The Development of an Integrated Waste Management Approach for Irradiated Graphite - 10131

A. W. Banford*, H. Eccles**, R. B. Jarvis* and D. N. Ross***

*National Nuclear Laboratory, Risley, Warrington, Cheshire, WA3 6AS, United Kingdom
**National Nuclear Laboratory, Preston Laboratory, Springfields, Preston, PR4 0XJ United Kingdom
***National Nuclear Laboratory, Central Laboratory, Sellafield, Seascale, Cumbria, CA20 1PG, United Kingdom

ABSTRACT

Globally, irradiated graphite is a significant radioactive waste stream with over 230,000 t requiring treatment, management and/or disposal. This waste has arisen from a wide range of reactors, predominantly from the use of graphite moderated reactors for base-load generation, but also from experimental research facilities. The UK National Nuclear Laboratory (UK NNL) is a participant in a European collaborative research project (CARBOWASTE) which brings together organisations from a range of countries with an irradiated graphite legacy to address this waste management challenge.

This paper describes the progress made within the CARBOWASTE project on the development of a harmonised approach to the management of graphite. In particular, the paper focuses on the synthesis of strategic options for graphite waste management and presents assessment criteria which can be used to evaluate the strategies and to select the appropriate option for each graphite waste stream.

INTRODUCTION

Graphite is used as a moderator in a wide range of reactors. Gas-cooled reactors, Reaktor Bolshoy Moshchnosty Kanalny (RBMK) reactors, plutonium production reactors and some materials test reactors use graphite. During reactor operation the graphite becomes radioactive as a result of neutron activation and, potentially, contamination by fission products. In the short term, retrieval and treatment of the graphite is made difficult by the presence of short lived radioisotopes such as Co-60 from metal impurities within the graphite. On longer timescales, the irradiated graphite is problematic for disposal both as a result of its content of long lived radioisotopes including C-14 and Cl-36 and due to the large quantities to be managed: some 230,000 t exist worldwide.

The CARBOWASTE project aims to develop an integrated waste management approach and so offers consistency among CARBOWASTE participants and facilitates adoption of best practice in the treatment of graphite wastes. The CARBOWASTE project was described at the Waste Management ’09 conference [1]. This paper builds on that early conference paper by describing what has been achieved by the UK NNL in Work Package 1 in the second year of this 4-year project.

One of the major outputs from the CARBOWASTE project is a ToolBox that will allow any stakeholder to assess waste management options. The ToolBox will be sufficiently versatile and flexible to allow stakeholders to input specific information relevant to their needs, for example cost data for treatment technologies, disposal etc. The ToolBox will contain a suite of information and methodologies that allow stakeholders to derive the most appropriate option for them; it does not select an option. Part of this Toolbox is a framework for synthesising and assessing strategic options.

This paper first provides a framework for generation of strategic options which will be considered by CARBOWASTE participants; some examples of potential options are outlined to indicate the range of options that will be considered. Second, the paper then describes a range of criteria which will be applied to assess each option. Finally, this paper outlines a potential decision framework which applies the criteria to assess the options to select the most favourable options for each waste stream.

The CARBOWASTE waste management approach allows sufficient flexibility to reflect differences in the nature and quantity of graphite in different wastes, as well as reflecting differences in policy and facilities available to different participants.

SYNTHESIS OF STRATEGIC OPTIONS

A range of strategic options are available for the treatment of irradiated graphite. In order to allow systematic and consistent review of all options, each of the strategic options can be represented as a number of distinct stages. Each of the processing stages results in material at a defined end point. This is shown in Figure 1 which identifies the following key processing stages:

1. Retrieval and segregation in which graphite is retrieved from its present location and, optionally, segregated into different streams. The resulting streams may be waste streams, or may be suitable for recycle or reuse.
2. Treatment of the retrieved streams may be performed. This might generate material for reuse, or separate the material into high and low activity streams suitable for different disposal options.
3. Disposal is the conditioning and permanent placement of the waste streams in suitable locations.

Each of these stages is now discussed in more detail.

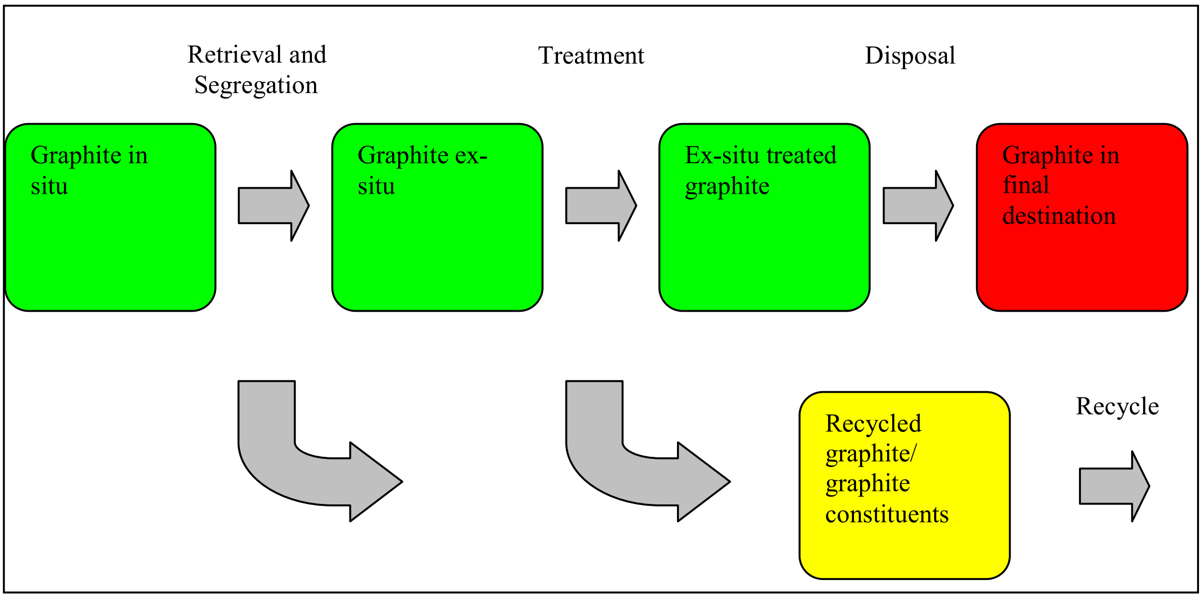

Figure 1: Overview of Graphite Lifecycle

Retrieval and Segregation

The first stage of the graphite treatment process starts with the graphite *in situ* in the reactor core, or in storage facilities. Subsequent operations are illustrated in Figure 2 and are briefly described below:

- The material may be left *in-situ* for a period to allow time for the short-lived activity to decay and facilitate subsequent processing options. This decay period is also a suitable period for material to be sampled and characterised, since characterisation of the graphite may inform the selection of subsequent processing routes.

- There may then be *in-situ* treatment such as thermal treatment or leaching to remove certain radioactive species. This treatment may be intentional, or a side-effect of another decision: for example, if retrieval is conducted under water then leaching may occur.

- Retrieval may take place in a number of different ways, each of which will require the use of different equipment. Some of the options that must be considered include: whether the graphite is to be retrieved as blocks, or as small fragments; whether the retrieval is to be hands-on or performed using remote handling equipment; and whether retrieval is to take place in air or from under water introduced to provide some shielding for operators.

- Segregation may be performed on the material retrieved, either to separate graphite from other reactor components, or to separate highly active graphite from less active graphite.

- Each of the resulting streams may then be further decay stored.

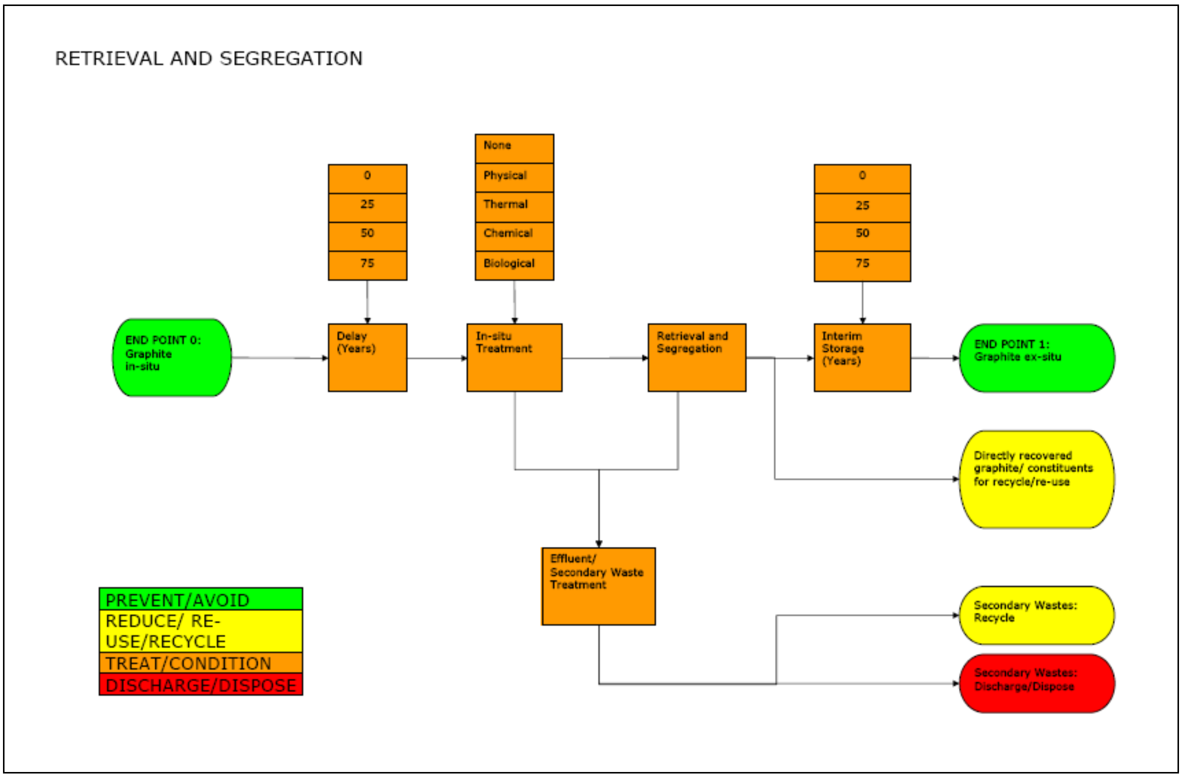

Figure 2: Retrieval and Segregation of Graphite

Treatment

The treatment stage is illustrated in Figure 3 and consists of the following steps:

- The graphite, if subject to *ex-situ* treatment, is 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 is 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.* Options include thermal treatment, chemical treatment or decontamination and physical treatment to remove surface deposits. Treatment may be able to produce materials suitable for reuse or recycle.

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

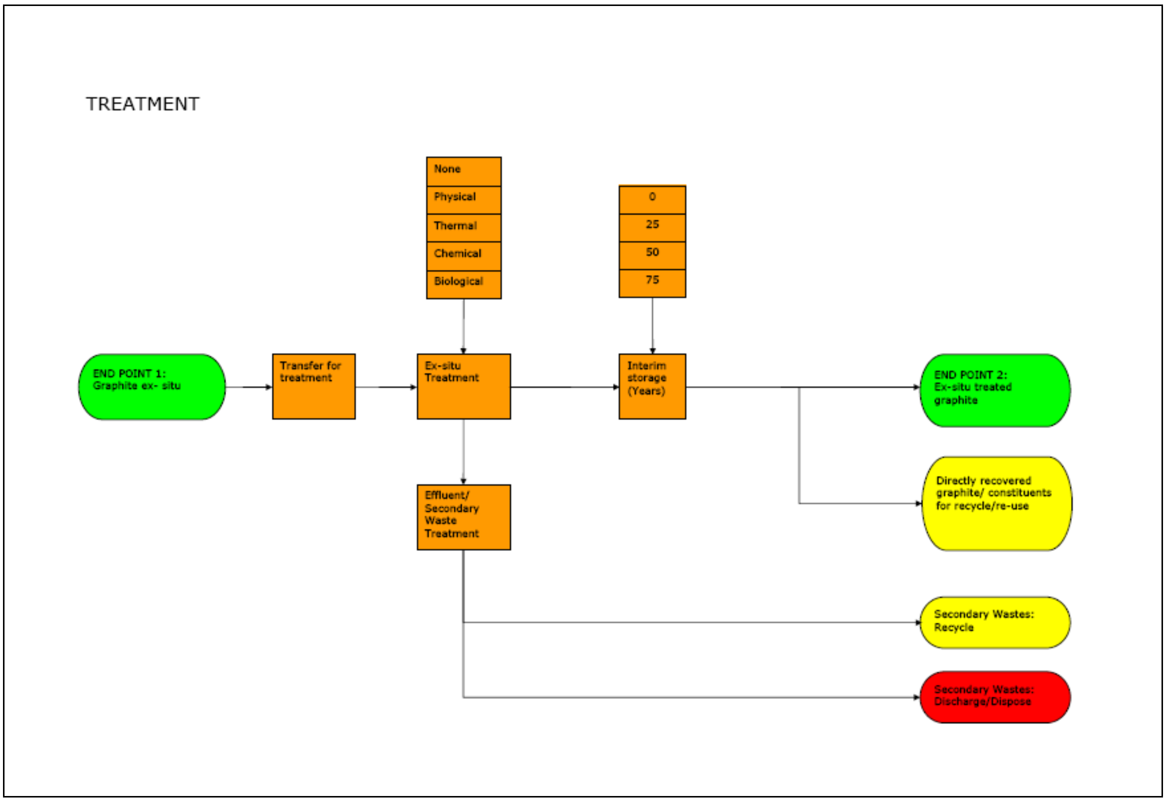

Figure 3: Treatment of Graphite

Disposal

The third, and final, stage encompasses the conditioning and disposal of the graphite. This stage is illustrated in Figure 4.

- Conditioning includes processing the wasteform into a product that meets the waste acceptance criteria for the receiving facility. Typical processes considered here include size reduction, packing and encapsulation.

- Once again, there may be a period of storage. In this period the waste form may be inspected to ensure that the product is acceptable for transfer to final disposal.

- Finally the waste products are disposed of, potentially to multiple destinations.

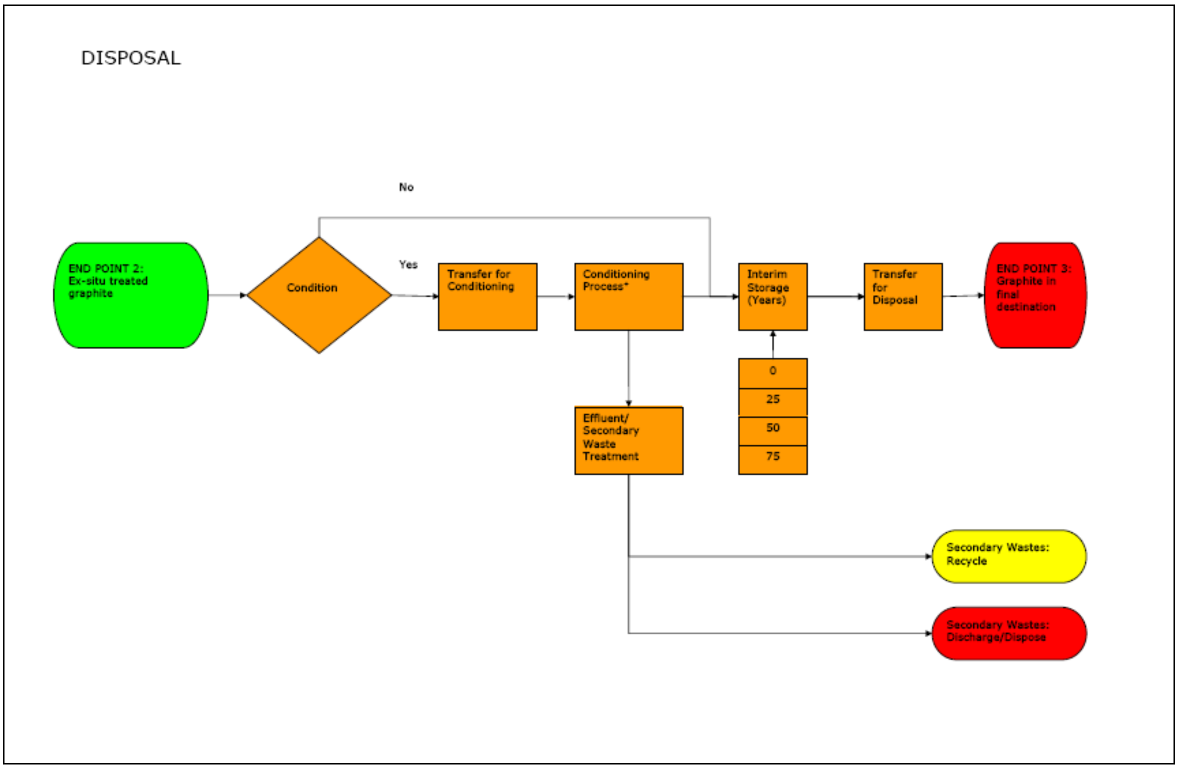

Figure 4: Disposal of Graphite

EXAMPLE PROCESS OPTIONS

The flow diagrams above can be used to construct a range of strategies that will then be compared and assessed. Some scenarios generated through this process are presented in Table 1; the list is not exhaustive but illustrates the wide range of potential scenarios that may be assessed.

CRITERIA FOR ASSESSING STRATEGY OPTIONS

The concept of achieving a sustainable solution to the challenge of irradiated graphite waste management is fundamental to the CARBOWASTE project.

The World Commission on Environment and Development (the Brundtland Commission, [2]) defined sustainable development as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs". It is from this definition that most interpretations of sustainable development emanate. The three objectives or ‘pillars’ of sustainable development are commonly referred to as:

- Environment and Safety;
- Economy, and
- Society.

Table 1: Example Process Options for Graphite Wastes

	Example Process Options
1	A decay store period of 75 years is applied followed by remote retrieval in air. No *in-situ* or *ex-situ* treatment is employed. The retrieved materials are boxed, encapsulated in grout and disposed of to a deep geological repository.
2	The graphite is promptly retrieved using remote handling in air. The graphite is treated to recover C-14 for reuse. The graphite is then pyrolysed and discharged to atmosphere with the ash being grouted, boxed and disposed of to a near-surface repository.
3	A decay period of 50 years is followed by retrieval by fragmenting the graphite and removing using suction. The fragments are gasified and the resulting carbon dioxide is sequestered for disposal. Metal fragments are grouted and disposed to a near-surface repository.
4	The graphite is promptly retrieved from a structure flooded with water to provide shielding. As a result of the flooding some constituents of the graphite are leached out. The contaminated water is cleaned by ion-exchange. The graphite, metal components and ion-exchange material are disposed of to grouted boxes. The waste packages are disposed to surface store.

These three objectives have been adopted as the fundamental objectives against which CARBOWASTE strategy options are to be assessed. These objectives are, however, too broad to be easily assessed and so further detail was required. The criteria were developed by review of the CARBOWASTE project aims and by considering basic principles which should be applied to the development of sustainable waste management processes. In particular the International Atomic Energy Agency (IAEA) nuclear energy basic principles [3], the European Nuclear Safety Regulator Group (ENSREG) principles [4] and the requirements of Environmental Impact Assessment [5] were reviewed. This process produced a set of criteria and sub-criteria which together reflected all the issues needed to successfully apply the objectives of sustainable development.

Based on the review, it is believed that the criteria and sub-criteria together reflect all technical issues that must be assessed to select the most appropriate strategy for a given waste stream. Moreover, duplication among the various criteria and sub-criteria has been minimised. This is important both to minimise the work required in any assessment and to avoid certain aspects being given undue weight during the assessment process.

The criteria and sub-criteria are summarised in Table 2, and then each is discussed to indicate its scope.

Table 2: Criteria for the Assessment of Waste Management Options

Objective 1: Environment and Safety
Criterion 1: Environment and Public Safety
Sub-criterion 1.1: Radiological Impact – Man
Sub-criterion 1.2: Radiological Impact – Environment
Sub-criterion 1.3: Resource Usage
Sub-criterion 1.4: Non-radiological Discharges
Sub-criterion 1.5: Local Intrusion
Sub-criterion 1.6: Hazard Potential
Criterion 2: Worker Safety
Sub Criterion 2.1: Radiological Worker Safety
Sub Criterion 2.2: Non-radiological Worker Safety
Criterion 3: Security
Objective 2: Economic
Criterion 4: Economic Cost and Benefit
Sub-criterion 4.1: Cost
Sub-criterion 4.2: Spin-off
Criterion 5: Technology Predictability
Sub-criterion 5.1: Concept Predictability
Sub-criterion 5.2: Operational Predictability
Objective 3: Social
Criterion 6: Stability of Employment
Criterion 7: Burden on Future Generations

Criterion 1. Environment and Public Safety

This criterion considers the potential for the 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.

Impacts are those due to both regulated discharges to the environment, and potential accidents resulting in releases to the environment. Releases may be radiological or non-radiological (e.g. toxic materials), or a mixture of both. The impacts are assessed by a number of sub-criteria:

- **Radiological Impact - Man**. This sub-criterion considers the impact of regulated discharges on man. The potential effect of accidents is considered in the separate category "Hazard Potential". The world collective dose arising from discharges from all facilities associated with an option (storage, retrieval, treatment and disposal) is calculated over a long period (in the UK 1 million years is considered an appropriate time horizon, though CARBOWASTE participants can select time horizons appropriate to their waste streams). While the world collective dose is known to be dominated by a large number of very low risks, it is still felt to be an appropriate relative measure and so this measure is recommended to derive the score for this sub-criterion.

- **Radiological Impact – Environment.** There is no guarantee that a measure of collective dose to man will adequately reflect harm to other parts of the environment. Recently the Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA) programme [6] has established a three-tier approach to assessing the impact of radiation on the environment. The first screening tier defined by ERICA provides a measure of the impact of radiation on the environment. This measure compares the concentration of radioisotopes in the environment to a value which results in a broadly acceptable dose to the most vulnerable organism. When the resulting quantity is summed over all radioisotopes a measure of the impact of the radiation on the environment is obtained. A tier 1 ERICA assessment produces a measure comparable to collective dose, but applied to the most exposed organisms in the environment rather than to man.

- **Resource Usage**. Various options may use more resources than others. These resources may include water, power, steel and concrete. It is suggested that these resources can be combined into a single measure by considering the energy used to produce the resources. For example, power for mining ore, extracting iron and producing steel would all be considered in the impact of using steel. Similarly, power used in the extraction and processing of minerals used in manufacture of concrete can be considered. This approach assumes that the detriments arising from use of power (e.g. global warming as a result of CO_2 discharges) dominate over the other detriments of depleting natural resources. This would cease to be true if world stocks of a resource were significantly depleted by completion of a particular option.

- **Non-radiological discharges**: In addition to the impacts of radiological discharges, the impacts of non-radiological discharges must be considered. Similarly to radiological discharges the impact must be assessed over all stages of the project for a significant time. Non-radiological discharges to water and air will be assessed by comparison to Environmental Quality Standards (EQS). The discharge of each material (in mass units) will be divided by the EQS for the material to give the amount dilution required to reduce the material to the EQS. The sum of these dilution factors over all species is treated as a measure of the impact of non-radiological discharges.

- **Local Intrusion**: This sub-criterion assesses the impact of noise, increased construction traffic, transport, artificial light, vibration and land use on man and the environment.

- **Hazard Potential**: Previous sub-criteria have considered the impact of regulated discharges on man and the environment. However, these sub-criteria have not considered the potential impact of accidents. In principle, such incidents could be incorporated into the sub-criteria above by considering the each potential accident's probability and consequences. In practice this results in large consequences and small probabilities being combined. The result is very sensitive to the probability which is difficult to establish without considerable work and is consequently rather difficult to explain to stakeholders and time-consuming to generate for a wide range of strategies. For this reason, the hazard potential [7] is considered as a basis. The emphasis of the sub-criterion is to encourage the selection of passively safe techniques with minimum hazardous inventory. Assessment is performed by multiplying the maximum mass of potentially mobile material (gases, liquids and powders) in each process stage by the number of years the process stage will continue to operate and by a risk factor which considers the probability of an incident, and a modifier for accidents considered essentially irreversible.

Criterion 2. Worker Safety

Criterion 1 above considered public safety as part of the environment, however the workforce will be exposed to risks over and above those borne by the public since they are working on a nuclear licensed site which is undergoing decommissioning. It is therefore important that worker safety is considered to select the preferred strategy option. Both radiological (dose) and non-radiological hazards (e.g. falls, asphyxiation) are considered as sub-criteria.

Criterion 3 Security

The Hazard Potential sub-criterion discussed above encourages passive storage of material. This assists in the mitigation of both accidents and security issues. However security must also consider the protection afforded against deliberate, malicious misappropriation of materials. Protection against misappropriation requires storage of materials on well protected sites, in well protected buildings and in difficult to move packages. Materials must also be protected during transport where sites and buildings provide no protection. The assessment is conducted at the point where the waste is most vulnerable since misappropriation is a deliberate action which can be targeted.

Criterion 4: Economics

Cost of project delivery must consider all aspects of the project including research and development, design, capital expenditure and operating costs. The measure to be used is the discounted lifecycle cost over the same period of time agreed for the environmental assessment. Due to the use of discounting of future expenditure, this measure will be less sensitive to future actions than are the environmental effects. Assessment of cost is complicated by the need to determine appropriate marginal costs of use of centralised resources such as waste repositories.

The potential economic benefits of use of research results in other arenas must also be considered.

Criterion 5: Technology Predictability

Options may differ in processing rates and so the time they take to achieve the desired end-point and in the degree of robustness of the options to uncertainty in performance.

Processing rates are considered by other sub-criteria. For example, slow processing rates will result in extended timescales and so increased cost. It has therefore not been considered necessary to have a processing rate sub-criterion. However, there will be uncertainty associated with the feed materials, and potentially equipment performance when it is deployed and resilience to uncertainty is not considered elsewhere.

Two aspects are considered:

- **Concept Predictability**: This considers the uncertainty associated with the technology chosen for a particular option. Well tested technology has lower risk than completely new concepts.

- **Operational Predictability**: This considers the uncertainty associated with the operation of a particular technology option. Uncertainty may be a result of feed variability, unreliability or equipment complexity or lack of experience with the technology.

Criterion 6: Employment

Economic factors include, at their simplest, the cost of delivering the project. However, wider economic factors such as employment must also be considered. Delivery of some options will result in greater levels of employment than others. A simple measure of number of employees does not seem appropriate. This sub-criterion therefore considers wider economic concerns such as targeting areas of high unemployment, acquiring transferable skills and stability (rather than absolute levels) of employment.

Criterion 7: Intergenerational Equity

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 here. Particular aspects are inter-generational costs, effort and environmental impact.

APPLICATION OF THE CRITERIA TO STRATEGY SELECTION

Figure 5 summarises the option evaluation process for graphite management. Following option identification, the option screening phase eliminates some options prior to detailed assessment. Identification of constraints that will result in options being eliminated at this stage is a matter for individual CARBOWASTE participants, however it is thought that compliance with national and international regulation is one constraint that would be applied, others might include requirements for site reuse that impose a time-scale for completion of the decommissioning activity. The options are then assessed using the criteria and sub-criteria described above. Option assessment requires each option to be assigned a score for each of the criteria and sub-criteria, with the highest scoring option being the most preferred. The details of scoring 'scales' are being developed as part of the CARBOWASTE project. Sub-criteria scores are aggregated into criteria scores, criteria scores are aggregated into objective scores, and finally into an overall option score using a series of option weights.

On completion of the option assessment phase, the preferred option is selected by CARBOWASTE participants, taking into account any external factors e.g. political, which are outside the CARBOWASTE project scope.

During the next phase of the CARBOWASTE project, the team will define measures for each of the subcriteria, synthesize options for each waste, and assess options against the criteria.

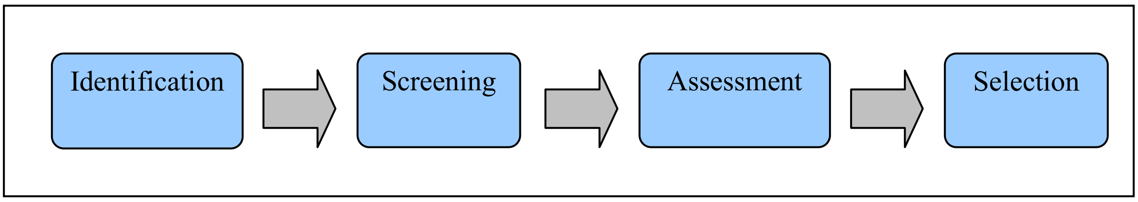

Figure 5: Option Evaluation

CONCLUSIONS

Globally, irradiated graphite is a significant radioactive waste stream with over 230,000 t requiring treatment, management and/or disposal. This paper has described the progress made within the CARBOWASTE project towards the development of a harmonised approach for the management of graphite. In particular, the paper has suggested a framework for the synthesis of strategic options for graphite waste management and has presented assessment criteria which can be used to evaluate the strategies and to select the appropriate option for each graphite waste stream.

The CARBOWASTE project will next define measures for each of the subcriteria, synthesize options for each waste, and assess options against the criteria.

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