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CARBOWASTE

Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste

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- Summary Report on Work Package 1 -

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Summary Report on Work Package 1
Publishable summary

A collaborative European Project 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (Carbowaste)' was launched in May 2008 under the 7th EURATOM Framework Programme. The aim of the project is to develop best practices in the retrieval, treatment and disposal of irradiated graphite including other i-carbonaceous waste such as structural material made of graphite, non-graphitised carbon bricks and fuel coatings (pyrocarbon, silicon carbide). Emphasis has been given to legacy irradiated graphite as this currently represents a significant problem that will have to be addressed in the short and medium term.

The project includes a comprehensive analysis of the key stages from in-reactor storage through to final disposal, with regard to the most economic, environmental and sustainable options. Six technical work packages cover the breadth of the issues addressed by the CARBOWASTE project:

- Integrated waste management approach (Work Package 1);
- Retrieval and segregation (Work Package 2);
- Characterisation and modelling (Work Package 3);
- Treatment and purification (Work Package 4);
- Recycling and new products (Work Package 5); and
- Disposal behaviour (Work Package 6)

Work Package 1 has successfully developed an integrated waste management approach for irradiated graphite. The approach has been developed by carrying out the following tasks:

Task 1.1 – Review the existing strategies and technologies for the waste management of i-carbonaceous materials and identify key issues;
Task 1.2 – Identify the end points for each key stage of the in-reactor storage to disposal route;
Task 1.3 – Identify gaps in knowledge base that impact on Tasks 1.1 and 1.2;
Task 1.4 – Review and select MCDA tools/methodologies and identify high-level objectives;
Task 1.5 – Undertake MCDA at key stages of the road map;
Task 1.6 – Agree assessment criteria and assess options for retrieval; and
Task 1.7 – Synthesise information between all CARBOWASTE work packages.

There has been significant interaction with the other CARBOWASTE work packages, both in terms of influencing the other work packages to provide coordination and by using the outputs from the other work packages as inputs to the analysis undertaken within Work Package 1.

The integrated waste management approach for irradiated graphite enables strategy options for the management of irradiated graphite to be evaluated using multi-criteria decision analysis (MCDA) against specific criteria and sub-criteria for each key stage of a route map defining the complete cycle of retrieval, storage, treatment, reuse/recycle and disposal.

The integrated waste management approach provides a tool that Member States can use to support their selection of the most appropriate management options for irradiated graphite, to meet their specific criteria, regulations and other considerations.

Revisions

Rev.	Date	Short description	Author	Internal Review	Task Leader	WP Leader
01	28/03/2013	Draft 1	Fowler, L NNL	Banford, A NNL	Banford, A NNL	Banford, A NNL
02	29/05/2013	Issue 1	Fowler, L NNL	Banford, A NNL [signature] Approver: Wood, M NNL [signature]	Banford, A NNL [signature]	Banford, A NNL [signature]

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1 Introduction

This report has been prepared as part of a European collaborative project "Treatment and Disposal of Irradiated Graphite and Other Carbonaceous Waste (CARBOWASTE)". It forms Deliverable D-1.0.0 Summary Report of Work Package 1. The aim of the report is to give an overview of the tasks undertaken within Work Package 1 and to summarise their outputs.

1.1 The Carbowaste consortium and project

A collaborative European Project 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (CARBOWASTE)' was launched in May 2008 under the 7th EURATOM Framework Programme. The aim of the project is to develop best practices in the retrieval, treatment and disposal of irradiated graphite including other i-carbonaceous waste such as structural material made of graphite, non-graphitised carbon bricks and fuel coatings (pyrocarbon, silicon carbide). The project addresses both existing legacy waste as well as waste from graphite-based nuclear fuel resulting from a new generation of nuclear reactors (e.g. Very/High Temperature Reactors (V/HTR)). The consortium is led by Forschungszentrum, Juelich (FZJ) in Germany and involves 28 partners from Belgium, France, Germany, Italy, Lithuania, Netherlands, Romania, South Africa, Spain, Sweden and the United Kingdom.

The project includes a comprehensive analysis of the key stages from in-reactor storage through to final disposal, with regard to the most economic, environmental and sustainable options. Six technical work packages cover the breadth of the issues addressed by the CARBOWASTE project:

- Integrated waste management approach (Work Package 1);
- Retrieval and segregation (Work Package 2);
- Characterisation and modelling (Work Package 3);
- Treatment and purification (Work Package 4);
- Recycling and new products (Work Package 5); and
- Disposal behaviour (Work Package 6).

1.2 The European graphite legacy

Across the world, graphite has been used extensively as a reflector and moderator material in over one hundred nuclear power plants, research reactors and plutonium production reactors. Indeed, according to the IAEA [1], there are over 230,000 t of irradiated graphite which will ultimately need to be managed, potentially as radioactive waste. A significant portion of this irradiated graphite is located in Europe. In the UK, for example, there is a large legacy of irradiated graphite as a result of its use in graphite-moderated gas-cooled reactors, the Magnox reactors and the Advanced Gas-cooled Reactors (AGR). Various European countries and other countries around the world also have legacy irradiated graphite. The reactors vary in size and type across Europe and include research/test reactors as well as larger base-load reactors; such as the RBMK at Ignalina in Lithuania, and the French gas-cooled reactors. Whilst some graphite has already been removed and packaged, as in the case of the Graphite Low Energy Experimental Pile (GLEEP) and Windscale

AGR (WAGR) in the UK, at other sites, the graphite remains in the reactor building. Some graphite also exists in silos/vaults.

1.3 Carbowaste Work Package 1

Work Package 1 is focused upon providing an integrated waste management approach for irradiated graphite. The participants in Work Package 1 are listed below:

Work Package 1 Participants			
UK NNL (WP Leader)	AMEC (UK)	ANDRA (France)	Doosan-Babcock (UK)
EDF (France)	ENRESA (Spain)	FI (Lithuania)	FZJ (Germany)
INR (Romania)	LEI (Lithuania)	PBMR Ltd (S Africa)	JRC (Ispra) (Italy) Joined year 3

A variety of end points need to be considered, relating to the individual decommissioning strategy/policy of each Member State. The end points will be influenced by the speed of decommissioning following the removal of fuel from a reactor and a range of other factors, including cost, treatment/disposal options and radiological impact.

The approach involves the definition of a route map for irradiated graphite with end points at key stages of the route map that are evaluated against specific criteria. This route map addresses the complete cycle, i.e. in-reactor storage, conditioning, retrieval, treatment and final disposal. Clear, definitive end points allow multi-criteria decision analysis (MCDA) to be undertaken, accounting for economic, safety, environmental and socio-political factors.

The tasks within Work Package 1 are:

Task 1.1 – Review the existing strategies and technologies for the waste management of i-carbonaceous materials and identify key issues;
Task 1.2 – Identify the end points for each key stage of the in-reactor storage to disposal route;
Task 1.3 – Identify gaps in knowledge base that impact on Tasks 1.1 and 1.2;
Task 1.4 – Review and select MCDA tools/methodologies and identify high-level objectives;
Task 1.5 – Undertake MCDA at key stages of the road map;
Task 1.6 – Agree assessment criteria and assess options for retrieval; and
Task 1.7 – Synthesise information between all CARBOWASTE work packages.

The nature of Work Package 1 is such that it has relied on significant interaction with the other work packages, both in terms of influencing the other work packages to provide coordination and by using the outputs from the other work packages as inputs to the analysis undertaken within Work Package 1.

The approach defined within Work Package 1 will help inform Member States in their selection of the most appropriate management options for irradiated graphite to meet their specific criteria and considerations. Emphasis has been given to legacy irradiated graphite as this currently represents a significant problem (Section 2) that will have to be addressed in the short and medium term.

1.4 Structure of this document

Following this introductory section, Sections 2 to 8 provide summaries of the work conducted under Tasks 1.1 to 1.7. Concluding remarks are presented in Section 9. Section 10 provides a list of references for this report.

2 Review existing strategies and technologies for waste management of i-carbonaceous materials (Task 1.1)

Task 1.1 consisted of a review of information relating to the strategies and technologies associated with the management of irradiated graphite internationally [2]. The review considered the challenges associated with the management of irradiated graphite and provided an overview of the situation and strategies under consideration in member states and other countries as of 2009 (shortly after the start of the CARBOWASTE project). Updates to these positions are provided in italics within Section 2.3, where information is available.

2.1 The irradiated graphite challenge

The challenge associated with the integrated waste management of irradiated graphite is summarised in Figure 1. Nuclear graphite is first manufactured and formed into components for nuclear applications, such as graphite bricks, fuel sleeves and fuel compacts. However, the graphite components formed contain impurities. Once in a reactor, the graphite components are exposed to radiation. As a result of reactor operation, these components will potentially have associated activation products from manufacturing impurities and through contamination by transported material in the circuits. The presence of these radioactive materials then complicates any future operations, be it retrieval, treatment, storage, disposal or recycle/reuse.

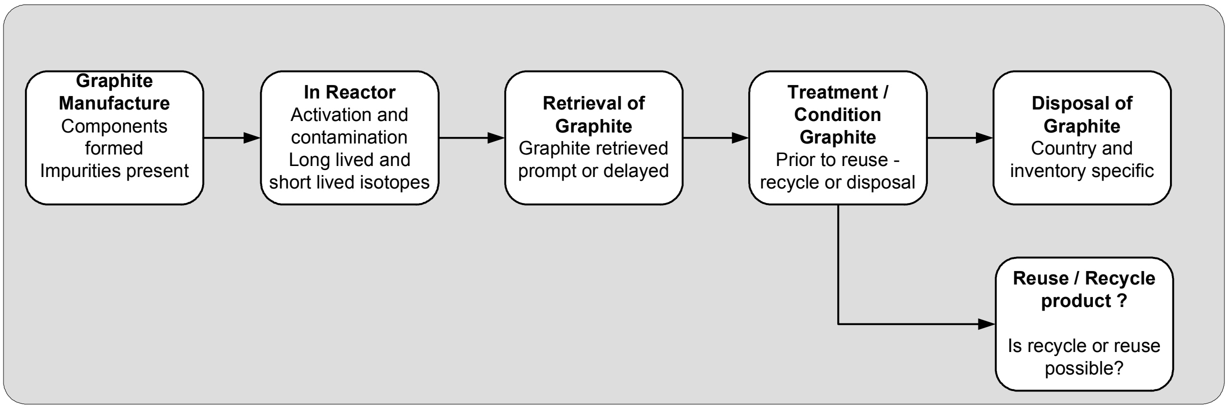

Figure 1. Irradiated graphite management

2.1.1 Graphite inventory

As previously noted, the IAEA [1] has estimated that the total quantity of irradiated graphite worldwide is over 230,000 t. This graphite has been used in a range of nuclear reactors, including the large power-producing reactors such as the gas-cooled reactors in France, the UK's Magnox and AGR stations, and the Russian-built RBMKs. Furthermore, graphite has been used extensively in a number of plutonium production reactors, research reactors, Material Testing Reactors (MTRs) and prototype/experimental reactors (for example, High Temperature Reactors (HTRs)). The graphite is present in a range of forms and geometries, depending on the reactor and fuel design. Within Europe, the largest quantities of graphite are associated with UK, French and Russian design reactors.

2.1.2 Retrieval of graphite

Graphite has been retrieved from a number of reactors world-wide. The most significant experience to date has been gained from decommissioning Fort St Vrain in the US, GLEEP at Harwell in the UK and WAGR at Windscale, also in the UK. The reactor at Fort St Vrain was a HGTR design and the graphite was removed under water, to provide shielding for the dismantling operations. An alternative approach was used in the UK with retrieval of graphite from WAGR being carried out dry but remotely. The GLEEP reactor, which was of a smaller size and lower radiation dose, was also dismantled in air but conditions allowed a more manual approach to be adopted.

The current position regarding dismantling of reactors varies both from country to country and from reactor to reactor. The current contrasting baselines in the UK and France illustrate the point. The current UK strategy delays reactor decommissioning to take advantage of the decay of short-lived isotopes, reducing the complexity of remote operations, whereas the strategy in France is for prompt (relative to the UK strategy) decommissioning.

The retrieval and segregation of graphite, including HTR fuel coatings, has been considered in detail in CARBOWASTE Work Package 2.

2.1.3 Treatment of graphite

The treatment of irradiated graphite may be desirable for many reasons:

- to reduce dose to workers;
- to reduce volumes of waste for disposal;
- to achieve the radiological requirements for disposal; and
- to facilitate recycle or reuse of isotopes or graphite.

A wide range of treatments has historically been considered [1]. These treatments range from immobilisation through to incineration.

Immobilisation using a range of encapsulants, including cement, polymer, resin, sand, bitumen, glass, metals and ceramics, has been considered and evaluated for the disposal of graphite. In the UK, the WAGR graphite has been immobilised in cement and is now stored awaiting disposal. A similar immobilisation approach is planned for graphite when retrieved from Bugey (France), although other options remain under consideration.

Thermal processes have also been widely investigated for the treatment of irradiated graphite, ranging from furnace incineration to steam pyrolysis. The goal of such an approach would be a dramatic reduction in waste volume. However, the associated challenges of separation of radioactive gases, disposal of ash and the difficulty of burning graphite must also be noted.

The CARBOWASTE project has considered the treatment of graphite in Work Package 4, with specific consideration of physical, chemical and microbiological processes.

2.1.4 Recycle - reuse

Recycling and reuse of graphite are addressed specifically in CARBOWASTE Work Package 5. It is, however, worth noting that recycling of material (either graphite or separated isotopes) will depend heavily on demand and cost. Notwithstanding this, material has been recycled from the nuclear industry into mainstream use, one example being the reuse of aluminium recovered from the redundant Capenhurst gaseous diffusion plant in the UK.

2.1.5 Disposal

Options for the disposal of irradiated graphite are influenced by many factors including radioactive inventory, volume, waste form, timing and, not least, by the availability of a suitable storage facility with its own associated waste acceptance criteria. The aims of any pre-treatment and conditioning of waste must be consistent with the disposal requirements. This is an area where local infrastructure, policy and regulation vary from country to country. Work Package 6 within the CARBOWASTE project has been addressing issues associated with disposal.

2.2 Nuclear graphite – properties and related issues for its management

Issues associated with irradiated graphite, which may need to be considered in the context of its management, have been identified, based on background information on the manufacture of nuclear grade graphite, its properties and the way in which these properties may change when the material is exposed to a nuclear reactor environment.

A number of processes exist for the preparation of polycrystalline carbons and graphites with a wide range of crystalline perfections and properties. Nuclear grade graphite has been manufactured from cokes produced as a by-product of the petroleum industry, from natural pitch sources and also from naturally occurring graphite (for example, Gilsonite). The choice of coke, binder and impregnation materials, together with the forming and final heat treatment processes can produce a wide range of properties and will affect behaviour under irradiation.

The process for the manufacture of nuclear graphite involves:

- sourcing of raw materials;
- calcination;
- forming;
- baking;
- pitch impregnation;
- graphitisation;
- purification; and
- graphite testing.

The primary raw materials for the production of nuclear graphite are calcined coke, coal tar binder and impregnation pitches, softening agents, wetting agents and lubricating oils. Cokes from different sources give powders with various crystallite morphologies and sizes. The properties of the final graphite matrix are strongly dependent upon the source of the coke.

Purification of nuclear grade graphites is important for minimising neutron absorption. Particularly important in this respect is boron, which has a very large neutron capture cross-section for the reaction B-10 (n, α) Li-7. The problem can be overcome by either selecting very pure coke sources (for example that used for UK Pile Grade A (PGA) graphite) or by including a purification stage in the production process. Halogens (chlorine gas or freons) have been used to purify graphite for nuclear use. The purification process can lead to some undesirable side effects, as the final graphite product may contain some residual amounts of either molecular chlorine or chlorofluorocarbon (CFC) and possibly residual BCl_3. On irradiation, the production of Cl-36, with its extremely long half-life, can have implications for decommissioning and disposal.

The irradiation of graphite within a reactor can potentially lead to three types of change in the material. In addition to affecting operation of the plant, these changes may also subsequently impact upon dismantling, handling of the material during decommissioning, treatment and disposal. The processes associated with these types of changes are:

- damage caused by fast neutron irradiation leading to physical, mechanical and thermal property changes;
- chemical changes produced by the irradiation chemistry leading to physical, mechanical and thermal property changes; and
- activation of impurities and transported materials deposited in the graphite pores leading to induced radioactivity.

These processes are described in the following subsections.

2.2.1 Irradiation damage

When a fast neutron collides with a carbon nucleus, while passing through a nuclear graphite, atoms are knocked out of their lattice positions and interjected into the immediate surroundings. Property changes due to irradiation damage could affect dismantling options. In particular, dimensional change will lead to the distortion of components which could affect disassembly.

One further significant effect arising from irradiation damage is the accumulation of Wigner energy by the displacement of carbon atoms into higher energy state interstitial positions. The higher the irradiation temperature, the lower will be the amount of stored energy. At all irradiation conditions, a saturation point may be achieved in terms of the total amount of stored energy for long periods of irradiation. The stored energy is capable of release if the material is heated above its irradiation temperature. An increase of 50K above the irradiation temperature is sufficient to achieve a significant energy release rate. This issue may affect treatment options.

2.2.2 Radiation chemistry effects

If the graphite is exposed to an oxidising environment (i.e. air or carbon dioxide), the rate of oxidation of the graphite is greatly increased by ionising radiation. This has significant implications for gas-cooled reactors operating with carbon dioxide based coolants. In helium cooled reactors, impurity levels in the gas will determine the extent of oxidation rather than any effect on rate by ionising radiation.

Exposure of graphite to carbon dioxide in the presence of gamma radiation results in radiolytic graphite oxidation. Increases in porosity due to radiolytic oxidation, causing an enlargement of graphite pores, result in a decrease in strength, elastic modulus and thermal conductivity and an increase in thermal resistivity. These property changes may affect dismantling and treatment options.

A second radiation chemistry effect specific to carbon dioxide cooled reactors is the production of reactive forms of carbon from minor components of the coolant gas, principally through the polymerisation of carbon monoxide. These reactive forms of carbon are deposited within the graphite pores near the surface of components, although some are found throughout pore structures. The significance of these deposits is their chemical reactivity in air (which is up to 10^3 times greater than that of graphite). The presence of carbon deposits may influence ways in which waste graphite is treated due to the exothermicity of the reaction with air and the potential release of containing radionuclides.

2.2.3 Activation of impurities and transported materials

Activation of impurities and of transported materials from elsewhere in the reactor (for example, corrosion products) deposited in the graphite is largely brought about through interactions with slow neutrons. Although graphite used in nuclear plant is extremely pure, residual impurities undergo neutron activation, producing radioisotopes including Co-60, Fe-55, C-14, H-3, S-35 and Cl-36.

The major C-14 producing neutron activation reactions in a nuclear reactor are the N-14 (n, p) C-14 reaction, O-17 (n, α) C-14 reaction, and C-13 (n, γ) C-14 reaction. A large fraction of the C-14 in the CO_2 coolant (of a carbon dioxide cooled reactor) is due to the N-14 reaction. Whilst nitrogen impurities arise during the graphite manufacturing process, impurities in the coolant gas can make a significant contribution. O-17 will originate from the CO_2 coolant.

C-14 is the dominant contributor to graphite activity once short-lived isotopes have decayed (>50 years post closure). The distribution of this isotope approximately follows the thermal neutron flux. Within a graphite block, the isotope is more likely to be present near the surface as most originates from the coolant. C-14 is retained in the graphite and associated carbon deposits primarily as elemental carbon, on surfaces, with some oxygen being associated with it.

The sources of tritium are lithium impurity in the graphite, and the fission process in the fuel followed by diffusion through the fuel cladding and absorption by graphite from the coolant. Halogens (chlorine gas or freons) and halide salts used to purify graphite for nuclear use are the sources of Cl-36. If halide salts are used as the source of the graphite purifying reagent (chloride or fluoride salts) then these will first melt and then vaporise (e.g. the boiling point of lithium, sodium, and potassium chlorides all lie in the range 1380 - 1440°C, and give off molecular metal halides, more accurately described as ion-pairs.

These may react with the boron present as impurity in the graphite to give the BCl_3 molecule. All the chlorine bearing species (metal chlorides, chlorine molecules, BCl_3, CFCs) are gaseous at the production temperature but on cooling the metal chlorides (if any persist) would first liquefy and then solidify. These gaseous species can also become physically adsorbed on to the graphite surface.

Isotopes with relatively short half-lives build up to a steady state level during reactor operation and can be expected to decay relatively quickly after end of generation (for example, Co-60 with a half-life of 5.3 years and H-3 with a half-life of 12.3 years). Such isotopes present a short-term hazard for decommissioning and their presence is a major argument to support a period of ‘safe storage’ in the reactor before dismantling activities commence. Other isotopes such as C-14 and Cl-36 have long half-lives (5,760 years and 308,000 years respectively) and their presence and mobility require consideration when choosing dismantling, treatment and storage options (noting that a long half life usually implies a low specific activity).

2.2.4 Irradiated nuclear grade graphite properties

Significant changes in graphite properties can arise from exposure to irradiation and to an oxidising environment. Graphite properties, for which changes may be of particular interest in decommissioning and graphite waste management, are:

- mechanical properties (strength, Young's modulus, fracture toughness);
- thermal properties – thermal conductivity and stored energy;
- dimensional change;
- oxidation characteristics; and
- radioactivity.

Further details on the changes to graphite properties that can arise from exposure to irradiation are provided in [2].

2.3 Overview of irradiated graphite management internationally

The following provides an overview of the situation in 2009 regarding irradiated graphite and its management internationally (European countries are presented first and then other countries). Updates to these positions are provided in italics, where information is available.

2.3.1 France

In France, irradiated graphite represents about 23,000 t, originating mainly from UNGG (Uranium Naturel Graphite Gaz) reactors (Gas Cooled Reactors). Most of the irradiated graphite lies in shutdown reactors except for small quantities of graphite sleeves temporarily stored in silos. EDF and CEA, who were the operators of the nine UNGG reactors from the 1960s to the 1990s, are the main producers of irradiated graphite in France. For all nine UNGG reactors, the IAEA level 2 decommissioning status has been achieved.

In 2001, EDF took the decision to achieve IAEA level 3 decommissioning status before 2025 for all the six EDF UNGG reactors, including three other shut down reactors without irradiated graphite (Chooz A, the first French Pressurised Water Reactor (PWR); Brennilis, a heavy water moderated reactor; and Superphenix, a fast breeder reactor). This strategy aims:

- to show the feasibility of total dismantling on an industrial scale;
- to show the capability to manage all the generated material and wastes;
- to take the opportunity to set up and to organise an internal decommissioning body (EDF Ciden in Lyon); and
- to be able to take in charge, when it occurs, the future decommissioning of the operated PWR, based on the case of Chooz A.

This strategy can also be considered as a response to the French Nuclear Safety Authority, which pointed out the risk of losing information about a shuttered plant over longer periods.

The UNGG Bugey 1 reactor is intended to be the first UNGG reactor to be dismantled. The decision was taken by EDF that the dismantling works would be done underwater, mainly because the shielding afforded by the water would enable a more “hands on” approach to be adopted rather than a fully remote operation. It is considered that it allows a greater flexibility to respond to unforeseen technical problems during dismantling. *Graphite retrievals from Bugey are now planned to commence in 2018.*

French irradiated graphite waste from UNGG reactors are considered as Low-Level activity waste but because small amounts of two long-lived radionuclides (C-14 and Cl-36) are present, their disposal at the existing Centre de l’Aube surface repository site for Low-Level and Short-Lived waste was not considered to be acceptable at the time (2009). A new repository site for irradiated graphite is to be commissioned. The design, licensing, construction and operation of this new disposal facility for irradiated graphite fall under the responsibilities of ANDRA, the French national radioactive waste management agency.

The preliminary irradiated graphite radiological inventory has been assessed from the highest measured values for each radionuclide among the numerous samples that have been analysed. This method led to an overestimated radioactive inventory used for preliminary studies on disposal. A new method based on data assimilation and activation calculation is being developed by EDF. Its objective is to provide a more realistic inventory for safety studies on disposal that is able to explain the variation in radionuclide measurements that has been observed depending on the sample localisation.

Concerning studies on graphite waste disposal, a major focus has been on the behaviour of long-lived radionuclides (C-14 and Cl-36) in irradiated graphite leaching experiments. It has been shown that the C-14 leaching rate is very low. These results are consistent with EDF activation calculation results showing that the C-14 in irradiated graphite originates mainly from C-13 activation.

The results obtained on Cl-36 leaching experiments are very variable from one sample to another. The temperature history of irradiated graphite during operation appears to be a key parameter for Cl-36 behaviour: the lower the working temperature, the higher the Cl-36 release.

2.3.2 Germany

Two helium-cooled high temperature pebble bed reactors have been built and operated in Germany. The AVR, a 15 MWe experimental reactor at Juelich was shut down in 1988 after 21 years of operation. The 300 MWe prototype Thorium High Temperature Reactor (THTR) was operated from 1985 until 1989 in Hamm-Uentrop. Both reactors are now permanently shut down and are at different stages of decommissioning. *The AVR reactor has undergone a process of temporary concrete entombment, followed by transport to a storage facility, with the long term plan of dismantlement and ex-situ decommissioning.*

The moderator graphite is an integral part of the spherical fuel elements of the AVR and THTR. Until the end of the seventies, a closed fuel cycle concept with reprocessing of the thorium-based spent fuel, similar to the US, was developed in Germany. This included the mechanical disintegration of the fuel elements, incineration of the moderator graphite, and recovery of the fissile material from the fission products by extraction. In early 1980, the Government decided to stop Research & Development on reprocessing, mainly due to economic reasons. Since then, the back-end option for the spent fuel is based upon direct disposal in a deep repository without reprocessing, thus using the special safety features of the fuel elements, i.e. the coated particle fuel stabilised in a graphite matrix, which is extremely resistant against all conceivable attacks during storage and geological disposal.

The spent fuel elements were removed from both reactors and are stored in CASTOR-type transport/storage casks in dry interim storage facilities on-site (at Juelich for the AVR) and at Ahaus (for the THTR) for up to 30 years, until a deep geological repository will be available.

Graphite and low-purity carbon were used in both reactors for reflector, thermal insulation and shielding purposes, amounting to 225 Mg (AVR) of ceramic materials in total and about 550 Mg in the case of the THTR. A radiochemical characterisation of the AVR ceramic materials was performed, leading to, for example, C-14 levels between 100 kBq/g for graphite and 9 MBq/g in maximum for low-purity carbon.

There is also a limited amount of graphite (reflectors, thermal columns) with low activation from water-moderated research and material test reactors in Germany. A 10 MW research reactor (Merlin type) with two thermal columns was operated at Juelich for 23 years and decommissioned to greenfield. 11 Mg of irradiated graphite with a medium C-14 activity of 71 Bq/g are being stored at Juelich waiting for disposal.

A 23 MW heavy-water material test reactor (DIDO) was operated at Juelich for 45 years and shut down in 2008. The irradiated graphite from reflector and thermal columns amounts to 30 Mg.

2.3.3 Italy

Although Italy has constructed 4 commercial reactors, only one (Latina) was graphite moderated. All of these commercial reactors are now shut down. It is estimated that about 2,100 t of irradiated graphite will arise from the decommissioning of the Magnox-type Latina reactor. The radionuclide composition of the irradiated graphite has been based on predictions that are similar to the UK's Magnox reactor values. Ten experimental/test reactors have also been constructed with about half of these still in operation.

2.3.4 Lithuania

Ignalina Nuclear Power Plant (INPP) is Lithuania's only nuclear power plant. Two RBMK-1500 type Soviet designed reactors (water-cooled graphite-moderated channel type reactors) are installed at INPP. These reactors are different from those operating in Russia.

In accordance with National Energy Strategy adopted by the Lithuanian Parliament, the first unit of INPP was shut down at the end of 2004. The shut down of the second unit was scheduled for the end of 2009. The Lithuanian Government has approved the immediate dismantling concept for the decommissioning of the first power unit of INPP. The INPP graphite waste consists of shattered graphite sleeves originating from spent fuel channels and CPS channels, of graphite bricks and sleeves resulting from decommissioning. Estimated quantities of graphite waste to be dealt with are 55 t of operational waste and 3788 t of decommissioning waste (graphite bricks and sleeves for the 2 units).

It was planned to conduct, by 2005, the necessary investigations and draft recommendations on the construction of a near-surface repository for low and intermediate level short-lived radioactive waste. In addition, as part of the radioactive waste management strategy, it was planned to operate Solid Waste Management and Storage Facilities (SWSF) by 2010. The design lifetime of the SWSF will be 50 years.

According to the INPP Final Decommissioning Plan, graphite waste will be stored in non-shielded containers placed in the Interim Storage of SWSF for long-lived waste, regardless of its radionuclide composition. The waste in the containers will be stored without grouting. The design life of the containers is 50 years.

The Lithuanian waste management agency (RATA) interim waste acceptance criteria show that the INPP graphite waste does not meet the criteria for near-surface disposal due to the C-14 inventory (criterion for intrusion scenario is satisfied, but for long term migration from the repository site is largely exceeded). Disposal of graphite waste should occur, after further treatment/conditioning, in a repository for long-lived waste, in cavities at an intermediate depth or in a deep geological repository.

2.3.5 Russia

In total 15 water-cooled graphite-moderated power reactors (11 RBMK-1000 and 4 EGP-6 reactors) are being operated in Russia. Three first-generation water-cooled graphite-moderated reactors (AM reactor in Obninsk and 2 AMB reactors at Beloyarsk NPP) are permanently shut down. In 2006, Rosatom stated that it was considering lifetime extensions and upgrading of its eleven operating RBMK reactors. Following significant design modifications made after the Chernobyl accident, as well as extensive refurbishment including replacement of fuel channels, a 45-year lifetime was seen as realistic for the 1000 MWe units. The Leningrad Nuclear Power Plant is the oldest one. The reactors were put into operation between 1974 and 1981. The oldest reactor received a 15-year prolongation of its engineered life span in 2004. It is assumed that the best strategy for handling graphite during decommissioning of the power-generating units of a nuclear power plant with uranium-graphite reactors is localisation and long-term storage of the graphite bricks/components together with the reactor in a concrete shaft at the plant site under surveillance. In 1998 a unique experiment on withdrawing of the graphite column from reactor RBMK-1000 of Leningrad NPP Unit 3 was performed. The graphite column (all 14 graphite bricks) was withdrawn from cells 12-36, after 18 years of reactor operation, for long scale investigation of graphite brick (GB) behaviour and estimation of methods of graphite core dismantling.

Thirteen high-capacity weapons plutonium production (industrial) reactors were in operation in Russia. The decommissioning concept for these reactors was developed in the mid 1990s, comprising the dismantling of low-activity structures, sealing of all reactor outlets, and filling of all reactor spaces with special compounds of concrete and bentonite. All these arrangements ensured multi-level protection with a number of safety barriers between the reactor and the environment. At that time a question about the possible reactor dismantling was not raised. The reactor shaft was intended to be transformed into the everlasting radwaste repository. The in-shaft waste disposal concept came into conflict with new waste disposal regulatory documents (NP-055-04, NP-069-06, GOST R 50996-96) so instead of disposal in the reactor shaft, a monitored safe storage period was defined. Therefore, the general scheme of decommissioning for these reactors (“storage” on site) is:

- preparatory period – reloading of the spent nuclear fuel;
- localisation of the stack in the shaft with additional protective engineering barriers;
- period of long-term storage (100 or more years) with monitoring and supervision of the reactor; and
- possibility for the dismantling of the reactor after long-term storage.

The decommissioning concept 'termination on site' for uranium-graphite reactors has been implemented in the Russian Federation for the I1, E2 and ADE3 reactors, with the capability to dismantle the rest of the equipment at the same time. A system of protective barriers (multi-level protection) was being developed in order to avoid environmental pollution from disposed radioactive waste and to protect the other reactor components from external natural or technical influences. A special monitoring system has been provided for the inspection of storage parameters, including measurements of temperature, humidity, gas composition, radioactivity, and location of support metal structures. A system of special environmental drill holes is provided on the site for inspection of the conditions. Unique technologies and equipment were developed for dismantling some of the structures and for the safe and successful performance of all works. As a result, the suggested decommissioning concept allowed qualification of the structure under the IAEA's Stage 2 and ensured its safety for over 300 years.

Results of detailed experimental investigations of the radioactive contamination of graphite bricks/components in the commercial reactors have shown that:

- About 500 samples have been taken from the graphite stack of the I-1, ADE-3 and EI-2 reactors and assayed. Contamination of these samples with radionuclides H-3, C-14, Cl-36, Co-60, Ni-63, Sr-90, Ba-133, Cs-134, 137, Eu-152, 154, 155, Pu-238, Pu-239, 240, Am-241, 243, Cm-244 and some others have been determined.
- It was discovered in this study that the dominant activity in the graphite is C-14, and its distribution in the graphite stack is a reflection of the thermal neutron flux. The concentration of C-14 in the graphite from this Tomsk reactor was about 6 times higher than in the graphite from a similar Hanford reactor. A significant fraction of the C-14 activity in reactor graphite was indeed due to the presence of nitrogen in graphite (nitrogen cover gas).
- The tritium content in the reactor graphite has been measured, and the content appeared to be very small (about several hundred times smaller) than predicted. H-3 is distributed non-uniformly in the graphite stack.
- The dominant fraction of the Co-60 concentration in reactor graphite is due to the presence of the original Co-59 impurity in graphite.

As indicated already, the concept adopted in Russia for the storage of the graphite bricks/components of the graphite reactors is *in-situ* isolation from the environment for about 100 years. As such , there has been little development of technologies for the treatment of the irradiated graphite. However, there has been consideration of the problems associated with the management of graphite sleeves that are under storage in different storage facilities at the reactor sites, and where, during maintenance periods, significant amounts of the graphite from graphite bricks were retrieved and replaced with new ones. There have been a few main areas of focus in the development of technologies for management of irradiated graphite in Russia:

- methods to establish engineering barriers for the long-term storage of graphite in the form of solid radioactive waste (storage of irradiated graphite in special containers);
- methods of graphite chemical transformation for the purpose of the separation of the dose-generating isotopes and the reduction of volumes for further storage;
- treatment of the irradiated graphite; and
- incineration of the irradiated graphite.

2.3.6 Spain

There are two graphite-moderated reactors in Spain, Vandellos 1 a 460 MWe commercial reactor and a material test reactor JEN-1. The isotopic composition of the graphite sleeves from Vandellos 1 and the thermal shielding of JEN – 1 have been reported. The C-14 content of the sleeves is significantly higher than the shield material. This trend is true for all other isotopes measured.

In addition to the irradiated-graphite in these two reactors (2,700 t) more than 1,000 t reside in 3 silos. *Retrieval of irradiated graphite from the Vandellos silos has been completed.*

2.3.7 UK

Graphite has been used extensively in the UK nuclear programme, in experimental/production/prototype reactors (8), Magnox stations (11) and AGR stations (7). Of the base-load reactors, one Magnox reactor (at Wylfa) and all the AGRs remain in operation, whilst the remaining Magnox stations are shut down awaiting decommissioning, in line with the UK “safestore” approach. This approach is expected to include a 70 to 80 year delay period prior to irradiated graphite retrieval.

The UK irradiated graphite inventory is large, with a total of over 80,000 m^3 forecast to arise. It is planned that most of this graphite will be routed to geological disposal.

The UK has practical experience of decommissioning graphite reactors gained from work on GLEEP at Harwell and the prototype AGR at Windscale (WAGR). In both cases, graphite was retrieved from the cores in air, although the higher radiation associated with WAGR required a higher degree of remote handling.

A significant quantity of irradiated graphite exists in vaults/silos, mixed with other waste types.

2.3.8 Other European countries

Although Belgium, the Netherlands, Romania and Switzerland have invested in nuclear reactor development, the likely combined arisings of irradiated graphite represents a small proportion of the total quantity for Europe. Consequently information regarding graphite characteristics is sparse but may be expanded when decisions are taken to decommission the three/four demonstration reactors, some of which are still in operation.

The criteria for retrieval, possible treatment and disposal that these countries will need to consider could have many similarities with considerations that will be examined by other European countries that have invested in graphite-moderated reactors.

2.3.9 Asia

China currently has numerous research reactors that may contain small amounts of graphite, with the exception of HTR-10 which contains about 65 t. As HTR-PM reactors come on line, the graphite waste inventory will increase significantly. The first pair of HTR-PM reactors will contain about 1000 t of graphite. North Korea has now closed the 5MWe Pyongbyon research reactor. No reference to the volume of graphite for this plant has been found. The second 50MW reactor, similar to a Magnox reactor, was not completed but the volume of graphite would have been significant, but is not irradiated.

2.3.10 Japan

Japan is in the process of decommissioning the Tokai-1 power station, a graphite-moderated reactor of Magnox design. This was Japan's first commercial nuclear power plant and ceased generating at the end of March 1998, after 32 years of operation. Tokai-1 is the first commercial nuclear power plant to transfer to the decommissioning stage in Japan. The project therefore has important roles for demonstrating the safe and economical decommissioning of a nuclear power plant and establishing key technologies for future reactor decommissioning in Japan. Graphite represents a significant element in relation to the challenge of the Tokai-1 decommissioning project.

In addition to the Tokai-1 plant, a High Temperature Test Reactor (HTTR) has been commissioned more recently.

There are two main strategies under consideration as a final disposition for graphite:

- packaging for direct disposal in a geological facility; and
- incineration with subsequent treatment of off-gas to reduce levels of the long-lived radionuclide C-14.

When examining the option of packaging for direct disposal, it was found that by judicious cutting of some of the blocks and placing the pieces in free space within and between blocks, a much better packing factor could potentially be achieved, leading to a smaller number of waste packages being required.

2.3.11 South Africa

European nations possess various quantities of irradiated graphite from reactors past and present. As such, the primary interest for these countries is strategies for managing the material they have or expect in the near term. South Africa has been a partner in the CARBOWASTE project due to its involvement in Pebble Bed Modular Reactors (PBMR). This has offered a different perspective regarding graphite in fuel and structural materials with respect to its post-irradiation management. because of the relatively early stage of the PBMR. Although the PBMR concept has since been abandoned in South Africa, South Africa has continued to share knowledge about its graphite waste minimisation research with the CARBOWASTE project, in particular, offering results of experiments performed to prove the concept of microbial treatment of irradiated graphite to remove radionuclides, especially C-14.

2.3.12 USA

There are 34 nuclear reactors listed in the Department of Energy (DOE) inventory as having graphite incorporated into the design. However, only twelve of these reactors contain (or contained) significant volumes of graphite: the Hanford production reactors, the Brookhaven Graphite Research Reactor, the Peach Bottom experimental high temperature gas reactor and the decommissioned Fort St Vrain high-temperature gas-cooled reactor. The amount of irradiated graphite in the US is estimated to be approximately 15,000 t of graphite based upon volumes of material from these sites.

There are two approaches to decommissioning in the US, depending upon whether the nuclear plant is within the commercial sector licensed by the Nuclear Regulatory Commission (NRC) or is managed by the US DOE. In the case of plant under the jurisdiction of the NRC, three methods for decommissioning are available: DECON (immediate dismantlement), SAFSTOR (facility maintained to allow decay of radioactivity, later followed by dismantlement) and ENTOMB (entombment and monitoring). The DOE approach covers transition, deactivation, surveillance and maintenance and decommissioning.

Decommissioning of US nuclear reactors containing graphite includes the dismantlement of the Fort St Vrain plant under DECON, the dismantlement of the SR 305-M Test Pile at Hanford (DOE jurisdiction) and the decommissioning and burial on site of the CP-2 (formerly Chicago Pile 1 and under DOE jurisdiction). The graphite from the fully decommissioned Fort St Vrain reactor is now stored on a DOE site. *Decommissioning of the Brookhaven Graphite Research Reactor is complete*. At present, the US has no plans for the treatment of irradiated graphite, with disposal as Low Level Waste on DOE sites being the favoured approach.

2.4 Carbon dioxide and sequestration

Specific consideration was also given in the review to capture and sequestration of carbon dioxide (carbon capture), since the treatment technologies for removing C-14 could give rise to the liberation of carbon dioxide.

There has been an extensive, international, scientific and engineering effort on the development of CO_2 sequestration technologies over the past few years. Significant progress on the development and, in some cases, demonstration of the technologies for the capture, processing and storage of the CO_2 emitted from large fossil fuel power plants, has been made. The key pre- and post-combustion CO_2 scrubbing technologies and the oxy-fuel combustion technologies, and the techniques for the purification of the CO_2 to the desired quality for further on-site processing, are reasonably well understood and are largely proven at small pilot plant and component testing scale. There are projects, both planned and under way, aimed at the construction and testing of demonstration scale plants. All of the currently available CO_2 capture technologies have significant cost and energy efficiency penalties, however, in parallel with the technology demonstration activities, significant development projects aimed at incremental improvement of the existing state of the art, and at the development of alternative technical approaches, are also in progress.

There are a number of ongoing projects in the North Sea, in Canada and in Algeria, which involve the large scale handling and geological storage of CO_2. The experience of these carbon capture and storage projects are in addition to the fairly extensive experience of the large scale use of CO_2 for enhanced oil recovery in the Texas oilfields, which has been practiced since the 1970s. Further developments of these technologies, and of ocean storage and other relevant options, are under way.

It is clear that the destructive thermal processing of irradiated graphite will be carried out at a much smaller scale, perhaps at a combustion rate of the order of one tonne per hour or so. It is likely that the most appropriate approach to the destructive thermal processing of graphite will involve combustion at high temperatures in a fluidised bed or grate-fired combustor, with natural gas or oil for light-up and possibly for combustion support purposes.

The relatively modest scale of operation of graphite combustion will also mean that the large-scale transport and storage technologies being developed for carbon capture and storage will not be relevant whilst some of the smaller scale mineral carbonation or industrial utilisation options for the CO_2 may be more relevant.

3 Address end point for each key stage of the in-reactor storage to disposal route (Task 1.2)

Task 1.2 involved the development of a route map [3] consisting of a hierarchical document that identifies the key stages and issues that must be considered to enable an informed irradiated graphite waste management option to be selected. The route map is specific for irradiated graphite management and therefore is only one contribution to the process of decommissioning nuclear reactors.

The route map has several pathways, or 'roads', that can achieve the required end-points[1] as shown in Figure 2. Information, data and knowledge are required for each key step. Some of this will be generic[2] for all key steps whilst other information will be specific[3] for the particular step.

It is conceivable that some key steps can be by-passed as the disposal options can accommodate this approach. It is important to note that it is essential to identify the disposal options and then consider the upstream stages.

The route map that was developed is not a stand alone decision-making activity. The route map needs to be used in conjunction with the MCDA (Tasks 1.4 and 1.5) and the information obtained from the review undertaken within Task 1.1. Together, the review and the route map has been used to identify the key factors and information that will influence any waste management strategy for irradiated graphite and to identify key gaps in knowledge that have subsequently been researched by other participants in the project. The MCDA provides the approach for identifying the most appropriate options (Section 6).

The steps in the route map, as shown in Figure 2, are presented in Sections 3.1 to 3.6. For each step, the information that is required, the contributions that need to be undertaken and the outputs obtained are described.

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[1] End-points are criteria such decommissioning policy and radiological considerations that affect decisions/considerations; for example, decommissioning policy that requires reactors to be fully decommissioned in 25 years.
[2] Generic considerations would include environmental, social and economic considerations.
[3] Specific information would include, for example, market opportunities for the re-use/recycle step.

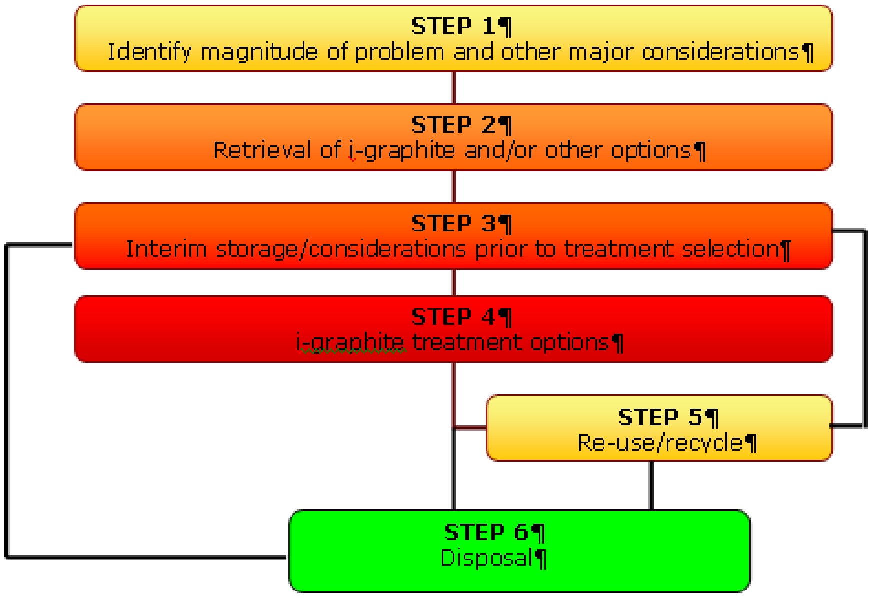

Figure 2. Irradiated graphite route map – Level 1

3.1 Identify magnitude of problem and other major considerations

STEP 1
Identify magnitude of problem and other major considerations

INTRODUCTION

This information is fundamental to all key stages of the route map.

INFORMATION

Reactor/Graphite history

1 Quantity of graphite involved
2 Disposition
3 Closure date of reactor
4 Decay period
5 Graphite irradiation history
6 PIE data
7 Origin of graphite
8 Reactor type
9 Reactor operational history
10 Fuel failures and other reactor perturbations
11 Reactor operational atmosphere

Offending radionuclides

1 Nuclides that will impact on:
[a] storage in-situ/ex-situ
[b] retrieval/removal
[c] treatment
[d] recycle issues
[e] disposal

Other considerations

Non radioactive species
Organic mater

Wigner energy

CONTRIBUTIONS

Information needed to allow:

1 estimate of degree of radioactivity of graphite
2 neutron activation products based on original impurities levels
3 residual activity due to delayed storage

The above will impact on decommissioning strategy, radiological, environmental considerations and cost.

H-3, C-14 and Cl-36 will have major implications to disposal options
Other neutron activation products such as ^{60}Co, depending on delay storage option (25, 50 or 75 years) will impact on decommissioning options.
Other isotopes resulting from fuel manufacturing routes for HTRs will also need consideration for decommissioning stages.

OUTPUTS

Understanding the importance and quality of the information/data available and knowledge gaps that need to be addressed before the next step in the routes map can be considered.
Waste disposal options.

3

3.2 Retrieval of irradiated graphite (i-graphite) and/or other options

STEP 2
Retrieval of i-graphite and/or other options

INTRODUCTION

Information from the previous step and considerations here will allow various options including retrieval to be examined.

INFORMATION

Contributory impacts	Confirm major issues
1 Physical/chemical properties of i-graphite from other materials	1 Reactor and graphite core designs and other relevant design/construction details
2 Potential methods of removal	2 Need to segregate i-graphite
3 Other materials e.g. thermocouples, securing wires	3 Agree mode of dismantling
4 Implications of reactor design on graphite retrieval	4 Consider radiological implications, time constraints, and costs etc
	5 Waste arisings
	6 Examine environmental impact

CONTRIBUTIONS

During this step major radiological and physical/mechanical graphite properties will have been considered and their impact on selection of graphite retrieval from the reactor or other options. Radiological and environmental impact assessments will have been undertaken.

OUTPUTS

Candidate retrieval and/or other options identified.

3.3 Storage considerations

STEP 3
Storage considerations

INTRODUCTION

Storage covers both buffer storage prior to treatment or other options and as an interim strategy prior to final disposal. The buffer store will allow any fluctuations in treatment to be accommodated. It will also allow treatment options to be considered (desk-top studies) prior to making preliminary selection or even if treatment is the preferred option. Interim storage may be needed if i-graphite has been removed from the reactor before a final disposal route is available.

INFORMATION

Agree environmental targets/end points

1 Identify environmental thresholds for waste options e.g. vLLW, LLW, ILW
2 Correlate threshold values with quantity
3 Examine current routes for disposal
4 Determine excess quantity requiring treatment
5 Climate change implications on decommissioning
6 Duration of material storage

Assess decontamination factors required for various end-points

1 Calculation of DF values needed to achieve the various disposal options for C-14 and other radionuclides

Other considerations (storage)

1 store boundaries
2 graphite/container interactions

CONTRIBUTIONS

Process technology evaluations will prioritise options most appropriate for further consideration
The determination of DF values will provide an indication of efficiencies required and whether the task appears practical.

OUTPUTS

Boundary conditions of potential C-14 decontamination processes identified.
Boundary conditions for storage.

5

3.4 I- graphite treatment options

STEP 4
I-graphite treatment options

INTRODUCTION

The treatment options will have to satisfy numerous criteria not least cost, environmental impact and socio-political considerations. Treatment and final disposal of secondary wastes/effluents generated from the i-graphite treatment process will be crucial to its acceptability.

INFORMATION

Review technologies capable of achieving required DF[4]

1 Consider if proven technologies can achieve the required DFs
2 Subsequent considerations of experimental/novel techniques
3 Consideration of timeframes for technology implementation

Identify key issues of candidate technologies

1 Identify waste/effluent arisings from candidate processes
2 Consideration of other process considerations such as:
- manpower needs
- radiological considerations
- energy requirements
- modular technology
- footprint
- other environmental issues
- flexibility of process

Secondary waste treatment options

1 select treatment with:
[a] no/low waste generation
[b] high efficiency
[c] flexibility
[d] proven technology

Waste arisings from candidate option

1 Identify all final wastes/ effluents
2 assessment of volumes/ quantities
3 prioritise severity of wastes
4 opportunities for recycle

Environmental impact assessment

1 environmental assessment of all waste/ effluent arisings from candidate process

CONTRIBUTIONS

The evaluation of current proven separation technology can be undertaken using calculated DF values. If existing technology is not capable of achieving the DFs required with single/dual pass system then novel/experimental stage technology could be considered. In this case risk, time to demonstrate and cost of commercialisation need to be considered.

Assessment of waste/effluents and their degree of treatment difficulty will be paramount to the final selection of the candidate treatment process

Treatment of wastes/effluents arising from the treatment of i-graphite will contribute to sustainable solution

OUTPUTS

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[4] DF is the ratio of C-14 present in graphite to the quantity acceptable for disposal

6

3.5 Re-use/recycle

STEP 5
Re-use/recycle

INTRODUCTION

Re-use/recycle may complement disposal. This will depend on the market opportunities for re-use/recycle and on the radioactivity that can be accommodated by users. Other issues such as cost of re-use/recycle etc will need consideration.

INFORMATION

Major considerations

1 Market potential i.e. more than one user
2 Usage i.e. tes/annum
3 Radioactivity
4 Other properties that will influence costs of re-use/recycle

CONTRIBUTIONS

OUTPUTS

Market survey indicating re-use/recycle graphite is acceptable

3.6 Disposal

STEP 6
Disposal

INTRODUCTION

The disposal option will need to consider both treated and untreated i-graphite, residues from recycle and re-use options and potential wastes/residues arising from the treatment option.

INFORMATION

Waste form optimisation

Optimise with respect to:
1 activity category
2 volume
3 package size
4 treatment and encapsulation requirement
5 waste/container interactions
6 wasteform/repository interactions
7 location transport
8 public acceptance
9 national/local agreement

Disposal design

1 Near-field[1] behaviour of i-graphite
2 Radiological assessment
3 Geosphere requirements
4 Design options
5 Location geology
6 Location transport
7 Public acceptance
8 National/local agreement
9 Climate change
10 Retrievability of waste

CONTRIBUTIONS

Disposal options and final waste categories to be considered through retrieval, treatment and storage stages e.g. retrieval processes need to consider suitability of powdered graphite and impact on volume minimisation, activity segregation, treatment options, radionuclide behaviour in waste form and repository

OUTPUTS

Upper level conditions for acceptance for graphite
National variations
Sustainable waste management option for i-graphite

[1] IAEA definition of near field – the excavated area of a repository near or in contact with the waste packaging, including filling or sealing materials, and those parts of the host medium rock whose characteristics have been or could be altered by the repository or its contents.

4 Identify gaps in knowledge base that impact on Task 1.1 and 1.2 (Task 1.3)

This task involved the consideration of the following areas:

- identification of end point gaps in the data/information;
- assessment of the impact of the lack of and/or inferior quality of data/information on the project deliverable; and
- consideration if other work packages can deliver the absent information and recommend consortium modifications to work programmes.

The data requirements for the assessment of the irradiated graphite management options identified under Task 1.5 (see Section 6) were defined in [4]. The options are built around the processing stages (see Task 1.2; Section 3) of:

- retrieval and segregation;
- treatment;
- recycle; and
- disposal.

The data for each of the stages aligns with the various CARBOWASTE work packages:

- Work package 2 for data regarding retrieval and segregation;
- Work package 3 for information about the graphite in-situ inventory;
- Work package 4 for information about graphite treatment;
- Work package 5 for information about recycling of graphite; and
- Work package 6 for data about graphite disposal.

The data requirements were defined by considering the assessment criteria taken from the MCDA approach (Task 1.5; Section 6) and a generic "process stage" for irradiated graphite waste management, as shown in Figure 3, which consists of the following items:

- **Feeds**: this includes the graphite, but may also include other items needed to process the graphite, such as reagents, packages, etc. Requirements for transport must be determined.
- **Resources**: this category includes items such as power, water, concrete and steel used within the Facility to manage the irradiated graphite wastes. Also included are the resources required to construct and decommission facilities built specifically for processing irradiate graphite. In the event that a facility is shared with other waste streams, a proportion of the resources used in construction/decommissioning the facility should be determined.
- **Facility**: in addition to the resources used in constructing a facility other details, such as workforce, technology used and cost, are required across the lifetime of the facility. Also the timeline for the facility from cradle to grave is needed.
- **Effluent**: these are the emissions from the processing step after abatement.
- **Products**: the products include the processed graphite stream, but may also include other items generated as a result of processing the graphite such as spent filters. Requirements for transport must be determined.

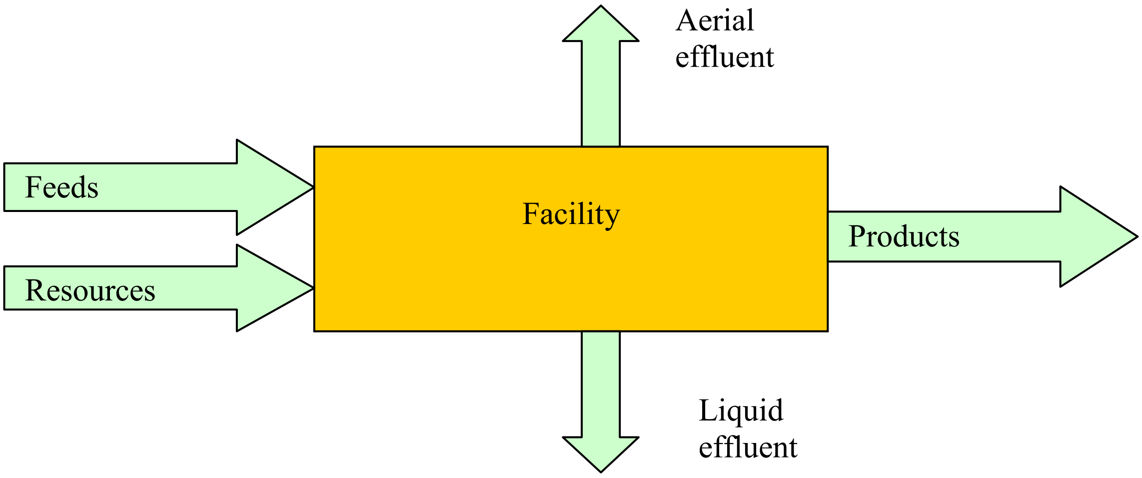

Figure 3. Process Stage

Table 1 to Table 6 present the data requirements in relation to the assessment criteria and generic process stage. In each case, all data/information items should be considered, but items which are expected to be most significant are highlighted in the tables. The data requirement for the complete waste management option is the total of the data requirements for all processing stages making up the waste management option.

Uncertainties in data/information (through lack of knowledge, information and quality of data/information) were discussed at Work Package 1 workshops. A discussion of uncertainties is included within Task 1.5 (Section 6.4).

At the Work Package 1 workshop in July 2011 [5], a review of the data available within the other CARBOWASTE work packages was undertaken. Actions were placed to obtain data that were not available at the time of the workshop. Undertaking a test assessment of the candidate waste management options supported the identification of data requirements. Discussions with the other CARBOWASTE work packages enabled the sources for the required data to be identified.

Table 1. Data requirements to assess criteria

Assessment Criterion	Data Required

Public Safety: Routine Radioactive and Non-Radioactive Discharges	• Nature of discharge (composition, phase)
	• Amount of discharge (TBq or kg)
	• Duration of discharge (yrs)
	• Either
	  ○ Specific critical group doses (mSv/TBq) AND
	  ○ Specific collective group doses (manSv/TBq)
	• Or:
	  ○ Discharge limit for each non radioactive discharge (kg/m^3)

Environmental Safety: Routine Radioactive Discharges (Non-radioactive discharges assessed above)	• Nature of discharge (composition, phase) • Amount of discharge (TBq or kg) • Duration of discharge (yrs) • Tier 1 ERICA coefficients (Bq/m3)

Environment and Public Safety: Hazard Potential	• Nature of stored material (composition, phase)
	• Amount of stored material (TBq or kg)
	• Control measures required to maintain safety
	• Either
	  ○ Effect of dose (mSv/TBq)
	• Or:
	  ○ Discharge limit for each non radioactive discharge (kg/m3)

Environment and Public Safety: Resource Usage	• Power used (GWhr) • Concrete used (te) • Steel used (te) • Fuel used (te)
Environment and Public Safety: Local Intrusion	• Number of transports per week • Impact of the transports compared to current situation (negligible – high)
Worker Safety: Radiological Safety	• Number of workers affected • Time for which workers are affected (yr) • Average dose of worker affected (mSv/yr)
Worker Safety : Conventional Safety	• Number of people at risk • >3 day injury rate per 100,000 workers per year
Security: Misappropriation	• Number of barriers preventing access to material • Time material is at risk (yr) • Amount of material at risk (TBq) • Resilience of the material to withstand a credible threat • Dose per unit exposure from ICRP72 (mSv/TBq)

Assessment Criterion	Data Required
Economic Costs	• Cost of constructing/operating/decommissioning the process (million euros)
Economic Benefits: Re-use and spinoff	• Value of reuse of materials and spin off opportunities from newly developed technologies (million euros)
Technology Predictability : Concept	• Technology readiness level of the technology to be used (TRL 1 to 9) • Cost to fully develop technology if not already mature (millions euros)
Technology Predictability : Operational	• Probability of failure affecting cost/duration beyond baseline assumptions • Impact of failure (months delay to project) • Cost of failure (million euro for repair)
Stability of employment	• Number and nature of staff required
Burden on Future Generations	• Decades until material no longer requires active management

Table 2. Data requirements associated with Feeds

Assessment Criterion	Data Required
Public Safety: Routine Radioactive and Non-Radioactive Discharges	Discharges will not typically be expected during transport of feeds, but might be possible if pneumatic or hydraulic conveying is used.
Environmental Safety: Routine Radioactive Discharges (Non-radioactive discharges assessed above)	Discharges will not typically be expected during transport of feeds, but might be possible if pneumatic or hydraulic conveying is used.
Environment and Public Safety: Hazard Potential	Hazard potential will typically not be recorded during transport. This is typically only significant for material stored for long periods.
Environment and Public Safety: Resource Usage	Some resources may be associated with the use of feeds, although these may be negligible in many cases.
Environment and Public Safety: Local Intrusion	Transport of the feed may result in disturbance of people and the environment. This is a primary concern for some transport operations.
Worker Safety: Radiological Safety	Large doses are unlikely during transport off nuclear licensed sites, but may be significant on-site.
Worker Safety : Conventional Safety	Off site transport opens up the risks of an accident
Security: Misappropriation	Materials in transit may be particularly vulnerable to misappropriation
Economic Costs	Cost of transport should be assessed, but may be very low compared to other parts of the process. Cost of key process consumables, e g. 3m^3 boxes
Economic Benefits: Re-use and spinoff	Reuse and spinoff not likely to arise from transport of feeds
Technology Predictability : Concept	In many cases the transport method will be well established, but pneumatic or hydraulic methods may be less mature.
Technology Predictability : Operational	Transport is not likely to pose significant operational problem
Stability of employment	Transport of feeds is unlikely to require large numbers of skilled workers
Burden on Future Generations	Not expected to be an issue for transport of feeds

Table 3. Data requirements associated with Resources

Assessment Criterion	Data Required
Public Safety: Routine Radioactive and Non-Radioactive Discharges	Discharges associated with the production of resources (e.g. NOx/SOx from power stations) are not considered
Environmental Safety: Routine Radioactive Discharges (Non-radioactive discharges assessed above)	Discharges associated with the production of resources (e.g. NOx/SOx from power stations) are not considered
Environment and Public Safety: Hazard Potential	Hazard potential will typically not be recorded for resources unless large quantities of hazardous materials need to be stored for an extended period.
Environment and Public Safety: Resource Usage	The amount of the resources to be used is the key issue here
Environment and Public Safety: Local Intrusion	Transport of the resources may result in disturbance of people and the environment. This is a primary concern for some transport operations.
Worker Safety: Radiological Safety	It is not expected that resources will pose significant radiological hazards.
Worker Safety : Conventional Safety	Worker safety as a result of the transport of resources should be considered; safety in producing the resources should be neglected
Security: Misappropriation	In most cases resources will not be radioactive and so this category is not relevant.
Economic Costs	Cost of resource purchase and transport should be included
Economic Benefits: Re-use and spinoff	Reuse and spinoff not likely to arise from acquisition/transport of resources
Technology Predictability : Concept	Resources are unlikely to be produced as part of the graphite waste management project, but will be acquired. In such circumstances this category is not relevant.
Technology Predictability : Operational	Ready supplies of certain materials are important, and the potential lack of specialised resources should be considered.
Stability of employment	Employment for resource production is outside the scope of the project and should not be assessed
Burden on Future Generations	Not expected to be an issue for resources

Table 4. Data requirements associated with Facilities

Assessment Criterion	Data Required
Public Safety: Routine Radioactive and Non-Radioactive Discharges	Discharges will typically be evaluated as parts of the effluents data item.
Environmental Safety: Routine Radioactive Discharges (Non-radioactive discharges assessed above)	Discharges will typically be evaluated as parts of the effluents data item.
Environment and Public Safety: Hazard Potential	Facilities with large, long-lived inventories are key facilities for the assessment of hazard potential.
Environment and Public Safety: Resource Usage	Data requirements are noted for "resources" above.
Environment and Public Safety: Local Intrusion	Construction and operation and decommissioning of a facility will generate transport (see feeds, resources and products). Additionally the impact of the facility itself on noise and visual impact is required.
Worker Safety: Radiological Safety	Operation and decommissioning of certain facilities is expected to result in the major dose to workers.
Worker Safety : Conventional Safety	Worker safety as a result of the construction , operation and decommissioning of facilities should be considered
Security: Misappropriation	Security of materials may be significant, especially if large amounts of material are stored for significant time.
Economic Costs	Cost of construction, operation and decommissioning of facilities should be considered
Economic Benefits: Re-use and spinoff	Reuse is captured in products below. Spin off of innovative technology may be possible.
Technology Predictability : Concept	Innovative processes may need extensive development; this is noted here. Cost of R&D is needed.
Technology Predictability : Operational	Some processes may be strongly dependent on the nature of their feeds and/or may be vulnerable in other ways.
Stability of employment	Employment requirements for facilities must be considered.
Burden on Future Generations	Duration of manned of facilities prior to release of the site may be significant.

Table 5. Data requirements associated with Effluents

Assessment Criterion	Data Required
Public Safety: Routine Radioactive and Non-Radioactive Discharges	This is a key issue associated with the discharge of effluents
Environmental Safety: Routine Radioactive Discharges (Non-radioactive discharges assessed above)	This is a key issue associated with the discharge of effluents
Environment and Public Safety: Hazard Potential	Hazard potential will not be assessed for effluents since large inventories will not be stored
Environment and Public Safety: Resource Usage	Resources used in scrubbing effluents will be considered.
Environment and Public Safety: Local Intrusion	Noise and visual intrusion (e.g. discharge stacks) should be considered
Worker Safety: Radiological Safety	Operating scrubbing plants may result in worker dose.
Worker Safety : Conventional Safety	Construction and operation of scrubbing plants may result in accidents
Security: Misappropriation	In most cases effluents will not be vulnerable to misappropriation.
Economic Costs	Cost of effluent treatment and monitoring should be included
Economic Benefits: Re-use and spinoff	Novel abatement techniques may have spin off applications
Technology Predictability : Concept	Novel abatement techniques may need to be considered
Technology Predictability : Operational	Vulnerability of effluent treatment systems to changes in operations and so effluent load must be considered
Stability of employment	Large numbers of skilled workers are not likely to be required unless effluent treatment is a significant problem
Burden on Future Generations	Burden on future generations will not be dictated by effluent treatment operations

Table 6. Data requirements associated with Products

Assessment Criterion	Data Required
Public Safety: Routine Radioactive and Non-Radioactive Discharges	Discharges will not typically be expected during transport of products, but might be possible if pneumatic or hydraulic conveying is used. There is the potential to account for discharges associated with key waste products
Environmental Safety: Routine Radioactive Discharges (Non-radioactive discharges assessed above)	Discharges will not typically be expected during transport of products, but might be possible if pneumatic or hydraulic conveying is used. There is the potential to account for discharges associated with key waste products
Environment and Public Safety: Hazard Potential	Hazard potential will typically not be recorded during transport. This is typically only significant for material stored for long periods.
Environment and Public Safety: Resource Usage	Some resources may be associated with the production of products, although these may be negligible in many cases.
Environment and Public Safety: Local Intrusion	Transport of the products may result in disturbance of people and the environment. This is a primary concern for some transport operations.
Worker Safety: Radiological Safety	Large doses are unlikely during transport off nuclear licensed sites, but may be significant on-site.
Worker Safety : Conventional Safety	Off site transport opens up the risks of an accident
Security: Misappropriation	Materials in transit may be particularly vulnerable to misappropriation
Economic Costs	Cost of transport should be assessed, but may be very low compared to other parts of the process.
Economic Benefits: Re-use and spinoff	Reuse and spinoff not likely to arise from transport of products
Technology Predictability : Concept	In many cases the transport method will be well established, but pneumatic or hydraulic methods may be less mature.
Technology Predictability : Operational	Transport is not likely to pose significant operational problem
Stability of employment	Transport of feeds is unlikely to require large numbers of skilled workers
Burden on Future Generations	Not expected to be an issue for transport of products

5 Review MCDA techniques (Task 1.4)

Task 1.4 has consisted of a review of MCDA tools/methodologies [6], recommendations on appropriate tools/methodologies for the CARBOWASTE project [7], and the definition of high level objectives, criteria and end points for the assessment of options (strategies) for the management of irradiated graphite [8]. There are many factors that affect and influence the selection of the best route for each waste stream and a method of rationally selecting between multiple options, each with different strengths and weaknesses, is required. A review of potential techniques for supporting decision making in the CARBOWASTE project using MCDA tools has therefore been undertaken. In addition, criteria by which options will be assessed and the most appropriate MCDA techniques to be applied to assist in selecting the best management option for a given waste stream using these criteria have been identified.

Importantly, the CARBOWASTE project is not intended to identify a single EU disposal option but to produce a unified approach that will allow each irradiated graphite management route to meet its own criteria and authorisation requirements. The aim of using MCDA techniques is to aid decision making, not to take the actual decision itself.

Various targets (end points) for an integrated waste management approach have been defined (Task 1.2). The key stages of the route map developed under Task 1.2 require analysis with regard to the most economic, environmental and sustainable options. The decision analysis is a crucial component of the CARBOWASTE project objective for an integrated waste management approach for irradiated graphite. The decision analysis enables:

- selection of disposal processes and repository conditions;
- multiple criteria comparisons of a base case option (such as disposal of all retrieved materials as encapsulated waste) to other options developed in the project; and
- sensitivity analysis of project decisions to changes in input data.

5.1 MCDA tools/methodologies

There are a number of definitions of MCDA in the literature; one definition [9] describes MCDA as:

"…both an approach and a set of techniques, with the goal of providing an overall ordering of options, from the most preferred to the least preferred option…"

The emphasis has been on legacy irradiated graphite as this currently represents a significant problem that will have to be addressed in the short and medium term.

There are a very large number of MCDA tools and techniques reported in the literature, ranging from basic 'elementary' techniques through to more sophisticated and flexible methods. The review of these tools and techniques undertaken for this task has drawn heavily on a number of previous reviews of decision-making tools and techniques, including several carried out at national and European levels. Recent EU projects that have evaluated MCDA techniques include the following examples:

- Strategic Environmental Assessment – Building Environmental Consensus (BEACON);
- Contaminated Land Rehabilitation Network for Environmental Technologies (CLARINET);
- Co-operative research on the Governance of Radioactive Waste Management (COWAM); and
- Multi-criteria Software Decision Analysis Tool for Renewable Energy Sources (MCDA-RES).

These reviews, in particular MCDA-RES, provide a 'benchmark' for provision of an MCDA tool box within the CARBOWASTE project.

The review also took account of a number of case studies in which decision-making methodologies have been applied, for example, within the UK nuclear industry in the context of Best Practicable Environmental Option (BPEO) studies; in Belgium to analyse whether low level radioactive waste should be stored at the surface or buried deep underground; and at a European level to assess the impact of partitioning, transmutation and waste reduction technologies on the final disposal of nuclear waste (within the Red Impact project).

Different MCDA approaches all follow the same basic approach shown in Figure 4, although some of the steps e.g. weighting are not always carried out.

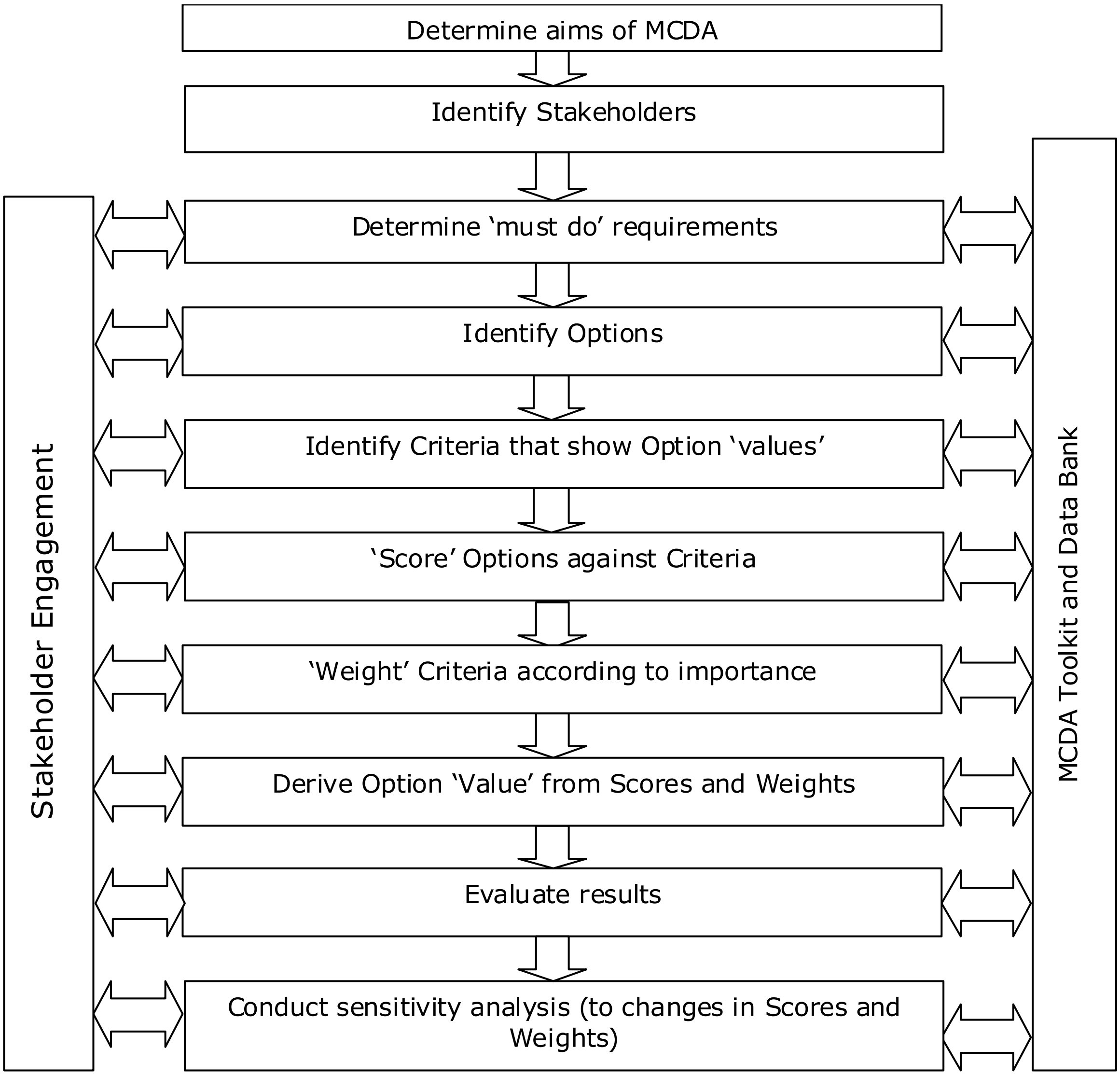

Figure 4. Generic decision-making process

Once the aim of the MCDA has been defined, the decision-making process then moves to establishing who is going to make the decision and who the stakeholders are in the decision. Stakeholders should be engaged throughout the process, particularly in the early process stages, so that their views can be captured.

The next step is to define the 'must do' requirements. Certain options may be eliminated during the decision-making process simply because these fail to meet essential criteria e.g. an upper cost limit.

Options may be pre-determined e.g. when considering different technologies to tackle a problem, or may need to be determined. In the latter case, this is typically undertaken by the decision-making team. When defining options it is important to state how each tackles the problem and what distinguishes it from other options. It is important that the start point and end point for each of the options is the same.

Criteria against which the options are to be evaluated should be carefully defined, and be:

- discriminatory between options;
- comprehensive;
- relevant;
- not repeated; and
- manageable in number.

The MCDA technique to be deployed needs to be determined at this stage because the scoring and weighting methods depend on the selected method.

Scoring of options against criteria is a means of defining the performance of the option against each criterion; weighting of each criterion allows the decision-making team to communicate the relative importance of the criteria with respect to each other.

The scoring and weighting of options can be performed using a mix of quantitative data and qualitative information. How these different types of quantities are compared and/or combined depends on the MCDA method chosen.

Evaluation of results may be a straightforward comparison of option scores; however it may also entail calculation of option scores per unit cost, or other assessment of the results. Sensitivity analysis is used to establish the impact of uncertainty in scoring and so provides a method by which the significance of differences between "values" can be determined.

Sensitivity to both scores against the criteria and weights applied should be performed. A sensitivity analysis will allow the robustness of the MCDA output to be demonstrated. The flow of Figure 4 is from top to bottom, but in reality it is not uncommon for earlier steps in the process to be re-visited in the light of new information or technologies. The decision-making team may utilise facilitation for the key steps to ensure that the process is followed correctly and that the rationale behind weighting and scoring is recorded in a transparent manner.

Rigour in following the process is important to ensure that the MCDA output can withstand challenges of being:

- biased towards particular stakeholders;
- simply a back-fit to an already determined solution.

There are two main classes of multi-criteria decision problems:

- Multi-Attribute Decision Making (MADM), where the strengths and weaknesses of a finite number of options are assessed; and
- Multiple Objective Decision-Making (MODM), where the MCDA methods themselves, sometimes using interactive computer programs, directly seek to specify what the best option should be.

As the challenge within the CARBOWASTE project has a focus on selection from a finite number of clearly defined alternatives, comparing against set criteria, the review has focused on MCDA techniques that are classified as MADM.

The many different MCDA methods are based on different theoretical foundations, such as optimisation, goal aspiration, or outranking, or a combination of these.

Optimisation

- Uses scoring of options on a single common scale which needs to be determined beforehand.
- Good performance on some criteria can compensate for poor performance against others.
- Options are scored against each criterion then aggregated into a total score which reflects overall performance.
- Research continues on multi-criteria optimisation. This work included studies on identifying the so-called "Pareto frontier", along which no further improvements can be made in performance against any of the criteria without adversely affecting performance against the other criteria.

Goal aspiration

- Uses comparison with pre-determined performance thresholds for each criterion.
- Options which exceed or are closest to these thresholds are scored accordingly.
- When it is not possible to meet all thresholds the solution can be found through the optimisation approach referred to above, through either:
    - minimising shortfalls between performance and threshold, or
    - meeting as many threshold levels as possible.
- When multiple options meet all thresholds then optimisation may be used to select between feasible candidates.

Outranking

- Compare performance of two or more alternatives at a time for each criterion.
- Ascertains preferred option through, for example, better performance against the largest number of criteria.
- Avoids the limitations of group evaluation of a number of options with significant numbers of criteria, at the same time.
- Does not need common units across criteria for scoring.
- Employs a variety of techniques for:
    - Ranking of options
    - Determining a single, preferred option
    - Eliminating options.

The main MCDA methodology groupings are described and compared in Table 7 in terms of inherent key strengths and weaknesses. It can be seen from the table that there are a number of considerations when selecting the most appropriate method, or combination of methods.

Table 7. Comparison of MCDA methods

Method	Description	Strengths	Weaknesses
Non-Compensatory 'Elementary' Methods	Range of methods which compare options against a common set of criteria without allowing any compensation between criteria i.e. strong vs. weak.	Uses elementary techniques so can be implemented rapidly.	Lack of compensation restricts application to simple cases.
Linear Additive	Option value scores are multiplied by the criteria weights and the weighted scores added.	Well established. Robust and effective on wide range of problems.	Uncertainty not formally built in (but can be appended). Variety of circumstances in which decision support is required has led to development of more sophisticated models.
Multi-Attribute Utility Theory (MAUT)	Expression of overall performance of an option in terms of a single non-monetary number representing the utility of that option. Criteria weights are often obtained by directly surveying stakeholders.	Easier to compare options whose overall scores are expressed as single utility numbers. Choice of an option can be transparent if highest scoring option is chosen. Based on utilitarian philosophy. Many people prefer to express net utility in non-monetary terms.	Maximisation of utility may not be important to decision makers. Criteria weights obtained through less rigorous stakeholder surveys may not accurately reflect true stakeholder preference. Rigorous stakeholder preference elicitations can be expensive.
Analytical Hierarchy Process (AHP)	Criteria weights and scores are based on pair-wise comparisons of criteria and options, respectively.	Pair-wise comparison is easier for the decision-maker(s) to undertake than comparing many options simultaneously.	The weights obtained from pair-wise comparisons may not truly reflect people's true preferences. Mathematical procedures used to generate summary scores can sometimes produce illogical results.

Method	Description	Strengths	Weaknesses
Outranking	One option outranks another if it out-performs the other on enough criteria of sufficient importance as reflected by the sum of criteria weights) and is not outperformed by the other in the sense of recording a significantly inferior performance on any one criterion. Allows options to be classified as incomparable.	Does not require the reduction of all criteria to a single unit. Explicit consideration of the possibility that very poor performance on a single criterion may eliminate an option from consideration even if that criterion's performance is compensated for by very good performance on other criteria.	Does not always take into account whether over-performance on one criterion can make up for under performance on another. The algorithms used in outranking can be relatively complex and may not be well understood by decision makers.
Ideal Point	Options are ranked according to their separation from ideal and nadir points.	Identifies best option quickly.	Relatively new method; not in widespread use.

In addition to the wide range of MCDA decision-making tools and methodologies, there are a number of approaches that are used in supporting MCDA. These include:

- The financial analysis tools Cost-Benefit Analysis (CBA) and Cost-Effectiveness Analysis (CEA);
- Life Cycle Analysis/Assessment (LCA), a technique for assessing the potential environmental aspects of a product or service; and
- Geographical Information Systems (GIS), used to display information on a geographic basis, e.g. for Strategic Environmental Assessment (SEA) studies.

The findings from the review of MCDA tools/methodologies are:

- there are many thousands of MCDA-related studies and reviews in the literature;
- there is no consensus favouring one particular method, each of the most common approaches have their pros and cons;
- the leading methods are based on techniques for Optimisation and/or Outranking/Dominance;
- methodologies are generally based on either multi-option or pair-wise comparison techniques;
- several techniques can allow for uncertainty in data; and
- the leading methods are supported by a range of software applications.

5.2 Selection of MCDA tool/methodology

The approach used for selection of MCDA techniques was taken from guidance available in the UK Government MCA Manual4, as it was found to cover all of the key generic selection criteria, namely:

A. Internal consistency and logical soundness;
B. Transparency (weights and scoring);
C. Ease of use;
D. Data requirements not inconsistent with the importance of the issue being considered;
E. Realistic time and manpower resource requirements for the analysis process;
F. Ability to provide audit trail; and
G. Software available where needed.

Each of the techniques was evaluated against these generic criteria. A further consideration is the context for the application of the MCDA technique as this introduces additional variables which may be site, region or country-specific. An indicative list of implementation considerations was included in Appendix 2 of [7].

The MCDA methods considered, as discussed in Section 5.1, were:

1. Multi-Attribute Utility Theory (MAUT)
2. Simple Multi-Attribute Rating Technique (SMART)
3. Analytical Hierarchy Process (AHP)
4. Outranking
5. Linear Additive
6. Ideal Point
7. Non-compensatory methods

Methods 1-5 were selected on the basis of meeting the criteria A-G above. Method 6 was deselected as it is not in widespread use. The group of methods referred to as 'non-compensatory' whilst not selected for further consideration under the main MCDA study were nonetheless identified as being useful for initial coarse screening of options. Techniques which use more input data to incorporate uncertainty in scoring and weighting such as the 'evidential reasoning' technique were not considered further as it was believed that the CARBOWASTE project would not require this level of sophistication to discriminate between options.

A key differentiator between methods 1-5 is the support software requirements (in terms of complexity), which varies from low (Linear Additive/SMART) to medium (MAUT) and high (AHP/Outranking). Detailed software requirements were therefore the focus of the next phase of evaluation of the techniques for selection. Detailed information on the evaluation is provided in [7].

From this evaluation, three MCDA methods were found to be suitable for deployment on the CARBOWASTE project, each with its strengths and weaknesses. It was concluded that:

- no single MCDA technique outperforms the others;
- three of the leading MCDA methods (MAUT (including SMART and Linear Additive), AHP and OUTRANKING) are suitable for deployment in the MCDA tool box;

- several previous (and current) EU projects have studied MCDA in depth, providing 'benchmarks' for the CARBOWASTE project; and
- software systems are available to support the methods; some of the simpler methods require minimal progamming.

5.3 Definition of high level objectives, criteria and end points

5.3.1 Objectives and criteria

A task was also undertaken to identify high level objectives and criteria for the ranking of strategy options for treating irradiated graphite using MCDA. End points were also identified for all the key stages of irradiated graphite retrieval, segregation, treatment and disposal.

The concept of achieving a sustainable solution to the challenge of irradiated graphite waste management is fundamental to the CARBOWASTE project. The three objectives or ‘pillars’ of sustainable development are commonly referred to as:

- Safety and Environmental;
- Economy; and
- Society.

These three objectives have been adopted for the CARBOWASTE project. However, they are too broad to be easily assessed, and are therefore supported by criteria and sub-criteria.

The three high level objectives are supported by seven criteria as follows:

Objective 1: Safety and Environmental
Criterion 1: Environment and Public Safety
Criterion 2: Worker Safety
Criterion 3: Security

Objective 2: Economic
Criterion 4: Economic Cost and Benefit
Criterion 5: Technology Predictability

Objective 3: Social
Criterion 6: Stability of Employment
Criterion 7: Burden on Future Generations

Each criterion is supported by a number of sub-criteria which underpin it. These sub-criteria were defined under Task 1.5. The seven criteria are described in more detail in the following.

Criterion 1: Environment and Public Safety
This criterion considers the potential for an option to have impacts on the environment. Since members of the public form part of this environment, impacts on members of the public are also included here. Workers employed on the project to deliver the option are subject to additional hazards and so are considered separately in Criterion 2.

Both regulated discharges to the environment and accidental releases are considered as part of this criterion. Releases may be radiological or non-radiological (e.g. toxic materials), or a mixture of both. Use of natural resources and impacts of operations on ecosystems are also considered here.

Criterion 2: Worker Safety
Criterion 1 above considered public safety; however the workforce will be exposed to risks over and above those borne by the public since they are working on a decommissioning site. It is therefore important that worker safety is considered to select the preferred strategy option. Both radiological (dose) and non-radiological (e.g. falls, asphyxiation) impacts are considered.

Criterion 3: Security
This criterion considers the protection afforded against deliberate, malicious actions. Two aspects are identified: protection against misappropriation of materials and vulnerability of materials and buildings to malicious, purposeful attacks. The criterion also considers any safeguards necessary to support nuclear non-proliferation.

Criterion 4: Economic Costs and Benefits
Economic factors include, at their simplest, the cost of delivering the project. This cost will be assessed over all project phases and will include the costs of research and development, design, construction, operation and decommissioning of any facility. Costs include the processing and treatment of wastes and secondary wastes formed as part of operating an option. Economics can also consider the benefits of potential spin-off work. Since time scales can be very long for the complete project, an appropriate discount rate must be selected and applied.

Criterion 5: Technology Predictability
Technology selection will have impacts on several criteria. Emissions and effluents will influence Criterion 1, the nature of the technology (e.g. hands-on vs. remote) will affect Criterion 2, capital and operating costs will influence Criterion 4. Thus, most performance measures are reflected elsewhere. However, there is uncertainty associated with the feed materials, and potentially equipment performance when it is deployed and this uncertainty results in the need for this criterion.

This criterion considers both the design uncertainty associated with untested equipment, and the flexibility and robustness of the equipment to variations in the feed and operating conditions.

Criterion 6: Stability of Employment
Nuclear power stations tend to be located in remote regions, and are frequently a major local employer. Dramatic swings in employment can therefore have significant local impacts. Closing facilities can result in high unemployment, while construction projects can stretch the local infrastructure, making life unpleasant for local residents. Managed change in employment levels allows the community time to adjust to change.

Criterion 7: Burden on Future Generations
A problem with the criteria above is that continual delay appears to be a good option: activity decays, costs are depreciated and arisings of activity are deferred and potentially reduced. However, staff experienced in the operation of the plant retire and knowledge about the nature of the wastes is lost, buildings decay and there are moral difficulties in leaving work for future generations when the

benefits of the reactor operation have been experienced by the current generation. These aspects are grouped together and assessed as part of this criterion.

A series of audit checks were performed as part of the development of the above criteria. These checks compared the criteria to relevant international legislation, principles and guidelines to ensure that the criteria reflect the full set of concerns for decision making without duplication. The audit was performed against the following sources:

- The IAEA nuclear energy basic principles [10]. These principles are intended to "provide a holistic approach to the use of nuclear energy".
- The European Commission have established a High-Level European Group on Nuclear Safety and Waste Management (ENSREG). This group have produced guidelines [11] for the content and objectives of national programmes for the management and the safety of radioactive waste and spent fuel. These guidelines set out principles for spent fuel and radioactive waste management.
- EU environment impact assessment directive 85/337/EEC[12] requires an Environmental Impact Assessment for many projects, including those aimed at storage and disposal of nuclear waste.

5.3.2 Option evaluation process

Figure 5 summarises the CARBOWASTE option evaluation process for irradiated graphite management. Following option identification, the option screening phase eliminates some options prior to detailed assessment. The application of the structure of objectives, criteria and sub-criteria within the MCDA process occurs within the assessment phase. On completion of the option assessment phase, the preferred option is selected by member states, taking into account any external factors e.g. political, which are outside the CARBOWASTE project scope.

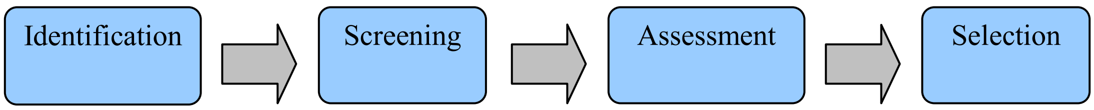

Figure 5. Option evaluation process

5.3.3 Option identification

A process of option identification is necessary at the outset in order to generate a set of options for the disposition of graphite. The options identified are discussed under Task 1.5.

5.3.4 Option screening

Options are then screened using a set of constraints (see Figure 6). These constraints are expressed as conditions which must be passed for the option to proceed further in the analysis. One example of a constraint is that options must meet all appropriate national and international legislation. Identification of constraints is also a matter for member states.

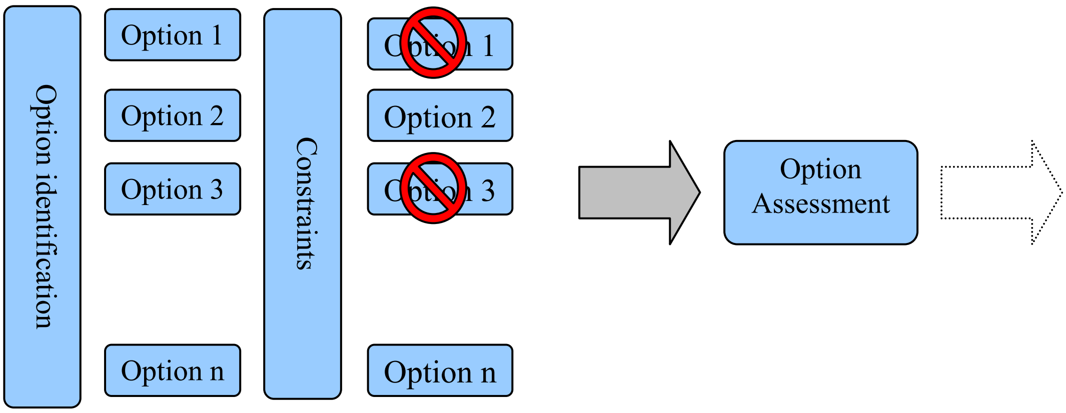

Figure 6. Option Screening

5.3.5 Option assessment

The MCDA process of option assessment utilises a ranking mechanism to derive ordering of options, with the highest scoring option being the most preferred. At each level, weightings to scores can be applied which reflect the relative importance ascribed by decision-makers to different objectives, criteria and sub-criteria.

This approach can be applied at two levels within CARBOWASTE; for strategy selection and, at a more detailed level, for technology selection for each of the key stages in the route map.

In order to facilitate such studies, it is necessary to have clearly defined end points for each of the stages (retrieval, treatment, recycle and disposal) in the route map.

5.3.6 Processing stages and end points

The definition of end points between the distinct stages in the processing of irradiated graphite can assist with the definition of options for assessment within the MCDA. The three processing stages are:

- retrieval and segregation;
- treatment; and
- disposal.

It is also essential to clearly define these stages if evaluation of technology options is to be performed using MCDA, since a meaningful comparison can only be done by considering the same start and end points for each processing stage. The processing stages and associated end points are illustrated in Figure 7.

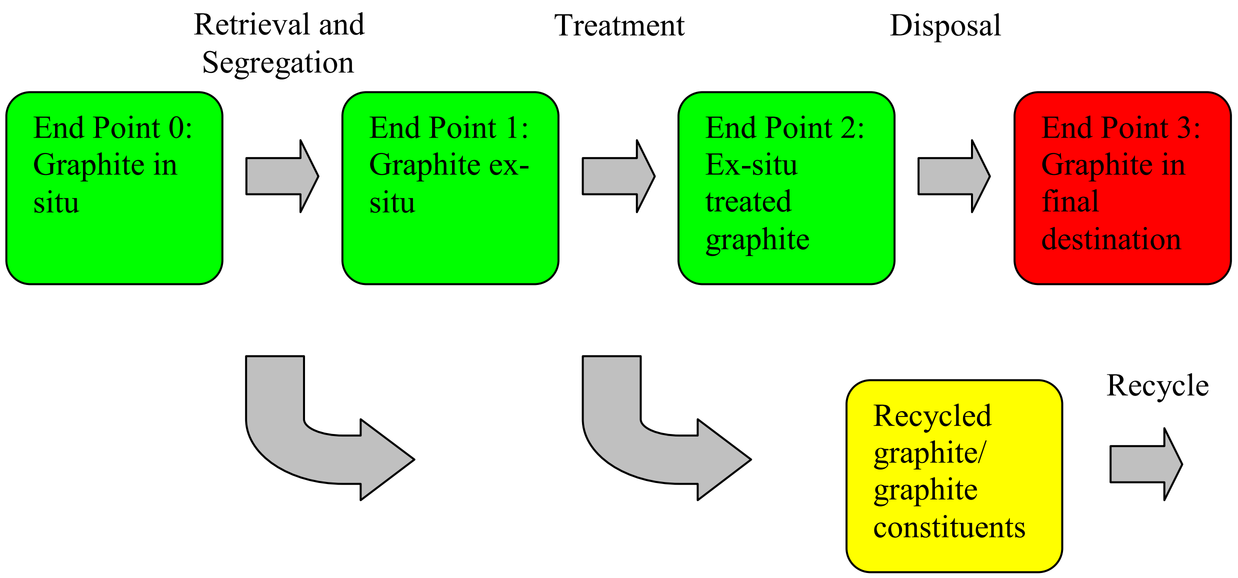

Figure 7. End Points

The end points are described further in the following.

Retrieval and Segregation: End Point 0 to 1
The processing stages commence with the irradiated graphite in the reactor core, or in storage facilities. This is *END POINT 0: Graphite in-situ*. After a delay period of 0, 25, 50 or 75 years (these periods have been selected in the CARBOWASTE project to reflect the most likely retrieval scenarios), the graphite may be subjected to some form of in-situ treatment. It is noted that treatment processes at this, and subsequent processing stages, produce secondary wastes which will lead to additional waste, unless it can be recycled.

Retrieval and segregation of the graphite then commences; retrievals may be manual (if there has been sufficient radioactive decay to permit access), or may use remote handling devices, or some combination of the two. The graphite may be retrieved intact or in fragments.

In some cases the graphite is immediately transported to the next processing stage, but it is possible that some member states would elect for some form of interim storage at this stage.

Reactor cores contain a wide range of non-graphite components such as thermocouples, securing wires and metallic connecting pins. These may need to be segregated from the graphite either at the point of retrieval or subsequently during the retrieval process.

Ex-situ graphite, potentially segregated from non-graphite components, and following an optional interim storage period forms *END POINT 1: Graphite Ex-situ*

Treatment: End Point 1 to 2
The treatment phase commences with the graphite ex-situ, potentially following a period in an interim store. The graphite, if subject to ex-situ treatment, is then transferred to the treatment facility. This may be at a location remote from the original reactor/graphite waste store site. As with

in-situ treatment there are a range of treatment techniques which may be deployed. The range of potential treatment technologies is likely to be much wider than those deployed in-situ.

Following treatment, as for the initial retrieval stage, there may be a period of interim storage prior to the next processing stage.

Ex-situ graphite, following treatment and, potentially, an interim storage period forms *END POINT 2: Ex-situ treated Graphite*.

Disposal: End Point 2 to 3
The third, and final, stage encompasses the conditioning and disposal of the graphite. Conditioning includes processing the wasteform into a product that meets the waste acceptance criteria (WAC) for the receiving facility.

The final end point for the graphite is *End Point 3: Graphite in final destination.*

Recycle and Re-use
The retrieval, treatment and disposal stages each manage graphite, or graphite constituents, which could potentially be recycled or re-used. This includes:

- graphite bricks and tiles;
- graphite constituents e.g. ^{14}C; and
- materials for potential re-use/recycle.

5.4 Summary

In summary, under Task 1.4, the following aspects were undertaken:

- a review of the most common MCDA approaches/tools, building upon previous experience from European-level projects and MCDA reviews;
- an evaluation of the MCDA techniques, which identified three that are suitable for deployment within the CARBOWASTE project;
- identification of three high level objectives and seven criteria that are consistent with the requirements of the CARBOWASTE project scope, the MCDA process, relevant EU Directives and IAEA Principles; and
- definiton of four end points for the various stages in irradiated graphite retrieval, treatment and disposal.

6 Undertake Multi-Criteria Decision Analysis (MCDA) at key stages of the road map (Task 1.5)

Task 1.5 has consisted of the agreement of lower level objectives and performance criteria for the MCDA [13], dissemination of high and low level objectives to the CARBOWASTE consortium [14], the undertaking of the MCDA assessments [15] and the identification of preferred options [16].

6.1 Agreement of lower level objectives and performance criteria

Following the identification of the high level objectives and criteria under Task 1.4, this task identified generic lower level objectives (referred to as sub-criteria) and performance criteria (referred to as performance measures) to facilitate the evaluation of strategy options for treating irradiated graphite. Technology Sub-Criteria were also introduced, which extend the strategy sub-criteria for technology selection and allow comparison of the operational performance characteristics of technology options in more depth.

Each sub-criterion is expressed on a numerical scale. Each of these numeric values is called a performance measure. The data requirements to calculate each Generic Performance Measure were also identified. Figure 8 shows the hierarchy of CARBOWASTE objectives, criteria and measures.

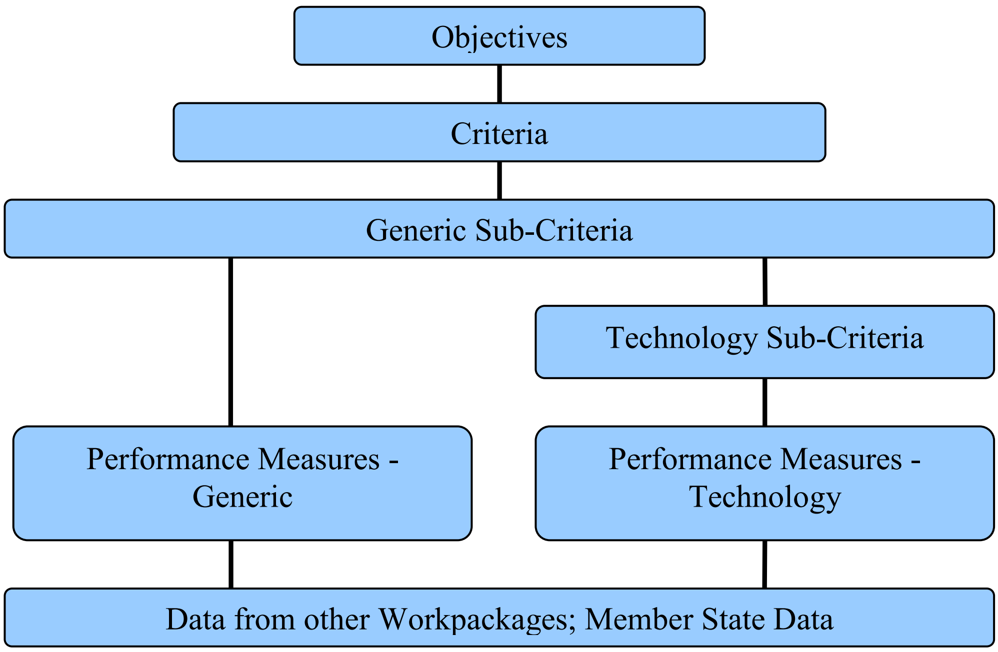

Figure 8. Hierarchy of CARBOWASTE objectives, criteria and measures

The sub-criteria were developed to deliver the fundamental aim of the CARBOWASTE project of providing a sustainable solution to the challenge of irradiated graphite waste management. A comprehensive set of sub-criteria that cover all aspects of safety and environmental, economic and social considerations is essential in achieving this aim.

These sub-criteria are described under two headings – 'Generic' and 'Technology'. Generic Sub-Criteria are used when evaluating high level 'strategy' options for retrieval, treatment and disposal of irradiated graphite, whereas Technology Sub-Criteria are designed for use in more detailed technical evaluation of specific technologies within each of the retrieval, treatment or disposal phases. Technology Sub-Criteria may be used on their own to evaluate technologies predominantly on a technical basis, or they may be used to support Generic Sub-Criteria in providing a more detailed evaluation of technical aspects.

Fifteen Generic Sub-Criteria were identified along with eight Technology Sub-Criteria. Performance Measures were determined to quantify the Generic Sub-Criteria. It is not always possible to allocate a quantitative value due to the subjective nature of the criteria, in which case a qualitative measure is used. Details of the Generic Sub-Criteria and the rationale behind the choice of performance measures are provided in [13]. These, together with the data requirements are summarised in Table 8. The Technology Sub-Criteria are outlined in Table 9.

Table 8. Generic Sub-Criteria, Measures and Data Requirements

Sub-Criteria	**Measure**	**Measure Units**	**Data Requirement**	**Data Units**
Radiological Impact - Man;	Collective Dose over 10^6 years	Man Sieverts	Time Varying Discharge Profile	End of pipe Tbq vs. time
			Aerial and Liquid Collective Dose Factors for each site	Man Sieverts/TBq
Radiological Impact - Environment	Tier 1 ERICA score	Dimensionless	Edge of mixing zone activity concentration for discharged species	TBq/m^3
Resource Usage	Energy	GWh	Lifecycle resource usage	tonne
			Energy required to manufacture unit of resource	GWh/tonne
Non-radiological discharges	Sum of dilution required to meet EQS for all toxic species	m^3	Time Varying Discharge Profile	te discharged
			Environmental Quality Standards	te/m^3
Local Intrusion	Impact value between 0 (no impact) and 1 (significant impact) normalised to known projects	Subjective Score	Lifecycle Environmental Impact Assessment of facility	None

Sub-Criteria	Measure	Measure Units	Data Requirement	Data Units
(Integrated) Hazard Potential	Hazard Potential	None	Duration of each processing stage	Years
			Active Process Materials Inventory	TBq
			Process Materials Inventory	te
			(Control and Form) Risk Factors	Numerical
Worker Safety (Radiological)	Collective Dose	Man Sieverts	Number of Operators	Numerical
			Number of Years Operators Required	Numerical
			Predicted Dose/Operator	mSv
Worker Safety (Non-Radiological)	Fatal Injuries	Numerical	Number of Operators	Numerical
			Number of Years Operators Required	Numerical
			Industrial Sector applicable to working environment	Information only
			Industrial Sector Death Rates	Number/100,000 workers/year
Security - Misappropriation	Misappropriation Factor	Numerical Value	Number of barriers to overcome Amount of each radioisotope vulnerable Duration of vulnerability	Numerical
Cost	Discounted Lifecycle Cost	Monetary Values	Lifecycle Cost (assumes no income from Graphite disposal)	Monetary Value
			Discount Rate	Annual Percentage

Sub-Criteria	Measure	Measure Units	Data Requirement	Data Units
Spin-Off	Discounted Lifecycle Value	Monetary Values	Lifecycle Net Present Value (NPV)	Monetary Value
			Discount Rate	Annual Percentage
Concept Predictability	Technology Maturity Level	Numerical	Technology Readiness Level	Numerical Value
			Process Flow Diagram	Information only
Operational Predictability	Operational Predictability Level	Subjective Score	Process Flow Diagram	Information only
			Throughput sensitivity to feed variations	Information only
			Feed probability distribution	Information only
			Equipment/System Reliability Data	Information only
			Equipment/System interface (familiarity and ease of use)	Information only
Employment Level	Employment Factor	Subjective Score	Employment profile for project lifecycle	Information only
			Employment history in project region (numbers, skills, stability)	Information only
			Transferable skills derived from project	Information only
Burden Level	Burden Factor	Subjective Score	Costs profile vs. time	Monetary Value
			Discharge profile for rad. species vs. time	TBq/m^3 vs. time
			Discharge profile for toxic species vs. time	Mass concentration vs. time
			Future cost parameter (penalty)	Numerical

Sub-Criteria	Measure	Measure Units	Data Requirement	Data Units
			Future discharge parameter (penalty)	Numerical

Table 9. Technology Sub-Criteria

Technology Sub-Criteria	Description
Versatility	The ability to accommodate a range of process feeds.
Flexibility	Flexible technology solutions are able to adapt to variations in process parameters/conditions with minimal effect on product quality.
Simplicity	Processing technologies that require minimal operator intervention, or are automated, are preferred over those which require a high degree of operator control.
Robustness	Processing technology needs to be inherently reliable and robust to deviations from normal conditions in the sense that there should be minimal resulting effect on environment, safety and product quality.
Efficiency	The most efficient processes require minimal rework and wastage to achieve product quality. The generation of secondary wastes such as filters and packaging should also be avoided or minimised.
Predictability	It is important to be able to predict, with certainty, the outcome of a decommissioning process because the opportunity to re-configure in-situ is often extremely limited. Being able to model, and optimise, the process accurately before installation has significant advantages.
Compactness	There are benefits from process equipment having a small footprint, given the limited availability of suitable space within, and adjacent to, reactor cores. Being able to deploy a modular approach to decommissioning nuclear reactor cores can also provide significant benefits.
Product quality	Processing technology should achieve the stated output quality e.g. treatment methods achieving a defined decontamination factor, package conditioning for disposal meeting the conditions for acceptance or recycled material meeting a product (or product feed) specification.

6.2 Dissemination of high and low level objectives to the consortium

Information from Task 1.4, on high level objectives, end points and criteria, and from Task 1.5, on low level objectives and performance criteria (sub-criteria, performance measures and data requirements) has been collated. The resulting report [14] was used to disseminate this information to the CARBOWASTE consortium members. Figure 9 shows the relationship between the identified high level objectives, criteria, sub-criteria and performance measures (quantifiers).

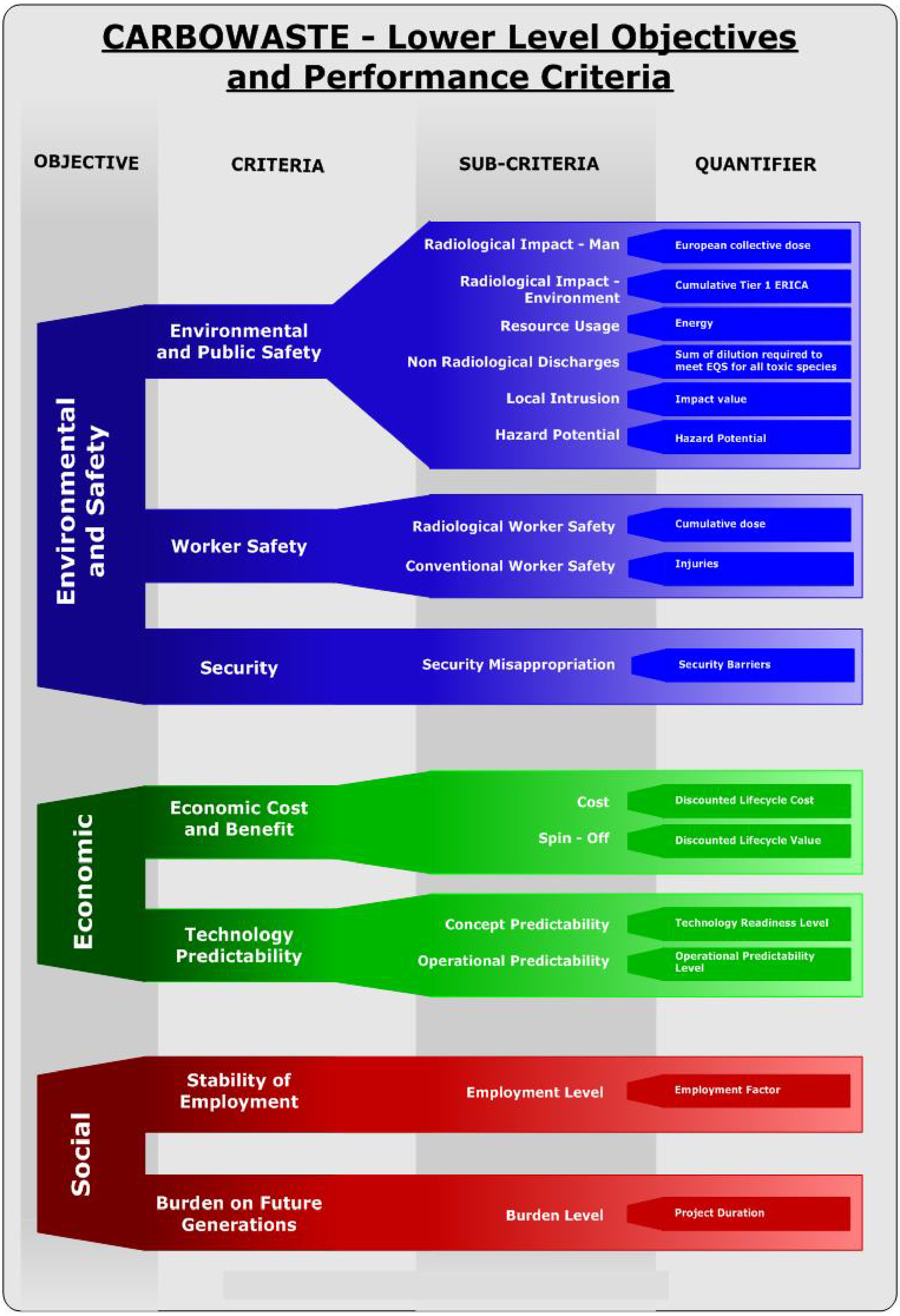

Figure 9. CARBOWASTE high level objectives, criteria, sub-criteria and performance measures

6.3 MCDA assessments

In order to implement the methodology developed under Task 1.4 and undertake the MCDA assessments, a set of graphite waste management options needed to be defined. These were synthesised during a Work Package 1 workshop held in January 2011 [17]. The flowsheet options consider:

- in-situ storage in the reactor;
- retrieval technique;
- treatment and conditioning of the primary and secondary wastes;
- effluent treatment (liquid and aerial);
- interim storage;
- transport of wastes and raw materials; and
- nature of the waste repository.

Twenty four graphite management options were identified and a flowsheet developed for each one. Figure 10 shows an example of a flowsheet for Option 1: Encapsulation and deep repository.

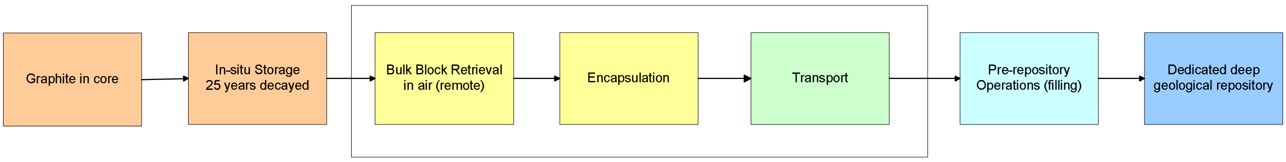

Figure 10. Flowsheet for Option 1: Encapsulation and deep repository

The twenty four options for the management of irradiated graphite identified for assessment, which cover the range of available retrieval, treatment, reuse and disposal options for irradiated graphite, are:

Option 1: Encapsulation and deep repository
Option 2: Size reduce graphite for minimised waste package volume; local immobilisation
Option 3: Minimum processing
Option 4: Deferred start with remote retrieval
Option 5: Deferred start with manual retrieval
Option 6: Minimum processing with deferred start
Option 7: Alternative retrieval and graphite form in package
Option 8: Alternative retrieval and repository
Option 9: Interim storage and repository
Option 10: Alternative retrieval, encapsulation and intermediate storage
Option 11: In situ treatment and near-surface repository
Option 12: Ex situ treatment and near surface repository
Option 13: Gasification and isotopic dilution with conventional fossil fuel CO_2
Option 14: Gasification and isotopic dilution with conventional fossil fuel CO_2 as a result of sequestration
Option 15: Gasification and isotopic dilution by dispersal as CO_3 in the sea
Option 16: ^{14}C re-use

Option 17: ^{14}C re-use with no isotope separation
Option 18: Graphite re-use for nuclear application only
Option 19: In-situ entombment
Option 20: Waste volume reduction and emission to atmosphere
Option 21: Make use of graphite as inert filler, removing the need for some encapsulation
Option 22: Immobilise in medium impermeable to ^{14}C
Option 23: Chemically bind ^{14}C
Option 24: Interim storage of raw waste and repository

At the January 2011 workshop [17], three case studies were also identified:

- Case Study 1 - A generic power reactor (based on data for a Magnox, UNGG or AGR reactor). This will have a significant inventory of graphite, with high activation and will have additional material (such as thermocouples) associated with the graphite.
- Case Study 2 - A generic test reactor (based on data for Dido or other MTRs). This may have relatively low inventory and activation, and will have minimal additional material.
- Case Study 3 - A generic vault (based on data for a vault such as those at Vandellos or Hunterston). This has an intermediate inventory of graphite, but potentially a wide range of additional wastes mixed with the graphite.

A full MCDA process has been performed for Case Study 1 (power reactor), whilst Case Studies 2 and 3 have been considered qualitatively and via sensitivity studies during the work to identify preferred options [16].

For Case Study 1, each of the 24 flowsheet options was expanded into a quantified flow diagram tracking the flow of radionuclides through the various flowsheet steps. The flow diagram was then extended to additionally calculate measures of each of the criteria for options assessment. The result is a set of metrics which assess all aspects of the performance of the flowsheets relevant for waste management option selection. The summarised output from the flowsheets and the assumptions that the flowsheets are based on are presented in [15].

All the required data, including decontamination performance, costs and discharges to the environment have been gathered from CARBOWASTE partners, the open literature and in some cases, especially regarding costs, estimated based on engineering judgement and a set of reference projects.

A first stage of MCDA was undertaken consisting of:

- considering each criterion in turn and examining the impact of each option on that criterion; and
- considering each option in turn and comparing its impact across all criteria (a pairwise comparison normalised against Option 1: Encapsulation and deep repository).

Figure 11 and Figure 12 provide examples of the MCDA output for considering each criterion in turn and examining the impact of each option on that criterion, for the criterion ‘Public safety’ and ‘Economic costs’.

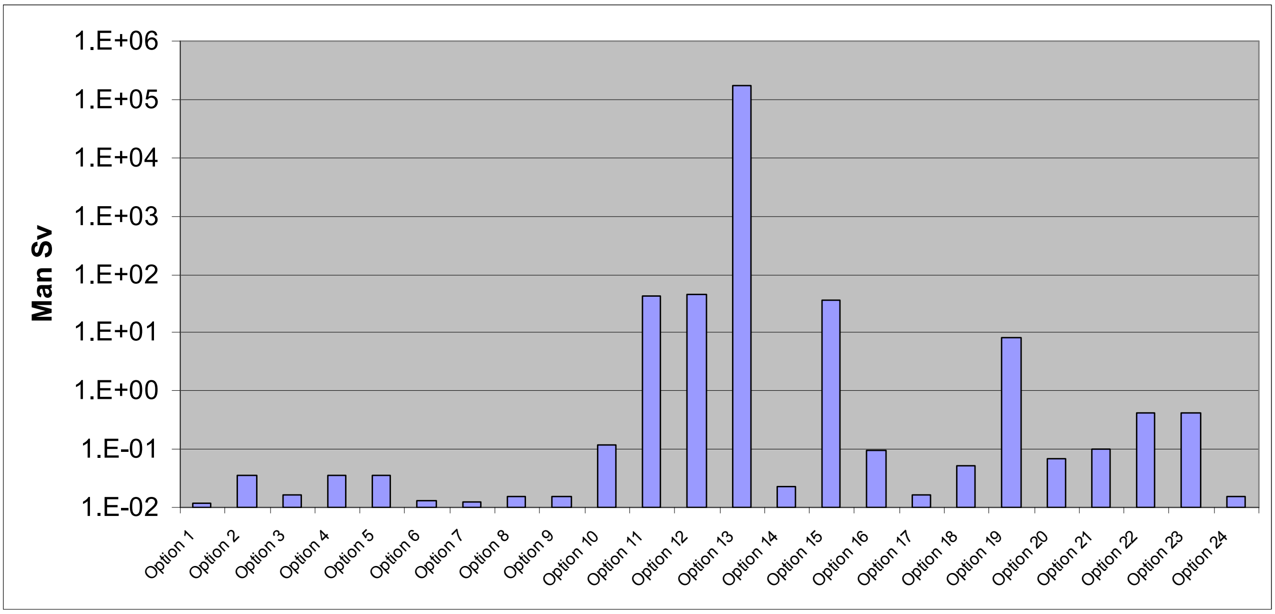

Figure 11. Public Safety: Routine discharges measured across all options

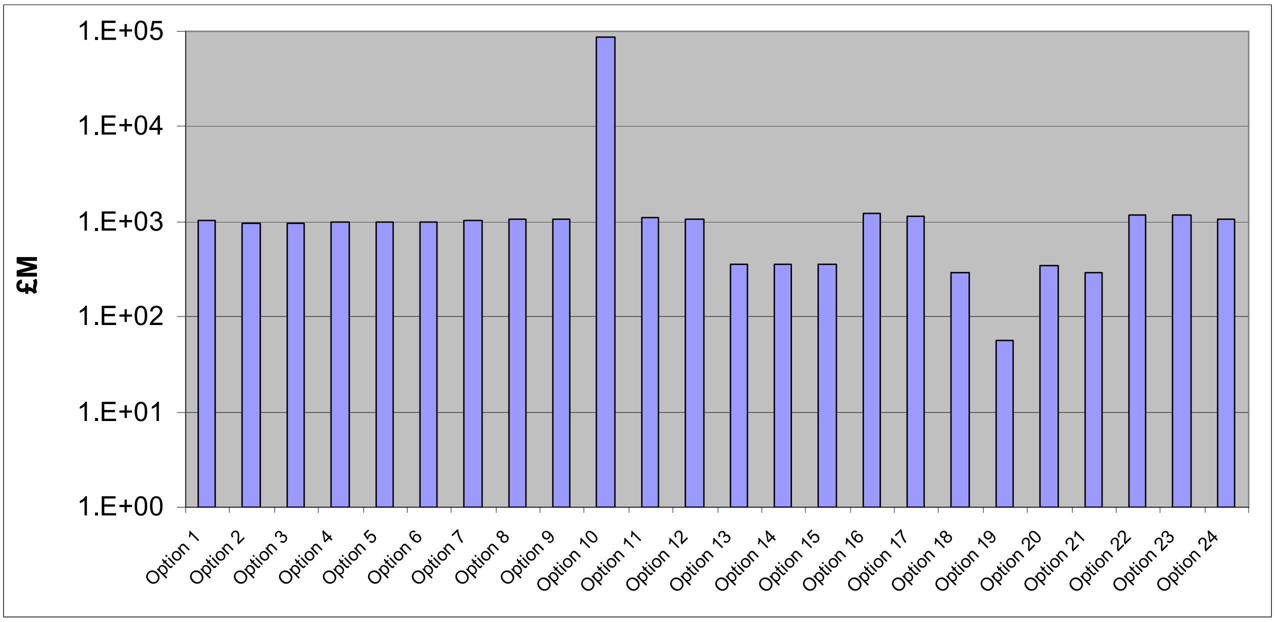

Figure 12. Economic costs measured across all options

Pair-wise comparison provided an alternative method for comparing options prior to scoring and weighting. This technique compares directly the measures for each of the criteria between two options. No weighting is used, and so it is not possible to produce an overall score for each option. Each of the sub-criteria must be considered individually when making the comparison, rather than judging overall performance.

The comparison is made by considering the relative difference between the measures of each option. A value of 100 indicates a measure in that criterion that is equivalent to Option 1 (Encapsulation and deep repository). A value greater than 100 indicates a higher measure in that criterion (poorer performance) and a value less than 100 indicates a lower measure in that criterion (improved performance).

Figure 13 and Figure 14 show example outputs from the MCDA in which each option is considered in turn and its impact is compared across all criteria (pairwise comparison).

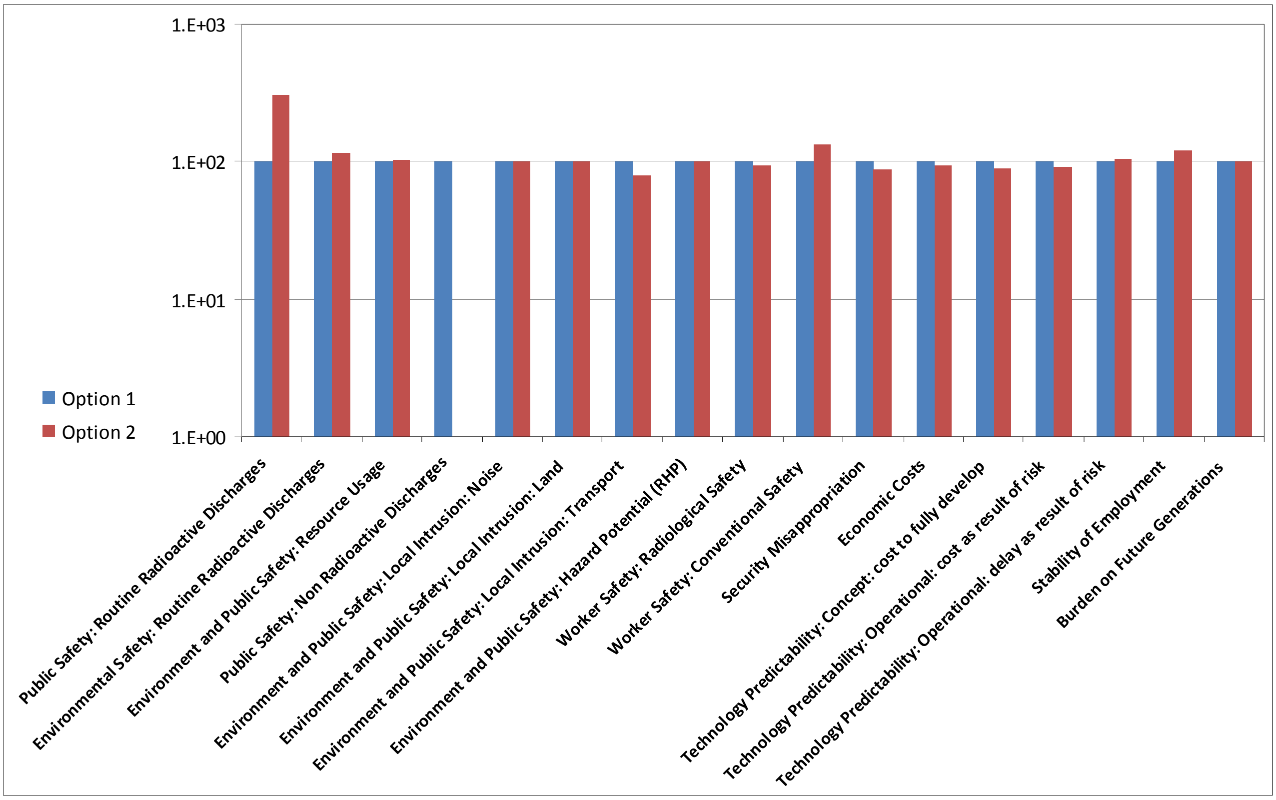

Figure 13. Option 2 sub-criteria measures normalised against Option 1

These results allow a detailed examination of the impact of each option on each of the criteria. Since the criteria consider a range of unequal measures, with different units, the direct comparison of performance between options was not possible at this stage. A second stage of the MCDA process was therefore undertaken in order to identify preferred options (Section 6.4).

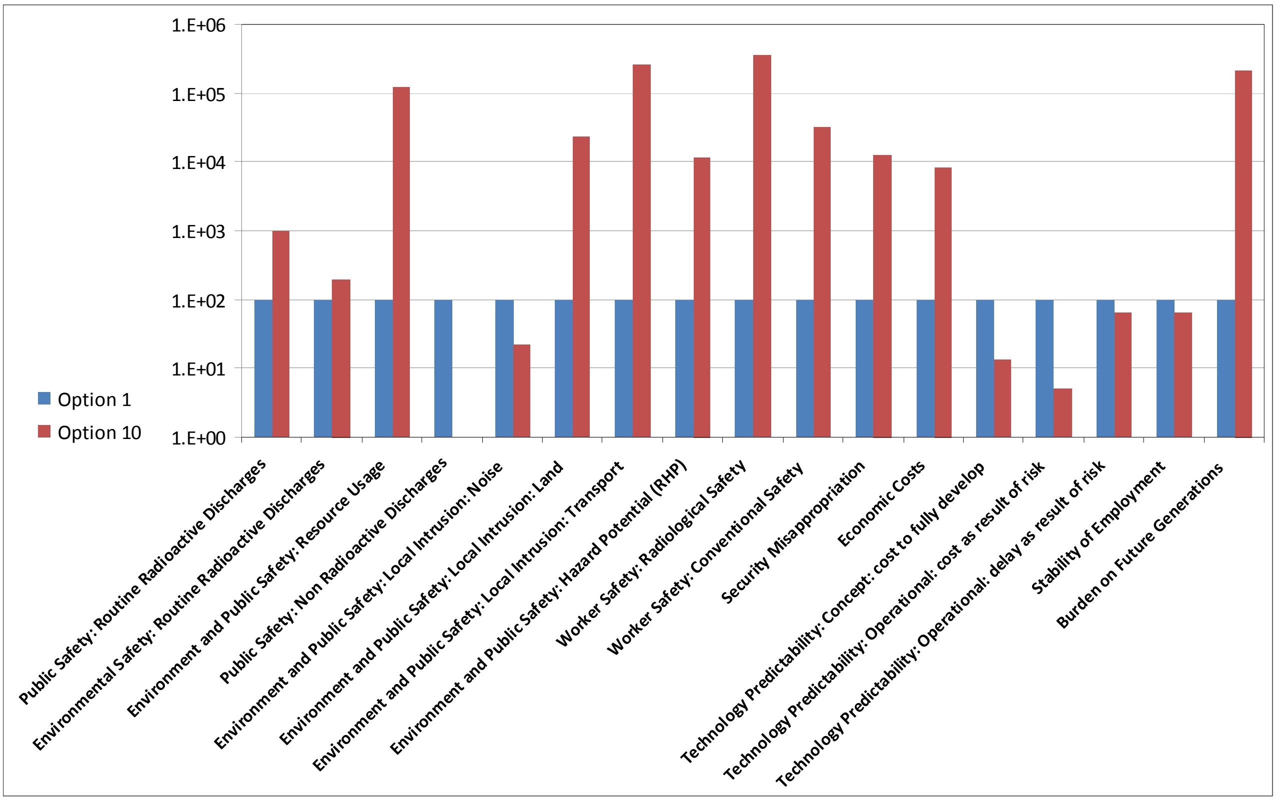

Figure 14. Option 10 sub-criteria measures normalised against Option 1

From the results of the first stage of the MCDA, it is clear that certain options have particular strengths and weaknesses which may make them suitable for certain irradiated graphite and associated materials but not for others:

- Geological disposal is a good option for much of the waste, with the key issue being the requirement to demonstrate containment for very long periods.
- Reuse is attractive for selected graphite, however careful assessment is required in each case. Using the estimates derived in the MCDA it is possible that resource usage in decontaminating graphite may outweigh the savings of graphite reuse.
- Options which have significant discharges (e.g. Options 13 and 15) perform poorly on environmental criteria, but these options reduce hazards, resource use and transport required, and may be cheaper than other options. These options may be appropriate in certain circumstances.
- Continued above ground storage is not a favourable option in most criteria. In particular, it is expensive, uses extensive land, resources and transport, imposes the largest burden on future generations, is expected to result in significant numbers of injuries during construction and has the poorest security. Reduced operation risk is the key advantage due to the wide international track record of constructing above ground stores.
- Options which retrieve material for interim storage score poorly on security and hazard, with no significant benefits. Such projects are likely to be motivated by criteria outside the scope of the criteria developed, such as the need to free a site for reuse, the need to empty an

unacceptable structure or the desire to demonstrate a particular technology to reduce risk to future projects.

- Under certain circumstances, entombment could be an attractive option, if it could be shown to be viable for a given material. It has low resource usage, low transport requirements and low cost. However, its key disadvantages are poor security and high radioactive discharges.

6.4 Identification of preferred options

Following on from the initial assessment of the MCDA process (Section 6.3) a weighting process was undertaken to allow best and worst-scoring options for the management of irradiated graphite to be identified from the twenty four options considered [16]. However, it should be noted that this assessment provides an example application of the methodology, to identify and test an MCDA process that can be utilised by the CARBOWASTE partner countries. It is not possible to select one generic preferred option for all countries, since each will have its own specific constraints and regulations that will preclude certain options from being viable.

The linear additive MCDA method used consisted of the following steps for scoring and weighting:

- Decide on the scoring system and scale (typically between 0 and 100); typically higher scores reflect better performance.
- Determine weighting factors e.g. between 1 and 100, and ascribe weightings to each criterion.
- The levels of performance for the two reference points (0 and 100) are determined. In a global scale model the scores of 0 and 100 are associated with the worst and best performances that could be encountered in any circumstances whereas in a local scoring model the low and high performance limit are derived from the scope of the current problems for which a range of options are being considered. Global scaling allows for the ready introduction of new options but it can be difficult to define the absolute performance limits for a number of criteria.
- For each option, allot a scoring value against the criterion.
- In the linear approach, the option's score against each criterion is multiplied by the weighting attributed to that criterion and then the weighted scores are added together to derive an overall score for the option.

The scoring and weighting of criteria was considered at the Work Package 1 MCDA workshop that took place in January 2013. The minimum and maximum values calculated for a sub-criterion across all options were considered and assigned a score of 1 for the lowest value and a score of 100 for the highest value. Intermediate values were given a score between 1 and 100 based on their relative position within the minimum and maximum values on a linear scale. This approach uses no judgement in the scoring process (as scores are applied automatically), although judgement is provided in determining the weightings.

It was noted that this linear additive approach has its downsides, e.g. for some of the radioactive discharges data, a value several orders of magnitude above a range of smaller values for other options skews the scores so that the option with the large discharges receives a score of 1, while all the other options receive a score of 100, ignoring the differences between them. This was addressed by removing outlying options and rescoring if necessary.

For each sub-criterion, the score was multiplied by the weighting to give a weighted score. These weighted scores were summed and an overall weighted score for that option determined. A consistent approach to scoring and weighting must be applied to all options being considered, i.e. it is not possible to use one method of scoring and/or weighting for one option and an alternative method for others.

Weightings were applied to each sub-criterion to allow prioritisation of certain sub-criteria over others. The allocation of weightings to each criterion was decided upon at the MCDA workshop. This included the allocation of extreme numerical weightings (high = 100, medium = 50, low = 1) (causing the high weighted criterion to be 100 times more important in determining the overall weighted scores than the low weighted criterion) and a narrower range of weightings as part of a sensitivity analysis (high = 75, medium = 50, low = 25) (causing the high weighted criterion to have three times more impact than the low weighted criterion) (see Table 10).

Figure 15 displays the overall weighted scores for all of the twenty four options considered. The best-scoring option is labelled green and the worst-scoring option labelled red. Following the initial assessment of all twenty four options, the worst-scoring option was removed, and the scores of the remaining twenty three options were re-normalised and re-allocated overall weighted scores. This process was then repeated, with the successive removal of the worst-scoring option each time (see, for example, Figure 16 with only four remaining options). This enables the user to gradually focus on a successively smaller number of the best-scoring options and obtain a greater resolution/discretisation of scores for those remaining options.

Table 10. Criteria weightings* decided upon during the MCDA Workshop (Allocation A)

Sub-criteria*	Weighting Band	Allocation A Extreme Weightings	Allocation A Narrow Weightings
Radiological impact - man	High	100	75
Radiological impact - environment	High	100	75
Resource usage	High	100	75
Non-radiological discharges	Medium	50	50
Local intrusion: noise	Low	1	25
Local intrusion: land use	Low	1	25
Local intrusion: truck journeys	Medium	50	50
Hazard potential	Medium	50	50
Radiological worker safety	High	100	75
Conventional worker safety	High	100	75
Security misappropriation	Medium	50	50
Economic cost	Medium	50	50
Concept predictability	Low	1	25
Operational predictability	Low	1	25
Employment level	Low	1	25
Burden on future generations	Low	1	25

*These weighting were defined by the participants at the international Work Package 1 MCDA workshop. They are example weightings for the purposes of applying the MCDA process and do not reflect any individual organisation's view.

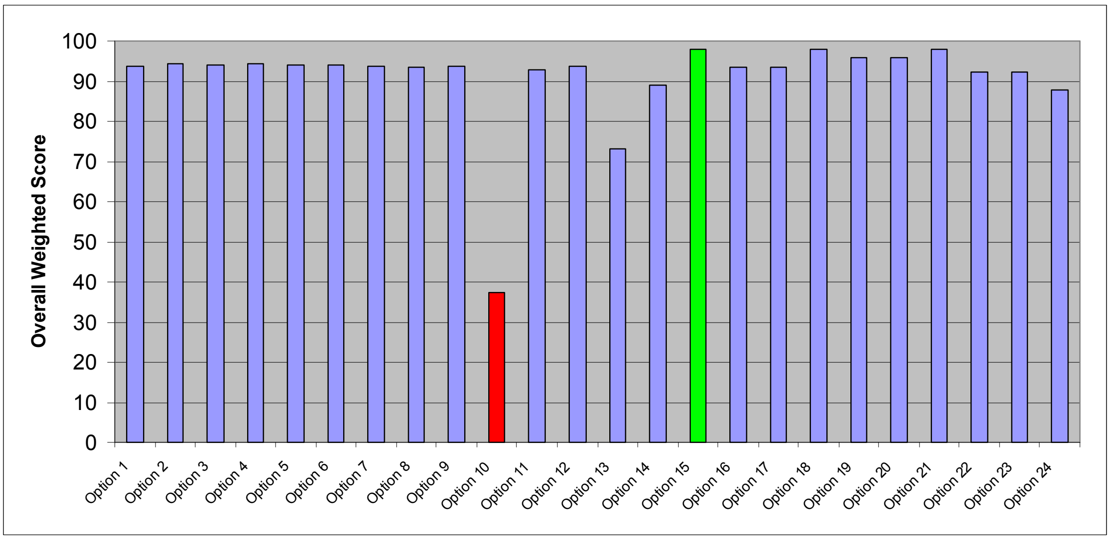

Figure 15. Overall weighted scores for all twenty four options based on 'Allocation A – Extreme Weightings'

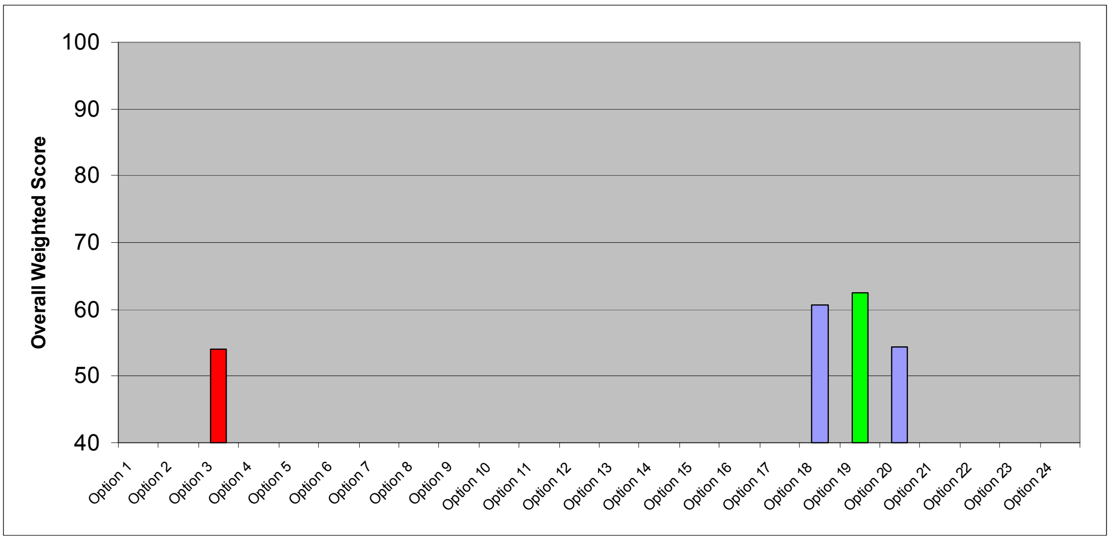

Figure 16. Overall weighted scores for remaining four options based on 'Allocation A – Extreme Weightings'

It was found that, due to the wide ranges of outputs considered, a small number of very poorly performing options can initially cause a large number of the best performing remaining options to appear to be equivalent in performance. A process of continual removal of the worst performing options and re-normalisation allowed the differences between remaining options to be assessed in more detail.

When assessing all twenty four options considered by the CARBOWASTE project (and not removing any based on constraints), Option 19 (in-situ entombment) performed the best and Option 10 (alternative retrieval, encapsulation and indefinite storage indefinite storage) performed the worst for Case Study 1 (power reactor). A brief review of the entombment concept was subsequently carried out, identifying some of the limitations. While there is some experience regarding entombment, or in-situ decommissioning, of legacy nuclear facilities in the United States, and as a temporary solution for acutely damaged reactors, the approach of long-term entombment has not been applied in practice to power reactors. As such, it is not a technically proven solution and would likely require significant technological development before a safety case could be demonstrated for its use in immobilising irradiated graphite in-situ. By including this option within the twenty four assessed here, it has been assumed that this concept is viable, which may not be the case in reality for any individual member state.

A variant case for Option 19, which considers a monitoring and maintenance period of 1,000 years, was assessed and produced results that are significantly different to the original variant case definition. In the first stage of this variant case assessment, Option 19 was the best-scoring option, but as the worst-scoring options were successively removed, its relative performance fell and it emerged as the worst-performing option part way through the process. Option 3 (Minimum processing) was the best performing option in this case.

Options that avoid the use of a deep geological repository performed well in this assessment due to the avoidance of the significant resource usage and economic costs associated with repository construction. The scaled allocation of these impacts to irradiated graphite needs to be considered alongside member states' national strategies, however. For example, if a geological repository were to be constructed solely for the disposal of irradiated graphite, the complete allocation of the repository's impacts to irradiated graphite would likely make such options unviable. If, however, a geological repository for other wastes, e.g. spent fuel or high level waste were already planned, or in existence, the additional inclusion of irradiated graphite would have much less impact. The assumptions and scaling of repository impacts to irradiated graphite made in the MCDA are detailed in [15].

Options that include the use of a deep geological repository performed moderately well in this assessment due to the improved radiological discharges, hazard potential and security impacts balanced against the negative impacts of repository construction. The worst scoring options were those which consider large, repeated construction activities, such as many treatment facilities or indefinite storage.

A number of sensitivity cases were also examined to determine the effects of various normalised scoring and weighting configurations. These used different weighting allocations (Allocation B and Allocation C - narrow weightings, as alternatives to those presented in Table 10) to investigate the impacts of prioritising the criteria differently to that decided upon in the MCDA workshop. This is because it is difficult for CARBOWASTE partners to assign a definitive set of weightings, since the priorities of scientists and engineers are likely to be different to those of governments, regulators or members of the public, for example. In choosing alternative weighting allocations, an attempt has been made to explore the effects of considering the priorities of two different, hypothetical, stakeholders.

The sensitivity analysis using the alternative weighting systems showed that, for the twenty four options considered, the different weighting allocations had little effect in determining the relative rankings (i.e. low sensitivity). Consistently, Option 10 (Alternative retrieval, encapsulation and indefinite storage) was the worst-performing option.

In addition to the MCDA carried out for Case Study 1 (power reactor), a qualitative assessment was undertaken for Case Studies 2 and 3 (irradiated graphite in a vault/silo, and a research reactor). Each of the twenty four options was examined to identify particular stages that could not be applied, or would require significant modification to apply, to Case Study 2 or Case Study 3. Other than the early process stages in all options: e.g. 'Graphite in Core' and 'Retrieval' not being applicable to graphite in a vault, the majority of options remain appropriate for each of the three case studies, although specific practicalities for application may vary slightly.

6.5 Summary

In summary, under Task 1.5, the following aspects were achieved:

- Generic low level objectives (sub-criteria) and performance criteria (performance measures) were identified to facilitate the evaluation of strategy options for managing irradiated graphite.
- Three case studies were identified along with twenty four options for managing irradiated graphite, for the purposes of testing the MCDA process. Data has been obtained to determine the performance measures for each option for the first case study (power reactor).

- An MCDA approach, as identified under Task 1.4, has been implemented. The linear additive method of MCDA adopted was found to be suitable for assessing CARBOWASTE options.
- High performing and low performing options have been identified using this process but it is not possible to state within the CARBOWASTE project which option is best for any individual member state.

Individual member states can use the tools and processes presented here to determine their own best option by applying their own scores, weightings and constraints. The assessment tool provides supporting arguments in a wider process for the identification of preferred options for the management of irradiated graphite that will need to take into account many more factors that cannot be represented quantitatively, such as regulatory approval or public acceptability.

7 Retrieval criteria (Task 1.6)

Under Task 1.6, a set of assessment criteria that can be used to select methods for the retrieval of irradiated graphite, were developed. A generic assessment of retrieval options against these criteria was also performed [18]. These activities were used to provide feedback, on issues relating to retrievals technology selection, into Tasks 1.3 and 1.4.

The criteria were developed based on workshops, the annual CARBOWASTE project meeting and other meetings/workshops organised in the UK involving NNL, Doosan-Babcock and AMEC. The criteria and selection process evolved during this process and were influenced by the development of the MCDA (Tasks 1.4) for the selection of strategies for the retrieval, treatment and disposal of irradiated graphite. Broad retrieval technology options have been considered as part of the CARBOWASTE strategy selection. The strategy then influences detailed retrievals technology selection. The interaction with the development of the MCDA criteria enabled the relationship between strategy selection and retrievals technology selection to be better defined.

7.1 Graphite retrieval as part of an integrated waste management strategy

The irradiated graphite retrieval criteria are synergistic with and have largely evolved from the route map [3] considerations. It is crucial that retrieval, treatment and disposal are integrated into an overall strategy selection process. Figure 17 illustrates how the MCDA approach to strategy selection is considered to interact with more detailed selection of retrievals technology.

Initially, a set of broad options for irradiated graphite retrievals, treatment (including recycle) and disposal must be identified. A range of potential strategies can then be synthesised using combinations of the broad options. The strategies are then assessed against the strategy selection criteria to select a preferred strategy.

The strategy selection will define a number of key decisions that will influence technology selection. In particular it is expected that the strategy will define:

- the decay period prior to beginning retrievals;
- the form in which the graphite is required following retrievals;
- the medium in which retrieval is to be performed (e.g. air or water);
- what segregation is required (e.g. between moderator and reflector graphite, or between graphite and other solid waste); and
- the required end date and so retrievals rate and acceptable duration for development of the retrievals technology.

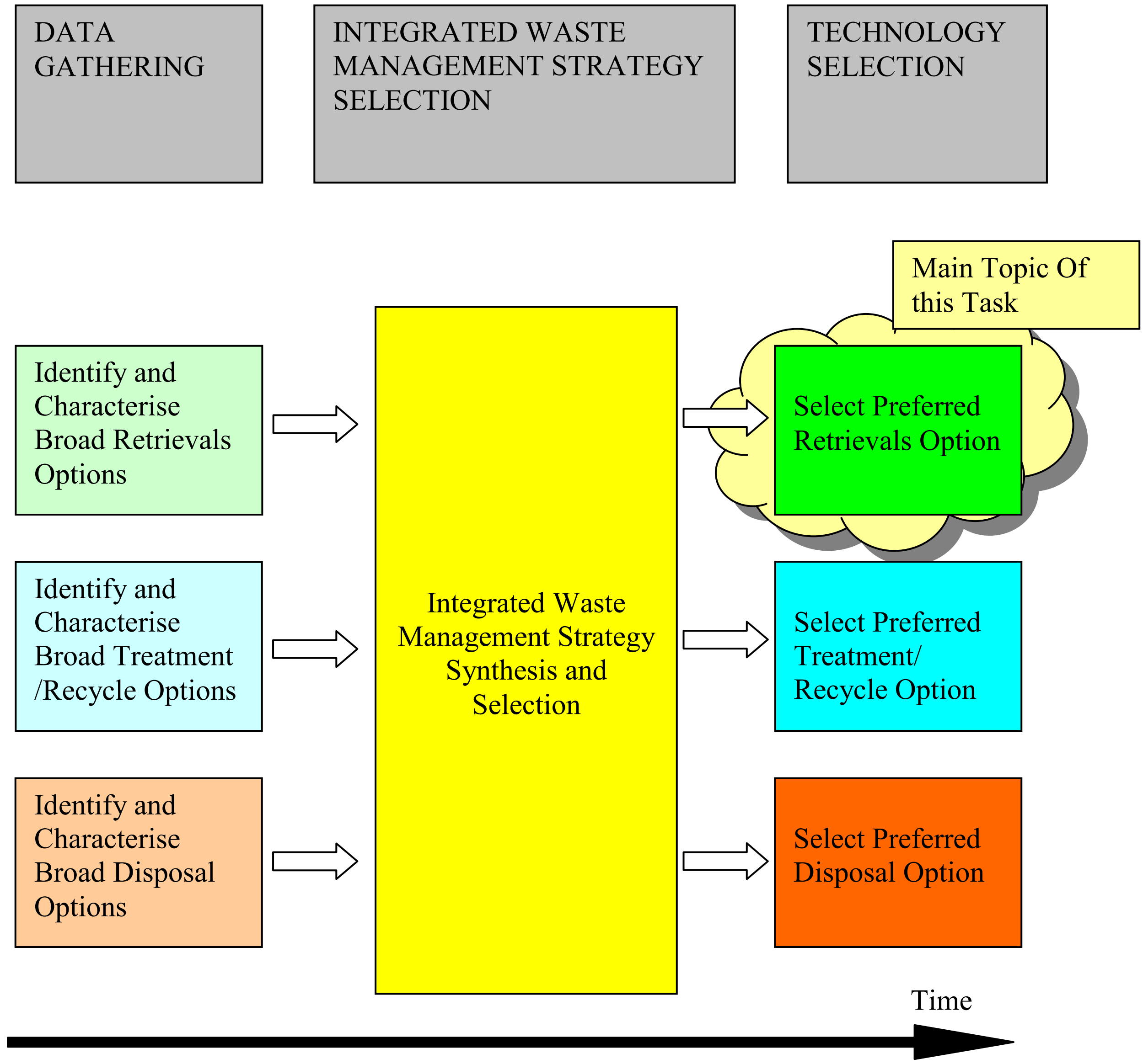

Figure 17. Selecting Strategy and Retrievals Technology

Finally, detailed technology selection can be performed to deliver the requirements of the preferred strategy option. In addition to strategy issues, technology selection will be influenced by such parameters as reactor and core design/configuration, quantity of irradiated graphite and contamination/impurity values. It is this final step, applied to retrievals technology selection, that has been considered under Task 1.6.

7.2 Key criteria for graphite retrieval

A broad range of potential criteria were developed over a number of workshop meetings in 2009. This resulted in a broad range of criteria; this list was subsequently grouped into a smaller number of retrievals technology selection criteria to minimise the amount of duplication in assessing the various candidate technologies. Under Tasks 1.4 and 1.5, the integrated waste strategy selection criteria have been developed and these have been reviewed to see whether they suggest additional criteria relevant for selection of retrievals technology. Consideration was also given to deciding whether the various criteria could be viewed solely as constraints, that is whether they acted as "go"/ "no go" decisions, rather than requiring options to be compared based on their strengths and weaknesses. Figure 18 has been adapted from the strategy selection process (Figure 6) for use in the selection of retrievals technology.

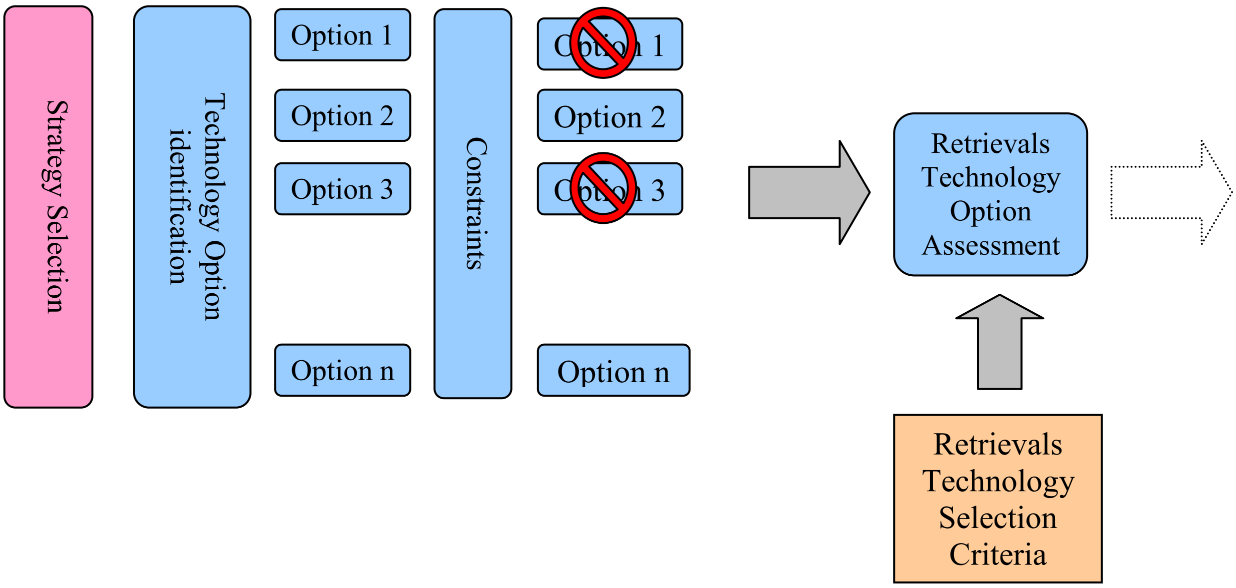

Figure 18. Process for selection of retrievals technology

Following strategy selection, the figure shows that a range of retrievals technology options is available. The options are then screened using a set of constraints. Such constraints may be imposed by the strategy that has previously been selected, or may be imposed by the structure containing the graphite. Constraints may include the need to extract largely intact blocks, deployment issues (such as equipment size and weight), timescale issues (such as the need for high retrieval rates or immediate deployment), shielding constraints (the need to provide adequate shielding) and any other constraint that can eliminate an option from consideration. The result of applying the constraints is a set of feasible options which proceed to assessment using the retrievals technology selection criteria.

Table 11 considers the strategy selection sub-criteria and considers whether these are appropriate for use as retrievals technology selection criteria. The lists of retrievals criteria previously developed in workshops were reviewed against this table to identify the selection criteria shown in **bold face**. Rows with a relevant criterion are shaded. The retrievals technology selection criteria developed through the process above are summarised in Table 12.

Table 11. Derivation of retrievals technology selection criteria from generic sub-criteria

Generic Sub-criterion	Applicability to Retrievals Technology Selection
Radiological impact - man	Selection of technology is not expected to have a great impact on this objective. The strategy defines the required end point (e.g. powder or blocks), decay period prior to retrievals and retrieval medium (e.g. under water, in air, in inert gas) and so will largely dictate this impact. Given these strategic decisions, differences between technologies for producing a similar product are expected to be small.
Radiological impact - environment	A similar argument applies to that for "Radiological impact – man" above.
Resource Usage	**Resource usage**: requirement for the treatment of secondary wastes may result in significant resource use. Resource use can be minimised if equipment can be reused.
Non Radiological discharges	A similar argument applies to that for "Radiological impact – man" above.
Local Intrusion	It is not expected that retrievals technology selection would have a significant impact on local intrusion – noise and light will be inside the reactor bioshield and the technologies are unlikely to result in dramatic visual impact. Size of the technologies is not sufficiently different that vastly different amounts of equipment transport to site would be required.
Hazard Potential	Hazard potential is affected by radiological inventory, form of materials stored and time to realise a potential risk. None of these items is directly affected by retrievals technology selection, though some are affected by the strategy.
Worker Safety - radiological	**Worker safety - radiological** is directly affected by technology selection – particularly by dose incurred during deployment or maintenance of equipment.
Worker Safety – non-radiological	**Worker Safety – conventional** is directly affected by technology selection – particularly the decision of hands on vs remote techniques.
Security - misappropriation	Retrievals technology selection is not expected to impact on the vulnerability of materials to misappropriation. Strategy will have an impact on security by defining end products.
Cost + Spin Off	**Cost** of retrievals technology is an important objective. Cost must be a lifecycle cost, including not only equipment purchase but disposal of PPE and other secondary waste. Spin off from retrievals technology both for use on other decommissioning projects and outside the nuclear industry is possible and must be assessed as a monetary value.

Generic Sub-criterion	Applicability to Retrievals Technology Selection
Concept Predictability	This is a key objective for technology selection and warrants subdivision into a number of contributing parts: • **Simplicity** – gives confidence that the equipment will perform as expected. • **Maturity** – also contributes to confidence that the equipment will perform as expected.
Operational Predictability	This is a key criterion for equipment selection and so has already been considered elsewhere (Table 9). The technology sub-criteria listed there are: • **Versatility** – ability to accommodate a range of process feeds • **Flexibility** – ability to accommodate changes in operating conditions • **Simplicity** – simplicity contributes to operational predictability as well as concept predictability • **Robustness -** inherently reliable equipment will be available when required and will not impose long outages • **Efficiency -** processes require minimal rework and wastage • **Predictability** – able to predict the outcome of decommissioning • **Compactness** – able to deploy equipment in a confined space • **Quality** of product and equipment – ability to test equipment and guarantee consistent product quality
Stability of Employment	Some options require availability of skilled workers and might suggest use of an alternate option if these were in short supply. **Employment** is therefore a relevant retrievals technology selection objective.
Burden on Future Generations	It is not expected that retrievals technology selection would have a significant effect on burden on future generations. Once again this is dictated by strategy.

Table 12. Summary of retrievals technology selection criteria

Retrievals Technology Selection Criterion	Discussion
Resource Usage	Must include the equipment itself, PPE required to operate and maintain the equipment, clean up aerial and liquid effluents and resources used for disposal of the equipment/PPE at the end of its life.
Worker Safety - radiological	Considers dose incurred by operators in operating and maintaining equipment.
Worker Safety – non-radiological	Some technology choices will expose operators to greater hazards such as working at height.
Cost + Spin Off	Cost of retrievals equipment will be a lifecycle cost, including not only equipment purchase but disposal of PPE and other secondary waste. Spin off from retrievals technology, both for use on other decommissioning projects and outside the nuclear industry, is possible and will be assessed as a monetary value.
Simplicity	Gives confidence that the equipment will perform as expected.
Maturity	Contributes to confidence that the equipment will perform as expected.
Versatility	The ability to accommodate a range of process feeds
Flexibility	The ability to handle variations in the nature of the feed materials and operating conditions is important since perfect characterisation is unlikely to be possible.
Robustness	Inherently reliable equipment will be available when required and will not impose long outages
Efficiency	Processes require minimal rework and wastage
Predictability	Able to predict the outcome of decommissioning operations
Compactness	Able to deploy equipment in a confined space
Quality of product and equipment	The equipment must be able to be tested and deliver the required product consistently
Employment	Access to appropriately skilled operators is required and an option that requires fewer highly skilled workers is more likely to be able to be operable taking into account available skills, sickness and so forth.

7.3 Retrievals technology assessment

A wide range of retrievals technologies are available [19]. For the assessment performed under Task 1.6, these have been grouped into five broad categories:

1. Robots, tele-manipulator or servo manipulators.
2. Airborne, ground and submerged Remotely Operated Vehicles (ROVs), crawlers.

3. Cranage (existing, purpose built or mobile) (overhead gantry, jib, polar, etc), gantry systems (x,y, z type), telescopic tube principle.
4. Master-Slave Manipulator (MSM) type manipulators (single piece, simple gimbal mounted tongs, 3 piece MSMs), simple hinged arms (mechanical or driven), tool poles, long reach tools (e.g. CeeVee reachers).
5. Manual entry and hands on access (with or without shielding/breathing air systems) within the legal requirements of health and safety (H+S) legislation.

The retrievals technology categories were assessed against the criteria in Table 13. These are necessarily generic assessments which cannot take into account constraints imposed either by strategy or the physical situation of a particular waste stream. When a specific technology is being considered for use on a specific waste stream, a strategy will already have been selected for handling that waste stream and a more specific assessment can then be performed.

Table 13. Assessment of Retrievals Technology Categories against Criteria

Criterion	Robots and tele-manipulators	ROVs	Crane or gantry mounted devices	Master-Slave Manipulator type manipulators	Manual deployment within constraints of H+S Legislation
Resource Usage	Can often be redeployed avoiding the need to dispose of the equipment after use.	Can often be redeployed avoiding the need to dispose of the equipment after use.	Cannot typically be reused and so must be disposed of after use. Large amount of equipment to dispose of waste on completion of project. Decontamination may be possible.	Can often be reused. Equipment is smaller than some other options.	Small equipment, but may produce significant amounts of PPE/worn out equipment for disposal.
Worker safety – radiological	Remote operations will minimise operator dose uptake, but sophisticated devices will require maintenance/ replacement and hence decontamination/ maintenance facilities will be required and these need to address dose uptake issues. Equipment must be designed to minimise contamination pick up, and have Emergency Recovery features.	Will also reduce operator dose uptake but will still require maintenance/ replacement and hence airlock/ decontamination/ maintenance facilities will also be required. Equipment must also be designed to minimise contamination pick up, and have Emergency Recovery features.	Remote capability will reduce operator dose uptake, but cranes will require inspection/ decontamination/ maintenance facilities and have Emergency Recovery features.	Localised shielding and/or containment facilities may be required to enable operation of these devices. Although using simpler equipment, maintenance/ replacement facilities will still be required.	This option will be the most dose intensive for operations, but will not require any sophisticated maintenance facilities for manual equipment. Will require appropriate PPE e.g. PVC suits, and possibly localised shielding and containment facilities, with extensive radiation/ contamination monitoring equipment.

Criterion	Robots and tele-manipulators	ROVs	Crane or gantry mounted devices	Master-Slave Manipulator type manipulators	Manual deployment within constraints of H+S Legislation
Worker safety – non-radiological	Minimal risk to workers during operations, but robots will require safety mechanisms/ guarding/ interlocking/ to ensure no man/machine conflict during testing/maintenance.	Minimal risk to workers during operations, but ROVs will also require safety mechanisms/ guarding/ interlocking/ to ensure no man/machine conflict during testing/maintenance.	Minimal risk to workers during operations when crane is used remotely.	Workers must be protected from risks such as over straining when manually operating/handling the equipment, possibly working from height etc.	This option presents significant risks which would have to be controlled e.g. from manual handling, slip/trip hazards, poor lighting, gas/fume/dust, confined space, working from height, moving machinery, heat stress, lifting operations/ suspended loads , emergency recovery of personnel etc.
Cost+Spin Off	Potentially expensive development and equipment purchase, but reuse of the robot may be possible and may save some expense. Reasonable potential for spin-off applications.	Potentially expensive development and equipment purchase, but reuse of the robot may be possible and may save some expense. Reasonable potential for spin-off applications.	Large, but relatively simple items. Deployment through the bioshield at a reactor may result in additional expense. Unlikely the equipment can be reused so disposal costs must be included. Unlikely to generate spin-off applications.	Simpler equipment that will be cheaper to acquire.	Cheap equipment, but with increased costs of labour and of disposal of used PPE. Unlikely to generate spin-off applications.

Criterion	Robots and tele-manipulators	ROVs	Crane or gantry mounted devices	Master-Slave Manipulator type manipulators	Manual deployment within constraints of H+S Legislation
Simplicity	This is usually the least simple of the options, although the class spans a wide range of simplicity/ complexity levels.	These devices are not inherently simple, but there is a wide range of simplicity/ complexity levels available between different ROV types.	Cranes are relatively straight forward and simple devices, but nuclearising them tends to compromise this simplicity e.g. by adding in back up redundancy, modularity and emergency recovery mechanisms. The devices may have an impact on structural integrity of reactor that may add complexity.	Some of these devices can be extremely cheap and simple e.g. tool poles, whilst some can be mechanically very complex e.g. through wall MSMs.	Simplest of all, but complex procedures require trained and skilled people to perform them safely and efficiently, and time to prove and perform.
Maturity	Extensively used and well proven in outside industries, but their application in the nuclear environment is not as developed or mature. This can cause real problems if the system is poorly designed e.g. due to poor reliability or difficulty in maintenance.	Extensively used and well proven in outside industries, with some limited application in the nuclear environment. Problems can easily arise if the system is not well designed e.g. due to unsuitability to the particular environment such as difficulty in surmounting unexpected obstacles.	Extensively used and well proven in outside industries, and also with many successful applications and proven record in the nuclear field.	These technologies are very mature, well proven and extensively used within the nuclear industry.	Manual access techniques and procedures are well developed and extensively used within the nuclear industry.

Criterion	Robots and tele-manipulators	ROVs	Crane or gantry mounted devices	Master-Slave Manipulator type manipulators	Manual deployment within constraints of H+S Legislation
Versatility	Potentially very versatile, although this may require reprogramming in some circumstances.	Access may make deployment of ROVs difficult for other work streams.	Fixed location makes using the equipment for multiple streams difficult.	Flexible equipment providing visibility to the target stream is adequate and access can be provided.	Maximum versatility providing man access is available for all work streams.
Flexibility	Usually have high dexterity and manoeuvrability to access unexpected areas. Can have high payload capacity, but sometimes their reach is limited and requires other means to access the whole environment. Most machines are designed for operation in air, but a smaller range of underwater devices are available.	Usually have high level of mobility to access a significant part of the work area, but this can be limited by the physical constraints of the environment. Can obtain machines with high payload capacity. Devices for air and underwater use are available.	Good design can provide sufficient work area coverage, and usually have very high payloads. Devices for air and underwater use have been used in the past.	Usually restricted to certain operating envelopes and restricted payloads, but can be moved relatively easily to different locations. Devices for air and underwater use are available.	Hands on access and vision provides great flexibility to cope with the unexpected, but payloads are limited. Not suitable for underwater recovery.
Robustness	Most complex option, hence least likely to be robust. Relies on efficient design to build in high levels of reliability/ maintainability. May need extensive inactive testing to prove acceptable levels of robustness.	Can still be complex equipment and hence can still encounter significant problems with robustness in certain environments. Relies on efficient design to build in high levels of reliability/ maintainability. May need extensive inactive testing to prove acceptable levels of robustness.	Relatively robust equipment but still relies on efficient design to build in high levels of reliability/ maintainability, e.g. modularity to assist maintenance and redundancy to increase reliability.	Simpler equipment hence usually more reliable and maintainable. Usually more easily replaced/ repaired/ disposed of upon failure.	Lowest levels of robustness required for this option but a certain level is still required for workheads otherwise throughput can be compromised and additional man entries are required to recover.

Criterion	Robots and tele-manipulators	ROVs	Crane or gantry mounted devices	Master-Slave Manipulator type manipulators	Manual deployment within constraints of H+S Legislation
Efficiency	Efficiency may improve over time if it is possible to program simple repetitive tasks.	Efficiency will depend on both the tooling and visibility to the workface as well as the skill of the operator.	Efficiency will depend on both the tooling and visibility to the workface as well as the skill of the operator.	Efficiency will depend on both the tooling and visibility to the workface as well as the skill of the operator.	Efficiency depends on ability and training of the workforce. This is often the most efficient option for complex operations.
Predictability	Potentially the most predictable for repetitive tasks, but can be expected to struggle with one-off tasks.	Predictability depends on details of the design.	Movements are predictable, but the performance of the end-effectors needs consideration.	Predictability depends on details of the design and the need to switch between alternate end-effectors.	Predictability can vary between operators depending on level of training and experience.
Compactness	Equipment size depends on the design and required duty.	Equipment size depends on the design and required duty.	The least compact of the options.	Can be compact, but light equipment may be able to handle only light loads.	Equipment is very compact, but access is required for men and possibly additional lighting and air lines.
Quality of product and equipment	Automation and repeatability should be possible due to the use of robotics, but still heavily reliant on the material behaviour and environment. Due to complexity of equipment, requires a very high level of quality of equipment, and needs to be fully tested/ proven before deployment.	Similar to robots/tele-manipulators, but perhaps slightly more variable due to the mobility of the ROV. Not quite as demanding as for robots/tele-manipulators.	Robust equipment with large coverage area should assist in ensuring product quality. Lifting equipment inherently has to have a high level of quality and to be tested/inspected at regular intervals.	Will be more reliant on the skill of manual operators than other techniques. Due to the simpler equipment, this option requires a lower level of quality and reliability.	Hands on access is a potentially good means of ensuring consistent product quality, but this is reliant on operators' competence and diligence. Lowest levels of quality required for this option but a certain level is still required for workheads otherwise throughput can be compromised and additional man entries are required to recover.

Criterion	Robots and tele-manipulators	ROVs	Crane or gantry mounted devices	Master-Slave Manipulator type manipulators	Manual deployment within constraints of H+S Legislation
Employment	Usually requires team of skilled operators/ technicians to maintain/ operate. Often reliant on specialist companies to supply/ support/ maintain. Automation has the ability to reduce the demand for a large labour force.	Similar to robots and tele-manipulators, but not quite as demanding.	Probably the least demanding option.	May require skilled operators with experience of handling these tools.	Dependent on the actual dose levels, this option may require a large team of operatives. Usually non specialist / unskilled workers but still require training in nuclear practices.

7.4 Summary

In summary, under Task 1.6, the following activities were achieved:

- A set of criteria for the selection of irradiated graphite retrieval equipment were produced.
- A process for the interaction between overall waste management strategy selection and retrievals equipment selection was proposed. Selection of an integrated waste management strategy must precede retrievals equipment selection.
- An assessment of retrievals equipment categories against the criteria was completed. This will inform detailed assessments required for each waste stream.
- The retrievals equipment selection criteria could be modified in the future as more information becomes available and the criteria are tested.

8 Synthesis (Task 1.7)

Task 1.7 comprises the synthesis of information between all the CARBOWASTE work packages. There has been significant interaction with the other work packages during the development of the integrated waste management approach for irradiated graphite and a number of methods used to disseminate information produced during the project.

The CARBOWASTE User Group (CUG) was established in the first year of the CARBOWASTE project (2008) as a forum for interested parties from the international graphite community to:

- share knowledge on the broader international irradiated graphite landscape;
- inform users of progress made during the CARBOWASTE project;
- disseminate the outputs of the CARBOWASTE project; and
- provide a forum for the user community to advise the CARBOWASTE consortium.

The membership of the CUG included utilities, regulators, waste management authorities, engineering groups, research and technology organisations, and academia.

CUG meetings were organised to run annually in parallel with the Electric Power Research Institute (EPRI) International Decommissioning and Radioactive Waste Workshops (Table 14).

Table 14. Carbowaste User Group meetings

Date	CUG Event	Location
29 October 2008	7th EPRI International Decommissioning and Radioactive Waste Workshop	Lyon, France
7 October 2009	8th EPRI International Decommissioning and Radioactive Waste Workshop	Hamburg, Germany
4 November 2010	9th EPRI International Decommissioning and Radioactive Waste Workshop	Madrid, Spain
21 September 2011	10th EPRI International Decommissioning and Radioactive Waste Workshop	Sweden
24 October 2012	11th EPRI International Decommissioning and Radioactive Waste Workshop	Rome, Italy

The CUG meetings featured presentations from the CARBOWASTE work packages, other graphite R&D programmes and industrial and user perspectives [20]. The meetings have allowed information from each work package to be disseminated during the course of the CARBOWASTE project.

Within Task 1.7, reports produced under the CARBOWASTE project have been disseminated to the CUG. Members of the CUG were provided with access to a special CUG forum on the SINTER document management system to aid dissemination of the CARBOWASTE project findings.

Data, information and analysis from each of the work packages have been collated and a summary produced [21] to provide a record of the main achievements and findings from each work package. This provides a concise source of information from which readers may develop methodologies for the management of irradiated graphite that are appropriate to their specific requirements. The report provides information at a relatively high level, above the more detailed individual work package summary reports. It also supports the final project 'synthesis report'.

An overall summary report for the CARBOWASTE project, the 'synthesis report' [22], has been produced to bring together the overall learning from the project. The synthesis report is a high level document providing a coherent, integrated approach for the management of irradiated graphite wastes, including information on:

- international experience in irradiated graphite management;
- the characteristics of irradiated graphite, graphite management end points;
- retrieval and segregation techniques;
- treatment processes;
- disposal assessments; and
- selection of graphite waste management strategies.

The key findings from each of the CARBOWASTE work packages have been assimilated and a set of overall conclusions for the project presented.

The synthesis report concludes that the project has created a European-wide collaboration on this specialist topic, which has now expanded to global cooperation through the IAEA. The project has achieved a better understanding of graphite waste management options through combining results and findings from different groups. This has started to make a practical difference to national plans and actions in managing graphite. The CARBOWASTE project has been an excellent example of knowledge transfer to the "next generation".

9 Concluding remarks

Work Package 1 of the CARBOWASTE project has achieved the objective of developing an integrated waste management approach for irradiated graphite. This approach enables strategy options for the management of irradiated graphite to be evaluated using MCDA against specific criteria and sub-criteria for each key stage of a route map defining the complete cycle of retrieval, storage, treatment, reuse/recycle and disposal.

The integrated waste management approach provides a tool that Member States can use to support their selection of the most appropriate management options for irradiated graphite, to meet their specific criteria, regulations and other considerations.

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