Actuation Lab

HYS2316 D1.17 Final Report

For reporting to DESNZ

V3 – 24 April 2025

Actuation Lab

Executive Summary

Fugitive emissions through valve stems have been shown to present a significant environmental issue, as well as causing a barrier to implementation of hydrogen systems due to increased safety concerns. To address these issues, Actuation Lab has developed the Dragonfly valve, which removes the need for a valve stem and thereby removes the issue of stem-related fugitive emissions.

The goal of this demonstration project was to develop the Dragonfly valve to TRL7, which involves proving the technology works in an operational environment, and completing necessary testing and qualification. To achieve this goal, a bespoke flow loop was designed and built at the University of South Wales Hydrogen Centre to be used as a test site for the Dragonfly valves. The flow loop was designed to operate using 100% hydrogen at pressures up to 90 bar, and to enable control of flow rates and pressure. This allowed us to test the Dragonfly valves in a representative environment, with a focus on monitoring any degradation of the valves when exposed to hydrogen or after cyclic operation. Existing hydrogen infrastructure at the Hydrogen Centre was used where possible, most notably the compressor.

Five variants of the Dragonfly valve concept were designed and verified, ANSI Class 1500 ⅜”, 1” and 2” valves and ANSI Class 300 ½” and 2” valves. Prototypes were manufactured of four of these variants. These prototypes were assembled and tested in-house to demonstrate their operation and to implement testing learnings in new design iterations.

Subsequent iterations of prototype units were functionally tested and qualified to appropriate standards by third party testing bodies, including testing witnessed by a notified body, to ensure they were safe and suitable for use in hydrogen production and supply systems.

The approved valves were tested on the aforementioned flow loop at the University of South Wales over a 4-month period. Tests were conducted to monitor the quality of the valve seat seal, the behaviour of the valves’ magnetic couplings, and the torque requirements of the valves over time and cycles. The valves operated successfully throughout the testing period, with no degradation in performance observed.

Go-to-market and trial partners were identified and approached to build working relationships to accelerate commercialisation and roll-out of the Dragonfly valve following this project, thereby maximising the impact of the technology. Two trials were agreed with end users operating with gaseous hydrogen and ammonia (for hydrogen transport). Valves were produced that met their requirements and delivered to site for trials which will take place in Q2 2025.

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Abbreviations & Acronyms

API – American Petroleum Institute
ASME – American Society of Mechanical Engineers
ATEX – ATmosphères EXplosibles (French for explosive atmospheres)
ATI – Aerospace Technology Institute
BD – Business Development
BEIS – Department for Business, Energy and Industrial Strategy
BVAA – British Valve and Actuator Association
CCUS – Carbon Capture, Usage and Storage
CFD – Computational Fluid Dynamics
CMM – Coordinate Measuring Machine
CNC – Computer Numerical Control
CompEx – Competency working in Explosive atmospheres
CR – Change Request
Cv – Valve Flow Coefficient
dP – Differential Pressure
DSEAR – Dangerous Substances and Explosive Atmospheres Regulations
EPC – Engineering, Procurement, and Construction
FID – Financial Investment Decision
GBIP – Global Business Innovation Programme
GHG – Green House Gas
H2 – Hydrogen
HAZOP – HAZard and OPerability study
HPU – Hydraulic Power Unit
IHA – Ignition Hazard Assessment
IMechE – Institute of Mechanical Engineers
IP – Intellectual Property
ISO – International Organization for Standardization
MCP – Manifolded Cylinder Pallet
MENA – Middle East and North Africa
NCR – Non-Conformance Report
NPS – Nominal Pipe Size
OEM – Original Equipment Manufacturer
P&ID – Piping and Instrumentation Diagram
PED – Pressure Equipment Directive (2014/68/EU)
PEEK – PolyEther Ether Ketone
PESR – Pressure Equipment (Safety) Regulations
PTFE – PolyTetraFluoroEthylene
QMS – Quality Management System
RFQ – Request For Quote
SIL – Safety Integrity Level
SMR – Steam Methane Reforming
SOV – SOlenoid Valve
STFC – Science and Technology Facilities Council
TRL – Technology Readiness Level
UKRI – UK Research and Innovation
USW – University of South Wales
WP – Work Package
XRF – X-ray Fluorescence

1. Background

A. Company/consortium information

Actuation Lab are a company based in Bristol, UK, developing industrial flow-control hardware, with 17 full-time employees. Our main market sectors are future fuels (including hydrogen), oil and gas, and chemical flow control. Actuation Lab spun out of the University of Bristol in March 2021, with the goal of using origami-inspired engineering principles to develop innovative solutions to industrial problems and inefficiencies.

Our partner organisation on this project is the University of South Wales, specifically the team at the Hydrogen Research Centre in Baglan. This site is the location for this project's demonstrator.

B. Project background

Valves are an incredibly common component in any fluid system, with valves being integrated throughout systems to control and isolate the flow. Unfortunately, valves are one of the main culprits of gas leakage from process equipment and pipelines, with most of this escaping from the valve stem, which is a shaft or rod protruding from inside the valve body to the outside world, and which is connected to the moving element in the valve that is used to block the pipe. This stem is moved to open and close the valve and is either connected to a manual handle or to an actuator (pneumatic, electric, hydraulic, etc.) which operates the valve. As this stem provides a path from the inside to the outside of the valve, it represents a potential leak path for process gases, and as such is sealed using packing material. This packing wears over time as the stem rubs against it, and therefore the potential for gas leakage increases as the valve cycles. Estimates suggest that 60% of natural gas leakage from gas production equipment comes from valves, posing a significant environmental issue (Dmitry Busalaev, 2021). Regular maintenance and repair are recommended to reduce the scale of these stem leaks, in the form of valve stem packing replacement, refurbishment or adjustment. Due to extensive maintenance backlogs, this maintenance frequently doesn't happen according to the manufacturer's recommendation. If this same valve technology is applied to the growing hydrogen supply chain, the rate of leakage will be significantly higher.

An estimated 2.3% of natural gas produced is lost to the atmosphere in the gas supply chain (Alvarez, 2018). Hydrogen has been shown to leak 3 times faster by volume than natural gas in the same circumstances (NREL, 2013), so we could expect higher levels of leakage in a hydrogen supply chain, without innovation. Studies have shown hydrogen has a global warming impact of 11x CO_2 over 100 years, so these leaks will lead to ongoing climate damage (Warwick, 2022). These leaks also cause notable safety concerns because hydrogen is highly flammable/explosive, with much wider flammability limits than natural gas (4%-75% vs 5%-15% respectively). Hydrogen also rapidly accumulates in covered spaces, which has been identified as a blocker by end users to its implementation as this again increases the risk of accumulation and resulting explosions. As a result, we have identified that in order to enable a sustainable transition to using hydrogen as an energy vector at scale, innovations in leak-free hardware are required.

Recognising these issues, Actuation Lab decided to develop a range of zero-emission valves, based on our proprietary “Dragonfly valve” mechanism. This design completely removes the traditional mechanical valve stem, replacing it with a non-contact, maintenance-free, magnetic torque transmission through the wall of the valve, with the assembly sealed through a proven static seal. Due to the relatively low torque potential of magnetic couplings, this requires a novel valve design which requires very low torque to operate. Frictional and pressure forces in typical valves make magnetic couplings non-viable, as it would require such a large coupling as to be impractical.

At the start of the Stream 1 Phase 1 project, Actuation Lab had a TRL4 prototype for the Dragonfly valve, with lab-tested proof of concept units having been produced, but had not yet developed or tested the valve in an operational environment (Actuation Lab Ltd, 2022).

2. Project Overview

A. Aims and Objectives

A.1 Alignment of the project's aim with the Hydrogen Supply 2 Competition objectives

As per the requirements of the competition, this project aimed to physically demonstrate the same core innovation that was the focus of the feasibility study in Phase 1 of the Stream 1 competition, i.e. the stemless, leak-free Dragonfly valve.

This project represented a step change in the development of the Dragonfly valve. It directly addressed the competition objectives as follows:

- **Reducing Hydrogen Supply Costs:** The Dragonfly valve minimises maintenance, replacement, and stem seal repair expenses while eliminating hydrogen losses from stem seal leakage. During the project, we initiated trials with a global industrial gas supplier who was experiencing plant shutdowns due to hydrogen valve leakage. Our analysis indicates a return on investment in under two years, driven by reduced product loss and uninterrupted site operations, ultimately lowering the cost of hydrogen supply. We have seen similar challenges across many prospective customers, highlighting a widespread industry need for this solution to lower operational costs and ensure safety.
- **Increase Carbon Saving potential**: The Dragonfly valve has potential to eliminate fugitive emissions from valves in hydrogen systems; every kg of hydrogen leaks to atmosphere has a warming potential of 11kg/CO_2. By 2050, we estimate that 7.2 million tonnes of CO_2e could be leakage from hydrogen valves, without innovations, such as our technology. Utilising the Dragonfly valve will also facilitate hydrogen use in enclosed spaces where it was not previously possible. This will enable hydrogen use in sectors such as aerospace and shipping, which currently contribute 10% of the world's emissions by burning traditional fuels (Urban, Nurdiawati, Harahap, & Morozovska, 2024). Targeted deployment of leak-preventing valves such as ours across the combined hydrogen and natural gas market could result in savings of up to 33.8 Mt CO_2e/year by 2050.
- **Develop novel technologies to increase market competition**: This project aims to commercialise an entirely novel valve design, and as a result generating an additional £18m in company revenues in the five years post-completion. Cost and carbon savings for suppliers will increase the financial viability and environmental impact of commercial hydrogen deployment and competition will diversify applications for hydrogen supply solutions by making it possible to utilise hydrogen in safety-critical situations.
- **Knowledge building to inform policy development**: Our studies have collected significant data which quantifies fugitive emissions (leakage) at an unprecedented level and generated significant insights into hydrogen-related engineering challenges such as materials and manufacturing techniques. We have also modelled the effects of hydrogen leaks from valves in enclosed spaces, which showed that even small

leaks can quickly create large, flammable clouds, with hydrogen explosions producing significantly higher overpressures than methane. Our demonstration project will significantly add to knowledge contributing to the understanding of the technical, regulatory and environmental issues relating to hydrogen supply roll-out.

- **Develop knowledge and skills to meet Net Zero**: The project engages with research partner USW and stakeholders including Protium, BVAA, Score Group, as well as various manufacturers, representing significant supply chain cooperation and skill sharing. An extensive knowledge dissemination programme is planned to further share findings with operators, policy-makers and the academic community.

A.2 Project objectives

The demonstration project aimed to develop Actuation Lab's leak-free Dragonfly valve to TRL7, allowing for commercial deployment of a leak-free valve solution that will be required for the realisation of a climate positive hydrogen economy.

In concrete terms, the five main objectives of the project were as follows:

Table 1 – Project objectives

Objective	Progress	Status
To develop a low-torque, stemless valve design specifically for hydrogen applications	Low torque verified. Hydrogen compatible materials used.	Complete
To design 5 sizes of the above valve	Mature design completed for 5 valve variants. Scope change was approved to design 2" Class 300 valve in place of 4" Class 1500 valve following end-user communication.	Complete
To manufacture, assemble, test and certify valves for use on a flow loop	4 valve sizes assembled and tested, 3 designed for the flow loop at USW, another for a trial with STFC's ammonia plant.	Complete
To demonstrate three of these valve sizes (⅜, 1, 2 NPS) on a hydrogen flow loop at USW over an extended testing programme	Flow loop build complete.	In progress
To develop a route-to-market model for the Dragonfly Valve	Route-to-market plan drafted for <1" gaseous, >1" gaseous and >1" cryogenic hydrogen valves.	Complete

B. Schedule, Deliverables & Finance

The funding allocated to Actuation Lab for this project was £2,992,596.93.
The final cost of the project was £2,819,195.01, i.e. ~94% of the budget, leaving £173,401.92 unspent.

The project was originally set to span 23 months, between 01 March 2023 and 31 January 2025, and was broken down into 6 work packages (1 – Project Management and reporting, 2 – Business Development/Knowledge Dissemination, 3 – Engineering Design Verification, 4 – Manufacture and Assembly, 5 – Test Certification and Qualification, and 6 – Demonstration), for a total of 57 deliverables, and 8 quarterly payment milestones.

Facilitated by structured change requests, the project was extended to 25 months (ending 31 March 2025), including 1 additional technical Work Package (7 – Manufacturing Study), with a total of 87 deliverables spread over 14 payment milestones.

3. Design Considerations and Challenges

A. FEED/System design

A unique selling point of the Dragonfly Valve is the reduction in fugitive emissions over the life of the valve. This is achieved by removing the stem and replacing it with a magnetic coupling to drive the actuation of the valve. In most stemmed valves, the dynamic seals around the stem wear out over time and allow leak paths for fugitive emissions. The removal of these seals from the design ensures that the main source of leaks is removed. Other sources of fugitive emissions could be from any joints on the pressure boundary of the valve. The number of these joints was minimised in the design, by using just one for top access of the internal components. Here, a pressure shroud sits inside the pressure body. Tight tolerances and an industry standard O-ring are used to ensure there are no fugitive emissions. There is no movement between these parts once assembled, ensuring that they do not wear over time.

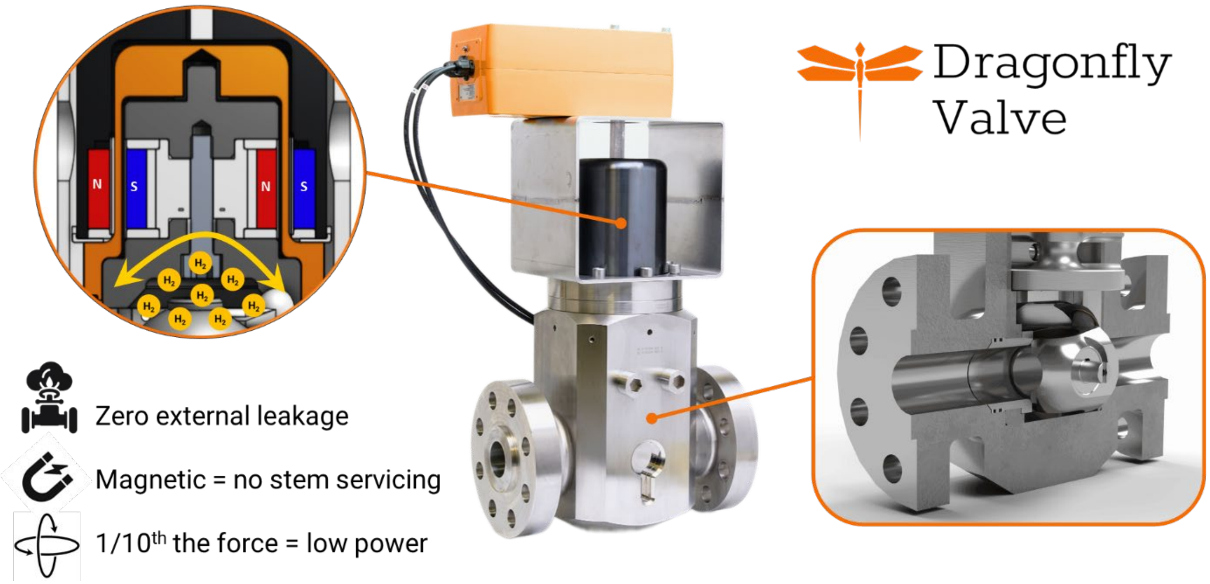

Figure 1: The Dragonfly Valve

Other stemless magnetic valves do exist, but their operating pressures are limited due to the limited torque that can be transferred by the magnetic couplings. This challenge is overcome with the Dragonfly valve's unique mechanism. We have estimated that to offer a viable product with a magnetic coupling, the torque to open the valve under max. operating pressure must be reduced to less than 20% of the operating torque of an equivalent stemmed valve. Initial modelling of the Dragonfly mechanism indicated that the operating torque would only be 10% of the torque needed with a conventional mechanism (as per D3.06 - Rigid Body Analysis of Torque).

The primary function of an isolation valve is to stop through-valve leakage. Therefore, ensuring that the design meets international leakage standards (ISO 5208, API 598) is an important requirement of the valve. An eccentric ball design, which uses a cam-like mechanism to move the sealing surface of the ball away from the sealing surface on the valve body as it rotates, helps to ensure positive engagement of the sealing surfaces as the ball closes. Careful selection of geometry and materials of the sealing surfaces is necessary to achieve a good seal. Industry standard geometry and materials were used for initial designs.

Other design considerations include ensuring that the valve can be used in existing facilities. International standards for pipe connections (i.e. ASME B16) were followed when designing to ensure that valves would fit into the pipework of potential customers. This restriction was an important design consideration in the development of valve geometries. Additionally, as these valves are primarily designed for hydrogen, a highly combustible gas, it is necessary to ensure that they do not add any explosion risks. Input from industry experts was sought to guide design decisions. Considerations included minimising risk of impacts that could lead to sparks and minimising surface contact speeds to avoid heating due to friction.

B. Challenges and verification activities

Several technical challenges were encountered to meet the design requirements with the assembled valves, including consistently reaching the defined low operating torque requirement and through-valve leakage requirement.

Initial operation of the assembled valves showed a peak in the torque required to operate the valve that wasn't discovered in the modelling. Small changes to the design resulted in a considerable reduction in the peak torque, to below targeted levels. Further work is being carried out to improve torque requirements further to facilitate the use of smaller magnets and actuators.

A key indicator of a valve's performance is the rate of through-seat leakage. Valves are tested to standards (i.e. ISO 5208, API 598) to determine the rate at which the fluid media passes the valve obturator when in the closed position, and the valve is given a defined rating corresponding to this leakage rate (i.e. in ISO 5208, Rate A is equivalent to zero visually detectable leakage during the test, Rate B is 0.01 times the Nominal Diameter of the valve in mm^3/s). A valve with a lower leakage rate will be viable in a wider range of applications, but will typically cost more than an equivalent valve with a higher leak rate due to the use of improved sealing materials and tighter manufacturing tolerances.

To maximise the potential impact of the Dragonfly valve we chose to target zero leakage (Rate A as per ISO 5208) when using a polymer valve seat. Through a combination of simulation (on the seat pressure loading), and empirical testing of valve sealing with tolerance variation and cyclic valve testing, we were able to achieve zero detectable leakage through the Dragonfly valve. This was verified by witnessed third-party certification testing.

A tolerance study was conducted to ensure the correct balance was achieved between cost/complexity to manufacture and performance. Critical dimensions were assessed through manufacture and test in full valve assemblies, which could then be reflected in the required tolerances given to manufacturing subcontractors.

C. HAZOP considerations

A hazard and operability study (HAZOP) was carried out for the demonstration flow loop, starting on 01 September 2023. The flow loop was broken down into three nodes for the purposes of the HAZOP:

- Node 1, flow regime continuous mode through the 2" Dragonfly valve (MV-ACT3) from the high-pressure storage tanks (TK-1604) to the low-pressure storage tanks (TK-1610).
- Node 2, the three flow paths together through each of the three Dragonfly valves on the loop (MV-ACT1/2/3) from the high-pressure storage tanks (TK-1604) to the low-pressure storage tanks (TK-1610).
- Node 3, recycle/refill of the high-pressure storage tanks (TK-1604) from the low-pressure storage tanks (TK-1610) through the existing PDC compressor on site.

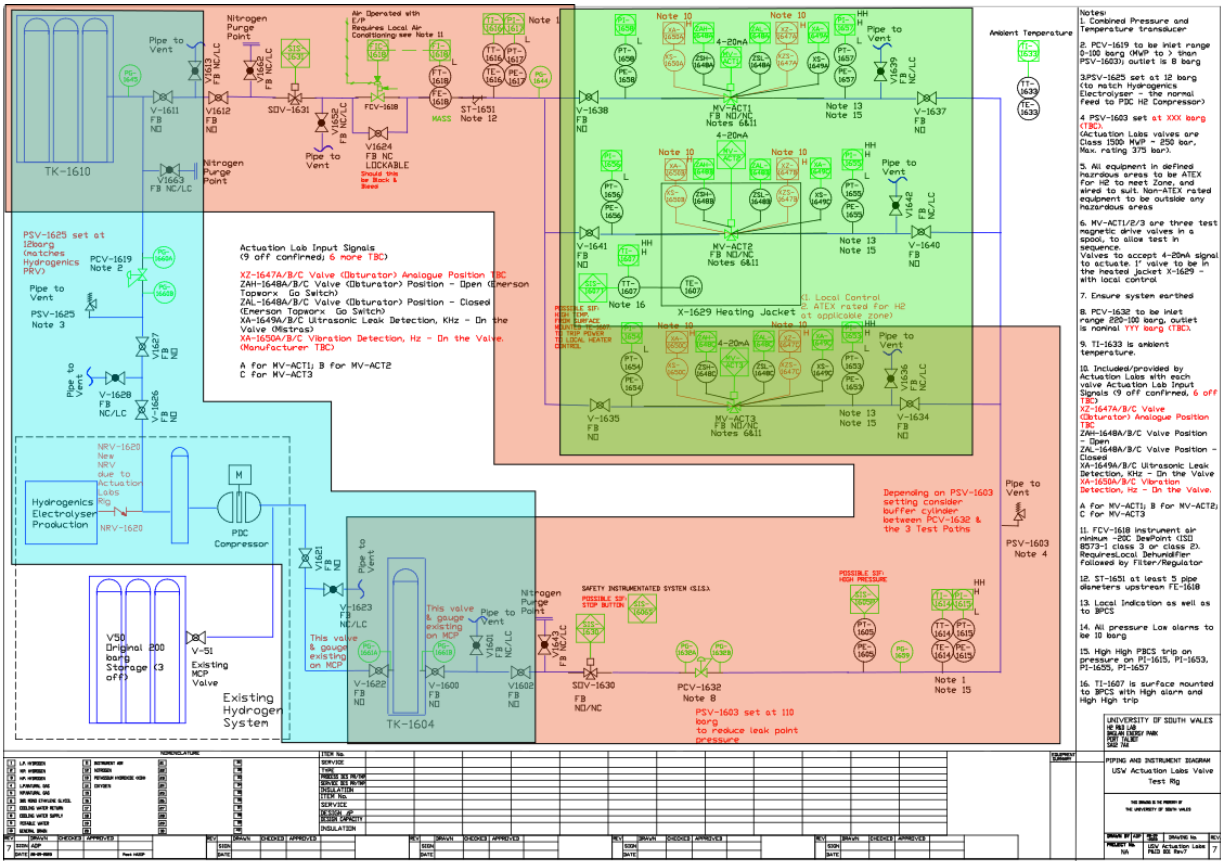

Figure 2: P&ID showing nodes used for HAZOP (#1 in red, #2 in green, #3 in blue)

The HAZOP utilised the existing USW guide word and parameter list for a standard assessment, following the guidance in standard BS EN 61882:2016. Notable recommended actions from the HAZOP included:

Table 2 – HAZOP actions

Node	Cause	Recommended Action
1	Air ingress into the system could create a flammable mixture within the pipework at isolated section either side of each Dragonfly valve.	Pressure indications added to section with low-pressure alarm set at 10 barg.
1	Control system crash leading to loss of control, increasing risk of overpressure or other causes of damage.	Configure software to send fail-safe positions to SOVs and control valves.
1	Oscillation of magnetic coupling on Dragonfly valve when holding against a differential pressure could lead to resonance in the pipework, increasing the risk of connection failure.	Install vibration sensors on each of the 3 sections of pipe containing a Dragonfly valve and at the 3-way split section with an alarm limit.
2	Large bending moments on pipework when moving between one test and the next, when opening/closing the valve and creating large pressure rate changes. Could damage/fail pipe connections.	Define minimum bend radius for pipework. Define maximum Cv of regulator PCV-1632 to match maximum measurable flow of FT-1618.
1/2	Manual valves in incorrect position during testing (particularly on test start) could lead to sudden pressure drop or venting.	Add labels to all valves and define starting position for each test in procedure prior to beginning tests.
2	Lack of local pressure indication up and downstream of the Dragonfly valves prevents operator from safely operating manual valves.	Additional of local pressure indication in relevant pipe sections.

Actions were assigned to individuals present during the HAZOP from both Actuation Lab and USW. These actions were completed prior to carrying out the DSEAR and SIL assessment. These were all carried out internally by USW according to their procedures. The completed risk assessment is available on request.

D. Selection of technical components

Most components of the Dragonfly valve are purpose-built for its application, with material selection driven by hydrogen and ammonia compatibility.

Stainless steel 316L was chosen for its resistance to hydrogen embrittlement. In space-constrained areas where its strength-to-volume ratio of 316L was insufficient, alternative high-strength hydrogen-compatible alloys were sourced.

Magnets were evaluated across suppliers to ensure hydrogen compatibility and adequate volumetric strength. Testing confirmed the selected magnet class remains viable in hydrogen service.

Bearings were selected for low friction to minimise operating torque, with material adjustments made for hydrogen and ammonia compatibility.

Industry-standard fittings and gaskets were used to ensure seamless integration with test facilities and customer systems.

The valve supports manual, electric, and pneumatic actuation. For development, electric actuators were preferred for their ease of integration into any facility with power access.

E. Procurement and fabrication activities

Early proof-of-concept components were manufactured through machining aggregators to enable fast design iteration, where quick assessment of design functionality was prioritised.

Later prototype components were procured from manufacturers with all required certifications and approvals to enable future commercialisation. Due to some issues with delays and non-conformance of components received from some suppliers, Actuation Lab established in-house machining capabilities to enable production of prototypes and design iterations while external manufacturers were assessed to prevent further issues. We sourced a 5-axis CNC mill and a CNC lathe to allow for: rework of out-of-specification components received from subcontracted manufacturers; machining of new design revisions of subcomponents; critical dimension studies. When scaling up production, out of specification components will be returned to suppliers for rework. This was often not feasible during this project as timelines required quick turnaround of component reworks to enable design iteration and testing.

F. Consents and permitting applications

F.1 ATEX

ATEX (ATmosphères EXplosibles) directives describe the minimum safety requirements for workplaces and equipment used in explosive atmospheres. The primary means of demonstrating that mechanical equipment is suitable for the atmospheres that our valves are most likely to be used in (ATEX Zone 2) is an ignition hazard assessment (IHA).

An IHA was completed on the 1 NPS Class 1500 valve before it was delivered to a European trial partner for installation in their test facility. This assessment was completed with assistance from DNV. Some usage limitations were identified through this assessment, then communicated and agreed with our trial partner through an installation and operation manual. These limitations include:

- Restrict allowable actuated opening time in the installation manual to 0.1 seconds to prevent excess contact speed which could in turn cause frictional sparks.
- Air must be purged from the system prior to operation (after install) to prevent build formation of a hazardous (ATEX Zone 0) environment inside the valve. This is standard practice for ATEX valves in hydrogen systems.
- Valve must be grounded externally when installed. This is again standard practice in explosive atmospheres.

The IHA undertaken with DNV can be used to help define requirements for future designs and as a basis for future IHAs.

F.2 Pressure Equipment Safety Regulations

While preparation for accreditation to PESR (and PED) is ongoing, additional test records for specific demonstration valves were sourced through witnessed third party testing to enable safe use of the valves in the demonstration flow loop. These tests were carried out in accordance with standards API 6D and ISO 5208 and witnessed by LRQA.

Development of our internal quality system has been carried out with PESR and PED in mind, such that full traceability of designs, parts, assemblies and testing is maintained.

F.3 Demonstration Flow Loop

This project involved testing on a flow loop at the USW Hydrogen Centre and did not involve construction or development subject to planning regulations. The site holds the relevant environmental permit to allow this activity (EPR/CB3690ZB). A HAZOP facilitation and DSEAR Assessment leading to Hazardous Area Classification were carried out as described in Section 3.C.

4. Secondary Project Benefits

A. Dissemination activities undertaken

Dissemination activities over the course of the project were varied and fit within six main categories, as detailed below.

Table 3 – Dissemination activities

Description of Activity	Stakeholders Engaged	Key Achievements/Outcomes	Date
Attended international hydrogen summit, Rotterdam and met with a range of stakeholders.	Various industry stakeholders including energy companies, manufacturers, and certification bodies.	Suggested routes to collaboration with Engineering, Procurement, and Construction (EPC) firms, engagement with key technology providers, and discussions on accurate leakage modelling for valves.	May 2023
Attended Valve world Americas met with key stakeholders.	Competitors, suppliers, and major industry players.	Invited to present at a major industry player’s facility, gained competitor insights for strategic analysis.	June 2023
Visits to Australian research institutes and businesses working in hydrogen.	Research institutes, universities, and government bodies.	Invitation to a grant opportunity for UK-Australia R&D collaboration, though time constraints prevented participation.	July 2023
Presented technology at SPE Offshore, Aberdeen	Energy and oil & gas companies.	Showcased developments at a key industry event.	September 2023
Attended European hydrogen technology expo, Bremen.	Regional hydrogen clusters and energy firms.	Established new industry connections.	September 2023
Exploring potential collaboration with industry supplier.	Leading industrial supplier in USA.	Identified as a potential licensing partner.	November 2023
Meeting with CEO of a green hydrogen	Hydrogen infrastructure firm.	Exploring potential trial opportunities.	December 2023

Description of Activity	Stakeholders Engaged	Key Achievements/Outcomes	Date
supply chain company.			
Attended Hyvolution, Paris, as part of a UK delegation.	Key players in the European hydrogen sector.	Connected with industry leaders, featured in a government trade department’s virtual catalogue.	January 2024
Trial agreement confirmed with ASPIRE (UKRI-STFC) green ammonia plant	Research and innovation organisation.	Trial confirmed for green ammonia production, opening broader industry opportunities.	January 2024
Visit to steel manufacturer’s production facility.	Steel industry firm.	Assessed hydrogen use in manufacturing and potential applications for valve technology.	January 2024
Visit to electrolyser manufacturer.	Electrolyser technology firm.	Discussed valve specifications and potential testing on their equipment.	March 2024
Visit to industrial components manufacturer.	Industrial technology firm.	Discussed roadmap for potential collaboration.	March 2024
Meeting with hydrogen infrastructure company.	Hydrogen energy firm.	Explored trial opportunities for hydrogen project.	March 2024
Meeting with hydrogen storage company.	Hydrogen storage solutions provider.	Discussed potential trial in storage applications.	March 2024
Visit to actuator technology firm.	Industrial actuator provider.	Discussed future collaboration opportunities.	April 2024
Attended MENA hydrogen summit, Dubai.	Key stakeholders in the MENA region.	Discussed technology with key players in the market.	April 2024
Attendance at Hydrogen South	Members of the regional hydrogen network.	Discussed potential opportunities in regional hydrogen projects.	April 2024

Description of Activity	**Stakeholders Engaged**	**Key Achievements/Outcomes**	**Date**
West quarterly meeting			
Attended international hydrogen summit, Rotterdam	Leading hydrogen technology firms.	Established connections with key industry players.	May 2024
Attended Industrial Valve Summit, Bergamo.	Potential suppliers, distributors, and partners.	Engaged with potential supply chain and distribution partners.	May 2024
Visit from potential partner to discuss collaboration.	Industrial supplier.	Shared market insights and discussed commercial roadmap.	May 2024
Selected for innovation programme.	Industry development agency.	Virtual introductory meeting held, inclusion in programme brochure.	June 2024
Co-exhibited at hydrogen technology expo in the USA.	Industry supplier.	Follow-up meetings with major industry players considering hydrogen adoption.	June 2024
Company profile added to European Enterprise Network	Enterprise network.	Received first collaboration request from an international hydrogen storage firm.	June 2024
Collaboration meeting with critical engineering firm.	Engineering solutions provider.	Positive feedback on technology, exploring partnership and trial opportunities.	June 2024
Online meetings with firms handling high-pressure hydrogen.	Various high-pressure hydrogen handling firms.	Identified industry pain points and expanded market research for high-pressure applications.	July – August 2024
Visit to Germany for hydrogen technology expo.	Various stakeholders including large industry players.	Pitched value proposition, engaged with major industry leaders, follow-ups planned.	Sept-Oct 2024
Co-exhibited at hydrogen technology expo in Hamburg.	Industry partner.	Identified high-pressure valve opportunity; business case in development.	October 2024

Description of Activity	Stakeholders Engaged	Key Achievements/Outcomes	Date
CEO visit to the USA.	Industry partner.	Continued collaboration discussions.	October 2024
Trial agreement with international fuel technology firm.	Hydrogen fuel technology provider.	NDA signed, site visit and valve delivery planned.	October 2024
Visit to hydrogen technology firm.	Hydrogen industry startup.	Discussed valve performance under supercritical conditions.	November 2024

B. Media coverage

The following articles were published, on the Actuation Lab online channels (website / LinkedIn) or on other online sources, within the duration of the project.

January 2025

- IMechE - Engineering a Hydrogen Economy Roundtable

December 2024

- Valve World tradeshow stand unveiled
- Publication by Actuation Lab CTO presenting the Dragonfly valve in the Valve World Magazine
- 16 Bristol Startups to watch, Sifted

November 2024

- Actuation Lab publicly advertise through social channels shipping of ammonia valves to ASPIRE project at the STFC
- New video and website launch ahead of Valve World Düsseldorf

October 2024

- Actuation Lab participation to GBIP Germany programme
- CTO and BD Manager attend the Hydrogen Technology Expo & Conference, Europe in Hamburg, co-presenting Dragonfly Technology with Rotork

July 2024

- Actuation Lab publicly advertise through social channels shipping of hydrogen valves to the USW flow loop

June 2024

- CTO presents the Dragonfly Valve at the Hydrogen Tech Expo in Houston, on a stand hosted by OsecoElfab

May 2024

- CEO & CTO attend World Hydrogen Summit in Rotterdam
- Team attend the International Valve Summit in Bergamo, Italy

April 2024

- BD Manager and CEO attending Connecting Green Hydrogen Conference, Dubai
- Mention in the BVAA 2023 annual training report

March 2024

- BD Manager was a speaker on the panel of Hydrogen event
- Mention in several publications:
  - Tech incubator supports creation of 300 jobs | Insider Media
  - February : SetSquared job creation | News and features | University of Bristol
  - Tech incubator supports creation of 300 new jobs (bristol247.com)

February 2024

- Manufacturing capacity thanks to arrival of CNC machines

January 2024

- Hyvolution, with Actuation Lab company and brand in Hyvolution Paris virtual catalogue
- Spotlight post by one of our investors, ZCC

December 2023

- CTO presented at Onshape conference

November 2023

- Move to our new facilities
- ASPIRE (UKRI-STFC) green ammonia plant visit, leading to trial agreement

October 2023

- Spotlight on Actuation Lab at Roxburgh Milkins anniversary party, and CEO speaking
- Spotlight on BVAA LinkedIn page

September 2023

- Mention in University of Bristol article about spin-outs
- Attendance at SPE Offshore in Scotland on NZTC stand displaying technology at tradeshow for the first time

August 2023

- CEO's participation to Global Business Innovation Australia programme
- Article published in Valve User magazine (BVAA publication - online and paper version) about this project

December 2022

- Investment announcement

C. IP generated

Although phase 2 on the HYSUPPLY competition has not resulted in new patentable IP (core valve patent GB2628006A Low operating torque non-contact valve came from phase 1 and was filed in March 2023), there has been significant knowhow generated that we will keep as trade secrets to protect and support commercialisation activities. This includes:

- Analytical models for predicting valve torque and test data on real valve operating torques, key for magnet sizing
- Valve design templates and procedures, including geometrical restriction for reliable performance
- Manufacturing cost models
- Key information of manufacturing constraints (tolerancing)
- Approved supplier database, including key suppliers and their capabilities with relation to:
    - Magnetic coupling
    - Plain bearings
    - Seals
    - Socket bearings

D. Number of new jobs created

Over the span of the project (March 2023 to March 2025), the following jobs were created at Actuation Lab in relation to the HYS2316 project:

- 5 R&D Engineers
- 1 Engineering Manager
- 1 Business Development Manager
- 1 Office Coordinator (providing admin, finance & procurement support to the project)
- 1 Machinist (on a temporary contract)

An existing employee was upskilled to the role of Project Manager.

The company also welcomed a total of 4 engineering interns over 2 summers.

More details can be found in section 7.B.

E. Improvements to skills/experience in sector

Through the development of our hydrogen valve, we have gained deep expertise in hydrogen-compatible materials, advanced sealing technologies and hydrogen compatible design. This knowledge has not only enhanced our own capabilities but has also in part been shared with the broader sector, through dissemination activities, helping to improve industry understanding.

A further advancement has been raising awareness of valve leakage risks with new equipment manufacturers. While leakage risks are often understood by those already operating hydrogen systems, our engagement with potential customers has revealed that many planning new hydrogen infrastructure are unaware of the extent to which traditional valves can be prone to leakage if poorly specified, or subject to high cycles, pressures or extreme temperatures. Through discussions with hydrogen supply companies and modelling results commissioned from Gexcon (specifically on valve leakage in containerised electrolysers) we have helped educate the industry on the risks and environmental impacts associated with conventional valve technology in hydrogen applications.

Our partners in the valve and pressure test sector have also gained new skills and awareness in the safe handling of magnets. As new technologies for low-cost, high-power magnet technologies begin to become commercialised, the usage of magnets is likely to increase in a range of new equipment, and greater knowledge of the hazards of magnets will be required by those who deal with them.

Other improvement to skills/experience include:

- Our simulation partners have also gained experience undertaking ASME code compliance assessment on thin wall pressure vessels in hydrogen safe materials.
- Our manufacturing partners have gained experience producing valve components with unusual geometries and working in new high-strength, hydrogen embrittlement resistant materials.
- Our magnet suppliers have gained experience in the preparation of, and acceptance testing for, placing rare-earth magnets in high-pressure hydrogen.

F. New partnerships formed from the project

As part of this project, we have formed partnerships in two forms: trial partners and go-to-market partners.

F.1 Trial partners

The table below summarises the trial partners who have signed trial agreements. These trials are a key stepping stone to valve commercialisation.

Table 4 – Trial partners

Partner	International Industrial Gas Company	STFC

Partner's problem(s) with current valves	Safety impact of fugitive emissions and through-valve leakage leading to plant shutdown	Safety impact of fugitive emissions through stem leakage
Our opportunities	Prove technology in customer conditions and, if successful, 200+ direct sales	Demonstration of technology in new media + build ammonia customer confidence
Medium	Hydrogen	Ammonia
Size	1 NPS	½ NPS
Pressure temperature class	1500	300
Target start date	January 2025	January 2025
Trial status	Valve delivered and installed in-line	Valves delivered and installed

F.2 Go-to-market partners

As outlined in the route-to-market section, market access partners will be key to rapid adoption of our technology in the hydrogen supply chain. We have focused on gaining partners from the valve, actuator and general industrial equipment sectors. Any partner considered for partnership had a global reach in the markets we are targeting, have shown strong interest in our technology and provide a clear route to market. By pursuing multiple partnerships, we derisk our route to adoption, but may need to focus on a single opportunity once the commercial opportunities materialise as these relationships mature.

G. Supply chain development

Developing a suitable and scalable supply chain has been a key objective of this project to enable fast roll-out of the technology once commercially ready. We have developed a supplier quality assurance and approval process for this technology to ensure that when commercialised, all Dragonfly valves are manufactured consistently and in line with the necessary regulations, particularly the Pressure Equipment Safety Regulations (and the Pressure Equipment Directive). This approval process includes:

- Checks for Quality certifications held,
- Checks for Environmental certifications held,
- Check for Health and Safety certifications held,
- Signing of mutual non-disclosure agreement,
- Assessment of supplier capabilities, financial position and capacity.

The above regulations necessitate the use of suppliers who have ISO 9001 compliant quality systems and have sufficient traceability of their production processes to enable full investigation of the root cause in the event of a failure in service. We have now developed our supply chain to only utilise manufacturers who meet these requirements for each of the critical manufacturing processes involved in the production of the Dragonfly valve (i.e. sand casting, investment casting, CNC machining).

5. Demonstration Study

The demonstration phase of this project consists of a bespoke flow loop which enables three Dragonfly valves of different bore sizes (⅜", 1" and 2") to be installed in parallel and actuated remotely. The loop contains 100% hydrogen, with a maximum operating pressure of 110 barg. The loop consists of the following sequence:

- Hydrogen is pressurised into the high-pressure side storage tank by the existing compressor on site.
- The high-pressure tank leads through a double block and bleed valve with a vent line, through a solenoid valve (for shutoff), through pressure control and safety valves, and then splits into three separate lines.
- Each of the lines has one Dragonfly valve installed with manual isolation valves installed on either side and a manually operated vent line immediately upstream.
- These three lines then rejoin and pass through a pneumatically actuated flow control valve with manual bypass.
- This leads through another solenoid valve, into another double block and bleed with vent, into the low-pressure storage tank.
- This then leads back through another double block and bleed with vent, then through the compressor system and back to the high-pressure tank.

The majority of the pipework and valves were procured from Swagelok, using their stainless steel ½" bore equipment. The flow control valve is a Baumann 24000SB Barstock Control Valve. Safety valves were sourced from Seetru. Solenoid valves were type 2/529 manufactured by GSR and procured from North Wales Controls. C&P Engineering Services were employed for mechanical and electrical fabrication/installation of the loop on site as the requirement for CompEx trained personnel prevented this being done by USW.

Figure 3: Flow loop at USW site with (left) low-pressure storage tanks, (centre) Dragonfly valves, (right) high-pressure storage tanks

A. Overview of test plan

Table 5 shows the scheduled testing plan. The objectives of this testing programme were to:

- Validate the primary function of the valve in sealing against high-pressure gaseous hydrogen,
- Monitor the opening and closing behaviour of the valve when exposed to 100% hydrogen over an extended period,
- Monitor the behaviour of the valve over a large number of cycles in an operational environment,
- Monitor any oscillatory/vibrational response of the valve during operation.

Table 5 – Test plan and schedule

Week(s)	Test	Desired Outcome
1 – 2, 6 to end of testing	Pressure drop / leak test when closed against range of pressure differentials (dP)	Ascertain the seat sealing potential of the valve against hydrogen as new
3 – 4	Open valve(s) against range of dP	Monitor the required torque to open on the valve
3 – 4	Close valve(s) against range of flows / upstream pressures	As above
5	Performance against a range of flows when fully open	Monitor vibrational response
6 to end of testing	Multiple cycle test	As in tests 1 and 2 over large cycle counts to monitor lifetime degradation
Throughout	Expose to hydrogen over time	Test lifetime performance of components when exposed to hydrogen

B. Results of demonstration study

Three valves were subjected to the above tests over a 4-month demonstration period. Outcomes from each of the tests are as follows:

B.1 Pressure Drop Testing

Two types of tests were carried out, Type 1 involving a slow buildup of pressure upstream of the closed valve by adjusting the upstream pressure regulator, and Type 2 where high pressure was introduced to the whole system, and then downstream of the valve was opened to storage to allow for a sudden pressure drop on the downstream side. The Dragonfly valve demonstrated better seat sealing with reduced pressure drop in Type 2 testing. This is explained by the differential pressure pushing the ball into the seat of the valve, and so having a higher differential pressure increases the sealing force on the valve seat. Differential pressures of 20 to 80 bar were applied across the valves.

B.2 Valve opening against differential pressure

The purpose of this test was to monitor the torque required to operate the valve, and to ensure that the magnets were able to transmit sufficient torque to continue to operate the valve throughout the testing and over large cycle counts. As of the end of March 2025, the ⅜", 1" and 2" valves had been cycled 1103, 528 and 506 times respectively, and the magnets continue to open the valves against differential pressure, with no indication of reduced input torque (which would be evident in longer opening times, seen as slower pressure and flow responses to valve position input).

B.3 Valve closing against flow

The purpose of this test is the same as that in the above test, to monitor the input torque of the magnetic couplings over time and cycles by closing the valves against flow, ensuring that the valve can continue to operate over a number of cycles without degradation of the magnetic couplings causing issues. After the number of cycles mentioned above, the valves were still able to close against flow without fault at flow rates of 10-30 kg/hr and a pressure of 90 bar.

B.4 Valve performance against flow

In order to determine the performance of the valves against different flows and conditions, vibration monitors were fitted to the test rig. These were fitted to piping up and downstream of the valve test section and on the individual valve test sections. Significant spikes in vibration amplitude were not in general associated with flow through or actuation of any of the valves, even at very high flow rates. The only times that significant spikes in the vibration amplitude were seen can be associated with manual valve operation (e.g. operation personal operating manual valves on the rig to change testing set up). There are no observed changes in vibration amplitudes during valve actuations of under any flow conditions, but some vibration spikes were observed. These are associated with brief, small flow events corresponding to changes in manual valve position releasing gas through previously depressurised sections, rather than any actuation or flow through of the Dragonfly valves.

B.5 Cyclic testing

The valves were actuated over multiple cycles in order to prove operation of the valve and monitor any changes in the performance over time and actuations. These are mostly carried out at 90 bar high side pressure and 10-20 bar low side pressure, giving a dP of 70-80 bar across the valve at each actuation. Some cycles were carried out at high side pressures of 30 and 60 bar to give an indication of performance in different conditions. As of 11/03/2025 the ⅜" valve has been actuated 1103 times, the 1" valve 528 times and the 2" valve 506 times, giving a sum of 2173 actuations across all 3 valves. So far, despite being under constant hydrogen duty since commissioning on hydrogen on the first of November 2024, no deterioration of valve performance has been observed.

1103 cycles as seen for the 3/8” valve would represent 1.5 years operation where our valve would be used to isolate a process once a day.

6. Project Metrics

A. TRL at start and end of project

The Dragonfly valve's unique technology is the mechanism that significantly reduces the torque required to actuate valves, allowing actuation using magnets and removing the need for a valve stem. Physical prototypes of this valve mechanism had been built and successfully operated in a laboratory environment at the start of the project, validating the technology to TRL4.

As of project closure, we have reached TRL6, such that the technology has been demonstrated in a relevant environment on a flow loop at the University of South Wales, with 100% hydrogen for an extended period.

We set a target at the project outset to advance the valve to TRL7, such that a prototype would be demonstrated in an operational environment. This will be achieved when our valves have successfully undergone industrial trials with potential future customers. Whilst we have delivered valves to commercial trial partners, trials have not yet commenced in either hydrogen or ammonia service, due to delays in our partners commissioning their equipment.

We have been informed that hydrogen trials will commence before the end of March 2025, and we have two 3-month trials agreed with our partner. With these trials being successful, we will reach TRL7 before the end of 2025, and progress to TRL9 in 2026.

B. Miscellaneous Dragonfly valve metrics

The following table summarises some metrics of the Dragonfly valve in line with the designs created (as opposed to the demonstration undertaken).

Table 6 – Dragonfly valve metrics

Metric	Data	Notes
% purity operating range	Up to 100%	However, valves for clean, high-purity applications such as fuel cells would require assembly in a clean room environment, which Actuation Lab do not possess.
Operating temperature	-40°C to 120°C	Covers a range below which metallic pressure containing parts may require additional materials certification tests from suppliers, up to a temperature where the magnets would no longer provide enough torque to reliably operate the valves.
Operating pressure	50 bar, 250 bar or 414 bar	Depending on the specific valve

Physical form of hydrogen	Gaseous	
Flow rates	At least 4 million Nm^3/h for largest valve	Assuming full rated pressure differential of hydrogen at 25°C
Flow rates	350,000 Nm^3/hr for largest valve 6500 Nm^3/hr for smallest valve	Assuming 20 bar pressure differential across the valve (more likely scenario than above)

C. Consumption of hydrogen in the demonstration study

The flow loop was charged with a commercially purchased manifolded cylinder pallet (MCP) with a water volume of 0.699 m^3. This MCP is filled to a pressure of 175 bar (at 15 deg C), which equates to a mass of 9.112 kg, which at atmospheric pressure would be a volume of 108.15 m^3. A single MCP was used for charging, with a second purchased for recharging the loop when required.

Hydrogen in the flow loop was recycled from the low-pressure side back to the high-pressure side through the compressor. The loop was originally charged with a single MCP of hydrogen purchased from BOC. An additional identical MCP was purchased to recharge the system after a fault developed in the compressor. When pulse-purging the system to charge with hydrogen, having previously charged with nitrogen, an estimated 2kg of hydrogen was lost.

D. GHGs mitigation for the commercial product

As very little hydrogen valve leakage data is currently available, we have used measured valve leakage rates from the natural gas supply chain and predictive hydrogen supply scenarios to estimate valve leakage from a future hydrogen supply system, and how our technology can have a positive impact.

An estimated 13 million tonnes of natural gas or 364 $MtCO_2e$, was lost through leaks in the US alone in 2015, representing approximately $2 billion in lost product (Alvarez, 2018). Field studies have shown that valve leakage makes up a large proportion of this, with 60% of gas storage and transmission sites having detectable valve leaks (Zimmerle, 2015). Due to its small molecular size, hydrogen has been shown to leak faster by volume than methane, and during our study, customers reported that hydrogen would leak through equipment that was previously shown to be leak-free with nitrogen. Studies have shown hydrogen has a global warming impact of 11x CO_2 over 100 years, so these leaks will lead to ongoing climate damage (Warwick, 2022).

D.1 Reviewing the scale of current valve gas leakage

D.1.a Bottom-up approach

From the equipment level measurements from 18 studies in US natural gas infrastructure (Brandt, 2016), the average emission rate from 3,197 leaking valves was 38 kg of methane per day or 388 tonnes of CO_2e a year. The largest emission from a single valve was equivalent to 46,501 tonnes of CO_2e a year. The most comprehensive equipment leakage survey of a complete gas supply network was that published by the US Environmental Protection Agency in 1996 (National Risk Management Research Laboratory, 1996). The leakage rates from thousands of components were measured, and each component given an “emission factor” for a section of the gas industry, such that for valves:

$$Valve\ emission\ factor = \frac{Sum\ of\ the\ emissions\ from\ all\ valves\ measured}{Total\ number\ of\ valves}$$

Table 7 gives a breakdown of valve data we have extracted from this study. When the US gas grid was surveyed, the total component leakage was measured to be 2.2 million tonnes of methane. There were over 19 million valves in the US supply chain, and each valve was losing on average 20.74 m^3 of methane a year. Valve leakage accounted for 287,307 tonnes of methane, or 8.05 million tonnes CO_2e. This was 5.11% of the total loss of methane to atmosphere from the gas supply chain, which includes operations such as venting.

Table 7 – Valve gas leakage data from USA gas industry

	Number of valves in use	Average valve leakage rate (m^3/year)	Total valve leakage (tonnes)	Tonnes CO_2e/year
USA gas production	15,682,360	18.3	206,148	5,772,146
USA gas processing	1,010,592	37.0	26,776	749,735
USA gas transmission	1,196,800	33.4	28,699	803,578
USA gas storage	1,427,270	25.1	25,683	719,127
Total US industrial gas supply (1992)	**19,317,022**	**20.74**	**287,307**	**8,044,586**

Source: (National Risk Management Research Laboratory, 1996)

This study concluded that 1.4% of all the gas product in the industry was lost, however, a recent methane loss study (Alvarez, 2018) estimated gas industry leakage levels to be 60% higher, at 2.3% or 13 million tonnes. This suggests that the values obtained by the EPA were an underestimate, or leakage has increased.

Since 1992, gas production in the US has doubled. We estimate that the number of valves in the US gas industry has scaled in line with the increase in the number of gas wells, by a factor of 1.78 (American Gas Association, 2021). Assuming US valve numbers scale to global numbers based on gas production volume, and valve emission factors of 20.74 m^3/year, a bottom-up estimate for valve emissions in the natural gas industry totals 71.5 million tonnes of CO_2e.

D.1.b Top-down approach

To approximate present-day valve losses in the natural gas industry with a top-down method (Alvarez, 2018) estimated that a total of 13 million tonnes of methane is lost to the atmosphere in the US every year. The US produces approximately 20% of the world’s natural gas, so scaling this estimate according to global volume equates to losses of 65 million tonnes of methane, or 1,820 $MtCO_2e$. Assuming 5.11% of total methane loss was through valves gives a current global estimated fugitive gas emissions from valves of 93 million tonnes CO_2e.

We have used data primarily from the USA to predict global leakage. There is little publicly available data on valve-specific leakage from UK assets, however we have worked with the National Physical Laboratory during a previous study (Actuation Lab Ltd, 2022) to verify leakage rates in the UK. Surveys carried out by the National Physical Laboratory (NPL) on UK sites handling natural gas have shown that 37.9% of total gas leakage that was detected was coming from valve stems (data set n=900).

D.2 Predicting leakage from hydrogen valves

Hydrogen leakage can exacerbate climate change by prolonging the atmospheric presence of methane and modifying ozone levels, thus producing indirect global warming effects. Although hydrogen leaks approximately three times faster than natural gas by volume due to its small molecular size, it leaks at only around 0.35 times the rate by mass in the turbulent regime (Frazer Nash, 2022). Combined with its lower global warming potential of 11 times that of CO_2 over a 100-year time frame (Warwick, 2022), the overall climate impact of hydrogen leakage in a future hydrogen system should be lower than that of leaking natural gas. However, current loss rates along the hydrogen supply chain are not well characterised and various studies currently estimate rates from 1-4% for compressed hydrogen and up to 10-20% for liquefied hydrogen (Arrigoni & Diaz, 2022). There is little component-level hydrogen leakage data published in available literature.

A top-down assessment of total hydrogen leakage from a future hydrogen grid was presented in a paper published by BEIS in April 2022 (Warwick, 2022). Their model estimates that a 2050 scenario in which approximately 23% of global energy consumption is supplied by hydrogen, replacing 40% of current fossil fuel energy, requires 859 Mt (Million Tonnes) of hydrogen to be produced every year. In this study, leakage rates were assumed to be between 1–10%, giving annual fugitive hydrogen emissions range from 9 to 96 Mt per year. Little justification was given for this leakage range, but it was commented that a 10% leakage rate would be likely to be both unsafe and expensive.

A more detailed analysis of likely leakage rates from a proposed future UK hydrogen supply system was laid out by Frazer Nash in 2022 (Frazer Nash, 2022) including all mechanisms where hydrogen may be released to the atmosphere including unintended leaks (e.g. from joints, pipework and storage) as well as deliberate purging or venting for a 2050 scenario. This study estimated a leakage rate of 1.5% of all hydrogen produced.

Using the global scenario where 859Mt of hydrogen is produced per year, a 1.5% leakage rate would result in a total of 12.9Mt of hydrogen being lost to atmosphere. With a 11x GWP, this would equate to 141.7Mt CO_{2e} every year. If 5.11% of the total hydrogen leakage originated from valves, as in the natural gas supply chain, valve leakage would total 7.2Mt CO_{2e} every year from valves in 2050.

D.3 Energy mix emissions in 2050

Methane will still be part of the wider energy mix in 2050. Imperial College London released a paper in 2021 which estimated that the natural gas industry would have to shrink by 35%

by 2050 to reach our Net Zero targets (Brogan, 2021). Assuming leakage would scale accordingly, methane valve leakage could total 60.45 Mt CO_2e in 2050 with no innovation.

Methane leakage from valves is still going to be a significant environmental burden as the hydrogen industry scales if action is not taken and will likely continue to exceed those of hydrogen even with a 35% reduction in extraction. The graph below illustrates that even with a near 10-fold increase in hydrogen production from today's levels, hydrogen leakage from valves would only represent about 10% of total valve emissions.

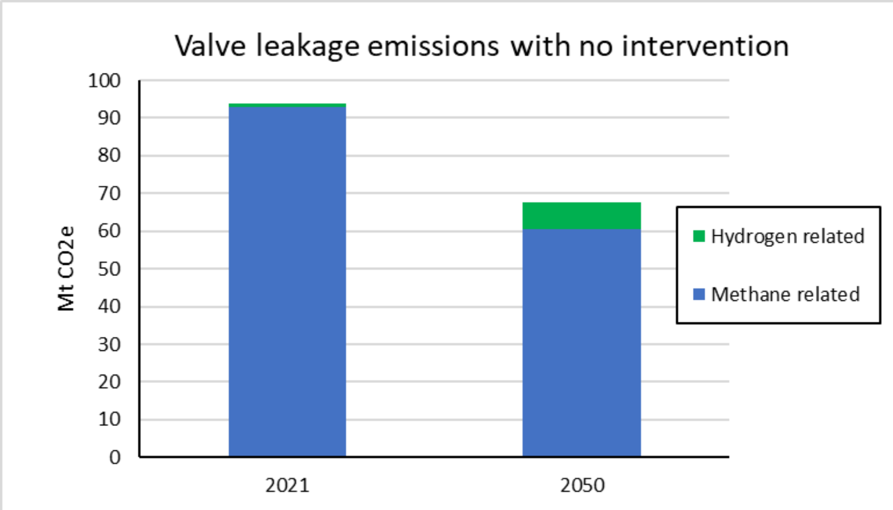

Figure 4: Predicted impact of valve leakage emissions if no intervention is undertaken using top-down estimates

Economically however, using a target price of $1.5/kg for green hydrogen in 2050 (World Energy Council, 2021), total hydrogen lost product through valves would total $989 million. Taking the 2018 estimate of the cost of natural gas leakage of $154 million/Mt from (Alvarez, 2018), lost natural gas in 2050 would represent $511 million in lost product. Even with significant natural gas price increases, it is likely that hydrogen lost from valves in 2050 will exceed the cost of natural gas lost, so there is a strong economic case for hydrogen valve innovation.

D.4 Projected Environmental Benefit

D.4.a Top down analysis

It has been shown that 5% of all valve leaks in US gas infrastructure are responsible for 79% of valve emissions in a study (Brandt, 2016). The leakage study carried out by the NPL of natural gas infrastructure showed that 5% of leaking valves were responsible for 47% of leakage.

The worst offenders in the NPL study were likely high-cycle valves or those operating under harsh conditions. By applying this data to the hydrogen supply chain and targeting these most leak-prone type valves with a leak-free alternative, we estimate that approximately half of hydrogen fugitive valve emissions, or 3.6 MtCO_2e per year could be prevented by 2050. Expanding this approach across both hydrogen and methane supply chains could eliminate up to 33.8 MtCO_2e per year in emissions.

In practice, replacing all valves with our current Dragonfly Valve design may not be feasible due to inherent performance constraints. While we are actively working to enhance our technical capabilities, there may be more cost-effective solutions in certain cases. For example, where high flow rates are not critical, solenoid valves could be used, or if actuation is infrequent, a superior stem packing might be sufficient. However, based on our review of industry leakage volumes, we strongly recommend that all potential solutions be urgently considered to prevent emissions from valves in the future gas energy mix, particularly focusing on high-cycle valves and those in harsh operating conditions.

D.4.b Bottom-up analysis

During the project we looked for opportunities to quantify the amount of hydrogen that is leaking out of current valves which are installed in hydrogen infrastructure. Hydrogen valve leakage was identified at the following locations through conversations with potential customers:

- Hydrogen Electrolyser site, UK
- Multiple Hydrogen Refuelling stations, mainland Europe
- Green ammonia production plant, UK
- Hydrogen refuelling equipment, UK
- Hydrogen trailer filling, mainland Europe
- Hydrogen trailer filling, USA
- Refinery, USA

Whilst the leakage was identified, and in some cases trials of our technology secured, none of the customers we have spoken to were able to quantify the leakage rates. In order to carry out an accurate assessment of the carbon savings per valve installed, further work is required, which should focus on collaborating with leak detection equipment manufacturers and service providers, and leak modelling companies. We commenced some modelling of this work during the project as follows.

D.5 Valve leakage modelling and safety considerations

Gexcon UK were contracted by Actuation Lab to conduct a gas dispersion study using the Computational Fluid Dynamics (CFD) code, FLACS-CFD. The key objective of the work was to examine a comparison of a methane vs hydrogen valve stem leak, in terms of flammable cloud size in enclosed spaces.

The dispersion modelling was conducted in a generic electrolyser geometry within a standard 20 ft x 8 ft shipping container, with pressures from 40 bar, up to 400 bar. The electrolyser container was placed in surrounding geometry representing tube storage and a refilling station. The container was modelled with mechanical ventilation in the roof, and passive air intakes near the ground. Equivalent methane and hydrogen leaks were modelled. Two hole sizes were considered, with one in the range normally considered in a DSEAR (Dangerous Substances and Explosive Atmospheres Regulations 2002) assessment (2.5 mm^2) and one representing a catastrophic failure of a valve stem (25 mm^2).

Leakage modelling showed that a 2.5mm^2 hole would lead to half a cubic metre of hydrogen escaping per second at 400 bar, and a complete failure of a valve stem would lead to the same rate at 40 bar. Even the smallest leak modelled of 2.5mm^2 hole from a 40-bar system would result in 158 kg of CO_2e being leaked from the valve per day, or equivalent to 58 tonnes of CO_2e/year if left unfixed.

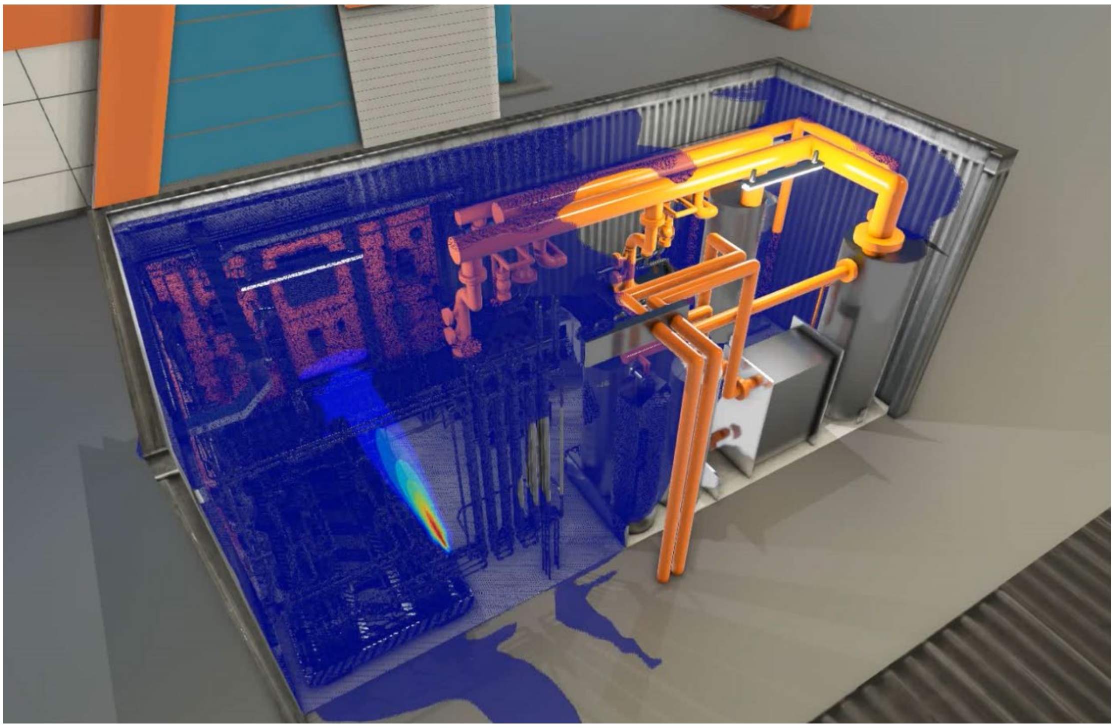

Figure 5: Visualisation of a hydrogen leak within the container

The dispersion modelling showed that a small leak at high pressure can quickly fill the container, demonstrating the hazard associated with high-pressure leaks in confined spaces, and the need for careful equipment selection. Mechanical ventilation at 1000 m^3/h (around 25 air changes per hour) was insufficient to limit the flammable cloud to a negligible size in all but the smallest leak scenario. In all these leak scenarios, gas sensors would likely be triggered that would shut down the process, leading to downtime, maintenance costs and lost revenue to the operator.

For the same release conditions, flammable hydrogen clouds were found to be much larger and to grow faster than methane, and this was due to the higher volumetric flow rate of hydrogen compared to methane. The difference in cloud size was also due to the wider flammable range of hydrogen. This meant that a smaller amount of fuel needed to be released to reach a flammable concentration, and that it took longer to produce fuel-rich concentrations that could not burn.

The findings from Gexcon UK's study illustrates the risk posed by valve stem and packing leaks in hydrogen systems, particularly in confined spaces. This study highlights the need for appropriate valve selection and maintenance to ensure these leaks do not occur. The Dragonfly Valve will be a unique solution in the marketplace that can eliminate stem and packing leaks, providing a safer and more reliable option for hydrogen systems, especially in confined environments.

Actuation Lab

D.6 Summary

With the various scenarios considered, hydrogen leakage from valves could have significant climate, safety and economic impacts. Hydrogen leaks approximately three times faster than natural gas by volume, and its extremely low ignition energy and broad flammability range make even small leaks a safety concern, particularly in enclosed spaces. Leaks can rapidly form large, flammable clouds, posing far greater immediate risk than equivalent methane leaks. From a climate perspective, hydrogen's GWP is estimated at around 11 times that of CO_2, lower than methane's GWP of 28, but still substantial. Estimates in our study outline that 7.2 million tonnes of CO_2e could be leaked from valves in a future hydrogen grid without innovation. This would also equate to nearly $1 billion in lost product. Methane emissions from valves in 2050 is likely to still exceed emissions from hydrogen valve leakage. In order to have the biggest positive climate and safety impact, our commercialisation plan must be to concurrently target the methane valve replacement market, both inside and outside of the hydrogen supply market. High cycle valves in harsh conditions should be targeted.

7. Project Management

Actuation Lab has been relying on project management software ClickUp for project and task scheduling, as well as personnel timesheets and risk management.

The company also uses tried and tested Excel trackers as well as some of the tracking features available in the Xero accounting software to track spend against deliverables.

These systems allowed the regular monitoring of labour used and spend incurred, so that conversations with the project's Monitoring Officer and the DESNZ team could happen in a timely manner in order to submit appropriate change requests as the project progress evolved, sometimes not quite according to the original plan.

They also allowed the submission of grant claims accurately reflecting the expenditure, both in effort and cost, required to achieve the objectives of each deliverable in the project plan.

A key outcome of the project was the successful transition of our company Administrator into the role of Project Manager. With support from DESNZ, this development was strengthened by mentorship and advice from a senior Project Management advisor, the CEO, and the COO, alongside formal training from the IMechE. The project provided valuable hands-on experience, allowing her to apply newly learnt strategies, enhance reporting, and develop the skills needed to optimise team performance. In addition to DESNZ's backing, the agile SME environment played a crucial role in enabling her rapid skills progression.

A. Structure and scheduling of project

The project was initially set to span 23 months and broken down into 6 work packages.

A seventh work package was added as part of CR11, and a 2-month extension was granted, so the actual project duration was 25 months.

The work packages were the following:

- WP1 – Project Management, Stakeholder Engagement and Reporting

This involved all project management activities, including grant-specific ones, like claim submissions and change requests, as well as reporting of project outcomes. The aim of this work package was to ensure that the project was managed successfully, and that the stated objectives were achieved. It also included the company's efforts to gain ISO 9001 certification through the building of a robust Quality Management System.

- WP2 – Business Development

This work package included tradeshow attendance, conference presentations, customer engagement to secure trials, as well as engagement with potential distributors and licensees of the technology. This work package also covered all activities leading to the development of a clear route-to-market model and commercialisation plan.

- WP3 – Engineering Design and Verification

This work package was largely concerned with expanding the range of valve sizes to be demonstrated on this project, and subsequently sold following certification. Outsourced verification work was conducted by CFD specialists PDL to ensure the valve met pressure body integrity requirements in line with ASME BPVC Sec VIII Dev 2. As part of this work package, we also undertook development of the manual override system, which we had learnt during the feasibility phase would be required for fire test certification. This work package also saw detailed design for the custom hydrogen-safe valve magnetic couplings undertaken. This work package included output drawings and required files to progress to the prototype manufacturing stage.

- WP4 – Manufacture and Assembly

This work package involved the sourcing of all off-the-shelf components, and contract manufacturing of all test articles required for certification, qualification and demonstration, as well as the assembly of all components into testable valve units.

- WP5 – Test, Certification and Qualification

Test and certification were critical parts of qualifying new safety-critical equipment like the Dragonfly valve. This first involved in-house testing of novel elements, including the bearings and seating arrangement. This was followed by third party testing to qualify the valves, both for sales and to deem them safe for demonstration deployment.

Some testing was carried out externally due to the requirements for witnessing by notified bodies for certification, and because of the large capital expenditure that would have been required to obtain the facilities needed to conduct these tests.

- WP6 – Demonstration

This demonstration follows the completion of the physical testing programme carried out in WP5, to ensure that the valve has been proven fit for purpose and thereby minimising the risk of early trial unit failure. Our partners at the University of South Wales (USW) designed a flow loop (based on the specifications of an electrolyser provided by Protium), specified and procured equipment, and ultimately built (with the help of subcontractor C&P Engineering) and housed the flow loop. The testing programme was able to start in early November 2024.

- WP7 – In-house Manufacturing

This work package was added in early 2024 because of issues with contract manufacturing of components, both from a lead time and a quality perspective. This revealed a need for in-house machining ability in order to rework components, and to develop learnings around critical component tolerances and surface finishes. CNC machines were leased by Actuation Lab from February 2024.

B. Recruitment activities

In order to have the necessary in-house resources to fulfil the project's objectives, Actuation Lab had to deploy an ambitious recruitment plan. Via such channels as LinkedIn or Indeed, as well as with the help of specialist recruitment agency Ernest Gordon, the team grew rapidly, with 4 R&D Engineers and a Business Development Manager joining the company in the first half of 2023. An Office Coordinator (hired to replace the person upskilled to the role of Project Manager), an Engineering Manager and a Graduate R&D Engineer also joined in late 2023 / early 2024. All these new recruits were full-time, permanent contracts.

With the arrival of CNC machines on the company premises in late February 2024, Actuation Lab hired a machinist to operate them. This was a full-time, temporary contract, ending on 31 January (the original project end date).

Actuation Lab's annual internship programme provides summer interns with mentoring from our junior engineers, supporting our mission to nurture UK engineering talent. In 2023 and 2024, two interns worked on this project, and one from 2023 has since joined our team as a key engineer.

C. Key risks, mitigations and issues

C.1 Risks

Most key risks evolved throughout the project, with a handful remaining active until the very end, and beyond.

Table 8 – Key project risks

Risk Title	Risk Event	Mitigation Actions	Resolution
Flow-loop build delayed	If the demonstration flow-loop build is delayed, then this will delay project completion, commercial roll-out and development to TRL7.	Design initiated at project kick off. Weekly update meetings ongoing with USW to track progress and ensure sufficient resources are assigned for timely completion. Issue of tendering process being mitigated.	Flow loop design now completed on time, and float time allowed at all stages of flow loop development. However, repeated delays to build & commissioning.
Manufacturing Delays	Long manufacturing and metrology lead times leading to reduced iteration count and redesign time.	A hybrid approach with some UK and some Chinese components may be required. Suggest moving manufacture of some components/ sizes/ configurations forward to reduce risk	Staff hired to investigate further, hybrid UK and overseas manufacturing strategy adopted. In-house machine capability assessed and costed. Hired former Operations Director at Severn Glocon, and

			Operations Director at Henrob as manufacturing strategy advisors. In-house CNC machines leased in early 2024 + in-house machinist hired.
Licensing	Unable to secure licensing agreements with manufacturers, preventing scaling for commercialisation beyond the demonstration phase.	Employ services of business development associates who are well established in the industry to accelerate agreements. Schedule dissemination meetings with potential licensors.	We hired a Business Development manager, consulted commercial advisors, and conducted market research. Rather than pursuing licensing due to low ROI and limited control, we will focus on trialling and directly supplying valves to customers over the next two years, revisiting licensing in 2026.
Magnet delays / quality issues	Magnetic coupling supplier subcontractors fail to deliver to time, cost and sufficient quality, delaying completion of milestones.	Original magnet supplier overdue on completion of their work. Alternative supplier employed.	New magnet supplier brought on. Ongoing collaboration is successful.
Lead partner unable to fund project expenditure	If claim payments are later than forecast then we may not have sufficient cash in the bank to fund the project.	Ensure timely completion of invoices to prevent delays to payment. Additional funding being secured from existing investors in Nov 2023. Monitor cashflow position throughout the project. Track proximity of large expenditures (e.g. subcontracting). Arrange for a loan facility if required.	Additional investment secured and loan facility in place if needed.
Delay to moving into facilities	Delay to moving into facilities that can support leak testing on schedule	Testing preparations happening before move confirmed. HPU ordered prior to	Premises accessed with delay. Testing started on new

		access to new unit to reduce lead time impact.	premises before the full business moved.
USW compressor out of commission	If the compressor remains out of commission by June 2024, then USW will not be in a position to generate and compress hydrogen for use in the flow loop. This will delay the start of the demonstration, or require a contingency plan.	Monitor situation at weekly meetings and plan for contingency action to bring stored hydrogen into flow loop.	Funding for remedial work on compressor obtained. Compressor refurbished.
Single source of supply for socket bearing	Only a single source of supply identified for socket bearing If these bearings are not suitable for the application, then the valve will not meet its requirements for torque or lifetime.	Only one supply of appropriate socket bearings has been found, engagement positive but slow. Bearings received from a single supplier are below required performance. Started internal programme to manufacture in-house.	Currently using bronze bearings in place of PTFE/steel.
Uncertainty regarding materials	Material from overseas manufacturers/suppliers may not be what is requested. Could lead to valve failures.	Include XRF scan to confirm material composition. Carrying out more manufacturing of components that require exotic materials in the UK with full traceability.	Engaging with UK-based third party who can carry out material composition inspection. Valve shell testing has shown that material capable of withstanding design pressure, verifying material properties.
Magnets not able to withstand hydrogen exposure	If the magnets are not properly sealed from hydrogen exposure in their encapsulation, then the valve will become inoperable before end of useful service life.	Conduct separate magnet hydrogen exposure testing. Investigate alternative magnet encapsulation methods.	Testing in progress (Framatome) on magnets with a variety of encapsulations.
Gaps in Existing Valve Hydrogen Standards	If existing standards relating to valve design are not suitable for future hydrogen applications and yet-to-	Engaging with trade associations to get early details of upcoming valve standards, including	API SPEC 6D: Specification for Valves was recently (September) updated

	be -released standards deviate significantly from these, then the valve will not be compliant with new standards and therefore not suitable for use in hydrogen applications, requiring potentially costly redesign.	having received a draft version of Annex M to API6D (informally API 6Z), which is the American Petroleum Institute valve standard. CTO now member of BVAA working group for hydrogen.	to add standards for Hydrogen.
Delay to development of new pressure class	If the processes and procedures we have developed to design a new pressure class of 2" valve do not work as intended then the new valve design work will take longer than originally scheduled, and will not be ready for commercialisation by the end of the project.	Capture detailed requirements early on in the project. Contacting potential suppliers early on in the design process to gain feedback with the design. Hold ongoing design reviews with suitable stakeholders to gain feedback early on in the project. Contact multiple suppliers for shorter lead times. Take photos of the pre-machined casting at the casting house before delivery. Contingency actions: Find casting suppliers with shorter lead times Releasing pressure body first as cast.	We are taking the time necessary to implement our QMS procedures, even if this means the valve will not be manufactured, assembled and tested until after the end of the project.
External Magnet and Internal Bearings Corrosion	Corrosion of outside magnet and internal bearings in outdoor conditions, leading to increased torque requirement to operate valves.	Changing bearing design and painting magnets	Spare magnets painted and swapped for rusty ones on flow loop.
Flow loop downtime	If any critical componentry on the flow loop becomes inoperable or damaged, then the flow loop will	Ensure regular visual inspection of flow loop is carried out to allow preventative maintenance where	Procurement of spares in progress.

	have to be shut down for repairs and maintenance, thereby reducing the window for testing time.	possible. Hold spares of equipment where viable.	

C.2 Issues

The following issues were encountered and resolved during the project.

Table 9 – Project issues

Issue Title	Issue Description	Response	Resolution actions	Resolution Date
Magnetic Coupling Subcontractor Delay	Delay in delivery of magnetic couplings and associated testing report from preferred manufacturers due to manufacturing issues and their subcontractor delays.	Contingency action undertaken, in employing alternative supplier to produce custom couplings.	The couplings from the second supplier have since been received and are within required specification. Not blocking further work.	August 2023
Delay in accessing new premises	New premises are required for running our internal testing plan, as an industrial site is required to run the hydraulic equipment safely.	To mitigate, nearby short-term rental units have been identified. Suitable locations have been found at the New Work Trust Co Ltd in Bristol. These can be accessed at very short notice, with a minimum 2-month rental.	Separate short-term rental units not required, as move to new premises imminent. Early, hand pump based testing to be carried out prior to HPU installation. Third party testing available as a contingency.	November 2023
Manufacturing Lead Times	Long lead times in manufacture and inspection of components have delayed assessment of initial design iteration and thereby delayed the second round of manufacturing.	Assessing in-house manufacturing potential for future iterations. Short lead time manufacturers identified.	Our first round of manufactured samples have been received and sent for independent metrology assessment. Quotes and agreements received for in-	December 2023

Issue Title	Issue Description	Response	Resolution actions	Resolution Date
			house manufacturing capability.	
Machined components out of spec	Valve components received from contract manufacturers and subsequently sent to CMM inspection have been shown to be out of specification.	Parts remanufactured for free by the same supplier, and CMM-inspected again. Expedite in-house capability assessment.	Quotes and agreements received for CNC machines and CMM. Change request to achieve this (CR11) has been approved. CMM machine arrived 28/11/2024 and CNC machines arrived 27/02/2024. Third party CMM company Avon Dynamics worked on reworked parts. Components successfully assembled, and preliminary testing indicates useful operability.	March 2024
USW delay and underspend	USW underspend so far due to some work being done in-house instead of being subcontracted, and delay to starting the procurement process, partly due to key personnel having to take unexpected extra leave in December.	USW will catch up in the coming months so that the flow loop can be commissioned by the end of July for the demonstration programme to commence in August. USW will produce an updated Gantt chart for the March progress meeting.	USW reprofiling data received, will require some change requests (movement of funds between spend categories + movement of funds from USW to Actuation Lab to avoid triggering USW tendering requirements).	May 2024

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Issue Title	Issue Description	Response	Resolution actions	Resolution Date
⅜ NPS Pressure Body NCR	The seat bore in the ⅜ NPS pressure bodies was not machined sufficiently deep to fit the seats by the subcontractor. This has reduced the total number of pressure bodies available for testing over the two sizes (⅜ and ½ NPS).	½” pressure bodies used in place due to cross-compatibility. ⅜” pressure bodies sent for rework.	Received reworked additional bodies to replenish stock. Additional bodies were manufactured by local machinist.	Nov 2024
Low Pressure Seat Sealing	Low pressure (less than 20 bar) seat sealing can be difficult to achieve with certain seat arrangements.	Work is underway to mitigate this by utilising new seat materials with greater stiffness.	Glass and carbon filled PTFE seats were trialled, having been machined internally from bar stock. Low-pressure seal achieved on Class 300, ½ NPS ammonia valve variant.	Nov 2024

D. Project management lessons learnt

Taking part in this project showed the need for the company to have a full-time Project Manager onboard. This role was responsible for developing detailed tools and methodologies to track project progress, resource allocation, and financial expenditure.

The 2-year project contained a significant element of development, and therefore a significant number of unknowns were inherent. As such, project modifications were inevitable as valves were built, tested and analysed, and new market data gathered.

We worked with DESNZ to reforecast our remaining work-plan and spend profile at three points during the course of the project, to ensure the project was completed successfully. These replanning efforts required input from multiple key team members and proved to be more time-intensive than initially anticipated.

A key lesson is the importance of ensuring conservative time estimates are used to plan activities have not been completed in the past. We have found that in a fast-paced development environment, engineers often underestimate the time required to achieve results, which leads to frequent plan adjustments. Further, during the course of the project we implemented more strategies to proactively identify potential changes which could occur. By doing this we could ensure sufficient time to implement contingency strategies and submit change requests, reducing the need for reactive planning.

When dealing with external suppliers, delays and quality issues are always a possibility, and mitigating these issues require flexibility in timescale margins or the existence of a plan B.

Risk management is an extensive activity that involves always trying to think about the worst, preventing negative events from happening through robust mitigation, and having a contingency plan when risks realise to prevent the project from being derailed.

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8. Commercialisation Plans

A. Route to market assessment

Through this project, we have defined three product lines for commercialisation within the hydrogen supply chain: <1 inch diameter gaseous hydrogen valves, >1 inch diameter gaseous hydrogen valves, and >1 cryogenic hydrogen valves. The cryogenic valves were not developed as part of this project, but their development has been a direct result of it, building on our gaseous valve technology.

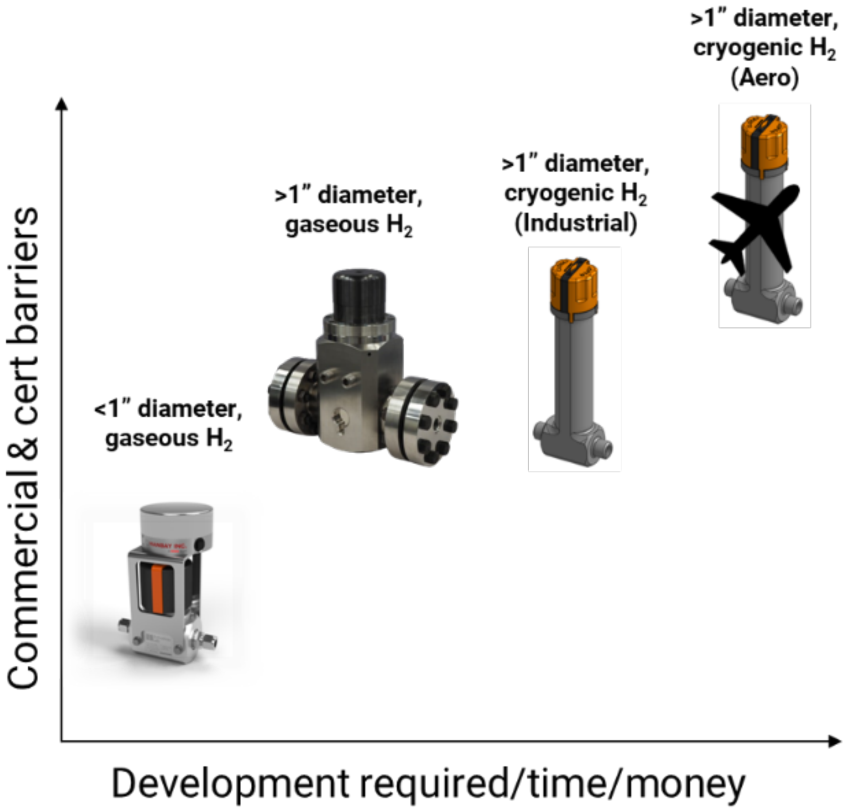

Figure 6: Route to market graph

Whilst some customers will use a combination of all our products in a single plant, each valve size range is likely to require a distinct route to market, serving different customers and requiring different timelines to achieve TRL9.

The first valves to be commercialised will be <1" gaseous hydrogen valves, targeting electrolysers and small, high-pressure piping systems, followed by larger gaseous valves and, subsequently, cryogenic valves.

Table 10 – Routes to market

Valve Category	Stage 1	Stage 2	Stage 3	Stage 4
<1” diameter, high-pressure gaseous H_2	Trials in electrolysers and refuelling.	Consider licensing the technology to a volume manufacturer.	Support license	
>1” diameter, gaseous H_2	Trials in established and larger projects.	Consider partnering with an established industrial equipment manufacturer to supply to customers.	Commercial Partnership/Joint Venture with established industrial manufacturer.	
>1” diameter, cryogenic H_2	Partner with aerospace manufacturers to accelerate development.	Spin off industrial variant for hydrogen storage and supply.	Consider partnering with an established industrial equipment manufacturer to supply to customers.	Commercial Partnership/Joint Venture with established industrial manufacturer.

A.1 Sub 1-inch diameter valve approach

The majority of green hydrogen production facilities utilise valves of 1 inch diameter or less. Target customer examples for valves in this area are the OEMs of electrolysers, who often buy valves directly from manufacturers, so we are approaching them directly.

We believe the valve market opportunity within electrolysers is currently between £75m and £100m. There are further opportunities for supplying valves into ammonia plants that these electrolysers supply, where ammonia is to be used as an energy vector. Ammonia is highly toxic, and leaks from valves can be fatal. We therefore sought opportunities within the green ammonia supply chain for our valves and secured a trial opportunity with the Science and Technology Facilities Council (STFC) in Didcot for their ASPIRE project. The green ammonia valve market is currently small and presents an opportunity of <£50m.

The opportunities with these customers are:

- Valves within our size range,

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- Match valve specs we can produce quickly,
- Enclosed spaces so customers will want to avoid leakage/explosive atmospheres,
- Looking to electrify systems, which is a good match for our technology.

The barriers are:

- Competitive market space with cheap alternatives,
- Lower pressures mean less leakage risk/severity, so less drive to buy based on leak-free feature
- Most systems have not been running long enough for users to report significant issues.

Further customers of small hydrogen valves include those in gas storage and vehicle refuelling. As a direct output of this project, we have been able to work with one of the world's largest gas suppliers, and provide trial valve units for their hydrogen refuelling stations to prevent leakage.

Refuelling stations are a good proving ground for our technology, as a number of potential OEMs building this new equipment have reported experiencing leaks. Leaks are more prevalent in these pieces of equipment than in electrolysers due to their higher operational pressures. The same is true with valves associated with storage, which may reach pressures of 700 bar.

The opportunities with these customers are:

- Valves within our size range,
- Match valve specs we can produce quickly,
- Enclosed spaces so customers will want to avoid leakage/explosive atmospheres,
- Looking to electrify systems, which is a good match for our technology,
- High likelihood of leakage from valves due to high pressures.

The barriers are:

- Competitive market space with some cheap alternatives
- We can currently supply valves that have a rated pressure up to 414 bar, so systems which are refuelling at 700 bar are currently out of scope.

Whilst the sub 1-inch diameter valve market for hydrogen and ammonia presents a modest market opportunity and the value of valves is low, working directly with end users who are developing new hydrogen equipment which utilises small valves provides a fast route to market by enabling quick trials and iterative development cycles. Unlike larger valves, which require Pressure Equipment Directive conformance and lengthy approval processes, small valves can be tested and refined more rapidly. Additionally, traditional hydrogen producers who utilise larger, high-value valves often have slower decision-making and deployment timelines. Partnering with agile end users allows us to demonstrate value and build credibility in the hydrogen market more efficiently, paving the way for broader adoption and scaling opportunities in larger markets.

During the project, we faced manufacturing supply chain challenges, which led us to establish an in-house manufacturing capability for valves in this class. This enabled us to rapidly prototype and significantly reduce production costs. Over the next two years, we will use a combination of in-house manufacturing and third-party contractors to produce trial-ready valves. As we scale operations, our goal is to fully outsource manufacturing and potentially license the valve design to high-volume manufacturers who can optimise pricing.

A.2 Above 1-inch diameter valve approach

Whilst green hydrogen production and hydrogen refuelling valve markets present an early entry point, more established hydrogen valve markets exist which present a longer-term business opportunity, and larger market.

The Steam Methane Reforming (SMR) segment produces over 90% of the 90 Mt of global hydrogen and could present a valve market opportunity of over £300m for valves over 1 inch in diameter. SMRs are primarily located within large industrial facilities such as refineries, petrochemical plants, and ammonia and methanol production sites.

Hydrogen valves in SMR, refinery and chemical production sites are larger and higher value items than in most green hydrogen projects. One US refinery we spoke with during this project was operating 16 6-inch diameter ball valves which had known stem issues when operating with a 95% hydrogen gas mix.

Geographically, there is a high concentration of potential customers around the US Gulf Coast, presenting a significant market opportunity. The major refinery and ammonia plants situated on the Gulf Coast that are handling significant quantities of hydrogen are listed in the table below, with the hydrogen demand values taken from a U.S. Department of Energy paper (Diaz, 2024):

Table 11 – Major Gulf Coast plants and their H2 demand

Plant type	Number of major plants	Total hydrogen demand, tonnes/day across these plants
Refinery	13	2,892
Ammonia Production	6	3423

These customers are more challenging to access than new projects, as they have established supplier networks and slower procurement processes. To overcome this, we have been collaborating with a US-based industrial equipment supplier. By leveraging their existing supply chain and customer relationships, we can lower the barriers to entry. Currently, we are working together to secure trials within facilities where leakage is being experienced, with our partner facilitating introductions and credibility. Our mutual goal is to eventually integrate our technology into their product offerings, either through a licensing or supply agreement, which would provide a clear and efficient route to market.

Beyond the US, there are further opportunities in Europe where SMRs are operated by industrial gas companies, energy giants, chemical producers, and petrochemical producers.

We will continue to build our established relationship with the industrial gas companies to gain trials for valves, going direct to the end users in the next 2 years. As for the US market, we are currently seeking a European supply partner.

Further, the adoption of CCUS at SMR sites to enable the production of “blue hydrogen” presents an opportunity for increased valve demand. Beyond the specialised valves required for carbon handling, the integration of CCUS technologies is expected to drive stricter scrutiny of emissions across these facilities. As a result, there is likely to be an increased focus on upgrading current equipment, including valves for lower emissions. In order to access these new build sites, we will build relationships with EPC companies, as they will be able to buy valves at volume for new projects. However, we will first have to have significant trial data through early adopters to reassure EPCs of our valve's performance.

The opportunities with these customers are:

- Valves are higher value than in small green hydrogen projects,
- Larger markets,
- Operating pressures within our valve range,
- Looking to electrify systems, which is a good match for our technology,
- High likelihood of leakage from valves due to regular use.

The barriers are:

- Customers slow to adopt and trial new technology,
- Stricter certification requirements, including the Pressure Equipment Directive,
- Established supply chain necessitate working with established valve manufacturers and EPCs to access customers.

A.3 Cryogenic hydrogen valves

Although the engineering development of cryogenic valves falls outside the scope of this DESNZ-funded project, we are leveraging key insights gained from this project to support the development of industrial cryogenic hydrogen valves. These valves are intended for use in hydrogen storage, transport, and aircraft applications. Currently at TRL3, this technology is in its early stages of development. As such, we have included only high-level details on the route to market for these valves.

Our approach focuses on three key areas to bring cryogenic hydrogen valves to market:

- **Market research and customer engagement**: We are actively conducting market research and engaging with customers to refine valve specifications for storage and transport applications.

- **Aerospace development**: In collaboration with the Aerospace Technology Institute, we are developing cryogenic valves tailored for aerospace hydrogen fuel systems.

- **Industrial applications**: Using insights from the aerospace sector, we aim to apply these learnings to industrial cryogenic valves and seek additional funding to advance this technology outside of aerospace applications.

To establish a presence in the cryogenic hydrogen valve market, we are pursuing a two-pronged strategy:

- **Collaborating with aerospace customers**: Joint development efforts with aerospace partners will help refine and validate cryogenic valve designs.

- **Expanding to industrial applications**: We plan to leverage high-criticality valve sales channels to trial and supply cryogenic valves for industrial gas applications. Key potential customers include Air Products, Air Liquide and Linde/BOC who represent significant opportunities in this sector.

A.4 Sales forecasts

By executing our go-to-market strategy, which will be supported by private investment in Q1 of 2025, Actuation Lab is targeting £18m in sales in the 5 years after project closure, as a result of funding from this project.

B. Access to revenue support mechanisms

As a result of this project, and the increase in TRL of our gas valve technology, the company has been able to present a credible route to developing a cryogenic hydrogen valve to the Aerospace Technology Institute (ATI). The company has now been awarded two grants totalling £1.8m from the ATI to develop and demonstrate this technology, with the support of commercial aerospace partners. Without this funding, cryogenic valve development would not have been possible.

Whilst Actuation Lab has developed high performance isolation valves for hydrogen, further funding will be required to expand the performance of the Dragonfly valve as a control valve. It is vital that we extend the capabilities of the Dragonfly valve to perform flow control, as control valves are often sources of leakage, so developing a leak-free alternative will further support the development of a green hydrogen supply chain. It would be advantageous that any funding that becomes available has a phased approach of both development and demonstration.

9. Conclusions and Next Steps

A. Objectives achieved

Out of the project's five main objectives, four are complete, while one is in progress and will be completed shortly after the end of the project.

Table 12 – Status of project objectives

Objective	Progress	Status
To develop a low-torque, stemless valve design specifically for hydrogen applications	Low torque verified. Hydrogen compatible materials used.	Complete
To design 5 sizes of the above valve	Mature design completed for 5 valve variants. Scope change was approved to design 2" Class 300 valve in place of 4" Class 1500 valve following end-user communication.	Complete
To manufacture, assemble, test and certify valves for use on a flow loop	4 valve sizes assembled and tested, 3 designed for the flow loop at USW, another for a trial with STFC's ammonia plant.	Complete
To demonstrate three of these valve sizes (⅜, 1, 2 NPS) on a hydrogen flow loop at USW over an extended testing programme	Flow loop build complete.	In progress
To develop a route-to-market model for the Dragonfly Valve	Route-to-market plan drafted for <1" gaseous, >1" gaseous and >1" cryogenic hydrogen valves.	Complete

With the core technical objectives achieved and the remaining testing programme nearing completion, our next steps will focus on further accelerated lifetime testing and competitor benchmarking, range expansion and commercialisation. Commercialisation includes finalising the route-to-market strategy, securing industry partnerships, and engaging with end users through trials to drive adoption. We will also leverage demonstration data to support certification efforts and strengthen our position with potential customers and suppliers.

B. Lessons learnt

For lessons learnt regarding project management, please refer to Section 7.D.

B.1 Commercial

Given the early-stage nature of the hydrogen energy market, predicting how the demand for specific valve sizes and pressure ratings will develop is challenging, and we carried out an extensive customer engagement campaign throughout the project, gathering insights from industry stakeholders to ensure we were developing the right valves.

During the project, in some hydrogen compression and storage applications, we have seen a shift towards OEMs favouring high-pressure needle valves, over ball-type valves. Conversely in other market areas, some OEMs have backtracked on plans to pursue 700 bar systems and reverted to much lower pressures, where our technology as it currently is proven could be applied.

Through market discussions, we identified that there was not yet a demand for 4” diameter, class 1500 valves in hydrogen projects that were currently in operation; a valve class we planned to build and prove when we set targets at the project outset. There was however demand for lower-pressure Class 600 and Class 300 valves in sizes up to 2” diameter in hydrogen storage applications. These insights directly influenced our development strategy, leading us to focus our valve range on sizes up to 2” in diameter, and design valves from a range of Class 300 up to class 1500.

While the primary aim of the project was to prove the functionality of our valves in hydrogen service, cost reduction became a secondary key focus. This allowed us to have informed discussions with customers about the return on investment they could expect now if they were to adopt our technology in trials, and in future once the cost optimisation had been implemented to the final product.

Cost-optimisation measures were assessed and implemented in both design and manufacturing, including casting valve bodies, design for manufacture and optimising toolpaths. Additionally, we standardised pressure body sizes for valves in the ⅜”–½” diameter range, altering only the machined bore depending on the arrangement, to allow for scaling of the manufacture of the range.

Although the number of hydrogen projects announced globally has increased significantly, the majority of new projects is in the feasibility stage. Financial Investment Decision (FID) rate for hydrogen and carbon capture projects are at 10%, compared to 59% for oil and gas projects (The World Bank, 2024). Low maturity levels of hydrogen projects in the UK and globally is a recognised barrier to immediate scaling up opportunities. Our current strategy focuses on larger project owners and EPCs who are involved in existing and new projects, and also exploring established markets that handle hydrogen for chemical production.

One of the biggest challenges to widespread adoption of our technology is our company's early stage, which limits our reputation and presence on approved supplier lists. We've observed that similar technologies in other markets have faced slow adoption for the same reasons. To overcome this, we will prioritise securing a well-established commercial partner to accelerate market acceptance and scale adoption.

B.2 Supply chain

After encountering significant delays to subcontracted work (notably for magnetic coupling supply), we implemented various mitigation strategies:

- allowing additional time for subcontracted manufacturing lead times to prevent delays to dependent work packages,
- outsourcing key work to at least two suppliers at the outset,
- strengthening our processes regarding sending out contracts to our suppliers, so that any delays are not without consequence on payment.

With regard to quality issues (i.e. receiving manufactured parts not to spec) we have discovered the need and implemented the means to:

- inspect parts received (via the use of reliable external partners, then, later, a leased CMM machine),
- have in-house machining capabilities, through the lease of CNC machines, to rework out-of-spec components.

B.3 General engineering

B.3.a Design error when designing for new valve size

When we first started designing a different valve size, a mistake was made when resizing the valve mechanism. This was due to a lack of clear processes, and lead to the implementation of clearer guidelines for future resizing, as well as an improved design checking process.

B.3.b Valve pressure shroud manufactured in wrong material

The pressure shroud that houses the internal magnet rotor, and is covered by the external rotor, is designed to be as thin as possible to maximise the torque transfer through its wall. The ⅜" valve variant was designed to use a high-strength alloy, yet was manufactured using the lower strength annealed variant, leading to failure at approximately ¾ of planned test pressure. Additional material specification details have been added to our release procedure and RFQs, including requirements for material certificates when necessary. Checking and approving of releases now includes design calculations and explicit description of material specification to mitigate against reoccurrence.

B.3.c Difficulty lifting valves dramatically slows testing timelines

Prior to any testing, valves must undergo hydrostatic shell testing to validate the integrity of the pressure envelope, and thereby ensure safety for any further testing. This requires all air to be removed from the valves, as any trapped air will be compressed and store a large amount of energy, which would be released suddenly and dangerously in the case of failure. Removing the air requires manipulation and rotation of the valve to ensure air is able to escape from any internal cavities. With a Class 1500 2" valve weighing over 100kg when filled with water, lifting and rotating the valve is difficult and potentially dangerous. Larger valves have therefore been redesigned with specific lifting points to simplify this process, as all valves will require shell testing prior to shipping to any customer in future.

B.3.d Low pressure seat sealing

It was found during testing that low-pressure seat sealing could be difficult to achieve with some valve variations. This is a result of deformation of the seat at high-pressure operation which then prevents the seat from engaging properly in the ball when the high-pressure forces are not acting to close the ball. These challenges are being mitigated through design strategies and material selection including utilising a range of seat materials including, but not limited to PEEK and filled-PTFE.

B.3.e No two (large) valves are the same

Through engagement with end users, prospective trial partners and industry-specific advisors, it is clear that larger valves (greater than 1" bore diameter) are generally tailored to specific customer needs (such as testing requirements, material specifications, pre-approved casting houses). This has driven the need for Actuation Lab to develop processes to create new valve designs according to customer specifications in a standardised method, that now forms a core part of our Quality Management System.

B.3.f Magnet rapid gas decompression possible

Through exploration of magnet encapsulation with weak materials (attempting to limit permeation), we experienced explosive magnet failures upon test chamber decompression. This taught us both of the importance on material strength in magnet encapsulation, and the requirement to ensure all magnets are hydraulically pressure tested before final weld inspection. This testing has been added to our magnet technical specification for suppliers.

B.4 Regulatory barriers/hurdles

As part of this project, we have researched and received training about the regulations that we need to comply with in order to take the Dragonfly valve to market. It soon became clear that extra time was going to have to be devoted to developing processes enabling compliance with pressure equipment regulations. As a first step, we are working towards ISO 9001 certification in Q1 2025, to be followed by PED (Pressure Equipment Directive) for the valve models that require it.

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