methodologies' might, by then, be available.

There appear to be six clear reasons for completing decommissioning as soon as possible:

Facilitating new nuclear. Early decommissioning underpins the case for building new nuclear plants;

Intergenerational equity: Care and maintenance places a requirement on future generations (i.e. individuals as yet unborn) to complete the job of decommissioning facilities that are properly our own responsibility. It can be argued that we have a moral obligation not to impose such responsibilities on future generations;

Release of assets: Completion of decommissioning of old Magnox reactors could release physical space for construction of new stations. Even where new build is not contemplated many nuclear facilities occupy environmentally important or commercially valuable land (e.g. part of the Snowdonia National Park). It is in everyone's interest to release the land for productive or amenity use;

Retention of skills and knowledge: The ageing staff profile and pressure on the industry to attract and retain new recruits are well known. It would be difficult to argue that preparing and then guarding structures constitutes attractive employment for new entrants to the industry. On the other hand the technical challenge of developing and implementing technology to complete decommissioning quickly is exciting and appealing. Another issue is the loss of information about the structures to be decommissioned which will inevitably occur during a delay of decades;

Benefits for 'UK plc': The vibrant technical work required to complete early decommissioning is likely to enhance opportunities for UK contractors both at home and abroad. It could also be argued that focus in other countries on early decommissioning has generated skills and capabilities which are now required here. As a result, there is a risk that decommissioning jobs in this country will be displaced by skilled workers from overseas, because we have hitherto followed the wrong strategy;

Reduced costs: Relative costs of early versus late decommissioning are difficult to determine rigorously, since they depend on such factors as discount rates and future policy decisions and circumstances. There is however a general underlying parallel with radiation dose. It has been found that nuclear plants which achieve short maintenance outages often also have low occupational

radiation exposure. Crudely, total dose is equal to dose rate multiplied by time, hence reduced time spent doing maintenance means less radiation dose. In the same way, reduced time spent decommissioning means less 'hotel' costs. Perhaps the one of the best examples of reduced cost for accelerated decommissioning is the Rocky Flats site in the USA. In 1995 closure was predicted to require 70 years and $22-36 billion. Accelerating the programme to complete by 2006 has reduced the cost to $7 billion.

In the specific case of the UK graphite, each site has reactors of a unique design with subtle differences in the construction of graphite stacks: in some cases, metal wires have been inserted into columns of bricks to prevent 'levitation'; elsewhere, zirconium pins were introduced to maintain core geometry and stability. Different forms of brick/tile stacking and interlocking have been utilised. In consequence, plant-specific engineering issues will arise which will affect mechanical dismantling as whole components. In Windscale Pile No 1, there is distributed fuel debris in the fire-affected zone which, along with the plant's Wigner-energy content, has been instrumental in delaying any significant dismantling progress for over fifty years. The arguments about 'not leaving problems to future generations' are clear.

Even if the bulk moderator graphite were to be left where it resides pending a further review, there remains a strong case for dealing with some of the smaller or special graphite problems at an early stage. This may be based on concerns over long term safety "in-situ" (e.g. Windscale Pile 1) or the financial or environmental value of land which could be released from restriction by virtue of graphite removal followed by site clearance as mentioned above. The solving of some of these smaller problems may act as a pilot and feasibility demonstration for future management of commercial reactor moderators, but would not commit the UK irrevocably to using that route in future.

We therefore strongly believe that there is a powerful case for demonstrating some significant dismantling and waste management progress. Development of the process described in this report appears to be a timely and valuable contribution to the armoury of dismantling procedures for graphite-moderated reactors, especially as international R&D work on gasification routes for graphite management is steadily increasing and there is commercial experience with gasification of similar types of radwaste (as with Studsviks THOR plant). It would also provide a firm demonstration of a way to 'de-couple' final site clearance from the GDF availability.

1.8. Rationale for this Proposal

This initial report is intended to identify the main issues involved in the proposed process and to define the evaluation tasks which need to be undertaken. It is also designed to act as a briefing document for those who will participate in the "User Group".

The proposed TSB Project as a whole will also define any residual uncertainties and the further investigations which would be required to resolve them, including taking into account any comments of the User Group. The project will evaluate a single "mainline" start-to-finish route for gasification management of graphite based on "nibble and vacuum" retrieval, gasification, carbon dioxide liquefaction and transport and PER and sequestration. Despite this mainline option being the choice of the combined team which has prepared this report, it is recognised that other sub-options to this mainline could ultimately prove better than the mainline itself. It is also recognised that there is uncertainty regarding the carbon capture and storage element of the proposal.

The establishment of an integrated flow sheet with a focus on industrialisation of the process will also be a key objective of this work.

If a practical and appropriately underpinned gasification management route is defined for graphite management by the proposed evaluation, the potential benefits include:

- decoupling final site clearance (FSC) from the availability of repositories or equivalent;
- defining a solution for graphite waste which constitutes Best Available Technology (BAT);
- removing the risk associated with transport to central facility post-retrieval;
- reducing waste facilities required (intermediate storage and GDF);
- reducing the Liability Estimates for dealing with the legacy graphite moderated reactors;
- follows the 'waste hierarchy' in minimising conditioned waste volumes as opposed to increasing them through conventional conditioning routes;
- potentially ALARP.

The output of the project should achieve sufficient maturity to enable in-principle regulatory support for the method.

2. DESCRIPTION OF THE APPROACH TO GRAPHITE MANAGEMENT

2.1. Background

Graphite is capable of being converted relatively simply to the gas phase and, because of its extreme chemical purity for reactor application, the residual "ash" from such gasification is very small in volume. If graphite is converted to carbon dioxide, it becomes a chemical species that is not harmful if discharged to the atmosphere, apart from its properties as a greenhouse gas. To put the greenhouse-gas issue in perspective, the entire world inventory of reactor moderators, if gasified, would contribute no more than the equivalent of a few days output of carbon dioxide from a single coal-fired power station.

The release of carbon dioxide to atmosphere from gasifying graphite would inevitably lead to some radioactive discharges to atmosphere. Although many radioactive species can be removed before the gas is discharged, the isotope ^{14}C is very hard to remove because separation of the isotope from the overwhelming natural ^{12}C and ^{13}C in the carbon dioxide being released would be extremely difficult and costly to achieve.

Discharge of the carbon dioxide to atmosphere is not the only available alternative. With worldwide interest in the possibility of sequestration of carbon dioxide, another possibility is that carbon dioxide from moderator graphite could be mixed with carbon dioxide from other sources and isolated from the biosphere for a prolonged period by "sequestration". In addition to the isolation from the biosphere that this would entail there is another benefit. The co-disposal of the carbon dioxide with larger quantities of radioactively-depleted carbon dioxide from fossil fuel burning would have important potential radiological safety benefits in its own right as discussed below.

In any scenario for gasification of graphite the intention is to retain the radioactivity other than 14C in solid form for disposal as radioactive waste. These developments could assist in:

a) reducing costs and radioactive waste volumes arising from graphite management;

b) improving the stability of the waste form in which the residual radionuclides are stored or disposed;

c) expediting the goal of reactor dismantling.

This proposal for gasification offers the opportunity to avoid significant radioactivity being released to the atmosphere should this be deemed Best Available Technology on safety, environment, cost and other grounds.

Another characteristic of graphite gasification is that it works best when it receives graphite in a small particulate form. This has led to the suggested synergism between this management route and a "nibble and vacuum" retrieval approach, where the graphite is removed from the reactor in this form rather than the more conventional block-by-block approach. This has the potential to reduce cost and to improve efficiency.

2.2. Overall Description

The four steps proposed are as follows:

1. Retrieval
2. Gasification
3. CO_2 Liquefaction and Transport
4. PER and Sequestration

Figure 2, sets out the proposed method of management of graphite by gasification at the site where the graphite arises.

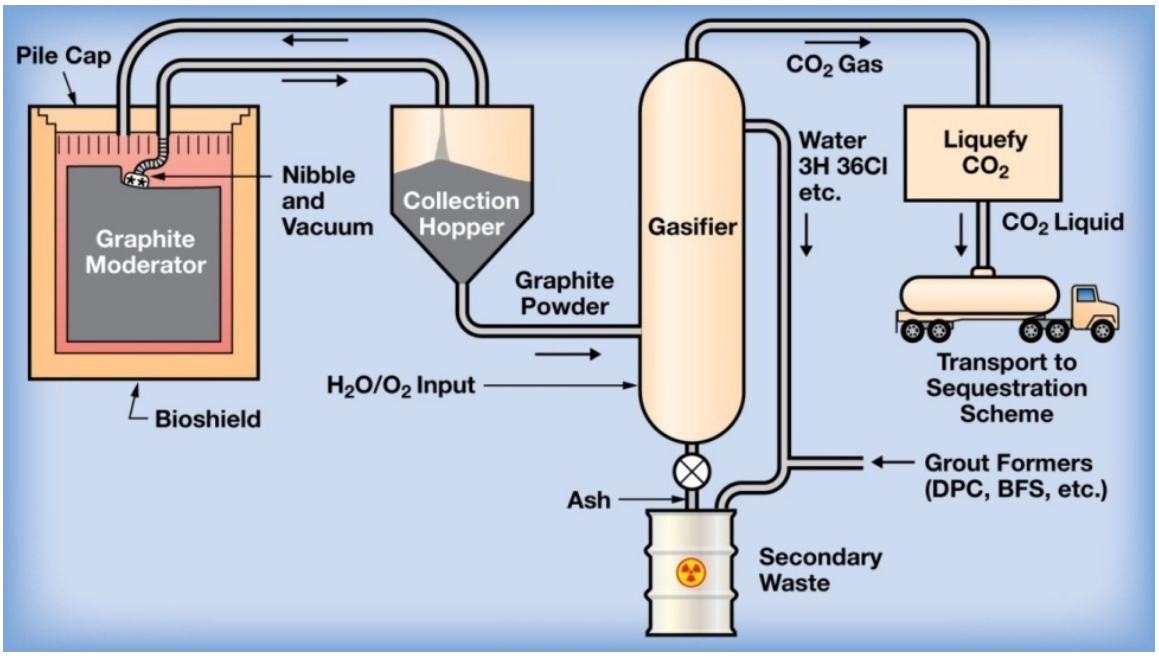

FIG. 2. Graphite Gasification Diagram

Graphite is retrieved by a device which breaks up the graphite inside the reactor core remotely and removes it by vacuum from the reactor core. The graphite "gravel" so generated is collected in a hopper and fed into a gasification process where the graphite is converted to carbon dioxide[2]. The resulting carbon dioxide is compressed and liquefied for storage on site and eventual transport to a

[2] An alternative which might also be considered is the transport of the 'graphite gravel' to a central processing facility in a convenient location adjacent to CO_2 sequestration facilities. The competing safety requirements of transporting liquefied CO_2 containing ^{14}C, against solid graphite containing all of its initial radioisotopic burden, need to be considered carefully in this respect.

carbon capture and storage scheme where it can be blended with other carbon dioxide going into the CCS facility.

Radioactive contamination, other than ^{14}C, is removed from the carbon dioxide in the form of solid ash or water scrubbing solutions which can be amalgamated to form a cement waste form for storage and ultimate disposal.

2.3. 'Nibble and Vacuum'

The principle of the nibble and vacuum process relies on combining three individual technologies. These are in-situ size reduction, vacuum transfer and the remote platform used to control the operation.

The size reduction tool (a modified planer/scabbler) is attached on to the remote platform at the end of a hydraulic arm. The arm enables the size reduction tool to be orientated as required, and has sufficient downward force to enable the tool to work the graphite surface. The graphite is size reduced, and the particulate graphite is drawn in to the vacuum transfer hose by the suction produced by the vacuum transfer unit. The particulate graphite passes through the flexible vacuum transfer pipeline and into the collection hopper, where the majority of the material falls out of suspension within the slack zone. The air flow continues from the other outlet in the skip, and any remaining particulate graphite (e.g. dust still in suspension) is transferred to a filter/filtration system which incorporates a hydrocyclone unit, thereby ensuring the air passing through the vacuum unit is free from suspended graphite. The air is then returned to the reactor vessel to allow for the circuit to be completed.

As summarized above, the nibble and vacuum system is a combination of 3 main technologies, these are:

Size Reduction Tool – Several tools exist which could be applied to the in-situ size reduction of graphite. The most appropriate of these are considered to be cold planning / scabbling / milling. It is a controlled and highly productive process by which (normally) asphalt or concrete is ground up and removed to a certain depth in order to repair or re-profile a chosen surface. The planer is a compact structure with a swinging support; it consists of a drum that is fabricated with combined picks fitted with tips. The swinging support, the fulcrum of which is on the same rotational axis as the planer, allows good holding on the surface to be planed and gives maximum operational balance and elimination of vibrations. These tools can be suitably modified to produce a range of particle sizes, from dust to circa 50 mm gravel, and can also handle the non-graphitic reactor core components present in the graphite moderator core (*i.e.* zirconium pins, thermocouples etc.).

FIG. 3. Scabbling Tool for Graphite Removal

Remote Platform – These are operable by remote control, allowing the operator to be positioned at a safe distance from high radiation areas, falling debris, cold and hot temperatures, and other environmental concerns. It has the ability to do work in out-of-sight conditions using image-stabilized cameras thereby decoupling the requirement for man access into the active area thus significantly reducing dose to the workforce.. Various options are available for the choice of remote platform, although initial indications favour electro hydraulic robotic equipment. Various suppliers exist for this type of platform, and at this stage no one design has been singled out as the most appropriate given the variations which exist in reactor designs..

Vacuum Transfer System - The vacuum transfer systems are used widely across a multitude of industries. The system identified for use in this application is an air conveying unit which is used primarily for the removal of sludge, solids or liquids from deep tanks, platform legs and separators where access is particularly difficult. The system is skid mounted and is readily transportable within a standard International Organization for Standard (ISO) container. This is combined with the vacuum transfer hoses (available in various diameters,) vacuum transfer skips and dust suppression and filtration system. It has the ability to vertically lift particulate solids (e.g. gravel) circa 45 metres (straight lift) and allows material to be passed through confined spaces and around corners due to the flexibility of the hosing.

By developing the concept of 'nibble and vacuum' into a useable, industry recognized technology, we are increasing the number of options available to ensure that we can successfully and safely deal with the variable properties demonstrated in the fleet of graphite moderated reactors which exist worldwide.

2.4. Gasification

2.4.1. Overview of the Gasification Process

This section outlines the design concept of the THOR process for treatment of bulk graphite waste arising from decommissioning. The main THOR process systems that are integrated into the graphite treatment facility include the following systems:

- Roaster and Roaster Gas Treatment;
- Fluidized Bed Gasifier Steam Reformer and Gas Treatment;
- CO_2 Handling;
- Solidification;
- Auxiliary and Support Systems.

The first stage thermal roaster and roaster gas treatment process for the treatment of graphite wastes includes the following major process components that are briefly described below:

- Moving Bed Roaster;
- Roaster Condenser;
- Mineralization Unit.

The first stage of the thermal treatment is the thermal Moving Bed Roaster (MBR) that consists of an electrically heated, vertical shaft vessel. Graphite pieces are introduced from an input lock-hopper into the middle section of the MBR. The use of an electrically heated MBR will eliminate the need to produce energy in the MBR by an exothermic process that would require the addition of oxygen: thus significant oxidation of the graphite at this stage is avoided. The roaster is expected to volatize 40 -

60% of the ^{14}C and the majority of the ^{3}H and ^{36}Cl, while minimising the gasification of the base graphite [25, 27]. Cycling the pressure within the MBR is expected to enhance the removal of volatile gases from the pores of the graphite to enhance the otherwise slow diffusion-limited gas exchanges. Roasted graphite pieces are removed from the bottom of the MBR and are transferred to the second stage reformer for gasification. A small purge flow of carbon dioxide gas enters the bottom of the MBR passing up through the downward moving graphite pieces allowing counter-current gas contact to facilitate maximum removal of volatiles. The anticipated graphite residence time in the MBR is approximately one day.

Downstream of the MBR is a high temperature filter, the Roaster Gas Filter (RGF), that will remove and collect any fine graphite particles that are carried out of the MBR in the gas stream. Any fine graphite particles removed in the RGF are transferred to the second stage reformer. The roaster condenser condenses the majority of the water vapour in the MBR outlet gas. The condenser water will absorb the ^{36}Cl that was volatilised in the MBR, along with tritium as $^{3}H_2O$, and will be transferred to the boiler where, over time, the traces of $^{3}H_2O$ and ^{36}Cl will accumulate. The boiler will be occasionally blown-down to remove accumulated solids and some of the water, $^{3}H_2O$ and ^{36}Cl to the mineralisation and solidification units for ultimate solidification of the $^{3}H_2O$ and ^{36}Cl as the water component in the solidification binder matrix.

The second stage of the thermal treatment is the Gasifier, a fluidised-bed steam reformer that includes the following major process systems. A brief description of each unit is given below.

- Graphite Gasification Reformer (Gasifier);
- Graphite Gasification Condenser;
- Graphite Gasification Filter/ HEPA Filter;
- Moisture Absorber;
- Boiler.

The Graphite Gasification Steam Reformer (Gasifier, or GGR), is designed to efficiently gasify graphite while producing a minimum volume of process gases that require treatment, to release the remaining fraction of ^{3}H, ^{36}Cl and ^{14}C, and to separate non-volatile radionuclides, such as ^{60}Co, ^{63}Ni, and ^{55}Fe, that are contained in the graphite structure. The gasifier is fluidised by steam and is heated by introduction of oxygen with the steam. The graphite is converted into CO_2 in the gasifier by a combination of steam reforming and oxidation reactions.

The Graphite Gasification Condenser (GGC) quenches the high-temperature gases from the outlet of the gasifier and scrubs out most graphite or ash particles in the gas stream. The non-graphite insolubles produced in the process include inorganic ash constituents and non-volatile radionuclides that are in granular form as spinels, metal oxides, and fused ashes. These insolubles are heavier than the very fine graphite particles and can be reasonably separated using commercial 'off-the-shelf-equipment that is substantiated for use on a nuclear site through the HAZOP and commissioning processes. The removed water and graphite particles are recycled back to the Gasifier through special water atomizing injection nozzles. The heavier ash components that are water insoluble, including ^{60}Co, ^{63}Ni and ^{55}Fe, settle in the bottom of the GGC and are periodically transferred to the mineralization unit and then to the solidification unit for preparation and packaging as for disposal as ILW.

The cooled gas stream is then double filtered to remove any particles not removed in the GGC. The Graphite Gasification Filter (GGF) is a pulse back filter with sets of sintered metal filter elements that

are designed to remove >99.95% of particulates smaller than 0.3 micron. A HEPA filter removes any final trace particulates.

The cooled, HEPA filtered gases then will be sent to the moisture absorber to remove any residual water vapour from the gas stream. The moisture absorber comprises a small molecular sieve unit capable of removing almost all moisture from the gas stream. The moisture absorber is periodically regenerated and the removed water vapour is returned to the process. Any $^{3}H_2O$ is thereby also removed from the gas stream so that essentially all the tritium from the graphite is retained in the system as water, which is used as make-up water for preparation of the solidified matrices.

The CO_2 is liquefied and transported to a remote site for PER and storage in a sequestration scheme.

A block flow diagram of the THOR steam reforming process for graphite treatment is provided in Figure 4:

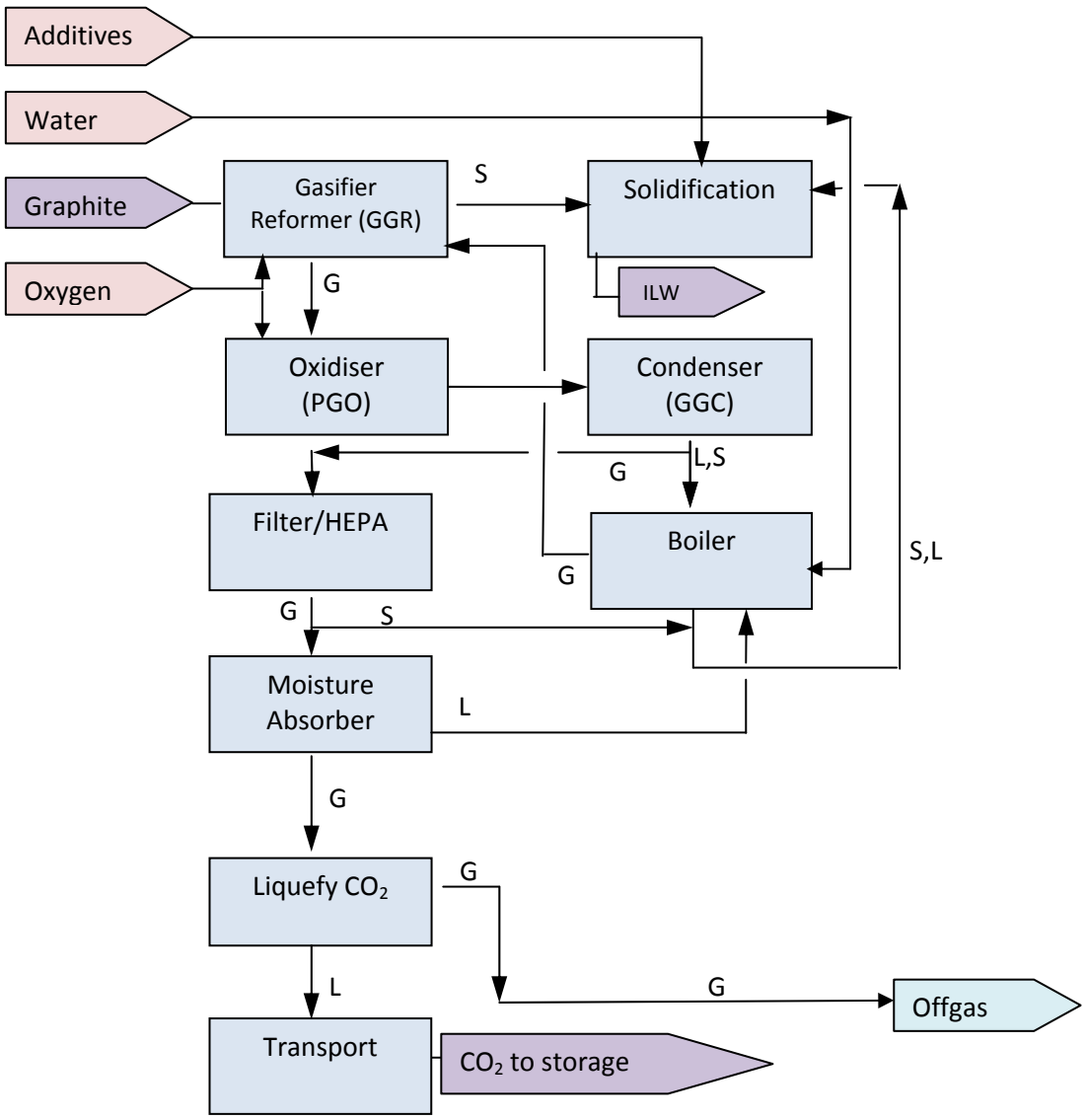

FIG. 4. Detailed Process Block Flow Diagram

2.4.2 Process Inputs

Various approaches to the processing of graphite for volume reduction and (where relevant) the release of the Wigner energy prior to its ultimate disposition have been evaluated to determine their technical feasibility, their regulatory and stakeholder acceptance, and their potential cost impact. The preferred option is to utilise a remotely operated mechanical nibbler to reduce the graphite blocks into small pieces of graphite in-situ in the reactor.

Furthermore, size reduction of large graphite pieces is required for the THOR process to increase the surface area to volume ratio. The increased surface area enhances the release of volatile radionuclides and increases the rate of gasification. Since the second stage steam reformer utilizes a fluidised bed to provide high throughput and high heat release in a small unit, the graphite pieces must be smaller than approximately 25mm so that they can be readily fluidised.

2.4.3 Process Outputs

The THOR process is designed to produce very little or no secondary process waste streams. The radionuclides that are non-volatile (e.g. ^{55}Fe, ^{60}Co, ^{90}Sr, Pu/U), and hence are part of the graphite ash, will remain in the GGR. The inorganic ash from the graphite is converted into small granules consisting of spinels and metal oxides. The ash that collects in the GGR will be removed from the system periodically and sent to the solidification/grouting process where it will be mixed with a qualified binder to produce a small-volume solid final waste form for disposal.

Any volatile radionuclides (*i.e.* ^{3}H, ^{36}Cl) that partition to the condenser solution will be captured in the solid final waste form by being utilized in the water in the solidification unit. Steam is required primarily to fluidise the graphite in the gasification reformer and to gasify the graphite waste. The steam will be condensed and then reheated in a small electrically-heated boiler/evaporator for re-use.

The tritium in the graphite waste will convert to water vapour and partition to this liquid stream. It is estimated that 95% of the ^{3}H in the graphite will be contained in the tritiated water stream for eventual solidification, with the balance being discharged as water. Further testing is required to confirm these values.

It is anticipated that at least 95% of all ^{36}Cl will be collected in the condensers and will subsequently be concentrated in the boiler prior to final disposition with the boiler-water blow down as discussed above where the water with ^{36}Cl will be the water used in the solidification unit. The traces of ^{36}Cl not retained in the condenser and boiler water will be discharged in the gaseous discharge. Again, further testing is required to confirm this.

The interfaces between the gasification process and the CO_2 liquefaction stage, and onward transport for storage will need further definition during the next phase of work. The planned work will address the disposability of the final solid waste form. This will incorporate any issues arising from the incorporation of the liquid wastes in the solidification step.

2.5 Options for CO_2 Management - CCS vs. Discharge

The use of the gasification technology described here allows for certain options for the management of the carbon dioxide gas arising from the process. "Calcination" of carbon based materials effectively requires the discharge of the gas where it arises or (alternatively) extra processing steps to separate the carbon dioxide from the more abundant nitrogen arising from air in the combustion process.

The carbon dioxide gas arising from this process can be dried compressed and liquefied for storage and/or transport. The principal options are as follows:

1) The carbon dioxide gas may simply be released where it is generated. This option may be appropriate in certain special cases where the radioactive inventory is very low, such as GLEEP;

2) The carbon dioxide gas can be mixed with large quantities of non-radioactive carbon dioxide from a fossil fuel burning plant (e.g. a coal or gas fired power station). In this case every effort would first be made to remove radioactivity other than ^{14}C from the carbon dioxide gas before transporting it in liquefied form to the power station and mixing it there with the stack gas;

3) The carbon dioxide can be prepared in the same way as in point 2 and delivered instead to a CCS storage scheme.

The options above are based on the model of gasification of the graphite being undertaken at the site where the graphite is retrieved. It should be noted that the alternative approach could be the co-location of a gasification plant with either a fossil power station or CCS scheme. In this case the graphite would be retrieved from the reactor(s) and transported to the gasification plant. Secondary waste (containing the non-^{14}C radionuclides) would be sent back from the gasification plant to the originating facility, or to a central storage location for conditioning, interim storage and eventual final disposal.

3. TECHNICAL READINESS OF RELEVANT RETRIEVAL, GASIFICATION, CO_2 LIQUEFACTION AND TRANSPORT, PER AND SEQUESTRATION

3.1. Retrieval

In considering the potential cost and time savings from gasification, the potential simplification of retrieval should be taken into account.

3.1.1. Conventional Retrieval

Only a very small number of graphite-moderated reactor stacks have so far been fully dismantled. There is the experimental HTR reactor Fort St. Vrain in the USA, the Brookhaven research reactor, the early GLEEP stack at Harwell UK, and the Windscale prototype AGR in the UK.

GLEEP is a special case in that the total irradiation was so small, and the consequent activation of impurities so equally small, that the stack was effectively dismantled by hand using only basic protective coveralls and gloves. As already explained, the graphite, once removed intact from the reactor, was size reduced (shredded) and then placed in containers for on-going management, following successful calcining trials on crumbled and intact blocks to remove the majority of the ^{3}H and ^{14}C content.

Fort St. Vrain presents the best-documented example to date of the dismantling operations and the restoration of the surroundings to “brown-field” status [28] and was the world’s first full successful decommissioning of a commercial nuclear power plant. In this HTR design the fuel was present as compacts within graphite fuel blocks, necessitating the simultaneous handling of graphite and fuel.

The reflector blocks from Fort St. Vrain – more than 5000 individual graphite components – were removed, along with other pressure-vessel internals, after cutting access through the concrete top head section (4.5 metres thick) and flooding the pressure vessel with water to minimise radiation dose to

the operators. A rotating service platform was inserted in order to transfer the graphite to a transfer basket which was raised into a 'shield bell' and the contents transferred to shipment flasks for eventual disposal. These reflector blocks were classified as low-level waste (LLW).

In the Windscale prototype AGR, where the graphite-sleeved fuel was removed to storage at an earlier stage, leaving only graphite moderator and reflector blocks to be dealt with in the absence of fissile materials, water flooding was considered but was deemed to be unnecessary – partially on the basis that no suitable water-treatment plant was available and that the potential environmental risk through water spillage in a location with a high water table was assessed as greater than operating in air. The dismantling operation in air was completely successful [29] – a closed environment being maintained as the graphite blocks were removed through the penetrated vessel.

A presentation on proposed "conventional" retrieval from a UNGG reactor in France indicated that a new platform and gantry weighing some 1,250 tonnes would be required, and that the operation of retrieval would take about 6 years [30]. In fairness, however, it should be pointed out that much non-graphitic material would also be retrieved by the same equipment during this period.

It is reasonable to say that mechanical removal of graphite in large pieces has been established as a proven technology, both underwater and in air. However, there may be challenges in specific circumstances, particularly where a high degree of irradiation has caused distortion and loss of strength in the graphite, or where other special circumstances apply.

3.1.2. Nibble and Vacuum

The encapsulation and burial methodology does not require or favour size reduction, so traditionally it has been proposed that graphite moderators will be retrieved from reactor cores by mechanical recovery of the graphite blocks and components more or less intact. If the proposed method of managing graphite is gasification, this may allow a wholly different and more convenient methodology for retrieval of the graphite moderator blocks from a reactor core. It may be more appropriate to retrieve the graphite by mechanically reducing it in size in-situ and simultaneously vacuuming the graphite out of the core. This methodology would deliver the graphite to a gasification process in a suitable "small particle" form, and could be operated by a travelling robotic arm controlled externally by an operator. The high cost, complexity and time requirements for mechanical graphite retrieval by current methods is a drawback which could potentially be overcome by such a development.

The nibble and vacuum retrieval methodology has not yet been used for graphite retrieval although each component of the system has been used widely used in various fields (e.g. demolition) including applications on nuclear sites.

We note here that various definitions of readiness levels exist and, for the purpose of this report, we adopt the NASA standards indicated in Appendix A.

The Technology Readiness Level's associated with each of the component technologies are allocated an 8 / 9 based on their proven application within the demolition industries. However, when combining these technologies for the purpose in question (in-situ graphite retrieval from a nuclear reactor vessel) the technology readiness level allocated would be a 5 (at the present time), with a view to increasing this through further development and prototype demonstration work under the current TSB project.

3.2. Gasification

The maturity of the THOR process and its commercial operating history at the SPF enables a 'Technological Readiness Level' (TRL) score of 8 to be demonstrated for many types of radioactive wastes.

The roaster reformer has been demonstrated at near full-scale at temperatures of up to 750ºC using the electrically heated THOR autoclave unit. Accordingly the roaster would logically be allocated a TRL of 6. The fluidized bed steam reformer (FBSR) has been operated at the full-scale, at temperatures of up to 1050°C using carbon in the form of charcoal, coal and coke. Therefore, the FBSR would have a TRL of 7.

Since most mineral products from the FBSR demonstrations have not been converted into stable monoliths on a full-scale commercial basis that meet the UK disposal requirements, the monolith preparation step of the THOR process is considered to have a TRL of 4. A TRL of 4 is justified since the monolith preparation and qualification to US DoE standards are being demonstrated and rigorously validated in a laboratory environment but it has not been validated with respect to specific wastes and disposal requirements associated with countries other than the USA.

We may also note that the original work relating to gasification of graphite by steam reforming also referred to the possibility of conducting the gasification process in-situ in the reactor core itself [26]. Before writing off such a possible development of a combined retrieval/gasification option as impractical, it should be remembered that in some regions in the UNGG and AGR reactor cores the graphite has lost up to 40% of its initial density by gasification during reactor operation.

3.3. CO_2 Liquefaction and Transport

An outline proposal for the handling of CO_2 resulting from graphite gasification is now described.

Gases resulting from gasification of the graphite will be oxidised to give a stream comprising predominantly CO_2 and water vapour. Cooling of this stream will condense the majority of the water, leaving a CO_2 stream containing small levels of nitrogen and oxygen.

Liquefaction of this CO_2 stream requires compression, full dehydration to avoid freezing, and refrigeration to liquefy the CO_2. Depending on the amount of nitrogen and oxygen present, there may also be a requirement to separate these incondensable components through fractional distillation. All steps are in conventional use for the purification and liquefaction of food or industrial grade CO_2.

There are two main options for refrigeration:

1. Compress the CO_2 to storage pressure and condense against a refrigerant such as ammonia provided by a mechanical refrigeration package;
2. Compress the CO_2 to high pressure, cool against air or cooling water. On let down to storage pressure, a proportion of the CO_2 stream will be liquefied and the flash vapour can be separated and recycled to feed the compression system.

In either case, power requirements for compression and refrigeration will total approximately 0.12 kWh/kg, for example 200 kW for a 40 TPD CO_2 liquefaction plant.

It is conventional in CO_2 liquefaction to utilise a mechanical refrigeration unit. Given the liquefaction capacity required, this will be a relatively small and conventional package.

Liquid CO_2 will be stored on site, at pressure, in insulated storage vessels. The CO_2 liquefaction plant can be designed to handle boil-off vapour to minimise losses.

The CO_2 will then be transported by road tanker, to a location with suitable access to CCS CO_2 transportation infrastructure. CO_2 pipelines are anticipated to operate at supercritical pressure, typically in excess of 100 bar.

The technologies and equipment are standard in industrial and food grade CO_2 production and distribution, with supply in the form of a small modular package plant. Further work may identify specific functional and design requirements, but these are considered unlikely to impact negatively on the technical feasibility of this approach.

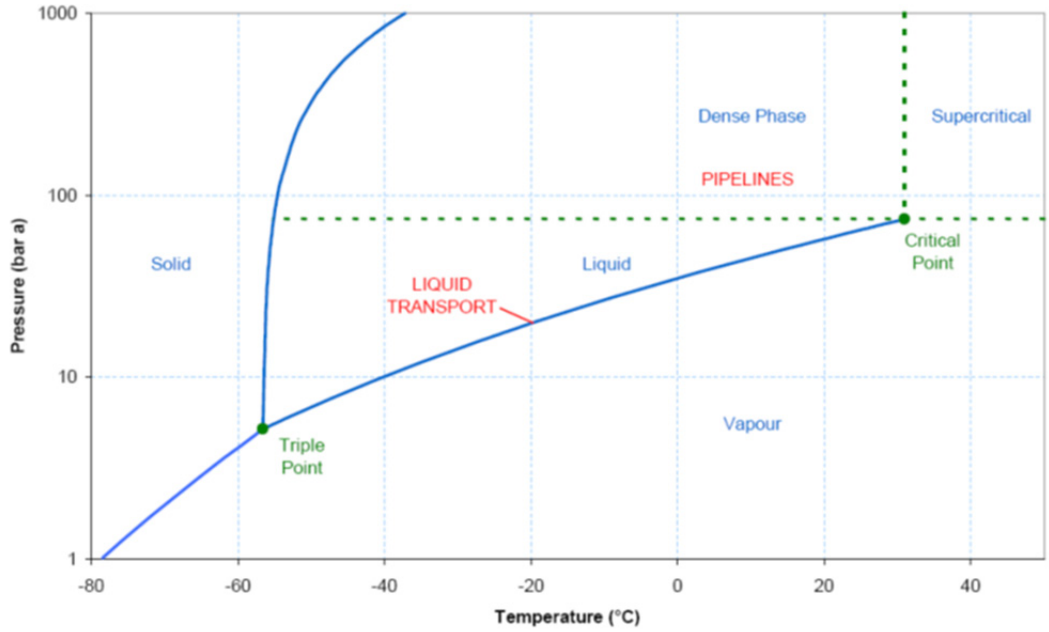

FIG. 5. CO_2 Phase Diagram

3.4. PER and Sequestration

The status of CCS in general, readiness of CCS technology and the timeline for development of facilities for capture and the associated infrastructure for transportation and storage, are important in the context of the proposed PER and sequestration of CO_2 from nuclear graphite gasification. These are discussed in Section 7.

4. CONVENTIONAL AND RADIOLOGICAL SAFETY CONSIDERATIONS

There are normal industrial and radiological hazards associated with the operation of a processing plant of the type proposed, which will involve high temperature, electrical energy, pressurized systems, heavy equipment and the potential for radiation dose and contamination. These hazards will require analysis according to the normal procedures of the industry (HAZOP/HAZAN etc.). In the following sections some special considerations are raised which will also need to be addressed in any safety analysis of the process.

4.1. Conventional Safety Issues

4.1.1. CO_2 Hazards

Liquid CO_2 cannot exist at atmospheric pressure. Depending on temperature, it will exist as solid or gas, and releases of pressurised liquid to atmosphere may therefore result in the discharge of a mixture of both solid and gas. Gaseous CO_2 is colourless and odourless but does have a distinctive taste. It is denser than air and can therefore accumulate at low levels. It is not flammable and is considered generally inert, although can react with other substances and is corrosive to certain common metals in the presence of water.

The primary hazard associated with CO_2 is as an asphyxiant; clearly one must take into consideration also the implications of storage under pressure, the large volume increase upon release and phase change, the associated generation of low temperatures and potential for cold burns, and its corrosivity in the presence of water.

The hazards of CO_2 handling, storage and transport are well understood from experience in the industrial gases sector, including supply of food grade CO_2. Also, pipeline transportation of CO_2 for enhanced oil recovery is commonplace in the US, although much of this is through areas of low population density. Pipeline transportation of CO_2 is proposed at high pressure >100 bar to maintain in the supercritical phase. A number of studies are being undertaken to assess the adequacy of current modelling tools to predict the nature and consequences of large releases on pipeline failure etc. from high pressure sources.

The HSE has commissioned work to examine whether CO_2 should be classed as hazardous for the purposes of assessing design of pipelines and transportation systems for high pressure CO_2. While the nature of the hazards associated with the transportation of high pressure CO_2 are somewhat different to those for existing liquefied natural gas pipelines, transportation of CO_2 is on balance considered to be less hazardous and therefore not a significant hurdle for CCS.

4.1.2. Dust Generation and Explosion / Deflagration Hazards

Graphite dust will inevitably be produced during the break-up of monolithic graphite structures by the methods proposed in this report. Graphite dust is classified as “weakly explosible” under standard ISO test conditions. There is a published comprehensive analysis on this latter topic, the conclusions of which give confidence that these hazards can be appropriately addressed [9]. Consideration of the additional complication of very high levels of Wigner energy reducing the effective ignition energy in suspended graphite dusts are currently under investigation within Magnox Ltd, but the issue is unimportant for commercial reactors as already stated. Graphite dust generation at BGRR was handled successfully and with no problems arising.

4.1.3. Wigner Energy Release

Any Wigner energy present in the graphite will be released totally upon gasification, and indeed the complete and everlasting neutralisation of the Wigner energy hazard represents a significant advantage of this method of graphite management. Wigner Energy release during gasification is of no concern, since the release will simply be balanced by the heat input and output flows of the process. Feed of the graphite to the process is steady and in the form of relatively small particles, meaning that sudden and unpredictable heat excursions can be avoided. Potential Wigner energy release is likely to be a more significant issue in the safety cases for retrieval process and during transport to the gasification stage, but it should be noted that a safety case was successfully made for robust mechanical break-up and removal of graphite containing of large amounts of Wigner energy at BGRR

(a reactor with comparable Wigner energy to the Windscale piles), and that experience should provide some reassurance.

4.2. Discussion of Radiological Characteristics of GDF vs. Gasification

The processes of scientific research and public consultation have established that burial of radioactive waste with appropriate engineered barriers represents an option which carries a relatively high degree of technical confidence, albeit that public consensus and acceptance is sometimes hard to achieve. For example it has been the conclusion of CoRWM that this methodology should be the way forward for the UK with the implementation of a Geological Disposal Facility (GDF).

Graphite waste is a special case and a possible exception to this general rule, however. There is a fundamental problem with assuring radiological safety of burial options for graphite waste due to the chemical "lability" (i.e. mobility of complexed species leading to ability to escape from confinement through aqueous or gaseous transport) and the longevity of two radionuclides present in graphite, namely ^{14}C and ^{36}Cl. These radionuclides will outlive any immediate containment of the waste and once in the biosphere they can then move rapidly by a myriad of mechanisms to places where they can potentially cause radiological harm. Because the possible pathways are so diverse (for example gas generation as methane followed by incorporation in plant roots) it is hard to assure that no pathway will lead to any radiological consequences. The problems with the two radionuclides in question should, however, not be overstated, especially when their probable chemical form is taken into consideration. As an example, current evidence indicates strongly that ^{36}Cl is bound to graphite in an 'organic' (covalent) form [31, 32] whilst the key reference for ^{36}Cl movement in the biosphere[33], cited throughout the waste-management industry, assumes the much more mobile anionic form, as chloride. As stated above, when considering burial it is quite possible that a robust case could eventually be made to satisfy regulatory and public concern because the radionuclides do not have particularly high radiotoxicity and the models which have predicted concern contain considerable pessimisms which can probably be overcome by further work.

There have been comprehensive calculations of collective dose commitment for the various land-disposal options, including the effect of the nature of the rock in the deep disposal site (and whether it is coastal or inland) and, for the shallow repository, the consequences of farming or building activities [19].

The proposal for gasification of graphite allows a totally different concept for radiological safety in which the two problem isotopes ^{14}C and ^{36}Cl are mixed with the respective stable isotopes. The pure radioactive isotopes are relatively low in specific activity (kBq/g and Bq/g respectively) in the first place due to their long half-lives, but mixing with stable isotopes renders the specific activity lower still. Because normal processes in nature are incapable of re-concentrating isotopes, whatever pathway for radiological exposure is calculated due to the pure radioactive isotope, the actual radiological exposure can be divided by the degree of mixing initially carried out. The procedure will ensure insignificant radiological consequences from these isotopes from any pathway at any time in the future. It should be noted that the necessary addition of non-radioactive material is on a different scale for the two isotopes. Thousands of tonnes of stable carbon are needed in admixture to reduce the ^{14}C in graphite to a permanently harmless level, whereas just kilograms of chlorine are needed for ^{36}Cl. Thus it is necessary to use a major source of CO_2 to achieve the desired result, whereas for ^{36}Cl it can be achieved by addition of modest quantities of stable chloride (e.g. salt) to the secondary waste package during processing.

This approach potentially offers an even more attractive prize. If it could be shown that by the PER technique the radionuclides have insignificant potential for harm in the future, there could be no further need for any regulatory control of them once the mixing process has been properly carried out.

Thus the careful and rigorous isotopic dilution of ^{14}C and ^{36}Cl can ensure insignificant radiation exposure from the isotopes in future in a way that burial of the raw wastes cannot. In order to achieve these benefits the PER must be done rigorously and properly - radioactive and non-radioactive isotopes must be intimately mixed in exactly the same chemical form. In the case of chlorine, it is likely (for example) that some appropriate chemical reducing agent must be added to the scrubbing water to ensure that all chemical chlorine forms are totally converted to chloride before addition of non-radioactive chloride. PER does not have to be "dilute and disperse" because the material can also be isolated from the biosphere, i.e. "dilute and contain" such as within a CCS Scheme.

Rigorous PER is only possible in the gaseous or liquid phase, and hence it is an opportunity which is not possible for any management route which retains the graphite intact in the existing solid phase. It is, however, ideally suited to the gasification management route.

The radiological safety benefits of the proposed process are comprehensive, complex, and risk confusion (by non-specialists) with "dilute-and-disperse". It is intended to produce a complete description during the programme, for discussion with the regulators and other interested parties.

The discussion in this paragraph is necessarily high level and it will be important to quantify the radiological characteristics of the options of GDF, shallow burial and CCS.

Although it is possible to be confident about the insignificant radiological consequences of radioactive chlorine and carbon that are processed and sentenced by the intended PER route, it will also be necessary to consider the consequences of any of these radioisotopes which escape the process. An example of such an escape mechanism would be any ^{36}Cl which is emitted in the gas phase with the CO2 during processing instead of being transferred as intended into the liquid phase by the gas scrubbing process, in which phase it would be mixed with inactive chlorine. However, the radiological consequences arising from the release of this ^{36}Cl should be very small so long as it only represents a small fraction of the total ^{36}Cl inventory. If carbon dioxide is transported from a gasification process to a CCS scheme and is accidentally released during transport, this would constitute release of "undiluted" radiocarbon and the consequences for local doses will need to be analysed.

4.2.1. Regulatory Considerations

There is an increasing, but not universal, acceptance that land or materials which have concentrations of radioactive material below a certain level constitute an insignificant hazard and should fall outside the scope of radiological controls. Examples of this can be found in the RP89 regulations [34] relating to decommissioning of formerly or potentially contaminated land and in the IAEA guidance [35]. These levels can be used as a guide to determine the levels of isotopes in $Bq.g^{-1}$ which would be appropriate to release.

The guidance as it currently stands cannot simply be applied to the proposed process, however, because a central principle of such clearance procedures and levels is that material must never be deliberately diluted in order to achieve the necessary clearance level. Besides the public distaste for the idea that a consignor of waste can remove his regulatory obligations by diluting waste, there is also good technical reason for this proviso. Under normal circumstances materials which are at first in concentrated form, then deliberately diluted, may subsequently be re-concentrated by natural processes in the environment. An innate appreciation of this is maybe at least in part what lies behind

the negative public attitude to dilution. As previously stated, PER is very different because it is irreversible in the natural environment.

Accordingly we propose that where material is to be subject to PER, the existing regulatory guidance relating to unconditional clearance could be used to determine the extent of such mixing necessary in order for regulatory control to be able to cease. A requirement for proper rigour in the process would be a pre-condition for dispensation from the usual "no deliberate dilution" provision.

We believe that the foregoing paragraphs represent a logical basis for the regulatory oversight of the environmental discharge aspects of the process. We note that regulators are already considering the gasification process in relation to treatment of waste at Sellafield.

4.3. Global and Local Dose considerations

The proposed process, even if in the worst case it resulted in the total release of all ^{14}C of all graphite to the atmosphere, would not cause any unacceptable increase in global ^{14}C atmospheric levels. This was originally discussed by Nair in the 1980s [16] and the theme has been developed by others since (for example, A.A. Bochvar Institute in Russia in regard to their newly designed graphite-incineration pilot plant). Nair calculated, allowing for absorption by the oceans, that the incineration of one Magnox reactor core per year for 20 years would increase the global dose rate from ^{14}C by less than one part in one thousand, against the predominant production from atmospheric ^{14}N by cosmic radiation. Such a tiny increment in the atmospheric content is trivial compared with natural variations in the background production rate of ^{14}C itself: for example, a recent study based upon tree-ring measurements in Japan [36] has shown a sudden increase of 12% in the years AD 774-5 arising from an unexplained cosmic-ray burst reaching the earth (the opinion of the paper's authors) or possibly the result of a gigantic solar flare (essentially protons) or supernova explosion. Another comparison of significance is that the Magnox reactor graphite (which constitutes about one fifth of the total global irradiated graphite) contains about 3,000 TBq of ^{14}C compared with approximately 220,000 TBq of this isotope released to atmosphere during the atomic bomb tests in the 1960s [37]. Such considerations do not, however, take account of possible local dose effects, and it is that concern which has effectively prevented simple incineration of graphite wastes.

An important underlying assumption of the next sections is that all radioisotopes in graphite other than ^{14}C can be removed from the carbon dioxide before discharge or amalgamation in a CCS scheme. Confirmation that this is the case forms part of the development trials.

4.3.1. Gasification with CCS

The intrinsic mixing of the gasification feedstock with CO_2 arising from conventional fossil fired power stations leads to CO_2 with nearly natural ratios of the various isotopes of carbon (e.g. ^{12}C, ^{13}C and ^{14}C). This is achievable because the CO_2 derived from fossil fuel is depleted in ^{14}C compared with carbon in the biosphere. ^{14}C in the biosphere is in equilibrium through radioactive decay and continual replenishment by natural atmospheric processes deriving from solar radiation. But coal, due to radioactive decay over the timescales from deposition of the flora (source material), its compaction, formation and its subsequent extraction for use as a fuel source has a depleted ^{14}C content. For example, the Carboniferous Coal Measures of the UK extend from the end of the Devonian Period, about 359.2 ± 2.5 Ma (million years ago), to the beginning of the Permian Period, about 299.0 ± 0.8 Ma, during which period virtually all the ^{14}C initially present will have decayed. Mixing carbon dioxide from this source intimately with carbon dioxide arising from irradiated graphite can lead to an isotopic mixture more typical of natural carbon dioxide in the biosphere.

The RP89 levels for release of materials containing ^{14}C are set at 100 $Bq.g^{-1}$. If this is taken as the appropriate standard, then fully irradiated reactor graphite (with inventory approximately 105 $Bq.g^{-1}$), would need to be diluted by a factor of 1,000 to reach these levels. Thus 10,000 tonnes of carbon dioxide arising from graphite from one UK MAGNOX reactor would need 10,000,000 tonnes of carbon dioxide from fossil fuel burning. To put this in context, the output of a single coal fired power station (Drax) is 22,000,000 tonnes of carbon dioxide a year.

As an additional safety measure the carbon dioxide product can be isolated from the biosphere by the process of carbon capture and storage. As stated in the previous section, it is assumed that at the point of mixing the carbon dioxide passes out of the scope of radioactive material control. Any subsequent concerns about continuing hazard will relate to the conventional aspects of the CCS scheme, and not the radiological aspects.

4.3.2. Gasification with Aerial Discharge

Another option would be to undertake graphite gasification (without the subsequent CCS step) and for the off-gas (CO_2) to be discharged from the stack of a fossil-fired power station, or in the case of very low level graphite, direct release of the process gas.

If the fossil-fuel option is chosen, then the radiological control considerations would be the same as previously discussed, namely that the carbon dioxide would pass out of regulatory control at the point at which it falls below the relevant level in the outlet stack. Nevertheless, an indication of the local dose implications is provided in the following discussion.

In order to estimate the likely doses to individuals living close to an outlet stack, a number of assumptions have to be made in order to identify a 'critical' group including:

- The way in which the activity is dispersed in the environment and potentially finds its way into local food chains has to be considered;
- The behaviour of local individuals, aspects of which could influence their local dose.

Over the years a number of computer models for activity release have been developed by the nuclear industry, government bodies and the Health Protection Agency. These models have been compared with each other and have generally been shown to agree reasonably well. A report produced by Magnox Ltd on this subject [38], describes the assumptions made and the models applied to present estimates of off-site dose per unit release factors associated with routine atmospheric discharges from Magnox-reactor sites in the UK. The output of the calculations for total adult dose reported for the three main isotopes of concern in relation to graphite management for the Berkeley and Hunterston A Magnox sites are presented in Table 1:

TABLE 4.1: COMMITTED RADIATION DOSE PER TBQ RELEASED FOR PER ADULT IN THE CRITICAL GROUP AT HUNTERSTON A AND BERKELEY ($SV.TBQ^{-1}$)

	^{14}C	^{3}H	^{36}Cl
Hunterston A	1.7E-05	1.5E-07	2.5E-03
Berkeley	3.5E-05	5.1E-07	8.0E-03

For illustrative purposes, ^{14}C predicted discharges to atmosphere and predicted local dose resulting from the gasification process are presented in Table 2.

TABLE 2: UK 'REFERENCE' MAGNOX GRAPHITE ACTIVITIES, PREDICTED GASIFICATION ^{14}C DISCHARGES TO ATMOSPHERE AND CALCULATED LOCAL DOSE PER ADULT IN THE CRITICAL GROUP

	Units	Reference	Hunterston A	Berkeley
Reference				
Reference Magnox reactor graphite after 10 years decay. *(Assumed mass = 2,233 tonnes).*	TBq	85.0		
Reference MAGNOX reactor graphite after 10 years decay. *(Adjusted mass = 2,000 tonnes).*	TBq	76.1		
Aerial Discharge				
Authorised annual airborne discharge limits for normal site operation	TBq		0.002	0.001
Predicted aerial discharge per annum from gasification process *'worst case' – 100% release*	TBq		76.1	76.1
Effective Dose Exposure to the Public (adult dose)				
Effective Dose Exposure to the Public *(due to nuclear industry)*	mSv/year	<1		
Per atmospheric release factor	Sv/TBq		1.7 E-05	3.5 E-05
Calculated local dose from 100% gasification process aerial discharges, no PER	mSv/year		1.3	2.7
Calculated local dose from gasification process aerial discharges post PER, 2,000MW coal fired station, $6x10^6$ tonnes coal per year	mSv/year		0.0005	0.0004
Carbon specific activity after PER	Bq/g		13	13

The calculations are based on a generic case, i.e. calculated activation inventories for UK 'reference' Magnox and AGR graphite (after 10 years decay) [19], and a treatment rate of 2,000 tonnes per annum. The results are compared with the annual airborne discharges and authorised limits for ^{14}C during normal site operation (0.001 TBq – Berkeley, and 0.002 TBq – Hunterston A) [39], and the effective dose exposure to the public (due to nuclear industry), not to exceed 1 $mSv.a^{-1}$ [40].The last line assumes that the carbon dioxide is mixed with the output of carbon dioxide from a 2,000MW coal fired power station. In making the calculation, an assumption is made that reducing the specific activity in the carbon by a given factor by the PER process reduces the critical group dose by the same factor. This may not be exactly the case, because large emissions of carbon dioxide from a facility may lead to some increase in the proportion of elemental carbon incorporated in a critical-group individual from the power-station source, but the assumption should nearly hold true. Clearly the

release would not occur geographically at Berkeley or Hunterston in this case, but the release factors provide an indication of the local doses which would pertain and the large reduction in local doses achieved due to the PER process.

The need for discharge and local dose calculations for ^{3}H and ^{36}Cl will depend on the partitioning behaviour of these isotopes and can be performed at a later stage as required. However, unlike ^{14}C, the process is designed to remove high proportions of these radionuclides before release as carbon dioxide. Other metallic radionuclides in the graphite will remain in the ash (post gasification) and treated a solid secondary waste.

5. LEGAL ISSUES

5.1. Introduction

A preliminary evaluation of this process needs to take into account the stringent regulations it would need to meet and these are set out and discussed in this section. It should be noted that what is proposed here is a novel process and the regulatory framework which covers it needs to be fully determined. A key activity in achieving this will be the interactions between the TSB project delivery team and the regulators (EA & SEPA) which is scheduled to take place in November 2013.

5.2. Issues Affecting Graphite Processing

Set against this therefore, is that siting a plant to treat graphite or moving radioactive graphite or products to and from this plant or dismantling and moving a plant that has already treated radioactive graphite from one site to another will be subject to very stringent regulations. There may also be issues relating to mixing high ^{14}C–containing CO_2 with low ^{14}C – containing CO_2 from combustion of fossil fuels in a power station. Such a practice would need to be accepted by both public and the Regulator who would need to be assured that this is not the same as dilution of radioactivity as would occur in say sea discharge. Once this had been resolved, the criteria set out in the safety case would need to be met for transporting liquid CO2 (which would still be labelled as radioactive). Further regulation and restrictions would then apply to diluting the ^{14}C-rich CO_2 with ^{14}C depleted CO_2 derived from fossil fuel combustion:

- If the delivery point is located at a power plant where fossil fuel is combusted, the owner of e.g. the power plant would need to accept a material labelled radioactive for mixing with this product;
- The process depends upon the viability (technically and economically with government subsidies) of sequestration of CO_2 from conventional fossil-fuel burning power stations;
- A connection between sources of high 14C-containing CO_2 and low ^{14}C containing CO_2 to effect PER would need to be made. Is the plant used for this connection then subject to decommissioning as any other plant constructed for radioactive waste treating?

5.3. Legislation Applying to Nuclear Waste

All operations involving nuclear materials are controlled /regulated to prevent harm to people and the environment. The legislation applying to nuclear materials is not simple to understand and has been

set up to ensure compliance with the obligations set up under the EURATOM Treaty. In particular, an obligation under Article 37 requires that:

> *"...each Member State shall provide the Commission with such general data relating to any plan for the disposal of radioactive waste in whatever form as will make it possible to determine whether the implementation of such plan is liable to result in the radioactive contamination of the water, soil or airspace of another Member State"* [41].

As a member state of the IAEA the UK also observes internationally agreed protocols on nuclear safeguards and safety standards [42].

Following Devolution of Scotland and Wales resulting in setting up of a Scottish parliament and Welsh Assembly, the way in which radioactive substances are regulated in particular in Scotland will differ slightly from that applied in the rest of the UK. However the effects of the legislation are consistent across the UK. Legislation applies to both the Radioactive Substances Act (RSA93) and the Environmental Permitting Regulations 2010 (EPR10). RSA93 is the relevant legislation in Scotland and NI; in England and Wales EPR10 applies (see HSE and DECC websites for more detailed information on legislation and documents relating to it).

In September 2011, DEFRA published Environmental Permitting Guidance on radioactive substances regulation for the Environment Agency (the Regulator) and organisations that use radioactive substances, In April 2012, DECC published statutory guidance for managing land contaminated by radioactive substances.

It is worth noting that legislation applying to radioactive substances is enforced by degree, and there are certain categories where the substances are not controlled at all. These apply to very low activity and the categories are:

- Out of scope of regulation: Effectively this equates with "not radioactive" for the purposes of the legislation. Radioactive substances which are out-of-scope are not subject to any regulatory requirement under this legislation.
- Exempt from permitting: Substances which are considered to be radioactive by definition may be exempt from the need for a permit. The Basic Safety Standards Directive 1996 (BSSD) refers to the need or otherwise for "prior reporting". In the UK this is assumed to be equivalent to permitting, and exemption to mean that prior reporting is not necessary.

Any new process or procedure requiring new applications of the use of radioactive substances needs to apply to DECC under the Justification of Practices involving Ionising Radiation Regulations 2004. This may have implications for aspects of the TSB graphite project and in particular:

- Design, procurement, construction, commissioning, operation, Post-Operative Clean Out (POCO), decommissioning and ultimate dismantling/demolition of the THOR plant and in particular the control of hazards, emissions and secondary waste arisings;
- The process to recover the graphite from its current location in the power-station/storage area
- The transport of the graphite across a site where it is stored;
- Transport off site of any materials to and from the THOR plant (this includes graphite and liquid or gaseous CO_2);
- Mixing CO_2 from the THOR Plant with CO_2 from a Power Station.

5.3.1. Categories of Nuclear Waste

The three categories of radioactive waste in the UK are designated Low Level Waste LLW, Intermediate Level Waste (ILW) and High Level Waste (HLW).

Low Level Waste (LLW) accounts for about 90% on a volumetric basis of solid radioactive waste produced in the UK. LLW is generally made up of everyday materials such as plastics, glass, metals, paper etc. that have become contaminated by contact with radioactive liquids or powders. While most of it comes from the nuclear industry, it is also produced by many non-nuclear industries using radioactive materials including hospitals, universities, research establishments and the oil and gas industry. The definition of what constitutes radioactive waste can be found in the Radioactive Substances Act 1993.

Around 10% of the remaining waste is Intermediate Level Waste (ILW) and 0.1% is High Level Waste (HLW); the latter, however, contains over 95% of the total radioactivity of all nuclear wastes. It is therefore vital that all waste produced as a result of nuclear activity is stored safely and disposed of.

In some documents the NDA refers to only two categories of waste: Lower Activity Waste (LAW) and Higher Activity Waste (HAW). Higher Activity Waste originates from reactor operation, spent nuclear fuel reprocessing and decommissioning and includes HLW, ILW and some LLW which is not suitable for disposal in the Low Level Waste Repository (LLWR).

5.4. Government Departments in the UK Responsible for Radioactive Materials

5.4.1 The Department of Energy and Climate Change (DECC)

DECC is the lead department for managing the use of and disposal of radioactive substances and waste and works closely with DEFRA and the EA. DECC sponsors the NDA created through the Energy Act 2004 (to manage the decommissioning and clean-up of civil public sector sites). In Scotland it works with Scottish Ministers. Both the Office for Nuclear Regulation (ONR) and the Committee for Radioactive Waste Management (CoRWM) provide DECC with specialist advice.

DECC controls hazards associated with radioactive substances by:

- Developing policies for the safe and secure disposal of radioactive wastes;
- Providing, monitoring and reviewing laws and regulations to enable regulatory bodies to store, use and transport radioactive substances;
- Making decisions justifying applications of ionising radiation;
- Managing spent fuel, reprocessing and nuclear materials;
- Providing a system to identify and remediate radioactive contaminated land.

5.4.2. The Department of the Environment, Food and Rural Affairs (DEFRA)

DEFRA is the UK government department responsible for policy and regulations on environmental, food and rural issues. The priorities are to grow the rural economy, improve the environment and safeguard animal and plant health.

DEFRA is responsible for policy and regulations on:

- the natural environment, biodiversity, plants and animals;

- sustainable development and the green economy;
- food, farming and fisheries;
- animal health and welfare;
- environmental protection and pollution control;
- rural communities and issues.

Although DEFRA only works directly in England, it works closely with the devolved administrations in Wales, Scotland and Northern Ireland, and generally leads on negotiations in the EU and internationally.

There is a 10 point growth plan underpinning these priorities but areas where radioactive materials are likely to be a concern are:

- To be proactive in safeguarding animal and plant health;
- Investment in flood and coastal protection.

5.5. Statutory Bodies Reporting to DECC and DEFRA

5.5.1. The Nuclear Decommissioning Authority (NDA)

The Nuclear Decommissioning Authority (NDA) is a non-departmental public body which was created through the Energy Act (2004). The NDA has inherited 19 nuclear sites and the associated civil nuclear liabilities and assets of the public sector; these were previously under the control of UKAEA and BNFL.

The NDA is responsible for

- decommissioning and cleaning up operations at 19 civil nuclear facilities, ensuring that all the waste products (both radioactive and non-radioactive) are safely managed;
- implementing Government policy on the long-term management of nuclear waste;
- developing UK-wide nuclear Low Level Waste (LLW) strategy and plans;
- scrutinising future decommissioning plans of the eight existing nuclear power stations of EDF Energy Nuclear Generation Group Limited;
- advising Department of Energy and Climate Change (DECC) on the quality of operator's decommissioning plans and associated cost estimates for new nuclear power stations under HMG's Funded Decommissioning Programme arrangements.

In England and Wales, the NDA reports directly to the Department of the Environment and Climate Change (DECC) and in Scotland to the Scottish Ministers in the Scottish Parliament. The purpose of the NDA is to deliver the decommissioning and clean-up of the UK's civil nuclear legacy in a safe and cost-effective manner, and where possible to consider accelerated programmes when these can reduce the hazards.

The NDA is therefore responsible overall for the disposition of all the irradiated graphite originating from power stations and experimental reactors. Most of this will be classified as ILW and if this were treated in the same manner as all other ILW must ultimately be processed in a timely and intrinsically safe manner so that it can be consigned to Intermediate Safe Storage and then ultimately to a Geological Disposal Facility (GDF). The Scottish Parliament, however, prefers near surface radioactive waste disposal for HAW (as well as LLW).

5.5.2. The Role of Radioactive Waste Management Ltd (RWML)

Radioactive Waste Management Ltd (RWML) is a section within NDA which is responsible for the delivery of the Geological Disposal Facility. In due course, ownership of the GDF may be opened up to competition in line with other NDA sites. It should be noted that RWML does not have a regulatory role.

Both ONR and the Environment Agency scrutinise, and advise on the work of RWML relating to the GDF. RWML also provides advice to nuclear site operators on the packaging of HAW for disposal through the Letter of Compliance (LoC) disposability assessment process. All HAW must be packaged in a passive and disposable form fully compliant with future transport and disposability requirements. Any secondary waste created by the THOR process as well as the POCO and decommissioning of required HAW packaging requirements. The secondary waste from a THOR plant will clearly be subject to LoC.

5.5.3. The Office For Nuclear Regulation (ONR)

In February 2011, a written ministerial statement announced the Government's intention to bring forward legislation to create a new statutory body outside of the HSE to regulate the nuclear power industry. The Office for Nuclear Regulation (ONR) was formed on 1 April 2011, as an Agency of the Health and Safety Executive (HSE), pending relevant legislation to create ONR as a statutory corporation.

ONR brings together the safety and security functions of HSE's former Nuclear Directorate, including Civil Nuclear Security and the UK Safeguards Office, which transferred in 2007 from Department for Trade and Industry, and the Radioactive Materials Transport team, previously within Department for Transport.

The vision of ONR is to become "universally respected for securing confidence in nuclear safety and security". ONR's strategy over the next few years is to address and meet the challenges facing the nuclear industry over the next few years which are:

- assessment of the safety cases for potential new nuclear power stations and their potential subsequent licensing, construction, operation and decommissioning;
- changing requirements of ageing nuclear power reactors and the generating companies aim to keep them producing electricity;
- delivery of the decommissioning programme and active management of legacy nuclear plants including high-hazard facilities;
- drive from the international nuclear industry for greater cooperation between regulators;
- leading to a convergence and harmonisation of regulatory requirements for new and existing nuclear facilities;
- need to improve the regulation of civil nuclear security while acquiring the capability to do so;
- increasingly competitive global nuclear skills market, which affects our ability to recruit the highly-qualified and experienced staff we require – something which is important given that a significant proportion of their existing inspectors are approaching retirement age.

5.5.4. The Committee for Radioactive Waste Management (CoRWM)

In September 2001, the UK Government launched a public consultation called "Managing Radioactive Waste Safely". One key outcomes of the consultation was a decision by UK Government to set up the independent Committee on Radioactive Waste Management (CoRWM) in November 2003. Its task was to review and recommend the option or combination of options that can provide a solution for the long term management of high and intermediate level radioactive wastes in the UK. CoRWM was asked to work in an open, transparent and inclusive manner, to provide an opportunity for members of the UK public and other key stakeholder groups to participate in and engage on the process of making recommendations to the UK Government. These recommendations were published in a report on 31 July 2006 [43].

The primary recommendation of CoRWM was that deep underground burial was the best available disposal option for Higher Activity Nuclear Waste. However, a robust programme of interim storage was required immediately, as the process leading to the creation of suitable facilities for geological disposal may take several decades.

The UK Government accepted the proposal and recommended that planning and development of the geological disposal option would be based upon:

- a strong and effective implementing organisation, with clear responsibilities and accountabilities;
- strong independent regulation by the statutory regulators - the Health and Safety Executive, the environment agencies and the Office for Civil Nuclear Security (OCNS);
- independent scrutiny and advice to Government on implementation;
- a partnership with the host community.

Whilst the UK Government and the Welsh and Northern Ireland devolved administrations consulted on a framework for the long term management of higher activity radioactive waste. the Scottish government did not accept deep geological disposal as the right way forward. The Scottish Parliament advocated long term local “near surface near site” storage to ensure that the waste can be monitored and retrieved and the need for transporting it over long distances is minimal.

In 2007, the UK Government set up a reconstituted CoRWM advisory Committee on Radioactive Waste Management (CoRWM), composed of 12 members, who are experts in different aspects of radioactive waste management.

CoRWM’s main priority in 2013 to 2014 was to provide advice to DECC on their Managing Radioactive Waste Safely (MRWS) programme and in particular the siting process for a Geological Disposal Facility (GDF). This will provide an independent overview of issues relevant to the Nuclear Decommissioning Authority’s (NDA) plans for the long term delivery of radioactive waste programmes and brings to the attention of ministers any issue considered to be worthy of note or of concern.

It is understood the CoRWM identified irradiated graphite as a special waste stream needing specialised treatment.

5.5.5. The Environment Agency (EA) and Scottish Environmental Protection Agency (SEPA)

The Environment Agency is responsible under the Environmental Permitting Regulations (EPR) for regulating all disposals of radioactive waste on and from nuclear licensed sites (NLS) in England and Wales:

- "Disposals" of radioactive waste includes discharges into the atmosphere, discharges into the sea, rivers, drains or groundwater, disposals to land, and disposals by transfer to another site;
- The term 'nuclear licensed sites' (NLS) refers to sites that have a nuclear site licence under the Nuclear Installations Act 1965;
- The Nuclear Installations Act 1965 (NIA65) and associated site licences cover certain regulatory requirements on nuclear licensed sites that we would otherwise regulate as a radioactive substances activity. These differences depend on whether the operator holds a nuclear licence (the licensee) or does not (a "tenant"). The regulator under NIA65 is the Office of Nuclear Regulation (ONR);
- Activities for which a nuclear site licence is required include nuclear power generation, nuclear fuel manufacturing and reprocessing, uranium enrichment, operation of research reactors, some national defence activities and some radioactive waste processing and disposal.

In Scotland this service is provided by the Scottish Environmental Protection Agency.

Regulation of nuclear licensed sites is important for the purposes of protecting the public from harm caused by the discharge and disposal of radioactive waste and to protect the wider environment. This is achieved within a framework of extensive Government Policy, Strategy and Guidance on the management and disposal of radioactive waste. A summary of this guidance can be found in the 'Government Guidance on Radioactive Substances Regulation' (RSR). Operators at nuclear sites are required to protect people and the environment by:

- minimising the generation of radioactive waste;
- minimising the amount of radioactive waste that has to be discharged into the environment;
- discharging that waste in ways that minimise the resulting radiological impact on the public and protect the wider environment, and using the optimal routes for disposal of solid waste. We require operators of nuclear licensed sites to assess the dose impact to the public.

ONR grants nuclear site licences on behalf of HSE. The nuclear site licence is a legal document, issued for the full life of the facility. It contains site-specific information, such as the licensee's address and the location of the site, and defines the number and type of installations permitted. Such installations include nuclear power stations, research reactors, nuclear fuel manufacturing and reprocessing, and the storage of radioactive matter in bulk.

It follows therefore that operation of the THOR process will require a nuclear site licence.

Radioactive Waste Advisers

Radioactive Waste Advisers (RWA) are specialists in radioactive waste disposal and environmental radiation protection who have demonstrated competence in the Radioactive Waste Adviser syllabus.

There is a requirement under European law for people who keep or use radioactive material, or who accumulate or dispose of radioactive waste, to appoint advisers, known as "qualified experts", to

advise them on radiological protection. In the UK we call the qualified expert for radioactive waste management and environmental radiation protection a 'Radioactive Waste Adviser'.

The environment agencies in the UK - i.e. the Scottish Environment Protection Agency (SEPA), the Environment Agency (EA) and the Northern Ireland Environment Agency (NIEA) - require anyone who is permitted or authorised to accumulate or dispose of radioactive waste to appoint a Radioactive Waste Adviser.

Environmental Permitting for Radioactive Substance Activities on Nuclear Sites

From 6th April 2010, the disposal of radioactive waste from nuclear sites will be subject to the Environmental Permitting (England and Wales) Regulations 2010 (EPR). These Regulations repeal, amend and replace much of the Environmental Substances Act 1993 (RSA93).

These also cover certain aspects of the keeping and use of radioactive sources on nuclear sites.

Higher Activity Waste Guidance in Scotland

The Scottish Government advocates the use of long-term 'near surface near site' storage facilities in Scotland. As intermediate and high level waste both require shielding (the latter also involving cooling), they are currently being stored at nuclear installations until long term storage facilities become available.

Some spent fuel from nuclear reactors is also reprocessed at Sellafield, where potentially re-usable uranium and plutonium are separated from radioactive waste. In the past, some intermediate level waste was disposed of in a disposal shaft at Dounreay.

Certain types of radioactive waste produced on nuclear licensed sites need to be treated and packaged (a process referred to as "conditioning"), in order to make them safe for long-term storage and disposal. SEPA and the Health and Safety Executive (HSE) jointly regulate this process on nuclear sites in Scotland. The Environment Agency (EA) and HSE regulate nuclear sites in England and in Wales.

Disposal Options for LLW

Currently, most low level waste in the UK is disposed of at the repository near Drigg, and some similar disposals were also made at Dounreay.

- Insufficient capacity within the UK to dispose of LLW expected to arise from the decommissioning of the UK's nuclear facilities, resulted in the UK Government and Devolved Administrations issuing a new 'Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom' in March 2007;
- The Policy allows disposals of high volume VLLW to specified landfill sites (including the practice of "controlled burial") and the general disposal of low volume VLLW to an unspecified destination, together with municipal, commercial or industry wastes;
- SEPA has a number of obligations under the policy and is working hard to implement them into its systems and procedures. Guidance on the maximum volume of low volume VLLW that may be disposed of will be issued as soon as it is produced, as will the requirements for LLW management plans for the non-nuclear industry.

5.6. Regulations For Transportation of Nuclear Materials

Transportation of radioactive materials in the UK is governed by the requirements of the Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations SI 2009 No.1348 (CDG2009) CDG2009 came into force on the 1st July 2009 and replaced CDG2007 and the

previously separate Radioactive Material (Road Transport) (Great Britain) Regulations SI 2002 No.1093. These Regulations are based upon the International Atomic Energy Agency's (IAEA) Regulations for the Safe Transport of Radioactive Materials (Safety Series No.TS-R-1) and the European Agreement re the International Carriage of Dangerous Goods by Road (ADR).

The basic philosophies behind the Regulations are that:

- package design should be such that the risk of any radioactive contamination or external radiation hazard should be kept to a minimum;
- all shipments should be traceable back to the sender;
- good quality assurance should produce public reassurance.

5.6.1. Main Implications of the Regulations

No definition of what constitutes a radioactive substance is actually given in the regulations but what is radiologically significant is implied by the description of what constitutes radioactive exempt material. This varies with the radiotoxicity of the nuclide - with some alpha emitters it is only $0.1 Bq.g^{-1}$ but for tritium it is $1 MBq.g^{-1}$.

For packages meeting radioactive exempt requirements, there is no requirement to provide information to the carrier in relation to the transport. It would appear that it is now possible to use public transport whilst transporting an excepted package. Excepted packages only need to be marked up with the appropriate UN number and consignor or consignee details. There is no professional user exemption and all persons must therefore conform fully to all the requirements of the regulations, but, display of smaller placards is allowed for cars (and other small vehicles up to 3500kg) carrying labelled packages.

Consignment notes are required for all categories of radioactive package above excepted packages. The UN numbers and descriptors have been expanded so that they are more specific. All NOS (not otherwise specified) numbers have been de-listed. There is a requirement for carrying fire extinguishers when carrying more than 10 labelled (Type A) packages where the combined Transport Index (defined below in Section 5.6.2) is greater than 3. When the TI >3 or more than 10 packages are being carried normal ADR requirements apply. The Department for Transport has the power to inspect premises as well as vehicles, to ensure compliance with CDG2009 but the Health and Safety Executive are now the main enforcing authority.

Contamination limits remain the same for all types of package.

5.6.2. Definitions

'Road' means any highway to which the public has unrestricted access. Therefore in a campus university if there are barriers to get passed before gaining access to the site, transport on the internal roads are not covered by the Regulations.

'Transport of packages' in these regulations covers much more than the transportation procedure and also includes the design, fabrication and maintenance of packaging, and the preparation, consigning, handling, carriage, storage in transit and receipt at the final destination of packages.

'Transport Index' (TI) is an indication of the external hazard that a package presents. It represents the maximum dose rate at 1 metre from a package measured in $mSv.h^{-1}$ and multiplied by 100. (*i.e.* it is the dose rate at 1 metre in the old $mrem.h^{-1}$ units)

'Consignor' is the person sending the goods and the 'Consignee' is the recipient of the goods. A full and extensive description of all terms used in the regulations can be found for Class 7 Radioactive Material in section 2.2.7.1 of the ADR.

5.6.3. Scope of the Regulations

The regulations cover the transport by road of all non-exempt radioactive material in the form of sources or waste conveyed in a vehicle both within the UK and for journeys in other European countries covered by the ADR (an ADR journey). There are some exceptions to this and relevant ones are as follows:

- transport on private roads;
- transport of radioactive material contained in the body of a person undergoing medical treatment, a dead person or a live animal undergoing medical treatment;
- transport of approved consumer products by a consumer;
- transport in accordance with an approved derogation.

5.7. Areas of Regulation for 'Core to Capture' Project

Regulatory Legislation emerges and changes and so it is difficult to predict what will be in place if and when this Project proceeds. However based upon the discussion above, it follows that:

- The Project will probably be funded by the NDA and subject to their conditions;
- Design and operation of the plant will be dependent upon a license being granted by ONR and the design will need to comply with local site regulation (where it is to be constructed) and CDM;
- The design will cover all phases of the project up to and including POCO and decommissioning
- Emissions and their disposition will need to be agreed with the EA and SEPA;
- All transport of graphite to the plant and transport of CO_2 away from the plant will be subject to transport regulations;
- CoWRM (if still in existence) will need to support the aspirations of the Project to ensure positive feedback to DECC. CoWRM were supportive of a new initiative for graphite disposal;
- All secondary waste will need to be minimized and subject to the disposal options supported by the EA and SEPA.

6. ADDITIONAL FEASIBILITY ISSUES

6.1. Pre-cursor Feed to Gasification

6.1.1. Work Rate

The nibble and vacuum retrieval methodology can easily accommodate a work rate of several tonnes of graphite per day - indeed the demonstration project will employ work rates (albeit for short periods) close to that which would be required on full scale. At this rate the moderator of a commercial graphite moderated reactor (e.g. Magnox reactor) could be extracted for subsequent treatment within one to two years.

6.1.2. Characterisation

One of the advantages of the gasification route proposed is that it converts graphite from a being a multiplicity of varying waste streams (different irradiation histories, levels of contamination etc) into a uniform product for disposal. We view this as being like a funnel, converting the multiplicity of different waste streams into a single or small number of products of a defined type. By contrast the storage and burial of raw graphite is like an "upturned funnel" which takes the apparently uniform graphite waste form and produces a multiplicity of slightly different packages for disposal. Because the graphite is never truly homogenised in the baseline route its accurate characterisation prior to disposal becomes difficult. We therefore see the possibility of our proposed route not only providing a significant simplification in the task of characterisation, but also greater accuracy and reliability of inventory information. Because the graphite is totally destroyed in processing there is no need to know many details of (for example) how radioactivity or impurities are distributed in the structure of the graphite.

The nibble and vacuum retrieval method is likely to be tolerant to large variations in the mechanical properties of the graphite being retrieved. The manufacturers of the (currently proposed) retrieval equipment claim that it can handle material which varies between wet slurry and reinforced concrete - hence variations in graphite mechanical properties resulting from irradiation – embrittlement, density reduction, changes in mechanical and thermal properties – should be readily tolerated and prior testing using unirradiated graphite would be entirely appropriate.

6.1.3. Lead Time

The lead time for development and deployment of the nibble and vacuum technology is likely to be consistent with the requirements of any actual graphite retrieval operation, given that whichever route is chosen (e.g. shallow burial or CCS) there is likely to be several years required for assuring regulatory sign-on and preparation for processing. However, this comment does assume that the appropriate demonstration work, as already defined, proceeds in a timely manner. The initial demonstration of nibble and vacuum retrieval (as described in Section 2.3) will be an important milestone in giving confidence that this part of the total plan will work and can be relied on.

6.2. Gasification

6.2.1. Ongoing Development Work

The general objective of the on-going development work is to apply a bench-scale gasification test programme in order to determine if the THOR process can remove and collect ^{14}C, tritium, ^{36}Cl from the graphite samples to an acceptable level and thereafter to gasify the graphite. To collect parametric data to allow future larger scale testing is also an important part of the bench scale trials.

The test samples will be subject to pre-processing by crushing at the SPF in Erwin. The product will then be transported in batches of less than 1kg to the laboratory in Knoxville. A composite sample of the irradiated graphite will be analysed to establish its baseline fingerprint and activity. The results from previous tests of sleeve graphite (both irradiated and non-irradiated) from other countries will be used to determine the starting parameters for the bench-scale system.

Parametric gasification tests will be undertaken, with analysis of evolved radionuclides to determine the optimum conditions.

The principal objectives of the first testing programme are as follows:

- Evaluation of the ability of the process to release primarily ^{14}C and tritium;

- Demonstration of the ability of the gasification / steam reforming process to gasify the remaining graphite;
- Evaluation of the fate and behaviour of ^{14}C, ^{36}Cl and tritium; Evaluation of the operating parameters needed to support the design of a pilot scale gasification system.

At present, a second bench-scale test programme is under way to further confirm the results from the first test programme, and to refine the optimum operating parameters for achieving the maximum ^{14}C release. The outcome of the testing programme will be a data set which allows the development of concept designs for graphite arising from similar sources (such as UNGG core graphite).

The testing programme will also provide data that will inform the assessment of off-gas management strategies including abatement, capture, liquefaction, transport and sequestration.

6.2.2. Feedstock Requirements

As stated above the process proposed is extremely robust and capable of dealing with a variable feedstock. The main requirement for the gasification process is that the particulate size of graphite feed is relatively small *e.g.* smaller than 25mm. For this reason the novel nibble and vacuum retrieval is proposed, but should this not be applicable graphite blocks can be retrieved in the conventional way and then size reduced for the gasification process. The principal aim of the proposed process is to provide a robust graphite processing scheme which can handle nearly all types of graphite whatever their input characteristics.

It is not envisaged that any specific radionuclide removal would be required prior to entry to the process, however, it is noted that various techniques are available such as washing, baking or chemical decontamination should these be needed. The use of such additional processes would generate additional types of secondary waste and should be avoided unless really needed.

The process proposed provides a single route through from initial graphite to CCS storage and secondary waste storage and ultimate disposal. The process can be applied on different scales, for example relatively small scale for fuel element debris management or full scale for power reactor moderators. The degree of shielding and contamination protection will depend on the feedstock, but it is likely that process plant will be designed to handle the full radioactive inventory of moderator graphite (except perhaps for pilot or demonstration plants).

6.2.3. Scalable Application

The THOR technology is a flexible and scalable technology that can be applied in a modular format depending upon the deployment option selected. At this stage, we envisage that the technology could be deployed in several ways, as follows:

- Demonstration plant, capable of processing several of the smaller NDA graphite waste streams such as Dragon, BEPO, or Chapelcross / Hunterston. This plant could be modularised and mobile if required;
- Full scale plant capable of treating the full inventory from a Magnox site. At this stage, we estimate that a throughput of around 2000 tonnes per annum would be suitable for this purpose;
- Re-use of the full scale plant at other Magnox stations. We envisage that treatment would be best performed on the reactor site rather than at a CCS site.

6.2.4. Lead Time

The lead time for development of the THOR process from completion of the testing programme described above to the deployment of a pilot scale plant in the UK is 24 months.

6.3. Carbon Capture & Storage (CCS)

6.3.1. Introduction

Carbon capture and storage (CCS) prevents large amounts of CO_2 from being released into the atmosphere, and has an essential role in reducing greenhouse gas emissions. It involves the use of established technologies to capture CO_2 produced by large industrial plants, compress it for transportation and then inject it deep into a rock formation at a carefully selected site, where it is permanently stored.

The three main elements of CCS are discussed in more detail below but, in summary, they involve:

i. Capture

The separation of CO_2 from other gases produced at large industrial process facilities such as coal and natural gas power plants, oil and gas plants, steel mills and cement plants.

ii. Transport

Once separated, the CO_2 is compressed and transported via pipeline, truck, ship or other methods to a suitable site for geological storage.

iii. Storage

CO_2 is injected into deep underground rock formations, often at depths of one kilometre or more.

There are no scientific barriers preventing CCS and, because the UK Government has opted for offshore storage, social barriers should be minimized. The regulatory regime for CCS is established. The safety issues are well understood and can be managed by prudent engineering as is already the case for the extensive infrastructure used for the transport and storage of natural gas.

6.3.2. Capture

Capture of CO2 involves the separation of carbon dioxide from the other gases produced in power generation and industrial processes, using one of three methods: pre-combustion capture, post-combustion capture or oxyfuel combustion.

i. Pre-combustion capture

A pre-combustion capture system involves converting solid, liquid or gaseous fuel into a mixture of hydrogen and carbon dioxide using processes such as ‘gasification’ or ‘reforming’. Reforming of gas is well-established and already used at commercial scale in refineries and chemical plants around the world. Gasification is also widely practiced around the world. The CO_2 is removed by solvent scrubbing processes, and the remaining hydrogen can be used for power generation and, as the hydrogen economy develops, to fuel cars and heat homes.

Pre-combustion capture from coal-derived synthesis gas has been proven at full scale, and gas turbines operating with the hydrogen rich streams resulting from de carbonisation of synthesis gas are already available. Pre-combustion capture is yet to be incorporated into a power plant, although the Kemper County project under construction in the US is scheduled to start up in 2014.

ii. Post-combustion capture

CO_2 is captured from the exhaust of a combustion process by absorbing it in a suitable solvent. The absorbed CO_2 is the released from the solvent and is then compressed for transportation and storage.

Post-combustion capture technologies have been demonstrated at pilot scale on flue gas from gas-fired and coal-fired plants (e.g. at Ferrybridge in the UK, Plant Barry in the US and Mongstad in Norway). Amine based solvents are widely used for removal of CO_2 in gas processing and have also found limited use in recovery of CO_2 from industrial flue gases.

The Boundary Dam project in Canada is due to start up in 2014. It involves the retrofitting of post combustion capture on one unit of the plant, with the CO_2 being destined for use in EOR. The project has favourable economics, and all the CO_2 has already been sold.

iii. Oxyfuel

In this process, the fuel is combusted in oxygen (produced from the separation of oxygen from air) diluted with recycled flue-gas, rather than in air. This oxygen-rich atmosphere results in final flue-gases which consist mainly of CO_2 and water, producing a more concentrated CO_2 stream for easier purification.

Oxyfuel combustion has been evaluated in large scale (40MW) test facilities in the UK by Doosan Babcock (Renfrew). The most significant oxyfuel pilot facility operating today is Vattenfall's 30 MWt plant at Schwarze Pumpe, Germany.

iv. Other

Technologies under development for early "next generation" plants include cryogenic separation, membrane filtration and adsorption/desorption processes.

The UK's Energy Technologies Institute is investing in the pilot scale demonstration of next generation capture technologies for coal, gas and waste projects. Costain leads the project related to coal-fired power generation which will demonstrate a new pre-combustion capture technology ready for incorporation into a full-scale power plant by 2020.

6.3.3. Transportation

For any of the above processes, the CO_2 needs to be compressed and transported for final storage: this is achieved using a pipeline, road tanker or ship. Millions of tonnes of carbon dioxide are already transported annually for commercial purposes by all of these methods: for example, the USA has forty years' experience of transporting carbon dioxide by pipeline for use in enhanced oil recovery projects.

6.3.4. Storage

Carbon dioxide is stored permanently in carefully selected geological rock formations that are typically located several kilometres below the earth's surface. The IEA has reported that four of the large-scale CCS projects currently in operation have sufficient monitoring in place to provide confidence that the injected CO_2 will be retained permanently. Globally, about 50 million tonnes of CO_2 have been stored, and nine further projects (due to be operation by 2016) will have the potential to store 13 million tonnes of CO_2 collectively [44].

The UK has a potential offshore storage capacity for 70 billion tonnes of CO_2, enough to meet the CCS needs of the UK (of up to 15 billion tonnes over the next 100 years [45].

i. Depleted Oil and Gas Fields

These are prime sites for CO_2 storage as they have been proven to retain reservoir fluids for millions of years, and a large amount of knowledge is already available about their characteristics. Potential storage capacity for over nine billion tonnes of CO_2 has been identified in depleted UK oil and gas fields, which is sufficient to store CO_2 from power plants and other industrial emitters for many decades.

ii. Saline Aquifers

There is more uncertainty in the estimation of the storage capacity available in deep saline formations, but it is certainly many times that available in depleted oil and gas fields (estimated at about 60 billion tonnes). As an example of implementation of this type of CO_2 storage, since 1996, ~10M tonnes of CO_2 have been injected into the Sleipner field in the North Sea (off Norway) and monitoring has not revealed leakage from the site.

iii. Enhanced Oil Recovery

There is also increasing interest in the use of CO_2 to achieve Enhanced Oil Recovery (EOR) and this forms a key element of some recent commercial-scale power project proposals in the UK, such as 2CO's Don Valley Power Project.

The UK is well positioned for access to both depleted oil and gas fields and deep saline formations, primarily offshore across the North Sea and the Irish Sea. A database of potential storage sites has been developed by the Energy Technologies Institute (ETI). This database is known as "CO_2 Stored" and is now available commercially via The Crown Estate (which has responsibility for the development of these sites on behalf of the UK). Figure 5 shows the location of storage sites and major emitters of CO_2 in the UK.

Deployment of 10 GW of CCS in the UK by 2030 would require an annual storage capacity of about 50 million tonnes per year (so 30GW would require 150 million tonnes capacity): to put this in context, at its peak (in 1999) oil production from the North Sea was about 130 million tonnes per year [45].

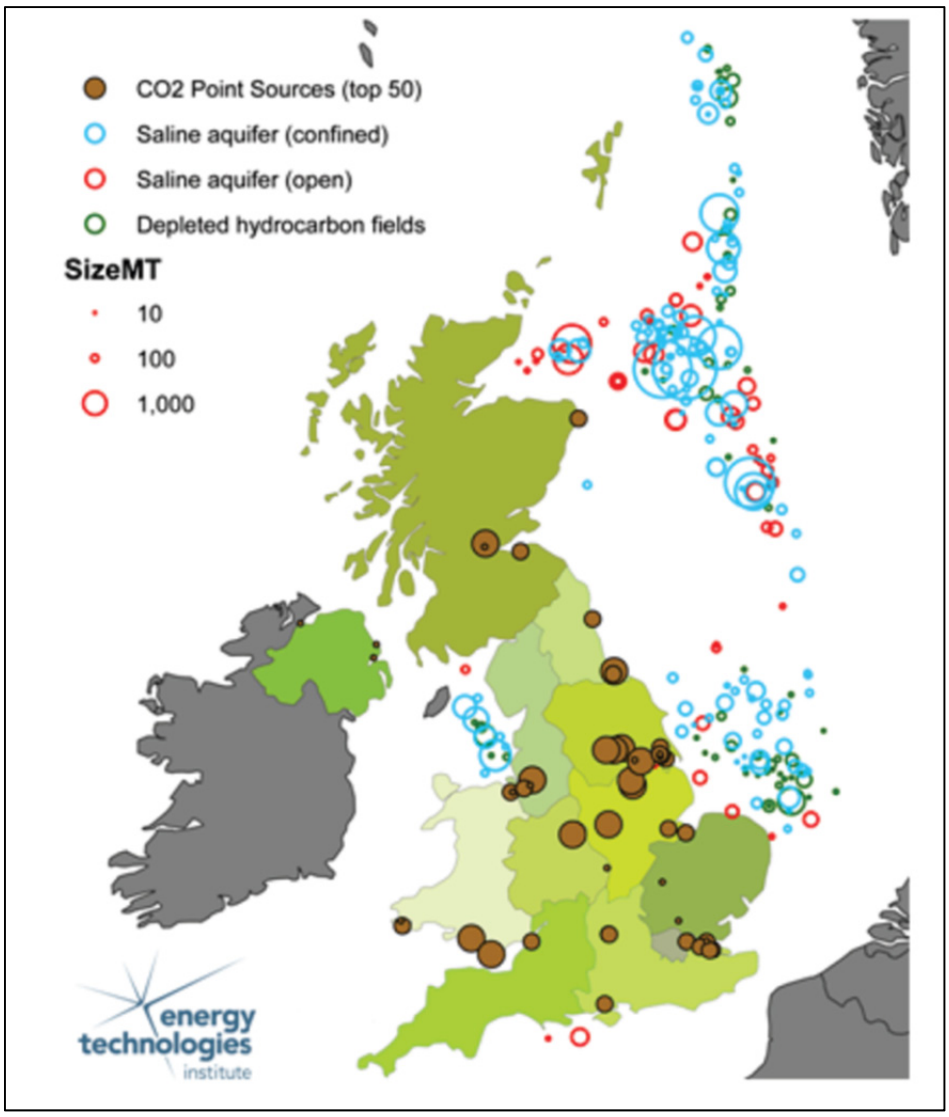

FIG. 5. Proximity of the UK's largest industrial emitters to CO_2 storage sites in the North and Irish Seas. (Source DECC CCS roadmap April 2012, map provided by the ETI)

7. IMPLEMENTATION OF CCS AND IMPLICATIONS FOR GRAPHITE GASIFICATION

7.1. Overview

CCS is expected to make a substantial contribution to reducing the UK's CO_2 emissions. In 2012, fossil fuels provided 70% of the UK's electricity and, if all of this generation was replaced by coal- or gas-fired generation with CCS, the emissions from power generation would be reduced by about 90%. Clearly, if the proportion of generation by nuclear and renewables increases, then the proportion of the reduction in emissions attributable to CCS will be reduced.

A UK target of 20-30GW capacity of CCS electricity generation on a mix of coal and gas by 2030 is compatible with the recommendations of the UK Committee on Climate Change to decarbonise the electricity system by 2030 and the ambitions for the UK published in the strategy of the Carbon Capture and Storage Association (CCSA) [44]. This level of ambition is consistent with the scenarios published in the new International Energy Agency (IEA) Roadmap for CCS [45], which envisages 30 projects globally by 2020 (50Mt of CO_2 stored per year), over 2,000Mt.a^{-1} stored by 2030, and over 7,000Mt.a^{-1} by 2050. The IEA Roadmap makes clear that as long as fossil fuels and carbon-intensive

industries play dominant roles in our economies, CCS will remain a critical greenhouse gas reduction solution.

Although the public response to CCS in the UK is uncertain, we note that CCS is quite benign in its impact: power plants may be somewhat larger, pipelines onshore will be virtually invisible like (but not by any means as extensive as) the high-pressure gas network, and injection (especially offshore) is unnoticeable. A recent (July 2013) initial public consultation regarding the proposal to build the UK's first full chain CCS project in North Yorkshire resulted in 76% in favour and 5% opposed to the plan.

7.2. Cost of CCS

CCS adds significantly to the cost of fossil fuel fired power generation, but these costs compare favourably with other low carbon generation and it is important to note that CCS allows Greenhouse Gas emissions targets to be met at a substantially lower cost than is achievable by other means. The IEA states [44] that CCS could reduce global carbon dioxide emissions by 19%, and that fighting climate change could cost 40% more without CCS [46]. Similarly, the UK's ETI Energy System Model ESME indicates that, without CCS, the costs of achieving the UK's carbon reduction targets will increase by £ 42 billion per year (2010 figures [47]).

The government's CCS Cost Reduction Task Force submitted its final report in May 2013 [48], and concluded that:

> *"UK gas and coal power stations equipped with carbon capture, transport and storage have clear potential to be cost competitive with other forms of low-carbon power generation, delivering electricity at a levelised cost approaching £100/MWh by the early 2020s, and at a cost significantly below £100/MWh soon thereafter."*

Comparison of the levelised costs of low-carbon electricity generation show the cost of generation by coal and gas with CCS (inclusive of capture, transport and storage) in the mid-2020s to be similar to low-carbon sources such as onshore wind and probably less than offshore wind. This simple comparison does not recognise the other cost advantages of CCS. Unlike wind, which is intermittent, CCS generated electricity does not require investment in back-up plant and, because the CCS power plants will be located at existing power plant sites, CCS does not require significant extra investment in the electricity grid.

7.3. UK Government Policy

The UK Plays a leading role in advocating a reduction in CO_2 emissions and is a strong supporter of the development of CCS as part of a suite of low carbon technologies. The government has signed the Kyoto protocol and has committed to an 80% reduction in greenhouse gas emissions by 2050.

DECC published the UK's first Roadmap for CCS in April 2012. This sets out the steps which the Government is taking to develop a new CCS industry for the 2020s, and confirms the requirements for the UK in terms of demonstration and deployment:

> *"To ensure CCS can contribute to the UK's low carbon future, the Government is taking forward a programme of interventions that aim to make the technology cost-competitive and enable the private sector to invest in CCS equipped fossil fuel power stations, in the 2020s, without Government capital subsidy. Development of cost-competitive CCS will mean that low carbon fossil fuel power stations and industrial plant can be widely deployed in the UK in the 2020s and beyond helping this country to meet ambitious carbon reduction targets at lowest cost to consumers whilst maintaining diversity and security of energy supplies."*

Actions already taken by Government include:

- The CCS Commercialisation Programme with £1 billion capital support focuses on learning by doing and sharing knowledge to reduce the cost of CCS so that it can be deployed in the early 2020s (Section 7.4). In announcing a competition to select Preferred Bidders for this programme, the Secretary of State for Energy and Climate Change said (3 April 2012) that:

  "The potential rewards from carbon capture and storage are immense: a technology that can de-carbonise coal and gas-fired power stations and large industrial emitters, allowing them to play a crucial part in the UK's low carbon future. What we are looking to achieve, in partnership with industry, is a new world-leading CCS industry, rather than just simply projects in isolation – an industry that can compete with other low-carbon sources to ensure security and diversity of our electricity supply, an industry that can make our energy intensive industries cleaner and an industry that can bring jobs and wealth to our shores."

- A £125m, 4-year, co-ordinated R&D and innovation programme covering fundamental research and understanding through to component development and pilot-scale testing; and establishment of the UK CCS Research Centre;
- Establishment of the CCS Cost Reduction Task Force (of which Costain was a member). The objective of the Task Force was to advise Government and industry on reducing the unit cost of CCS so that it can compete with other low carbon technologies in the electricity market by the early 2020s, and the final report was issued in May 2013;
- Reform of the electricity market is in hand to enable investment in low carbon power generation including developing long-term contracts which recognise the potential contribution of CCS to a balanced low carbon electricity system.

Current policy is that all new coal fired power stations in the UK will demonstrate the full CCS chain from the outset on at least 300 MW net of their total output. These plants will also retrofit CCS at full capacity in the 2020s once the technology is proven.

Both the UK and Scottish governments have introduced legal and policy frameworks to support CCS, including:

- the Climate Change Act came into force in November 2008, providing a framework to achieve a mandatory 80 percent cut in the UK's CO_2 emissions by 2050 (compared to 1990 levels).
- In October, 2010, the government announced a plan in which a combination of renewable energy, CCS, nuclear and other low-emission energy sources would satisfy over half its energy needs by 2025.
- DECC has established a new Office of Carbon Capture and Storage (OCCS). The role of OCCS includes setting the strategic path for the use of CCS, facilitating the delivery of the demonstration programme, creating the policy and support arrangements to stimulate private sector investment, and working with stakeholders to remove barriers to investment and development in the UK and globally. The DECC Roadmap for CCS outlines actions and policies.
- Scotland's Climate Change Act of 2009, sets a target of producing 80 percent of Scotland's energy from renewable sources by 2050 (nuclear is not included in the portfolio).
- The Government is currently investigating the use of an Emissions Performance Standard in the UK. Such a standard would set a legal limit on the emissions from power generation. In November 2010, the Energy and Climate Change Select

Committee concluded that there was value in the UK introducing an EPS ahead of the EU.

- In September 2010, the UK Parliament transposed some important provisions of the Energy Act of 2008 and the CCS Directive into national law. The law defines "CCS Ready" and requires all new power plants over 300MW to be CCS Ready.
- A Directive of the European Parliament sets out a legal framework for the safe geological storage of carbon dioxide and has been transposed into UK law.
- The Government is currently working with the North Sea Basin Task Force to develop common principles for managing and regulating the transport, injection and permanent storage of CO_2 in the North Sea sub-seabed.
- Currently CO_2 is not classified as a 'dangerous substance' for the purpose of the Control of Major Accident Hazards Regulations 1999 (COMAH), but it is being considered by the Health and Safety Executive (HSE). Capture plant and pipelines will be regulated under the Health and Safety at Work etc Act 1974.
- In April, 2012, the Engineering and Physical Sciences Research Council (EPSRC) and the Department of Energy and Climate Change (DECC) announced the establishment of a UK Carbon Capture and Storage (CCS) Research Centre.

7.4. CCS Programme in the UK

7.4.1. Commercialisation Programme for Power Plants

The specific challenge for the CCS industry is to demonstrate the entire CCS chain at commercial scale. This is the main driver for the UK's £1 billion CCS Commercialisation Programme, which is now underway. Following a competition and initial screening process, DECC announced (20 March 2013) that it was taking two Preferred Bidders forward. FEED contracts have now been announced for these two bidders, and these are expected to lead to the delivery of up to two full chain CCS projects. The Government's key objective for these projects is that they contribute to the deployment of cost-effective fossil fuel generation with CCS in the UK in the early 2020s.

The two projects are:

1) White Rose CCS Project

This is an oxyfuel power plant project, 450 MW in size. The main project partners are Alstom, Drax Power and BOC, with National Grid leading on the pipeline and, with partners, storage development. This project is also aiming to secure funding from the EU's NER300 competition.

2) Peterhead CCS Project

This is a project to retrofit post combustion capture to an existing Combined Cycle Gas Turbine and will be a world-first for a full chain CCS project on a gas fired plant. The plant will capture 1m tonnes of CO_2 per year for an operating period of about 10 years. The main partners are SSE and Shell.

Once these projects are under development the intention is that investment in follow-on CCS projects will be stimulated by reforms currently taking place to the electricity market that are intended to bring forward investment in all low carbon forms of electricity generation.

Given the aging state of the UK's coal-fired power stations the majority of current capacity is expected to come off line in the 2020s. If CCS technology is considered proven by 2020, the age of

the existing stations means investment in retrofit is unlikely to be justified for these stations. Consequently, opportunities at commercial scale are likely to be focussed on new-build projects.

7.4.2. CCS in Industry

CO_2 emissions from industry are similar in scale to emissions from power generation and will need to be tackled in a manner similar to that for power plants. Key industrial sectors include iron and steel, oil refineries, cement manufacture and chemical production. In many cases, CCS provides the only mitigation option for meeting climate goals since, for example, CO_2 production is an inherent part of many industrial processes and so alternative measures are not available.

7.4.3. Cluster Development

For CCS, the term "cluster" is used to describe a group of CO_2 emitters (power and/or industry) which share a common infrastructure of pipelines and storage sites.

Clusters have been proposed in Yorkshire and Humber, Teesside, Thames, the Firth of Forth and Merseyside. These are all potential locations for CCS projects and cluster development, reflecting the presence of existing power and industry emitters and the proximity of suitable storage.

Formation of a cluster requires the development of infrastructure which is larger in scale than that required to handle emissions from a single power plant. Installation of oversized pipeline capacity in the early years of CCS implementation, which future projects could use, would give significant economies of scale. National Grid has estimated that the cost of a pipeline for a demonstration project sized for transportation of 2 to 5 MTPA CO_2 would be about £350m, with the same pipeline route, but a capacity of 40 MTPA, costing about £500m [49].

7.5. International CCS Programme

Large-scale integrated projects currently in operation are removing 20 million tonnes of CO_2 annually (2011 figures). Operational projects include:

- Val Verde Natural Gas Plants (formerly Sharon Ridge) in Texas, U.S.A: operational since 1972 and capturing 1.3 million tonnes of CO_2 annually
- Enid Fertilizer in Oklahoma, U.S.A: operational since 1982 and capturing 0.7 million tonnes of CO_2 annually.
- Shute Creek Gas Processing Facility in Wyoming, United States: operational since 1986 and capturing 7 million tonnes of CO_2 annually.
- Sleipner is in the North Sea, about 160 miles west of Stavanger, Norway: operational since 1996 and injecting over 1 million tonnes of CO_2 annually.
- The Great Plains Synfuels plant and Weyburn-Midale Project in Saskatchewan, Canada: operational since 2000 and capturing 3 million tonnes of CO_2 annually.
- In Salah is in central Algeria: operational since 2004 and injecting over 1 million tonnes of CO_2 annually
- The Snøvit plant in northern Norway: operational since 2008 and, at full production, the plant has a capture and storage capacity of 700,000 tonnes of CO_2 per year.
- Century Plant (formerly Occidental Gas Processing Plant) in Texas, U.S.A: operational since 2010 and capturing 8.5 million tonnes of CO_2 per year.

When six new CCS projects go live by 2015, the amount of sequestered CO_2 will rise to about 33 million tonnes per year [50].

7.6. Implications for Graphite Gasification

CCS provides a new opportunity for the treatment of irradiated graphite. As has been noted in the previous sections, CCS is being developed for application on both coal- and gas-fired power plants and also for the treatment of emissions from industry.

The volume of CO_2 arising from gasification of all the irradiated graphite from the UK's nuclear programme will be less than 0.2M tonnes. This can be compared with a net 459 million tonnes of CO_2 generated annually in the UK in 2011, of which 182 million tonnes was from the energy sector, and 34 Billion tonnes globally [50].

As already noted, CCS requires the development of a transport and storage infrastructure. Given that this is in place, the additional volume of CO_2 to be stored from the gasification of graphite is small, and so additional transport and storage costs are likely to be low.

8. BUSINESS CASE

The business case for management of graphite by the method described in this report will need to be continually refined as the TSB Project develops and the relevant uncertainties are resolved. In particular the views of regulators and other relevant stakeholders are being sought and the consequences of addressing those views are likely to impact the business case as the project develops.

As a starting point to the discussion of the business case, the consortium partners prepared a report on the option and generated a business case in 2010 and submitted it to the NDA. An abbreviated summary of that business case now follows. It is clear that some of the aspects of the business case will need to be revised in the light of more recent information.

The primary aim of developing and then implementing gasification management of graphite is to provide a means to permit final site clearance of graphite moderated reactors (e.g. Magnox stations) in advance of the availability of a Geological Disposal Facility.

The volume reduction of graphite-related ILW waste achieved by the graphite gasification process will be about 95%. When coupled with similar volume reduction efforts for other decommissioning wastes (*e.g.* dissolution of Magnox waste, thermal treatment of organics, decontamination and recycling of metals and concrete) this would allow the waste arising from full dismantling of a Magnox power station to be stored on just a small part of the site or transported to another location or centralised facility for storage. These possibilities would allow the release of either the whole of, or a large proportion of, the site for other purposes (e.g. nuclear new build).

In order to demonstrate the potential savings (both in both cost and time), a high level business case assessment has been undertaken to compare the current baseline approach to graphite management (encapsulation and long term storage in a GDF), to that of gasification and CCS which is the basis of this technical report.

In terms of gasification costs, this covers the following areas:

- Retrieval;
- Gasification;
- CO_2 Liquefaction and Storage;
- PER and Sequestration.

A preliminary cost assessment for the above areas is included to allow comparison versus the baseline scheme and demonstrate the potential cost benefit of the gasification process.

The baseline scheme for the treatment of graphite requires a significant investment due to treatment, transport and final disposal costs. The business case discussion (see following sections) highlights the potential cost benefits in adopting a gasification strategy for the UK graphite inventory, the table below provides an initial indication as to the potential scale of these cost savings:

TABLE 3. ESTIMATED GRAPHITE MANAGEMENT COSTS (BASELINE *vs.* GASIFICATION)

	Baseline	**Gasification**
Cost Range (£M)	1915 to 2485	725 to 1520
Retrieval	Excluded	Included
Treatment	Included (encapsulation)	Included (gasification and CO_2 liquefaction)
Transport	Included	Excluded
Final Disposal	Excluded	Excluded
	N.B. It is likely that final disposal using CO_2 sequestration is cost beneficial over the incremental GDF cost for the baseline.	

The following sections provide the background and context to the figures in Table 3 above. Further work is required to refine the business case cost data to ensure that an equitable comparison is being made between both options, particularly regarding transport costs. However, the cost comparison above is compelling enough at this stage to justify the further work that will support a more robust business case.

8.1. Baseline Assessment

Graphite inventory data has been extracted from the summaries of material content and site data sheets in the 2007 UK Radioactive Waste Inventory [5]. Of particular relevance here was the information regarding container type, which in general were 4m boxes for reactor graphite. The graphite inventory has been extracted and summarised on a 'per site, per stream basis', however, 'rolled up' figures in the following categories are presented in Appendix A:

- 'MAGNOX North' FED Graphite (Hunterston A)
- 'MAGNOX South' FED Graphite (Berkeley)
- 'MAGNOX North' Reactor Graphite (various sites)
- 'MAGNOX South' Reactor Graphite (various sites)
- NDA Miscellaneous (various sites)
- AGR Fuel Stringer Graphite (various sites)
- AGR Reactor Graphite (various sites)

Cost data has been extracted from the 'MAGNOX South' Basis-of-Estimate Package for Final Site Clearance. Using the data relating to building and decommissioning encapsulation facilities together with ILW waste management operations (treatment, transport and storage), unit costs have been derived on a '4m box' basis. This has also been extrapolated by factoring to a '3m3 box' basis. In summary, unit costs (£k) are:

TABLE 4. UNIT COSTS FOR BASELINE GRAPHITE MANAGEMENT (£K)

	4m box		**3m³ box**	
	Lower	*Upper*	*Lower*	*Upper*
Treatment	268	345	91	118
Transport	45	60	15	21
Disposal	113	146	38	50

It should be noted that retrieval costs were unable to be derived from the available information. Also, it was decided to remove disposal costs from the baseline cost assessment because it was believed that the derived figures would be unfairly high on the basis that a GDF was required anyway and the incremental cost for additional storage would be much lower than the derived figure.

Refer to Appendix B for the assessment of baseline costs.

8.2. Gasification Assessment

8.2.1. Overview

The gasification process under consideration comprises the following start to finish "mainline" stages:

- Retrieval – Using nibble and vacuum retrieval;
- Gasification – Using Studsvik THOR technology;
- CO_2 Liquefaction and Transport – Using conventional CO_2 liquefaction technology and CO_2 transport adapted to suit the transport of radioactive material;
- PER and Sequestration – Using a conventional CO_2 vaporisation technology followed by injection into a future CCS scheme mixed with an appropriate quantity of conventional CO_2.

The above stages of the process all present their own challenges, for example, technology maturity, application with nuclear graphite feedstock, application in a nuclear environment, availability of final storage from a commercial and regulatory perspective.

Therefore at the start of the project lifecycle it is important to have a phase of work that addresses a number of issues where relevant across the mainline stages, for example, R&D, early regulator and other stakeholder engagement, conceptual design. This is referred to as the development and feasibility phase and allows an increased confidence prior to entering into the remaining project phases. The complete project lifecycle phases are as follows:

- Development and Feasibility;
- Front-End Engineering Design;
- Detailed Engineering, Procurement, Construction and Inactive Commissioning;
- Active Commissioning and Operation;
- Decommissioning and Relocation.

The investment in the development and feasibility phase does not tend to have a direct relation to plant throughput or physical size. Conversely, investment in the subsequent phases, which includes the actual equipment supply, tends to increase as plant throughput or physical size increases.

A development and feasibility phase alone is not sufficient to demonstrate that the technology, or combination of technologies, will perform adequately. Therefore a smaller scale 'demonstration' plant is proposed to give the necessary confidence that the technology will be commensurate with a technology readiness level (TRL) of 7-8 (a level of 9 would be achievable when trials with radioactive material have been completed successfully) whilst ensuring that cost is controlled to an acceptable level.

However, the demonstration plant will be of a scale to be relatively mobile to provide beneficial operation in dealing with a significant quantity of the graphite inventory, for example, Chapelcross, thus it is justified to offset this benefit against the cost incurred.

The 'lessons learned' and efficiencies arising following the project lifecycle for the demonstration plant will ensure value becomes integral within the larger scale plants required to deal with the significant reactor core graphite inventory.

Refer to Appendix C for an assessment of retrieval, gasification and CO_2 liquefaction costs.

8.2.2. Retrieval

The initial stage in the development of this retrieval technology was undertaken through a contact with the Electric Power Research Institute (EPRI) in the USA. The result of this work was the identification of existing industrial equipment in the market place (typically size-reduction tooling and heavy duty vacuum systems), which, when used in the correct combination can be designed to retrieve graphite from the reactor core through a process now referred to as 'nibble and vacuum'.

In addition to the design work a specification for an inactive trial was defined and costed in preparation to progress and demonstrate the viability of this approach - undertaking this trial is the next key stage in the continued development of this retrieval technique.

The costs attributed to the development of this new 'nibble and vacuum' approach to graphite retrieval are based on two main areas:

- The development of the technology itself;
- The engineering requirements for accessing a reactor core.

The 'nibble and vacuum' retrieval technique overcomes difficulties such as wedged, clamped, cracked or broken graphite blocks (due to swelling and mass loss during irradiation) and is configured to minimise man access requirements into the reactor itself and also graphite handling, external to the reactor, during the removal process, this accords with the ALARP principle.

It should be noted that there is a significant opportunity for this retrieval system to be utilised not only for the removal of the graphite, but potentially (with minor modification) for other aspects of the decommissioning of a reactor (e.g. concrete). Although the development of the ancillary uses (other than graphite) have not been costed as part of this report, but could potential provide further cost benefits downstream.

Beyond that it should also be recognised that this technique has potential application to a very wide range of intractable nuclear decommissioning problems (not just reactors). Any problem which requires highly radioactive material to be removed from a storage facility for processing and storage/disposal can potentially benefit from this retrieval technique. Although there is no attempt at this stage to address these wider opportunities just yet, the development of the technique for retrieving graphite will be an important first step.

8.2.3. Gasification

Studies for gasification of graphite have been undertaken in bench scale laboratory equipment, with very promising results. Further small scale trials are planned with UK nuclear graphite to study the optimal conditions for gasification.

Following the small scale trials, the next phase is to build a demonstration plant to optimise parameters that are not possible in a bench scale facility, for example:

- Graphite particle size to suit gasification and the retrieval process. The optimal process would be for retrieval to produce a particle size range that matches the gasification feed requirements without further size reduction;
- Outlet gas composition from gasification. This drives the capacity and performance requirement of gasification and downstream liquefaction;
- Composition and form of the solid ash arising from gasification.

A demonstration plant can then be used for demonstrating the processing of radioactive graphite in order to produce sufficient secondary solid waste, i.e. ash, for analysis to support the production of a LoC for the GDF.

8.2.4. CO_2 Liquefaction and Transport

The liquefaction process proposed is based on well-established Costain technology. The technology required is considered conventional with the focus on delivering a simple, robust process to deliver CO_2 liquid at high purity with high recovery. Liquid is produced at a temperature and pressure consistent with industrial grade CO_2, allowing hold-up in conventional standalone temporary storage tanks prior to transport off site by refrigerated tanker.

At this stage, costs for CO_2 transport have not been accounted for.

The process plant and storage tanks will be modularized for ease of construction and relocation. In addition to end of life decommissioning there will be a requirement to replace and dispose of any gas clean-up systems at regular intervals over the lifetime of the plant.

8.2.5. PER and Sequestration

Although this is a key section of the proposed gasification scheme there is no credible data available regarding the costs that will be charged by the CCS operator to dispose of the CO_2. Also, it would be a reasonable assumption that there will be a premium to be paid for disposing of 'nuclear' CO_2.

On the basis that these operating costs will probably outweigh the costs of the relatively simple storage, pumping and vaporisation equipment required at the injection point, there has been no assessment of the latter at this stage.

However, because the baseline cost assessment has excluded final disposal costs it would be unreasonable to factor in any CO_2 disposal costs until it can be done on an equitable basis.

8.2.6. Implementation

Following on from the theme discussed in Section 8.2.1 it is proposed to implement this initially as a mobile small scale demonstration plant that can provide benefit in handling some available irradiated graphite, followed by a full-scale plant that can be built at a reactor site. It would be the intention to

be able to decommission and relocate part or all of the full-scale plant to enable operation in succession at each reactor site although the practicalities of this together with the required timescales for retrieving reactor core graphite would require due consideration during the development and feasibility phase for the full-scale plant.

Table 6 below describes some of the key activities performed in each phase within the project lifecycle:

TABLE 6. PHASED APPROACH TO PROCESS IMPLEMENTATION

Project Phase	**Key Activities**
Development and Feasibility	Includes supporting R&D, optioneering, preliminary out-turn costing (+/-30%), preliminary safety report.
Front End Engineering Design	Includes the development of P&ID to Hazoped status, +/-10% out-turn costing, development of PCSR, identification of long lead equipment.
Detailed Engineering, Procurement, Construction and Inactive Commissioning	Includes all detailed design activity to allow procurement and construction of plant, finalisation of PCSR.
Active Commissioning and Operation	All operations where active materials are introduced into the plant.
Decommissioning and Relocation	Decontamination of plant and dismantling for final disposal or relocation to another site.

With the exception of development and feasibility, the above activities apply to the project lifecycles of both the demonstration and full-scale plants. The development and feasibility phase is anticipated for the demonstration plant only.

8.2.7. Options

At this stage it would not be appropriate to rule out any options, whether they are sub-options of the gasification scheme described here or other alternatives.

For example, a key option identified is having a centralised graphite gasification facility that receives nuclear graphite transported from the source sites. This may provide clear benefit in terms of safer and fewer transport movements (solid graphite vs. liquefied CO_2), particularly if located near to the CCS injection point. In addition, there is the advantage of eliminating the need to decontaminate and relocate at the end of each campaign on a reactor site.

Some additional options are presented in the mitigation steps within Appendix D - Opportunity, Risk and Mitigation Capture.

The development and feasibility phase will have an Optioneering Study and this will be a key underpinning activity for the development of the BAT Assessment and Preliminary Safety Report.

8.3. Business Case Discussion

The best way to approach the business case discussion is to consider an approach to the way that UK graphite might be dealt with using gasification. In the following discussion, baseline cost data is taken from Appendix B and the gasification cost data for both demonstration and full scale plants is taken from Appendix C.

A mobile 300 te.a^{-1} demonstration plant is used to treat 1672 te of FED graphite at Hunterston A[3]. For gasification this equates to a cost of £55.9M compared to the baseline range of £60.2M to £79M. This demonstrates an opportunity to prove the gasification concept at a cost of similar magnitude to the baseline. There are other opportunities to obtain nuclear graphite as a feed stream for the demonstration plant, for example, AGR graphite sleeves at Sellafield or research sites' graphite (*e.g.* BEPO, DIDO, and PLUTO).

The mobile plant could then be relocated to Berkeley to treat 857 te of FED graphite stored there. For gasification this equates to a cost of £18M (i.e. operating costs only) compared to the baseline range of £38.3M to £50.2M, a significant saving.

Once the gasification concept has been demonstrated, say a year into the successful operation of the demonstration plant, this would then justify the investment into a 2000 te/y full scale plant. As a worst case scenario, consider a full scale plant located at each of the Magnox and AGR sites, i.e. thirteen full scale plants, equating to a capital cost of £582.4M. The total graphite inventory across the thirteen sites is 77,500 te, equivalent to 39 operating years, giving an operating cost of £448.5M. Hence the combined gasification cost across the thirteen sites is £1030.9M compared to the baseline range of £1438.6M to £1861.4M, a significant saving.

At the other end of the scale, an alternative scenario would be to have two plants (giving approximately 20 years lifetime each) located at one of the sites or a completely new site, giving a significant capital cost saving. Here the gasification cost to deal with 77,500 te of graphite would be £538.1M, a very significant saving compared to the baseline range stated above.

The residual 19,761 te of 'NDA Miscellaneous' graphite may be able to be dealt with using the gasification facilities proposed above, equating to a cost in the range of £113.6M to £415M (i.e. operating costs only) compared to the baseline range of £379.5M to £491.5, a marginal saving which will be improved by using the full scale plant rather than the demonstration plant.

Even though it is recognised that there are other factors to be considered to ensure the comparison is made on an equitable basis, we believe that there is sufficient evidence here to justify further investigation into the cost benefits of using gasification compared to the baseline scheme.

Lastly, it should also be acknowledged that the potential savings afforded by the management of graphite by gasification which have been referred to previously in this section, are based solely on the UK situation. If this business case was expanded to cover foreign graphite waste streams, for example, that of France and Russia, then the potential savings could be even more significant.

8.4. Reduction in the UK National Liability Estimate for Dealing with Graphite Waste

Graphite waste is expected (according to baseline plans) to amount to approximately 30% of the total UK national inventory of intermediate level waste destined for disposal in the GDF. Besides the cost of actually disposing of this much material in the GDF, there are the costs of packaging and transporting all that material.

The marginal saving due to this reduction of nearly 30% in the national ILW volume for disposal may actually not be that great, since the GDF will need to be built anyway and extra space has relatively low marginal cost. However, it is possible that other volume reduction opportunities for other ILW wastes could be coupled with the savings from graphite gasification. In that case the overall reduction

[3] We recognise that this is not now perhaps the best source of material, but it serves for the purpose of this financial analysis.

in ILW volume could become more dramatic, and might ultimately lead to significant simplification in the concept of the GDF and hence cost savings.

8.5. UK Early Final Site Clearance

The original draft strategy of the NDA set as an aspiration the clearance of the Magnox sites within twenty five years. For a number of reasons, not least of which has been the understandable focus on hazard reduction at major sites like Sellafield, this aspiration has had to be delayed. The lack of a practical and available route for graphite management has been one reason for this change. It is worth repeating here the "drivers" for early final site clearance:

- Early final site clearance underpins the case for building new nuclear plants. Another even more important practical point is that completion of dismantling of Magnox reactors could release physical space for construction of new power stations. Recent land sales by the NDA adjacent to Magnox sites have underlined the financial value of the land on which the current structures reside. The same may apply in due course to the AGR stations;
- Intergenerational Equity. The current care and maintenance philosophy places a requirement on future generations to complete the job of decommissioning facilities that are this generation's responsibility. In respect of "sustainability" of the NDA' operations, this point is important;
- Release of Assets. Even where new build is not contemplated many nuclear facilities occupy environmentally important or commercially valuable land (e.g. part of the Snowdonia National Park). It is in everyone's interest to release the land for productive or amenity use and not to occupy it casually for the storage of redundant structures;
- Retention of skills. The ageing staff profile and pressure on the industry to attract and retain new recruits are well known. The technical challenge of developing and implementing technology to complete early final site clearance is exciting and appealing;
- Benefits for "UK plc." The innovative technical work required to complete early final site clearance is likely to enhance opportunities for UK contractors both at home and abroad;
- Reduced long term costs and reduction in the National Liability Estimate. Relative costs of early versus late dismantling are difficult to determine rigorously, since they depend on such factors as discount rates and future policy decisions and circumstances. However, reduced time spent decommissioning means less "hotel" costs, and it is clearly in the NDA's interest to achieve wherever possible early de-licensing of its legacy facilities.

8.6. Opportunities for UK PLC

The UK is not the only country with irradiated graphite to deal with. As has been stated elsewhere other countries also need irradiated graphite management. Some of the countries have relatively small quantities of graphite to deal with, possibly making it uneconomic for those countries to develop their own indigenous graphite management capability.

If the UK develops a capability for graphite management along the lines suggested in this report, there is a possibility that the UK suppliers can supply those same services to other countries which need them. This is a distinct advantage compared with the NDA's baseline case, because if the UK instead

follows a strategy of long in-situ delay before any graphite management takes place, there will be no short term market for such services.

9. UK DEMONSTRATION PROJECTS

9.1. Identification of Possible Projects

The concept proposed in this report is that the development of this method of graphite management should not be forced through on a short timescale by proposing urgent and short term treatment of commercial quantities of graphite. Rather it is suggested that the technology is introduced through a long period of engagement with regulators and public and then a graded programme of demonstrations in which lessons can be learned and improvements made before committing to full scale commercial processing.

There are a number of potential projects in the UK which could act as forerunners of full scale processing, they are listed here with some brief comments:

- BEPO. This was one of the first reactors in the UK, built at Harwell. Its clearance could potentially release a significant quantity of valuable land;
- DRAGON. This is the HTR reactor at Winfrith. Current plans are to decommission thie reactor by the early 2020's in support of achieving Early Final Site Clearance at Winfrith [2].
- Windscale Piles. The motivation for an early project here is not release of land, but the need to stabilise these reactors;
- Chapelcross and Hunterston Graphite. Longer-term target but which by adoption of this process could support the current Scottish position;
- AGR Fuel Sleeves. This is an AGR project which might attract funding from AGR related sources, such as the Nuclear Liabilities Fund. Demonstration of management of these sleeves could open the possibility of Early Final Site Clearance in decommissioning of the AGR's, which in turn could reduce liabilities.

9.2. Integration into International Developments

Following successful completion of EC Funded CARBOWASTE Project, there has been significant international interest in the development of a collaborative international or European project with the express aim of taking developments made under CARBOWASTE to pilot /demonstration scale. Various national demonstration projects have been defined in countries such as Spain, France and Germany which look to demonstrate key advances in the management of graphite developed under Carbowaste at an industrial scale. These approaches include the thermal treatment of graphite to support the down classification of graphitic wastes to enable final disposal waste acceptance criteria to be met, and the potential impregnation of graphite with a glass matrix to reduce significantly the potential for leaching of the volatile radionuclides associated with the waste.

The collaborative project team brought together to deliver the TSB 'From Core to Capture' Project are looking to develop the approach to graphite management from concept to commercialization during its 3 year timeline. Following successful completion of the TSB project the team is looking to undertake a UK pilot scale demonstration project to demonstrate the benefits of this approach. It is the intention of both the project team, and that of a potential funding partner that this demonstration project be part of a larger international/European collaborative project.

In support of this endeavour, Bradtec, as lead for the consortium, are working with EdF and Forschungszentrum Juelich GmbH (FZJ) to define and establish a European/International project (CarboSOLUTIONS) focused on bringing together various national approaches to graphite management. It has been proposed that the national and industrial activities on irradiated-graphite management should be confederated around a 'Programme-related R&D approach' targeting to near-term national and industrial solutions at the pilot scale. This fully coincides with the 'Horizon 2020' FP8 objectives towards programme-related logics and it is strongly recommended to take such a topic into account within the first FP8 Call. The overall funds are also based on national programmes, industrial efforts, structural funds and international activities on i-graphite management.

Establishment of this proposed project obviously takes significant time and effort, however the timelines associated with this project coming to fruition are commensurate with the timeline for completion of the TSB 'Core to Capture' project. The project team, by the end of the TSB project, are looking to be in a position where we can scope, define and implement a UK pilot scale demonstration of this technology as a core component of the CarboSOLUTIONS Project.

The benefits of this approach include the generation of interest in UK Plc's offering to both the European and International Nuclear Markets, as well as provide an alternative graphite management approach which would support the argument for Early Final Site Clearance (EFSC).

10. CONCLUSIONS AND RECOMMENDATIONS

A new method of graphite management has been proposed based on four elements

- Retrieval, using a novel retrieval methodology based on breaking up the graphite in situ and vacuuming it out of the reactor core.
- Gasification using established technology to convert graphite to carbon dioxide gas and a small volume of residual secondary waste containing the majority of the radioactivity
- CO_2 Liquefaction and Transport/Storage
- PER and Sequestration of carbon dioxide in a Carbon Capture and Storage scheme.

The proposal for gasification of graphite allows a totally different concept for radiological safety in which the two principal problem isotopes ^{14}C and ^{36}Cl are mixed with stable isotopes.

The primary aim of developing and then implementing gasification management of graphite as per this report is to provide a means to permit final site clearance of MAGNOX power stations in advance of the availability of a Geological Disposal Facility. The same arguments will probably apply to AGR when these stations are shut down.

The proposal has the potential to reduce the volume of graphite-origin intermediate level waste by 95% and save up to £2.4bn in graphite management costs.

A further programme of work is proposed to substantiate the process and its potential advantages and reduce the uncertainties and risks described above.

The business case figures presented demonstrate the potential cost benefit of applying the gasification process instead of the baseline scheme.

However, this report has been assembled using fairly high level information and it is accepted that a more detailed assessment is required to fully substantiate the business case. If this business case was

expanded to cover other graphite waste streams, for example, those of France and Russia, then the potential savings could be even more significant.

It is proposed that a development and feasibility phase should be initiated which will allow the necessary detail to be established including R&D, optioneering, conceptual design, cost estimates, programme and a quantified opportunity, risk and mitigation capture.

Subject to successful completion of the TSB project, potential funding may be available to support a demonstration project of this process on a discrete graphite waste stream, such as fuel sleeve graphite. If this project comes to fruition it will act as an enabler for the continued development of a robust modular system capable of managing the irradiated graphite arising from decommissioning activities in the short to medium term. Should this approach become BAT, then work would begin on developing the process on a larger scale to enable commercial reactor moderator graphite to be targeted.

The successful delivery and operation of the demonstration plant will give the necessary confidence in a full scale facility that can be applied to the graphite in each reactor core.

The purpose of the report is not only to provide information about this novel approach, but also to prompt a debate about the underlying principles of radiological safety that it implies. While direct burial of graphite might be made adequately safe by appropriate underpinning work, direct burial of graphite cannot match the "a priori" radiological safety of our alternative for the radionuclides carbon-14 and chlorine-36. For the other radionuclides we propose the equivalent conventional burial route anyway. The authors hold the view that the PER process output has particular merit for radiological safety.

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DEFINITIONS

AGR	Advanced Gas-Cooled Reactor
ALARP	As Low As Reasonably Practicable
ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs
BAT	Best Available Technology
BEPO	British Experimental Pile Zero-Energy Reactor
BGRR	Brookhaven Graphite Research Reactor
CCS	Carbon Capture and Storage
CCSA	Carbon Capture and Storage Association
CDG	Carriage of Dangerous Goods
CDM	Construction Design and Management
CEC	Commission of the European Communities
CEGB	Central Electricity Generating Board
CfD	Contract for Difference
CNE	Commission Nationale d'Evaluation
CO_2	Carbon Dioxide
COMAH	Control of Major Accident Hazards Regulations 1999
CoRWM	Committee on Radioactive Waste Management
CRP	Coordinated Research Programme
DECC	Department of Energy and Climate Change
DEFRA	Department of the Environment, Food and Rural Affairs
EA	Environment Agency
EdF	Electricité de France
EFSC	Early Final Site Clearance
EGP-6	Scaled down version of the RBMK reactor design
EPR	Environmental Permitting Regulations
EPRI	Electric Power Research Institute
EPSRC	Engineering and Physical Sciences Research Council
ETI	Energy Technologies Institute
EU	European Union
EURATOM	European Atomic Energy Community
FBSR	Fluidised Bed Steam Reformer
FED	Fuel Element Debris
FZJ	Forschungszentrum Jülich GmbH
GDF	Geological Disposal Facility
GGC	Graphite Gasification Condenser
GGF	Graphite Gasification Filter
GGR	Graphite Gasification Reformer
GLEEP	Graphite Low Energy Experimental Pile
HAW	Higher Activity Waste
HAZOP	Hazard and Operability
HLW	High Level Waste
HSE	Health & Safety Executive
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency

IEA	International Energy Agency
ILW	Intermediate Level Waste
INL	Idaho National Laboratory
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation. ("ISO" is not an acronym)
LAW	Low Activity Waste
LCPD	Large Combustion Plant Directive
LLW	Low Level Waste
LLWR	Low-Level Waste Repository
LoC	Letter of Compliance
LWR	Light Water Reactor
MAGNOX	Type of UK Nuclear Power Reactor, (named after the alloy used to clad the fuel rods inside the reactor)
MBR	Moving Bed Roaster
MSR	Molten Salt Reactor
MTPA	Mega Tonne per Annum
MWRS	Managing Radioactive Waste Safely (White paper, UK Government Policy)
NDA	Nuclear Decommissioning Authority
NIEA	Northern Ireland Environment Agency
NLE	National Liability Estimate
NLF	Nuclear Liabilities Fund
NLS	Nuclear Licensed Site
NPP	Nuclear Power Plant
NSIP	Nationally Significant Infrastructure Projects
NSP	National Policy Statement
NUPEC	Nuclear Power Engineering Corporation
OCCS	Office of Carbon Capture and Storage
ONR	Office for Nuclear Regulation
PBMR	Pebble Bed Modular Reactor
PCSR	Pre-Commencement Safety Report
PER	Potential Exposure Reduction
P&ID	Piping and Instrumentation Diagram
POCO	Post Operation Clean Out
PSA	Pressure Swing Adsorption
Radwaste	Radioactive Waste
R&D	Research & Development
RBMK	Reaktor Bolshoy Moshchnosti Kanalniy (a class of Russian Graphite-moderated Nuclear Power Reactor)
RGF	Roaster Gas Filter
RSA	Radioactive Substances Act
RSR	Radioactive Substances Regulation
RWA	Radioactive Waste Adviser
RWML	Radioactive Waste Management limited
SEPA	Scottish Environmental Protection Agency
SLC	Site Licence Company
SPF	Studsvik Processing Facility
THOR	Thermal Organic Reduction

TRL	Technology Readiness Level
TSB	Technology Strategy Board
UK	United Kingdom
UKAEA	United Kingdom Atomic Energy Authority
UNGG	Uranium Naturel Graphite Gaz (a design of nuclear power reactor developed by France)
US DoE	United States Department of Energy
VHTR	Very High Temperature Reactor
WAGR	Windscale Advanced Gas-cooled Reactor
$3m^3$ box	Container 1720mm square (with rounded corners) and 1225mm high
4m box	ISO style container 2438mm wide, 2200mm high and 4013mm long

APPENDIX A

TECHNOLOGY READINESS LEVEL

Definition Of Technology Readiness Levels (from http://esto.nasa.gov/files/trl_definitions.pdf)

TRL 1 Basic principles observed and reported: Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

TRL 2 Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept: Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.

TRL 4 Component/subsystem validation in laboratory environment: Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5 System/subsystem/component validation in relevant environment: Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.

TRL 6 System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space): Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.

TRL 7 System prototyping demonstration in an operational environment (ground or space): System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.

TRL 8 Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space): End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.

TRL 9 Actual system "mission proven" through successful mission operations (ground or space): Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

APPENDIX B

BASELINE COST DATA

Appendix A - Baseline Cost Summary

	Magnox North FED Graphite		Magnox South FED Graphite		Magnox North Reactor Graphite		Magnox South Reactor Graphite		AGR Fuel Stringer Debris Graphite		AGR Reactor Graphite		NDA Miscellaneous		Totals across all sites	
Site(s)	Hunterston A		Berkeley		Chapelcross Hunterston A Oldbury Trawsfynydd Wylfa		Berkeley Bradwell Dungeness A Hinkley Point A Sizewell A		Hartlepool Heysham 1 & 2 Hinkley Point B		Dungeness B Hartlepool Heysham 1 & 2 Hinkley Point B Hunterston B Torness		Calder Hall Sellafield Springfields Nexia Solutions (Sellafield) Dounreay Harwell Windscale Winfrith Culham Berkeley			
Inventory Data:																
Waste weight, te	1672		857		30816		20918		996		24770		19761		99790	
Conditioned waste volume, m^3	1500		952		28462		19855		961		24015		15579		91324	
No. of packages:																
4m box (no shielding)					1512		1054				327		107		3000	
4m box (100mm shielding)									69				421		490	
4m box (200mm shielding)											1634		215		1849	
$3m^3$ box (round corners)	568		361										1		930	
500 litre drum													355		355	
WAGR box													6		6	
Comments													Approx. 10,500 te of graphite has an unspecified container type in the NDA inventory. Therefore the above container quantities only relate to approx. 9000 te of graphite			
Baseline Cost Data:	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Unit costs, 3m3 box, £:																
Treatment	91000	118000	91000	118000	91000	118000	91000	118000	91000	118000	91000	118000				
Transport	15000	21000	15000	21000	15000	21000	15000	21000	15000	21000	15000	21000				
Unit costs, 4m box, £:																
Treatment	268000	345000	268000	345000	268000	345000	268000	345000	268000	345000	268000	345000	Insufficient data to warrant detailed analysis. However, the grand total costs indicated below have been derived from a simple pro-rata on waste weight.			
Transport	45000	60000	45000	60000	45000	60000	45000	60000	45000	60000	45000	60000				
Total costs, £																
Treatment	51688000	67024000	32851000	42598000	405216000	521640000	282472000	363630000	18492000	23805000	525548000	676545000				
Transport	8520000	11928000	5415000	7581000	68040000	90720000	47430000	63240000	3105000	4140000	88245000	117660000				
Grand total costs, £	60208000	78952000	38266000	50179000	473256000	612360000	329902000	426870000	21597000	27945000	613793000	794205000				
Grand total costs, £M	60.2	79.0	38.3	50.2	473.3	612.4	329.9	426.9	21.6	27.9	613.8	794.2	379.5	491.5	1916.5	2482.0

APPENDIX C

GASIFICATION COST DATA

	Demonstration Plant		Full Scale Plant	
Capacity	300 te graphite/y		2000 te graphite/y	
	Capital	Operating	Capital	Operating
	£M	£M/y	£M	£M/y
Retrieval	1.5	1.0	2.9	5.0
Gasification	16.8	4.6	36.0	5.1
CO_2 Liquefaction	2.5	0.7	7.0	1.4
Total	20.8	6.3	45.9	11.5

Notes

1. Decommissioning and relocation costs are excluded.
2. Transport costs are excluded.

APPENDIX D

RISKS, OPPORTUNITIES AND MITIGATION CAPTURE

Appendix C - Opportunity, Risk and Mitigation Capture

Risk / Opportunity	Root Cause of Risk / Opportunity (Cause) As a result of....	Risk / Opportunity Event (Impact) There is a risk / opportunity that....	Impact Description (Consequence) Which may result in....	Mitigation Plan Details
Opportunity	the application of the nibble and vacuum process.	the removal of graphite from the reactor cores can be performed with less complexity and greater efficiency.	increased safety and reduced costs and timescales.	N/a
Opportunity	the application of gasification and CO_2 sequestration.	the management of graphite can be decoupled from the availability of the GDF.	earlier FSC and less reliance on inter-generational support.	N/a
Opportunity	the application of gasification and CO_2 sequestration.	there is a significant reduction in ILW waste requiring treatment and disposal.	reduced costs and required storage capacity for GDF.	N/a
Opportunity	the application of gasification and CO_2 sequestration.	the treatment of problematic and labile isotopes ^{36}Cl and ^{14}C can be improved.	improved radiological safety.	N/a
Opportunity	the development of the nibble and vacuum, gasification and CO_2 sequestration process.	this could enable the UK to be an international leader in application of this technology.	demonstration of commitment to 'UK plc' nuclear credentials.	N/a
Opportunity	the availability of graphite fuel element debris.	early but limited funding for a demonstration plant using a readily available feedstock could be justified.	the ability to achieve a technology readiness level of 9 for this process to give the necessary confidence in application for reactor core graphite.	N/a
Opportunity	the application of the nibble and vacuum process.	would allow retrieval of reactor concrete.	more efficient retrieval.	N/a
Opportunity	the application of the nibble and vacuum process.	the removal of cracked, broken or clamped graphite blocks can be achieved without the use of additional retrieval methods.	reduced costs and timescales delivered through the simplified approach.	N/a
Opportunity	the vacuum transfer system.	the transfer of graphite from the reactor to the storage buffer is substantially simplified	increased flexibility in the available transfer routes, reduced dose implications, timescales and costs.	N/a
Opportunity	consideration of a centralised location for the gasification process.	the requirement to decontaminate, dismantle and relocate or provide multiple facilities at a number of reactor sites.	more efficient operation and reduced costs; reduced and possibly safer transportation requirements.	N/a
Risk	the nibble and vacuum process not working as intended.	this process cannot be used to retrieve graphite from the reactors at the desired throughput rate.	reversion to conventional retrieval methods leading to increased retrieval costs, programme delay.	The effectiveness of the nibble and vacuum process will be demonstrated during inactive trials. In the event that conventional retrival methods are used a crusher would be employed to size reduce graphite to suit downstream processing.
Risk	uncertainty in the scoping requirements for the gasification process.	gasification is not an economic process compared to the baseline scheme.	reversion to baseline or alternative scheme.	In addition to preliminary costs assembled in this report there will be a development and feasibility phase proposed to give greater confidence in out-turn costs.
Risk	regulatory or public concern regarding the use of gasification in a nuclear application with the UK.	gasification cannot gain acceptance as a viable process.	reversion to baseline or alternative scheme.	The development and feasibility phase will include engaging with relevant stakeholders to understand regulatory needs and public concerns to ensure they are appropriately managed.
Risk	the gasification process not being able to be tailored to suit the treatment of nuclear graphite, for example, achieving the desired partitioning of radionuclides.	gasification is an impractical process to be applied.	reversion to baseline or alternative scheme.	The development and feasibility phase will include the necessary underpinning R&D work to demonstrate the viability of gasification.
Risk	end-user, regulatory or public concern regarding sequestration of 'radioactive CO_2' into a CCS scheme.	there is no final destination agreed for the 'radioactive CO_2'.	reversion to baseline or alternative scheme.	The development and feasibility phase will include engaging with relevant stakeholders to understand regulatory needs and public concerns to ensure they are appropriately managed. Other options to be considered, for example, removal of ^{14}C, production of carbon black, solidification as CaCO3, discharge to marine environment as dissolved carbonate.
Risk	CCS technology not being implemented.	there is no final destination agreed for the 'radioactive CO_2'.	reversion to baseline or alternative scheme.	The development and feasibility phase will include engaging with relevant stakeholders to understand regulatory needs and public concerns to ensure they are appropriately managed. Other options to be considered, for example, removal of ^{14}C, production of carbon black, solidification as CaCO3, discharge to marine environment as dissolved carbonate.
Risk	a lack of available funding.	the potential benefits of applying this technology will not be fully identified and exploited.	a lost opportunity to reduce the National Liability Estimate for dealing with NDA legacy facilities.	To work in close collaboration with the NDA in a phased stage-gated manner to identify scope, cost and risks with an appropriate level of surety to release funding to proceed to a subsequent phase of work.
Risk	a delay in releasing funding.	development opportunities will be missed, for example, the use of Hunterston A FED graphite.	alternative sources of active graphite to be sourced to provide adequate demonstration of technology.	Other graphite sources are available (excluding Magnox and AGR core graphite) which may be able to be utilised instead.