Retrieval of Damaged Fuel from Wet and Dry Storage using Innovative Remote Handling Techniques

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Abstract. James Fisher Nuclear (JFN) has supplied remote handling solutions to the nuclear industry for over thirty years. This paper describes innovative remote handling techniques and equipment used for the retrieval of damaged fuel from both wet and dry storage, plus the removal of damaged fuel in a reactor being de-fuelled prior to decommissioning. In all these cases the fuel could not be retrieved by the installed fuel handling equipment and new solutions were required to remove the fuel safely and cost effectively.

The retrieval of damaged fuel from the dry fuel stores at the Wylfa Magnox power station in the UK is described. The challenge for JFN was the provision of suitable equipment for the removal of the fuel through the existing fuel removal route and loading into the standard transport flasks for onward transport to the Sellafield reprocessing plant. Stringent requirements needed to be met including there should be minimum modifications to the plant and there should be no attachments left on the damaged fuel elements prior to placing in the transportation flasks. Another example of damaged dry fuel retrieval using specialised equipment is the retrieval of damaged fuel from two Magnox power stations during de-fuelling operations prior to decommissioning. A legacy fuel pond at Sellafield is an example of wet storage retrievals. The pond contains 1200 storage skips of spent fuel and has also accumulated sludges from the corrosion of fuel cladding and the fuel itself, fuel fragments, other debris and organic matter which have blown into the pond. Submersible Remote Handling Vehicles (ROV) have been deployed for the retrieval of damaged fuel from the floor of this pond and the sorting and segregation of fuel in the storage skips.

1. Introduction

At their peak in the mid 1970’s, Britain’s 26 Magnox reactors, spread across 11 sites, had an installed capacity of around 4200MWe [1]. Today only one reactor, at the Wylfa site on the Isle of Anglesey, is still operational, whilst the remainder are at various stages of decommissioning or have been placed under a care and maintenance regime. These latter stages of the Magnox reactor lifecycle pose a number of significant engineering challenges, not least in the handling and recovery of stuck or damaged Magnox fuel, be that from within the core of the reactor itself or from pond or dry storage facilities.

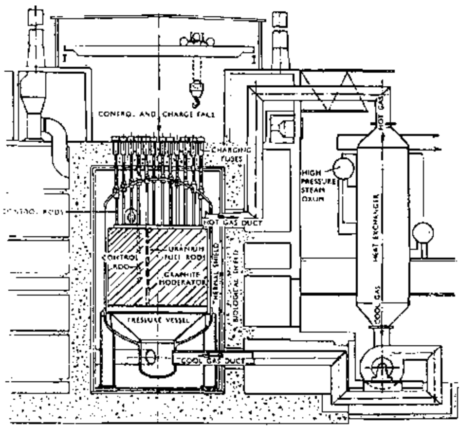

FIG. 1 Schematic of Calder Hall, the first Magnox power station [1]

Early Magnox reactor designs *(see FIG. 1)* had the reactor core inside a steel pressure vessel with a concrete shield surrounding it, and the steam generators outside. Later designs were purely intended for power generation and had a concrete pressure vessel with integral steam generators. The reactors use natural uranium metal fuel, have a graphite moderator and are cooled by carbon dioxide at a pressure of approximately 20 bar [1]. Unlike the fuel stringers used in the later and more efficient Advanced Gas Reactor designs, Magnox reactors are fuelled by thousands of individual fuel elements *(see FIG. 2)* stacked nose to tail in vertical fuel channels formed by holes through the individual graphite blocks making up the core.

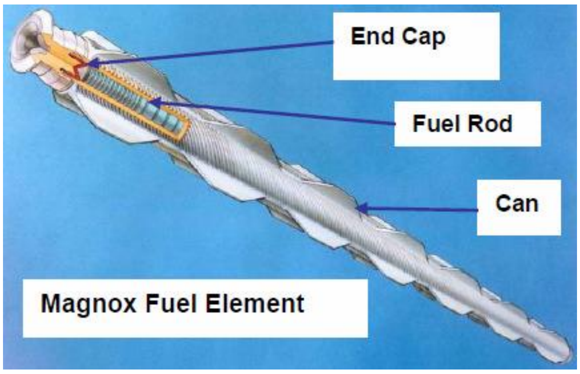

FIG. 2 A typical Magnox fuel element with lifting button[2]

Although the exact design of the Magnox fuel element varies dependent upon the station, each element comprises of a natural uranium bar (i.e. not enriched) sheathed in a magnesium alloy cladding (magnesium non-oxidising which is where the Magnox name is derived). Grooves milled into the external diameter of the cladding and sets of fins equally spaced over the length of the element provide an enhanced surface area for heat transfer. The fins also provide central axial location of the fuel elements in the reactor fuel channels.

The top of the element features a “button” or “spider” that is used as the lifting feature for the transfer of the fuel element to and from the reactor cores. The bottom of the element features a cone which locates into the feature on the neighbouring lifting feature to enable the elements to be stacked in the fuel channels of the reactor. As an example, a Wylfa design fuel element has a diameter across the fins of 95mm, a length of approximately 1150mm and an overall mass of 18kg.

Once the irradiated fuel is removed from the reactor it is stored locally at the facility for a minimum period of 90 days, traditionally in an aqueous pond environment. The chemical reactivity of the Magnox fuel cladding with water means that the fuel cannot be stored indefinitely in this form, so it must be reprocessed.

In routine fuelling and defuelling operations, Magnox fuel elements are handled using standard grabs designed to interface with the lift feature on the top of the fuel element. In certain circumstances, where the lift feature has become damaged or the element is jammed in its location, the standard handling equipment and techniques cannot always be employed to recover the element.

Faced with such challenges, specialist tooling is often required to facilitate the successful recovery of damaged or stuck elements, be that from within the core of the reactor itself, from storage ponds or from dry storage cells. Utilising an iterative, pragmatic, trials based approach, JFN have designed, manufactured and operated machinery to successfully solve these fuel handling challenges in each of these environments.

Adopting a trials based approach offers a number of distinct advantages over more classical design methodologies, namely that key risks are mitigated and addressed as the design progresses; continual assurance is gained through the trials, operators become familiar with the equipment before it is used on site, and overall risk, cost and programme time is reduced.

Three case studies of novel fuel handling challenges are presented below, along with a description of the successful solutions developed by JFN.

2. Case Study One: Damaged Fuel Recovery from Reactor Core at Chapelcross

First commissioned in 1959, Chapelcross in south west Scotland was one of the first generation of Magnox facilities, and was the sister station to Calder Hall, the UK's first commercial nuclear power station.

The design of the Chapelcross reactors mirrored that of its sister station, with the reactor core being enclosed in a steel pressure vessel, surrounded by a concrete shield. Contained within the pressure vessel is a complicated 24 sided, 6 metre high graphite structure made up of alternate layers of interlocking blocks and tiles. The structure, which weighs approximately 1150 tonnes, acts as the moderator and reflector for the reactor.

1696 vertical fuel channels penetrate the graphite core, and under normal operations, each of the fuel channels contains six fuel elements stacked nose to tail, making a total of 10176 elements in the core, with a combined fuel weight of approximately 120 tonnes [1].

When the irradiated fuel elements are exhausted they are removed from the core using the discharge machine grab. The grab locates onto the lifting "spider" on the top of each fuel element and placed them into the carousel in the discharge machine. Up to 24 fuel elements could be transferred into a discharge machine. They are then lowered from the discharge machine on the pile cap via the shielded discharge well and packed into a standard Magnox fuel flask, and are exported to the Fuel Handling Plant at Sellafield for reprocessing.

As Chapelcross reached the end of its operational life, consideration was given to the full defuelling of each of the four reactors, and in particular how a number of elements with damaged lifting spiders could be successfully recovered, given that the standard discharge grab was not able to acquire this lift feature.

JFN was therefore engaged to design and develop a device capable of recovering these fuel elements from the core of the reactor. The device had to fit within the tight dimensional constraints of the existing discharge machine grab, and be lowered by the discharge grab to remotely locate onto the fuel element over the damaged lifting legs. The device then had to be able to exert a pull force of up to 500kg on the element. When attached to the fuel element the device had to fit into a standard Magnox fuel skip, with the elements packed normally, to ensure that the maximum packing density could be obtained, and hence the discharge rate required to meet defuelling deadlines could be maintained.

Following early concept generation and optioneering activities, it was decided to embark upon the manufacture of a series of prototype devices to enable their relative merits to be easily assessed, and to inform the development of the design as the project progressed. This approach also ensured continual and progressive stakeholder buy in, and ultimately helped to ensure that the final design was fit for purpose. The early prototypes of this device *(see FIG. 3)* involved a series of fixed and pivoting barbs arranged in different housings, incorporating variations to the barbs and their pivot orientations.

Several versions of these devices were designed, built and tested in order to determine the most effective design in terms of reliability and maximum load capacity. Through undertaking this prototype testing, issues were highlighted over the ability of the device to retain its grasp on the fuel elements towards the limit of the load capacity requirement. Problems were encountered with the pivoting barbs losing their grip on the outer surface of the fuel element as the jaws 'bit' into the element, sliding upwards as the surface layer of the magnesium cladding became damaged and distorted.

FIG. 3 Testing of an early prototype device

At this stage, the operation of the device was revisited and a new design conceived. This revised design incorporated a series of small jaws mounted inside an internal, downward tapering sleeve. Once positioned over the fuel element body, the jaws were designed to grip around the outside diameter of the fuel element in a similar manner to a collet.

The jaws had small teeth running circumferentially around their inside face to form grooves that aided the grip on the fuel element. The grooves needed to be large enough to dig into the outer diameter of the cladding, but still ensure that the device could be readily released once the element had been recovered.

Initial trials with this design proved that the ease of deployment over the fuel element, and the load carrying capacity of the grab were considerably greater than those of the early barb based prototype models. Full design substantiation was then undertaken to prove the grab was fit for purpose, including Finite Element Analysis of all the load bearing components to determine maximum stresses and deflection.

FIG. 4 The final device design

After minor modifications to optimise the performance of the device, by increasing the lead-in chamfers, it was found that the grab could be easily positioned over the fuel element without intervention, and was capable of repeatedly lifting in excess of 500kg. The final device design *(see FIG. 4)* was therefore manufactured by JFN and a number supplied to Chapelcross. These devices have been subsequently used to successfully recover a number of fuel elements with broken lifting spiders from the reactor. The elements, complete with the recovery device, were then exported in a standard Magnox fuel flask to Sellafield for reprocessing.

The simplicity of the design and its successful operational deployment has led to further developments to accommodate different types of fuel elements and discharge arrangements. As well as those supplied to Chapelcross, JFN has also supplied the devices to Calder Hall and Wylfa power stations for similar fuel recovery projects.

3. Case Study Two: Magnox Fuel Recovery Using ROVs

The First Generation Magnox Storage Pond (FGMSP) at Sellafield is one of the site's four legacy storage pond facilities (two ponds and two silos). The pond was constructed in the late 1950's to receive and store irradiated fuel from Magnox reactors in open topped containers called skips. In its 26 year operational life the FGMSP facility stored and prepared nearly 2.5 million fuel rods (approximately 27,000 tonnes of fuel) for reprocessing [3].

During the 1970's Magnox reprocessing slowed causing fuel to be stored in the pond for longer periods than normal. This has resulted in the magnesium alloy casing corroding in the pond leading to the creation of radioactive sludges and poor underwater viewing.

The pond is located in a highly congested area, surrounded by buildings which originated in the early years of nuclear operations on the site. This limits the opportunities for new infrastructure, heavy lifting and temporary facilities around the perimeter of the pond.

Over the years the pond has accumulated significant quantities of waste materials, including sludge from the corrosion of fuel cladding, fuel itself, fuel fragments and other debris and organic matter which has blown into the pond. The skips used to store the fuel elements were originally stacked up to three high, and some of these have been dislodged or have tipped over, contributing to the accumulation of sludge, fuel elements and fuel debris on the pond floor. Currently the pond contains 1200 skips, an estimated 1500 cubic meters of radioactive sludge and 14000 cubic meters of contaminated water.

In order to aid the clean-up of the facility and to provide enhanced risk and hazard reduction within the ponds, the export of fuel from the FGMSP is required as soon as the export capability becomes available. In order to meet the downstream reprocessing requirements, there is a need to sort, segregate and consolidate the fuel within the storage skips, as well as recover fuel from the floor of the pond.

Owing to the high dose rates and corrosive environment associated with the ponds, any decommissioning work needs to be undertaken using remote handling techniques. Traditionally this has been done using long reach tooling and remote handling systems deployed from outside of the pond, however this approach has a number of inherent drawbacks and risks associated with it. JFN and Sellafield Ltd have therefore worked together to develop the use of Remotely Operated Vehicles (ROVs) to support the fuel recovery process.

The use of ROV technologies within the pond provides a number of advantages over alternative methods:

The ROVs are controlled remotely at a distance from the side of the pond to minimise operators' exposure to radiation and to avoid potential radiological contamination.

The ROVs are able to access all areas of the pond, which other remote handling techniques cannot.

By modifying mature, commercial off the shelf (CoTS) technology, significant cost and programme savings can be made without compromising the quality, function or safety of the solution.

The submersible ROV market is a large, mature high technology market, which principally serves the offshore energy industry. ROVs are also used in other sectors including defence, security and film making, but their use in the nuclear industry has been relatively small, with visual surveys being their principal application.

Sellafield first deployed ROVs in the FGMSP in 1999, as a tool for visual inspection. Although this programme demonstrated that ROVs were capable of operating in the challenging pond environment and could gather useful information, it was not expanded to consider other applications. Therefore, in 2008 JFN (who had been operating ROVs since 1999) were engaged to develop the ROV capability and to extend the scope of operations beyond visual surveys to include more advanced characterisation techniques and to investigate the remote handling capabilities of ROVs to carry out actual fuel handling within the FGMSP.

Working collaboratively, JFN and Sellafield Ltd identified potentially suitable ROVs and tooling which could be modified and developed to carry out these new activities. During this early phase of development close working relationships were established between JFN, Sellafield Ltd, the ROV suppliers and others in the supply chain, including specialist tooling manufacturers and subject matter experts, which was to prove crucial to the successful outcome of the project.

The complexity and unique nature of the engineering challenge meant that in order to ensure a successful outcome, the project was built up over a series of incremental developments. The methodology of design, test, refine, test, train and rehearse meant that perceived risks with both the technology and techniques were mitigated as part of the ongoing development process.

In order to provide a remote handling capability within the pond, a bespoke skid was developed for the existing ROV, which had previously been modified and used to perform visual surveys of the pond. The skid interface was designed to be modular to allow a range of bespoke skids with specific tooling to be created and quickly exchanged on the ROV *(see FIG. 5)*.

FIG. 3 Hydraulic manipulator in use in the JFN test facility

Mounted on this skid is a manipulator. The manipulator is based on a CoTS unit, which has been modified to meet the necessary project requirements and to ensure it is compatible with the pond environment. The manipulator has been designed to be failsafe i.e. to release its load under fault conditions or loss of power, to ensure that the ROV is always recoverable from the pond. Barbs on the gripper increased the gripping effectiveness, and key components of the manipulator are coated in a protective layer of Cerakote to enable the manipulator to withstand the alkaline conditions within the pond.

The manipulator skid was deployed from the ROV in JFN's test tank to enable extensive trials and training to be undertaken. As well as verifying the function of the manipulator, these trials also enabled operator skills to be built up and appropriate operational methodologies to be experimented with and finalised ahead of deployment within the pond itself. This approach improved the effectiveness and efficiency of the in pond operations, reducing the dose uptake and risk on plant. In addition the trials were also used to support PUWER assessments and HAZOP studies of the new equipment, procedures and processes, and enabled the equipment to be readily demonstrated to all stakeholders, giving them confidence in the performance and reliability of the ROVs and tooling in the pond.

Following these intensive trials, the ROV and manipulator skid was deployed in the FGMSP to pick up the loose fuel elements from the floor of the pond and place them in a skip. The ROV with its manipulator arm was successfully able to acquire and move fuel between skips. To date more than 4500kg of fuel elements have been sorted and segregated using ROV technology, with many of these recovered from the pond floor. This work is on-going.

Although all ROV fuel recovery to date has been carried out using hydraulic manipulators, JFN has also developed two electric manipulators in response to a Sellafield Ltd requirement to reduce the risk of contaminating the ponds with hydraulic fluids. Not only does the use of an electric manipulator remove this risk but lifetime maintenance and operational costs are potentially lower than their hydraulic counterparts.

JFN has worked closely with a specialist company to re-engineer their standard manipulator products for use in nuclear ponds. Modifications included manufacture from stainless steel rather than aluminium to withstand the alkaline conditions of the FGMSP. The control system hardware of the manipulator was also thoroughly tested to ensure it could tolerate the high radiation environment. This was done by exposing the system to a Cs137 radiation source in the JFN radiological calibration service facility, where the effect of the radiation on its performance was tested and evaluated. A new gripper was designed for general manipulation tasks and this also was fitted with a fail-safe mechanism. Two electric manipulators have been developed for the ROV: a “forward facing manipulator” and an “underslung manipulator”. These have been extensively trialled and demonstrated to Sellafield Ltd at all stages of the development in the JFN test facility.

4. Case Study Three: Stuck Fuel Recovery from Wylfa Dry Storage Cells

Wylfa Nuclear Power Station on the Isle of Anglesey was the last Magnox station to become operational, in 1971. Wylfa has two reactors with a combined total capacity in excess of 900MWe. Each reactor houses 6156 vertical fuel channels and each channel contains a stack of eight Magnox fuel elements, making a total of 49,248 elements per reactor [4]. Wylfa does not have fuel storage ponds but relies on dry storage cells with carbon dioxide cooling for spent fuel storage.

The fuel is removed from the reactors using the fuelling machine, which then transfers the irradiated fuel into the tubes in one of three Primary Dry Store Cells (DSC 1, 2 & 3), which are accessed via three plugs in the Pile Cap. When the fuel has cooled for its minimum period of 90 days, it is removed from the Dry Store Cells and is transferred via the Primary Discharge Route into flasks for transport to Sellafield and eventual reprocessing.

The Primary Dry Store Cells each contain 588 vertical tubes of 105mm internal diameter. These tubes are suspended from a header plate and are configured at 11 different concentric pitches. 576 of the tubes are designated for the storage of irradiated fuel elements, and each tube can accommodate a maximum of 12 vertically stacked fuel elements, giving a total storage capacity of 6600 elements in each dry store cell. All tubes are cooled internally by natural carbon dioxide circulation, and externally via an air circulation system.

Each dry store cell has a dedicated transfer chute with an electrically powered hoist which is equipped with a standard discharge grab. This solenoid operated grab is fitted with three jaws which locate onto and close around the lifting button on the top of the fuel element. The hoist is then used to transfer the element from the dry store cell into the flask filling area ready for export.

A number of fuel elements within the dry store cells were unable to be recovered with the discharge grab because of: damage to the lifting button preventing acquisition by the standard grab *(see FIG. 6)*; or the elements are jammed in the storage tubes, meaning that the discharge winch is unable to supply sufficient force to free the stuck elements.

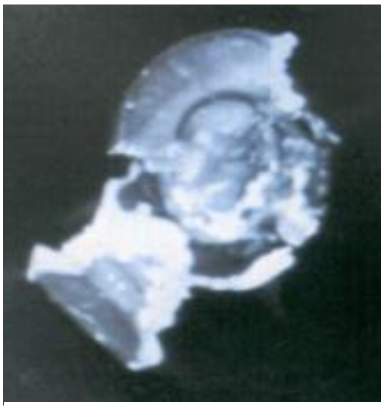

FIG. 6 An element with a damaged lifing button in DSC 1

As Wylfa neared the end of its operational life, the need to recover the stuck fuel elements became more necessary, partly to aid final defuelling and decommissioning of the station, but also to enable cross-reactor refuelling to take place, an activity that was vital to being able to extend the operational life of the facility.

Cross reactor refuelling meant permanently shutting down reactor one owing to a lack of new Magnox fuel, and transferring the best fuel from reactor one into reactor two to enable the remaining reactor to continue to operate efficiently. A prerequisite to the cross-reactor refuelling process was the retrieval and export of all the stuck or damaged fuel elements from dry store cells 1 & 2 to enable sufficient free positions to be obtained in the cells to allow the necessary shuffling of fuel elements to take place between the reactors. In 2012 JFN were awarded the contract to design and manufacture a machine to recover these stuck fuel elements from the dry store cells to enable cross-reactor fuelling to commence. JFN has previously worked alongside Wylfa to recover damaged fuel elements from their secondary dry store cells.

Working closely with the client's operators, engineers and safety case team a specification for the machine was drawn up, with the fundamental requirement being to enable a pull force of up to 1000kg to be incrementally applied to free the stuck elements, without piercing the magnesium alloy outer casing of the element. The machine also had to satisfy a number of other significant requirements including knowing the position of the grab and recovered fuel element at all times, monitoring the force applied to the element, knowing when the element is free and preventing the accidental raising of an element onto the Pile Cap.

Using these requirements as the basis for the design, a number of potential solutions were devised and discussed with the client. The preferred solution from this optioneering process was an electro-mechanical grab, deployed by a single umbilical from a hoist unit on the Pile Cap.

With the concept design chosen, it was decided to embark on a series of trial based activities early in the scheme design stage. Initial trials focussed on the critical interaction between the fuel element casing and the grab jaw profile, to ensure that sufficient force could be exerted to free the element without piercing the casing. A number of different jaw profiles were machined and tested, ranging from abrasive diamond coated jaws to tool steel jaws with a series of teeth designed to bite into the element casing.

These jaws were tested on a Magnox element sample using a simple test rig. A fixed grip force was applied across the jaws and the resultant pull force prior to jaw slippage was recorded. The fuel element was then visually inspected, and the outcomes recorded. Not only did this initial testing allow the jaw profile to be optimised, but it also provided useful data for the design of the grab itself, such as the grip force required, which in turn provided a starting point for the sizing and scoping calculations for the grab design. The trial also highlighted the need for the grip force to be continually applied as the grab was loaded, again providing key data for the sizing and rating of drivetrain components.

The outcome of this initial trial was then used as the basis for the design of the grab unit itself, with the geometry and profile of the jaws following that which was used on the test rig. This design was underpinned with calculations to verify the functionality and structural integrity of the grab. The final grab design featured an electric motor and gearbox, with a lead screw and nut arrangement used to provide the jaw closure force. Torque limits on the motor ensured that more force was always available to open the jaws than to close them, ensuring that the fuel element could always be released from the jaws after successful recovery. The jaws themselves were manufactured from 'Vanadis 4 Extra', a tool steel which has the necessary mix of hardness to ensure the teeth retained their sharp edge with repeated use and toughness to withstand the forces experienced by the jaws during use.

The grab also contained a number of notable design features, including a set of removable pins to enable the jaws of the grab to be remotely released via a fixture in the fuel discharge route in the unlikely event of grab failure. This meant that any element held in the jaws could be released and the grab recovered to the Pile Cap for maintenance. One jaw of the grab was deliberately lengthened to aid locating the grab over the fins of the fuel element. The grab also contains integral cameras and lights to provide full visibility of the remote operations.

Once the design of the grab was complete, and had been subjected to the necessary governance, it was manufactured and assembled *(see FIG. 7)* ahead of the completion of the rest of the design. This approach enabled the performance of the grab to be verified early in the manufacturing phase, gave the opportunity for stakeholder buy-in and also enabled early engagement of the site operation team.

FIG. 7 Completed grab mechanism

The design of the remainder of the machine followed a more traditional design process, in keeping with the reduced level of technical risk in these areas. The grab was designed to be suspended from a bob weight that not only aided deployment through the fuel route, but also contains a set of switches to detect the presence of an element in the grab. The hoist unit is based around a servo-motor powered drum and reeving mechanism, onto which the combined electrical and load bearing umbilical was wound. The servo-motor has variable speed and torque settings which can be adjusted incrementally as required, together with a mechanical clutch to provide overload protection.

The hoist is mounted on four load cells to give an indication of the pull force being applied to the element, and a combination of a manual cam box and encoder readout provide position indication. Three diverse systems are employed to prevent an element being accidentally brought to Pile Cap, the first using a combination of hoist position and bob weight switch position, the second using a Canberra gamma detector and the third using a physical stop that is installed around the umbilical and can only be removed once the gamma gate is closed below the grab, which cannot be physically achieved with an element in the grab. The control system for the machine has been designed to have a similar look and feel to the standard hoist control system, to assist with operators' familiarity and training.

Following the completion of the machine, an intensive series of testing and trials was undertaken at JFN's facilities. These trials not only enabled the performance of the machine to be verified and the function of all interlocks checked, but they also enabled the operators to become familiar with the control of the equipment in a non-critical environment. In addition the trials were also used to support the writing of procedures and processes for on plant operations, and enabled the equipment to be readily demonstrated to all stakeholders, giving them confidence in the performance and reliability of machine ahead of delivery.

FIG. 8 The finished machine in operation on the Pile Cap at Wylfa

Following successful completion of factory acceptance testing and operator training, the machine *(see FIG. 8)* was transported to Wylfa, where JFN supported both pre-operations and inactive commissioning activities. The system has now been used to successfully recover 53 damaged fuel elements from the Dry Store Cells, winning a Magnox i4 implementation award in the process. This was a key enabler to permitting cross reactor refuelling to be carried out, which in turn, has enabled the generating life of the station to be extended well into 2015. During 2013 alone, Wylfa was able to deliver 3.63TWh of electricity to the grid, a figure that could not have been achieved without cross-reactor refuelling [4].

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