Active Cells: The robotic radioactive waste processing facility at the European Spallation Source[*]

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The European Spallation Source Active Cells Facility is a unique facility for processing highly radioactive waste produced by the experiment. Due to the levels of radiation produced by the waste components combined with the scale of operations, the facility was designed to be operated without windows, using robotic manipulation systems and cameras for visual feedback. This article presents the challenges faced in delivering the processes required for size reduction and packing of the waste components along with the resulting design of the facility including key equipment and infrastructure developed to support the facility. Key subsystems are described in detail along with the considerations for maintenance and upgrades and the overall approach to safety. Finally, lessons learned and useful experiences are shared in the hope of informing the successful delivery of other similar facilities in the future.

Keywords: ESS, robotic, waste, hot cell, radiation, size reduction

I. INTRODUCTION

The European Spallation Source (ESS) is a high-performance, multi-disciplinary research facility centred on the worlds most powerful neutron source [1]. At full capacity, a 5 MW proton accelerator delivers 2 GeV protons onto a rotating tungsten Target Wheel. The resulting spallation reaction produces free neutrons, which are moderated and reflected using water, hydrogen, and beryllium before being directed via beamlines to experimental stations.

Although the principles and technology behind spallation sources are well established [2], the ESS surpasses all previous facilities in scale and beam power, introducing a range of new engineering challenges and complexities.

The Target Wheel assembly, including its central shaft, has a total mass of 10 tonnes, a height of 5.6 m, and a wheel diameter of 2.7 m. During operation, the wheel and adjacent components become highly radioactive, precluding direct human access. As such, these activated components must be removed and processed using remote handling systems.

The extraction from the target 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, the facility designated for processing and packaging the waste components.

This paper provides an holistic overview of core remote system design enabling safe, long-term operations of Active Cells Facility at the European Spallation Source.

A. The Active Cells facility

The Active Cells Facility (ACF) is a large, shielded hot cell complex designed for the remote processing and packaging of activated waste materials generated by the spallation source. An overview of the facility layout and cell contents is shown in Figure 1.

Given the scale of the ACF and the high radiation levels involved, conventional through-wall operations using lead-glass windows for direct viewing is not feasible. Instead, the facility is operated entirely remotely, employing a combination of camera-based viewing systems and electrically and digitally controlled manipulators, hoists, and associated tooling. This approach enables safe and effective handling of high-activity components while maintaining operational flexibility and precision.

A wide variety of activated components are expected to be transferred to the Active Cells during the scheduled six-monthly shutdowns of the neutron source. Component lifetimes vary from approximately six months to five years, necessitating a processing throughput that can match the maintenance schedule to avoid delays in restarting operations, while maintaining strict safety standards for personnel.

The primary components identified for remote handling and processing include the Target Wheel assemblya large structure comprising a 2.6 m diameter tungsten wheel [3] mounted on a 5 m vertical shaft [4]and the Moderator Reflector assembly, which incorporates beryllium and steel elements. In addition, a number of smaller but still highly activated components will require processing. These include, but are not limited to, instrumentation plugs and the proton beam window.

All components entering the Active Cells will be predrained of process fluids, and will therefore consist exclusively of solid waste. The bulk of the structural material is stainless steel (grades 304 and 316), with component-specific materials included depending on functional requirements. Notably, tungsten and beryllium are present in the target and moderator assemblies respectively, while other com-

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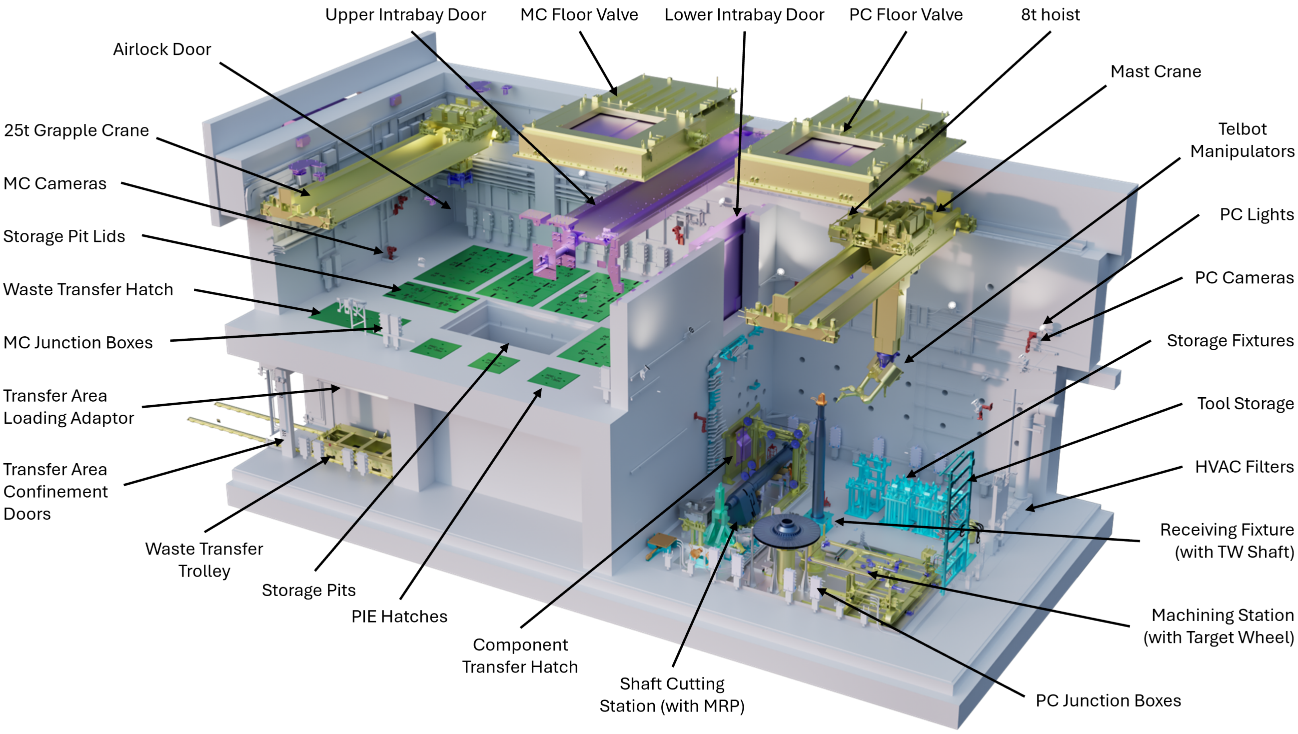


Fig. 1. Overview of the ESS Active Cells Facility with Process Cell shown on the right and maintenance cell shown on the left, separated by intrabay doors. The intrabay doors allow the transit of cranes between the process cell and maintenance cell whilst providing shielding protection for the maintenance cell. Key equipment within the facility is labelled.

ponents may include copper, silicon wafers, and various types of embedded instrumentation, such as thermocouples.

The processing operations within the Active Cells are focused on three core objectives that define the current handling strategy for activated components. First, large components must be reduced in size to meet the dimensional and mass constraints of standardised waste packages, enabling compliant storage, transport, and disposal.

Second, material segregation is essential for both radiological and waste classification purposes. The tungsten used in the Target Wheel must be separated from the structure of the Target Wheel to allow for appropriate treatment and disposal pathways (including size reduction of the wheel itself for transportation and storage). Likewise, the beryllium incorporated in the Moderator Reflector assembly must be carefully isolated from its stainless steel housing. This is necessary due to berylliums unique radiological, chemical, and regulatory handling requirements.

Third, sample retrieval allows for post irradiation samples to be extracted from a defined location within the Moderator Reflector assembly. This requires precise cutting operations and delicate handling to extract the samples without damage or contamination.

These processing tasks drive the specification of remote handling equipment, including cutting tools, gripping systems, and inspection technologies, as well as influencing the spatial layout and shielding requirements of the Active Cells Facility.

The tungsten within the Target Wheel is distributed across thirty-six radial cassettes, while the beryllium is housed within the body of the Moderator Reflector. To accommodate the differing geometries and material configurations, cutting operations are categorised into two primary types: single-directional cuts for large, roughly uniform structures such as shafts and instrumentation plugs, and more complex multi-directional cutting for smaller, irregular components. As a result, two dedicated size-reduction stations are incorporated within the Active Cells to address these distinct processing needs.

Carrying out these cutting operations presents several significant challenges. Neutron irradiation causes substantial hardening and embrittlement of the component materials, particularly the steels [5], presenting challenges for mechanical cutting. These effects directly impact the choice and design of cutting technologies. Reference data used to inform processing strategies are drawn from established nuclear engineering codes, including the French RCC-MRx for the design and construction of nuclear installations [6], and the ITER structural design criteria for in-vessel components [7]. The use of cutting fluids is prohibited due to radiological safety and waste handling constraints, necessitating dry cutting methods. Additionally, strict limits are imposed on the generation of airborne radioactive particulates, requiring close control of the dust generation and management within the Active Cells.

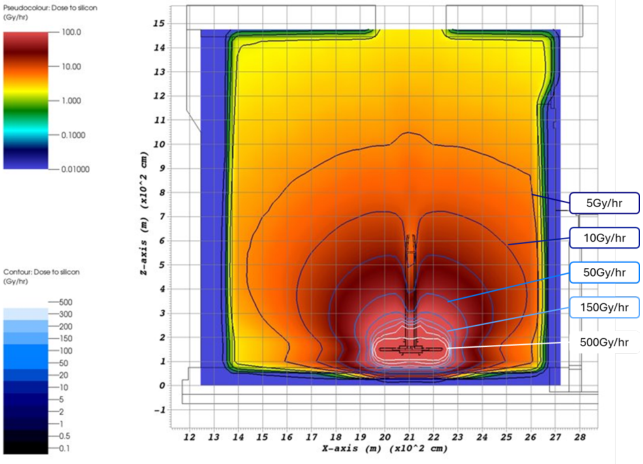


Fig. 2. Dose to silicon for a 4 year cooled Target Wheel placed within the process cell.

B. Key challenges

The operations carried out within the Active Cells Facility are not only complex from a mechanical and logistical standpoint but are further complicated by the extreme radiological environment. The primary radiological hazard arises from intense gamma radiation emitted by the activated components, particularly along direct shine paths and in close proximity to the waste materials. In addition to gamma emissions, there is some off-gassing of radioactive isotopessuch as tritium or activated noble gases depending on the component and its operational history. Furthermore, a low-level of secondary neutron flux is expected due to photodisintegration reactions, particularly involving the beryllium in the moderator assembly.

The gamma dose rate in the vicinity of activated components has been assessed through a multi-stage simulation workflow [8].

In the first stage, the neutron flux induced in components during service in the spallation source was modelled using MCNP6 [9]. These simulations provided spatially resolved, energy-dependent neutron flux distributions, predominantly generated by spallation reactions in the tungsten target.

In the second stage, the neutron-induced activation and subsequent radioactive decay of structural and functional materials at the end of their service life were evaluated using MCR2S [10] and FISPACT-II [11]. This allowed for the generation of gamma source terms and the production of unshielded gamma radiation intensity maps, which represent the raw emission profile from the activated components.

A final set of simulations was performed using MCNP6 to assess the dose distribution within the fully modelled Active Cells Facility. These simulations incorporated the physical geometry and shielding characteristics of the cell infrastructure, yielding detailed maps of gamma dose rates throughout the facility. An example dose map within the process cell volume is shown in Figure 2.

The components processed in the Active Cells are expected to accumulate radiation damage levels of up to 4.5 displacements per atom (dpa) over their operational lifetime. This radiation damage will result in source terms including gamma emitters such as Tungsten-187 and Hafnium-172, beta emitters like Tritium and Tantalum-182 and pure alpha emitters such as Gadolinium-148 [12]. Following shutdown and cooling, some components (such as the Target Wheel) can exhibit surface gamma dose rates as high as 700 Gy/hr.

The primary challenge relates to the radiation levels present in the facility, however in tackling the radiation challenge, a number of knock-on secondary challenges are seen. These include the need to incorporate features to allow for remote operations and maintainance of the equipment in the cell using a robotic handling system, and impacts related to the need for significantly limiting the range of technology based on radiation tolerance. Additionally, the levels of hazardous contamination that will be present complicates and limits the use of liquids due to the risk of spreading contamination and producing additional hazardous waste, creating complications and limitations on systems such as cutting and fire suppression systems where liquids would normally be used.

In typical cutting scenarios, cutting fluid is used to remove heat and reduce friction, however the use of cutting fluid is prohibited by the ESS facility owner due to concerns that it would spread contamination and prove difficult to decontaminate and dispose of. Without it, tool life becomes significantly reduced and the cutting significantly more challenging.

Early in the project, a survey was conducted to identify potential cutting methods, and a series of trials conducted using bandsaws and milling machines to establish feasibility of the identified methods including whether bandsaw blades could be changed remotely using remote-handling compatible technology. The feasibility trials established that, although challenging the dry cutting was achievable on material samples that presented similar challenges.

The trials also measured the volume of airborne dust produced during bandsaw cutting. By scaling this to account for the full cross section of the largest waste component, it was established that a typical density of airborne dust 0.3m from the cut was $0.058mg/m^3$. By taking measurements at various distances from the cut, the total airborne dust produced during the trial was estimated to be around 33mg. 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 22g of cutting dust, significantly higher than what was measured in the trial.

The result of the preliminary work indicates the need for a fully remotely operated facility with capability for large-scale size reduction and segregation tasks. All equipment installed into the cell would require remote operation as well as fully remote maintenance through the lifetime of the equipment.

C. Translating experience from fusion remote maintenance at the Joint European Torus

Robotic technology in support of remote handling has been a central part of fusion energy research for decades. A key example of this is the remote handling system at the Joint European Torus (JET) experiment [13], a capability developed at UKAEA over a long period of maintaining and upgrading the JET system with robotic systems including long-reach booms for deployment into the vessel as well as haptic telemanipulator technologies such as MASCOT [14].

More recently, the potential for translating capability developed through remote maintenance of the JET experiment has been explored in other areas including maintenance of future fusion plants [15], the decommissioning of legacy nuclear facilities in the UK such as gloveboxes [16], and in support of decommissioning operations following the nuclear disaster at Fukushima Daiichi [17].

It has been recognised that there is significant opportunity to apply remote handling technology, operational experience, and know-how developed within the fusion domain more widely [18]. This includes other challenging environments including high-energy physics experiments like the European Spallation Source and beyond.

In particular, operational expertise developed during decades of remote operations at JET was utilised in analysing tasks to be undertaken within the Active Cells Facility as well as equipment to be used. This allowed for translating practical experience from a similar remote handling domain in order to influence the equipment selection and design as well as the ways in which the operations would take place towards a practical and robust solution.

D. Overview

This paper presents an overview of the overall design and intended operation concept for the Active Cells Facility, the waste processing cell at the European Spallation Source. The specific challenges of carrying out the necessary processes and environmental conditions will be explored along with an exploration of how knowledge gained from other facilities can be translated to the Active Cells Facility.

An overview of high-level subsystems is then provided, followed by descriptions of each of the key subsystems. Additionally, specific detail on some of the key subsystems, and more challenging subsystems is provided. A discussion of future needs and planned upgrades - the future of the ACF is then laid out, exploring how the facility is anticipated to evolve, and what accommodations have been made for potential future changes.

Finally, lessons learned and implications for other future hot cell and similar facilities is presented, with the aim of sharing useful experiences relevant to other high energy physics experiments and environments that stand to benefit from remote or robotic operation and maintenance.

II. OVERALL FACILITY DESIGN AND APPROACH

Requirements for the facility were initially developed from the ESS facility needs. This captured the necessity for transitioning large, activated waste components into boxed waste suitable for road transportation. Development of the Active Cells was constrained by the existing civil design of the building which included the division of the facility into defined areas, including the Process Cell and Maintenance Cell.

The complexity of the facility development necessitated a systems engineering approach. A systems requirements document was developed in conjunction with the ESS organisation to ensure that the requirements for the facility were fully 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 ensured that every functional requirement identified at a system level was addressed by the lower-level conceptual subsystems and equipment. The management of interfaces was of vital importance, with interfaces carefully defined to ensure that concurrent development could proceed successfully.

Feasibility studies were undertaken by assessing existing products and technologies, as well as similar use cases, to assess technological risk and maturity. The constraints of the facility dictated that some non-standard or challenging unconventional approaches were required, steering the overall approach and determining the necessity for further practical trials. Requirements and concept designs were provided to suppliers, while allowing for alternative concepts to be provided, encouraging innovative solutions. Over the course of the project over £30 million has been spent in the UK and European supply chain, with over 345 companies directly involved.

In the resulting design, the Process Cell includes 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 designated for maintenance of equipment. 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 in protective suits 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 for 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, where it is then removed from the Active Cells using the waste transfer trolley.

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.

The safety case for the facility was developed in parallel with the design and delivery of the facility, as were the main infrastructure elements such as electrical and data systems.

A. Cross-cutting infrastructure design

The overall design features the distinct encapsulated subsystems such as the handling system and shaft cutting station but also elements of cross-cutting infrastructure that interfaces with all of the major subsystems, providing essential services. This infrastructure was more difficult to fully specify in advance in the absence of detailed information about the individual subsystems and machines, and so was developed centrally throughout the delivery of the facility in parallel with the design, manufacture, and installation of other items of equipment.

The major cross-cutting infrastructure elements include:

- Electrical infrastructure
- High-Level Control System and data distribution
- Emergency Stop system
- Radiological Safety System

B. Electrical infrastructure

The electrical infrastructure of the cell is a significant, complex, and critical part of the overall system design. This includes:

- 80km of specialist radiation resistant cable
- 37 densely packed electrical control cubicles across 2 rack rooms
- 11 fully remote handleable Junction Boxes in the Process Cell
- 16 modular and easily replaceable Junction Boxes in the Maintenance Cell
- 4 modular and easily replaceable Junction Boxes in the Waste Transfer Area
- 35 conduits into the active cells forming part of the containment boundary.
- 43 cold-side junction boxes

Fig. 3. Electrical Junction Boxes installed within the Active Cells Facility.

Dedicated low voltage distribution racks provide a bespoke and easily customisable means of power distribution within the two rack rooms provided for the Active Cells. Each one has a 120A feed and together these supply nearly all of the other subsystems with power.

The electrical infrastructure provides power and signals to the Safety Systems, Lighting and Viewing systems, Component Transfer Hatch, Floor Valves, Environmental Monitoring System, Machining Station, Waste Transfer System, Intra-bay Doors, and Supervisory Control System. The infrastructure is built with redundant cabling that can be utilised in the event of failures, or for reconfiguration or expansion of the capabilities.

C. Network and Data Processing Design

The diverse range of equipment present within the Active Cells include a variety of low level electronic control systems under the direction of a higher level control architecture (See Figure 4). In addition, a multi-camera, low latency, radiation hardened viewing system gives operators a detailed view of operations. Also, virtual reality displays show additional views of operations with viewing angles that are not viable with camera deployment.

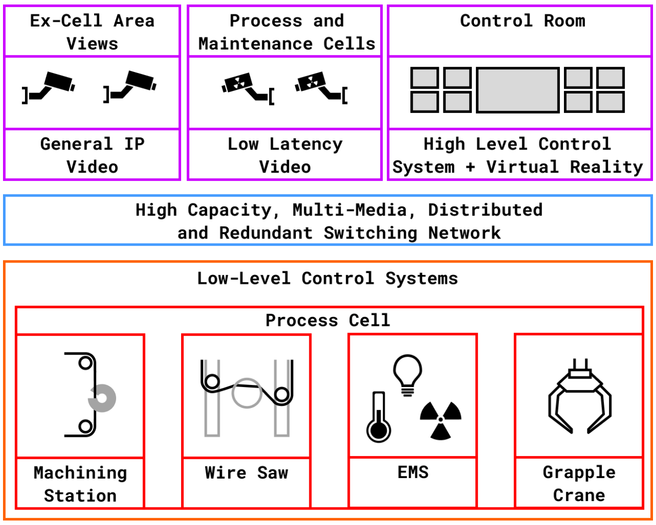


Fig. 4. ESS Active Cells operational systems, cameras, and high-level control systems are interconnected via high capacity network systems.

The network and data processing systems for the ESS active cells facilitates the support of a wide range of network traffic types, a data integrity policy that is resilient to power disturbances and component failure, and a security policy that is compatible with the wider ESS facility policies.

Whilst the network and data processing systems interface with the wider ESS systems, they allow for operation that is fully autonomous from the wider ESS facility, except for the exchange of status data. Comprehensive status reporting of systems within the Active Cells is provided to the wider ESS facility, for diagnostics and preventative maintenance.

The network implementation utilises commercial off-the-shelf enterprise grade switching and routing equipment. To satisfy security policies, the major firewall implementation is located in the wider ESS network, however, a last line of defence is implemented within the active cells network in the form of an access control list. With control of network and server configurations confined to an isolated management network.

Advanced queue management within the switches protects different classes of traffic from mutual disturbances, whilst providing guaranteed bandwidth for vital inter-server communications. A fully automated run up / run down system, backed by uninterruptible power supplies, assures data integrity of the data processing systems in the event of power disturbances. Potentially damaging power inrush at startup is avoided using automated power sequencing.

Data processing is supported as a virtualised environment across multiple servers. Data storage is implemented as a multiply replicated, software implemented and distributed storage system. This affords maximum data integrity with fast recovery times and fast inter-server movements of virtual machines as required. Backed up virtual machine images allow for fast re-establishment of services in the event of major application software failure.

III. OPERATIONAL ANALYSIS AND DEVELOPMENT

From the first phase of specifying and designing the Active Cells Facility, analysis was conducted into the tasks that were expected to be performed in the cells in order to provide detail to the requirements, and identify any risks and issues.

The operational analysis provided significant input into the design and development of the Active Cells overall facility and remote handling system. Operational assessments have been developed across all aspects of the cell that require remote operation, ensuring that the functions of all equipment can be delivered reliably, repeatedly, safely, and with low risk.

The experience gained from operating the JET RH systems [19] has been used to offer input into the design process of the tooling and equipment to optimise operability and minimise operational risks and unforeseen issues.

Space is very limited inside the process cell with all equipment in place, therefore it is vital that operations can run in the most efficient manner. Virtual Reality (VR) assessments were undertaken on a wide range of components and assemblies for the active cells in order to explore feasibility of operations and maintenance activities. Areas of focus have included the Shaft Cutting Station, electrical junction boxes, and waste basket storage. The studies fed back into the design of the components and tools where necessary to ensure that tooling, equipment, and components were able to be manipulated effectively in the cell.

During the delivery of the Active Cells Facility, consideration was given to operator training needs, and a comprehensive training package was developed to be delivered to operators at the facility. Training needs follow on from sequence development as the training must be in sufficient depth to prepare competent and safe operators, including having a strong knowledge of the tooling, equipment, processes, and other aspects of the operations.

Significant experience from training and operating remote handling systems at the JET facility has been translated into the context of the Active Cells Facility and its equipment. This transfer of knowledge is essential in delivering equipment and hardware that will not only succeed to operate in the given conditions, but will do so in an optimal way.

The Active Cells Facility requires a large number of diverse tasks to be performed remotely during its lifetime. This includes operations in confined, cramped and awkward spaces that need careful consideration. Operational sequences defining step-by-step plans for each of the anticipated tasks were developed using virtual realty simulations and CAD models, taking experience from operational development processes used at JET [13]. Throughout this process, assessments were made on the effectiveness of tooling and positions within the cell. An example of this is the removal of the target wheel shaft, where the manipulator is required to remove a number of bolts from the joining flange. The order of these tasks is also significant. For example, by minimising tool and equipment changes the in-cell operations can be optimised to save time and resources.

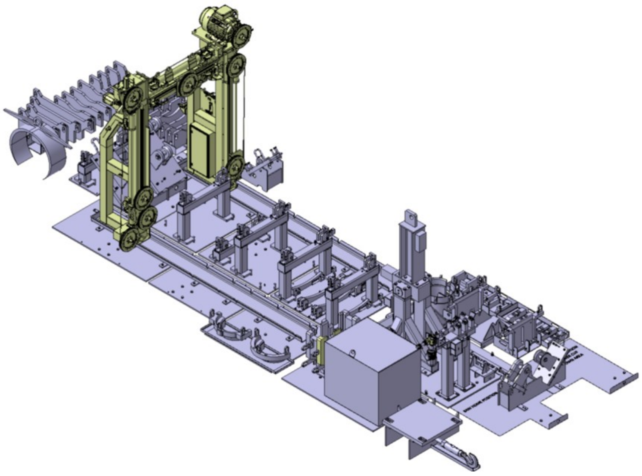


Fig. 5. Design of the Shaft Cutting Station. The wire saw shown in yellow sits above the rails and stands for supporting the shaft as it is cut into sections.

IV. PRIMARY FUNCTIONAL SUBSYSTEMS

The Active Cells Facility can be broken down into a number of distinct subsystems. The following sections provide a brief description of the most significant subsystems.

The primary functions of the cells relate to size reduction of waste components, transfer, and storage of waste. As such, the following sections will explore the implementation and design of the Shaft Cutting Station, the Machining Station, the Intrabay Doors, the Component Transfer Hatch, and the Waste Transfer System.

A. Shaft Cutting Station

The Shaft Cutting Station (SCS) performs the large-scale primary size reduction of activated items removed from the target station, such as cutting the 6.3m long Moderator Reflector Plug into smaller sections. The SCS is a large, remotely-operated wire saw as shown in Figure 5.

A diamond wire is used to cut through large components, reducing them to smaller sections compatible with handling, storage and export constraints. The cutting operations can require multiple wires and multiple days for a single cut. 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.

The wire saw is moved between cutting locations using the 8 tonne hook on the Mast Crane, and locates in recessed features in two rails.

Cutting trials were conducted to assess the performance of the cutting system, as well as investigate other aspects such as the spread of contaminated swarf and dust during cutting. Super-duplex stainless steel was used as an approximation for the material properties of irradiated 304 and 316 stainless steels with copper inserts used to represent the range of other materials present.

Initial trials were conducted with no ventilation present in the Active Cells. Dust measurements showed that airborne dust levels exceeded 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.

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 diamond beads and creates the need for premature replacement of the wire.

The test piece used were representative of the expected shaft cross sections, but thinner out of plane - with significantly less mass overall than the real waste components. Therefore, differences in the experienced heat transfer means 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 using a reacher-grabber tool operated manually to simulate the manipulators. During the Factory Acceptance Testing of the manipulator a further trial was conducted to ensure that the operation can be completed successfully.

B. Machining Station

The Machining Station (See Figure 6) is a diamond wire saw for performing accurate cuts on irradiated components, enabling the segregation of materials into specific waste streams, size reduction of components, and the retrieval of samples for analysis. The Machining Station is located in the Process Cell and is operated and maintained entirely remotely.

The diamond wire saw is mounted on a 4-degree of freedom gantry, enabling it to move in the X, Y and Z translational axes, as well as rotating the cutting face to enable vertical, horizontal and angled cuts. There are two stands that support distinct monolith components, and each is able to rotate presenting different faces of the component to the saw.

The machining station is operated using a suite of 8 motors, 8 resolvers, 8 limit switches, and 2 linear displacement sensors. Remote handleable connectors provide a cabling route to the control hardware, which is located outside the cell.

Operational challenges to the machining station include:

- Performing accurate cuts as the wire flexes during cutting
- Ensuring cables neither snag, or are damaged by the saw, in the full range of machine motion

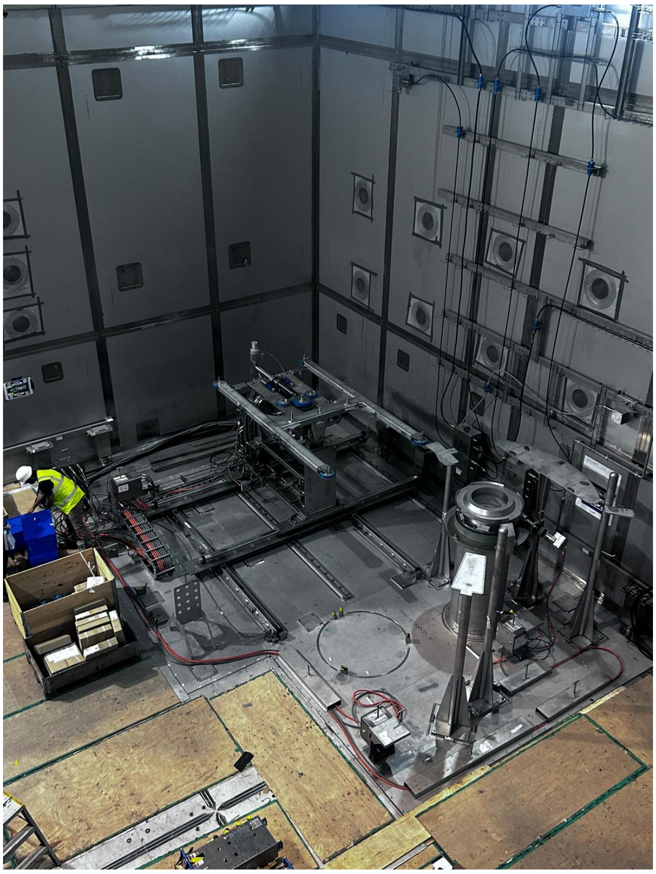


Fig. 6. Picture of the machining station during installation within the Active Cells, showing the diamond wire saw (back) mounted on its cartesian motion platform. On the bottom right, the component support stand for the target wheel can be seen (with the MRP stand still to be installed). The component stands include rotational functionality for the components, adding another degree of freedom to allow for more intricate cutting.

- Confirming complete cuts, and lifting cut sections, using only the remote manipulators and cameras

- Remote wire change

Maintenance challenges to the machining station include remote replacement of motors, sensors and junction boxes, interface management ensuring compatibility between existing and replaced components, as well as the high radiation environment which prevents human access, limits the lifespan of polymers, and requires bespoke electrical components.

Both Shaft Cutting Station and Machining Station are highly complex systems with significant technical challenges. These include moving parts with drag chains, electromagnetic interference challenges, intricate cutting paths, and remote maintenance. The remote nature of the cutting systems means that maintenance including routine changing of cutting wires is required to be conducted remotely using the manipulator system with feedback via cameras.

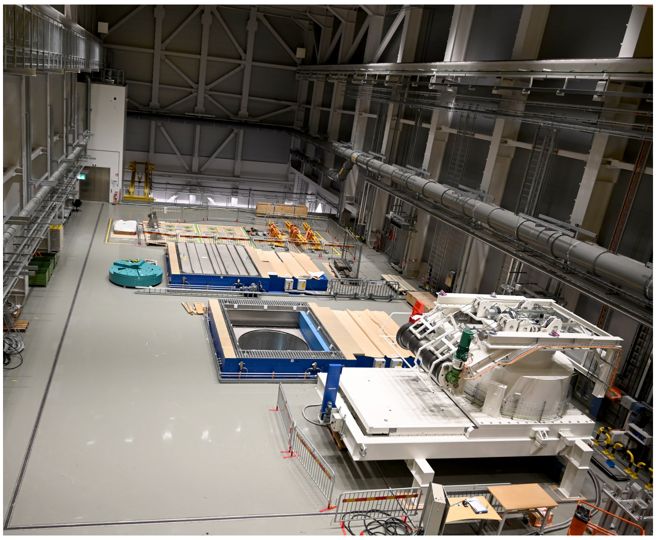


Fig. 7. View of the ESS High Bay, showing the floor valves and one of the ESS Transfer Casks

C. Floor Valves

The Floor Valves (See Figure 7) are a pair of gamma gates which cover two large openings in the ceiling of the Active Cells, each of which is 2.9m in diameter. The Floor Valves are the interface for the Active Cells with the ESS Transportation Casks - which are used to deliver components into the Active Cells from the ESS Monolith. When closed the Floor Valves provide the confinement and shielding barriers between the Active Cells and the ESS High Bay (which is a worker access area). The shielding requirement for the Floor Valves was defined as being equivalent to 1300mm of high density (MagnaDense 8s) concrete, with the shielding parameters enhanced through the design process using neutrons analysis to minimise the risks to workers. The overall height of the Floor Valves is less than 1000mm, with the low profile required to minimise the lift height of the casks above the Active Cells.

Each of the Floor Valves weigh in excess of 72,000 kg, with the shielding provided by a large steel gamma gate, which is mounted on a pair of rails to allow for the shielding to be translated sideways to open the aperture. This process is controlled via the Active Cells high level control system, with permissions for operation controlled by the radiological safety systems via interlocks to prevent accidental opening.

D. Intrabay Doors

The Intrabay Doors are doors that provide safety-critical shielding within the Active Cells to protect operators in the Maintenance Cell from radiation originating in the process cell, whilst still allowing transfer of the crane and loads between here and the Process Cell. They form part of the barrier between the Process Cell and Maintenance Cell of the ESS Active Cells facility. The barrier is achieved with 2 separate shield doors, an Upper Intrabay Door and a Lower Intrabay

Door.

Both doors open to allow passage of the cranes and suspended loads. The Upper door includes a number of small cut outs to allow for passage of the crane rails, crane resolver track and crane drag chains. Both doors are controlled via the Active Cells High-Level Control System by an operator situated within the Active Cells Control Room.

In the event of failure, recovery systems located outside of the Active Cells Facility can return both the Lower and Upper Intrabay Doors to the closed position without the need of workers access to the Active Cells.

The doors have only a small opening, which provides a dynamic confinement function due to the air flow through from the Maintenance Cell to the Process Cell. The Intrabay doors also provide a physical barrier to minimise dust and contamination entering the Maintenance Cell.

The Lower Intrabay Door is constructed from S355 carbon steel, 360mm thick in sheets, clad with 4mm stainless steel. It moves horizontally along a floor rail using a rack and pinion system, with a balance rail midway up the wall. The system incorporates a manual recovery drive system through a gearbox actuated from outside the cell

The Upper Intrabay Door is constructed from S355 carbon steel 150mm thick, clad in 4mm stainless steel. It swings vertically to open using a wire rope and pulley system. In the open position, the door is held flat against the ceiling supported by two shotbolts actuated external to the Active Cells. The pulley drums are located outside of the cell via penetrations.

E. Component Transfer Hatch

The Component Transfer Hatch [20] provides means for transferring small components of up to 30kg in and out of the Active Cells via a tunnel which extends the steel lining of the cell through the concrete shielding wall, whilst maintaining the safety of the facility. It forms part of the ESS Active Cells outer perimeter; the hot side hatch is to be located in the Active Cells Process Cell and the cold side hatch located in the Technical Galleries Penetration Room connected to a glovebox.

In all scenarios the Component Transfer Hatch must provide a shielding and confinement barrier to protect workers in the Penetration Room from radiation and contamination hazards in the Active Cells. This means providing the required radiological shielding (equivalent to 1300mm of high density (MagnaDense 8s) concrete) and ensuring the Active Cells confined area remains at a lower pressure than its surroundings so that any leakage is avoided.

The Component Transfer Hatch is composed of two doors, which individually provide the required shielding, a payload transfer mechanism, and a glovebox that ensures confinement and prevents the spread of contamination into the Penetration Room. The main design drivers are:

- to provide the required shielding needs
- operational performance
- to pursue a standardised and optimized design,
- to enable ease of installation
- to ensure a simple and quick maintainability paying special attention to the Remote Handling Compatibility of the Hot Side design and the ergonomics of the Cold Side design solution.
- Decontamination aspects to minimize the accumulation of radioactive debris.

The doors are composed of two monocoque parts based on an optimised stainless steel shell configuration filled of poured lead, where the shell serves both as structure of the door and as mould for the lead casting. With the aim of standardising the design and optimising efforts and costs, a single solution has been developed for both hot and cold doors.

Shielding needs have been determinant for the dimensional configuration of the doors so that each door independently provides the required radiation protection. The shielding configuration has been defined as a result of an iterative process starting from very simple ray tracing studies to detailed and exhaustive calculations performed with Particle Transport Codes (MCNP) [21] that have confirmed the shielding capabilities of the system.

Challenges posed by the installation constraints have also been overcome through a modular design solution. This modular design provides a simple solution to the constrained spaces and apertures for installation at both sides, being the dimensions of the Floor Valves apertures in the Hot Side and the restrictive dimensions of the Penetration Room the main challenges for the installation.

The design of both doors has been developed so that, while maintaining the same architecture at both sides, it is adaptable to the dissimilar arrangement of the building interfaces present in the Process Cell and Penetration Room minimizing to the maximum extent its impact on the aesthetics of the doors design.

The transfer mechanism transfers the payload into and out of the Active Cells. The maximum volume that can be transferred between the hot side and cold is 290 x 290 x 160mm. The design of the transfer mechanism:

- Is characterized by its modularity and encapsulated nature.
- Maximizes the predictability of this system
- Provides a reliable and fail-safe design
- Eases the installation and maintenance operations.

The glovebox is the component in charge of ensuring the confinement of the system. The design has been conceived to be a monobloc configuration that contains the whole system within its confinement barrier having only electrical feedthroughs crossing the confinement boundary, which minimises the number of leak barriers and associated risks.

F. Waste Transfer System

After waste is processed and packaged in the Process Cell, the waste packages must be transitioned through the Maintenance Cell, into the Transport Hall via a the Waste Transfer Hatch, where they can be collected by lorry for road transport to off-site storage facilities. The confinement and shielding barriers between the Transfer Area and the Transport Hall are provided by a large confinement door and external shield block.

The Waste Transfer System provides a means for transporting filled Waste Storage Baskets within shielded stainless steel tanks along this route, with the steel tanks loaded by the grapple crane. The system is centered around a trolley which is capable of supporting loads of 115 tonnes in order to accommodate the mass of the waste plus the mass of the shielded containers in which it is packed. Features are included to ensure the robustness of the interactions between the Grapple Crane and the Waste Transfer system for transitioning waste packages between the two.

The Waste Transfer System is connected into the safety system to ensure safety of the facility whilst the hazardous waste packages are being transitioned.

G. Storage Pits and Lids

The Storage Pits sit beneath the floor of the Maintenance Cell and provide safe storage locations for processed materials and for specific high-activation components to cool prior to processing. The storage space within the Active cells was sized to allow for storage of more materials than would be processed in any single operational campaign.

The Storage Pit lids provide a shielding barrier between the Storage Pits and the Maintenance cell, and can be remotely opened and closed using the Active Cells handling system. The Storage Pit Lids also provide a shielding barrier on the waste export route from the Active Cells and on a number of opening which are included to allow for future expansion of local post irradiation examination capabilities. The Storage Pit Lids were required to provide an equivalent to 1300mm of high density concrete of shielding, with neutrons analysis conducted to validate the design. The Storage Pit Lids are primarily constructed using re-enforced high density concrete with a stainless steel cladding, with some special cases manufactured from mild steel with a stainless steel liner.

The Storage Pit Lids have been designed for full remote handling by the grapple crane (as shown in Figure 8). To allow for larger storage pit openings whilst remaining within the load capacity of the Grapple Crane, the storage pit lids have been segmented - with between 2 and 4 lids per pit (with individual lids weighing up to 22,000 kg). In total there are 26 separate Pit Lids, providing approximately 400,000 kg of shielding.

Additional safety locks have been provided which prevent the pits being opened by the grapple crane, to safeguard workers from accidental exposure during hands-on maintenance.

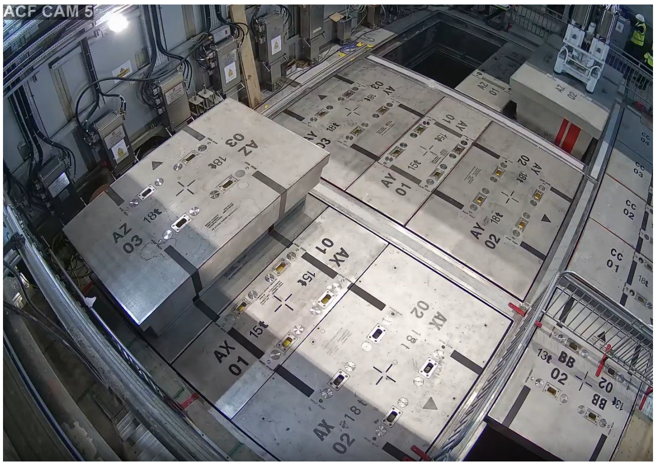


Fig. 8. Storage Pit Lid being handled by the Grapple Crane in the Maintenance Cell

V. DESIGN OF THE HANDLING SYSTEM

To facilitate the movement of materials around the Active Cells, remote maintenance of equipment, and other dexterous or lifting tasks, a remote handling system is needed. In the Active Cells Facility, the handling system consists of a telescopic mast crane equipped with a high-capacity two-armed tele-manipulator robot and a 25t grapple crane. See Figure 1 for an illustration showing this full arrangement in the context of the Active Cells, with a detailed illustration of the mast crane shown in Figure 9. Due to space constraints, the two crane systems share a single set of rails mounted on corbels at the top of the Active Cells.

In order to allow for flexibility and creativity in potential solutions, whilst allowing for the use of existing technologies in order to maximise value for money, the requirements for the handling system were abstracted to a set of generic requirements.

Firstly, 56 initial handling tasks were identified by analysing the known operations using remote operations experts. These were then narrowed down to 18 abstract tasks which covered all identified functionality. These are listed below:

1. Storage Pit Lid handling activities (Operational Volume A)
2. Large Target Station component handling activities (including layover) using the Grapple Crane
3. Waste Basket handling activities using the Grapple Crane
4. Lifting Chain installation and use activities
5. Target Station component lifting adapter installation activities
6. Medium sized Target Station component handling activities (including layover) using the 8t hoist

Fig. 9. Arrangement of the handling system. A telescopic mast interfaces with the crane bridge to provide X-Y-Z positioning within the cells. At the bottom of the mast, the dual-armed Telbot manipulator is mounted to provide dexterous tele-robotic manipulation capabilities.

7. Waste Basket handling activities II (For handling of lighter/empty baskets using the 8t hoist)
8. Shaft Cutting Station and Machining Station line replaceable unit replacement
9. Cutting Station wire replacement
10. Activities involving large bolts and tooling installation
11. Floor and wall mounted item removal activities
12. Handling of delicate components
13. Junction Box replacement activities
14. Camera replacement activities
15. Pipe and wire cutting activities
16. Contamination survey activities
17. Active Cells cleaning activities
18. Maintenance control for installation and maintenance Use

These could then be considered as bounding tasks on the cell for initial specification of needs and also as a known baseline for capability of the handling system when considering new additions or modifications to equipment within the Process Cell.

Challenges faced in designing the handling system included accounting for recovery scenarios, ensuring operational coverage of the full volume, compatibility with the radiation environment, mast travel constraints (including cable routing), long travel drag chains, camera and signal cable runs, and limited headroom for maintenance.

To support fully remote operations across a large working volume, the Active Cells Facility requires a handling system capable of both precise manipulation and heavy lifting. Operational requirements and infrastructure constraints led to the definition of two functional payload capacities 50 kg for dexterous tasks and up 25 tonnes for large component handling. However, the single set of crane rails limited system deployment, prompting the definition of operational zones with specific equipment and task allowances. To extend lifting capacity in the manipulator area without compromising fine control, an 8-tonne auxiliary hoist was included on the Mast Crane as a mid-range lifting solution [8] and a 3-tonne crane hook was added to the base of the mast as a lower-range lifting solution.

A. Mast Manipulator

The selected manipulators for dexterous manipulation tasks are dual-arm Telbot systems from Walischmiller, each arm rated for a payload capacity of 50 kg and equipped with integrated force-feedback functionality. The manipulator assembly is mounted on a telescopic vertical mast with a maximum extension of 8 metres, which can be retracted to allow passage through the transfer opening into the Maintenance Cell. This vertical mast provides a stable platform for dexterous manipulation tasks anywhere within the Process Cell.

The mast base is capable of rotating $\pm 180\,\mathrm{deg}$ around the vertical axis, enabling the manipulators to access a wide range of positions and orientations within the Process Cell. In addition to the manipulators, an 8-tonne lifting hook is suspended from a hoist on the overhead crane gantry. This hook falls within the reach envelope of the manipulator arms, allowing the operator to rig and unrig heavy components for lifting and transfer.

Control of the manipulators is achieved through kinematically equivalent master arms, which the operator interacts with. The in-cell manipulators replicate these motions in real-time. Simultaneously, forces exerted on the manipulator arms are scaled and fed back to the operator via the control interface, enabling tactile awareness of the task environment. This force-feedback capability significantly enhances precision and control, making it possible to perform delicate or complex operations remotely.

The dexterous manipulators have been specified to allow for direct handling of tooling, some line replaceable units, and lifting equipment, with several options for gripper interfaces including pre-defined geometries and defined bolting patterns which allow for use of a standardised gripper block.

Fig. 10. Grapple crane carrying stainless steel waste storage basket.

B. Grapple crane

The Grapple Crane (See Figure 10) is a dual bridge beam overhead gantry crane, which deploys a 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 $\pm 180\,\mathrm{deg}$ 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 interface for the Grapple Crane was standardised early in the design process. 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 compatible loads without requiring operators to perform any rigging.

VI. DESIGN OF THE HIGH-LEVEL CONTROL SYSTEM AND OPERATOR INTERFACES

The High-Level Control System (HLCS) is a vital part of the ESS Active Cells Facility. The ESS ACF contains a vast array of lower-level control systems developed by various 3rd party suppliers. These systems need to be operated from a unified interface with enhanced functionality to reduce the likelihood of operator error. These mechanisms include interlocks, simulators, user authorisation, command sequencing and action monitoring.

The HLCS is separated into vertical slices. Each slice controls an individual system such as the machining station, grapple crane or lighting control. The different sections of the vertical slice are integrated via ROS 2 [22]. For each connected device, a driver is provided that allows ROS2 to communicate with the device via OPCUA [23]. Each driver uses the RTI OPCUA-DDS Gateway along with some custom software.

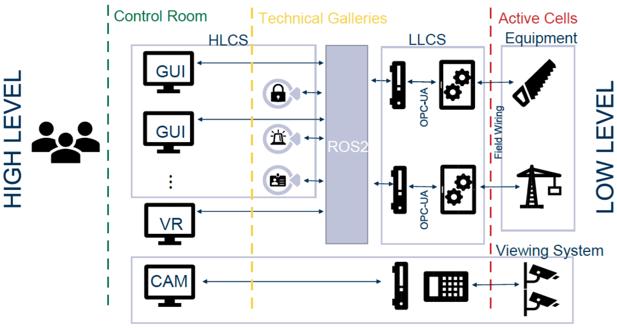


Fig. 11. Architectural design of the High-Level Control System. Operators interface with equipment via Graphical User Interfaces (GUIs) illustrated on the left. Control and communications of data is then transferred via layers including a ROS2 element, and OPC-UA interfaces to the low-level control systems of individual equipment controllers (right).

ROS2 Manager Nodes add configurable interlocks, command authorisation, enhanced command interfaces (Actions), and other high-level functionality to support operations. Graphical User Interfaces have been developed using QML integrated with ROS2 to communicate with the manager nodes.

A. System Architecture

The HLCS has been developed in a layered structure (see Figure 11) where clients such as GUIs interact with the system through ROS2 Actions and Services. These invoke specific commands across the various low-level control systems and devices. In addition to commands, a Condition Engine Node continuously monitors the current states of the subsystems and generates Conditions, used by Manager Nodes to prevent or allow the execution of commands.

The HLCS can connect to either the physical system or a simulation. When connected to the physical system, the Driver Node interacts with the individual system Low Level Control Systems (LLCSs), whereas in simulation-mode, it interacts with an emulation of the system instead.

B. High Level Functionalities

In order to accommodate multi-user interactions with the system, a role-specific authorisation system ensures that users can only interact with permitted subsystems and only approved personnel can override inhibit conditions within the system.

Concurrent interaction is prevented through the use of Conditions whilst the Graphical User Interfaces (GUIs) continuously update the Human Machine Interfaces (HMIs) based on the availability of operational commands. This increases the usability of the GUI for multi-user interactions.

An alert system continually monitors the Conditions and can alert operators to concerning situations clearly and quickly.

A comprehensive logging system allows for the recording of all interactions across the HLCS components. These records can be kept for future reference and retracing of events. In simulation mode these can serve as a task development tool.

C. Viewing and Lighting Systems

Due to the operations being conducted remotely without the use of windows, a comprehensive viewing and lighting system was required to allow for remote monitoring and operation of the equipment within the Active Cells. The Viewing System provides visual feeds for operators in the control room. Due to the number of interconnected elements, it is one of the most complex electrical packages across the facility.

Cameras include 12 Radiation Tolerant Cameras in the Active Cells, 6 in the maintenance cell and 6 in the process cell, as well as 8 cameras on the cranes and 1 mobile camera in the Process Cell. The system provides views to 5 workstations (desk positions in the control room), including 1 workstation for the manipulator operator.

A bespoke Lighting System has also been installed with considerations made to the radiation environment. Features of the lighting system include radiation tolerant lights rated up to 1MGy total lifetime dose, dimming controls, and individually switchable lights. The lighting system is designed to be fully maintainable by the remote handling system, as well as featuring mobile lights that can be positioned by operators remotely to provide lighting for specific tasks as required.

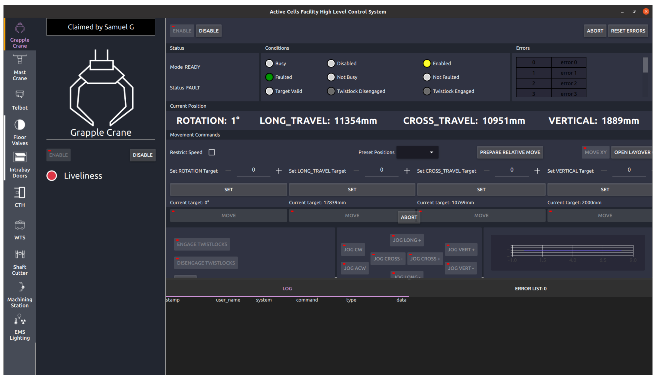
In order to eliminate stroboscopic effects on Viewing System, a 230V direct current power supply is used to power the lighting system.

D. Graphical User Interfaces

Graphical User Interfaces have been provided for all of the given systems using the UKAEA Commander tool, combined with QML, allowing operators to control and monitor the equipment. Figure 12 shows an example of the user interface provided for the Grapple Crane.

Multi-user interaction is enabled by ROS 2/DDS and governed by a Preconditions and Claims system. Execution requires an active Claim on the subsystem and satisfied Preconditions. This supervision and governance, along with enhanced feedback and context awareness, is what makes concurrent GUIs operationally viable. This functionality allows for a user interface or status display to be duplicated on multiple screens, however access to send commands or operate equipment can only be "checked out" by one operator at a time. This effectively is a set of inhibits and interlocks functionality for protection within the HLCS.

The modular and agile design allows for any of the desks to be used by any of the operators depending on operational needs with a high degree of interchangeability. User login functionality is also provided to ensure only operators who are suitably qualified and experienced can control items of equipment on a granular basis.



Claimed by Samuel G

Mode READY

Status FAULT

0	error 0
1	error 1
2	error 2
3	error 3

ROTATION: 1° LONG_TRAVEL: 11354mm CROSS_TRAVEL: 10951mm VERTICAL: 1889mm

Set ROTATION Target 0 Set LONG_TRAVEL Target 0 Set CROSS_TRAVEL Target 0 Set VERTICAL Target 0

Current target: 0° Current target: 12839mm Current target: 10769mm Current target: 2000mm

Fig. 12. Example Graphical User interface for control of the Grapple Crane. The interface shows different control modes for each axix, including jog and drive to set point. These include a visual indicator showing the position of the axis within its range of motion and limits (which are visualised using an accompanying VR system).

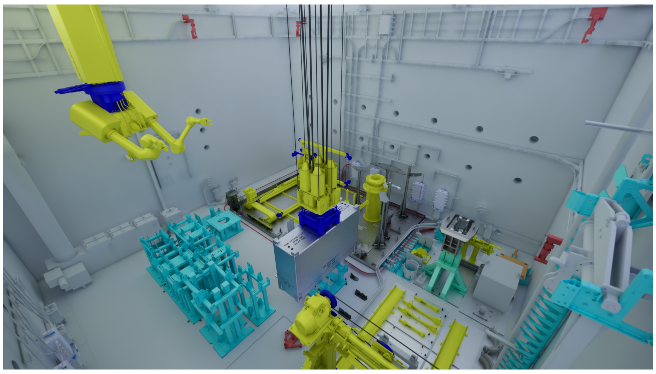


Fig. 13. Virtual Reality visualisation showing views from the process cell during a simulated remote handling operation.

E. Virtual Reality Visualisation

A Digital Twin or Virtual Reality (VR) model is updated in real-time with the status and positional information of all instrumented systems within the facility as shown in Figure 13. The spatial information provided by the VR system is displayed on computer monitors, and can be used by the operators for monitoring, and planning consecutive actions for the task at hand.

The VR Visualisation is provided by RHOVR, a software system to provide support for remote handling engineers. It provides advanced 3D visualisation for remote handling equipment in challenging environments.

The primary goal of RHOVR is to deliver a real-time interactive 3D model powered by the 3D visualisation software (Unreal Engine [24]). 3D models of the equipment are ani-

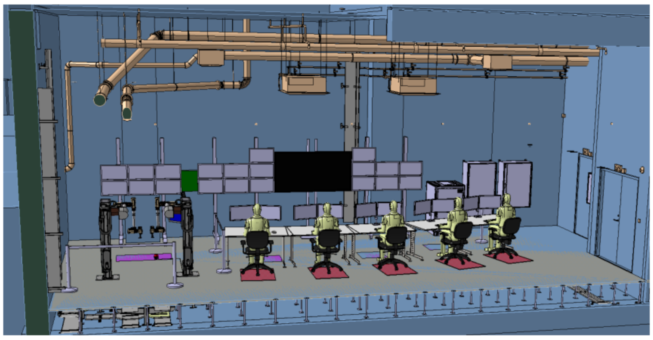


Fig. 14. Layout of the Active Cells Control Room showing operator stations and display screens.

mated in real-time to match the state of equipment as reported by the control systems.

The system also allows for offline task development and training in a safe and controlled, yet realistic environment, reducing cost and risk associated with developing new or challenging tasks, and training new individual operators and teams to conduct operations within the Active Cells Facility.

F. HLCS Integrated Subsystems

In order to the perform various tasks including size-reduction and waste-handling, there are 13 subsystems such as overhead cranes, manipulators, diamond-wire saw and cutting stations, etc. Every system is interfaced with the HLCS through the industrial OPC UA communication protocol.

OPC UA is a connection-oriented protocol and is not directly compatible with ROS2. In order to communicate with the LLCS systems, OPC UA Gateways are used to read values, which are then published as Topics. Conversely Driver Nodes are used to write commands directly to the subsystems. To ensure operational integrity, a bidirectional heartbeat system consisting of assertors and monitors are implemented.

G. Control Room

The design for the Control Room was deeply informed by the overall concept and operational method from the Remote Handling Control Room at JET. The ESS Active Cells Facility hosts significantly more equipment than the JET remote maintenance systems, and so the design could not be directly translated, but was adapted to meet the needs of the new context. Additionally, it was desirable to leverage advantages of new technological developments and some of the known shortcomings of the JET design in delivery of the Active Cells Control Room.

The overall design includes a set of connected desks for the operations team in front of a wall of display screens for monitoring camera views and software displays as shown in Figure 14. Thin client computing is available and provides access to displays and user interfaces for equipment at the desks. A set of control arms, kinematically similar to the remote Telbot manipulator are provided as the primary operator interface for performing remote handling and manipulation tasks. Feedback is provided via camera views relayed via the display screens, as well as some haptic information rendered to the operator through motors actuating the control arms.

Considerations have been made for adaptability and versatility of the control room for example by providing the ability to interchangeably switch any display to any viewing monitor.

VII. DESIGN OF THE SAFETY AND MONITORING SYSTEMS

The Active Cells Facility includes a range of subsystems for safety and monitoring of the status of the facility, ranging from conventional machine safety systems, radiological safety systems, and environmental monitoring systems. These are described in the following sections.

A. Radiological Safety system

The Radiological Safety System provides thirty different Safety Instrumented Functions which together protect workers from exposure to radiological hazards when inside or outside the active cells. These Safety Functions can be grouped into:

- Detecting the radiation levels inside and outside the active cells.
- Detecting that movable radiation shielding blocks and doors are in the correct positions to protect workers from radiation shine paths and prevent these shielding elements from being moved while operators are in the potential shine path.
- Managing access to the cells (for the limited scenarios that human access is required) by only releasing the airlock key for entry when all shielding is in place and radiation levels are within acceptable safe limits.
- Pressure monitoring to ensure that dynamic confinement is maintained (by ensuring the air pressure in the cells lower that air pressure outside the cells by a defined margin). This ensures any air and leakage across the seals to the cell will be inwards rather than potentially contaminated air escaping.
- Initiating alarms to alert operators and evacuate personnel in the case of any unexpected radiological event.

The risk reduction required is achieved by two independent safety systems with diverse approaches to ensure the likelihood of significant exposure occurring is extremely low, and within the limits set by the European Spallation Source Organisation. The two independent safety systems are called the Radiological Protection System and the Radiological Alarm System.

The Radiological Protection System is a SIL-2 rated system implemented via a Safety PLC. It primarily acts by removing power from cranes, doors, trays, hatches, trolleys and manipulators when an unsafe configuration of automated systems is detected. The Radiological Protection System also prevents unsafe access to the cells via a key interchange. The Radiological Alarm System is a SIL-1 rated relaylogic based safety system which causes alarms to activate if interlocks or confinement fails. This provides a backup to the Radiological Protection System, allowing operators to evacuate if all other systems fail.

B. Differential Pressure Monitoring System

The pressure within the Active Cells is maintained below the pressure of the surrounding areas to contribute to the confinement boundary. This pressure difference is monitored by the Differential Pressure Monitoring System (DPMS). The DPMS delivers a Safety Instrumented Function to monitor the difference in pressure between the inside and outside of the ACF. It raises an alarm if the difference falls below a threshold value.

The system takes two independent measurements of the pressure difference per cell and a 2 out of 2 to alarm architecture is used to reduce the risk of spurious alarm trips due to transient pressure fluctuations.

Remotely handleable dust filters are located on the hot side to prevent contamination ingress into the pipes, and three-way valves allow a compressed air line to be fitted to the system in order to purge the pipelines of contamination.

Exposure to the Active Cells atmosphere for the DPMS is provided via the Media Couplings, which are through wall penetrations with a labyrinth shape to prevent shine paths. As these are cast into the building structure the number and locations of these needed to be considered early in the facility development.

C. Master Emergency Stop System

It is a legislative requirement under the Machinery Directive to provide Emergency Stop functionality for industrial machines and this function is provided by safety systems local to each machine. All of the machinery described is designed to be operated from the Active Cells Control Room and there are a wide variety of possible hazardous scenarios in which the operators may need to quickly stop the operation of machinery to keep personnel safe and for asset protection.

The Master Emergency Stop System provides the functionality for the operator to press a single button, bringing everything in the Active Cells to a stop, removing the need for operators to spend time identifying specific stops for individual equipment.

The Master Emergency Stop interfaces with nine other systems and machines including:

- Remote Handling System
- Intrabay Doors
- Component Transfer Hatch
- Transfer Cask System
- Intellegent Extraction Tool Cask System
- Machining Station
- Floor Valves
- Shaft Cutting Station
- Waste Transfer System

The Master Emergency Stop system also monitors faults which may occur in any of these interfacing systems. It provides logic to allow central reset of the interfacing systems with appropriate monitoring to prevent unsafe reset in the case of faults or local safety demands.

The local safety systems for individual pieces of equipment are implemented using a diverse range of physical hardware, which interface with the Master Emergency Stop System, ensuring the same functionality is delivered across the Active Cells.

The installed Master Emergency Stop System is software/-PLC based and meets Performance Level d in compliance with key Machinery Safety Standards EN ISO 12100, EN ISO 13849-1 and EN ISO 13850.

D. Fire Suppression System

The overall approach towards fire safety within the facility began with minimising the risk of fires occurring, and then minimising the risk of fires spreading if they were to occur.

Approaches to minimising risk of fire include use of Low-Smoke Zero Halogen cables throughout the facility, compounding technology constraints imposed by radiation hardness requirements, as well as minimising the use of oils, greases and other combustible materials.

A fire detection system is installed, which includes detection systems to monitor the rate of temperature change, as well as monitoring for smoke.

If a fire were to be detected, airflow in the facility will be restricted and controlled, minimising spread. A fire suppression system including a water mist spray is also in place, balancing the need to suppress potential fires, whilst minimising the impact of water interactions with active dust such as spread of contamination. The water mist system is not immediately triggered on a fire detection, but instead is assessed by a central ESS fire control unit which allows for manual activation of the system. The actuation and control systems related to the fire suppression system are installed outside the Active Cells in order to minimise complexity related to the challenges of the environment inside the Active Cells.

E. Environmental Monitoring System

The Environmental Monitoring System (EMS) is a non-safety system for monitoring operational data of the Active Cells and the surrounding Ex-Cell Technical Gallery areas.

The primary functions of the EMS include monitor the ambient temperature in the Process Cell and Maintenance Cell, as well as monitoring the ambient temperature, relative humidity, cubicle temperatures, and presence of flooding in the Technical Galleries. Miscellaneous signals from around the facility, such as non-safety gamma monitors in the Waste Transfer Area are also monitored.

Overall this subsystem includes:

- 40 Temperature sensors
- 8 Humidity sensors
- 15 position switches to detect doors for confinement
- 8 Leak sensors
- An operational gamma monitor

Analogue sensors were preferred throughout the EMS design due to increased radiation tolerance, simplicity of integration, and ease of replacement in future compared with digital equivalents.

All data collected by the Environmental Monitoring System is to be provided to the Active Cells Control System to be displayed via a human interface. Operators in the Control Room will have the collated data at their disposal via logs and via visual representations. The EMS will also send alerts to operators via the Control System, should the environmental monitored values become of a concern. For example, in the case a cubicle reaches 50 °C, the operators in the control room will be alerted.

VIII. CONSIDERATIONS FOR MAINTENANCE OVER THE FACILITY LIFETIME

Due to the restrictions on human access into the facility, especially the process cell, specific considerations had to be made for maintenance and modifications of the facility over its multi-decade lifetime. Approaches to this included features to enable remote replacement of components expected to fail, alongside high reliability and robustness for elements that were expected to last the lifetime of the facility.

Any equipment being designed for use in the Active Cells has been designated as either line replaceable, or non-maintainable. The challenges of operating completely remotely steered the overall maintenance approach away from in-situ repair activities and towards simpler operations involving only replacement of modules in-situ. Overall this approach required simpler operations to be conducted in the cells, however made system designs more complex and non-standard compared with typical industrial systems.

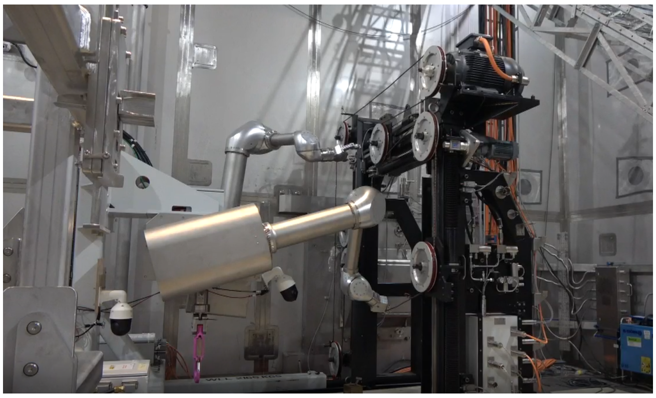


Fig. 15. Remote changing of a diamond saw wire using the Telbot manipulator within the Process Cell.

Items designated as non-maintainable are mostly simple structural steel elements. Whilst they are considered non-maintainable, considerations have been made for their permanent removal from the facility, allowing for some flexibility with future needs as well as eventual decommissioning.

Maintainable items including sensors, actuators, and many other items were typically mounted on plates with features for remote connection and disconnection of services as well as remote handling including installation and removal using the facility Remote Handling system.

A. Remote Diamond Wire Replacement

One of the key items requiring frequent replacement due to routine operations is the diamond wire blade of both the Shaft Cutting Station and Machining Station. The wire is twisted to evenly wear the diamonds, and the wires coiling makes direct handling with the manipulator challenging. This is however achieved with the Handling System as shown in Figure 15.

Trials were carried out to identify methods to retain the wires, with multiple integrated and external handling aids investigated. The key learnings being to lock the pulley as well as the wire, working with gravity, and that the key wire retention points are at the opposite diagonal pulleys in the set-up (top left and bottom right pulleys).

B. Electrical Junction Box Replacement

Experience from remote maintenance at JET revealed that electrical connection points can be a relatively common source of faults and failures. With the Active Cells Facility housing numerous pieces of equipment, sensors, and actuators, combined with the expectation of remote replacement of many of these elements, there are risks associated with electrical connectivity issues.

In order to mitigate these risks, electrical and signal connectivity to the machines in the facility has been provided via cables with connectors which interface with the junction boxes mounted on the walls of the cell. These wall mounted junction boxes provide feed-throughs to relay signals and power to areas outside the cells where human access is permissible.

The junction boxes feature remote handling compatible features and interfaces to allow for remote connection and disconnection of services to the equipment within the facility. In some cases, dual, redundant junction box positions have been allocated to allow for potential failures, as well as potential future expansion to the systems.

IX. FUTURE NEEDS AND PLANNED UPGRADES

Whilst the Active Cells Facility was designed to perform a specific set of known tasks on known components, it is anticipated that there will be some differences in future needs. During design and delivery, some accommodations were made for flexibility and agility in the capabilities and equipment provided by the facilities.

The most strongly anticipated change to the needs of the facility would result from variations in the components to be processed. The facility was designed to process waste components in an initial design, however it is likely that these designs will evolve as the facility transitions into operations.

Some accommodations (including modularity of equipment and interfaces) have been included as discussed in previous sections, allowing for future changes to equipment. Additionally, the removal of non-maintainable items has been considered, allowing for the potential of a future overhaul and refit of the facilities from scratch in the case of a significant change to the required processes.

Digital aspects of the system (including the High Level Control System) have been created in a manner that allows for future upgrades with relatively low impact. It is expected that the digital twin system might be enhanced to provide additional functionality such as automated updating and object tracking, using data from the cameras.

Finally, one area of possible automation to boost efficiency might lie in automation of some of the longer but relatively simple tasks. For example, the process of opening a Pit involves the serial removal of up to 4 Storage Pit Lids, resulting in a 2-hour overall process. It is conceivable that this type of well-understood task could be automated.

A. Identifications for future improvements

Throughout the design and delivery of the Active Cells, potential enhancements have been considered that would improve the efficiency of operations, or provide other benefits. A selection of these are described in brief below:

1. Automated motion sequences for cranes, providing functionality for pre-programming movement sequences for common locations and tasks.
2. General resolved motion for cranes, allowing more than one joint moving at a time, defining motions directly at the lifting point. This is currently in place for for specific tasks (layover operations) to enable the tracing of arcs, however it is believed there is potential for further benefits through use of this type of resolved motion.
3. Improved viewing on the manipulator, including camera enhancements such as roll function (digital or physical).
4. Automated tracking of components and equipment with cameras. This could include pulley positions on the Shaft Cutting Station.
5. The addition of boundaries and anti-collision zones for cranes and manipulators, which could be manually defined by operators, or dynamically defined from tracked objects.
6. A physical mock-up facility for training, task development, and trials.
7. Digital Twin based training and operation planning packages.
8. Joystick control of cranes with fully variable speed.
9. Additional Telbot end effectors to replace the gripper, with a remote exchange at a gripper change station, facilitating alternative interfaces to equipment and the environment.
10. Wire saw cooling system to improve the cut times and life of the wire.
11. Additional tooling suites for optimised material processing and handling.
12. Enhanced sensing capabilities within the cell, for example mobile gamma monitors or 3D geometric measurement systems for object tracking, mapping current status of the cell, and localisation of gripper interfaces.
13. Leveraging Artificial Intelligence to improve processes in the cell through utilisation of gathered process data for condition monitoring or process optimisation.

These thoughts are provided as potential considerations for future facilities, as well as to stimulate research in the topic areas.

X. FURTHER IMPLICATIONS AND LESSONS LEARNED FOR OTHER FACILITIES

The ESS Active Cells Facility is a first-of-a-kind large scale hot cell facility designed to perform highly challenging waste size reduction and waste storage tasks entirely remotely over decades of operation. This includes remote handling and manipulation of equipment and components using a robotic manipulator system within a high radiation environment. As such, it has paved the way in terms of establishing technological solutions and processes that will likely be relevant to other waste processing facilities and high-energy physics experiments.

Windowless hot cells are possible - Despite the facility still being in the process of delivery at the time of writing, we are confident that it is possible to design, deliver, and operate a fully remote hot cell with operations spanning a wide spatial volume. The Active Cells Facility was designed for fully remote operations with robotic manipulation and feedback via radiation tolerant camera systems. Preliminary testing of fully remote use of the manipulators, cranes and cutting systems using the viewing system has demonstrated this capability. It was designed for decades of operations, accounting for future maintenance, modifications, and upgrades.

Cost evaluations - Cost estimates were calculated at the beginning of the delivery process, however until engaging directly with the market it was highly difficult to accurately estimate costs associated with supply of some of the bespoke equipment needed. Benchmarking against existing products and equipment delivered into similar facilities, taking into account differences in requirements, proved an invaluable tool for improving the accuracy of cost estimates as well as identifying delivery risks.

Design for remote - Many aspects of design and delivery of the Active Cells would have been significantly simpler and cheaper if components were designed for remote operations from the start. Engagement with remote handling and operations expertise during initial design of the facility and components to be processed would have been highly beneficial.

Allowing suppliers to innovate - The approach to engagement with industrial supply chain through delivery of the facility was largely seen as a success. In particular, specifying requirements whilst allowing for divergence from conceptual designs allowed suppliers to find innovate ways to solve the real problems, in some cases using existing solutions in novel ways, driving down cost.

Robustness to supply chain and technology changes - The functional approach, applying systems engineering frameworks, has allowed UKAEA to adapt rapidly to supply chain issues (such as supplier insolvencies) and technical challenges to maintain project progress without necessitating significant rework.

XI. SUMMARY

This paper has explored the overall approach to delivery of the ESS Active Cells Facility, a hot cell designed for size reduction and packing of large highly radioactive waste components from the ESS experiment.

Operational analysis was conducted in order to analyse the required tasks and aid in specifying requirements on equipment that would be needed in the facility. During this process, operations engineers with experience from operating the remote maintenance systems at the Joint European Torus fusion experiment were engaged in order to translate know-how from the similar operations conducted over several decades.

The overall design and approach to design of the Active Cells was presented, including highlighting some of the key cross-cutting infrastructure. Some of the key challenges were analysed and used to help assess maturity of available solutions as well as outstanding technical risk.

An approach to delivery of the individual subsystems in a manner that encouraged innovative solutions from the supply chain was presented, as well as some descriptions of the key equipment resulting.

Considerations for maintenance and upgrades is an important topic when designing a facility intended to operate for decades, and this is particularly challenging when doing so in extreme high radiation environments such as in the Active Cells. The overall approach to accommodating maintenance and modifications was discussed in some detail.

Finally, in the hope of informing the future design of similar facilities, some of the more salient lessons learned and highlights were presented. This included aspects related to design, procurement, and cost estimation, but with the key lesson being that the undertaking is an achievable one.

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