Remote Retrieval, Disruption and Processing of Legacy Nuclear Waste – 16179

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ABSTRACT

The UK National Nuclear Laboratory (NNL) is currently undertaking, in conjunction with Sellafield Ltd, a series of high profile trials of robotic equipment on a full scale test facility at their Workington Laboratory in England. These trials are designed to underpin and substantiate the processes proposed for the remote retrieval, disruption and processing of legacy Miscellaneous Beta Gamma Waste (MBGW) from a number of different donor plants on the Sellafield site, including some of the older fuel storage ponds and storage silos. These processes will be conducted inside the new Box Encapsulation Plant (BEP) which is due to be commissioned at Sellafield by 2020.

These processes will subsequently enable Sellafield Ltd to safely recover legacy Intermediate Level Waste (ILW) from the older storage facilities on site and process it into a safer form which is more suitable for long term storage and then ultimately final disposal in a Geological Disposal Facility.

As part of this legacy waste processing within the BEP plant, MBGW waste items will have to be remotely removed from a variety of different types of import skips. This waste will then be transferred, using robots, into the export container, which is a $3m^3$ box liner, where the processed waste will be flood grouted to produce an encapsulated waste package. As part of this processing, any MBGW items consisting of sealed containers will have to be remotely disrupted before being grout encapsulated. This disruption is in order to (a) release any trapped liquors or gases from the containers and (b) ensure full grout infiltration of the container contents, thus minimising the amount of free liquors and voids within the final waste product.

The NNL are conducting this technical work to confirm the viability of the proposed concept, processes and equipment.

The developed solution consists of a linear layout of processing equipment with a pair of heavy duty, standard industrial, ‘commercially off the shelf’ (COTS) robots positioned around a Waste Handling Table. These robots have a 500 kg payload capacity and are operated remotely to handle all of the various types of MBGW waste, including the heavy and bulky items. The robots can be operated in manual tele-operation mode as well as pre-programmed automatic mode and have a range of primary and secondary tooling in order to perform the waste processing and disruption tasks as well as undertake general house-keeping and cleaning duties within the cell.

The main tools include two types of hydraulic grab for the main waste recovery and handling tasks and a hydraulic shear for the waste disruption activities, but a number of other tools have also been designed and built for ancillary activities, such as a set of general purpose gripper jaws, drilling tool, bolt removal tool, pump tool, spray tool and a number of different housekeeping tools etc.

The robot trials were started in November 2014, and have attracted a significant degree of high level stakeholder interest, including the UK Nuclear Decommissioning Authority (NDA), Office for Nuclear Regulation (ONR), Environment Agency (EA) and Radioactive Waste Management Limited (RWML) witnessing a number of the critical demonstration trials.

Robots of the type selected are readily available, robust, reliable and easy to use. The trials have been very successful in proving the retrieval, processing and disruption operations, reducing the burden in the legacy waste facilities. Utilising robots to perform these tasks will lower the probability of producing non-compliant waste packages. In addition the robots can increase the consolidation of incoming waste skips into outgoing $3m^3$ box liners, significantly increasing packing efficiencies and reducing the overall number of export containers produced thus lowering the decommissioning and waste storage/disposal costs.

The trials have also enabled an assessment of the optimum way to operate the robots, as well as their reliability and maintainability issues. Engineering work associated with recovering failed robots and removing them from a typical Sellafield plant environment and then subsequently replacing them with functioning robots has also been undertaken and further work is now planned.

The success of the trials, completed safely to a very challenging timescale, has enabled the use of robots in BEP to be endorsed as a viable option by the key stakeholders. Following a robust decision making process, this was a clear cut decision. The technical development and testing of the robot technology is currently continuing in order to investigate areas such as robot reliability, failure recoveries, human factors, ease of waste identification, optimisation of throughput rates, nuclearisation modifications etc.

INTRODUCTION

At the Sellafield site in the UK there is a pressing requirement to decommission some of the older legacy facilities such as the fuel storage ponds and waste storage silos, some of which started operations in the 1950's.

As part of the decommissioning of these facilities, they will need to have their radioactive waste contents safely removed. These contents will include a range of Intermediate Level Waste (ILW) such as fuel elements, Magnox fuel cladding swarf, corroded Magnox swarf sludge and large quantities of a wide variety of different types of Miscellaneous Beta Gamma Waste (MBGW).

Sellafield Ltd are currently designing and constructing a new plant on the Sellafield site, known as BEP (Box Encapsulation Plant). The purpose of this new plant is to receive, process, package and then grout encapsulate the legacy Miscellaneous Beta Gamma Waste from a number of these different donor plants on the Sellafield site, including the older ponds and silos.

These BEP processes will enable Sellafield Ltd to safely recover the legacy Intermediate Level Waste (ILW) from the older facilities on site and subsequently process it into a form which is safer and thus more suitable for interim storage and then ultimately transfer to and final disposal in a Geological Disposal Facility (GDF), when the UK has selected the appropriate site. The BEP project is working to an accelerated timescale in order to assist in delivering the Sellafield High Hazard and Risk Reduction programme, and the project has adopted a 'decommissioning mind-set' in order to achieve this.

The UK National Nuclear Laboratory (NNL) is currently undertaking, in conjunction with Sellafield Ltd, a series of high profile trials of robotic equipment on a full scale test facility at their Workington Laboratory in England, see Figure 1. The primary purpose of these trials is to underpin and substantiate the processes proposed for the new BEP plant which is due to be commissioned at Sellafield by 2020.

Figure 1: Full scale test rig at the NNL Workingtion Laboratory

BOX ENCAPSULATION PLANT PROCESSES

The BEP process building will consist of 4 main areas:

1. The Package Import Area: where different types of import containers of ILW waste inside different types of shielded flasks are imported into the facility from the various donor plants at Sellafield.
2. The Waste Treatment Cell (WTC): where all the waste treatment and grouting processes are undertaken remotely as described in detail below.
3. The Box Operations Cell (BOC): where the filled $3m^3$ boxes of processed waste are remotely lidded, bolted up and swabbed for contamination monitoring purposes before transfer to the:-
4. Waste Transfer Tunnel: where the filled and sealed $3m^3$ boxes of processed waste are transferred to the adjacent storage facility for interim storage: the Box Encapsulation Plant Product Store (BEPPS).

As mentioned above, all the waste processing operations are performed remotely inside the Waste Treatment Cell (WTC) of BEP, the proposed layout of which can be seen in the CAD image of Figure 2. Once the cell goes active, man access will be prohibited due to the radiation and contamination levels, as the cell is to be designated as a R5/C5 area.

Figure 2: CAD image of proposed layout of the BEP Waste Treatment Cell (WTC)

At the left hand side of Figure 2 can be seen the waste skip import and buffer storage area where the waste filled import containers, i.e. pond skips (from the fuel storage ponds) and SEP (Silo Emptying Plant) skips from the Magnox Swarf Storage Silos (MSSS) will be imported into the cell and buffer stored pending processing operations by the robots.

At the right hand side of Figure 2 can be seen the grouting and curing stations where the export containers, i.e. 3m^3 box liners, which have been filled with processed ILW will be subsequently flood grouted and then allowed to cure for a period of time in order to produce a fully encapsulated waste package ready for export to the Box Operations Cell (BOC).

All the waste processing operations are performed in the central portion of the Waste Treatment Cell shown in Figure 2, around a Waste Handling Table, which measures 4 m long by 2 m wide. At either end of this table are located two standard heavy duty industrial robots, each capable of lifting a total payload of 500 kg. Each of the robots can be driven in both manual teleoperation mode using a pair of joysticks and also in automatic pre-programmmed mode running pre-taught sequences.

The left hand robot in Figure 2, known as Robot 1, will be driven by the operators to retrieve MBGW from the import container, either a SEP skip or a pond skip, which is located to the left hand end of the Waste Handling Table in Figure 2.

The operators will then remotely identify, by the use of the in cell CCTV camera system, the waste that has been retrieved from the skip using Robot 1. If the operators decide that the retrieved waste does not require further processing, they will use Robot 1 to transfer the waste directly to the export container, a standard

$3m^3$ box liner, located below the central portion of the Waste Handling Table in Figure 2.

If, on the other hand, the operators decide that further processing of the retrieved waste is required, then Robot 1 will be used to deposit the waste onto the central portion of the Waste Handling Table. Another team of operators will then drive Robot 2, the right hand robot in Figure 2, to process or disrupt the waste on the table to an acceptable level of disruption, using a number of different types of tools available to the robots.

The primary purpose of processing or disrupting certain types of waste items is to break them open sufficiently to ensure that;

1. any trapped liquors or gases are released from the interior of the waste items and thus excluded from the export container and
2. during the subsequent encapsulation process, that the liquid flood grout is able to fully infiltrate the internal contents of the waste item.

These two objectives are aimed at (a) minimising the amount of free liquors and (b) minimising the amount of voidage or free spaces within the final encapsulated waste product. This is with the intention of producing a waste package that is compliant with the regulator requirements for eventual final disposal in a GDF, when this becomes available in the UK.

The only waste items that are required to be disrupted by the robot tooling to a degree sufficient to achieve the two objectives above are cans and containers which are considered to be ‘thin walled’. Any waste items that do not contain internal sealed voids, e.g. pipes, do not have to be disrupted. Similarly any sealed containers that do contain internal voids but are considered to be ‘thick walled’ or ‘robust containers’ do not require disruption either.

Any liquor released onto the Waste Handling Table, either from cans and containers during disruption or from table wash down activities with the robot, will flow down the table to a $3m^3$ box liner, known as the Settling Liner, at the right side of the table as seen in Figure 2. Here the liquor will be given a period of time for any solids to settle out before decanting off the clear supernate and transferring it to the effluent management system.

Due to the number of legacy donor plants exporting waste to the BEP plant and the number of years those plants have been operational for, there is anticipated to be a very diverse range and large quantity of waste items delivered in the import skips. The following is a list, though not exhaustive, of some of the waste types expected to be delivered to BEP in the import waste skips:

- Drums, cans and containers (incl. tins and fuel bottles)
- Pipes, hoses and tubing
- Plastic bags and sheeting
- Filters
- Wire rope and reels, cables, slings, chains etc..
- Plant equipment (incl. valves, motors, gearboxes, pumps etc..)
- Generic scrap (incl. chutes, trays, plates, angle iron, bracketry, sheets etc..)
- Boxes (incl. ammo boxes, lug boxes etc..)
- Graphite blocks
- Magnox swarf
- Aluminium doughnuts
- Magnox sludge carryover
- and specific waste types such as Zeolite skips, Ionsiv cartridges, wet bay baskets, SMF (Silo Maintenance Facility) waste, swarf bins etc...

Some of the waste items delivered are expected to be heavy and bulky, which is one of the reasons for selecting the high payload industrial robots, as this provides a capability to handle any waste items as long as they are below 350 kg in weight and below 600 mm length in any one dimension. Any waste items heavier or larger than this will have to be delivered to BEP in a special basket inside the import skip, and this waste will be sent for direct grouting.

In addition the delivered waste will be submerged by liquor in the import skips and is expected to be submerged or coated in significant quantities of corroded Magnox swarf sludge.

The quantity of waste to be processed by BEP from the various donor plants on the Sellafield site is such that the plant is expected to be operating for between 40 and 50 years.

SELECTION OF ROBOTS

As can be seen from Figure 2, the developed solution consists of a linear layout of processing equipment using robots for the remote handling operations. The principle of this layout was proposed and demonstrated with a full scale mock up rig by the National Nuclear Laboratory in 2012, on behalf of Sellafield Ltd. At that time, as it was a ‘proof of principle’ investigation, teleoperated hydraulic Brokk ROV vehicles and hydraulic manipulator arms were used for the remote handling demonstration trials.

Following the successful completion of this work, Sellafield Ltd continued the study and further investigated the optimum type of remote handling device for the tasks to be performed inside the Waste Treatment Cell of BEP. This investigation considered the use of:

1. Master Slave Manipulator (MSM) type of devices.
2. Commercial ‘through the wall’ hydraulic manipulators.
3. Commercial hydraulic manipulator devices such as Brokk type machines.
4. Commercial off the shelf industrial robots.

This analysis concluded that type 4 was the optimum solution for the BEP application due to a number of significant reasons:

- robots are available with a high payload capability,
- robots have high levels of accuracy and repeatability,
- robots are a well proven technology with a high Technology Readiness Level (TRL) rating,
- robots have proven track records of high reliability levels
- robots come with well prove standard features such as automatic tool changing capabilities
- robots are available that can be operated in teleoperation mode,
- but most importantly, being robots, they can operate in automatic pre-programmed mode repeating pre taught sequences reliably and repeatedly thus reducing the workload and stress on the operators.

As man access to the cell for maintenance purposes is prohibited once the cell goes active, the robots obviously have to provide very high levels of reliability and performance over an extended period of time.

As the BEP project is working to an aggressively accelerated schedule for the Sellafield site, the project has adopted a philosophy of

- minimising development work and trials where possible,
- benefiting from Learning From Experience (LFE) from other similar projects and sites,
- utilising, where feasible, proprietary Commercial Off The Shelf (COTS) equipment with a high TRL rating and a proven track record of reliability and performance,
- and on selection of such equipment, minimising (if possible) the amount of ‘nuclearisation modifications’

And hence these points further justified the selection of standard industrial robots for the BEP remote operations.

Following the analysis work mentioned above, Sellafield Ltd continued the investigation of available industrial robots and concluded that the Kuka KR 500 F was the optimum type of robot for the BEP Waste Treatment Cell application. This was confirmed, in December 2013, by an independent study and market survey by the National Nuclear Laboratory of the currently available robots and their suitability for the BEP WTC tasks. This report also concluded that the Kuka KR 500 F was the optimum robot for this application for a number of significant reasons, including the following:

- this robot has a high payload of 500 kgs, but the robot itself weighs less than 3 tonnes (important for remotely recovering a failed robot from cell and deploying a new one into cell),
- this robot uses resolvers rather than encoders for joint positional monitoring and feedback purposes, and is thus inherently more radiation tolerant than a robot fitted with encoders,
- this robot is supplied with a capability of being operated in tele operation mode, using a pair of joysticks, as well as in the more familiar automatic pre-programmed mode,
- this robot can be supplied with a wrist force feedback capability, using a Force Torque Sensor, which provides the operators with very useful additional feedback information when driving the robots,
- this robot can be supplied with area zoning and collision avoidance features, which also provide the operators with useful additional protection when driving two robots in close proximity to each other and in a congested cell environment,
- this robot represents well proven technology, and can be fitted with standard automatic tool changing capability with a wide range of different service provision for the tools,
- this robot has high accuracy and repeatability e.g. ± 0.08 mm,
- this robot is supplied with an IP67/65 rating which is essential for dealing with the wet, dirty and sludgy environment that it will operate in,
- this type of robot has proven high levels of reliability,
- concepts have been developed for robot modifications to enable it to be safely removed from cell in an Emergency Recovery (ER) mode following a robot failure,
- this robot can be supplied with a live 3D CAD simulation of the robots and the cell environment, which provides the operators with useful additional positional feedback information when driving the robots,
- Kuka robots were also being considered or trialled for other projects in the UK nuclear industry handling radioactive materials,
- the robot supplier, Kuka Systems UK Ltd, displayed a willingness and eagerness to work with Sellafield Ltd, NNL and their collaborative partners in delivering an effective solution to the BEP process.

A desktop radiation tolerance assessment of the robot and its individual components is currently being performed, but to date has not identified any major issues or components or materials which will have to be replaced or ‘radiation hardened’ to extend the life of the robot, which is expected to be a number of years in the BEP WTC environment.

One important issue which has to be taken into account in the design of the plant and robot equipment is obsolescence. The robot supplier quotes a product life cycle for each robot of around 10 years, after which each model is upgraded to a newer version. As the BEP plant will be operational for around 40 to 50 years, and man access to the cell is prohibited, the plant design has to be sufficiently flexible and versatile to cater for potentially different robot designs in the future.

ROBOT TOOLING

In order to remotely perform the necessary waste handling, processing and disruption operations inside the Waste Treatment Cell, a range of robot primary tooling has been designed, manufactured and tested on the NNL full scale mock up. In addition, a range of robot secondary tooling has been designed, manufactured and tested in order to perform ancillary tasks inside cell such as general house-keeping and cleaning duties, pumping operations etc.

Primary tools are automatically connected to the wrist unit of the robot when required, and are automatically returned by the robot to their storage locations on toolposts adjacent to the robot when not required.

The current suite of robot primary tools, for each robot, consists of:

- one large and one small hydraulic grab for the main waste recovery, handling and export liner filling tasks (large grab shown in Figure 3)
- one hydraulic shear for the waste disruption activities (Figure 4)
- one set of pneumatic general purpose gripper jaws,(Figure 5), which are used for general pick and place activities of small ancillary equipment and for handling the robot secondary tooling such as the housekeeping tools. The gripper jaws are also fitted with a water spray feature to assist with clean down activities of the table and tooling.

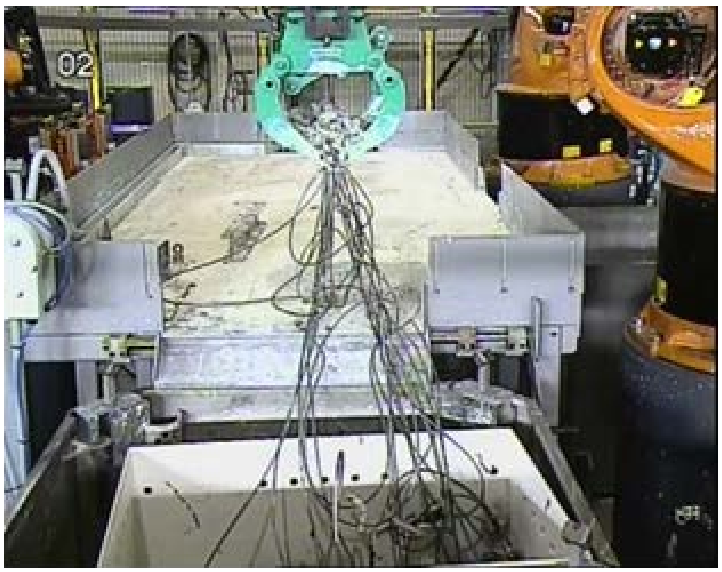

Figure 3: large hydraulic grab handling wire rope onto the Waste Handling Table

Figure 4: Hydraulic shear being used to disrupt mock-up waste can

In addition Robot 1 will be provided with:

- one pneumatic bolt removal tool, which is used for removing the bolts from one specific waste type, an Ionsiv cartridge, to assist with filling it with grout.

And Robot 2 will be provided with:

- one pneumatic drilling tool, which is used for drilling holes in one specific waste type, a Zeolite skip, to assist with draining it of pond liquor and filling it with grout.

In maintaining the BEP Project philosophy of utilising commercial off the shelf (COTS) equipment and attempting to minimise design and development where possible, all the tools mentioned above are based on proprietary commercial units with a minimal amount of modifications to interface them with the robot and its control system.

The current suite of robot secondary tools which are handled using the robot general purpose gripper jaws include the following:

- a pneumatic pump tool which is used for pumping out liquor from the import skips and liners,
- protection features designed to prevent waste material from falling into the lift points of the $3m^3$ box liners,
- a suite of housekeeping tools.

The suite of housekeeping tools, one of which can be seen in Figure 5, consists of a range of simple tools designed to assist in keeping the Waste Handling Table clear of debris, particulate matter and sludge following the waste disruption activities. Other housekeeping tools are designed to extract sludge and smaller debris from the base of the import skips, and to clean the sealing face of the import SEP skip, before export back to the donor plant.

Figure 5: a housekeeping tool for cleaning the table held in the jaw grippers

A typical robot control station can be seen in Figure 6. For the development trials, each of the robots was controlled by a team of three: one robot supervisor and two robot operators. The two robot operators work as a pair taking turns of driving the robot or the CCTV camera control system. The robot supervisor keeps an overview of operations and directs the development trials. It is envisaged that on plant, a team of two operators per robot will be adequate.

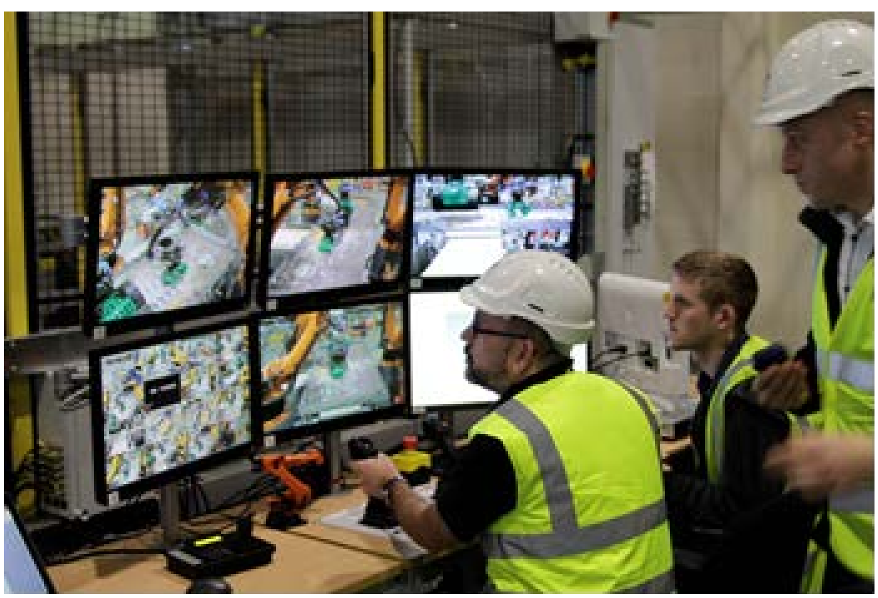

Figure 6: typical robot control station

ROBOT TRIALS

Using standard industrial robots for the tasks required in BEP is a very challenging and arguably an unusual application in the nuclear industry. This is because of factors such as the robots having to work reliably and repeatedly, handling a variety of waste for years at a time in a wet, dirty, sludgy environment with high radiation levels and where no man access is possible for maintenance purposes. In addition, for a large proportion of the tasks, the robots will be driven by the operators in teleoperation mode using CCTV cameras for guidance, and hence there is the potential for accidental maloperation of the equipment.

Because of these factors there was a need, in 2014, to convince certain stakeholders that the robots, their tooling and the proposed process methodologies were capable of delivering the functionality required of them in BEP.

This drove the need for a series of full scale 'proof of principle' trials in the autumn of 2014 aimed at proving the capabilities of the robots and the functionality of the proposed processes. These proving and demonstration trials attracted a significant degree of high level customer and stakeholder interest, including the UK Nuclear Decommissioning Authority (NDA), Office for Nuclear Regulation (ONR), Environment Agency (EA) and Radioactive Waste Management Limited (RWML) witnessing a number of the critical trials.

The robots were delivered to the NNL Workington Laboratory on 20 October 2014. It took only 2 weeks to construct the full scale mock up, install and fully commission all the equipment shown in Fig 1. After just two days of joystick training for the operators, the Proof of Principle Trials commenced on the 6 November 2014.

The initial set of proving trials culminated in a Project Review on 16 December 2014 by the Sellafield Ltd Chief Technology and Engineering Officer (CTEO) who concluded that the use of robots in BEP had been satisfactorily demonstrated to an acceptable standard sufficient to be endorsed as a viable option for the BEP process.

The trials over the past twelve months have utilised a wide range of test materials and sludges loaded into the import skips in an attempt to simulate the behaviour and types of waste expected to be delivered to BEP. The robot operators have then remotely driven the robots, their tooling and ancillary in cell kit, in the manner that would be performed on plant, in an attempt to both prove the equipment and processes and optimise them further.

The trials undertaken in 2015 have enabled the optimum way to operate the robots to be assessed, as well as their reliability and maintainability issues to be determined.

Another purpose of the trials is to prove that the normally very high reliability figures of the robots can be transferred from the normal production environments that the robots are used in to this challenging application where they are, on occasions, being manually driven.

The technical development and testing of the robot technology is currently continuing in order to investigate areas such as robot reliability, human factors, ease of waste identification, optimisation of throughput rates, nuclearisation modifications etc.

Engineering design work associated with equipment and techniques to remotely recover failed robots, remove them from cell and then subsequently remotely replace them with functioning robots is currently being undertaken, and a new test rig to trial this will soon be constructed at the NNL Workington Laboratory. This rig will also test the equipment designed to remotely connect and disconnect the umbilicals to the robot carrying electrical, pneumatic and hydraulic services.

CONCLUSIONS

At the time of writing, the development and proving trials on the full scale mock at the NNL Workington Laboratory have been ongoing for nearly 12 months. During this time all of the wide range and variety of test materials trialled on the rig have been, using two robots, successfully recovered from the different types of import container, handled on and around the Waste Handling Table, disrupted to different degrees as required and then finally deposited in the export container. These operations have been demonstrated remotely using CCTV cameras in the same positions as available on the plant, and have been demonstrated to achieve plant throughput rates that are considered acceptable to Sellafield Ltd i.e. potentially up to two import containers processed per day.

In addition effective housekeeping regimes on and around the table and effluent liquor management systems have been demonstrated using the robots.

Controllable degrees of waste disruption have been demonstrated. In other words, disruption ranging from small holes pierced in the cans, if that is deemed all that is necessary, up to complete destruction of the can, if that is required.

The robots have been demonstrated to have a very high degree of dexterity & control, both in terms of accuracy and repeatability, and this applies in both manual teleoperation mode & automatic pre-programmed mode.

The robots have been found to be reliable, robust and easy and intuitive to operate. Some of the robot operators recruited to be part of the team had no previous experience of remote handling, and yet have become proficient at the tasks required of them with very little formal training being required. This finding was of particular interest to Sellafield Ltd and the relevant stakeholders, as it meant that potentially less specialist personnel could be utilised on plant, and that less extensive training programmes would be needed.

The operators have found the Force Torque Sensors fitted to the wrists of the robots provide very useful additional feedback to them when performing certain activities such as recovering waste from the base of the import containers where visibility from the CCTV cameras can be restricted.

The advantages of using robots to run pre-programmed sequences for the more routine and repeatable operations such as toolchanges and housekeeping activities is ensuring consistent repeatable error free results, and is reducing the operator workload and stress levels.

One of the main advantages of using robots in the Waste Treatment Cell, as opposed to the ‘no robot’ option of direct transfer of the waste for grouting, is that by virtue of the fact that all the waste items are being processed, there is a far greater possibility of producing a final waste package that is less likely to contain voids and liquors and hence has a greater chance of being compliant with the regulators' requirements for GDF disposal. Producing a non-compliant package would imply suitability only for interim storage and then subsequent further processing would be necessary at a later date before being suitably compliant for final GDF disposal.

Another advantage of using robots for the tasks in the cell as opposed to the ‘no robot’ option is that it enables higher waste consolidation and increased packing efficiency of the waste in the export liner. This can lead to a reduction in the total number of export containers being required for the waste inventory, and thus a subsequent decrease in the size of the interim waste storage facility, and ultimately a potential reduction in the size of the GDF, hence potentially contributing to a significant cost saving in legacy waste storage.

Associated with this last point was the efficient ability of the robots to cope with large quantities of plastic bags and sheeting in the imported waste stream, loading them into new sacrificial cans, which the robots compacted when full, thereby ensuring high packing efficiencies, and low voidage and low liquor content in the final waste product.

The success of the robot development and proving trials, completed safely to a very challenging timescale, has enabled the use of robots in BEP to be endorsed as a viable option by the key stakeholders. Following a robust review of the trial results and the benefits that robots bring to the BEP process, the decision making process by the relevant customers and stakeholders led to a clear cut decision in favour of the robots when compared to the no robot option for BEP.