HyDUS - Hydrogen Storage in Depleted Uranium

Phase 2 Final Report

University of Bristol, UK Atomic Energy Authority, EDF Energy R&D UK and Urenco (2026)

Authors

This report was prepared by the HyDUS Phase 2 consortium, including contributors from the University of Bristol, UK Atomic Energy Authority, EDF Energy R&D UK and Urenco.

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Acronyms

Acronym	Definition
ALARP	As Low As Reasonably Practicable
ATEX	Atmosphères Explosibles (EU directive for explosive atmospheres)
BNG	Biodiversity Net Gain
C&I	Control and Instrumentation
CfD	Contracts for Difference
COSHH	Control of Substances Hazardous to Health
CTS	CTS Logistics (dangerous goods carrier)
DESNZ	Department for Energy Security and Net Zero
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
DU	Depleted Uranium
DUBA	DU Bed Assembly
EA	Environment Agency
EMIT	Engineering Maintenance, Inspection and Testing
ESD	Electrostatic Discharge
FAT	Factory Acceptance Test
FCS	Fuel Cell System
FLIR	Forward-Looking Infrared (thermal imaging)

Acronym	Definition
FOAK	First-of-a-Kind
G99	Grid Connection Standard
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HAR	Hydrogen Allocation Round
HEPA	High-Efficiency Particulate Air
HCS	Hydrogen Compression System
HGS	Hydrogen Generation System
HyDUS	Hydrogen Depleted Uranium Storage
iCAM	Intelligent Continuous Air Monitor
IRR	Ionising Radiation Regulations
KJL	Kurt J. Lesker (bed manufacturer)
LCOS	Levelised Cost of Storage
LDES	Long-Duration Energy Storage
LEL	Lower Explosive Limit
LOLER	Lifting Operations and Lifting Equipment Regulations
LV	Low Voltage
MAT	Most Advantageous Tender

Acronym	Definition
MCL	Mobile Containerised Laboratory
MEAT	Most Economically Advantageous Tender
MFC	Mass Flow Controller
NCC	National Composites Centre
NCS	Nitrogen Cooling System
NOAK	Nth-of-a-Kind
NPPF	National Planning Policy Framework
NSR	Nuclear Safeguards (EU Exit) Regulations
ONR	Office for Nuclear Regulation
PCSR	Pre-Construction Safety Report
PCmSR	Pre-Commissioning Safety Report
POSR	Pre-Operational Safety Report
PESR	Pressure Equipment Safety Regulations
PRR	Pressure Regulating Reducer
PRV	Pressure Relief Valve
PSSR	Pressure Systems Safety Regulations
PUWER	Provision and Use of Work Equipment Regulations
PVT	Pressure-Volume-Temperature

Acronym	Definition
RPA	Radiation Protection Adviser
REPPIR	Radiation (Emergency Preparedness and Public Information) Regulations
SAT	Site Acceptance Test
SHRD	Stakeholder Requirements Document
SOP	Standard Operating Procedure
SRD	System Requirements Document
SQEP	Suitably Qualified and Experienced Personnel
TMF	Tails Management Facility
TRL	Technology Readiness Level
U_3O_8	Triuranium Octoxide
UF_6	Uranium Hexafluoride
UH_3	Uranium Hydride
UKAEA	United Kingdom Atomic Energy Authority
UKCA	UK Conformity Assessed
UPS	Uninterruptible Power Supply
UoB	University of Bristol
VCRM	Verification Cross Reference Matrix

Executive Summary

Project Context

The HyDUS (Hydrogen in Depleted Uranium Storage) Phase 2 programme was established to demonstrate the technical feasibility, safety, operational viability and commercial potential of reversible hydrogen storage in depleted uranium (DU) as a novel form of long-duration energy storage. The project forms part of the UK government's Long Duration Energy Storage Demonstration Programme and was funded by the Department for Energy Security and Net Zero (DESNZ).

The original scope of Phase 2 was to deliver two complementary demonstrators:

- A single-bed experimental system at the University of Bristol to characterise hydriding and dehydriding behaviour in detail;
- a multi-bed, fully integrated electricity-to-hydrogen-to-electricity system at the United Kingdom Atomic Energy Authority (UKAEA) to demonstrate full system performance.

In addition to technical demonstration, the programme included laboratory and facility design, safety case development, procurement and installation, DU supply-chain assessment, material processing and end-of-life studies and early-stage commercial pathways analysis.

Engineering Design Summary

A bespoke HyDUS laboratory was designed and constructed at the University of Bristol within the National Composites Centre in Filton. The facility comprises a dedicated controlled area, a supervised radiation-monitoring zone and a fully enclosed Mobile Containerised Laboratory (MCL) housing the HyDUS bed system and associated equipment. The facility incorporates a HEPA-filtered, pressure-stepped ventilation system, an Intelligent Continuous Air Monitor (iCAM) for radiation detection and a comprehensive suite of hydrogen, oxygen, pressure and temperature sensors to ensure safe operation.

The HyDUS bed design is a double-skinned, pressure-certified vessel configured to safely contain both hydrogen and DU. The DU is housed within an inner chamber lined with copper to minimise hydrogen migration and to enhance thermal conductivity. A copper helix assists heat distribution. Hydrogen is introduced and withdrawn through filters to prevent particulate migration.

The University of Bristol demonstrator integrates pressure regulating equipment, hydrogen purification, buffer vessels, vacuum pumps, heat exchangers, nitrogen cooling systems and over 100 distributed sensors to allow detailed control and observation of system behaviour during hydriding, dehydriding and passivation operations.

At UKAEA, a larger integrated demonstrator was designed to combine DU beds housed within an MCL with electrolysers for hydrogen generation, hydrogen compression systems, nitrogen cooling, a fuel cell system for electricity export and a remotely located control room. The

HyDUS compound and control infrastructure at Culham were constructed, and all major subsystems were procured. However, the integrated system was not commissioned or operated within Phase 2.

Safety Case and Regulatory Compliance

Safety case development represented a major programme work package. At the University of Bristol, safe operation was established through multiple Hazard and Operability Studies (HAZOPs), an independent Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) risk assessment, a fire safety risk assessment and the development of several detailed Standard Operating Procedures. Remote operation was mandated for all hydriding and dehydriding activities.

Regulatory approval at UoB was secured through an Environment Agency permit under the Environmental Permitting Regulations, authorising possession of up to 500 kg of DU as an open-source radioactive material.

At UKAEA, a full Facility Safety Case Report was developed in alignment with UK nuclear regulatory practice. The design was assessed against DSEAR, COSHH, IRR, REPPIR, PSSR and PE(S)R. The safety case demonstrated that risks arising from hydrogen release and radiological hazards could be reduced to As Low As Reasonably Practicable (ALARP) through engineered safety systems, procedural controls and emergency response integration with the wider Culham site. A key lesson is the importance of phased safety case development aligned to design maturity for FOAK nuclear-hydrogen technologies.

Procurement, Installation and Commissioning

Procurement of the University of Bristol MCL and cooling system was undertaken through specialist international suppliers. The containerised laboratory successfully completed Factory Acceptance Testing in February 2024 and was delivered to Filton shortly thereafter. The surrounding laboratory construction and ventilation integration were completed by May 2024. However, delays in the delivery of the nitrogen cooling system, safety instrumentation requirements (iCAM) and extensive safety documentation resulted in operational readiness being achieved only in July 2025.

At UKAEA, procurement of the MCL, hydrogen generation system, hydrogen compression system and fuel cell system was conducted under public procurement regulations. The HyDUS compound and associated cabling and control infrastructure were installed. Despite this progress, the system was not fully commissioned due to the complexities of meeting all the system requirements, combined with uncertainty in the technology's operational parameters.

Testing Programme Results

Limited surface oxidation of the DU was observed during loading but was deemed negligible in relation to overall storage performance. Testing at the University of Bristol successfully characterised hydriding and dehydriding behaviour, thermal responses, pressure dynamics and operational control of a single HyDUS bed loaded with approximately 30 kg of DU. Overall, the campaign demonstrated that full-scale DU hydride beds can repeatedly achieve rapid hydriding and controlled dehydriding when appropriate thermal management is employed. Hydriding performance is most strongly enhanced by increased temperature, pressure and cooling, while dehydriding efficiency relies heavily on uniform heating and adequate temperature sustainment. These findings inform operational strategies and design requirements for future HyDUS-type hydrogen-storage systems.

The UKAEA testing programme was defined in detail, including charging, discharging and sensitivity scenarios intended to simulate real market operation. However, no operational data were obtained from UKAEA due to the lack of commissioning and operation within the Phase 2 timeframe.

Based on the Phase 2 outcomes, the HyDUS depleted-uranium storage bed and the integrated system architecture have reached Technology Readiness Level (TRL) 5 (as the bed is planned to go through new design iterations and the integrated system at UKAEA has not yet been demonstrated), while the underlying storage of hydrogen in depleted uranium is assessed at TRL 6.

DU Material End Of Life (Decommissioning)

This project demonstrated that DU hydride can be reliably passivated into a stable oxide waste form through controlled oxidation. Late-stage testing showed negligible temperature rise and minimal residual oxygen uptake, indicating that unreacted metal was very limited. This confirms that end-of-life HyDUS beds can be rendered into a stable and transportable waste form when oxidised under controlled conditions.

However, disposal via current academic routes is prohibitively expensive. Cost estimates provided by Nuclear Waste Services indicated that incineration-based disposal of a single 30 kg DU bed could exceed £150,000 in charges for disposal of alpha particles.

Future Commercial HyDUS: Supply Chain and Commercial Pathways

This section examines the requirements for the future commercial deployment of HyDUS, combining the assessment of the DU supply chain with the commercialisation pathways for scaling the technology beyond the demonstrator stage.

The supply-chain assessment confirms that while significant inventories of DU exist within the UK nuclear sector, future deployment depends on the availability of DU processing routes into metal, long-term supplier agreements, transport and handling capability and regulatory engagement with the Environment Agency and the Office for Nuclear Regulation. The section also considers the capital, material and operating costs associated with DU metal production, alongside potential business models for long-term DU supply.

HyDUS is currently a demonstrator and is not yet cost-competitive with mature hydrogen storage solutions. However, it addresses a distinct niche for high-purity, distributed and safety-constrained hydrogen storage. While the technology is not commercially viable at present, the evidence from Phase 2 indicates that HyDUS could achieve long-term commercial viability, subject to cost reductions, hydrogen storage demand developing, DU supply-chain development, design optimisation, and scaling from FOAK to NOAK systems. The report outlines the most promising pathways through which commercial viability might be achieved in the future.

A phased commercialisation pathway has been defined:

- Stage 1 - TRL6 prototype (0-3 years): Finalisation of single-bed designs, thermal optimisation and early pilot deployments
- Stage 2 - Commercial demonstrator (3-5 years): Deployment of a containerised 20-bed HyDUS system and validation in real-world industrial settings
- Stage 3 - Market entry (5-10 years): Industrial-scale DU processing, system manufacturing and hybrid integration with other energy storage technologies

Progression through these stages is dependent on bed design finalisation, DU supply-chain readiness, regulatory clarity, system-level thermal efficiency improvements and early customer adoption.

Overall Summary

Phase 2 of the HyDUS programme has delivered the world's first meaningful-scale demonstration of reversible hydrogen storage in DU supported by comprehensive work across engineering design, safety assurance, procurement, materials handling, experimental testing, supply-chain assessment and commercial pathways definition. Although the integrated UKAEA demonstrator was not commissioned within the programme timeframe, the University of Bristol demonstrator has provided a robust technical validation of the HyDUS concept. The programme has established a substantial evidence base that significantly de-risks the technology and provides a clear foundation for future large-scale demonstration and commercial deployment.

Introduction

The transition to a net-zero energy system will require a diverse suite of long-duration energy storage (LDES) technologies capable of supporting an increasingly renewable, decentralised and flexible UK energy system. As renewable penetration grows and electrification increases demand-side variability, storage solutions across daily, weekly and seasonal timescales will become critical for maintaining security of supply, reducing curtailment and increasing system resilience. Existing long-duration options such as pumped hydro provide only limited national capacity and are geographically constrained, while other approaches such as gas peaking plant are incompatible with long-term decarbonisation goals. These system challenges have created a growing need for novel LDES technologies that can store energy efficiently, safely and economically over extended periods.

Hydrogen is expected to play an important role in this evolving landscape. As both an energy vector and a feedstock, hydrogen can absorb surplus renewable electricity through electrolysis, be used directly as an energy feedstock in multiple industries and can support dispatchable low-carbon power generation. However, the effectiveness of hydrogen within the future energy system depends heavily on the availability of safe, compact and cost-effective storage solutions.

The HyDUS (Hydrogen in Depleted Uranium Storage) concept explores one such option. By reversibly storing hydrogen within depleted uranium (DU) metal beds (i.e. DU storage vessels) as a hydride, HyDUS provides solid-state hydrogen storage at ambient pressures, enabling safe, stable, long-duration hydrogen retention with no self-discharge. This Phase 2 programme represents the first global demonstration of reversible hydrogen storage in DU metal at meaningful scale. The original scope of the HyDUS Phase 2 project was to design, construct, commission and operate two complementary demonstrators to validate the technical feasibility of hydrogen storage in DU and demonstrate an electricity-to-hydrogen-to-electricity system. The programme aimed to deliver a single-bed test system at the University of Bristol to characterise hydriding and dehydriding behaviour and a multi-bed integrated demonstrator at UKAEA to assess end-to-end system performance including electrolysis, storage and fuel-cell discharge. Alongside the technical build, the scope included laboratory and facility design, installation and commissioning activities, development of the safety case, DU procurement and processing, regulatory engagement, a DU supply chain assessment, revenue modelling and initial commercial and scale-up pathway analysis. Together, these work packages were intended to provide the evidence base required to support future scaling and commercialisation of the HyDUS technology.

UKAEA has not completed the full Phase 2 programme due to the underestimation of the duration of the development phase of hydrogen storage beds and trying to maximise the progression of the technologies' readiness, leading to additional challenges in the integrated system design. As a result, the UKAEA demonstrator has not been commissioned or operated. While significant progress was made in system construction, installation and safety case development, the outstanding activities could not be concluded within the project timeframe.

Consequently, no operational data or performance results are available from the UKAEA system and the operational findings presented in this report draw primarily on the University of Bristol demonstrator and associated analysis.

As a novel and evolving technology, the HyDUS demonstrator at the University of Bristol is not yet cost-competitive with mature alternative technologies. In particular, HyDUS does not compete directly with large-scale cavern storage or mature electrochemical technologies but instead fills important gaps for high-purity, distributed and safety-constrained hydrogen storage applications, supporting both industrial hydrogen demand and future hybrid energy hubs. This initial phase has been essential for unlocking future cost reductions and informing subsequent design iterations. With further design refinement and scaling, costs could be reduced compared to the demonstrator phase.

The work presented in this report reflects the learning from the full Phase 2 demonstration cycle. Procurement, installation, commissioning, DU handling, safety case assessment and the experimental campaigns at UoB have provided a unique evidence base for evaluating technical feasibility, risk reduction measures and practical implementation challenges.

The objective of this final report is therefore twofold:

- to summarise the steps across engineering design, safety, procurement, DU supply chain development, testing and system integration; and
- to provide a summary of the assessment of the future potential for HyDUS, including routes to commercialisation and implications for scaling the technology.

This document forms the final deliverable of the programme and consolidates findings from all underpinning work packages. The report is structured as follows.

- **Engineering design**

  Describes the design and configuration of both the demonstrators at the University of Bristol and the UKAEA.

- **Safety case**

  Summarises the regulatory compliance processes followed at both sites.

- **Procurement, installation and commissioning**

  Outlines the procurement of DU material and system components, together with the installation and commissioning activities for both demonstrators.

- **Testing programme results**

  Presents the results from the experimental campaigns undertaken at the University of Bristol, including hydriding and dehydriding behaviour, thermal characteristics and operational insights. This section also includes the plan for future operations at the UKAEA.

- **DU material end of life (decommissioning)**

Provides an overview of depleted uranium waste processing at end-of-life (passivation) and the available disposal routes

- **Future commercial HyDUS: supply chain and commercialisation pathways**

  Examines the future potential depleted uranium supply chain, processing routes, regulatory constraints and implications for future system scale-up. This section also sets out the technical, supply chain and market steps required for scaling HyDUS beyond the demonstrator stage, including potential early markets and longer-term deployment routes.

- **Conclusions**

  Summarises the work across engineering, safety, procurement, testing, end-of-life, supply chain and commercialisation

This programme was funded by the Department for Energy Security and Net Zero (DESNZ) under the Long Duration Energy Storage Demonstration competition. The project team gratefully acknowledges this support. The progress achieved during Phase 2 - including the manufacture of DU beds, construction of the demonstrator facilities, development of the supporting safety case, operation of the demonstrator and economic and financial modelling - would not have been possible without the funding and guidance provided through the DESNZ programme.

Engineering Design

In this section, the engineering design of the laboratories built in the University of Bristol and UKAEA will be described in detail. The goal of the experimental campaign in the University of Bristol was to 'stress-test' the single prototype bed module to identify the optimum conditions for hydrogen loading (hydriding) and unloading (dehydriding). These optimum reaction conditions for hydriding/dehydriding would have been later adopted by UKAEA and their experimental campaign.

University of Bristol System

Due to the novel nature of the project and the various potential hazards involved (not least, notable quantities of DU and hydrogen), it was determined that a bespoke facility would need to be designed and constructed to house the HyDUS beds. This facility was constructed by the UoB Campus team and their design consultants to a series of stringent design standards and has been widely lauded as an excellent example of a nuclear-grade laboratory facility, delivered using offsite modular construction to speed up onsite construction.

The University of Bristol HyDUS laboratory is based in the National Composites Centre (NCC) in Filton, Bristol, UK (Figure 1).

Figure 1: Satellite image of National Composites Centre (NCC) in Filton, Bristol

Source: Google Maps

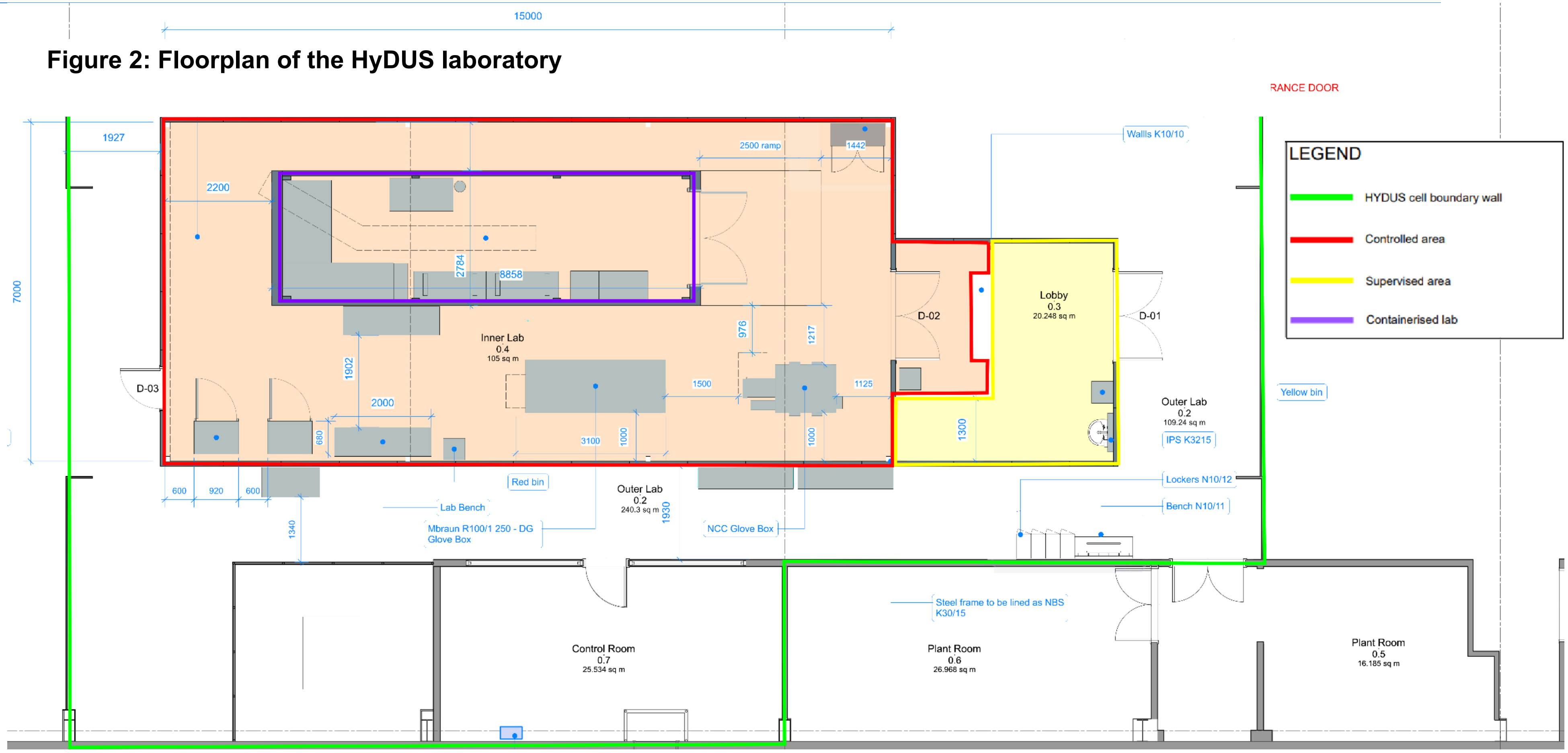
The HyDUS 'cell' facility houses:

- A control (remote operation) room;
- A small workshop;

- A Supervised Area serving as a preparation/radiation-monitoring space for entering/exiting the main lab;
- A Controlled Area which accommodates two gloveboxes, furnaces, the DU material safe and the Containerised Laboratory where the HyDUS experimental campaign took place.

A floorplan of the HyDUS laboratory is presented in Figure 2.

Figure 2: Floorplan of the HyDUS laboratory



Containerised laboratory

The Mobile Containerised Laboratory (MCL) serves as a fully integrated and compact space that accommodates the HyDUS bed prototypes, the system demonstrator and supporting equipment such as the cooling system, heat exchangers, C&I components, electrical cabinets and others. The laboratory was designed by Bristol University and Smolsys ltd. The latter, who was responsible for delivering this high-spec container, is a Swiss company specialising in building and installation of hydrogen and hydrogen-isotopes storage laboratories across the world.

The HyDUS MCL/ Smolsys containerised laboratory is a fire-resistant lab, equipped with sensors and pre-installed ventilation ducts. It can be integrated in a building and attached to an existing ventilation system. Through wall transits allow to connect to outside resources, such as gas, electricity and signals (IT). The lab is accessible via a loading ramp for equipment installation or via the two-wings doors for everyday routine access. The lab is fitted with an Electrostatic Discharge (ESD) floor, to allow to conduct research on electrical components or handling electric sensitive material. An integrated fine filter (HEPA14) keeps particles contained. The laboratory is built to F60 fire resistance. The sketch diagrams and a view of the inside of the containerised lab are shown in Figure 3 and Figure 4. The items in these diagrams are listed in Table 1.

Figure 4: Side view sketch diagram of the MCL

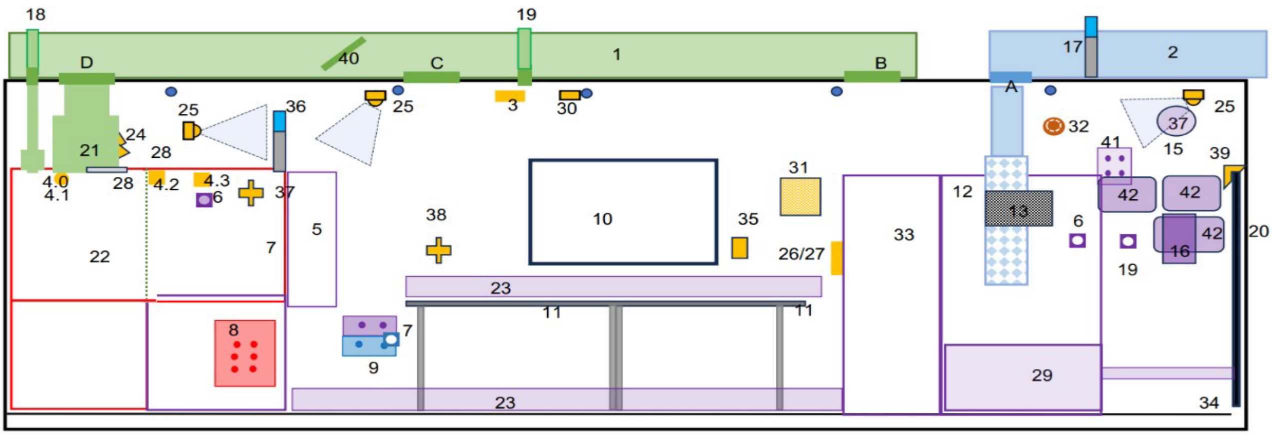


Figure 3: Top view sketch diagram of the University of Bristol/Smolsys container displaying the

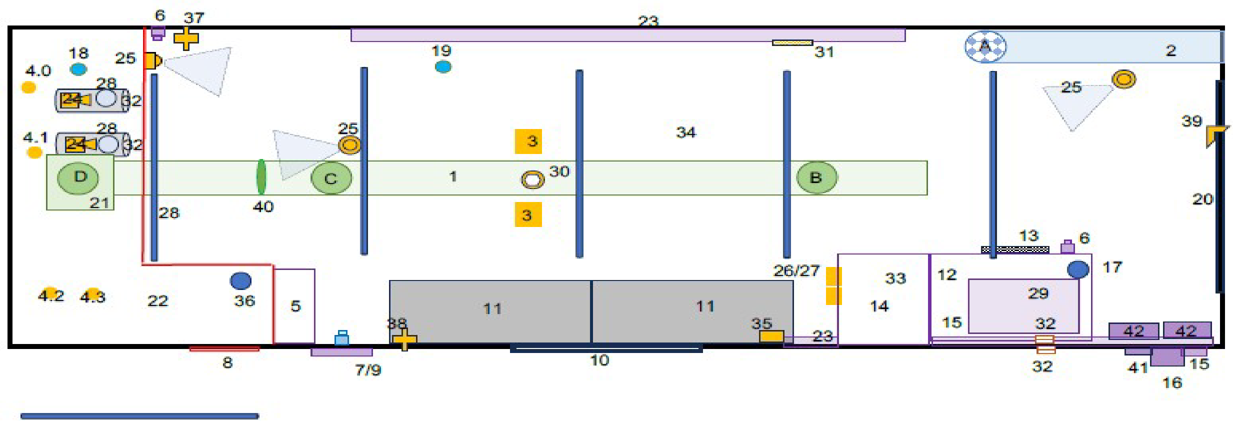


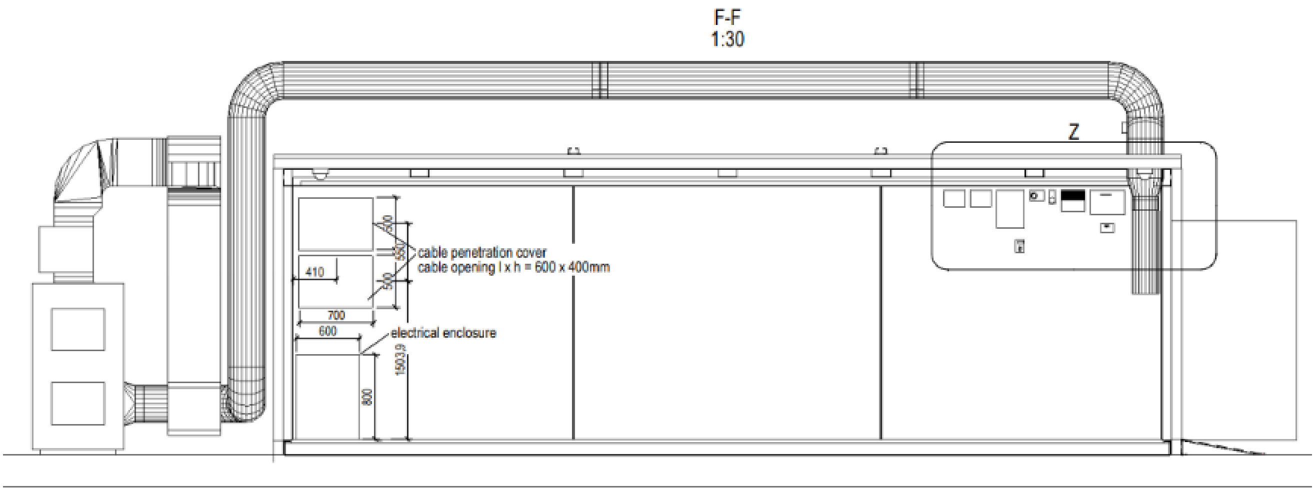
Table 1: MCL Container Item IDs

ID	Item	ID	Item	ID	Item
1	Waste Air duct with fire dampers (non ATEX)	2	Fresh Air duct with fire damper (non ATEX)	3	In Room H2 Sensors
4	Cabinet H2 Sensors (Atex)	5	Cabinet ATEX Cupboard	6	Cabinet Electric Emergency Shutdown
7	Compressed Air Shutdown	8	Gas Transits	9	Electric Transits for Heater / Compressed Air
10	Window	11	Worktable	12	Main electric cabinet
13	Display	14	Experimental Cabinet	15	Electric & Data transits
16	Main electric plug	17	Outside Alarm beacon	18	Cabinet Hydrogen static release
19	Work area Hydrogen static release	20	Main doors	21	Camfill Cabinet HEPA filters
22	Cabinet for experiments	23	Electric / Data cable ducts	24	FLIR Cameras
25	Surveillance Cameras	26	Oxygen Sensor Kimessa	27	CO2 Sensor Kimessa
28	FLIR Windows	29	UPS	30	Smoke Detector
31	Control Panel	32	Acoustic Hydrogen Alarms	33	Cabinet for Experiments
34	ESD Floor	35	Inside Humidity / temp sensor	36	Inside alarm beacon
37	Differential Pressure Sensor (ATEX)	38	Differential Pressure Sensor (non ATEX)	39	Door Contact for ventilation

ID	Item	ID	Item	ID	Item
40	Ventilation Flap	41	Data transit	42	Fire damper PLCS

The wider facility is a custom-built design delivered by the University of Bristol Campus division. The Campus team managed a team of sub-contractors, including Dukes, Grundy and M&M medical to plan, build and commission the facility. This includes a bespoke ventilation system providing powerful extraction for the MCL (Figure 5) and the surrounding laboratory, allowing for a pressure step down between each room - critical for ensuring any potential gas or particulate release to remain within the lab.

Figure 5: Schematic diagram of the ventilation system over the containerised lab



The containerised lab has a powerful HEPA filtered ventilation system that discharges via a purpose-built flue, four metres above the top of the building, fuelled by two load-balanced

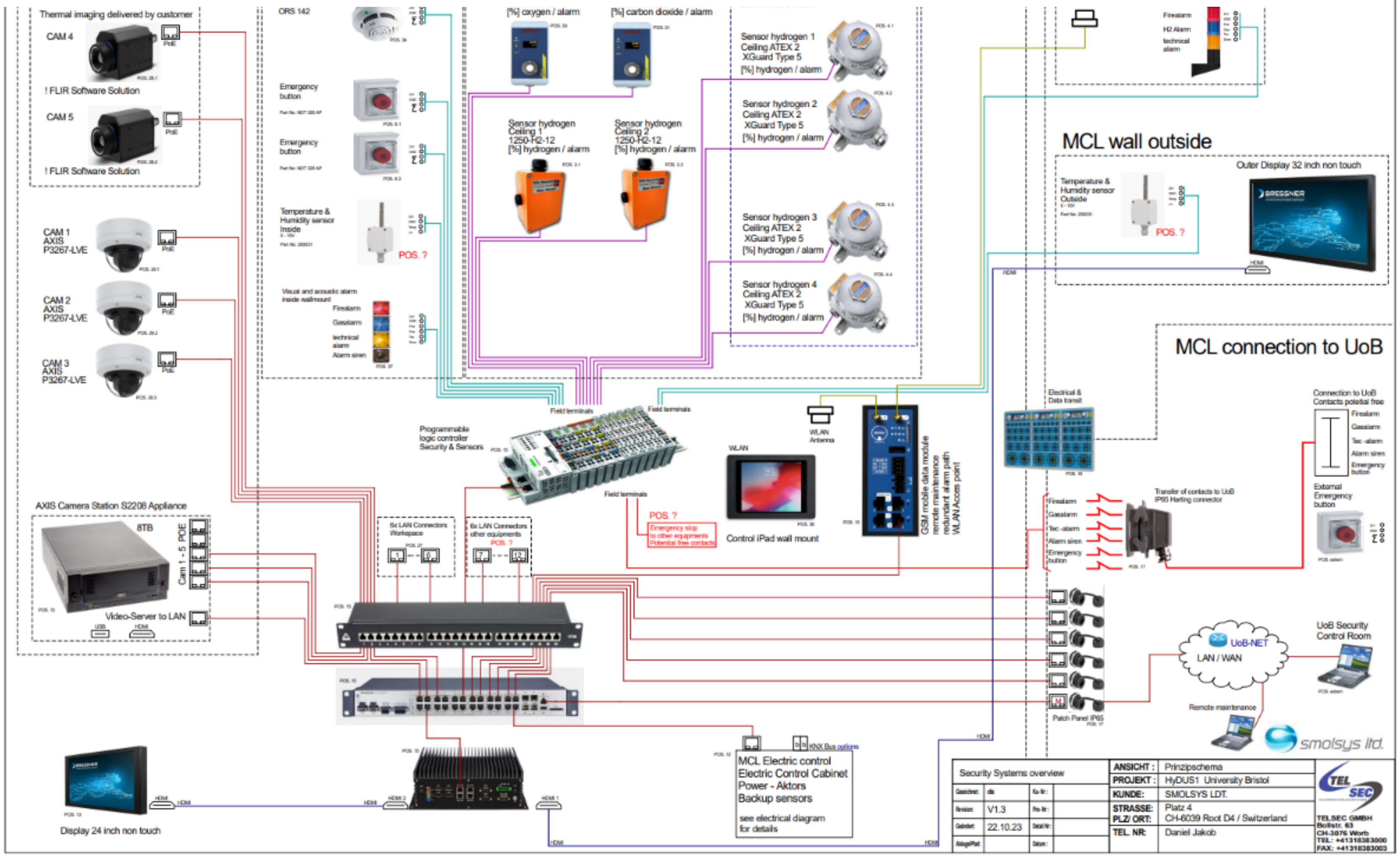
Figure 7: Load balanced extraction fans

Figure 6: iCAM

extraction fans (Figure 6). This ventilation system has an iCAM (intelligent Continuous Air Monitor) installed - purchased from Mirion - to monitor and evidence alpha / beta emissions (Figure 7). The iCAM provides an additional layer of radiation security, with detection threshold alarms set to provide warnings if emissions over pre-determined thresholds are detected.

The containerised lab integrates multiple, connected, sensors, gas detection systems and imaging systems (Figure 8). All critical data is displayed either on the control room screens or, for fire and ventilation systems, on the external control panels.

Figure 8: Schematic of sensors, gas detection systems and imaging systems of the MCL



Demonstrator design

The demonstrator system design (as shown in Figure 9 and Figure 10) consists of the following:

- Pressure Reducing Regulators (PRR)
- Pressure Relief Valves (PRV)
- Pneumatic valves
- Pressure transmitters (0-10 bar)
- Type K thermocouples various sizes.
- ½-inch and 1-inch Swagelok piping and connectors.
- Various gas sensors (O2, N2)
- In-line filters (5-15 µm, 40 mm length, 40 mm in dia.).
- Flow meters
- Flowmeter and pressure controllers
- Pressure regulators
- Buffer vessel tanks
- High pressure hydrogen and oxygen tanks
- Hydrogen purification systems
- Heat exchangers
- DU storage beds (2x)
- Dry scroll pumps
- Turbo pump

A detailed description of the beds design, as key components of the system and proprietary design of UoB, is given in the next section.

Figure 9: Section view of the lab, showing the HyDUS beds and the cooling system

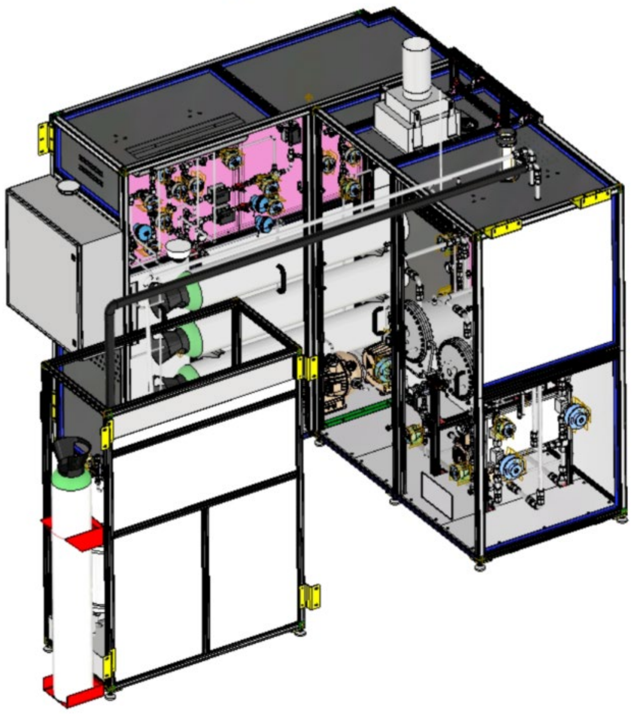
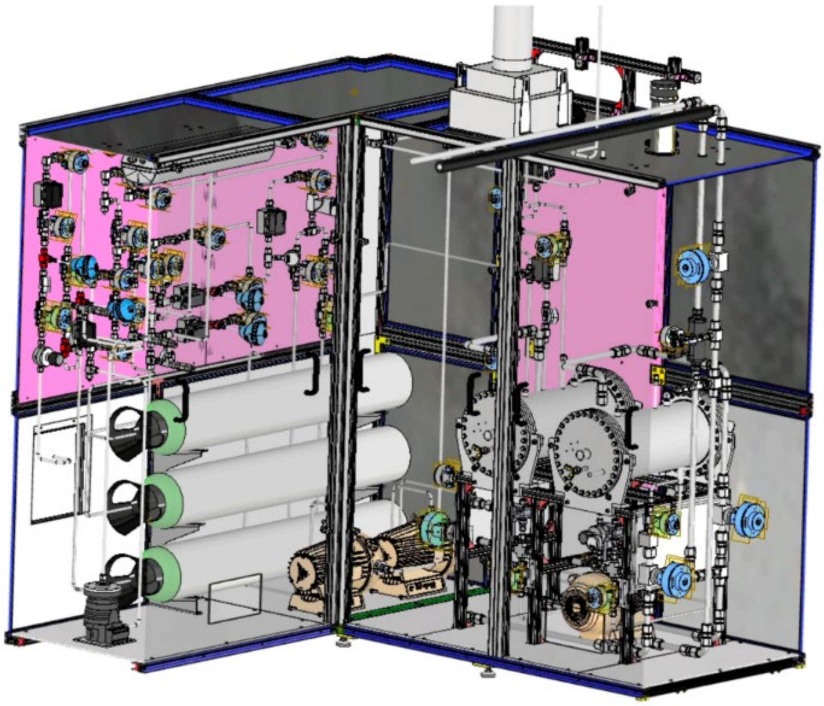


Figure 10: Section view of the lab, showing the HyDUS beds and other components



Bed design

The HyDUS project is the world's first demonstrator for the reversible storage of hydrogen using DU. By forming a chemical hydride compound, hydrogen can be stored indefinitely as a solid at room temperature and pressure and later released by heating the hydride material to approximately 350°C. This demonstrator project utilises a double-skinned bed system to contain the material, effectively creating a vessel within a vessel to ensure the safe containment of both hydrogen and uranium.

Whilst hydrogen storage beds are not a new concept, the approach taken by HyDUS to include the involvement of DU and demonstrate its capacity for the high density, high efficiency reversible storage of hydrogen, resulted in a pressure-certified vessel that was, most importantly, safe to use. The bed design took three primary considerations into account:

- The need to adequately protect the reactive DU inside the bed;
- To effectively manage heat flow into and out of the bed to enable efficient loading and unloading of hydrogen;
- To safely accommodate the volumetric change of the reactive material inside the bed as it takes up hydrogen.

The DU is held in the inner chamber which has been lined with copper to act as a barrier against hydrogen migration through steel parts, increasing the lifetime of the beds. A copper helix aids in distributing heat from the heater cartridge to the DU. Three thermocouples are installed in the inner chamber to provide the critical temperature, information that is needed for bed operation. Hydrogen is supplied and exhausted through a 5-micron sintered metal filter, which confines fine particulates of DU to the inner chamber. The inner chamber is joined to the outer chamber by a ceramic decoupler which thermally isolates the two chambers and a metal bellows which provides flexibility between the two chambers, easing assembly and preventing damage to fragile parts. The inner vessel is held concentric to the outer by two support rings that are joined by a threaded rod that have a ceramic foot in contact with the outer chamber to thermally isolate the two chambers.

The design and operation parameters of the DU demonstrator are shown in Table 2.

Table 2: Operational and design (maximum allowable) parameters for the HyDUS bed system

Parameter (unit)	Value
Maximum pressure in the system (bar)	10
Hydriding pressure range (bar)	0.5-2.5
Dehydriding pressure range (bar)	0.15-4

Parameter (unit)	Value
Maximum allowable temperature in the bed (°C)	500
Operating temperature (hydriding) (°C)	25-350
Operating temperature (dehydriding) (°C)	375 -480
Average estimated flow (hydriding) kgH2. h-1	0.278
Average estimated flow (dehydriding) kgH2. h-1	0.072

UKAEA System

In this section, the UKAEA outlines its approach to utilising existing knowledge of uranium-hydrogen storage beds in designing an integrated energy storage demonstrator.

Requirements and documentation

The following consortium requirements were set to demonstrate and evaluate the technology's functionality.

- Include the University of Bristol's DU storage beds in the demonstrator.
- Demonstrate the application of the storage bed technology through operating an integrated product.
- Use the UKAEA Culham Campus grid connection.
- Utilise as many commercial-off-the-shelf components as possible.
- Demonstrate resolving challenges of implementing the technology on a brownfield site.
- Ability to passivate the beds at the end of their operations.
- Demonstrate operational modes relevant to future commercial-scale applications.

The UKAEA identified the following additional optional requirements, which were seen as beneficial for supporting the future commercialisation of the technology.

- Utilise as many components as possible that would be economical in future scaled applications of the design.
- Maximise the system efficiency to retain hydrogen which was not consumed for electricity generation.
- Include design considerations which would enable future automation to be demonstrated.

The complexities of meeting all these system requirements, combined with uncertainty in the technology's operational parameters, led to delays. The concept and preliminary design stages, along with the procurement of the major components, were all completed, accounting for the full consortium requirements. The decision was taken in the second half of 2025 to resolve the remaining detailed design challenges by limiting the requirements to the first five consortium requirements and passivating the beds. This section of the report will record the UKAEA's knowledge from resolving design challenges for the demonstrator, including learning from working towards the full consortium requirement during the early design phases.

The reduction of the number of requirements for the final detail design reduced the number of operational modes that needed to be demonstrated; this also enabled simplification of the installation and the instrumentation to be commissioned. This, in turn, shortened the time to implement the design. Provisions were made so that, in the future, the system could be modified to demonstrate relevant operational modes. The required instrumentation for safety and environmental protection, enabling the system's functionality, was fully implemented.

The stakeholder requirements for the UAKEA demonstrator are displayed in Table 3. The second column highlights the changes in the requirements. An explanation of the revision is presented in the *Key design decisions* section.

Table 3: UKAEA HyDUS demonstrator key stakeholder requirements

Initial stakeholder requirements	Revised requirements
Demonstrate safe performance on site, with operational storage of 2.6 kg of hydrogen	Reduced initially to 6 small DU beds, 43 kg (2.6 kg total storage capacity of hydrogen), then reduced to 2 small DU beds of 35 kg (0.7 kg total storage capacity of hydrogen).
Store hydrogen in multiple DU beds to demonstrate different use cases	Limited to 2 beds (process design has provision for 6)
Determine and optimise the responsiveness of the systems to “dispatch” and “charge” commands.	No change
Must charge using electricity for at least 4 hours.	No change
Demonstrate the ability to remain charged for over 4 hours, without significant self-discharge	No change

Initial stakeholder requirements	Revised requirements
Must have the flexibility to increase electricity demand at times of low demand and high renewable output	No change
Provide a cost-effective design demonstration with good round-trip energy efficiency	No change

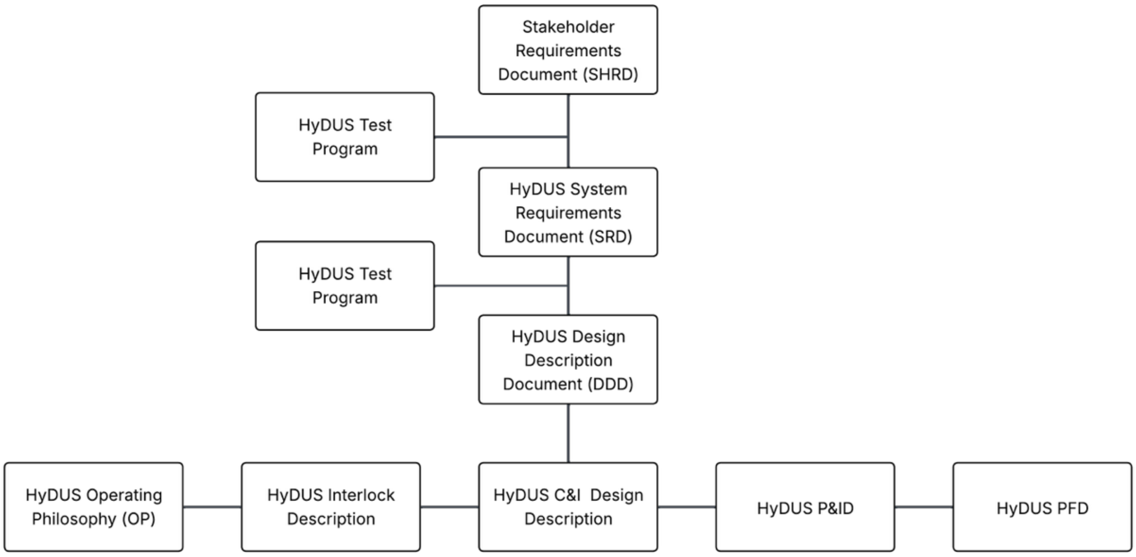
The design was assessed against compliance with a range of regulations, including: the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR), Control of Substances Hazardous to Health (COSHH), Ionising Radiations Regulations (IRR), Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR), Pressure Systems Safety Regulations (PSSR) and Pressure Equipment (Safety) Regulations PE(S)R.

The UKAEA followed its internal technical control process to ensure the traceability and version control of design documents. The gate reviews of documents ensure an internal second line of assurance over compliance between the design, legislation and design codes. This was seen as a benefit for potential parties interested in the commercialisation of the technology, as the demonstrator design documentation captures potential solutions to challenges in its deployment.

The project team formally captured the complete list of UKAEA HyDUS requirements, including those in Table 3. The System Requirements Document (SRD) was developed as a technical response to stakeholder needs. The design description outlines the HyDUS system's design. The system's goals are captured in the experiments defined in the HyDUS Test Program Specification. The compliance of the HyDUS system with these requirements is tracked by a Verification Cross Reference Matrix (VCRM). The HyDUS design description document is supplemented by 5 documents that provide detailed coverage of design aspects, the structure is shown in Figure 11.

- **HyDUS Operating Philosophy** - Defines how the key operational and functional states/configurations of the system and the process control aspects of the system, are managed safely.
- **HyDUS Control System Interlocks Description** - Defines the system’s hardwired and software interlocks, when applicable and the controls they impose.
- **HyDUS System Control & Instrumentation Design Description** - Defines the design of the control and analysis sub-systems.
- **HyDUS System Piping and Instrumentation Diagram** - Defines the system layout and design.
- **HyDUS Process Flow Diagram** - Defines the key system process flow parameters.

Site location



The UKAEA HyDUS compound is situated at the UKAEA Culham Campus in Oxfordshire, internal estate reference is B29. The control room is housed in the main Tritium Fuel Cycle building known as B24, approximate distance between the two is 150 meters (Figure 12).

Figure 12: Representation of the UKAEA Culham Campus. The pink box and insert magnification show the location of the HyDUS compound (B29) and the building housing the HyDUS control room (B24)

Figure 11: Design document tree

The UKAEA Environment Agency permit initially did not allow for the storage of sufficient quantities of DU on the Culham site; the Environment Agency issued a revised permit that would allow the HyDUS project to bring the required DU quantities onto the site to meet the full scope of consortium requirements.

The HyDUS compound requires a 300 kW power supply from the B24 facilities' primary Low Voltage (LV) distribution. The main load comes from the hydrogen generation system, with additional significant power demand from the DU bed heating, the nitrogen cooling system pumps and the hydrogen compression system pumps.

The HyDUS fuel cell is planned to export up to 28kW back to the National Grid network, via a connection complying with the Engineering Recommendation G99 Connection Procedure.

The HyDUS system is required to be controlled and monitored both locally from the mobile containerised laboratory and remotely via a control room. A 12-core fibre-optic cable serves as the primary signal transmitter, accompanied by a control cable, which runs between the two areas (B24 and B29 HyDUS Compound).

In addition to control room connections, appropriate synchronisation between the emergency alarm and response systems of HyDUS and the B24 building, as well as the wider UKAEA site, was established. For example, a fire alarm trip is connected to the Culham site gatehouse.

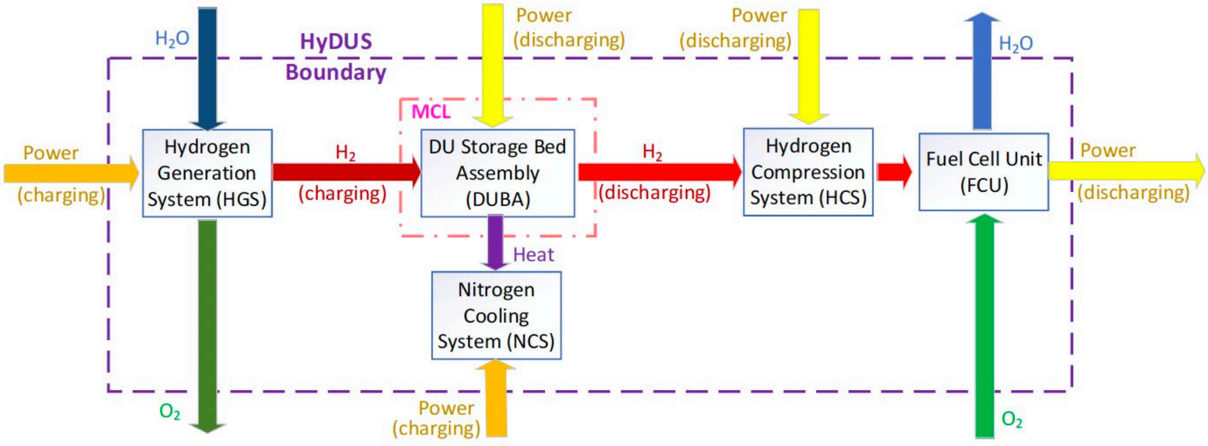
Components description and specification

The UKAEA HyDUS demonstrator can be broken down into six major components:

- Depleted Uranium hydrogen storage bed (DU beds) (provided by the University of Bristol)
- Mobile Containerised Laboratory (MCL) & Nitrogen Cooling System (NCS) (to house and cool the DU beds)
- Hydrogen Generation System (HGS) - Electrolysers
- Power Generation - Fuel Cell System (FCS)
- Hydrogen Compression System (HCS), interconnecting pipework and integrated control system
- HyDUS compound (B29) & control room

A block flow diagram of the demonstrator is shown in Figure 13. The HGS use electrical power to extract hydrogen from water, the H2 is generated at 35bar(g) which is then manually regulated to an output between 12bar(g) and 2bar(g). The hydrogen is stored in DU beds as a metal hydride (in the form of UH3). This process generates heat, which is then extracted by the NCS to facilitate the storage process. The process of storing hydrogen is referred to here as ‘charging’. After charging is complete, the stored hydrogen can be made available when needed to generate electrical power. This is performed by heating the DU beds to liberate the stored hydrogen at between 1.5/2bar(g) (‘discharging’). It is then compressed/pumped by the HCS to 16bar(g) to be fed into the FCS at 12bar(g), which uses the hydrogen to generate electrical power, which is exported back to the grid.

Figure 13: Simplified basic block flow diagram of the HyDUS demonstrator concept



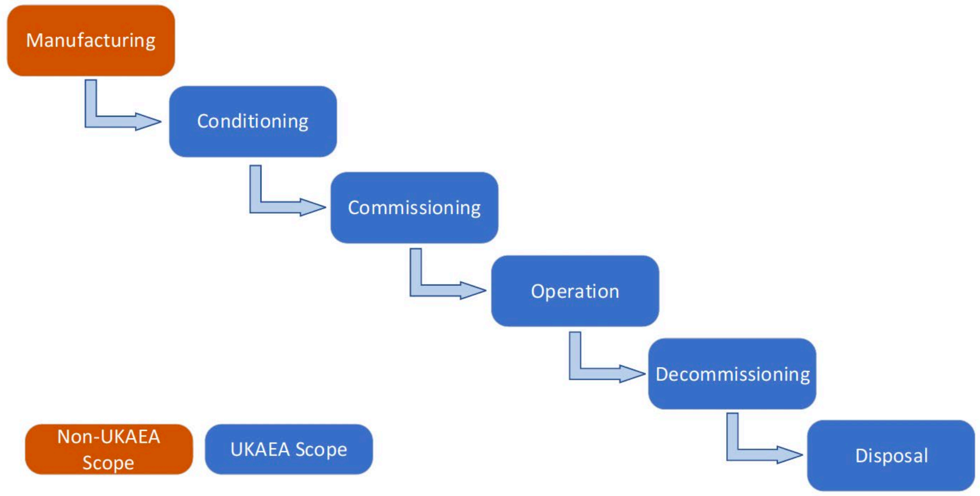
A brief description of each component is given below.

DU hydrogen storage bed

The UKAEA has experience and knowledge of operating smaller DU beds located within the Active Gas Handling System situated on the Culham site; therefore, arrangements to accept the University of Bristol manufactured DU beds were in place. The DU beds were to be shipped to the UKAEA in a non-conditioned state, whilst the vessel would be filled with an inert gas. This was deemed the optimum transport condition, as the pyrophoric risk is negated compared with a hydride state, whilst monitoring the pressure within the vessel confirms the integrity of all sealing surfaces and pressure boundaries.

The HyDUS lifecycle of the DU storage beds may be broken down into the stages shown in Figure 14, the UAKEA did not accept the DU beds within the project time frame.

Figure 14: HyDUS lifecycle activities of the DU storage beds with a key indicating those within the remit of UKAEA



Mobile Containerised Laboratory & Nitrogen Cooling System

The purpose of the MCL is to provide a controlled, protected environment for housing and monitoring the DU beds. The laboratory ventilation maintains the atmosphere within it below the explosive limit, with additional mitigation possible if hydrogen is detected. This approach was driven by the aim of enabling non-ATEX (Atmospheres Explosibles) components to be included in part of the design. The inclusion of non-ATEX components was intended to be representative of a future commercial approach to the technology.

The NCS is required to cool the DU bed during the 'charging' stage of processing. The NCS was supplied by the same supplier as the MCL and was specified to meet the University of Bristol's DU bed specifications.

The MCL ventilation system stack is monitored for DU dust and elevated hydrogen, as specified see Table 4. Within the MCL itself, there are 2 monitors for oxygen depletion and 4 for elevated hydrogen, in addition to a single monitor for Alpha/Beta radiation (DU dust). In the event of any monitoring alarm, all HyDUS apparatus is shut down. The compressed air is vented, causing all valves to close, the DU Bed heaters are electrically isolated and the HGS shuts down.

Table 4: MCL ventilation specification

Parameter	Specification
Container	
Outer volume	81 m3 (9 m x 3 m x 3 m)
Inner volume	50 m3 (8.4 m x 2.5 m x 2.4 m)
Ventilation	
Ventilation type	Monoblock, active fresh and waste air ventilation
Max net air volume	665 - 3700 m3/hr
Inlet filter	HEPA
Differential pressure	Suggested 60 - 80 Pa
Max filter flow	1800 - 2000 m3/hr

Parameter	Specification
Max air change	>39 Air Changes Hour

Hydrogen Generation System

The HGS and the FCS were intended to use commercially available products which matched the flow and pressure specifications of the integrated system. The challenge for the commercial systems was the transition of operation steps required for the demonstrator functionality. This required the inclusion of buffer volumes to smooth pressure and flow spikes whilst minimising the system hydrogen volume to reduce inventory. A lower hydrogen inventory supported the safety approach and improved the system's energy conversion efficiency.

The HGS produced hydrogen that may be contaminated with low levels of water vapour and other gases. These contaminants could compromise the DU beds by permanently reacting with the uranium, thereby reducing its hydrogen storage capacity. To prevent poisoning of the DU, hydrogen from electrolysis will be delivered at (or subsequently purified to) >99.9% purity and checked with oxygen and moisture sensors. The HGS parameters can be seen in Table 5.

Table 5: Hydrogen Generation System operating conditions and parameters

Parameter	Value	Comments
Total maximum H2 production rate	0.45 kg/hr	10 units can generate 10.8 kg / 24 hr
H2 internal pressure	< 36 bar(a)	
H2 output pressure	13 bar(a)	
H2 output purity	99.9% (at 36 bar(a), 25°C) 98.8% (at 9 bar(a), 25°C)	
Water consumption	~ 4.2 L/hr	10 units @420 mL/hr at 25 °C
Water input pressure range	1 - 4 bar(g)	
Ambient operative temperature range	5 - 45 °C	

Parameter	Value	Comments
Ambient operative humidity range	0 - 90 %	Non-condensing
Power consumption	24 kW (operative)	
Electrolyser type	Anion Exchange Membrane	
Electrolyte	1% Potassium hydroxide (KOH)	

Fuel Cell System

The FCS is supplied with high-pressure hydrogen from the HCS. The fuel cell must be provided with high-purity hydrogen at a pressure between 8 and 12 bar(a). Hydrogen reacts exothermically with oxygen to produce water, with the released thermal energy used to generate electrical energy. The FCS has a dedicated control and safety system. In the event of smoke or overheating, the system automatically shuts down. If the fuel cell enters such an unexpected shutdown, the control system sends a signal to close a valve to prevent additional hydrogen from being delivered. A filter before the fuel cell prevents any potential DU dust from entering the cell and the steam vent is unmonitored. However, the system's hydrogen vent is directed to the DU-monitored external vent. The FCS operational parameters are shown in Table 6.

Table 6: FCS Operational Parameters

Parameter	Value	Comments
Inlet H2 pressure	9 - 13 bar(a)	Pressure must be stable (no large oscillations)
Maximum H2 inlet temperature	50 °C	
Maximum H2 inlet flow rate	3.65 kg/hr 80.6 L/min	@ 28 kW net power
Minimum H2 inlet flow rate	0.436 kg/hr 677 L/min	@ 5.1 kW net power

Parameter	Value	Comments
Ambient cooling air operating temperature	-10 - 40 °C	
Ambient cooling air operating pressure	1.01 bar(a)	
Ambient cooling air operating humidity	5 - 99 %	

Hydrogen Compression System

The HCS and the interconnected pipework physically connected all the commercially available products. The challenge with the UKAEA integrated design was managing the differences in specifications between non-bespoke subsystems, to enable the sub-process to interface across the range of operational modes. The UKAEA was also responsible for the integrated safety functions system. The design has included consideration of additional operational modes beyond ‘charging’ and ‘discharging’ to enable generated hydrogen to be recovered when processes are interrupted.

Table 7 gives an overview of the HCS pump specifications.

Table 7: HCS Pump specifications

Parameter	Unit	Value
Maximum Pressure (Set by relief valve)	P0	17.01325 Bar(a)
Downstream Pressure Range	Pa	1.01325 Bar(a)
Fluid Maximum Temperature	T1	473.15 K
Maximum Discharge Mass Flow @ Maximum Pressure	Qm	0.14087 kg/hr2
Safety Factor	SF	

The process connections used were predominantly 316L stainless steel seamless tubing, ½” Outer Diameter with 0.065” thickness (Table 8). Pipe connections were specified as twin-ferrule wherever possible, to provide enhanced leak tightness. This enabled the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) assessment to identify zoning requirements around non-enhanced leak-tightness fittings and permit some non-ATEX (Atmosphere Explosible) components to be used.

Table 8: UKAEA HyDUS Process Pipework Specification - Main Process Tubing

Parameter	Specification	Justification
Outer Diameter	0.5 inch	Minimum hydrogen inventory, whilst remaining within the operational envelope of the process
Wall Thickness	0.065 inch	Wall thickness of 0.065 inch was determined to be the optimal choice, providing sufficient structural integrity while maintaining gas flow performance without any measurable impact on flow efficiency
Material	316L Stainless Steel	High resistance to weathering (outdoor demonstrator), hydrogen use is common

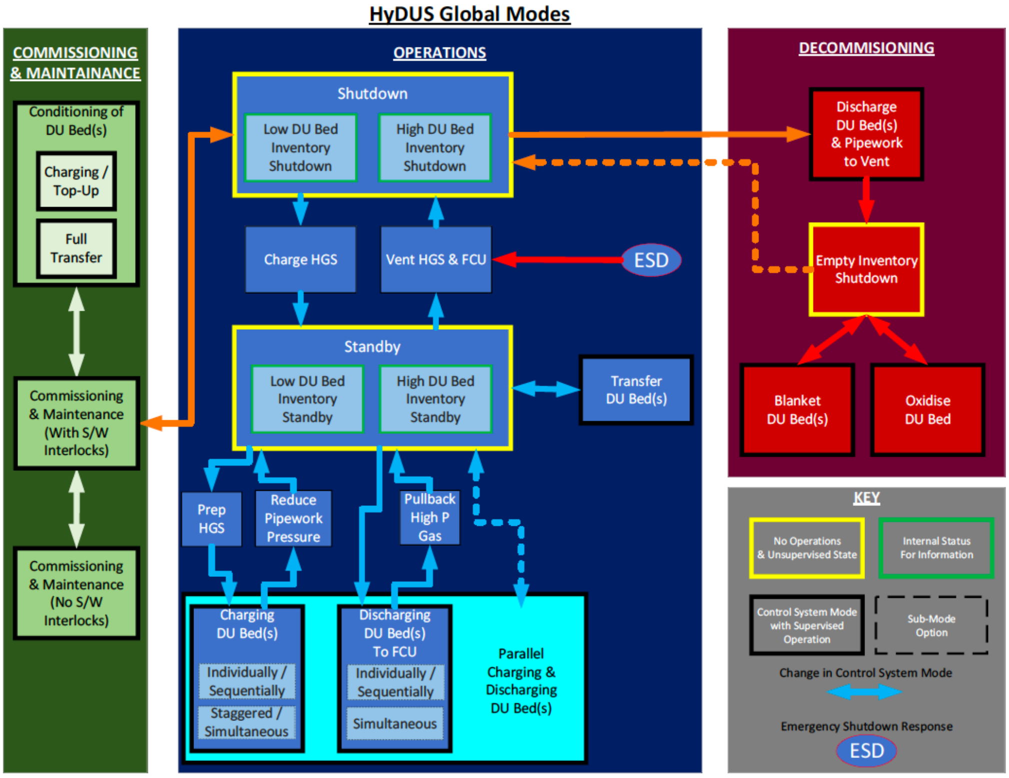
The initial interconnected pipework and integrated control system design included additional instrumentation and process flexibility beyond what was needed to monitor the basic process. This was intended to assess the accuracy and quality of the process design and the subsystem's performance. The information would have assisted in evaluating the approach to scaling the design and operational cost to maintain the system.

HyDUS compound & control room

The HyDUS compound and control room were designed to aid the further development of the technology beyond its own functionality. The design was intended to be replicable and could be implemented in a future location where a proof-of-concept with an energy storage application can be demonstrated. The UKAEA's chosen location for the compound addresses the challenges of locating the demonstrator on a brownfield site. This included service supply, environmental protection, security and access requirements.

The HyDUS System has several states and operational modes, as summarised in Figure 15. The diagram indicates three different modes: commissioning & maintenance, operations and decommissioning. The system must be able to transition between the modes indicated by the orange arrows. Within each mode, there are also different states and each subsystem must be in the correct status to enable the next transition to the next state. The diagram outlines the states and status of each subsystem to begin developing the logic for automation sequences.

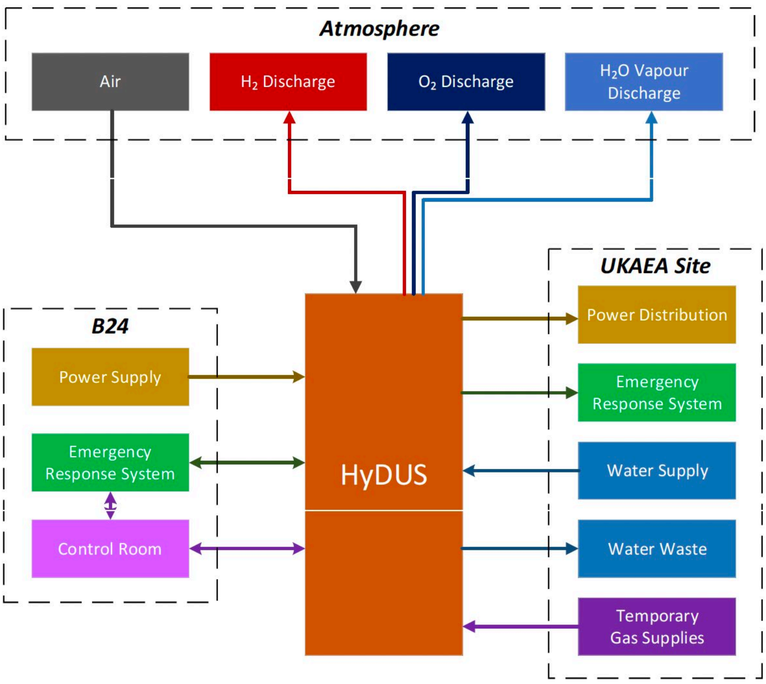
Figure 15: Schematic of the main HyDUS states and modes for operational, commissioning/conditioning/maintenance and decommissioning phases



Demonstrator services and discharges

The system is located in a controlled-access compound (B29), with a separate control room in a nearby building (B24). The HyDUS system interfaces with several different UKAEA facilities and services, as shown by Figure 16.

Figure 16: Indicative HyDUS system context diagram



The HGS requires deionised water as an input; the demonstrator uses portable containers to supply it. Water is also exhausted during fuel cell operations as a by-product in the form of vapour and entrained liquid droplets, which are collected in containers. A batch water management approach was designed to be used for the UKAEA demonstrator; however, further design considerations remain regarding water management for a standalone commercial system.

Regular process discharges will occur during the operation of the HGS. Discharges occur during the shutdown of the HGS when its accumulation tanks are depressurised. Discharges also occur during start-up, when the system performs a sequence of hydrogen purges to remove any air. The FCS also discharges its hydrogen inventory during its startup and shutdown sequences.

Additional hydrogen discharges from the HyDUS system will occur during commissioning and decommissioning. All process discharges will be directed to external vents, not into the MCL space or the ventilation system. The HGS has a dedicated hydrogen discharge point, located three meters above the MCL's roof. In contrast, all other HyDUS discharges will be via a common vent point, which will be monitored for DU (entrainment). Further emissions may occur during off-normal events, such as emergency shutdowns or pressure relief valve activation. These will discharge into a dedicated external vent line to prevent release into the MCL zone or around equipment. Electrolysis will generate oxygen, which will be discharged to the atmosphere via a dedicated vent located 3 meters above the HGS container's roof. An independent review of the UKAEA's Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) report was commissioned from an external organisation.

Key design decisions

The UKAEA design has been guided by two key decisions that have impacted the initial systems engineering, controls and safety case approach. These decisions were:

- Decision 1: The storage system design evolved from an initial plan of six identical DU beds to a reduced configuration of two DU beds.

  Rationale: Originally, six equal-capacity DU beds were chosen to simplify manufacturing and reduce complexity compared to a mixed-size configuration. However, as project timelines tightened and UKAEA deliverables fell behind schedule, the design was revised to include only two DU beds. This change accelerated implementation and addressed safety concerns identified during the hazard and operability study, which showed that reducing the number of beds would mitigate potential risks.
- Decision 2: The MCL hosting the DU beds will not have an ATEX zone.

  Rationale: MCL ventilation will keep the overall condition of the MCL below the lower explosive limit of 4% hydrogen saturation. This enabled the same specification to be used for all components within the MCL, with the aim of including non-ATEX components in part of the design.

Following the first design decision, the amount of DU to be filled into the six DU beds was reviewed. The sizing and manufacturing of the DU beds account for the four-fold volumetric expansion of DU metal into uranium hydride. An opportunity was identified to fill the six beds with three different weights of DU metal. This, combined with the design flexibility of the UKAEA demonstrator system at the time, would enable more detailed analysis to optimise the DU bed design and assess the scaling of the demonstrator design. Following the decision to reduce the number of DU beds to be included in the UKAEA system from 6 to 2, beds were selected to maximise the system's hydrogen storage inventory.

The 194kg of DU would have a storage capacity of 2.44kg of hydrogen. The experimental plan was to cycle the beds between 10% to 90% capacity. This would yield a usable storage capacity of 1.95kg of hydrogen from all DU beds, or for any two DU beds, a usable storage capacity of 0.60kg to 0.71kg of hydrogen.

These decisions led to the process flow diagram being updated and the change in the DU beds led to a corresponding reduction in the number of nitrogen-cooling system modules that needed to be commissioned. It also reduced the number of pump loops in the hydrogen compression system.

Safety Case

In this section, the safety cases development for the University of Bristol and UKAEA demonstrators are described. The aim of this work was to establish safe operating boundaries for handling and storing hydrogen in DU beds and to ensure that both demonstrators complied with the relevant regulatory frameworks. The two sites followed distinct but complementary safety processes: UoB focused on demonstrating safe operation of a single-bed system within a controlled laboratory environment, while UKAEA progressed a full facility safety case for an integrated system with multiple bed modules. The following subsections outline the key regulatory requirements, hazard assessments, procedural controls and assurance steps undertaken at each site.

University of Bristol system

Since December 2021 when Phase 1 of the project was first funded under the LoDES programme, up until project conclusion in December 2025 UoB has actively developed the bed system, leading to progressing the design through UKAEA's internal safety appraisal and sign-off process, as well as obtained UKCA safety certification through an independent specialist company, Conformance Ltd.

To enable safe operations, the following key safety elements were completed.

- Multiple HAZOPs (Hazard and Operability Study) of the system were carried out by a specialized team from the University of Bristol, UKAEA and NCC (Figure 17).
- A DSEAR risk assessment, in accordance with the Dangerous Substances and Explosive Atmospheres Regulations (2002), was conducted by an independent specialist company, ORBIS Environmental and Safety (Figure 18).
- A Fire Safety Risk Assessment was performed by Balmoral Systems Ltd to ensure comprehensive safety measures are in place.
- Seven Standard Operating Procedures (SOPS) were developed and maintained that focused purely on normal operations within the lab (Figure 19). Amongst other things, these SOPS specified that during system operation, no personnel were allowed inside the containerised laboratory; all operations were conducted remotely from an external control room.
- To facilitate the procurement and use of DU at the NCC Filton site, the University of Bristol applied to the Environment Agency for a permit under the Environmental Permitting Regulations (Figure 20). This permit covers the use of uranium for purposes other than its fertile, fissile, or radiological properties, specifically its use as a reactive metal. The application included provisions for the possession and use of radioactive material in open form, the accumulation of radioactive waste on-site and the disposal of radioactive waste from the premises. The Environment Agency subsequently issued Permit EPR/GP3428XC-A001, authorizing UoB to hold up to 500 kg of DU as an open-

source radioactive material, along with the accumulation of up to 100 kg of solid radioactive waste (with a maximum volume of 1 m^3) over a period of two years.

- All UoB on-site staff were provided with First Aid training.

As well as the training and SOPS, the lab itself is designed with a specialised, sensor-rich, semi-automated control system equipped with multiple safety sensors and features. Not least of these is a number of fire extinguishers and emergency stops as seen in Figure 21.

It should be noted that development of the required documentation was more difficult than anticipated due to the shifting safety requirements of a novel project. The upside of this, however, is that the university is now well equipped to proceed at pace with similar projects in the future.

Furthermore, substantial time had to be spent explaining the safety of the design and that the materials used were non-fissile to key stakeholders to ensure university approval to proceed. As such, one of the key aspects to consider going forward is the naming convention of the technology, primarily due to the potentially negative associations of Depleted Uranium.

Finally, the mismatch of requirements between UKAEA's safety case and UoB's was not something that the consortium anticipated at the beginning of the project. Significant time was spent working closely with UKAEA in order to satisfy requirements that were beyond the scope of prototype R&D. For future projects, having the exact requirements identified at project initiation would allow for party agreement before project commencement.

Figure 17: A snapshot of a HAZOP run in 2023

No.	HAZOP ID (based on numbering of Table 2)	Context	Action	Completion by
HAZ1	General	Compressed air supply for the pneumatic actuation of the valves of the system will come from lines of the NCC site.	No action	During installation
HAZ2	General	Positioning of oxygen /process gas cylinders for the passivation of DU outside the container but adjacent to it.	No action	During installation
HAZ3	General	Exchanging of sensor in position 10 into an oxygen or other sensor	Modification of the system diagram	
HAZ4	General	Back-up small compressor system for pneumatic actuation in the event of compressed gas supply loss from NCC	No action	Order prior to installation
HAZ5	3	What if the mass flow meter/pressure controller fails and highly pressurized gas is directed to the bed?	Safety-interlock between the H2 mass flow meter/pressure controller device and pneumatic valves number 32 and 41 (immediately before the bed) to isolate the bed if the pressure mass flow controller fails.	During PLC programming

Figure 18: A snapshot of the DSEAR report

Area / Plant / Process	Hazard or associated activity and how it can harm	Potential Ignition Sources	Control Measures	L	S	Risk factor	Additional Control measures required? (Where Yes, see action plan)
COSHH Depleted Uranium Safe Storage Area	Depleted uranium (DU), though less radioactive than natural uranium, presents significant hazards primarily due to its chemical toxicity and low-level radiation. In solid form, it poses minimal risk; however, when DU is in fine particles or powdered form, it becomes more dangerous. If inhaled or ingested, these fine particles can cause kidney damage and increase the risk of lung cancer. Additionally, powdered DU is pyrophoric, meaning it can spontaneously ignite when exposed to air.	One key hazard is static electricity, which can build up on equipment or personnel and potentially ignite the DU. To prevent contamination, fire risks, and prolonged exposure, safe storage, proper ventilation, grounding, and strict handling procedures are essential.	• A dedicated smoking area is provided outside, near bicycle racks with proper disposal bins. • High housekeeping standards are maintained with regular patrols by H&S and Operations teams. • Early fire detection systems are installed and maintained by the contractor (Mite). • An intelligent fire alarm system is in place, though at the time of inspection, it had a fault in the main reception lobby. • Fire extinguishers, installed per the FRA recommendations, are managed by NCC and positioned according to BS5306. • Ian Williams is the designated fire safety responsible person, and all staff have undergone fire warden training. • Occupational health arrangements are in place, led by the University, and reviewed when new occupants arrive. • Spill kits, including radiation-specific kits, are placed throughout the facility. • A negative pressure system ensures containment, maintaining -30 to -90 pascals across different areas. • The health and safety policy, including DSEAR, is reviewed annually.	1	3	3	Yes
Compressed gas bottle storage	Storing compressed gas bottles containing hydrogen, argon, and nitrogen in an outdoor cage presents several hazards. Hydrogen, being highly flammable, poses a significant fire and explosion risk, especially if there are leaks or ignition sources like static electricity or electrical sparks. Inert gases like nitrogen and argon, while non-flammable, all compressed gases are stored at high pressure, and improper handling or damage to the cylinders could result in rupture or uncontrolled gas release. Temperature extremes can also increase internal pressure, further heightening these risks. To mitigate these hazards, the cylinders should be secured upright in a well-ventilated, grounded area, regularly inspected, and clearly marked with appropriate safety signage.	Potential ignition sources in an area storing hydrogen, argon, and nitrogen, especially during transport on a manual trolley, include static electricity generated by movement, friction sparks from dragging the trolley, nearby electrical equipment, hot surfaces from machinery, and open flames from unauthorised activities like smoking or welding. To mitigate these risks, grounding equipment, using spark-resistant tools, and maintaining proper separation from ignition sources are essential.		2	3	6	Yes

Figure 19: List of Operational SOPs

SOP title	SOP reference number	Summary of SOP content
Delivery and safe storage of depleted uranium (DU) at NCC Filton	HyDUS SOP 001	This SOP describes the delivery process in detail. Related and relevant documents are the School of Physics risk assessment and radiation risk assessment for the process.
Personal property in the HyDUS cell	HyDUS SOP 002	This SOP firmly states that personal property must not be taken into the Controlled Area of the HyDUS cell
Entering exiting the HyDUS Controlled area	HyDUS SOP 003	This SOP describes the step-by-step procedure to follow when entering and exiting the Controlled area of the HyDUS cell.
Contamination, ventilation and personal dosimetry monitoring	HyDUS SOP 004	This extensive SOP describes our monitoring procedures throughout the HyDUS cell. It describes how we perform surface contamination monitoring (including within the ventilation network) and how we track the doses received by regular HyDUS cell users as well as contractors and visitors.
HyDUS beds preconditioning	HyDUS SOP 005	Defines the bed preconditioning process. Achieved by heating the beds while under dynamic vacuum at 120 °C to initiate the 'degassing' process for the material DU.
Container and system interlock monitoring.	HyDUS SOP 006	Describes the procedure and expected outcomes of routine tests that verify the functionality of the HyDUS container and system interlocks. Also included is a record spreadsheet.
Operational conditions	HyDUS SOP 007	Describes the procedure for commissioning, decommissioning, hydriding and dehydriding the beds.

Figure 20: EA Permit

Permit

Permit number
EPR/GP3428XC

The Environment Agency hereby authorises under regulation 13 of the Environmental Permitting (England and Wales) Regulations 2016

University of Bristol *("the operator")*

whose principal office is

Beacon House
Queens Road
Bristol
BS8 1QU

to carry on radioactive substances activities at

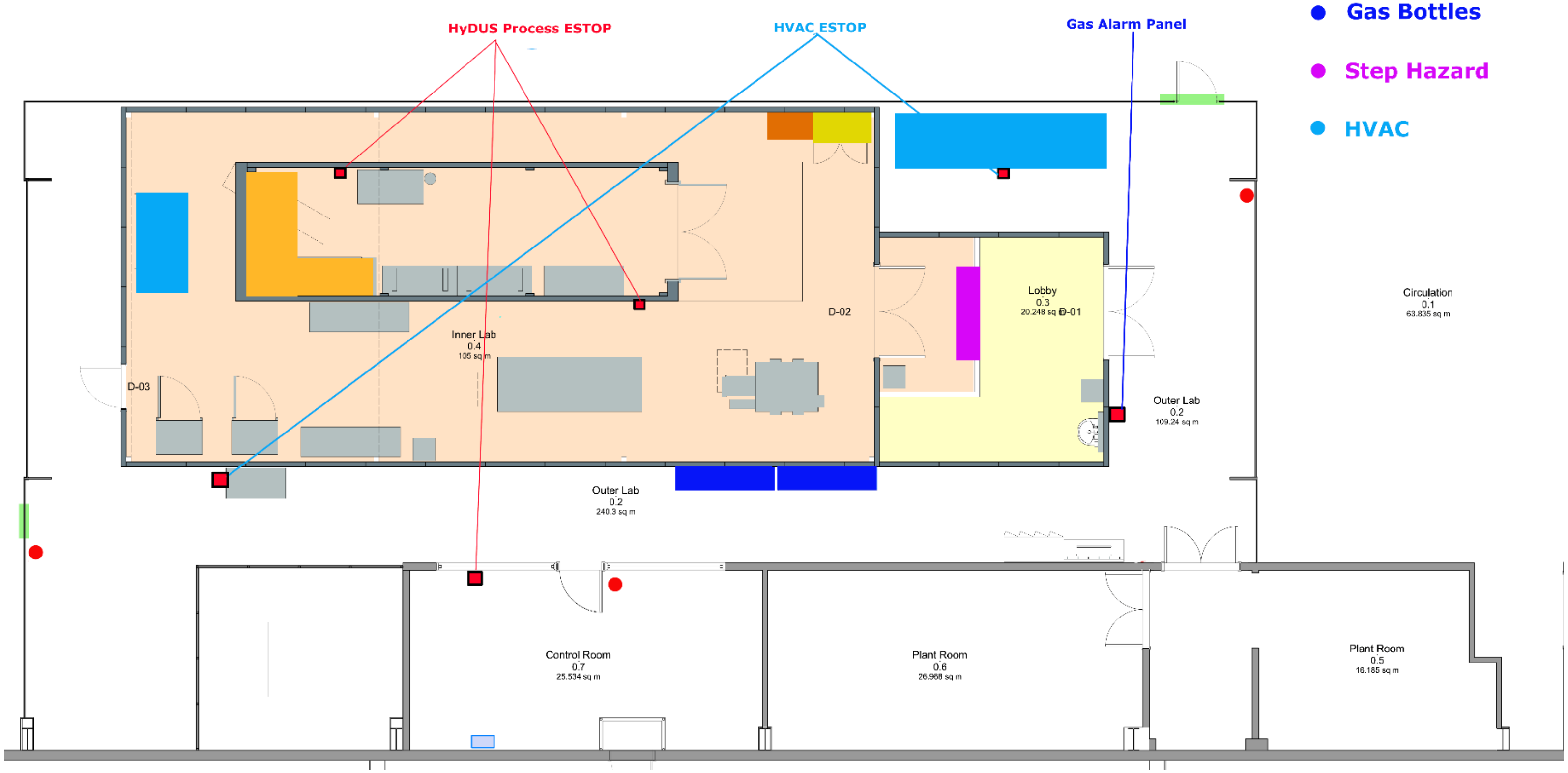
National Composites Centre (NCC)
Blenheim Building
Golf Course Lane
Filton
Bristol
BS34 7RP
("the premises")

to the extent authorised by and subject to the conditions of this permit.

Name	Date
Tim Shaw	***14/08/2023***

Authorised on behalf of the Environment Agency

Figure 21: Relevant location of the beds, hazards, sealed source safe & emergency stops for the facility



UKAEA system

The UKAEA safety case team has produced a Facility Safety Case Report to justify the safe operation of the HyDUS demonstrator and to meet UKAEA requirements for new facilities. The safety case was necessary because HyDUS involves hazardous materials - DU and hydrogen - whose properties pose significant risks, including high flammability, chemical and radiological hazards. The Facility Safety Case Report provides assurance that these risks have been identified, assessed and reduced to a level that is As Low As Reasonably Practicable (ALARP) throughout the facility's lifecycle. The approach adopted was to develop an integrated safety case covering the design and construction, while commissioning, operational phases and decommissioning hazards, such as DU bed passivation, would be addressed separately. Hazard assessments, including hazard identification (HAZID) and hazard and operability (HAZOP) studies, were conducted at concept, preliminary and detailed design stages. Two principal hazards were identified: the release and accumulation of flammable hydrogen gas and the release of radiologically active DU particulates.

Fault scenarios considered examining hydrogen leaks within the MCL and hydrogen leaks associated with a fault in the HGS, which could form flammable atmospheres and lead to fire or explosion. During normal operations, neither operators nor members of the public would receive a radiological dose.

To manage these risks, compatible materials were selected to prevent leaks and ensure consistent performance throughout the system's specified lifetime. The process design requirements included minimising the mobile hydrogen inventory for each operational step. Engineered protections, such as excess flow valves and pressure relief valves, were included to limit inventory and pressure in different parts of the system. There are control interlocks that interrupt the hydrogen supply to a downstream system if a fault is detected. Ventilation and purging strategies mitigate flammable gas accumulation, with hydrogen sensors linked to ventilation and shutdown process systems. Additional safeguards include fire detection systems, ATEX-rated ventilation and strict access control. Personal Protective Equipment and procedural discipline provide additional protection during installation and decommissioning phases.

The remote operation of the system also minimised personnel exposure and the required detailed operating instructions further reduce operator presence in hazardous zones. Emergency planning aligns with Culham site protocols, including annual drills, automatic shutdown sequences and evacuation procedures. Incident reporting follows UKAEA standards, with lessons learned feeding into continuous improvement.

The Facility Safety Case Report also defines forward actions and hold-points to ensure readiness and compliance. These include issuing substantiation documents for Safety Related Equipment, issuing an Engineering Maintenance, Inspection and Testing (EMIT) schedule, maintaining a Suitably Qualified and Experienced Personnel (SQEP) register and holding points for Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) actions. The status of actions will be reviewed at the Operational Readiness Review, which also enables a separate Commissioning, Operation and Decommissioning Safety Case Report to be prepared.

The safety case concludes that, subject to identified controls and the implementation of actions, the risks to operators, the public and the environment are reduced to As Low As Reasonably Practicable.

Procurement, Installation and Commissioning

In this section, the procurement, installation and commissioning activities undertaken for the University of Bristol and UKAEA demonstrators are described. The objective of this work was to acquire, prepare and install all components required for safe and effective operation of the HyDUS systems, including the DU material, fabricated bed modules and containerised laboratories. Installation activities at both sites involved the integration of mechanical, electrical and control systems, followed by commissioning procedures to verify system integrity and readiness for operation. The following subsections outline the key steps associated with procurement, installation and commissioning at each site.

University of Bristol system

Procurement

DU

The DU material was obtained from MSC, a US based company. The material was cast to specification (Figure 22). The DU was then cut into manageable sizes and cleaned (Figure 23) before being cut into a mixture of quarter and half pucks (Figure 24).

Figure 22: Depleted uranium cast to size

Figure 23: Depleted uranium after being cut cleaned

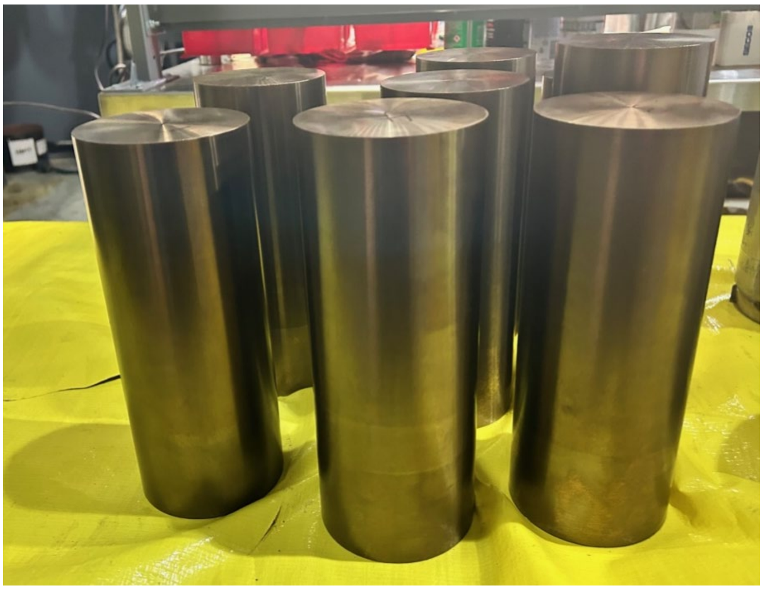


Figure 24: Depleted uranium after being cut into a mixture of quarter and half pucks

Finally, the DU was packaged in a series of paint cans, packed into large drums and shipped via CTS (a dangerous goods carrier) to UoB’s site at in Filton, Bristol (Figure 25).

Figure 25: Drums containing the depleted uranium for shipping

The material was stored within a secure safe within the controlled area of the lab (Figure 26).

Figure 26: Storage area of depleted uranium in the lab

DU Beds

The beds were manufactured by Kurt J Lesker (KJL), a UK manufacturer specialising in pressure vessels and welding. Following the university procurement process that included a tender to ensure fair competition, KJL was awarded the work. An initial two beds were designed and purchased. The design approach involved detailed design documents based on the 3D models of the beds and detailed information supplied by the UoB team.

The initial design process with KJL began after the order was placed on 20th February 2023, with detailed design commencing immediately thereafter. The beds were delivered on 5th March 2024, giving a total design-to-delivery period of approximately 12 months. For an initial set of prototype beds, UoB was happy with the speed at which the work progressed, knowing that further orders would take less time.

Figure 27 shows the two beds that are being used within the HyDUS facility. Six more beds were also fabricated for use at the UKAEA facility, three of which can be seen in Figure 28.

These beds are double-skinned and UKCA-rated pressure vessels, ensuring that they are as safe as they can possibly be. A description of the beds design is given in the *Engineering Design* section.

Figure 29: Completed beds

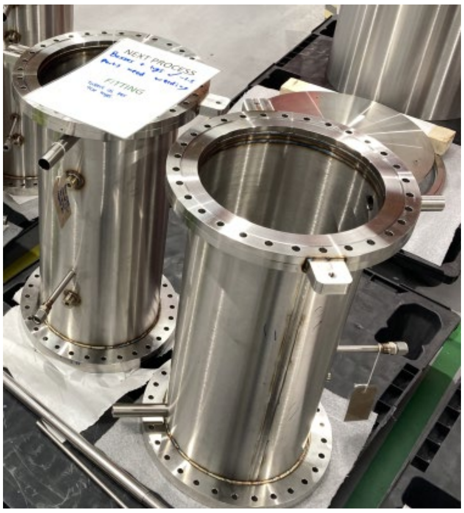


Figure 27: Beds being produced at KJL

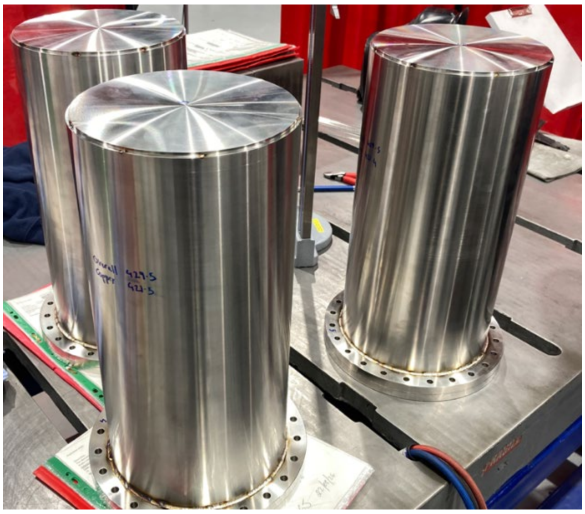
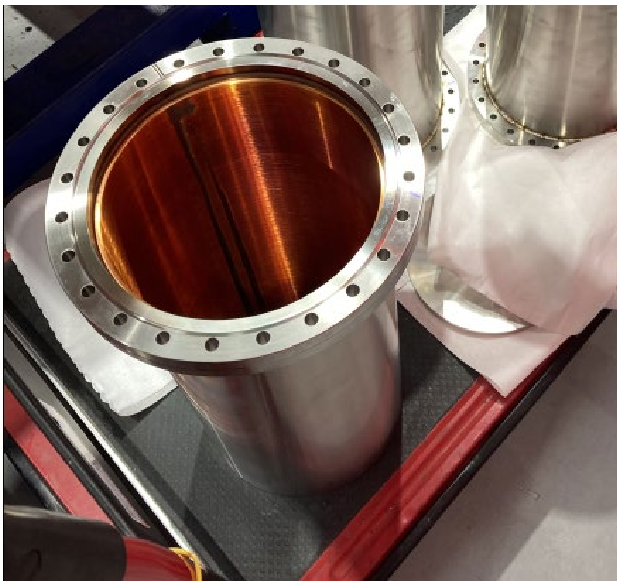


Figure 28: Inside view of the inner most vessel



The inside of the inner most vessel is copper-lined to allow for increase thermal conductivity, resulting in more efficient hydriding of the DU (Figure 29). Figure 30 shows the final bed wired into place within the containerised lab.

Figure 30: Final bed wired in the containerised lab

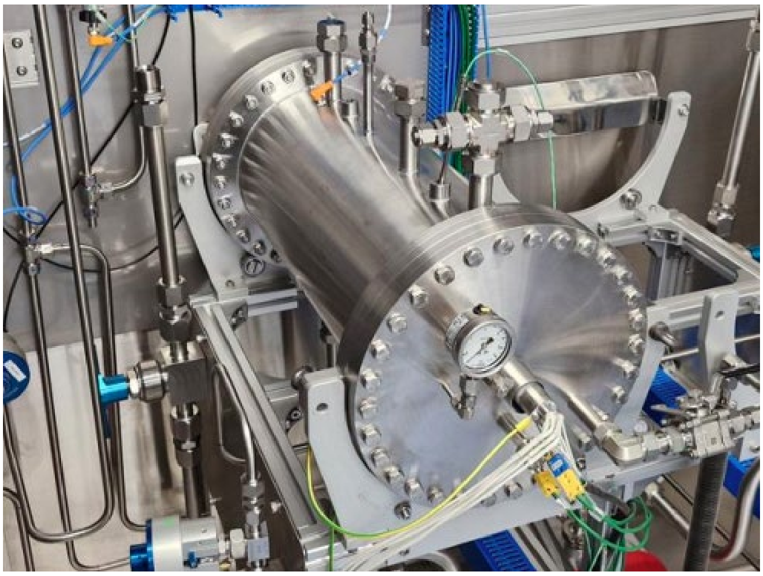
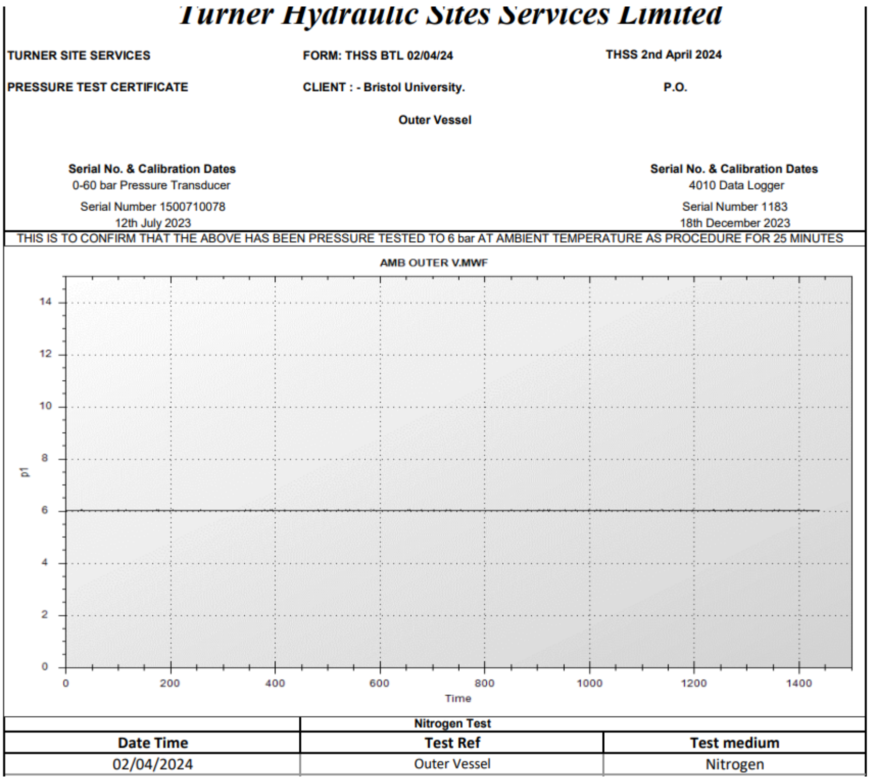


Figure 31: Turner Pressure Test



Turner Hydraulic Sites Services Limited

TURNER SITE SERVICES	FORM: THSS BTL 02/04/24	THSS 2nd April 2024
PRESSURE TEST CERTIFICATE	CLIENT : - Bristol University.	P.O.
	Outer Vessel	

Serial No. & Calibration Dates
0-60 bar Pressure Transducer
Serial Number 1500710078
12th July 2023

Serial No. & Calibration Dates
4010 Data Logger
Serial Number 1183
18th December 2023

THIS IS TO CONFIRM THAT THE ABOVE HAS BEEN PRESSURE TESTED TO 6 bar AT AMBIENT TEMPERATURE AS PROCEDURE FOR 25 MINUTES

Nitrogen Test

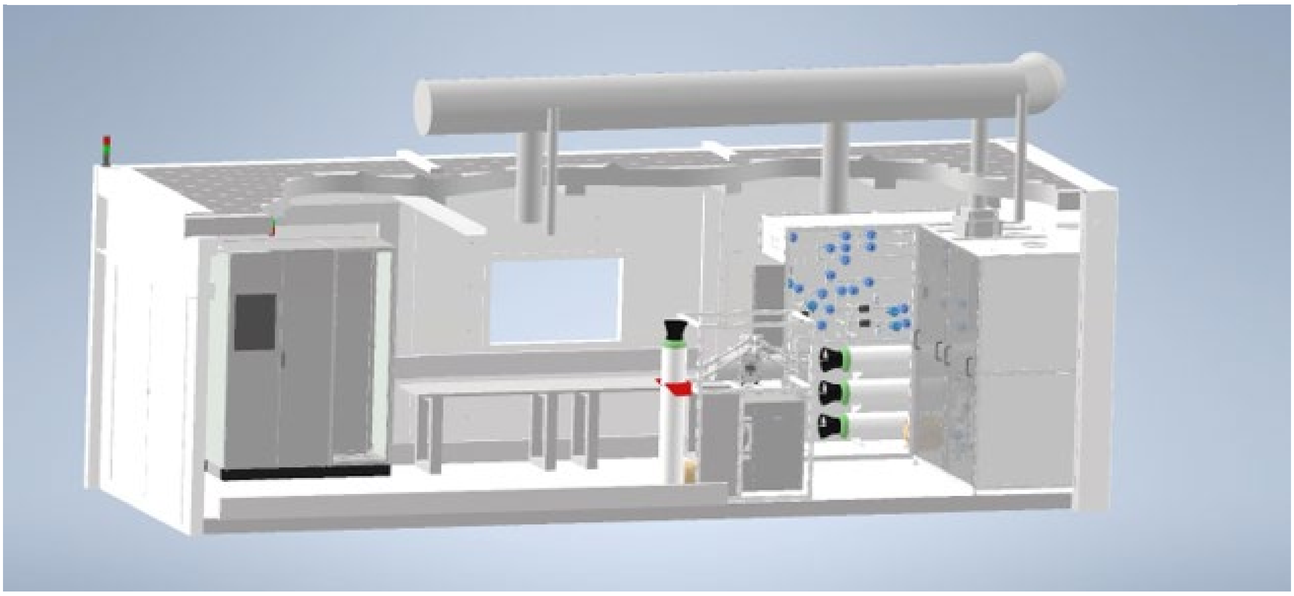
Date Time	Test Ref	Test medium
02/04/2024	Outer Vessel	Nitrogen

Certification of a prototype bed is an unusual step at this TRL, however, to ensure safety and assist in satisfying UKAEA requirements, the beds were tested by Turner Hydraulic and passed at 6.6 bar (Figure 31). The beds hold vacuum extremely well and UoB has had no safety concerns with their use.

Facility

The primary lab was a MCL provided by Smolsys. The design is described in the *Engineering Design* section. The University created a Systems Requirements Document that outlined all necessary requirements for the MCL unit. This document had basic CAD models that formed the basis of the engagement (Figure 32).

Figure 32: Initial CAD model of the MCL



This went to tender and Smolsys was the selected supplier. Figure 33 shows the initial design of the MCL within the wider lab, including the specialist ventilation ducting that was integrates with the wider lab's overarching system. Figure 34 again highlights the focus on the ventilation - crucial for safe operations, particularly when faced with a novel combination of DU and hydrogen.

Figure 33: Initial layout of the lab and MCL

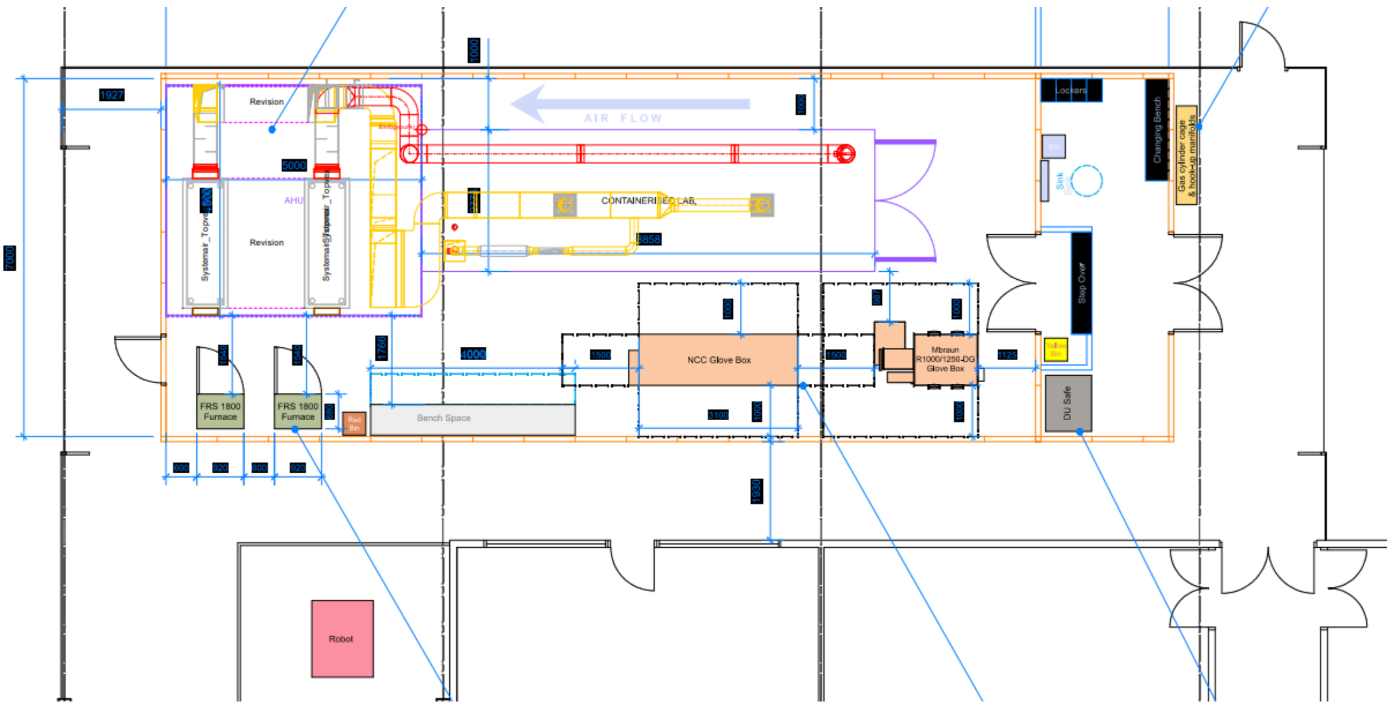


Figure 34: Ventilation unit of the MCL

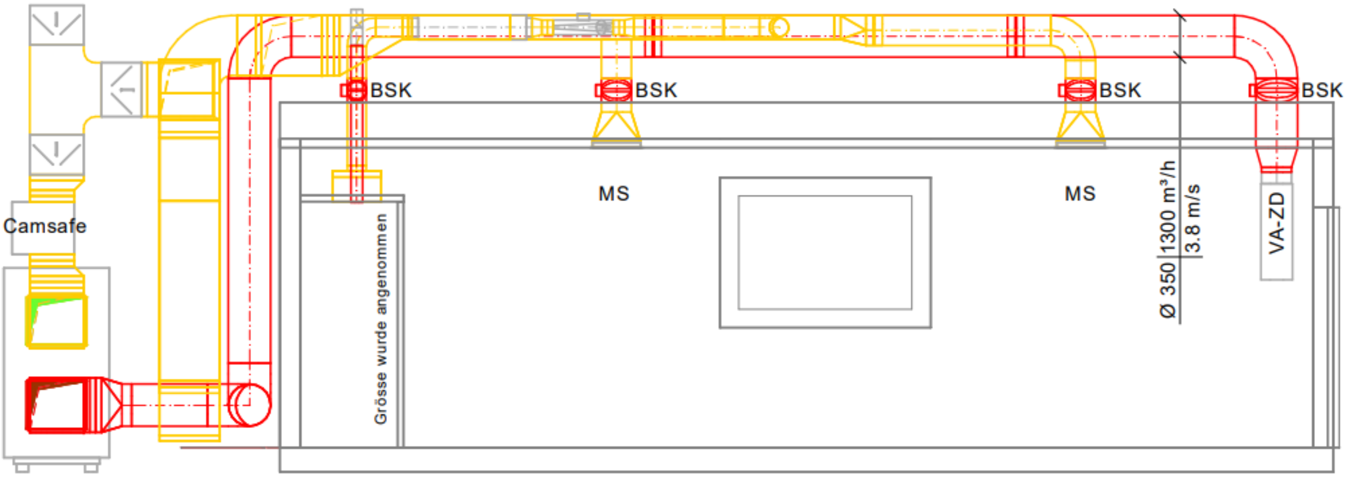
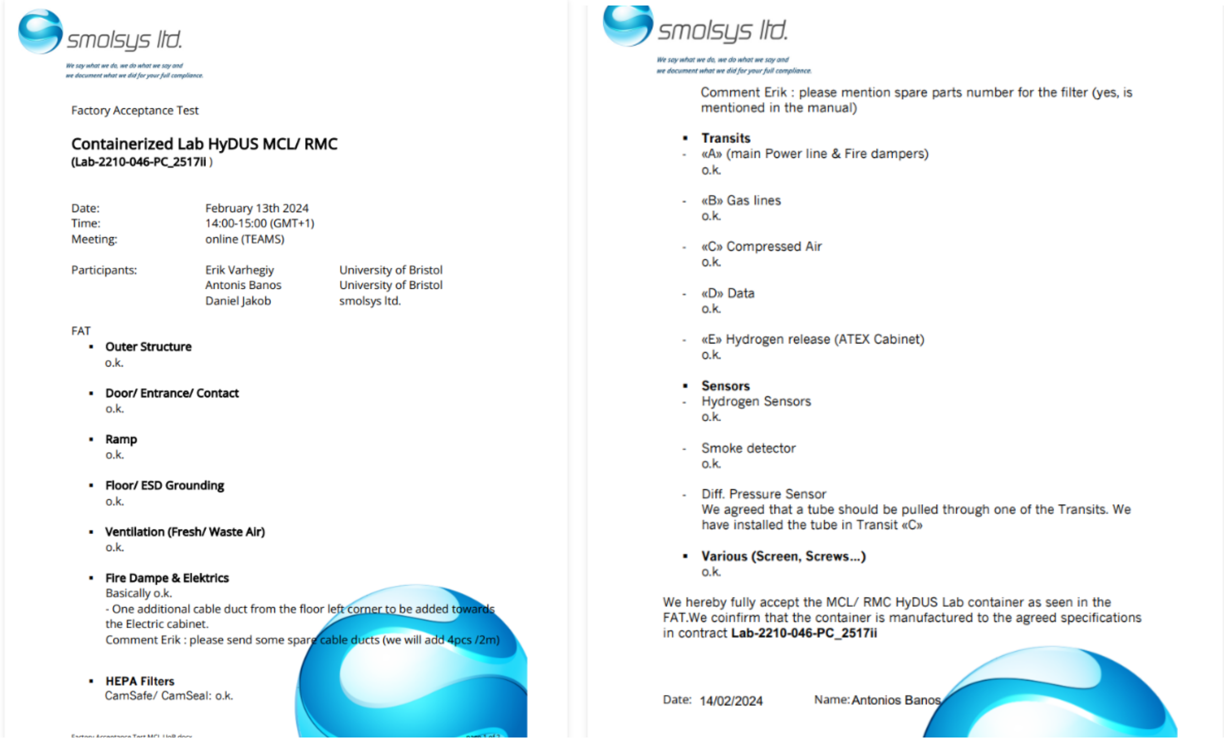


Figure 35: Factory Acceptance Test documentation



smolsys ltd.

Factory Acceptance Test

Containerized Lab HyDUS MCL/ RMC
(Lab-2210-046-PC_2517ii)

Date:	February 13th 2024	
Time:	14:00-15:00 (GMT+1)	
Meeting:	online (TEAMS)	
Participants:	Erik Varhegiy	University of Bristol
	Antonis Banos	University of Bristol
	Daniel Jakob	smolsys ltd.

FAT
- **Outer Structure**
  o.k.
- **Door/ Entrance/ Contact**
  o.k.
- **Ramp**
  o.k.
- **Floor/ ESD Grounding**
  o.k.
- **Ventilation (Fresh/ Waste Air)**
  o.k.
- **Fire Dampe & Elektrics**
  Basically o.k.
  - One additional cable duct from the floor left corner to be added towards the Electric cabinet.
  Comment Erik : please send some spare cable ducts (we will add 4pcs /2m)
- **HEPA Filters**
  CamSafe/ CamSeal: o.k.

smolsys ltd.

Comment Erik : please mention spare parts number for the filter (yes, is mentioned in the manual)

- **Transits**
  - «A» (main Power line & Fire dampers)
    o.k.
  - «B» Gas lines
    o.k.
  - «C» Compressed Air
    o.k.
  - «D» Data
    o.k.
  - «E» Hydrogen release (ATEX Cabinet)
    o.k.
- **Sensors**
  - Hydrogen Sensors
    o.k.
  - Smoke detector
    o.k.
  - Diff. Pressure Sensor
    We agreed that a tube should be pulled through one of the Transits. We have installed the tube in Transit «C»
- **Various (Screen, Screws...)**
  o.k.

We hereby fully accept the MCL/ RMC HyDUS Lab container as seen in the FAT.We coinfirm that the container is manufactured to the agreed specifications in contract **Lab-2210-046-PC_2517ii**

Date: 14/02/2024 Name: Antonios Banos

Smolsys worked with the wider team to develop the plans, before agreeing a design and beginning production. The completed container was given a successful Factory Acceptance Test on the 14/02/24 (Figure 35).

The shipment of the MCL went through a specialist shipping company, Integrated Equipment Services (IES, Figure 36), who lifted the completed MCL from the manufacturing location in Switzerland and delivering it to the NCC lab in Filton, Bristol in late February 2024. The rest of the wider lab was built around the MCL and Practical Completion of the entire HyDUS facility was achieved in May 2024. Smolsys was also tasked with delivering the cooling system, which faced considerable delays. The system was loaded for transport in early November 2024 (Figure 37) and delivered for installation in late November 2024.

Figure 36: Cooling system loaded for transport

As Figure 38 shows, the MCL was placed within the designated location of the HyDUS lab and the rest of the facility was built around it. Figure 39 highlights how much construction took place, with the entire outer shell of the lab being created around the MCL, before final wiring, ducting and ventilation connections were made.

Figure 38: MCL in HyDUS pre-build

Figure 40 shows the full HyDUS lab, completed and ready for operations. The flooring is a specific flooring for radiation labs, with a rounded edge to allow for easy cleaning of corners. Gas lines are in place (left hand side of Figure 40) for glovebox install.

The remaining activities involved the wiring of alarms, sensors and the electrical control system for the bed-controlling components located within the MCL. Furthermore, due to the novel nature of HyDUS substantial time was spent developing the safety documentation and Risk Assessments for safe operating of the overarching facility. Initially the HyDUS team aimed for a December 2024 start to operations, however due to delays with the DU, safety documentation requirements and a late requirement for the installation of an iCAM (a radiation monitor) coming from the external Radiation Protection Advisor (RPA), HyDUS was not actively operational until the 15th July 2025. Many of these delays can be attributed to the unknowns of delivering a novel project, with the university now much better equipped to take on similar projects in the future, using HyDUS as a benchmark. The results of the testing programme are summarised in the *Testing Programme Results* section.

Figure 39: MCL in lab under construction

Figure 40: MCL in completed lab

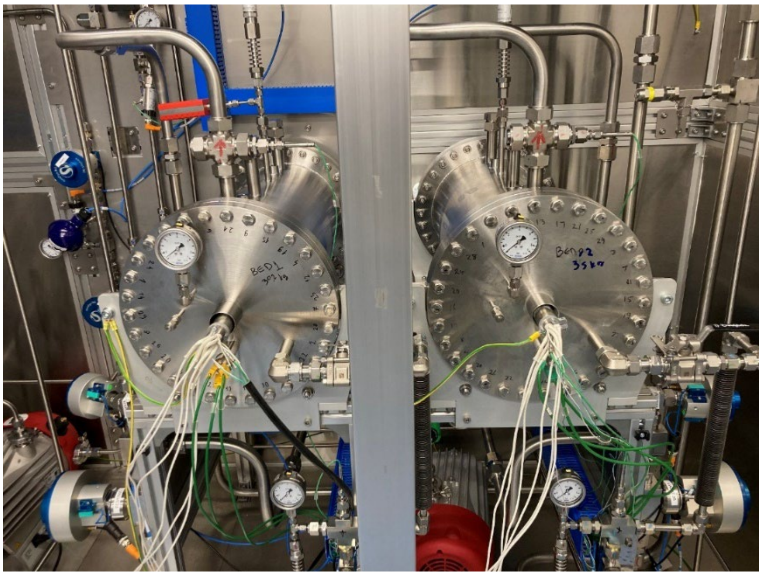
Installation

The preparation and installation of HyDUS beds was logistically difficult, as the beds weigh nearly 120kg without the addition of the DU. Being able to fill a bed with DU (see 5.5.1 for specifics of DU into the bed), seal it, and position it within the MCL for operations required a number of distinct Risk Assessments and bespoke lifting equipment.

Figure 41: Team in PPE

Whilst bed loading took place, the team wore full protective equipment (Figure 41), including respiratory protective equipment to prevent inhalation of radioactive particulates. The bed was then lifted into position within the MCL using dedicated lifting equipment, including an engine hoist and counterweight crane, and wired into place (Figure 42).

Figure 42: Beds being installed into MCL



Commissioning

Operational commissioning of the facility took place in July 2025. To enable commissioning, a checklist of actions was created with the School Safety Manager. The comprehensive list of actions included.

- Proving all HAZOP actions had been concluded.
- Creating an interlock monitoring document that highlighted: 1. What has been tested, 2. When was it tested, 3. What were the outcomes and 4. Who performed the tests.
- Dry run of the HyDUS Emergency Response Plan.
- Verified First Aid training.
- Verified Fire Warden training.
- Evidence of pre-requisite training for operational staff, such as manual handling, radiation protection, gas handling.
- Verified installation of ICAM
- Confirmation of all relevant SOPS
- Confirmation of Access control
- Confirmation of servicing schedule
- Appointment of DSEAR coordinator

Following the above, the beds were fully connected to the system and hydrogen, for the first time, was attached to the gas line and entered into the system. On the 15th July 2025, HyDUS was fully commissioned and in operation.

UKAEA system

Procurement

During the primary procurement phase of the HyDUS project, the UKAEA, as a non-departmental public body and Public Sector Research Establishment, operated under the Public Contracts Regulations 2015 (PCR 2015). These regulations mandated prescriptive procedures and focused on awarding contracts based on the Most Economically Advantageous Tender (MEAT). Following the revocation of PCR 2015, UKAEA now complies with the Procurement Act 2023, which introduces a more streamlined and flexible framework. Notable changes include adopting Most Advantageous Tender (MAT) criteria, enhanced transparency requirements, mandatory consideration of SME inclusion and the use of a centralised digital platform for supplier engagement. This updated approach is designed to improve procurement efficiency, accountability and overall value.

The UKAEA initiated the acquisition of the four foundational components essential for the demonstration and operational objectives of the HyDUS system during FY22/23. These comprised the MCL, HGS, dual hydrogen pumps for the HCS and the FCS. Procurement activities were conducted under the Public Contracts Regulations 2015 (PCR 2015), applying prescriptive procedures and the MEAT criteria to ensure compliance, value for money and technical suitability.

Core components

The selection of suppliers for each of the four core components of the HyDUS project was guided by the specifications outlined in the SRD. This document served as the technical benchmark for evaluating tenders, ensuring alignment with project objectives, operational performance and regulatory compliance.

- MCL
    - Supplier selection for the mobile containerised laboratory focused on the unit's ability to support field-based diagnostics, environmental control and modular integration with hydrogen storage systems. The SRD specified requirements for mobility, structural resilience, internal instrumentation compatibility and safety standards. Suppliers were evaluated on their capacity to deliver a turnkey solution that met these criteria while offering scalability and ease of deployment.
- HGS
    - The electrolyser selection criteria included efficiency (kWh/kg H_2), operational pressure range, purity of output gas and integration capability with existing electrical infrastructure. The SRD outlined performance thresholds, maintenance expectations and control system interoperability. Suppliers were assessed on technical compliance, lifecycle cost and proven experience in delivering similar systems.
- Hydrogen Pumps for HCS
    - For the hydrogen pump, the SRD defined parameters related to flow rate, pressure control, material compatibility (especially with hydrogen embrittlement concerns) and safety certifications. Supplier proposals were reviewed for mechanical reliability, energy consumption and ability to operate within the environmental conditions specified for the HyDUS deployment site.
- FCS
    - The hydrogen fuel cell selection was based on electrical efficiency, start-up time, load-following capability and emissions profile. The SRD provided detailed specifications on power output, cooling requirements and integration with the containerised lab's energy management system. Suppliers were evaluated on technical maturity, warranty terms and alignment with G99 power export regulations.

The tender for the HGS will be discussed as an example of the process step followed during the procurement phase at the UAKEA, responders were required to demonstrate adherence to critical design and regulatory standards.

Two suppliers responded to the HyDUS electrolyser tender: Company A and Company B *[this section has been redacted for confidentiality reasons]*.

Company A proposed a modular electrolyser system integrated within a containerised solution, demonstrating compliance with relevant regulations. Company A's solution was designed for outdoor operation in UK conditions and featured variable hydrogen output and a gas purification system achieving 99.999% purity. Company A also committed to delivering a comprehensive installation and commissioning plan and training for UKAEA personnel.

Company B submitted a solution comprising multiple electrolyser modules, demonstrating compliance with relevant regulations. The design offered flexibility to scale output up to 1 kg/hr. However, container integration was presented as an optional element rather than a fully integrated solution. Additional features such as hot standby mode less clearly defined and lifecycle support commitments were limited to basic installation and training services.

Company A was ranked first in the tender evaluation outperforming Company B. Both suppliers met the mandatory technical requirements; however, Company A demonstrated superior performance in key technical areas (the following percentage indicates the Company A scores):

- **Design Process & Technical Solution (24%)**: Company A provided a fully integrated containerised electrolyser system, the Company B proposed a modular solution but lacked full integration
- **Capability & Resourcing (20%)**: Company A technical expertise with proven experience in hydrogen systems and containerised solutions, with quality assurance processes. Company B's team had limited experience in delivering fully integrated outdoor systems, relying on commercial off-the-shelf components
- **Tendered Assessed Price (18%)**: Company B's price score was better than Company A's - the technical advantages outweighed the cost difference
- **Project Plan (12%)**: Company A provided adequate planning, though Company B scored higher here
- **Social Value (6%)**: Both suppliers offered limited social value contributions.

Both suppliers met the mandatory requirements, but Company A provided a solution better aligned with UKAEA's operational and compliance needs. These factors positioned Company A as the preferred supplier for the HyDUS electrolyser.

The UKAEA and its suppliers developed and delivered specific technical enhancements to meet operational, safety and compliance requirements. The key advancements identified from working with suppliers for different systems were following.

- MCL
  - Independent ATEX certified ventilation system: a dedicated explosion-proof fan was implemented to ensure safe air circulation and compliance with hazardous area standards.

  - Modular process boards: custom-designed boards were installed to enable flexible integration of sensors, control systems and ancillary equipment, supporting rapid reconfiguration for experimental setups.
- HGS
  - Remote control and monitoring capability: implemented to allow full operational oversight, including pressure data relay, fault alarms and emergency shutdown capability, reducing operator exposure and enhancing safety.
  - Pneumatic spring system: designed to smooth hydrogen flow and reduce the hammer effect during pressure transitions, improving system stability and protecting downstream components.
- HCS
  - Hydrogen-compatible sealing technology: developed to mitigate hydrogen embrittlement and leakage risks under high-pressure conditions.
  - Dynamic pressure control system: enabled precise regulation of hydrogen flow between electrolyser, storage beds and fuel cell, ensuring stable operation during variable load scenarios.
- FCS
  - Advanced cooling integration: designed to maintain optimal operating temperatures and prevent thermal degradation during extended runs.
  - Load-following control algorithm: implemented to allow rapid response to fluctuating power demands, supporting grid-interactive demonstration objectives.

One key learning from the UKAEA procurement activities, is that when public money is being utilised, the fiduciary duty is increased and therefore, transparency is a key element. As positive as this is for fostering equal opportunity, it can limit options for optimising, negotiating requirements during the tender submission stage and increase costs. This impacts novel projects such as HyDUS more as they might need to develop requirements between design phases - the Procurement Act 2023 has a more flexible approach, which could alleviate these issues faced.

Installation

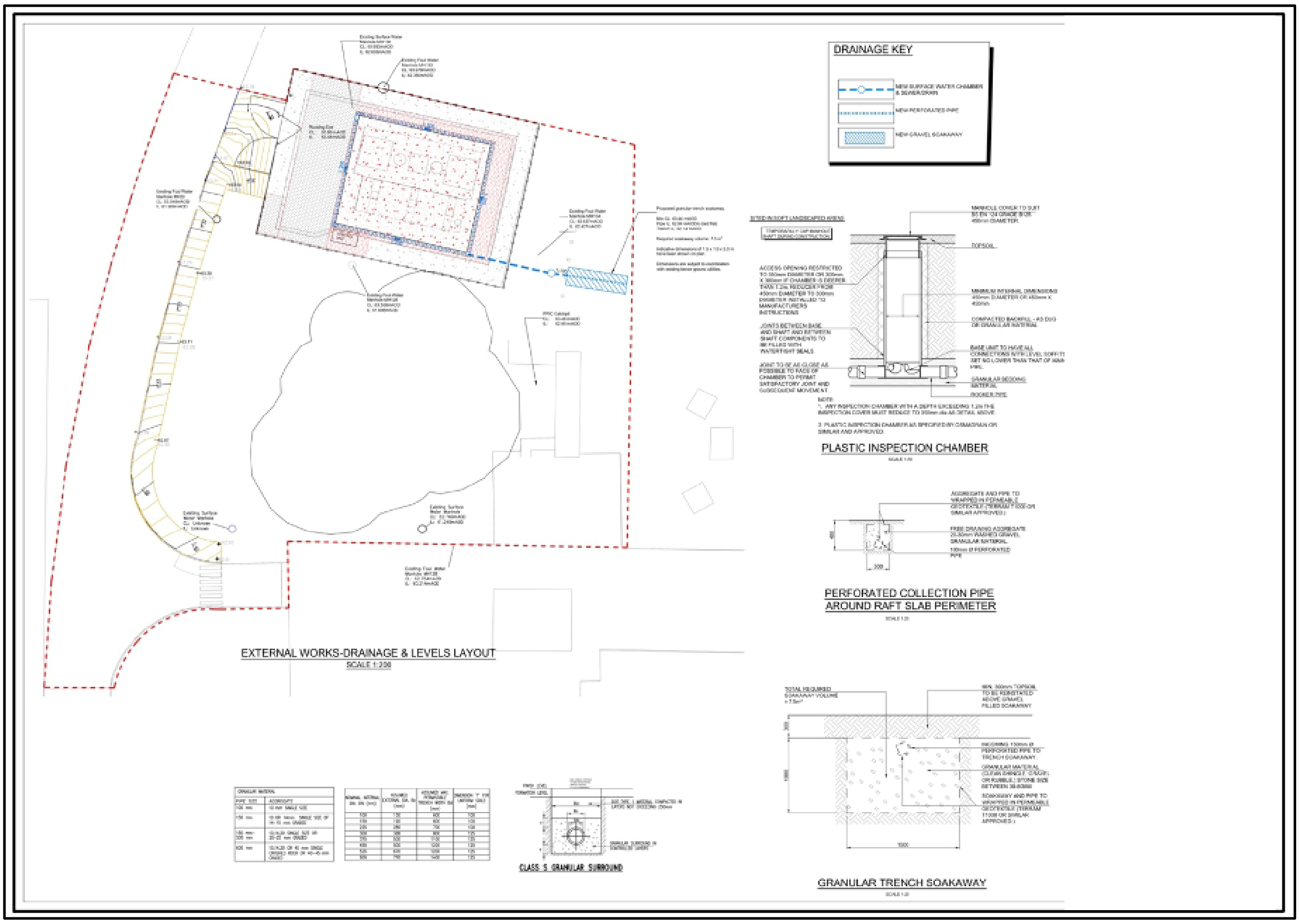
UKAEA selected a brownfield area within its site so that the HyDUS demonstrator could operate with appropriate independence while maintaining a safe degree of separation from central facilities. This location provided adequate space for enabling works and permanent infrastructure. This provided the opportunity to develop a design interface for a standalone compound. The chosen site lacked direct access to essential commercial services, including electrical power, trade drainage and industrial gases, as described in the *Engineering Design* section. The project sought to deliberately accept those constraints to test methods and controls under realistic conditions. The separation from the main buildings further supported safety case arguments and day-to-day operational independence, allowing the team to ring-fence activities associated with hydrogen and the DU storage media from unrelated site operations.

Preparing the site required a carefully staged sequence of investigations and designs. The work began with comprehensive site surveys and ground investigations to establish subsurface conditions and to identify buried obstructions, legacy services and load-bearing capacity. These preliminary studies informed the conceptual design phase, during which the functional layout and spatial requirements of the facility were fixed to support equipment footprints, access and egress routes, exclusion zones and future maintenance envelopes. Site elevation drawings were then developed to set out topographical adjustments and to ensure that levels, gradients and falls directed surface water away from critical assets. The focus at this stage was not simply geometric; drainage performance and structural stability were treated as integrated outcomes of the same design. Following that, the project progressed to full-scale construction, integrating permanent utility infrastructure, secure perimeter systems and facility-specific architectural elements to meet operational and regulatory requirements.

From the beginning, the team had to plan for the absence of an existing service matrix. Dedicated utility corridors were installed to route power and data to the compound, with secure, maintainable alignments. These corridors were designed to be segregated from process pipework and any potential gas lines to maintain discipline between electrical and mechanical risks. A secure perimeter was established as part of the same phase to protect critical assets, support controlled access and align with UKAEA physical security protocols. The perimeter served as a primary control for site entry, ensuring that only trained personnel operated within the compound, but it also defined an envelope within which hazardous zoning, emergency lighting and alarm coverage could be rationalised.

Managing drainage was a key technical and environmental challenge (Figure 43). Because experimental discharges could present contamination risks, the facility’s drainage had to be isolated from the broader site network. The solution adopted was to separate uncontaminated surface water from any process effluents. A French drain and a soakaway were installed to handle clean runoff, ensuring rainfall and washdown water are captured and dispersed safely without entering the trade drainage system. In parallel, experimental effluents were engineered to be contained in secure vessels for controlled treatment and disposal, thereby preventing the creation of unassessed discharge pathways. This segregation-maintained compliance with environmental and radiological safety protocols while keeping the installation straightforward to monitor and audit.

Figure 43: UKAEA site drawings



Formal planning permission was obtained from Oxfordshire County Council, which granted consent to authorise the establishment of the compound and the supporting infrastructure for the HyDUS demonstrator. Although the planning submission was made in 2023, when Biodiversity Net Gain was not yet a statutory requirement under national planning law, the council required a Biodiversity Net Gain assessment as part of the package. UKAEA therefore carried out baseline ecological studies and identified opportunities to enhance biodiversity value (illustrated in Figure 44), aligning the development with the National Planning Policy Framework and anticipating the forthcoming regime under Schedule 7A of the Town and Country Planning Act 1990, as amended by the Environment Act 2021, which made a minimum 10% increase in biodiversity value mandatory for most schemes in England from February 2024. In practical terms, this meant that the project accounted for on-site wilding and planting where feasible and recognised the need for off-site Biodiversity Net Gain credits, allocating budget accordingly through an external scheme used by HyDUS.

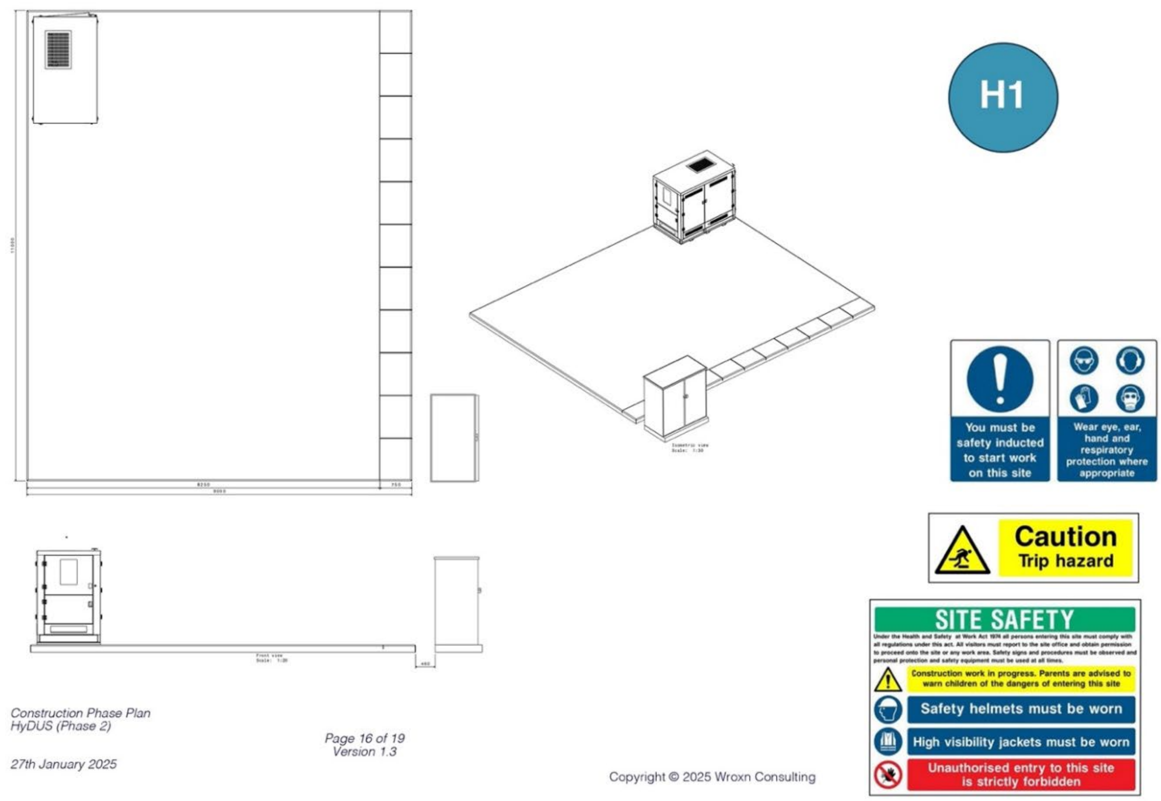
Figure 44: UKAEA Biodiversity Net Gain Proposal/Scheme

The experience of building on a brownfield plot offered several lessons. Where historical records and past health and safety files are accurate and complete, preliminary survey scopes can be optimised and early-stage risks reduced. In the HyDUS context, however, some records were incomplete or inaccurate and further investigative work was required to close gaps and verify assumptions. Those activities absorbed time and budget and required revisions to the programme to accommodate resurveying and design updates. While the brownfield context accelerated certain permissions and allowed reuse of disturbed land rather than development on a greenfield site, it demanded additional caution when exposing ground, proving services and defining construction interfaces. The cumulative effect of these realities was that allowances for uncertainty, design development and contingency had to be maintained and actively managed.

With planning secured and enabling works in train, installation commenced at the B29 compound. The first physical element was the construction of a reinforced concrete raft slab measuring 11 × 9 metres, designed for a uniform imposed load of 10 kN/m². The slab reinforcement and detailing were selected to withstand dynamic loads arising from equipment operation and to accommodate thermal gradients that could occur during heating and cooling cycles in adjacent systems. Around the working area, the compound boundary was established with a 2-metre-high fence, complemented by controlled access gates, CCTV coverage and high-intensity lighting to ensure secure working conditions at all times. Electrical and data services were routed into the compound through the new corridors, while potable water services were deliberately excluded to avoid creating unnecessary contamination pathways or water-induced risks within the hydrogen process environment.

Once the civil works and services were in place, major equipment was positioned in accordance with engineering drawings and compliance requirements. The FCS was set in its designated location (Figure 45) and electrically integrated to meet G99 grid export compliance. Hydrogen feed lines to the FCS were fitted with particulate filters and vent lines were routed externally to ensure safe discharge. Adjacent to the FCS, the MCL was installed. The laboratory ventilation was configured with HEPA filtration, and an ATEX-rated emergency fan was incorporated to support safe operation under abnormal conditions. Integrated sensors were installed to monitor hydrogen concentration, oxygen depletion and radiation levels. Within the laboratory, electrical integration included heater circuits for the storage media, control panels for local operation and supervisory functions and uninterruptible power supplies to maintain critical monitoring and control during transient power events.

Figure 45: Fuel Cell System position on reinforced concrete slab



The HGS was placed adjacent to the laboratory. This package comprised electrolysers, dryers, accumulator tanks and a local control system to produce and condition hydrogen. Hydrogen lines across the installation used stainless steel tubing of ½ inch outer diameter, grade 316L, assembled with Swagelok fittings to provide leak-tight joints and corrosion resistance appropriate to service conditions. Adequate equipment supports were installed, with spacing and allowances for thermal movement to protect joints and instruments. Safety features, including dedicated vent lines and pressure relief valves as seen in Figure 46, were integrated to prevent overpressure and to channel any releases to safe locations. Between the laboratory and the FCS, the HCS was installed. The compression train incorporated diaphragm pumps, buffer vessels and heat exchangers and was set up to comply with ATEX and Pressure Equipment Directive requirements, as applicable to the equipment class and duty. The isolated view in Figure 47 shows all the external pipework and instrumentation utilised in the design, whilst Figure 48 shows the HCS train.

On completion of mechanical assembly, the plan called for comprehensive leak and pressure testing with inert gases to confirm integrity before introducing hydrogen. Those tests would be followed by functional checks of valves, interlocks and instrumentation to verify the control logic progressively.

Figure 46: Top view of the compound showing the pipe runs

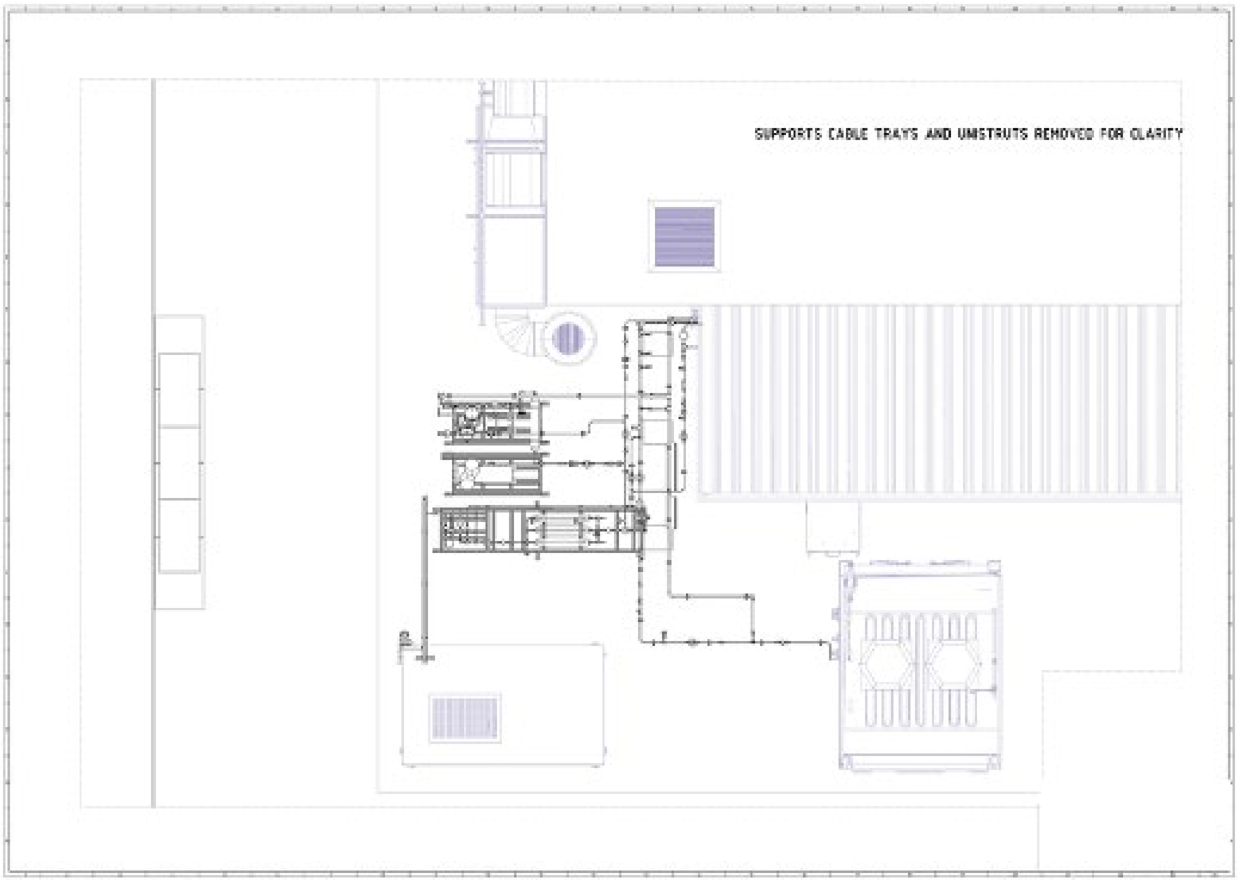


Figure 47: Pipework and instrumentation used externally for HyDUS

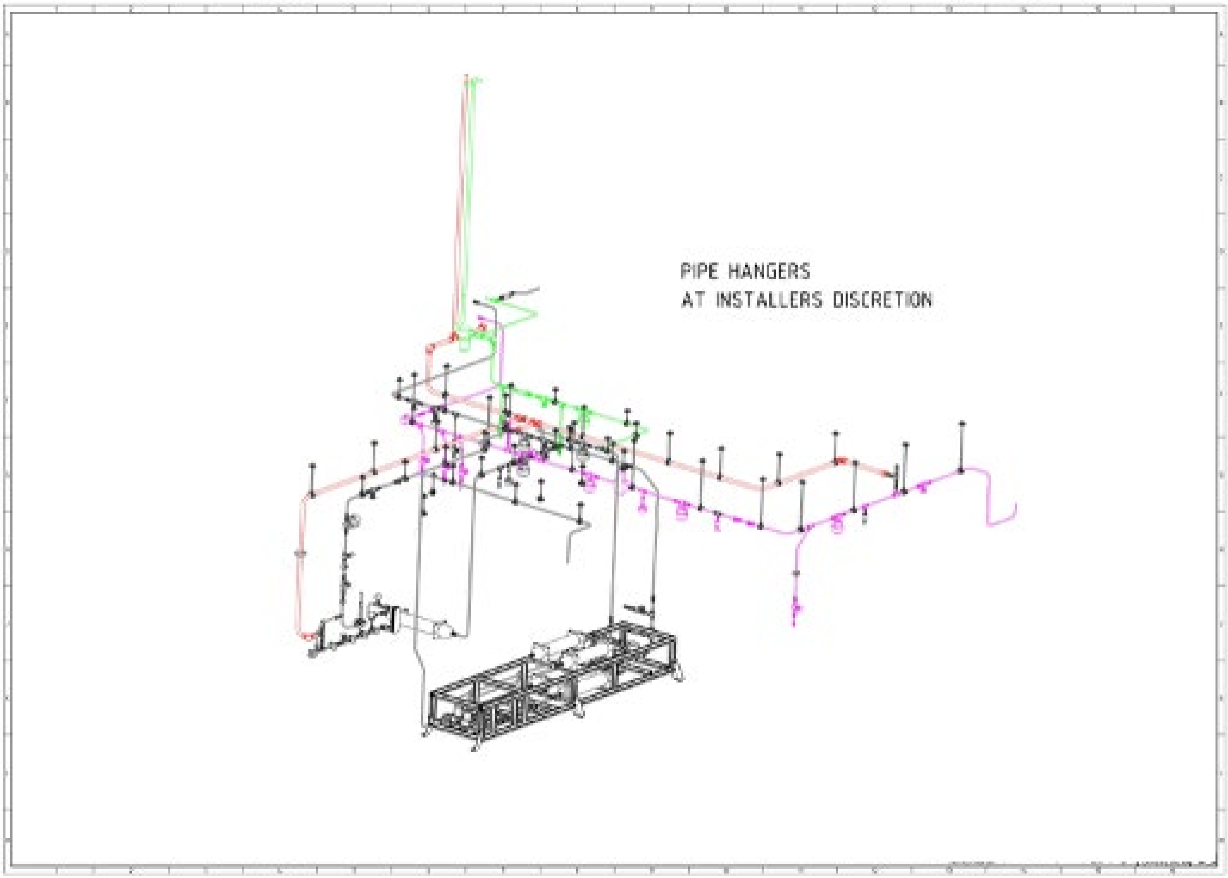


Figure 48: Top view of the HyDUS pump train

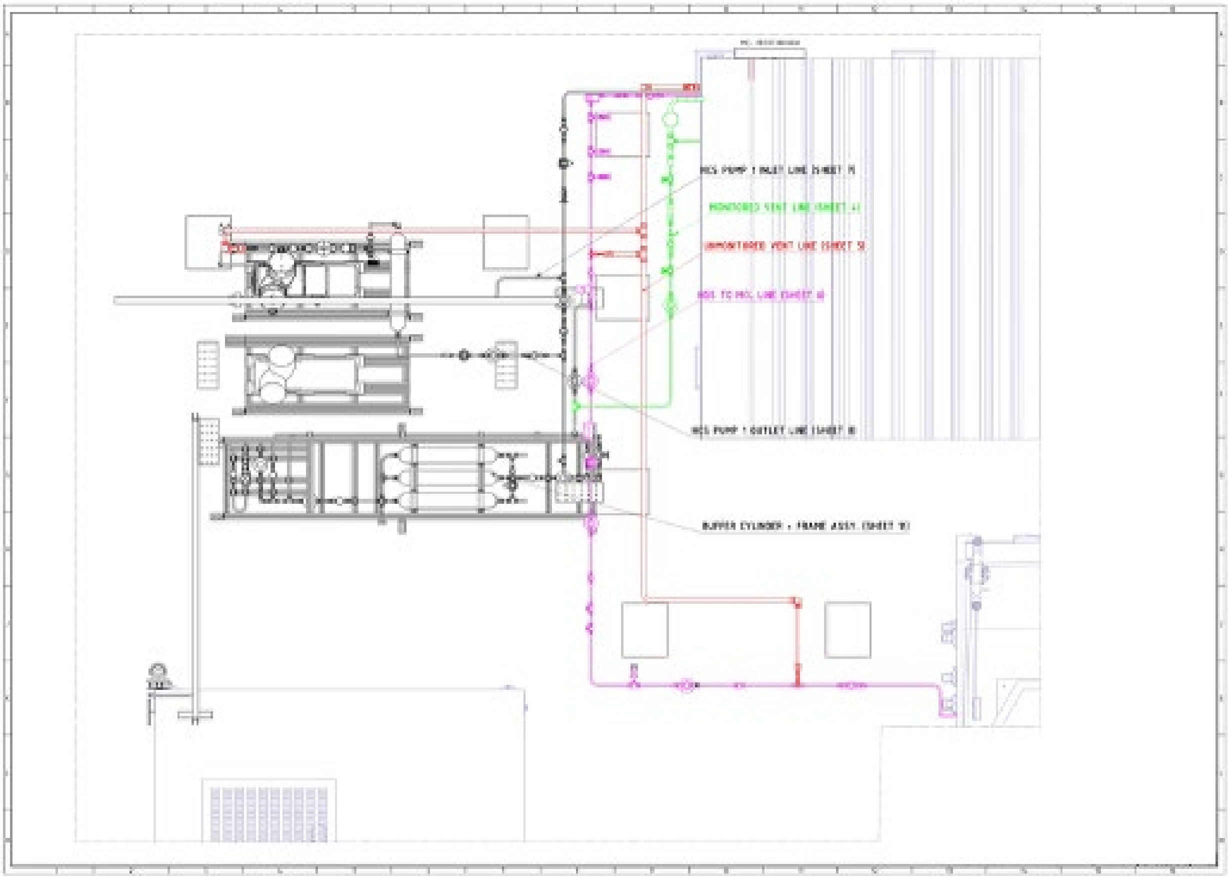


Figure 49: CAD render of the UKAEA HyDUS demonstrator

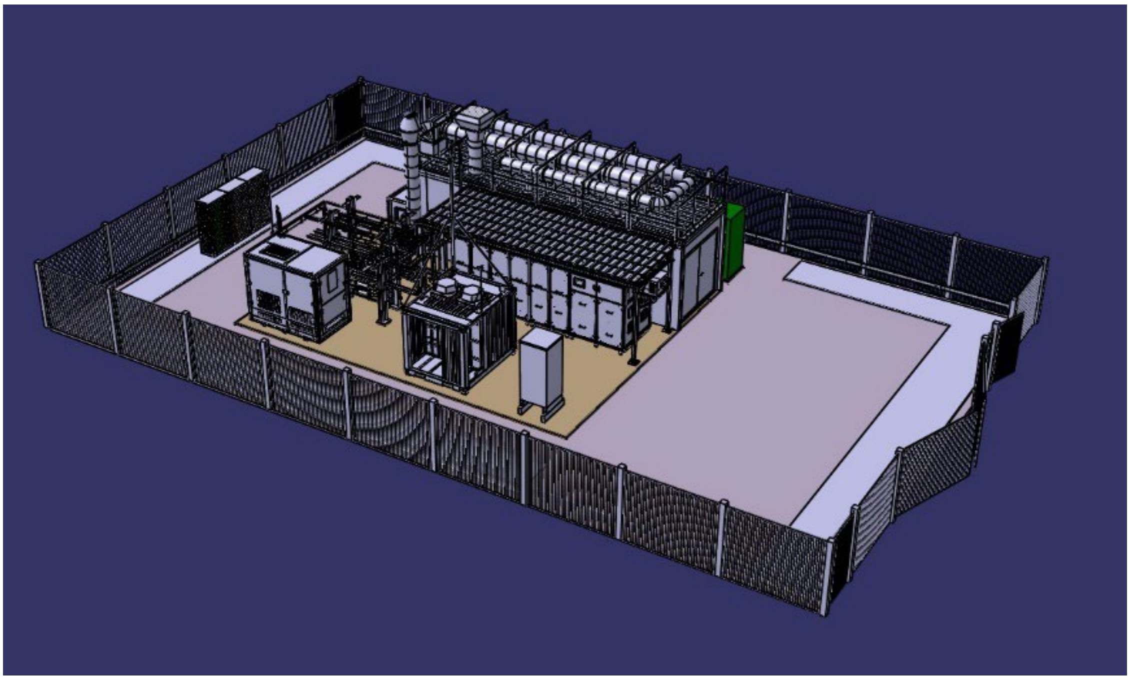
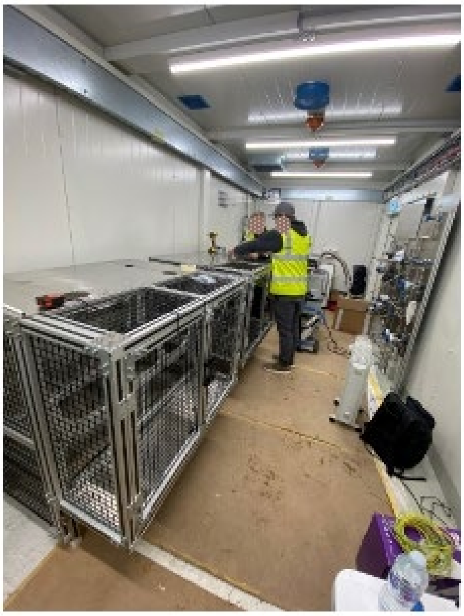


Figure 50: Physical development of the demonstrator

The design includes frames to support the DU Beds within the MCL, as seen in Figure 51. These frames have provisions to allow connection to the hydrogen pipelines and nitrogen cooling circuits. Instrumentation and sensor connections will be made in parallel to support monitoring of the operational envelope defined for the laboratory. Once installed, the sensor interlocks would be validated to verify that anticipated fault conditions triggered the correct responses. Gas sampling would be used to verify line cleanliness and dryness where relevant, while the programmable logic controller architecture would be commissioned step by step, allowing alarms, trips and permissive boundaries to be tested and signed off.

Figure 51: Installation of DU Bed frames in the MCL



Commissioning

The UKAEA has commenced the initial commissioning phase of the HyDUS demonstrator under the Site Acceptance Test (SAT) methodology. This phase ensures that all independent (bought-in) systems and components meet the agreed technical and operational requirements before integrated commissioning and eventual operation.

Systems with Site Acceptance Test completed by the end of the project (Q4 2024):

- Hydrogen Generation System
- Mobile Containerised Laboratory - ventilation system
- Hydrogen Compression System pumps

Systems with Site Acceptance Test due:

- Fuel Cell System
- Nitrogen Cooling System
- Mobile Containerised Laboratory - process panels

The UKAEA HyDUS commissioning strategy defines a structured approach for validating the safe operation and performance of the integrated system. The sub-project aims to demonstrate critical stakeholder requirements, particularly the successful integration of the system, with each subsystem interface proven across the integrated design. Subject to receiving the University of Bristol DU bed, UKAEA hopes to demonstrate the round-trip efficiency of the energy storage technology. The commissioning strategy ratified in September 2025, ensures that all systems are installed, tested, and operated safely in accordance with design intent. It supports a 4-6-week experimental phase to assess system conformance and performance, ensuring safety and environmental requirements are met, systems are operable and maintainable, and knowledge transfer occurs for safe operation and maintenance. The strategy also covers roles and responsibilities, safety management, operational documentation, and training needs.

Activities will be managed by a commissioning manager and team, accountable to a commissioning panel comprising the Authority To Operate Holder, Health Physics, project sponsor and Design Authority. The team includes operators, electrical, control & instrumentation engineers, mechanical technicians, process engineers and vendor specialists.

After subsystem-level Site Acceptance Testing and commissioning, system-wide commissioning is conducted with Installation Qualification (for components not tested in each subsystem), Operational Qualification and Performance Qualification and (if received) DU bed conditioning.

The approach can be summarised in two major stages:

- Stage 1 covers Site Acceptance Tests and commissioning of individual subsystems (except DU beds)
- Stage 2 involves system-wide commissioning and handover for experimental operations

Stage 2 identified two phases of system-wide commissioning: inactive commissioning and active commissioning inactive commissioning uses inert, non-flammable materials such as water, air and nitrogen to confirm system integrity under safe conditions.

- The inactive phase: verifies trips, interlocks, alarms and operational sequences and includes pressure and vacuum leak testing. It simulates process conditions to ensure the plant can achieve expected performance without introducing hazards.
- The active phase: introduces hydrogen gas into the system to validate functions that cannot be tested with inert materials. It confirms full operational capability across hydrogen generation, compression and power conversion through the fuel cell.

Active commissioning is the final step before experimental commissioning, which will demonstrate round-trip efficiency and compliance with safety requirements. A key operational qualification is testing the interlock system associated with emergency shutdown, including ensuring that the FCS enters a safe state under fault conditions without operator intervention. The different subsystems have specific performance qualification requirements that need to be verified. For example, the HGS focuses on gas purity and control functionality. The MCL emphasises ventilation performance and interlocks with hydrogen monitors. Other subsystems, such as the NCS, HCS and FCS, require checks on flow regulation, leak detection and cooling efficiency.

Testing Programme Results

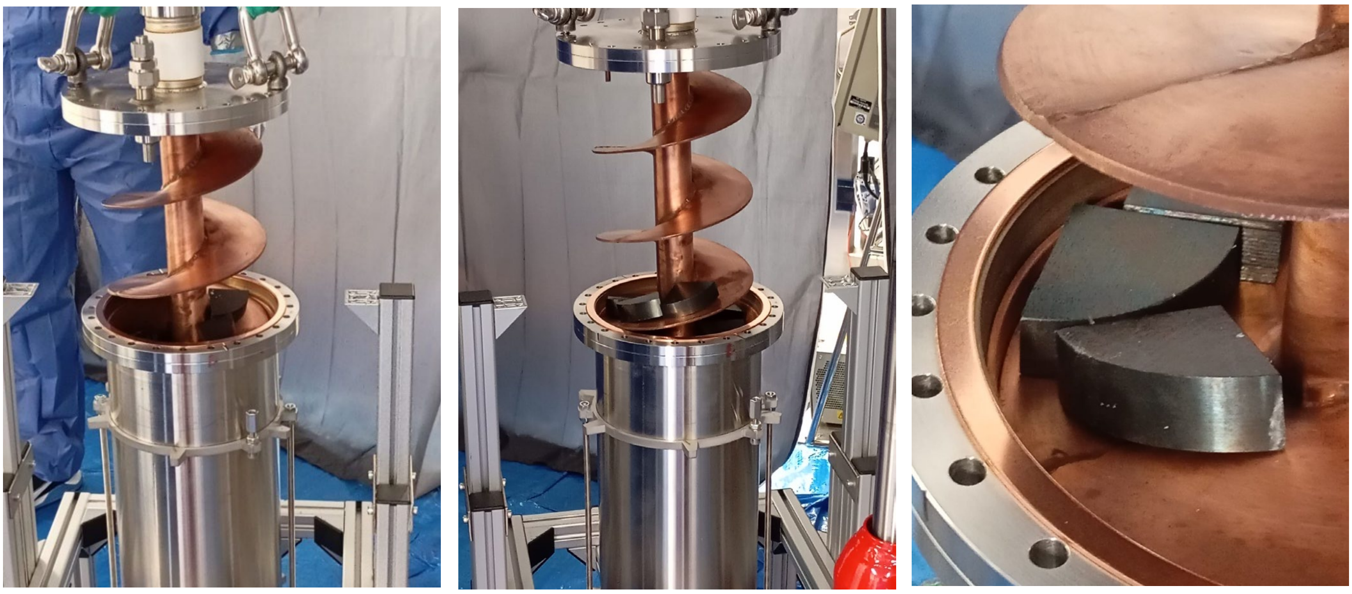
In this section, the results of the testing programmes carried out at the University of Bristol are presented. The testing aimed to characterise hydriding and dehydriding behaviour, assess temperature and pressure responses and evaluate the performance of the system components. At UoB, a single-bed setup enabled detailed, sensor-rich investigation of bed behaviour under a range of operating conditions.

University of Bristol system

System and material preparation prior to experimentation

Bed 1 of the HyDUS system was loaded with approximately 30.242 kg of DU, in accordance with the HyDUS Bed Loading and Assembly Risk Assessment. The total hydrogen storage capacity of the bed depends on the precise mass of uranium loaded; based on the nominal amount, the maximum theoretical hydrogen capacity is estimated to be 384.2 g or 190.6 moles of H2. The bed assembly process is shown in Figure 52.

Figure 52: HyDUS bed assembly process



Limited surface oxidation of the DU material was observed during loading. As the oxidised portion of DU does not participate in the hydriding and dehydriding processes, it is effectively considered a "poisoned" metal hydride. However, in this case, the extent of oxidation is considered negligible compared to the total mass of DU loaded into the bed.

Before the commencement of experimental procedures, all safety systems and security interlocks were thoroughly tested to ensure proper functioning. The system was also validated using PVT (Pressure-Volume-Temperature) testing to confirm the accuracy of flow meters and volume calculations. These checks were performed using both argon and hydrogen as test gases. Additionally, all system sensors - including temperature, pressure and flow - were verified for accuracy and the heating components were tested for performance.

Once the system was confirmed to be operating reliably and safely, the material underwent a preconditioning step. This step involved heating the material up to 150°C under dynamic vacuum, a procedure commonly referred to as the bake-out. The purpose of this step was to remove any residual oxygen and moisture from the material's surface. Eliminating these impurities is beneficial, as it helps prepare the material for initial hydriding process, improving the efficiency of hydrogen absorptions. Having completed this stage, the conditioning of the bed phase commenced. This phase involved 1 conditioning cycle of hydriding and dehydriding to ensure the breakage of the material, increasing surface area, resulting in improved reaction kinetics.

Bed conditioning

Two full-scale HyDUS storage beds, each loaded with ~30 kg of DU metal in quarter-puck form, were conditioned through hydriding–dehydriding cycling to establish reproducible ("steady-state") kinetics. The conditioning of two beds was required to support separate program goals:

- Bed 1 was used to demonstrate the passivation process, in which the reactive DU metal powder is deliberately and carefully oxidised to form a more chemically stable uranium oxide, thereby preparing the bed for safe long-term storage and eventual disposal
- Bed 2 was used for extended experimentation following hardware modification (band heaters integration)

After initial assembly, leak-testing, evacuation, and degassing at 100 °C, both beds were prepared for hydriding. The initial hydriding cycle led to near-complete conversion of DU to UH_3 in each bed, with Bed 1 completing the process over two days and Bed 2 achieving >80 % conversion within ~6 hours due to improved thermal control from the integrated band heaters. Early-stage hydriding exhibited induction periods of 5–9 minutes, and notable exothermic temperature rises were recorded across the bed cores.

Dehydriding behaviour, by contrast, was significantly slower, reflecting the high temperatures (350–450 °C) required and the strongly endothermic nature of UH_3 decomposition. Bed 1 required a multi-day dehydriding sequence during the conditioning phase due to slow kinetics, extensive preheating requirements. Bed 2, which benefited from continuous operation and improved heater configuration, achieved ~68 % dehydriding in ~27 hours of active reaction time. For both beds, conversion estimates derived from the Sievert's method proved more reliable than flowmeter calculations, particularly at low reaction rates where the flow meter fell below its sensitivity threshold. Overall, a single hydriding–dehydriding cycle was sufficient to powderise the DU stock and establish stable, rand quasi-repeatable reaction kinetics, enabling both beds to proceed to subsequent operational testing under the HyDUS program.

Bed operation results

This study examined the hydriding and dehydriding performance of two full-scale DU beds (~30 kg of DU each and same basic design) after their initial conditioning cycles, as described in the previous section. Bed 2 incorporated additional band heaters to improve thermal uniformity during dehydriding. Reaction progress was measured using both a mass-flowmeter and the Sievert's volumetric method; however, as previously discussed the Sievert's method was found to be more reliable, particularly during dehydriding, where slow kinetics frequently caused the flowmeter to fall below its sensitivity limit. Across all hydriding cycles, no induction period was observed, indicating that the powderised material reacted immediately following H_2 admission. Reaction rates were initially limited by flowmeter saturation, but higher temperatures, higher H_2 pressure, and active N_2 cooling all improved kinetics, enabling 80 % conversion in under three hours for several operational conditions. Faster kinetics could be achieved if a broader range flow meter was employed.

Dehydriding, an endothermic and slower process, required sustained temperatures of 390–440 °C to decompose UH_3 back to metal. Bed 1, heated only from the centre, exhibited large temperature gradients and slower kinetics due to heat losses and poor thermal conductivity of the powder. The addition of band heaters to Bed 2 substantially improved performance by providing a more homogeneous temperature field and reducing heat loss at the bed perimeter. As a result, Bed 2 achieved significantly faster dehydriding rates, reaching 80 % conversion (relative to the previous hydriding cycle) in as little as ~6 hours at 440 °C. For both beds, the evolution of the characteristic surface area across successive cycles, also contributed to the progressive improvement in kinetics.

Overall, the campaign demonstrated that full-scale DU hydride beds can repeatedly achieve rapid hydriding and controlled dehydriding when appropriate thermal management is employed. Hydriding performance is most strongly enhanced by increased temperature, pressure, and cooling, while dehydriding efficiency relies heavily on uniform heating and adequate temperature sustainment. These findings inform operational strategies and design requirements for future HyDUS-type hydrogen-storage systems.

UKAEA system

While testing of the HyDUS demonstrator was planned within this project, UKAEA expects testing to occur after the closure of HyDUS Phase 2 as part of changes agreed to the project to deliver by March 2026. The UKAEA will utilise the test plan developed during the project.

The UKAEA test plan aims to safely and practically demonstrate the system's round-trip energy efficiency. The reduced goal would be to achieve approximately 0.6 kg of hydrogen storage (90% of design capacity), validate system control for charge/discharge commands, meet DESNZ requirements for a minimum of 4-hour charge/discharge cycles and confirm the integrated design performance.

A full test plan was created, defining several test cases grouped into key categories to be tested by the UKAEA demonstrator.

- Safety & purity: confirm DU is not entrained in hydrogen output, validate filtration system design and test water from fuel cells for contamination.
- Performance mapping: create flow-time curves for full and partial cycles, validate DU levels and volumetric density and determine operational limits.
- Startup & transition: measure time to start charging/discharging from various states and evaluate transition times.
- Rate variation: map charging/discharging at different rates (>4 hrs minimum) and test controllability during cycles.
- Market simulation: simulate day-ahead and real-time market signals, assess responsiveness and optimise operations.
- Extreme scenarios: slow discharge over 3 days and simulate co-location with renewable generation or battery storage.

Testing durations range from hours for startup tests to weeks for performance mapping and market simulations. Key considerations include electrolyser capacity, DU bed cooling, temperature control and buffer cylinders for slow discharge scenarios.

The successful completion of the full test plan would validate HyDUS as a safe, flexible and scalable hydrogen storage solution. It would provide data to help evaluate the market-responsiveness and support business cases for future integration with the grid. Table 9 lists the UKAEA's test plan.

Table 9: UKAEA Test Cases - HyDUS Demonstrator

ID	Test Case	Priority	Rationale	Testing Time minimum
1	Demonstrate DU not entrained through a) monitoring hydrogen offtake during the trial and b) smear testing as part of decommissioning	1	Prove hydrogen suitable for export to any end user of hydrogen Potentially reduce costs of filtering for a scaled solution Prove the capability of the filtration system and confirm the suitability of the design.	Throughout project.

ID	Test Case	Priority	Rationale	Testing Time minimum
2	Map charging at different rates >4 hours for minimum time T. e.g. Map the charging profile from discharged to fully charged at T hours, T+1 hours, T+2 hours.	1	Assess ability to vary charging rates as required to match market signals. Provide hydrogen flow, heating/cooling, time profile at different rates.	6 days (1 test every other day to allow for full discharge)
3	Test varying the charging rate during one cycle (±50% from a given case above).	1	Assess the controllability of the charging rate during a charge.	1 day per test
4	Start-up time test (discharging): From the charged state. Assess how quickly the bed can start to discharge.	1	Demonstrate time to start discharging.	1 day per test
5	Map discharging at different rates >4 hours. E.g. Map the discharging profile from charged to fully discharged at minimum time (T). T hours, T+1 hours, T+2 hours.	1	Assess ability to vary discharging rates as required to match market signals. Provide hydrogen flow, heating/cooling, time profile at different rates.	6 days (1 test every other day to allow for full charge)
6	Map discharging at different rates from partially charged (25%, 50%, 75%).	2	Assess ability to vary discharging rates as required to match market signals. Provide hydrogen flow, heating/cooling, time profile at different rates from partial charge. Consider transition from charging to discharging	One day per test (12 days for all combinations)

ID	Test Case	Priority	Rationale	Testing Time minimum
7	Test varying the discharging rate during one cycle (±50% from a given case above).	1	Assess the controllability of the discharge rate.	1 day per test
8	Matching demand from a slow discharge scenario. Discharge very slowly over 3 days.	3	Determine potential operation at very slow discharge.	3 days
9	Match the capacity market operation. Respond to the dispatch signal within 4 hours from 3 scenarios (fully charged, charging and partially charged, discharging and partially charged).	3	Determine potential operation for the capacity market.	1 day

DU Material End of Life (Decommissioning)

In this section, the DU waste management and end-of-life considerations for the HyDUS demonstrators are described.

Demonstrator DU supply chain

For the demonstrator, approximately 500 kg of DU metal was sourced by the University of Bristol from Manufacturing Sciences Corporation (MSC) in the United States, as described in the *Procurement, Installation and Commissioning* section. The material was supplied in the form of uranium-metal pucks and transported to the UK by CTS Logistics under instruction from UoB. Upon receipt, the DU was weighed, inspected and cleaned to remove any surface oxide prior to bed filling. These preparation steps ensured material quality and safety for subsequent hydriding. Supplier choice was constrained by the requirement to comply with safeguards and administrative reporting for international transfer of DU to a university site. It was recognised that this constraint could be overcome in a commercial supply chain operating under a nuclear-licensed site regime, which would reduce administrative barriers and allow multiple DU-metal suppliers to participate.

Although the HyDUS demonstrator required only a modest quantity of DU, the end-to-end logistics chain established for its procurement and handling represents a proof of concept for a potential commercial process. The experience gained through this activity provides practical insight into the import, transport and preparation stages that would need to be replicated or adapted within a future industrial-scale supply chain. Integration of bed filling within a licensed DU-metal manufacturing site has been identified as the most efficient and secure approach, as it enables consistent regulation, minimises transport of unpackaged material and maintains full traceability of DU through manufacture and use.

The demonstrator also highlighted the HyDUS system lifecycle from DU manufacture through to disposal and decommissioning. At the end of the life of the storage bed, the DU within the bed will need to be managed through to final disposal by conversion to a stable oxide form such as U_3O_8.

Demonstrator passivation

At end-of-life, the DU inside a HyDUS storage bed exists as a finely divided mixture of metallic uranium, uranium hydride (UH_3) and uranium oxides generated during service. In metallic or hydride form these powders are highly reactive and can exhibit pyrophoric behaviour if exposed to oxidants such as oxygen or moisture. Consequently, neither DU metal nor UH_3 is an acceptable chemical form for transport or disposal. To meet disposal requirements, the reactive bed contents must be converted into a chemically stable and inert oxide, with U_3O_8 recognised as the preferred end-state.

The conversion of DU metal or hydride to oxide is strongly exothermic. If large quantities of high-surface-area material are exposed to an unrestricted oxidant supply, rapid heat release can lead to uncontrolled temperature excursions. For this reason, the HyDUS passivation approach is based on controlled, pressure-limited exposure to dry oxygen, with the oxygen supply moderated according to the temperature of the bed. This ensures that oxidation proceeds gradually, with heat dissipation maintained and temperatures kept within safe limits. Additional measures, such as agitation of the sealed bed to disturb protective oxide layers and intermittent heating to promote diffusion assist in overcoming the “blanketing effect” that can slow the oxidation of deeper unreacted material.

The first full-scale passivation trial was carried out at the University of Bristol on a HyDUS bed containing approximately 30.3 kg of DU that had undergone four hydriding/dehydriding cycles, as described in the *Testing Programme Results* section. These cycles produced a high-surface-area metallic powder. The bed was subjected to a multi-stage passivation programme involving pressure-limited dry oxygen exposure, periodic agitation and controlled heating steps. Progress was monitored primarily through oxygen consumption measurements, supported by temperature data from thermocouples installed within the bed. Oxygen uptake provided the most reliable indication of the extent of reaction, particularly in cases where oxidation kinetics were slow and heat signatures were minimal.

The UoB programme demonstrated that controlled passivation of a full HyDUS bed is feasible and effective. Key outcomes are below.

- High overall conversion: approximately 92% of the DU metal was converted to oxide during the 14-day passivation campaign, based on cumulative oxygen consumption.
- Dominant formation of U_3O_8: temperatures recorded during most oxidation stages exceeded the threshold at which U_3O_8 becomes the favoured product (>250 °C). The majority of the material is expected to have formed U_3O_8, with a smaller fraction potentially present as UO_2.
- Minimal residual reactivity: in later stages, introducing oxygen at elevated pressure resulted in negligible temperature rise and negligible oxygen uptake, indicating that very little unreacted metal remained.
- Effective use of agitation and controlled heating: iterative cycles of bed rotation and moderated heating successfully overcame instances of slow kinetics caused by protective surface oxide layers “blanketing effect”.

Overall, the trial provides strong evidence that end-of-life HyDUS beds can be reliably transformed into a stable oxide waste form suitable for handling, transport and disposal, provided that oxidation is conducted under controlled conditions with appropriate monitoring of temperature and oxygen consumption.

Demonstrator disposal

Currently, due to current classification and use cases of DU, disposal is either via long term storage, or extremely expensive incineration. Based on several quotes received and discussions with Nuclear Waste Services in April 2025, disposal via incineration has a cost based on MBq. The calculations provided resulted in a charge of £156,000 in Alpha charges alone for the disposal of a single 30kg bed. Obviously, this figure is not financially viable for HyDUS - the figure alone was almost as much as the cost to acquire all 500kg of the DU.

HyDUS at scale assumes that Urenco is involved as the supplier and continuous owner of the DU metal throughout the HyDUS lifecycle, meaning that any scaled version of HyDUS will require a close partnership between the HyDUS team and Urenco, wherein the material is loaded into the HyDUS beds, used for the length of the bed's lifespan and eventually returned to Urenco for storage / disposal.

The current demonstrators utilise material owned by the University of Bristol. This material was purchased for research purposes and the end-product, even passivated, is of academic interest to the UoB team, allowing for iterative improvements to beds and related processes - essential for making the HyDUS technology more effective and efficient.

As such, whilst UoB has proven the method of passivation, the decision was made to retain ownership of the material and not dispose of it for the purposes of a method that would not be representative of disposal at scale. UoB has, however, researched potential methods for successful and safe disposal at scale with the key primary learnings from this project as:

- DU particulates remain the primary radiological hazard, demanding HEPA and negative-pressure systems;
- Bed integrity is essential to minimise particulate formation at end of life;
- Automated passivation significantly reduces risk and should be standardised;
- Demonstrator-scale waste handling methods can be adapted for gigawatt-scale, but must be industrialised.

Future Commercial HyDUS: Supply Chain and Commercialisation Pathways

The preceding sections of this report have focused on the delivery, operation and learning from the HyDUS Phase 2 demonstrator programme, setting out what has been designed, built, tested and proven to date. Having established the current technical and operational status of the technology, this section now looks forward to the future commercial deployment of HyDUS. It shifts the emphasis from experimental demonstration to the practical requirements for scaling, DU supply chain readiness and market entry.

This section brings together the assessment of the DU supply chain and the commercialisation pathways for HyDUS, drawing on the findings of earlier dedicated studies.

Supply chain for depleted uranium and components

In this section, the supply chain for DU required for a future HyDUS commercial system is described. The assessment examines how DU could be sourced, processed and managed at scale, alongside the commercial structures, regulations, cost drivers and deployment models that would support future rollout.

Future potential DU supply chain

DU is produced as uranium hexafluoride (UF_6) during the uranium enrichment process. Urenco generates DU in UF6 form at its enrichment facilities in the United Kingdom, the Netherlands, Germany and the United States. The material, known as uranium “tails”, is owned and managed by Urenco and stored on licensed sites following the provision of enrichment services. Although UF_6 is a convenient chemical form for enrichment operations, it is volatile and unsuitable for long-term storage, so it is routinely converted to the stable oxide U_3O_8.

Conversion of UF_6 to metal suitable for use in HyDUS storage beds is often (but not always) follows a two-stage chemical process. The first stage converts UF_6 to uranium tetrafluoride (UF_4) and the second stage reduces this to uranium metal. Following conversion, mechanical forming techniques can be used to produce pellets or pucks of DU metal for system loading.

Urenco’s Tails Management Facility (TMF) at Capenhurst provides industrial-scale deconversion capacity, processing up to 10 000 tonnes of DU-metal equivalent per year into U_3O_8. This operation allows the long-term, safe management of the UK’s DU inventory.

The commercialisation of a DU supply chain for HyDUS depends on establishing a favourable economic and business case for the reuse of DU compared with its long-term storage and disposal. This requires a clear understanding of the capital, material and operating costs associated with large-scale DU metal production.

Regulatory requirements

HyDUS requires large volumes of DU, a reference 10 MW system is estimated to require circa 150 tonnes of metallic DU. Handling and converting such quantities is a non-trivial activity. Importantly, in the UK and globally, a robust regulatory framework surrounds the handling of nuclear materials. Whilst a deployed HyDUS system would seal the DU within a static system, the manufacture of DU metal will not be able to make any similar claims. A high-level review of the regulatory framework for producing DU metal and managing its use in HyDUS identified several barriers that would need to be overcome to commercialise DU metal production. In the UK DU metal production would most likely need to be located on a nuclear-licensed site, which sets out several conditions that must be demonstrated by the operator. This is recognised as adding cost and complexity to projects, particularly where first-of-a-kind (FOAK) systems are being deployed.

More broadly, a commercialised HyDUS system incorporating DU will be subject to a range of UK nuclear, environmental and safety regulations. These govern both the manufacture of DU metal and its integration into HyDUS storage beds, as well as the eventual operation and decommissioning of the system.

For normal operation, the following regulatory frameworks are applicable:

- Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR): governs the control of flammable gases and materials, including hydrogen, within the HyDUS process environment.
- Ionising Radiation Regulations 2017 (IRR): establishes requirements for protecting workers and the public from exposure to ionising radiation during handling or processing of DU metal.
- Environmental Permitting Regulations 2016 (EPR): sets conditions for the management and disposal of radioactive material and any associated waste streams.
- Nuclear Safeguards (EU Exit) Regulations 2019 (NSR): ensures compliance with international safeguards obligations and nuclear-material accountancy for DU movements and use.
- Radiation (Emergency Preparedness and Public Information) Regulations 2019 (REPPIR): requires the preparation of on-site and off-site emergency plans for radiological incidents.
- Nuclear Installations Act 1965 and associated Nuclear Site Licence: applies to any facility where quantities of uranium exceed the limits for non-licensed operations, requiring oversight by the Office for Nuclear Regulation (ONR).

Any organisation responsible for manufacturing or integrating HyDUS storage beds must be able to demonstrate full compliance with these regulations.

The regulatory assessment undertaken for HyDUS concluded that the handling of large quantities of DU metal constitutes a prescribed activity under the Nuclear Installations Act. As such, filling of HyDUS beds is likely to need to occur within an existing nuclear-licensed facility to remain within legal limits. Depending on where HyDUS systems are ultimately deployed, there are three potential approaches to regulatory compliance during bed filling and operation:

- Integration of bed filling within the DU-metal manufacturing site, under the same nuclear licence;
- Bed filling at a separate licensed site with appropriate handling and storage authorisations;
- Integration of bed filling with HyDUS operations, provided the deployment site is appropriately licensed.

Each option presents different balances of regulatory burden, operational complexity and cost. The preferred approach will depend on the commercial arrangements selected for DU manufacture and ownership, as well as the scale and location of future HyDUS deployments.

Together, these regulatory frameworks provide the foundation for safe, compliant and transparent operation of a DU-based hydrogen storage technology within the UK's nuclear sector.

Capital, material and operating costs of DU metal production

[this section has been removed for confidentiality reasons]

Analysis of value to waste disposal of DU

Urenco holds significant stockpiles of DU managed under its custodianship at the Capenhurst site. The management of these inventories incurs ongoing costs for conversion to uranium oxide (U_3O_8) and for secure storage and disposal. Identifying a route to utilise some or all this material, rather than moving it directly to long-term disposal, may help to mitigate these future costs.

The potential reuse of DU through the HyDUS process offers a pathway to convert part or all this liability into a productive asset. In this context, DU reuse could reduce the quantity of material requiring permanent management and deliver measurable economic and environmental benefits. Understanding the potential value of DU reuse compared with disposal therefore remains an essential next step. This analysis will quantify the scale of cost avoidance associated with long-term DU management and provide the evidence base needed to justify investment in DU-metal production capability.

Development of business model for DU metal supply

Multiple business models could be applied to the manufacture and supply of DU metal for HyDUS. The most appropriate model will depend on several factors, including regulatory constraints, the requirement for DU metal conversion, the possible requirement for HyDUS bed filling to take place on a nuclear-licensed site and the commercial appetite of the organisations involved.

Three potential approaches have been identified for DU metal supply:

- Vertical integration of DU manufacture by Urenco on a Urenco site;
- Tenant organisation manufacturing DU metal on a Urenco site;
- Third-party organisation manufacturing at a different site under its own licence.

Based on the relative strengths and weaknesses of the identified approaches, the most likely approach is identified as the integration of the bed filling with the DU metal manufacturing facility. This makes use of the regulatory basis for DU metal manufacture and the capability that would need to exist at such a facility for the safe handling and movement of DU outside of the HyDUS beds.

An integrated facility manufacturing DU metal and filling HyDUS beds with the metal could be operated by Urenco as the current DU owner, or another commercial entity who transfers the UF6 tails from Urenco before conversion and bed filling. In the latter, the operator would need to demonstrate competence to be able to receive the DU from Urenco under Urenco's duty of care requirements. Whichever of these options is followed, the development needs of the supply chain and the future cost of DU will be similar.

A major consideration in the selection of a suitable business model is the management of long-term DU liability. Any proposed business model must provide a clear legal and regulatory route for the transfer or retention of responsibility through the entire DU lifecycle.

The selection of a preferred business model will depend on the ability to demonstrate a clear commercial advantage over existing disposal routes and to deliver a viable return on investment. Given the complexity of DU ownership and liability at end of life, establishing a robust business model for DU-metal supply will be essential to the wider commercialisation of HyDUS. The combination of Urenco's existing enrichment and oxide conversion capability and the development of new metal-conversion and integration operations could provide the foundation for a fully domestic DU supply chain. A viable business framework built on these capabilities could enable DU reuse at scale, supporting a sustainable and economically defensible route for HyDUS deployment in the UK.

Next steps for accessing the DU supply chain

Establishing access to the DU supply chain will be a critical step in progressing HyDUS from demonstration to commercial deployment. There are several key steps that need to be taken to enable this, focused on defining the commercial, regulatory and technical conditions under which DU can be converted, supplied and integrated into HyDUS systems at scale.

- The first requirement is to engage with Urenco as the custodian of the UK's DU to define the framework for future supply. This will involve confirming the quantities and specifications of DU available for reuse, the conditions under which transfer from Urenco could occur and the safeguards, transport and accounting obligations that would apply. Agreement on these principles will be essential to establish a secure and legally compliant supply route.
- Reviewing the maturity of DU metal conversion technology and the ability to produce metal at scale - the report identified the uniqueness of this requirement when compared

to the scale of existing technology used globally. A suitable R&D programme would be required to develop the processing technology at the scale of production required. That said, there is plentiful suitable feedstock for a new process, with Urenco producing ~20,000 tonnes of uranium in UF6 per year, which would be suitable feed for a metal production process.

- Once the R&D programme has established a proven and scalable DU-metal production process, a detailed commercial assessment should then be undertaken to evaluate business model options for DU-metal supply. This will need to consider cost recovery, liability transfer mechanisms and ownership of DU throughout the processing chain. Establishing a viable economic case for DU reuse compared with long-term storage will be central to attracting investment and industry participation.
- Any production of DU metal would need to appropriately consider the impacts of additional, novel waste streams, as well as the end-of-life management of the metal. Current DU tails management routes convert the UF6 into a chemically stable form that would be suitable for direct disposal in a future waste repository, whilst pure metal may not be considered suitable for direct disposal.

Commercialisation pathways

The HyDUS system has progressed from a laboratory proof of concept to a modular demonstrator, confirming the viability of hydrogen storage in DU. To unlock its commercial potential, the technology must now move through a set of defined scale-up stages. These focus on technical optimisation, development of the DU supply chain and the establishment of a commercial product offering. This section sets out the required steps for scalability - covering technological, supply chain and commercial considerations - alongside the indicative timeline for scale-up and the resulting commercialisation pathways.

Technology scalability

Scaling the HyDUS system from a laboratory demonstrator to a commercially viable solution requires targeted improvements across several technical domains. Table 11 outlines the key design features, the improvements required and the expected timeline for each step.

Table 10: Key steps for technical scale-up

Design feature	Description	Steps required	Expected timeline
Bed size and volume density	Current beds are small-scale with limited DU mass per unit volume.	Scale up to larger single-skin beds (~92.7 kg DU), optimise internal layout. Requires design and testing of new beds.	3 years

Design feature	Description	Steps required	Expected timeline
Alloying for thermal optimisation	Current DU beds require high temperatures for dehydriding, limiting response time and efficiency.	Investigate alloying strategies (e.g. uranium-iron) to reduce dehydriding temperature by 100-150°C and improve thermal response. Requires lab-scale testing and material validation.	3 years
Thermal management	Current system uses basic heating and cooling with limited heat recovery.	Integrate heat exchangers to enable heat recovery between hydriding/dehydriding cycles - this would allow the technology to applicable for off-grid applications (when additional heat is available). Requires design and testing of heat management system.	3 years
System module design	Current system uses 6 beds, with integrated heating and cooling in each bed.	Design of containerised lab for 20 beds, including optimised heating and cooling, bed layout for maintenance and new C&I.	3 years
DU handling and filling	Manual handling and filling of DU powder is time-consuming and hazardous.	Develop automated DU filling and sealing process for safe transport.	3 years

DU supply chain scalability

The availability and handling of DU are central to the scalability of the HyDUS system. While the demonstrator phase used a small quantity of DU sourced outside of the UK, commercial deployment will require a secure, scalable and cost-effective supply chain. This includes sourcing, processing, transport and regulatory compliance. The main aspects which need addressing to ensure commercial scale-up of the technology with respect to DU supply chain are listed in Table 12.

Table 11: Key steps for DU supply chain scale-up

Aspect	Description	Steps required	Expected timeline
Material Availability	DU is produced through uranium enrichment and is stored in the UK, primarily by Urenco.	Confirm long-term access agreements with UK-based supplier(s). A profitable business model is required to ensure interest of supplier(s) in changing current routes of processing, disposal and storage.	5 years
Material Classification	DU is currently classified as a waste material, which may reduce acquisition cost but introduces regulatory complexity.	Explore reclassification with nuclear authority as a useful material for industrial use to simplify handling and reduce barriers.	2 years
Processing and Form	DU must be converted into a metal, in suitable form (e.g. powder or compacted hydride).	Develop industrial-scale DU processing procedures.	10 years
Regulatory Engagement	Use of DU outside nuclear sites requires engagement with regulators to ensure safe and compliant deployment if quantity higher than 27 tonnes (under current regulation).	Collaborate with ONR and EA to define a regulatory pathway for non-nuclear deployment. Explore maximum quantities allowed before nuclear licence is required with new classifications of material for industrial use.	5 years

Commercial offering

To support early market entry and build investor and customer confidence, the HyDUS system must be offered as a technically robust and suitable product for the target market. Table 13 presents the key steps for commercial offering scale-up.

Table 12: Key steps for commercial offering scale-up

Aspect	Description	Steps required	Expected Timeline
System Format	Current demonstrator is not suitable for commercialisation.	Develop standardised 20-bed container module with integrated services.	5 years
Customer identification	A range of different applications have been identified but predicted costs require the filtering of these based on the USPs of the technology, to address relevant markets.	Identify target markets which are large enough to offer assurance for next stage development.	2 years
Deployment Model	No defined commercial model.	Define purchase, lease and service-based options.	5 years

Timeline for scale up

The scale-up of HyDUS follows a phased approach aligned with its TRL, supply chain development and market engagement. Early pilot deployments will be critical to validate performance, build confidence and unlock investment. Based on the required stages for scale up detailed above, a phased approach is detailed here, ensuring HyDUS can adapt to evolving policy, supply chain and customer needs.

Stage 1: TRL6 prototype (0-3 years)

- Objective: Demonstrate a fully functional HyDUS prototype with its final bed design.
- Configuration: New design of single beds
- Key Activities
    - Finalise single-skin bed design to improve volumetric efficiency
    - Test alloying strategies (e.g. uranium-iron) to reduce dehydriding temperature
    - Optimise thermal management (i.e. insulation and heat recovery)
    - Develop automated DU filling and sealing process
    - Explore reclassification with nuclear authority as a useful material
    - Identify target markets / Conduct pilot deployments in niche applications (e.g. semiconductors, mining)

- Performance Targets:
    - Hydrogen-to-hydrogen round-trip efficiency: ≥80%
    - Electricity-to-electricity round-trip efficiency: ≥45%
    - Response time (start of heating to hydrogen delivery): ≤60 minutes
    - Loading kinetics (80% conversion): >2 h
    - Unloading kinetics (80% conversion): >3-4 h
- Dependencies / Risks
    - DU availability: Limited access to DU for testing may delay bed validation and alloying trials.
    - Thermal management complexity: Inefficient heat recovery could prevent achieving target round-trip efficiency.
    - Regulatory uncertainty: Delay in ONR guidance on DU exemptions could restrict pilot deployments.
    - Material behaviour: Alloying strategies may not yield expected temperature reductions without detailed testing.

Stage 2: Commercial demonstrator (3-5 years)

- Objective: Deploy a containerised 20-bed HyDUS system in a real-world setting.
- Configuration: 20 bed modular system, ~0.8 MWh LHV capacity, transportable and hybridisable.
- Key Activities
    - Design of containerised lab for 20 beds.
    - Confirm long-term access agreements to DU with UK-based supplier(s).
    - Engage with regulators (ONR, EA) for site-specific licensing.
    - Validate performance in target sectors (e.g. chemical sector).
    - Finalise business model (e.g. purchase, lease, service).
- Dependencies / Risks
    - DU supply chain readiness: Pilot-scale production (ca. 2 tonnes) must be secured to support demonstrator rollout.
    - System integration risks: Scaling up from 6 to 20 beds may introduce unforeseen thermal or mechanical challenges.
    - Regulatory engagement: EA and ONR approvals may be delayed or require additional safety measures.
    - Customer engagement: Lack of early adopters in target sectors could slow validation.

Stage 3: Market entry and expansion (5-10 years)

- Objective: Launch HyDUS as a commercial product across multiple sectors.
- Configuration: Scalable systems tailored to application (e.g. off-grid mining, backup power).
- Key Activities:
    - Develop industrial-scale DU processing procedures: expand DU production capacity (10-100 tonnes/year).
    - Integrate HyDUS into hybrid systems (e.g. batteries, salt caverns).
    - Secure policy support (e.g. Hydrogen to Power).
- Dependencies / Risks
    - DU production scale-up: Expanding to 10-100 tonnes/year requires investment.
    - Market maturity: Premium hydrogen markets (e.g. chemicals) may evolve slower than expected.
    - Hybrid system complexity: Integration with batteries or salt caverns may require bespoke engineering and site-specific adaptation.
    - Policy support: Lack of inclusion in policy schemes could undermine competitiveness.
    - Manufacturing capacity: Scaling to e.g. ≥10 units/year demands robust supply chains.

Priority commercial pathways

Three pathways emerge clearly from the modelling, cost analysis and sector requirements identified as part of the commercialisation analysis.

Pathway 1 - hydrogen-to-hydrogen storage for high-purity and niche applications (near term)

Hydrogen-to-hydrogen operation eliminates the electrolyser and fuel cell CAPEX and efficiencies, making this configuration the lowest-cost option in both FOAK and NOAK systems. The FOAK LCOS for this mode is *[this section has been redacted for confidentiality reasons]* and falls to *[this section has been redacted for confidentiality reasons]* in the NOAK case. These reductions arise mainly from the removal of electrolyser and fuel cell costs and their efficiencies and the reduced installation and contingency allowances in the NOAK assumptions.

This mode aligns with early-market users identified, including:

- Semiconductor manufacturing;
- Chemical synthesis applications using catalyst-sensitive processes;
- Remote and off-grid sites requiring modular hydrogen storage at low pressure (as long as additional heat is available).

HyDUS provides high-purity hydrogen and no self-discharge in storage supporting applications where stability and purity are more important than large-scale capacity.

Pathway 2 - electricity-to-hydrogen operation for distributed industrial hydrogen demand (medium term)

Electricity-to-hydrogen mode introduces an electrolyser but not a fuel cell. The FOAK LCOS for this mode is *[this section has been redacted for confidentiality reasons]*, reducing to *[this section has been redacted for confidentiality reasons*] for a NOAK system. Electrolyser cost reductions assumed for the NOAK case include a *[this section has been redacted for confidentiality reasons]* reduction in electrolyser CAPEX and removal or reduction of several installation-related factors.

This mode is suitable for industrial hydrogen users, particularly:

- Dispersed industrial sites outside cavern zones;
- Industrial processes requiring high purity hydrogen;
- Locations integrating local low-carbon electricity and hydrogen demand.

Pathway 3 - electricity-to-electricity long-duration storage for strategic applications (long term)

This pathway uses both an electrolyser and a fuel cell to provide electricity-to-electricity operation. Because of the capital intensity of both components, the FOAK LCOS is *[this section has been redacted for confidentiality reasons]*, falling to *[this section has been redacted for confidentiality reasons]* in the NOAK scenario.

Although this remains above the cost of mature short-duration technologies, modelling results show that:

- Round-trip efficiency could improve in the commercial system through better bed heating efficiency, improved electrolyser and fuel cell efficiencies;
- Utilisation has the largest effect on cost performance, with two cycles per day reducing LCOS to *[this section has been redacted for confidentiality reasons].* These sensitivities reinforce the importance of deployment in applications with high utilisation.

Strategic users of this configuration include:

- sites requiring resilient backup energy;
- locations with restricted grid connections;
- hybrid systems integrating local renewables, hydrogen production and conversion.

HyDUS therefore offers multi-vector flexibility in settings where resilience and siting constraints outweigh cost-per-MWh considerations.

To summarise HyDUS is best suited to high-purity and distributed hydrogen storage applications in the near term due to its low-pressure operation, high volumetric density and its lowest LCOS in hydrogen-to-hydrogen mode. Medium-term opportunities arise in electricity-to-hydrogen applications for dispersed industrial users. Longer-term potential exists for electricity-to-electricity operation as efficiencies improve and NOAK costs mature. The economic modelling, system performance improvements and market analysis collectively support a phased, targeted commercialisation pathway with early deployment focused on high-purity hydrogen users and strategic industrial sites. Since, there were already improvements in bed and system performance through minor modifications as part of this program, it is expected that the key optimization steps that are required for this technology to become commercially viable can be achieved in the medium term, allowing for wider technology adoption.

Conclusions

Phase 2 of the HyDUS programme has delivered the first meaningful-scale global demonstration of reversible hydrogen storage in DU metal at the University of Bristol. The programme successfully designed, constructed, commissioned and operated a highly instrumented, single-bed demonstrator facility, providing a unique experimental and practical evidence base for this novel long-duration hydrogen storage technology. The original project scope also included the delivery of a multi-bed integrated electricity-to-hydrogen-to-electricity demonstrator at UKAEA; however, this element was not commissioned within the project timeframe.

The engineering design work demonstrated that reversible hydrogen storage in DU is technically viable and can be implemented within a robust safety envelope. The bespoke University of Bristol facility incorporated a highly sensorised containerised laboratory, ventilation and filtration systems, radiation monitoring and a double-skinned DU bed design. The demonstrator integrated pressure regulation, buffer vessels, cooling systems and extensive instrumentation, enabling precise control and detailed observation of hydriding, dehydriding and passivation processes under a range of operating conditions.

The safety case development across both sites represents a major achievement of the project. At the University of Bristol, multiple HAZOP studies, an independent DSEAR assessment, a fire safety risk assessment and the development of several detailed Standard Operating Procedures enabled safe remote operation of the demonstrator. Regulatory approval was secured via an Environment Agency permit allowing possession and use of up to 500 kg of DU as an open-source radioactive material. At UKAEA, a full Facility Safety Case Report was produced demonstrating that the principal hazards associated with hydrogen release and radiological contamination could be reduced to As Low As Reasonably Practicable (ALARP), subject to specified engineered and procedural controls. A key learning from Phase 2 is that novel nuclear-hydrogen technologies require phased safety case development through Pre-Construction, Pre-Commissioning and Pre-Operational Safety Reports rather than a single, combined safety submission.

Procurement, installation and commissioning activities delivered a fully operational facility at the University of Bristol, although these activities required significantly more time than originally anticipated. Long lead times associated with the bespoke manufacture and certification of DU beds, delays in delivery of the nitrogen cooling system, extensive safety documentation requirements and late-stage radiation monitoring enhancements (iCAM) all contributed to schedule pressure. As a result, active operation did not commence until July 2025. These experiences highlight the importance of realistic contingencies, early regulatory engagement and supply-chain maturity for first-of-a-kind nuclear-hydrogen infrastructure projects.

The UKAEA integrated demonstrator achieved substantial progress through system design, procurement, compound installation and safety case development. Major components including the mobile containerised laboratory, electrolysers, hydrogen compression system and fuel cell system were procured, and the HyDUS compound and control room were constructed. The learning from developing and executing the integrated design has addressed key technology challenges in creating a system connected to the power gird. However, challenges associated with underestimating the DU bed development timescales and the complexity of subsystem integration led to the reduction of the system from six DU beds to two, and ultimately to the decision not to proceed with full commissioning and operation within the Phase 2 programme. Consequently, no operational performance data were obtained from the UKAEA system, and all experimental findings reported in Phase 2 are derived from the University of Bristol demonstrator.

The University of Bristol operational campaign evaluated hydriding and dehydriding performance of two full-scale DU beds (~30 kg each) following their conditioning cycles, with Bed 2 incorporating band heaters to improve thermal uniformity. All hydriding cycles showed immediate reaction with no induction period, higher temperatures, increased H_2 pressure. Active N_2 cooling positively affected the kinetics enabling up to 80% conversion in under three hours over multiple scenarios, even including the flow restriction introduced by the flowmeter. This was already a better performance than the set target. Dehydriding required sustained temperatures of 390–440 °C, with Bed 2 achieving markedly faster rates, including ~80% conversion in ~6 hours, due to its more uniform heating, which was a considerable improvement compared to the early dehydriding sessions. Overall, the study showed that effective thermal management is critical for achieving rapid hydriding and efficient dehydriding in full-scale DU hydride beds, informing future HyDUS system design.

Material processing and end-of-life studies demonstrated that DU hydride can be reliably passivated into a stable oxide form under controlled conditions. Late-stage oxidation tests showed minimal residual reactivity and negligible oxygen uptake, providing strong evidence that end-of-life DU beds can be rendered into a safe and stable waste form. However, current disposal routes are prohibitively expensive, with incineration costs far exceeding the original acquisition cost of the DU material.

The assessment of the DU supply chain confirmed that while significant quantities of DU exist within the UK nuclear sector, future scale-up of HyDUS depends on the establishment of regulated DU processing routes, clarification of regulatory classifications and long-term supplier partnership agreements. Scaling HyDUS beyond the demonstrator stage will require the development of industrial-scale DU metal production and handling capability alongside engagement with the Environment Agency and the Office for Nuclear Regulation.

Based on the Phase 2 outcomes, the HyDUS depleted-uranium storage bed and the integrated system architecture have reached TRL 5 (as the bed is planned to go through new design iterations and the integrated system at UKAEA has not yet been demonstrated), while the underlying storage of hydrogen in depleted uranium is assessed at TRL 6.

Commercialisation analysis confirms that HyDUS is currently not cost-competitive with mature hydrogen storage solutions such as underground cavern storage or electrochemical batteries. However, HyDUS occupies a distinct niche for high-purity, distributed and safety-constrained hydrogen storage applications. A phased scale-up pathway has been defined, progressing from a refined prototype to a containerised commercial demonstrator, and ultimately to wider market deployment over the next decade. Progression through these stages is dependent on DU supply-chain readiness, regulatory clarity, bed optimization, thermal management improvements and early market adoption. It should be noted that the programme has not demonstrated commercial viability. Instead, it has identified the technical improvements, supply-chain developments and cost-down trajectories required for HyDUS to potentially become commercially viable in the medium-long term.

Overall, Phase 2 has achieved its primary objective of establishing the technical, safety, regulatory and operational foundations for depleted-uranium-based hydrogen storage. Although full system integration at UKAEA was not realised in full within the programme timeframe, the project has generated a comprehensive evidence base across engineering design, safety assurance, materials handling, testing, supply-chain assessment and commercial pathway development. This work substantially de-risks the HyDUS concept and provides a robust foundation for future scaled demonstration and commercial deployment.

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