UKAEA-RACE-CP(22)01

J. Davies, H. Robinson, W. Blyth, A. Wagner, J. Naish, S. Bradnam, R. Worral

Fully remotely operated waste processing in the European Spallation Source Active Cells Facility

Fully remotely operated waste processing in the European Spallation Source Active Cells Facility

J. Davies, H. Robinson, W. Blyth, A. Wagner, J. Naish, S. Bradnam, R. Worral

This paper has been submitted to
Waste Management Symposium 2023, PHOENIX, ARIZONA, USA, 26 February - 2 March 2023

Remotely operated waste processing in the European Spallation Source Active Cells Facility – 23520

James Davies*, Harry Robinson*, William Blyth*, Adrian van Arkel*, Alex Wagner*, Steven Bradnam*, Jonathan Naish*, and Ross Worrall*
*UK Atomic Energy Authority

ABSTRACT
The Active Cells Facility will be the world's largest hot cell and will be used to process radioactive waste generated in the operation of the European Spallation Source. Several innovative technologies and approaches have been developed for the ESS Active Cells, drawing on advances made in remote handling techniques and technology from fusion research. These new approaches have the potential to inform and provide benefits to many other facilities around the world. This paper discusses the fully-remote processing of the waste components including a dual-crane remote handling system, size reduction using fully remotely operated and maintained wire saws and remote packing of the waste for export off-site.

INTRODUCTION

Facility Context

The European Spallation Source (ESS) is a multi-disciplinary research facility based on the world's most powerful neutron source [1]. When completed and at full capacity, the facility will use a 5 MW proton accelerator to irradiate a spinning "Target Wheel" containing tungsten cassettes with protons at an energy of 2 GeV. The resulting reaction between the tungsten nuclei and protons releases neutrons. The released neutrons are then moderated and reflected using water, hydrogen, and beryllium as the active materials. The neutrons are then delivered to scientific instruments through beamlines.

The Target Wheel and its associated shaft have a combined mass of 10 tonnes, a total height of 5.6 m and the wheel diameter is 2.6 m (see Fig. 1). During the spallation process, the Target Wheel and surrounding components are heavily irradiated and must therefore be extracted from the target area and processed for disposal using remotely controlled equipment, without the presence of operators. The extraction from the target area is carried out by the Cask Assembly – a set of shielded casks with an internal hoisting system. The casks are then used to deliver the components to the Active Cells for processing and packaging.

Fig. 1 The ESS Target Wheel © ESS

The machinery and equipment required to carry out the remotely operated processing and packaging of the waste components is being delivered by the Remote Applications in Challenging Environments (RACE) division of the UK Atomic Energy Authority (UKAEA).

A variable set of components are expected to arrive during a 6-monthly shutdown of the monolith, with different component lifetimes ranging from six months to five years. The processing must keep pace with this, whilst ensuring the safety of all personnel.

Active Cells Facility Overview

The Active Cells Facility is shown in Fig. 2.

The Process Cell is shown to the right, and contains equipment for receiving, temporarily storing, cutting, and packing the waste components. The nature of the operations carried out mean that the area will become highly contaminated, and as such, the entire Process Cell is designed to be operated and maintained without requiring access for operators: all activities will be conducted by remote control. The volume of the cell is too large for effective use of viewing windows, so the facility will be operated using cameras.

The Maintenance Cell is shown to the left of Fig. 2. Access between the Process Cell and Maintenance Cell is controlled by two steel shielding doors, allowing operators to access the Maintenance Cell whilst waste components are present in the Process Cell. When open, these doors allow the cranes of the Remote Handling System to pass between the two cells. With the doors closed, operators will be able to access the Maintenance Cell to maintain the cranes and other critical systems.

Beneath the floor of the Maintenance Cell are six storage pits to allow the temporary storage of waste prior to shipment off site. When a shipment is ready, it is lowered from the Maintenance Cell into the Waste Transfer Area (lower left of Fig. 2), where it is then removed from the Active Cells Facility.

The walls of the Active Cell are 1.3 m thick high-density concrete for shielding, lined with a stainless steel liner for confinement. A ventilation system keeps the cells at a depression of 200 pa from the surrounding rooms to ensure that any leaks result in airflow inwards. All penetrations into the cell need to ensure that the shielding and air-tight confinement are not compromised.

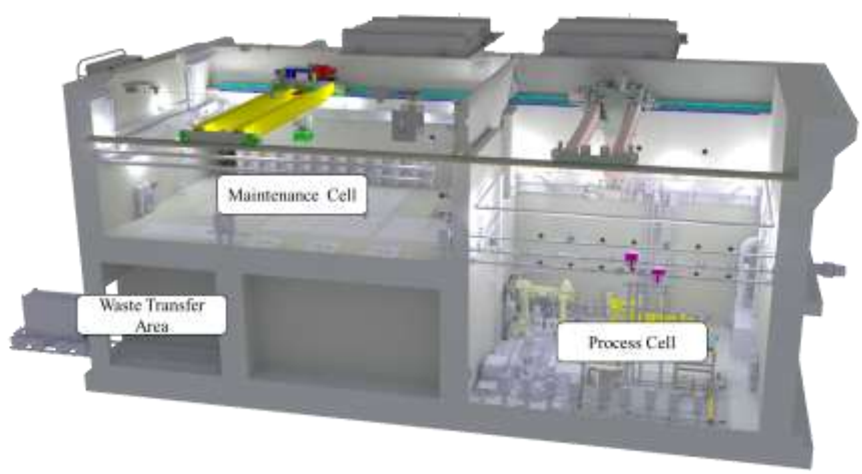

Fig. 2 Overview of the Active Cells Facility

Remote handling Context

Remote handling has a central part of the fusion research for decades. This includes the Remote Handling System used in the operation of the Joint European Torus experiment [2], as well as significant research into how remote handling will contribute to future fusion power plants [3]. More recently, these approaches have been deployed more widely, such as in the UK nuclear industry to improve efficiency and reduce hazard to operators [4]. It has been recognized that there is huge opportunity to apply remote handling technology and know-how developed in the fusion environment more widely [5].

System requirements and system concept

The complexity of the facility development necessitated a systems-engineering approach. A systems requirements document was developed in conjunction with ESS to ensure that the requirements for the facility were understood and well defined.

These requirements were then further developed by breaking them down into functional subsystem groups, then further into requirements for specific “equipment” which could relate to hardware or purely software. This structure is shown in Fig. 3. This structure ensures that every functional requirement identified at a system level is addressed by the lower-level subsystems and equipment.

The management of interfaces was of vital importance. Interfaces between equipment were carefully defined to ensure that the concurrent development could proceed successfully.

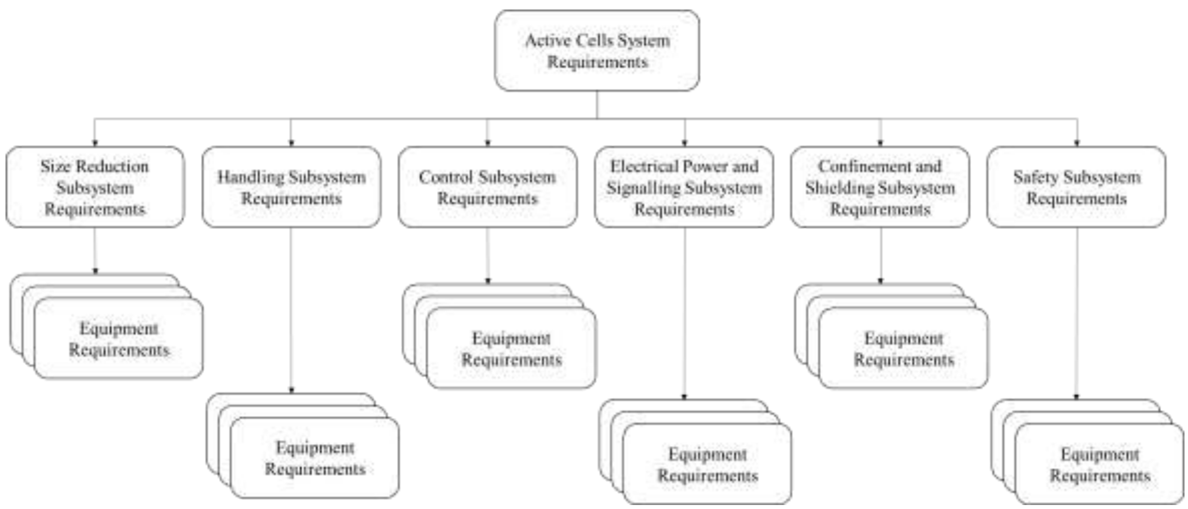

Fig. 3 Requirement breakdown structure for the Active Cells System

Waste characterization

The waste components received by the Active Cells will be drained of all process fluids prior to entry, so will consist of solid waste. The component structures are largely comprised of stainless steel (316 and 304), with other materials present in different components depending on their function. In addition to the tungsten and beryllium in the target and moderator respectively, other components contain copper, silicon wafers and various instrumentation such as thermocouples.

The most significant radiation hazard from the components will be direct shine from gamma radiation, although there will also off-gassing of radioactive gasses and a small neutron radiation contribution from photodisintegration of the beryllium in the moderator.

The gamma dose rate in the proximity of these components was determined by progressive analyses:

- The level of neutron production in the components induced during operation of the plant was simulated utilizing MCNP6 [2] to calculate the spatial distribution of energy dependent neutron flux, produced primarily by spallation.

- The resultant activation and subsequent decay of surrounding components was calculated using MCR2S [3] and FISPACT-II [4].
- Finally, a further MCNP6 simulation placed the activated components in a model of the Active Cells and calculated the gamma dose seen throughout the cell.

The components processed in the Active Cells will see radiation damage during operation of up to 4.5 dpa and the resulting activation gives a surface gamma radiation dose of up to 700 Gy/hr. The gamma radiation dose due to silicon from the target wheel is shown in Fig. 4.

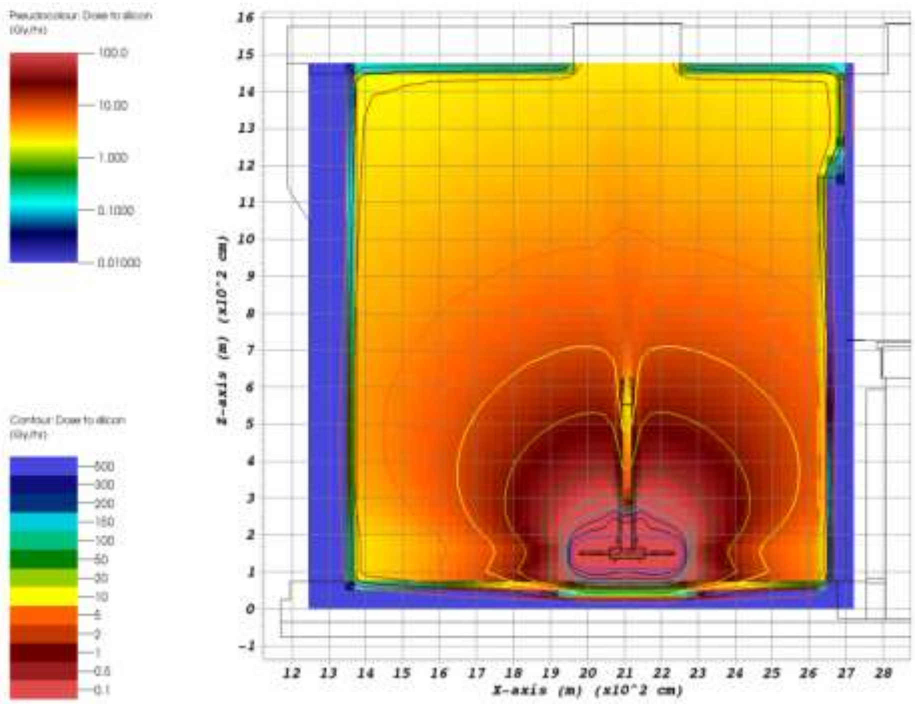

Fig. 4 Gamma dose to silicon near to the ESS Target Wheel after 5 years of irradiation.

REMOTE HANDLING SYSTEM

Requirements Development

Requirements for the Handling System were derived based on the overall strategy for the operation and maintenance of the facility: handling of high mass radioactive components and fully remote operation in the Process Cell. This drove the need for two distinct handling capabilities – dexterous manipulation of small tools and objects, and gross movement of heavy components. Early conceptual work, combined with a thorough review of the existing market capability identified the mass limits for these as 50 kg and 25 tonnes respectively.

The arrangement of the cell placed practical limits on where these capabilities could be deployed. The building had only made provision for one set of crane rails. It was anticipated that the requirements would require two separate crane bridges to operate on these rails, making access to all areas impossible. Minimum deployment areas were therefore defined as shown in Fig. 5, placing limits on the mass of the installed equipment and the type of operations that could be performed in each area. To allow for items heavier than 50 kg, an additional capability of an 8 tonne crane hook was added to the manipulator area.

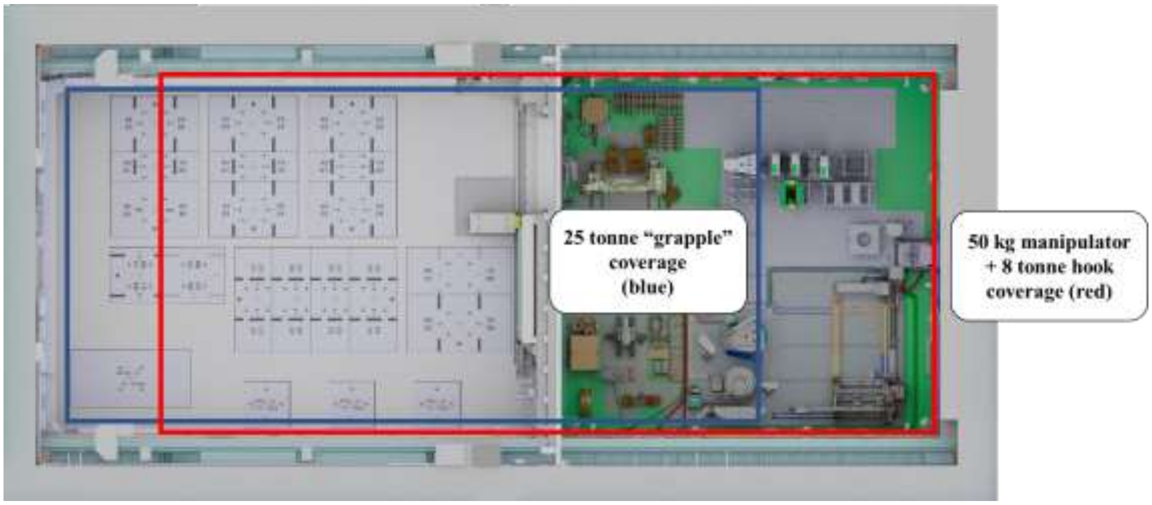

Fig. 5 Plan view of the Active Cells showing deployment areas for the 25 tonne and 50 kg handling capabilities.

The interfaces for these capabilities were standardized early in the project and shown in Fig. 6 . This was essential to allow concurrent development of the equipment within the cell, but also to ensure that the remote handling operations could be conducted as efficiently as possible. The heavy-lift interface was defined as four actuated twistlocks to be deployed by the crane and their respective pockets in the interfacing component. This allows the crane to attach to loads without requiring operators to perform any rigging. The dexterous interface was defined as a bolting pattern, with the intention that a suitable "interface block" would be attached using the bolts once the manipulator had been selected.

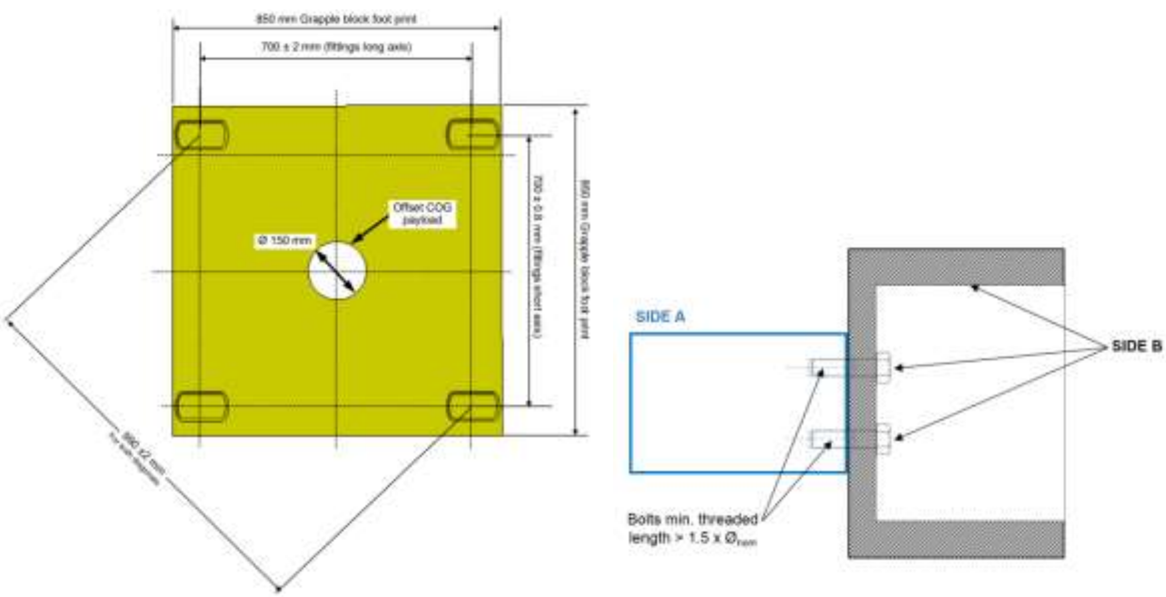

Fig. 6 The 25 tonne grapple interface (left) and the gripper interface (right)

To ensure that the capability supplied met the facility needs, a set of example tasks were defined which the developed systems would have to meet. These included: lifting and locating heavy components, handling of electrical cables, installing, and removing bolts and precise location of equipment into mating features.

Solution

The solution has been developed by James Fisher Nuclear as a subcontractor RACE. It consists of two electric, overhead gantry cranes (Fig. 7). Both have been designed to account for the very high radiation rates at the point of interaction, but allowing for the benefit provided by distance at the crane bridge.

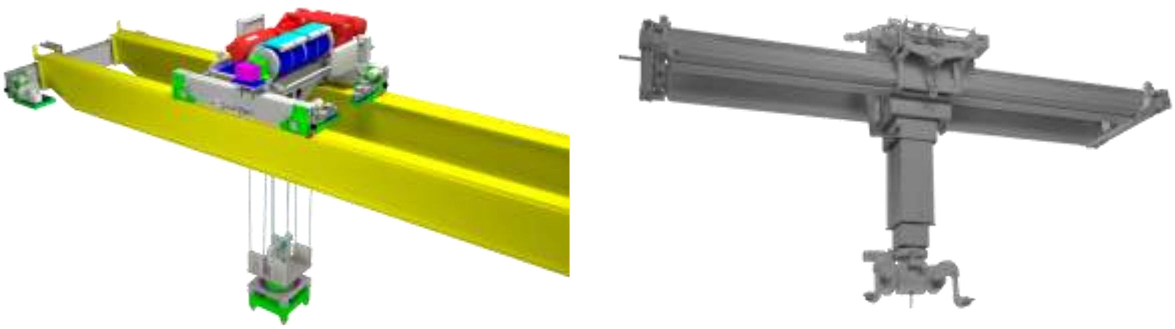

Fig. 7 Design images of the Grapple Crane (left) and Manipulator Crane (right)

The Grapple Crane deploys the grapple interface via four hoist ropes for stability. The four twistlocks are actuated by radiation tolerant stepper motors, and the whole interface plate can rotate by ±90° about the vertical axis whilst carrying loads. Each axis of motion has redundant drives to allow recovery back into the Maintenance Cell in case of failure.

The system has been installed and commissioned on site and is now being utilized to aid the installation the remaining equipment. Based on the testing so far, the accuracy and repeatability of the system have exceeded requirements.

Fig. 8 The Grapple Crane installed in the Active Cells

The Manipulator crane bridge is still under construction. Two Wällischmiller “Telbot” manipulators are deployed from a 9 m long mast which can be retracted to 1.3 m to pass through into the Maintenance Cell. The base of the mast supporting the manipulators can rotate ±180° about the vertical axis, allowing them to be deployed to any location or direction within the Process Cell. The 8 tonne hook is deployed from a hoist located on the crane gantry. It is within reach of the manipulator arms to allow rigging of items to be lifted.

Factory Acceptance Testing of the manipulators themselves has been completed, with all tasks able to be completed successfully (Fig. 9). The manipulators are operated using kinematically similar control arms that are manually moved by the operator. The manipulator replicates the motion of the control arms, and forces felt by the manipulator are scaled and transmitted back to the operator through the control arms. This allows the operator to “feel” the forces experienced by the manipulators, enabling more delicate and complex tasks to be undertaken.

The complete Manipulator Crane is due to be delivered to site in 2023 to allow full integration and commissioning of the system.

Fig. 9 Images from Factory Acceptance Testing of the Telbot Manipulators

WASTE PROCESSING

Requirements Development and Feasibility Studies

An initial study was initiated to determine the extent and nature of the processing required. The goals of the processing are:

a) Size Reduce the waste so it can fit into standardized waste packages
b) Segregate the tungsten from the remainder of the target wheel
c) Segregate the beryllium used to reflect neutrons from its stainless-steel casing

The tungsten in the wheel is contained within thirty-six radial cassettes and the beryllium is contained in a tub within the body of the moderator. The required cutting operations were divided into two groups: one-directional cuts through large shafts, and more complex multi-directional cutting, typically on a smaller scale. Based on this outcome, two separate size-reduction stations were specified.

It was identified that performing the required cutting operations faced three significant challenges:

1. The materials would be significantly hardened due to the neutron irradiation
2. Cutting fluids were prohibited from use

3. The amount of airborne radioactive dust produced during cutting must be kept within specified limits for the facility
4. The high gamma dose meant that all operations must be conducted remotely

Neutron irradiation of steels has a significant impact on their mechanical properties, which in turn will significantly affect how easy they are to size reduce. To quantify this effect, data was taken from the French RCC-MRx code for the design and construction of nuclear installations [5] and the ITER Structural Design Criteria for In Vessel Components [6]. The data for 316L stainless steel, a typical and representative material, is plotted in Fig. 10 and shows a significant increase in both yield and tensile strength, making the irradiated state significantly harder to machine.

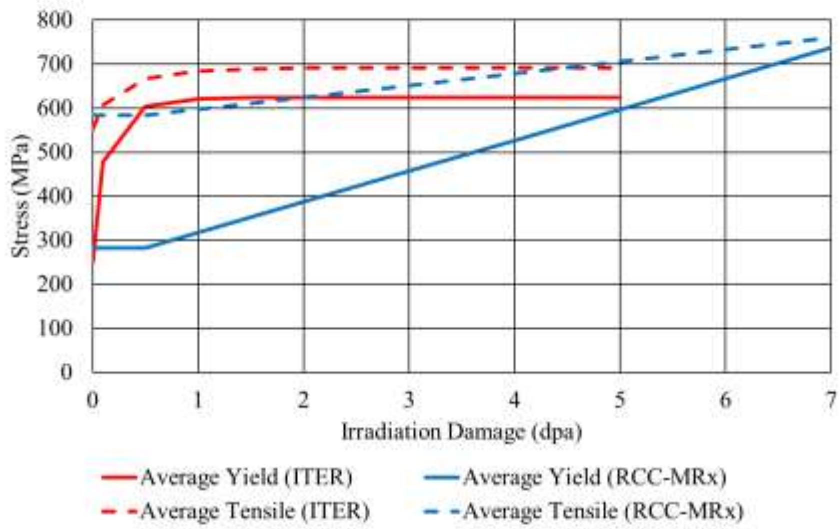

Fig. 10 Effect of neutron irradiation damage on the yield and tensile strength of 316L Stainless Steel.

The use of cutting fluid was prohibited by the facility owner due to concerns that it would spread contamination and prove difficult to decontaminate and dispose of. Cutting fluid is typically used to remove heat and reduce friction. Without it, tool life becomes significantly reduced and the cutting significantly more challenging [7]. A survey was conducted to identify potential cutting methods, and a series of trials conducted using bandsaws and milling machines to establish feasibility for different cut types (Fig. 11). These established that, although challenging the dry cutting was achievable on material samples that presented similar challenges.

The airborne dust produced during the bandsaw trials was also measured. By scaling this to account for the larger cross section of the largest waste component, this showed that a typical density of airborne dust 0.3 m from the cut was 0.058 mg/m^3. By taking measurements at various distances from the cut, the total airborne dust produced during the trial was estimated to be around 33 mg. The limit for airborne dust in the cell had been set at 4000 DAC (Derived Air Concentration) to ensure the safety of personnel in areas surrounding the Active Cells if a leak were to occur. By assessing the radioactive content of the material being cut, this was calculated to correspond to total of 22 g of cutting dust, significantly higher than what was measured in the trial.

Fig. 11 Cutting feasibility trials carried out by UKAEA

The gamma radiation dose near to the components is extremely high, meaning that the size reduction tools must be capable of full operation and maintenance using the Robotic Handling System. No previous examples of being able to operate machine tools of this size fully remotely could be identified. As proof of concept, a trial was conducted to test if a bandsaw blade could be changed using remote-handling compatible technology (Fig. 12). This employed a cassette system to install and remove the saw blade, with suitable guidance features, and lever clamps to secure it in place.

Two cutting stations, both based around wire saws have been developed.

Fig. 12 Feasibility trials for remote-handling compatible change of a bandsaw blade.

Shaft Cutting Station Solution

The "Shaft Cutting Station" performs the large-scale shaft cutting operations. The components arrive in the cell vertically oriented and must be rotated horizontally to be cut. This is achieved by placing the component in a configurable, hinged cup, and laying it over by tracing an arc with the Grapple Crane. The components rest horizontally on a set of stands that are configured for each component using the Robotic Handling System.

Fig. 13 VR simulation of laying over the Moderator Reflector Plug (left) compared to Factory Acceptance Testing of the layover cup (right)

The wire saw is moved between cutting locations using the 8 tonne hook on the Manipulator Crane, and locates in recessed features in two rails. The saw has been commissioned on site and trials are currently underway to prove the cutting capability of the saw (Fig. 14).

Fig. 14 The Shaft Cutting Station saw design (left) and during cutting trials (right)

Super-duplex stainless steel is being used to simulate the irradiated condition of the material with copper inserts used to represent the range of other materials present as shown in Fig. 15.

Fig. 15 Sample used for Shaft Cutting Station trials before and during cutting

Initial trials were conducted with no ventilation present in the Active Cells. Dust measurements showed that airborne dust levels were increasing well beyond acceptable limits during the cutting. The trials were then repeated with a temporary ventilation system to simulate the airflow which will be present during operation. This showed a significant reduction in airborne dust, bringing the results comfortably back within acceptable limits.

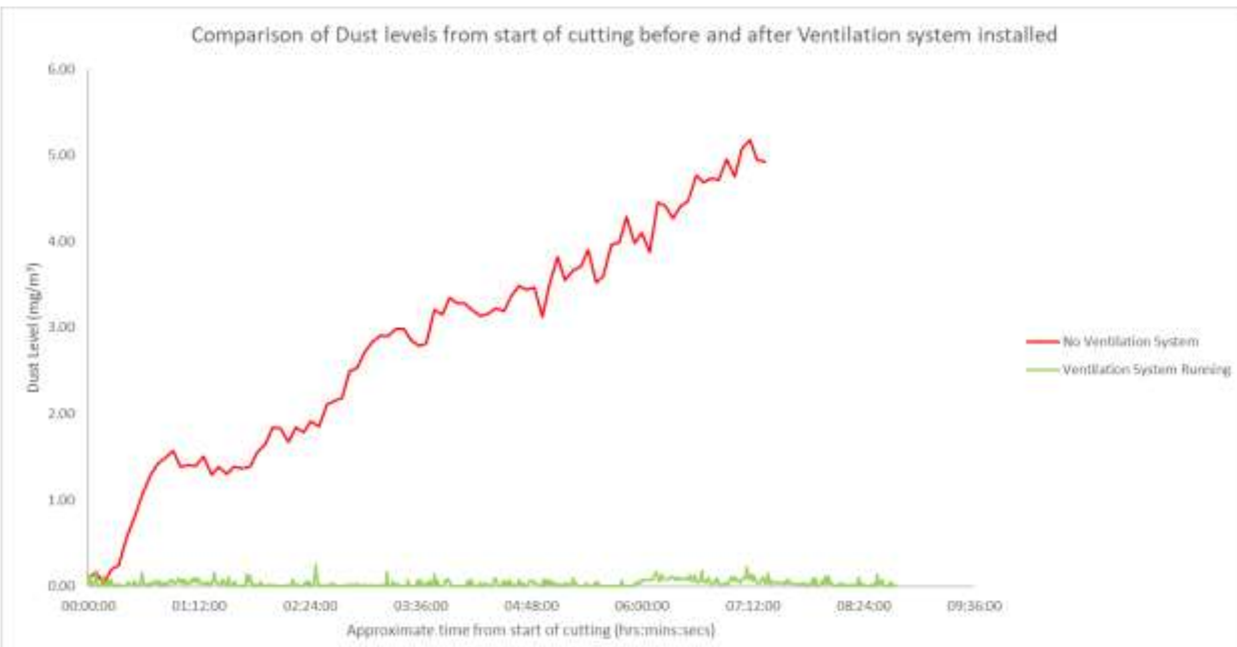

Fig. 16 Dust measurements close to the cut location during site cutting trials with and without a ventilation system in operation.

The trials have shown that heat management is highly important during cutting. The wire temperature is a key parameter measured, and is used to control the progress of the cutting – when the wire is too hot, cutting is slowed or halted. Overheating of the wire causes “glazing” of the wire which blunts the cutting and requires premature replacement. This appears to be caused by a combination of blunting of the diamond cutting edges and the deposition of metal from the workpiece smoothing out the cutting surfaces. The test piece used is representative of the cross section, but is thinner and significantly less massive than the waste components. Work is ongoing to understand how the actual components will heat up during cutting.

A key challenge in the operation of the saw is the remote replacement of the cutting wire itself. Early trials were conducted on a representative pulley arrangement. As the manipulators were not available, the manipulator was "simulated" by using a reacher/grabber tool operated manually. During the Factory Acceptance Testing of the manipulator a further trial was conducted to ensure that the completed arms could perform the operation. Final verification of this approach will be conducted when both systems are installed in the Active Cells.

Machining Station Solution

The "Machining Station" performs the more complex cutting operations and is shown in Fig. 17. The saw is mounted a bed allowing two linear axis of motion during cutting, and can be rotated about a third axis to cut horizontally or vertically. There are separate cutting beds for the Target Wheel and Moderator Reflector plug. The Target Wheel bed is able to rotate the wheel to allow the saw to access the full circumference.

Fig. 17 The Machining Station design (left) and during cutting trials (right)

The Machining Station has been built and commissioned in the UK and is currently undergoing trials before shipment to the Facility in Sweden. Early testing has proven the multi-axis cutting capability, with further work ongoing to optimize pulley design and refine the control system.

Fig. 18 Example cut from early trials of the Machining Station

WASTE STORAGE BASKETS

Requirements Development

Road transport of the radioactive waste will be inside an “ATB 1T” road transport container [12], with an internal steel tank providing additional shielding. The thickness of the internal steel tank depends on the activity of the components. These barriers provide the required shielding and confinement barriers for outward transport.

The requirement for the Active Cells Facility is therefore to provide a “Waste Storage Basket” to allow:

- movement of the size-reduced waste from the Process Cell
- temporary storage within the Storage Pits underneath the Maintenance Cell
- delivery to the ATB 1T

All of this must be completed without direct operator intervention. It was determined that no safety requirements were to be placed on the Waste Storage Baskets in terms of shielding or confinement of waste. However, they should include means to reduce the spread of contamination from the Process Cell into the Maintenance Cell and beyond.

Solution

A range of modular Waste Storage Baskets was developed, with the modularity accounting for different sizes and shapes of waste, as well as the different thickness of shielding material and therefore dimensions of the baskets (Fig. 19).

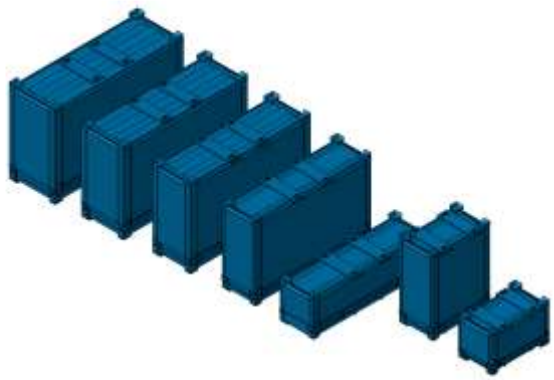

Fig. 19 Modular range of Waste Storage Baskets

Each basket consists of three main elements

1. The base frame
2. The component support frame
3. The lid

The base frame consists of four lengths of stainless-steel box section arranged in a rectangle with “feet” welded at each corner, and a stainless-steel plate welded onto the base to catch any dust or swarf dislodged from the component. This standard arrangement allows different component support frames to be inserted depending on the waste to be inserted into the basket – examples of this are shown in Fig. 20

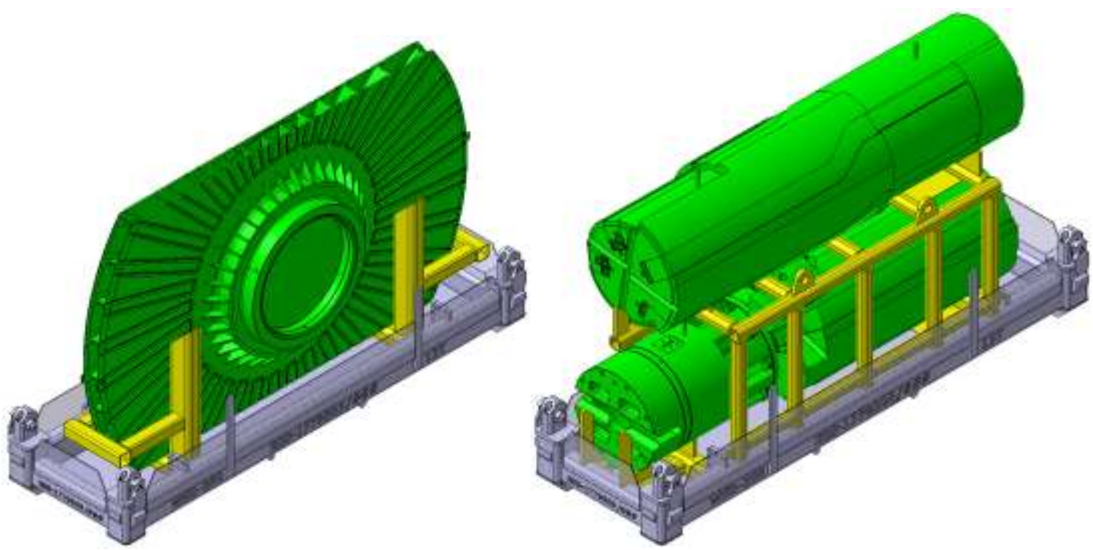

Fig. 20 Waste Storage Basket base frame and example component support frames for the parts of the target wheel (left) and moderator reflector plug shaft (right).

The lid of the Waste Storage Baskets is a rectangular box with five closed sides and the base open. The lid is secured to the base with four locking pins which are inserted and removed by the manipulator (Fig. 21). The top face of the lid includes the Grapple interface allowing it to be lifted independently of the base or for the entire assembly to be lifted when secured. The Baskets allow for normal operational forces in lifting and loading, as well as accidental loads such as a collisions during transport whilst safely retaining the component.

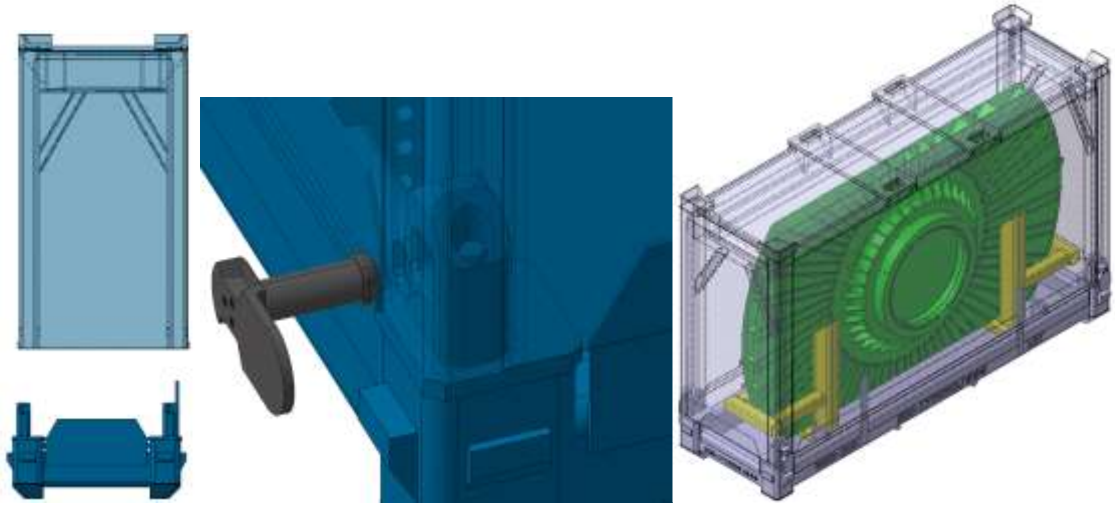

Fig. 21 Lid of the Waste Storage Basket above the base frame (left), locking pins (centre), and the full Waste Storage Basket assembly (right).

A prototype Waste Storage Box is currently in manufacture. Once completed it will be delivered directly to the Active Cells Facility to conduct testing with the Grapple Crane.

CONCLUSIONS

Processing of radioactive waste produced at the European Spallation Source presents several challenges due to the size and high activity of the waste components. The Active Cells facility has been developed to allow fully remote size reduction of these components, drawing on remote handling tools and techniques originating in fusion research.

Several novel approaches have been taken in terms of the handling, size reduction and packing of the waste. Testing of the solutions has made significant progress in proving the viability of this approach.

REFERENCES

[1] Garoby, Roland et al., “The European Spallation Source Design,” *Physica Scripta*, vol. 93, 2018.

[2] B. Haist, S. Mills and A. Loving, “Remote handling preparations for JET EP2 shutdown,” *Fusion Engineering and Design*, vol. 84, no. 2-6, pp. pp875-879, 2009.

[3] O. Crofts and et al., “EU DEMO Remote Maintenance System development during the Pre-Concept Design Phase,” *Fusion Engineering and Design*, vol. 1794, 2022.

[4] J. T. Goorley and et al., “Initial MCNP6 Release Overview - MCNP6 version 1.0,” 2013.

[5] A. Davis and R. Pamin, “Benchmarking the MCR2S system for high-resolution activation dose anaylsis in ITER,” *Fusion Engineering and Design*, vol. 85, no. 1, pp. pp87-92, 2010.

[6] J.-C. Sublet, L. W. Packer, J. Kopecky and R. A. Forrest, “The FISPACT-II User Manual",” UKAEA, Culham, UK, 2015.

[7] Afcen, “MCC-MRx Design and Construction Rules for mechanical components of nuclear installations: high temperature, reaseach and fusion reactors,” Afcen, Paris, 2018.

[8] ITER, “222RHC version 3.0 Structural DEsign Criteria for In-Vessel Components (SDC-IC),” ITER Organization, Saint-Paul-lez-Durance, France, 2012.

[9] D. Snow, Plant Engineer's Reference Book, Oxford, UK: Butterworth-Heinemann, 2003.

[10] O. Tokatli and et al., “Robot-Assisted Glovebox Teleoperation for Nuclear Industry,” *Robotics,* vol. 10, no. 3, p. 85, 2021.