Selection of Retrieval Techniques for Irradiated Graphite during Reactor Decommissioning - 11587

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ABSTRACT

Globally, around 230,000 tonnes of irradiated graphite requires retrieval, 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. Much of the graphite is presently still in the reactor core while other graphite is stored in a variety of forms in waste stores. The first step in the management of this significant waste stream is retrieval of the graphite from its present location. Doosan Babcock and the UK National Nuclear Laboratory are participants in the CARBOWASTE European research project which brings together organisations from a range of countries with an irradiated graphite legacy to address the graphite waste management challenge.

This paper describes the issues associated with retrieval of graphite from reactors, potential approaches to graphite retrieval and the information needed to select a particular retrieval method for a specified application. Graphite retrieval is viewed within the context of the wider strategy for the management of irradiated graphite waste streams. The paper identifies the challenges of graphite retrieval and provides some examples where modelling can be used to provide information to support retrievals design and operations.

INTRODUCTION

A four year collaborative European Project 'Treatment and Disposal of Irradiated Graphite and other Carbonaceous Waste (CARBOWASTE)' was launched in April 2008 under the 7^{th} EURATOM Framework Programme [1]. The aim of the project is to develop best practises in the retrieval, treatment and disposal of irradiated graphite (i-graphite), addressing both existing legacy waste as well as waste from graphite-based nuclear fuel resulting from a new generation of nuclear reactors (e.g. V/HTR). The consortium is led by Forshungszentrum, Juelich (FZJ) in Germany and involves 29 partners from Belgium, France, Germany, Italy, Lithuania, Netherlands, Romania, South Africa, Spain, Sweden and the United Kingdom.

Approximately 230,000 tonnes of legacy graphite exists worldwide. The majority of this irradiated graphite, or i-graphite as it is referred to in this text, currently resides in the

UK, France and the former Soviet Union and results from the use of commercial power-generating reactors. Irradiated graphite is also found in demonstration and research reactors in many countries around the world.

The CARBOWASTE project was set up to develop integrated waste management strategies for legacy i-graphite reflecting the diversity of policy and regulations that exist between the various states of the European community. In the UK, for example, i-graphite is considered as waste unsuitable for disposal in the existing LLW (low level waste) repository while in France plans are to dispose of i-graphite at a considerably shallower depth than has previously been considered in the UK.

The research team considered how an integrated solution could be developed. It was recognised that a 'toolbox' approach would be necessary, developing knowledge based on previous practise, where possible, that individual States, utilities or regulators could further develop to provide local solutions.

The CARBOWASTE project comprises 6 principal work packages:

Work Package 1	Integrated Waste Management Approach [2, 3]
Work Package 2	Retrieval and Segregation
Work Package 3	Characterisation and Modelling
Work Package 4	Treatment and Purification
Work Package 5	Recycling and New Products
Work Package 6	Disposal behaviour of Graphite and Carbonaceous Waste

29 Beneficiaries in 10 European States and South Africa, who have examined the gaps in knowledge, are undertaking specific tasks to fill in gaps and developing a toolbox of techniques to assist waste managers and others to reach preferred and pragmatic solutions. The project is also promoting knowledge, understanding, and skills among new entrants to the industry, a key EU requirement.

Current experience of legacy i-graphite retrieval and segregation comes from the completion of several decommissioning projects. These include; GLEEP Research Reactor Harwell, Windscale AGR, Vandellos 1 silos, Fort St Vrain and Leningrad NPP. An overview of three of the above cases is given in this work. Currently no i-graphite core removal from large scale commercial reactors has been observed.

This paper presents the main findings from the work package on retrieval and segregation of legacy waste. The work has focused mainly on the two approaches that might be adopted, via retrieval and segregation in-air or underwater. The paper also gives some examples of where developments in modelling may assist the planning of graphite retrieval and segregation.

RETRIEVALS AS PART OF AN INTEGRATED WASTE MANAGEMENT STRATEGY

As part of the CARBOWASTE project, a set of criteria for assessing different integrated waste management options has been defined [4]. The criteria are shown in Figure 1. Each of the criteria was expanded into a set of sub-criteria to reflect the information needed to assess an option. This process was completed for the whole lifecycle of a graphite treatment option and so is outside the scope of the present paper, however those parts directly related to retrievals are summarised here.

The selected waste route has a significant impact on every stage of the integrated waste management strategy, including retrievals. In addition to this, the key issues impacting on an integrated waste management option directly related to retrievals were:

- **Economic Cost - Preparations Needed**: the structure must be assessed to determine ability to access the graphite requiring retrieval; restrictions may be imposed by the size of penetrations or weight limits. If existing cranes are to be used then these may impose load or access constraints. There may also be a need to fit equipment for the suppression of dusts, depending on the retrieval technique chosen. The radiological properties of the graphite and other parts of the reactor structure must be defined. This allows the crucial selection of when remote operations can be replaced by hands-on operation. Hands-on operation is more flexible and cheaper, but is not possible if radiological dose to workers would be too high. There is also a need to prepare utilities and infrastructure and to perform R&D to develop and test equipment.
- **Economic Cost - Men/Machines/Treatment Needed**: the performance of the men and machines to be used will dictate the duration and cost of the retrievals phase. The i-graphite condition will affect this choice and the assessment must take into account the changes in graphite properties during reactor operation. For example, the graphite swells and blocks may interlock, and the graphite becomes porous and may not be sufficiently strong to allow some types of grabbing during retrieval.
- **Worker Safety - Radiological Safety**: Dose to workers must be minimised. This may make hands-on operations difficult or impossible early in retrievals. It may be possible to perform remote operations to allow man access later in the retrievals process, or to increase shielding.
- **Worker Safety - Conventional Safety**: a retrievals site possesses the usual hazards associated with demolition: falls from height, asphyxiation and so forth. This may suggest the use of machines for certain tasks.
- **Technology Predictability - Technical Risk**: this affects the likelihood of the equipment performing as planned. Highly complex equipment often carries high risks of unforeseen operational difficulties in an active environment if it is inadequately tested. Conversely, hands-on actions can often be deployed more flexibly, although unforeseen levels of radioactivity may bring work to a halt. Minimising risk by maximising retrieval system operability is a key consideration for retrievals.

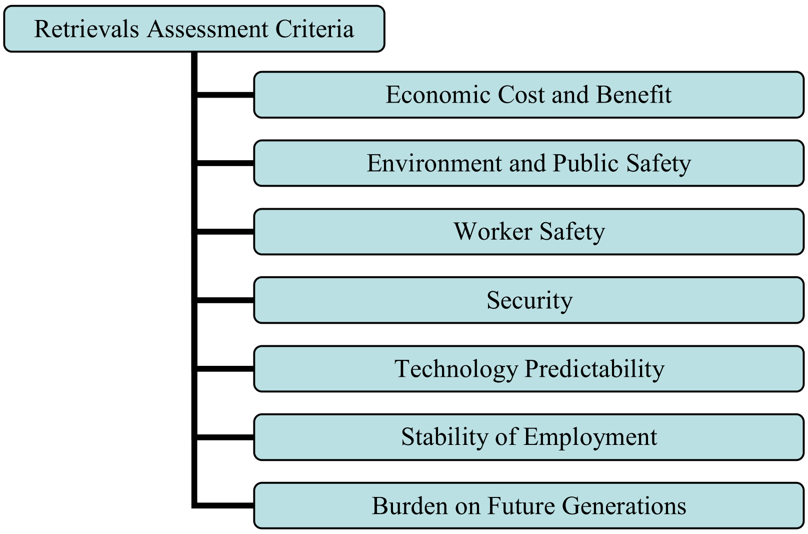

Figure 1: Retrievals assessment criteria

THE GENERIC RETRIEVAL AND SEGREGATION PROCESS

The CARBOWASTE project developed the generic flow diagram for retrievals and segregation which is shown in Figure 2. The key influences in retrievals process selection were identified above. In summary these are: the primary waste route, the access within the reactor, the i-graphite condition, the working environment, and operability. The generic flow diagram is intended to fit the majority of i-graphite retrieval and segregation projects. Each step of the flow diagram is discussed below.

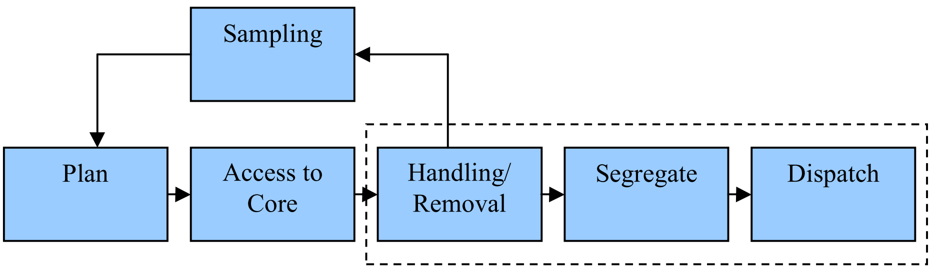

Figure 2: Generic flow diagram for an i-graphite retrieval and segregation process

Plan

The planning step requires the following information to be obtained:

1. Regulatory requirements.
2. Description of the original reactor design.
3. Records of operational history that may impact on i-graphite condition.
4. Review of previous experience that has been applied to access the core, for sampling, handling and removal of i-graphite.
5. Timescale/Endpoints.
6. The available waste routes.
7. Risk Management - relating to the feasibility of the process.
8. Costing for the retrieval and segregation options.
9. Use of existing infrastructure/staff/knowledge should be considered as far as possible to avoid unnecessary expenditure, minimise risks and encourage process rationalisation.

Access to Core

The access step is integral to the retrieval process. The processes that need to be considered when designing access include:

1. Access for retrieval equipment and other processes associated with segregation, volume reduction or processing.
2. Routes out, i.e. how the graphite approaches the access point, the export through the access, which for example may involve airlocks/gamma gates.
3. Reach all parts from the point of view of size of core, layout of core and obstructions, range of jigs/tools and how these are safely supported, viewed, controlled and recovered.
4. Environmental controls: a. Dose/shielding/containment b. Air/water/gas management and quality c. Dust management d. Sealing
5. Existing or new routes.

Handling/Removal, Segregate, Dispatch

Handling/Removal, Segregation and Dispatch involve many similar and integrated operations and so it was decided to review this group of activities together. The issues that affect this entire process are:

1. Sampling/validation for risk management, health and safety, and

	environmental management purposes. Radiation and Physical/Mechanical properties need to be understood and/or estimated.
2.	Working environment: - Air/Gas/Water.

In selecting the appropriate processes, tools and procedures the following need to be understood:

3.	Physical dimensions and geometry of containment and components.
4.	Condition of i-graphite and other components for lifting.
5.	Choice of Solutions (e.g. tools appropriate to the environment).
6.	Protection - Proximity optimisation.
7.	Risk and Hazard Analysis.
8.	Mechanical and Chemical Engineering Design; e.g. Graphite supporting systems (structure to handle tooling loads and facilitate efficient handling and movement of i-graphite).
9.	Process and Logistical Engineering; e.g. Secondary Wastes, Number of operations, and Technology status (including reliability, integrity, durability, suitability, and functionality).

Sampling

The sampling of i-graphite is a key and vital part of the process but sampling itself requires, planning, access to core, handling/removal, segregation and dispatch as well as analysis. So it was not considered separately, but is included in the discussion above.

RETRIEVAL CASE STUDIES

Learning from past experiences is integral to safe retrieval and segregation of future i-graphite decommissioning projects. The following section gives a brief overview of the removal of legacy i-graphite from three reactor cores. Each of the cases presents an example of where utilising different access routes to the reactor core and tooling selection were selected to best suit the retrieval activity.

GLEEP – UK

The retrieval process for i-graphite in the Graphite Low Energy Experimental Pile (GLEEP) reactor represents a low background activity retrieval process that was carried out in-air.

The GLEEP reactor at Harwell was the first reactor in Europe, built in 1946. It was also a low energy test reactor and although it operated for over 40 years, radiation doses received by the graphite were not high. In fact, much of the GLEEP core was dismantled manually with the aid of a simple lifting hoist. The primary lifting mechanism for the graphite blocks was a process called drill and tap, placing a group of blocks in a basket, hoisting them out of the reactor and lowering to a floor monitoring station and shredding plant prior to dispatch in plastic drums for thermal treatment (see Figure 3a and b). Outside the reactor, blocks were handled by vacuum lift and a conveyor table.

Core graphite from GLEEP was lifted from its position within the core into steel baskets using the combined drill-tap bits within a sprung housing. The flat base of the tool was placed on the upper surface of the graphite brick and the tool pushed down until all three drill bits drilled into the graphite (see Figure 3c and d). The bits cut and threaded holes before remaining in situ, allowing subsequent lifting of the bricks using the same tool. The drills would then be reversed to release the bricks [5, 6].

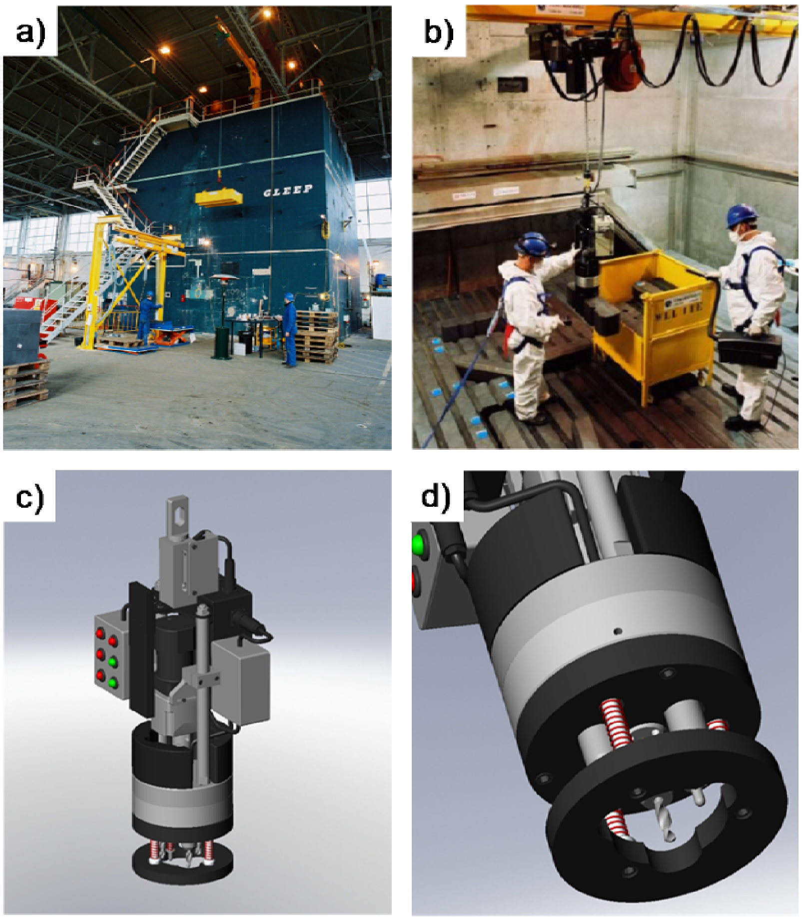

Figure 3: Images a) and b) are from the decommissioning operation and the retrieval of i-graphite from the GLEEP test reactor [6]. Images c) and d) show the GLEEP Drill & Tap tool

Windscale AGR – UK

Windscale AGR (WAGR) represents a high background radioactivity retrieval process that had to be carried out entirely using remote systems. However, some earlier intervention works to gain entry to the reactor containment involved manual intervention. The process was carried out in an air environment.

The WAGR was decommissioned in nine phases, not all involving the removal of i-graphite. Access to the reactor was by removing the head of the pressure vessel and installing a remote dismantling machine, which supported various manipulator arms and hoists. The tooling to remove the i-graphite was supported from both arms and hoists and tools used included ball grab for blocks with channels in them, drill and tap, grabbing, sweeping and vacuum lifting.

WAGR was built using the same type of PGA graphite as the proceeding UK's Magnox reactors. In contrast the UK's commercial AGRs used Gilsocarbon in their core construction, which behaves differently to PGA graphite. Thus tools and techniques applied during decommissioning of the WAGR graphite core are directly relevant to UK Magnox reactors but must be carefully assessed prior to application elsewhere. WAGR was operated at relatively low energy throughout its lifetime and so the radiation doses seen by the core graphite were much lower than those in commercial Magnox reactors. As such, material properties are likely to be considerably different.

A tool successfully used for removal of graphite from WAGR was the ball grab shown in Figure 4a. This is an internal expander type tool consisting of a mandrel which is inserted into the inner bore of the graphite brick (e.g. the fuel channel) before steel balls mounted within the mandrel engage with the graphite. The tool uses a ball and taper mechanism as shown in Figure 4b. Under the effect of gravity the balls apply sufficient contact forces when the mandrel is raised to overcome the weight of the graphite brick.

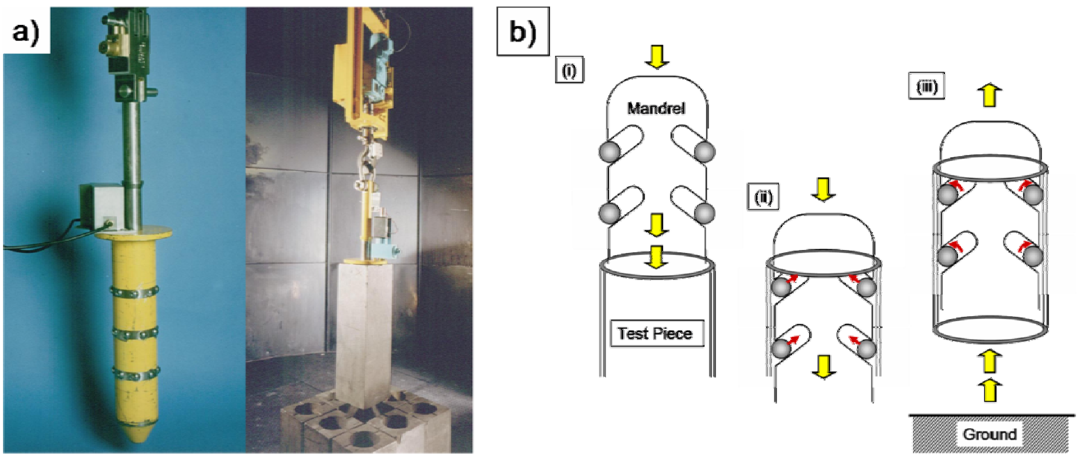

Figure 4: a) WAGR Ball Grab tool, and b) Schematic representation of Ball and Taper mechanism, showing i) mandrel with balls fully extended – at rest position, ii) balls inserted into mandrel whilst lowering into the test piece/graphite brick – balls

remain in contact with test piece surface throughout, and iii) Pull Out – as lift is applied radial grip force of balls increases allowing the tool to lift the test piece

Fort St Vrain – USA

Fort St Vrain represents the case study of high background radioactivity retrieval and an example of i-graphite retrieval undertaken underwater. The process was carried out using remote systems. Fort St Vrain's graphite was removed as part of the fuel route with only reflector graphite being part of the decommissioning process. This example is discussed in more detail in the USA sub-report of the Work Package 1 Review Report [7].

The project was primarily of interest in terms of demonstrating the reactor access underwater and the underwater retrieval methods utilised. A very similar approach is being considered for Bugey in France [8, 9].

The plans for Bugey also include a retrieval process using water as a shield to limit the high radiation environment that will be encountered during i-graphite removal and reactor decommissioning. This approach will be taken because of the need to dismantle in less than 25 years post closure and to be able to use i-graphite handling techniques, which because of the presence of water allows worker proximity to the i-graphite and associated visibility of the workface. The presence of the water adds a variation in that some Cl-36 is expected to be extracted from the i-graphite and Bugey requires a water treatment system as opposed to GLEEP and WAGR which were concerned with airborne discharges.

WORKING ENVIRONMENT

The case studies of GLEEP, WAGR, and Fort St Vrain present the selection of two possible working environments for the retrieval of i-graphite; in-air and underwater.

In-air

The selection of i-graphite retrieval in-air, remotely or with manual intervention, presents the problem of dust management. Such operations require the selection of tools that keep dust formation to a minimum and the need to ensure that tools and instrumentation do not become clogged. There is also the need to collect the dust generated by the i-graphite retrieval/tooling operation by the use of dust suppression systems and HEPA filters. There is also then the need to ensure correct disposal of these filters.

High levels of dust were collected in HEPA filters during the i-graphite retrieval at the Windscale AGR reactor leading to the disposal of significant numbers of filters in the same disposal boxes as the i-graphite.

To date, water sprays have not been used to suppress dust generated by retrieval operations in-air. Water sprays were deployed at the GLEEP reactor but only on the concrete bioshield dismantling and not the i-graphite retrieval operation. As previously mentioned, the drill and tap tooling method was selected for graphite handling at GLEEP. Reports suggest that this tooling method was non-aggressive, producing only a small pile of debris/dust that could be collected easily by a vacuum cleaner [6, 7].

Underwater

Underwater retrieval operations provide the benefits of radiological shielding, dust suppression, and use of more reliable closer approach tools.

Potential pit falls to operations underwater include the requirement to design the equipment to be submersible and corrosion resistant to the specific water chemistry expected on the retrieval project and the need to consider retrieval of failed equipment.

Dismantling underwater is not suitable in every case for the same class of reactor due to structural design variations.

When selecting between in-air or underwater retrieval of i-graphite it is important to consider the entire decommissioning operation. In many cases the tools selected for i-graphite retrieval will also be utilised for other reactor decommissioning tasks. The comparison between a transparent shielding protection in the case of water and the need for remote robotic tools supported by remote visual equipment for in-air is a key consideration to remove the risk of not being able to see or interface easily with the work face. Air filtration systems with capability for a high dust burden are not required underwater, but on the other hand water treatment systems to removed suspended solids and maintain water condition and clarity are.

MODELLING TO SUPPORT RETRIEVALS

The key criteria affecting retrievals were assessed and it was found that some of them could be, at least in part, addressed using modelling performed as part of the CARBOWASTE project.

Structural modelling of the stresses in reactor cores was identified as potentially being extremely beneficial in supporting retrieval and segregation operations of i-graphite [10]. Structural modelling may be used to consider structural issues such as the thermal and oxidation impact on a structure, in-core stresses, the locking of bricks, and the importance of understanding the condition of bricks to retrieve. Structural modelling can also be considered and utilised for analysing the structural loading of i-graphite blocks during the direct tooling operations necessary for retrieval operations.

The following section gives three examples of where tooling operations of i-graphite bricks were modelled and shows the structural loads in relation to the irradiated material properties. As referred to in the case studies of GLEEP and WAGR, theses examples include the operations of a) Ball Grab, b) Drill and Tap, and c) Vacuum lift.

Models a) and b) are specific to the removal of i-graphite from the Oldbury core, both as a result of the use of Oldbury core geometry [11], but also the parameters used to calculate the materials properties of graphite after irradiation by utilising GPAS software [12]. However, both models are applicable to any graphite object if geometry and material properties can be provided.

These studies allow an assessment of the loads required in order to lift the i-graphite bricks out of their locations in the reactor core. The potential for the graphite bricks to fracture if loads applied by retrieval operations exceed maximum material properties can also be estimated. Using the models, it is straight forward to perform sensitivity studies to evaluate the effect of various tool design parameters. Such modelling data is considered a valuable technique to support selection of the correct tool for the retrieval application. It is thought that FEA (Finite Element Analysis) of the tooling operation could form an integral part of the CARBOWASTE toolbox.

To simplify the model in a) and b), the geometry of an octagonal graphite brick was reduced to a $1/8^{th}$ segment, as shown in Figure 5a. This simplification assumes symmetrical loading, uniform dimensional change, and averaged irradiated material properties throughout the brick. Such assumptions are commonly not observed in reality but serve the purpose of demonstrating this simplified modelling approach. The finite element models and subsequent analyses were completed using the proprietary general purpose code Ansys [13].

Ball Grab Modelling

The finite element model used for the ball grab assessment is shown in Figure 5a. The ball grab is represented by six rigid spheres, paired at three axial positions. This represents a tool consisting of 24 balls in total, similar in design to the WAGR ball grab tool. The mandrel of the tool is not included in this model as it does not impose any load on the graphite during normal operation.

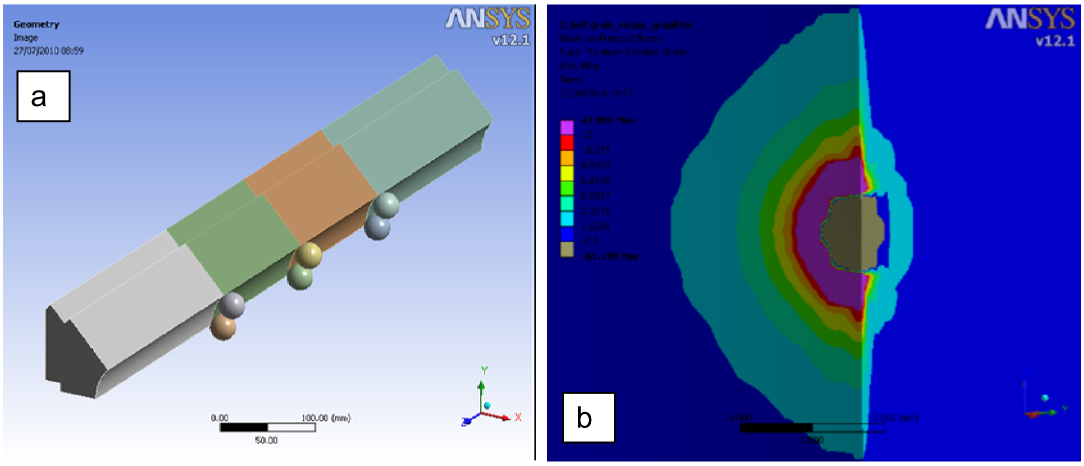

Figure 5: a) Ball Grab finite element geometry and b) Contour plot of stress in Ball Grab Model

Averaged material properties from GPAS [12] were included using the materials behaviour function within Ansys [13]. Material properties were derived for layer 6 of the Oldbury core and averaged across a whole brick.

This modelling approach demonstrates how to calculate the necessary loads that must be applied through this mechanism in order to at least equal the weight of the graphite brick segment. The loads are calculated using the weight of the brick and the coefficient of friction. The result is divided equally by the number of balls in contact with the brick segment. An assessment can then be made on the effects of applying such loads to i-graphite bricks. A representation of the stresses associated with such a tooling assessment can be found in Figure 5b.

The resulting reactions provided a minimum 'pull-out' force required and as such successful lifting could be predicted providing that the total pull out force was greater than the weight of the brick. Through this approach it would be possible to study different pull-out speeds in order to determine a maximum allowable tool velocity.

Drill and Tap Modelling

The finite element model used for the drill and tap analysis can be seen in Figure 6. The model was simplified by not considering the taped thread geometry of the drilled holes. Instead, lifting features for the tooling operation were considered as non-deforming straight-sided cylinders. In reality the threaded hole will have some capacity to change shape under load and so such a constraint is overly rigid. However, it is expected that this will result in additional stress concentrations which will provide a conservative estimate of stress levels during lifting. Consideration of the thread geometry would allow for a more accurate calculation of the stresses on i-graphite during lifting.

The material properties were again calculated from GPAS and were included using the materials behaviour function within Ansys.

This modelling approach demonstrates the ability to calculate the loads experienced during the lifting of a graphite brick under gravity and at different lifting velocities. The maximum principal stress can be seen in Figure 6 for slow lifting and lifting at a speed of 1m/s. In each case, the plot is a cut through section of the brick and exposes the drilled hole.

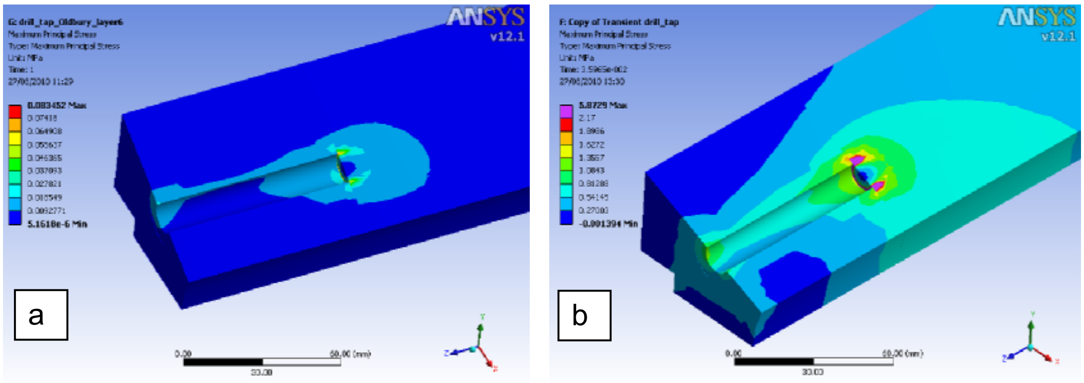

Figure 6: Maximum principal stress due to lifting under (a) gravity and (b) due to lifting at a speed of 1m/s

Vacuum Lift Modelling

Vacuum lifting equipment has previously been used as part of the decommissioning of GLEEP. The equipment has the advantage of requiring no drilling or other modifications to the i-graphite blocks, resulting in minimum dust production and a simpler process.

GLEEP graphite was subjected to much lower irradiation than is the case for full-scale commercial reactors. Higher irradiation results in an increased porosity of the material which can make vacuum lifting more difficult.

A model has been produced which predicts the effectiveness of vacuum lifting for a graphite block with a specified porosity. The model includes the facility to represent the presence of fuel channels and other penetrations which may make handling blocks with vacuum lifting difficult.

The block has been modelled in-air with an applied vacuum on a specified area of one face and the flow of air to the vacuum equipment through the block estimated as a function of time. Given the operating characteristics of the vacuum pump this permits the ability of vacuum lifting equipment to raise irradiated graphite blocks to be assessed.

The model solves Darcy law equations modified to represent (potentially) anisotropic permeability in order to obtain a pressure distribution within the block.

Results can be plotted as pressure and concentration variation throughout the block. A set of results is shown in Figure 7 for a case in which the vacuum is applied to the centre of the top of the block (z=1). Integrating the pressure distribution over the top and bottom of the block allows the force that can be supported by vacuum lifting to be determined. This is compared to the force required to accelerate and/or support the block in order to determine whether vacuum lifting is suitable for the particular application.

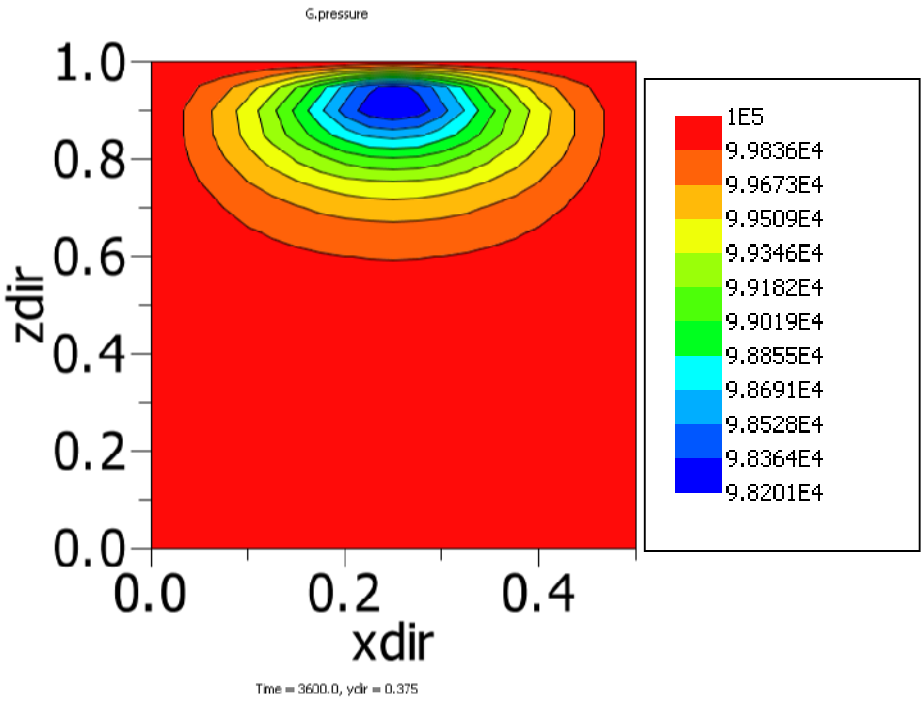

Figure 7: Pressure distribution in a graphite block

CONCLUSIONS

The work presents some of the findings from the current CARBOWASTE project (Work Package 2) on retrieval and segregation of legacy waste. A generic retrieval process of i-graphite has been developed and is analysed in terms of the criteria that control process selection. The key influences are: the preliminary waste routes, the access to the reactor, the i-graphite condition, the working environment (in-air or underwater) and the risk assessment process to select the working environment and operability.

Two finite element models have been developed, based on the WAGR ball grab and GLEEP drill & tap tools, to demonstrate appropriate methods for modelling core graphite retrieval. A third finite difference based model was also developed to simulate vacuum lifting operations.

On the basis of these demonstrations, modelling is considered as a valuable technique supporting tool selection for retrieval and segregation operations of i-graphite. These modelling methods will form an integral part of the CARBOWASTE toolbox.

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