Manufacture and Testing of Electroformed Cryogenic Piping Systems

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Executive Summary

Overview of the demonstration

This project was led by Ultima Forma in collaboration with leading hydrogen testing specialist Element and supported by the Hydrogen Innovation Initiative (HII).

Liquid hydrogen has been identified in the Aerospace Technology Institutes FlyZero programme and technology roadmaps as the best candidate future fuel for the sector to significantly reduce its carbon emissions by 2050. Hydrogen's high gravimetric energy density and low environmental impact when produced from green energy makes it an ideal fuel for either combustion or use as a fuel source in hydrogen fuel cells. Hydrogen is a liquid below -253°C and so must be stored in vacuum insulated containment systems to prevent boil off.

Conventional vacuum insulated pipes are heavy and have design limitations due to manufacturing methods. This project designed, produced and tested electroformed twin walled vacuum pipes, with a flexible joint on the inner pipe to withstand thermal contraction. The pipes use advanced electroforming manufacturing technology to produce a thin metallic gas-barrier with integrated vacuum. This results in improved fuel-to-system mass efficiency with weight-savings at the fuel-system level.

Key findings and outcomes

Two pipe systems have been successfully tested, thus maturing Ultima Forma's cryogenic pipe system from TRL4 to TRL5. Electroforming has been proven as a viable and scalable manufacturing process, able to make efficient and lightweight cryogenic piping systems. Vacuum performance of the test articles was one of the best Element had tested at their facilities, with the cryopumping pulling a vacuum of at 4.5×10^{-7} mBara. Compared to other pipe systems, the measured heat flux was reduced by a factor of 3, and the mass per length at least 2× lower. Element also noted that during testing the thin-walled copper pipes chilled down to cryogenic temperatures more quickly, which reduced boil off losses. These efficiency improvements demonstrate that Ultima Forma's technology can play a role within hydrogen propulsion systems.

A follow-up project is currently being planned, that would raise the TRL from 5 to 6, by fitting a pipe within ground test equipment for testing over an extended duration.

Relevance to the hydrogen industry

Being able to produce lightweight liquid hydrogen pipes brings a number of advantages. Weight savings extend aircraft operating range or allow greater payload at the aircraft operation level, enhancing the business case for market adoption of zero-carbon technology in the sub-regional and regional sectors, and accelerating development of narrow body aircraft. The technology contributes to the UK supply chain for zero-emission aircraft, supporting early adopters such as Zero-Avia as well as the Airbus ZEROe programme. The team is engaging with these stakeholders together with the CAA to develop the regulatory framework around these new technologies.

Complementary applications for this technology include vacuum protection of other parts of the on-aircraft liquid hydrogen system, as well as for ground-based refuelling infrastructure and fuel transportation.

1. Introduction

1.1. Purpose

This report showcases new technology for lightweight liquid cryogenic pipes and containment systems. It provides essential test data that can be used to assist with the modelling and design of new systems. In addition, the key learnings will enable industry to access technologies for the development of new lightweight and low-loss propulsion systems for future liquid hydrogen powered aircraft.

1.2. Background to the technology

Electroforming is an additive, net-shape forming process that produces continuous metallic forms that act as hermetic hydrogen barriers, avoiding the need for welding or joining processes. Strong structures can be formed into complex shapes with integral fixing points, feed-throughs and sensors. The interior surfaces can be polished and silver plated providing low emissivity for further reduced radiative heat transfer.

Ultima Forma's hermetically sealed systems provide a range of advantages. They minimise welding related failure modes, enable conformable shapes for optimal thermodynamics, reduce heat losses, and maintain vacuums without the need for continuous pumping. This patented technology combines material and manufacturing processes using copper to contain the liquid hydrogen, which retains ductility and low permeability under cryogenic conditions.

Existing vacuum jacket systems for cryogenic liquids are mostly composed of fixed pipe networks joined by fittings and welds and constructed from stainless steels. Such systems are bulky and are susceptible to leakage and hydrogen embrittlement for liquid hydrogen. Fixing points and flanges have to be welded on. Alternative aluminium structures have to be fabricated by welding preformed parts together with weld lines leak-tested to ensure vacuum tightness. Thermoplastic solutions are new but difficult to produce to required vacuum performance specifications. All of these issues make competing technology solutions heavy, inefficient and expensive with restrictions in design freedom. Systems have been developed for pressurised gaseous hydrogen, e.g. for fuelling hydrogen powered cars in Japan, including leak proof nozzles and valves, but these are operating near room temperature. Currently, there are no light-weight, vacuum jacket flexible systems that could be adopted for automated aircraft fuelling with liquid hydrogen (LH_2).

By contrast, electroformed solutions maximise system gravimetric efficiency for liquid hydrogen and cryogenic fuel storage and transport, with mass per lengths of less than 1kg/m achievable. Electroforming is a low power, scalable and automatable process.

1.3. Demonstration

Major initiatives are already underway to accelerate development of aircraft fuel lines and ground systems necessary to implement liquid hydrogen technology, e.g. the Airbus ZEROe and ZeroAvia programmes. While large-scale hydrogen generation and storage systems are under development, the ability to build lightweight systems and fuel aircraft at airports within existing turn-round times remains a potential barrier to introduction of LH_2 powered aircraft. On-aircraft systems also need to be lightweight with minimum thermal losses.

Specific challenges our project sought to address were as follows;

1. Hydrogen pipe systems with flexibility to cope with thermal gradient.
2. A system that could be operated by autonomous robotics.
3. A system that is lightweight.
4. A leak-tight system.
5. High flowrate systems for fuelling and defueling do not exist which has an impact on aircraft turnaround times, and operator costs.
6. Work to relevant ISO standards to maintain vacuum.

Systems are required that could fuel and defuel aircraft using liquid hydrogen. Whether on or off aircraft, it is important to minimise hydrogen boil off losses across a variety of geographies where ambient temperatures could fluctuate from -40˚C to +50˚C. In addition to ground refuelling, light-weight, vacuum insulated, flexible pipes are needed onboard the aircraft.

Existing market solutions for cryogenic piping systems tend to have a mass per length of 3-7kg/metre with a 25mm inner pipe bore diameter. Our proposed solution has a mass per length of <1kg/metre. For example, if an aircraft required 200 metres of vacuum jacketed pipes, current state of the art solutions have a parasitic mass of 600kg – 1400kg. Whereas the proposed electroformed design would only add 200kg, providing for increased payload or fuel capacity.

Another major challenge is minimising losses in ground support equipment (GSE) and the transportation of cryogenic fuels from the point of manufacture to the point of use. Research has shown that transfer of LH_2 from a fuel tanker to a static tank can induce boil off losses of up to 15%[(1)]. Proposed solutions include boil off capture hardware, adding additional capital cost, but combined with Ultima Forma technology, boil off losses can be reduced, and the costs of additional hardware can be offset.

In cryogenic liquid transfer, the initial cool down of the pipework results in significant loss of the liquid. At NASA's Kennedy Space Centre when loading propellant onto the Space Shuttle, more than 45% of the liquid hydrogen delivered was lost in transfer and system cool down[(2)]. Minimising thermal mass of the pipelines can therefore have a major impact on system efficiency.

2. Project Description

2.1. Design Background

The aims for the HII project demonstration pipe system were as follows;

- Demonstrate how electroforming can be used as a manufacturing process for cryogenic piping systems, showcasing its benefits over traditional processes.
- Create a prototype cryogenic liquid pipe system, matching or exceeding thermal performance of existing market solutions.
- Gather test data on heat flux and leak tightness performance.
- Improve on the mass per unit length and volumetric/gravimetric efficiency of existing market solutions.
- Investigate and demonstrate how the manufacturing process can be scaled up to an industrial level.

Constraints;

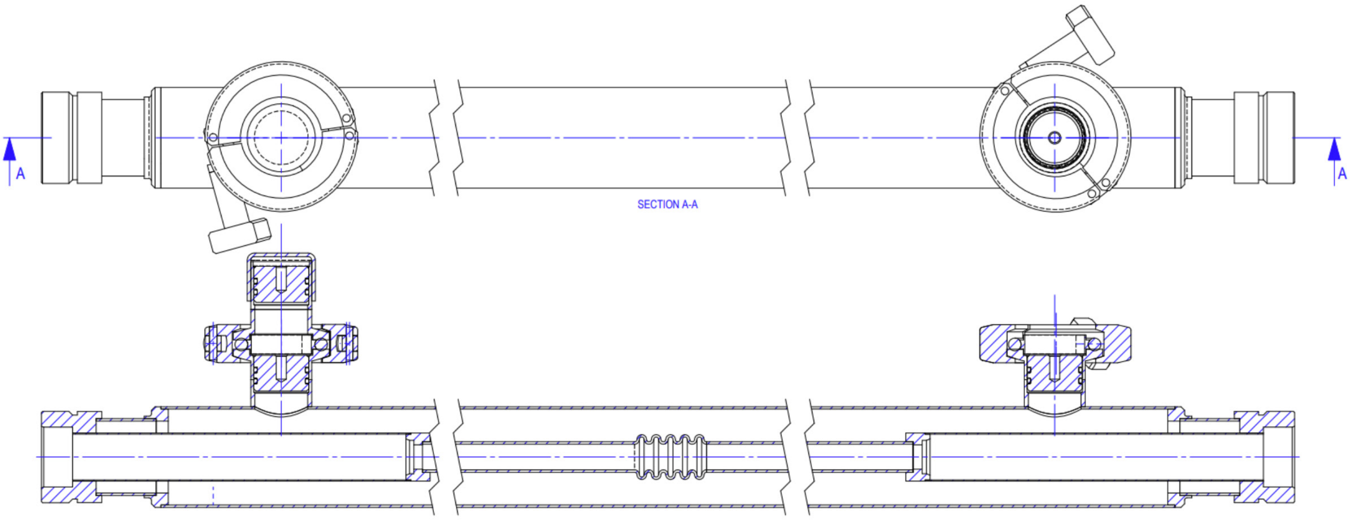
- For the initial protoype, a 1 metre length was chosen as a manageable size for data gathering and testing. This is easily scaled for future manufacturing of larger units.
- Test rig connections – standard cryogenic bayonet fittings (CryoComp CB704-5F6[3]) and KF16 vacuum flanges were required to allow integration into existing test facilities at Element.
- Two vacuum ports and two bayonet fittings were required for each test unit.
- Cryogenic bayonets must be installed in a vertical orientation.

Electroforming as a manufacturing technology unlocks many key features previously impossible with conventional manufacturing techniques. In a cryogenic pipe run, wherever there are joins there exists a potential for thermal losses. Electroforming allows complex pipes, such as manifolds and pipes with varying cross sections, to be manufactured as a single piece of metal. This reduces the number of joins and fittings, and therefore increases the efficiency, of a cryogenic pipe run. As demonstrated in this project, machined fittings and fixtures can be grown into the electroformed pipe, removing the need for high temperature brazing or welding that could create vacuum leakage points.

Several designs were considered in the early stages of the project. These included having a pipe system with only one coaxial fill port, allowing a straight pipe to be made and placed in a vertical orientation during testing. However this was discounted due to the changes that would need to be made at the existing test facility.

2.1. Design Background (Contd.)

Figure 1. **Early design concept**



2.2. Final Design

The final design of the test article consists of a straight section of pipe, with the two ends turning by 90 degrees to a vertical orientation, with the pipe forming an elongated 'U' shape. This is to fulfil the requirement of the bayonet fittings being oriented vertically, with the longer horizontal section simulating the likely in-service orientation. The pipe consists of two concentric copper tubes with a vacuum in between, and the necessary fittings electroformed onto the outer pipe. Further design enhancements to future prototypes have been considered, they will include a polished and silver plated inner surface to reduce radiative heat transfer. A triple-walled pipe design with active cooling is also envisaged, which would further improve thermal efficiency.

Figure 2. **Render of final assembly**

2.2. Final Design (Contd.)

Copper was chosen as the primary material for the pipe system. It is electroformable with the added benefit of it being easily brazed and soldered to.

In order to quantify the heat flux, two units of different lengths were designed and manufactured. The longer being 1000mm and shorter being 500mm, both otherwise identical.

The smaller test unit had a mass of 1.38kg and a working volume of 0.26L. The larger unit had a mass of 2.32kg and a working volume of 0.42L. The mass per length (excluding fittings) is approximately 1.6kg/m with a 20mm inner pipe diameter.

The inner pipe contains the LH_2. It has an inner diameter of 20mm and is electroformed together, meaning the inner pipe is one continuous copper surface, with no welds or joins. During testing and in service, the inner pipes see a drop in temperature of approximately 270°C over a sub-5 second time duration. Copper contracts at a rate of $17\times10^{-6} m\cdot m^{-1}\cdot°C^{-1}$, meaning that a contraction of 4.6mm per metre length occurs. If the pipes were fixed and rigid, this would lead to strain in the material, in turn causing strain in the joints and fittings of the test unit. To accommodate the thermal shrinkage and induced strain, a thin-walled copper electroformed flexible bellows was incorporated into the straight section of the inner pipe, weighing just 23 grams.

Figure 3. **Inner pipe assembly showing electroformed bellows**

The outer pipe consisted of two halves which come together to form a 'clamshell' type design, creating an internal volume that becomes the vacuum jacket, encapsulating and insulating the inner pipe. The diameter of the outer pipe changed along its length to accommodate the KF16 vacuum fittings cryogenic bayonets, which were 'grown in' during electroforming, creating a hermetically sealed, continuous copper piece without joins or seams.

2.3. Project partners

Ultima Forma is a materials science, design and manufacturing specialist SME with deep expertise in electrodeposition processes. Based near Basingstoke they have a state-of-the-art electroforming facility where the test units were manufactured.

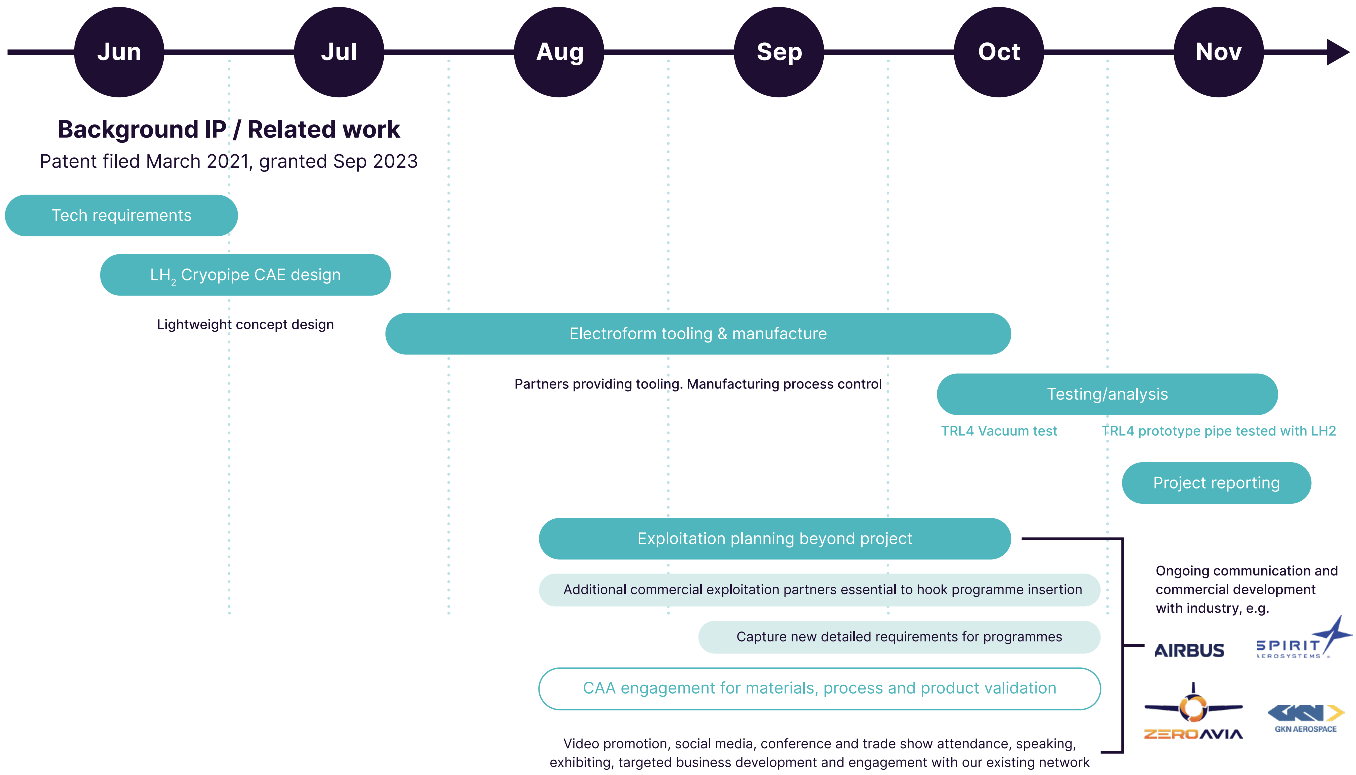
Ultima Forma has previously designed, manufactured and tested a flexible cryo-pipe, using proprietary electroformed technology including multi-layered functionally graded materials for the bellows. This twin-walled vacuum pipe was tested successfully using liquid nitrogen. The next step was to test this next-generation version within a liquid hydrogen environment. This project acted as the basis for the partnership between Ultima Forma and Element.

In 2021 Element built its LH_2 test facility (Fig 4). This takes gaseous hydrogen, liquifies and stores it before fuelling and defueling systems under test. The facility can liquify 10kg of Hydrogen per day and since 2021 has been developing and testing LH_2 fuel components and systems for many well-known aerospace companies in the UK. Element has recently added a large vacuum chamber to their testing portfolio, enabling rapid testing of insulated or uninsulated components. Working with a supply chain of aerospace companies to help develop their LH_2 fuelled propulsion systems, Element have identified the supply of lightweight vacuum insulated pipes as a particular challenge.

Figure 4.
Cryopipe under test at Element, Cotswold Airport test site

2.4. Project timeline

The project duration was 6 months in total, including several interlinked pieces of work. Project follow on activities involve briefing industry on the results and securing further development programmes against specific project requirements and applications.



3. Demonstration Activity

3.1. Methodology and Procedures

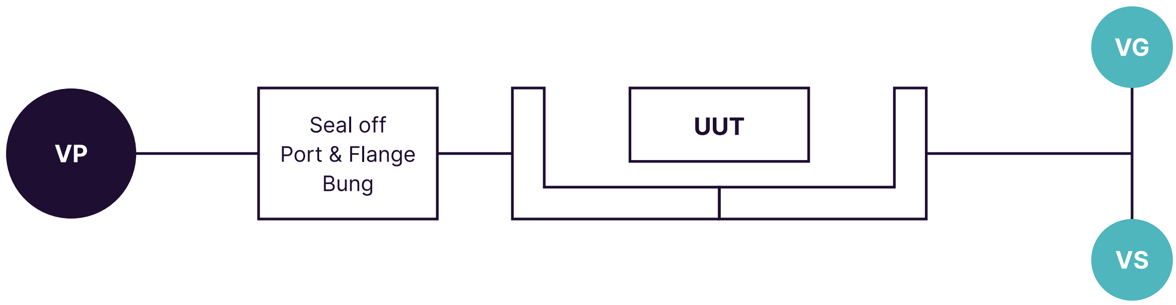
An initial vacuum proof test was first performed on all vacuum jacketed test articles at Element's facility at Cotswold Airport. This was done to outgas and extract any contaminants from the vacuum cavity which would hinder performance under cryogenic test, and to check for leaks. The vacuum test carried out on both pipe units was as follows.

The vacuum pump removed air from the pipe, with the initial pressure reading recorded from the pressure gauge. Pumping continued until the pressure reached approximately 10^{-3} mBara, and the system was checked for any significant leaks, which were addressed to ensure maximum airtightness. The vacuum pumping process was maintained for two weeks, during which time the vacuum performance was monitored. Regular decay tests were performed hourly, with vacuum results recorded every 15 minutes. After two weeks, the vacuum seal-off connection and pump were removed from the unit under test (UUT). The final pressure reading was recorded upon reaching stability, and the system was observed to maintain this pressure for 24 hours to verify vacuum performance.

The test set up for the initial vacuum test is as shown below. This consists of:

- Vacuum Pump (VP) – To pull vacuum from the vacuum space of the unit.
- Seal off port and flange bung – To hold vacuum in the vacuum space and disconnect the unit from the vacuum pump.
- Vacuum Gauge (VG) – Provides vacuum level feedback on the current vacuum in the unit.
- Vacuum Switch (VS) – Installed for safety and set at a vacuum level, if it exceeds the set level it will remove power from the test equipment and shut everything down.

Figure 6. **Vacuum test set up diagram**



Following a successful vacuum proofing, the pipes were tested with liquid hydrogen (LH_2).

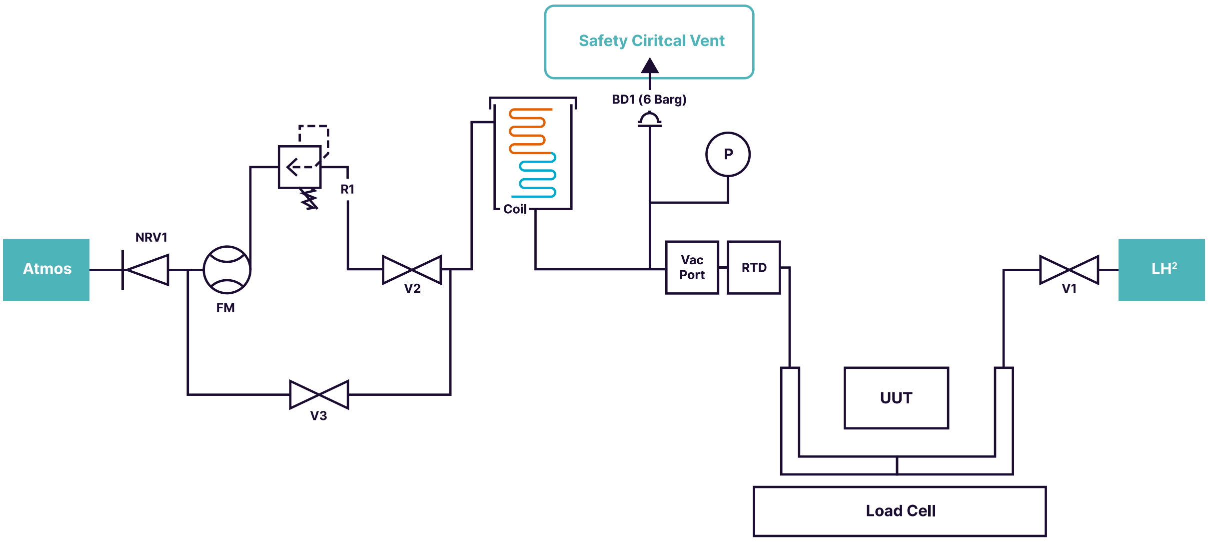
The LH_2 supply line was connected as per procedure, with valve V2 opened and V3 closed. The LH_2 supply valve (V1) was gradually opened to initiate the filling process, and regulator R1 was set to achieve a system pressure of 1.5 bar. The fill process was closely monitored through the RTD temperature sensor until stabilisation occurred. Once the system was filled, the LH_2 supply valve was closed, and the system pressure was increased to 4 bar by adjusting R1.

3.1. Methodology and Procedures (Contd.)

The LH_2 supply valve was then reopened, and the system pressure was increased to 4 bar by adjusting R1. The pressure rise was continuously monitored as it increased to 4 bar, once at 4 bar R1 self regulated the pressure at 4 bar by relieving flow through the flowmeter. The hydrogen vent flow was measured using a designated flow meter, with both the flow rate and total vented volume recorded. The vent pressure was maintained at 4 bar throughout the measurement process. All data, including flow rate, total volume, vacuum, and temperature, were logged.

The boil off flow and temperature were measured to calculate heat flux performance. The unit was monitored throughout for signs of damage caused by thermal shock or loss of vacuum.

Figure 7. **The test set up for the LH_2 tests is displayed below;**



The test set up consists of:

- LH_2 supply
- V1 – Isolation valve.
- Load cell – A back up to measure the weight delta on introducing LH_2. Primarily the RTD is used.
- RTD (Resistive temperature device) Thermocouple – To measure the temperature of the LH_2, when the temperature flatlines this is an indication that the unit is full of LH_2.
- Vacuum port – To allow vacuum purging.
- Pressure transducer (P) & burst disc (BD1) – Safety system that monitors and releases the LH_2 If exceeds a set pressure.
- Heat exchanger - Heats the H_2 to an ambient temperature.
- V2 – Isolation valve.
- V3 – Bypass valve.
- R1 – Back pressure regulator.
- Flow Meter (FM) – To measure the flow and total vented volume of H_2.
- NRV – Non return valve.

3.2. Safety, risk management, and regulatory considerations

Prior to any commencement of testing risk assessments were carried out and signed off. All equipment relating to LH_2 testing on site and/or coming on to the site is ATEX rated. Commissioning of the rig requires thorough and extensive checks to be carried out and signed off prior to test.

3.3. Data collection and monitoring methods

Measurement instrument data is be sampled / recorded at a rate of 1Hz where possible with manual data recording from the calibrated equipment if required. Test rig pressures, flows and temperatures are monitored and recorded via Element's NI DAQ system.

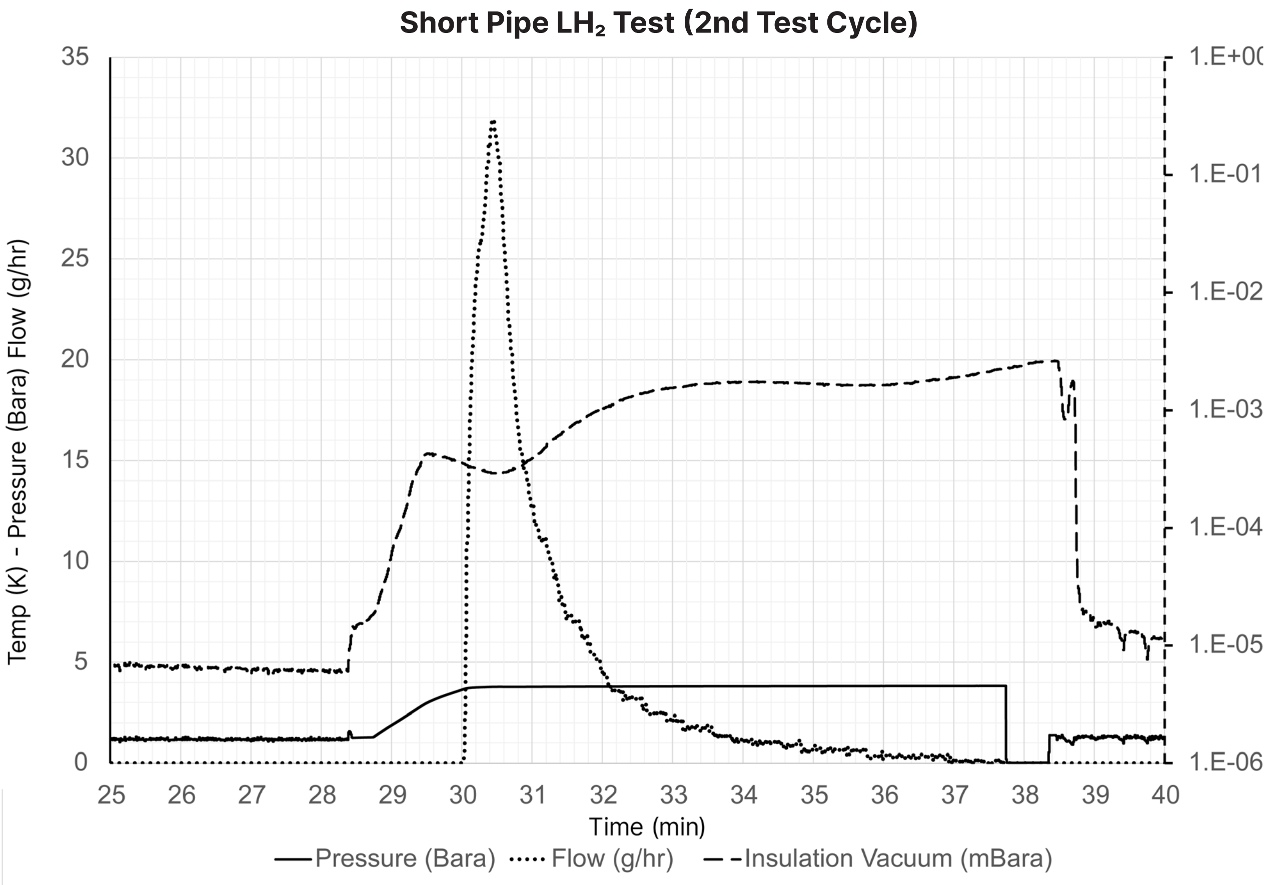
4. Results and Analysis

4.1. Results

Both test articles successfully passed vacuum proof testing. The short pipe was pumped down for two weeks reaching a maximum vacuum of 7.8×10^{-3} mBara. The long pipe was pumped down for a shorter period of 2 days and reached a maximum vacuum pressure of 3.7×10^{-3}.

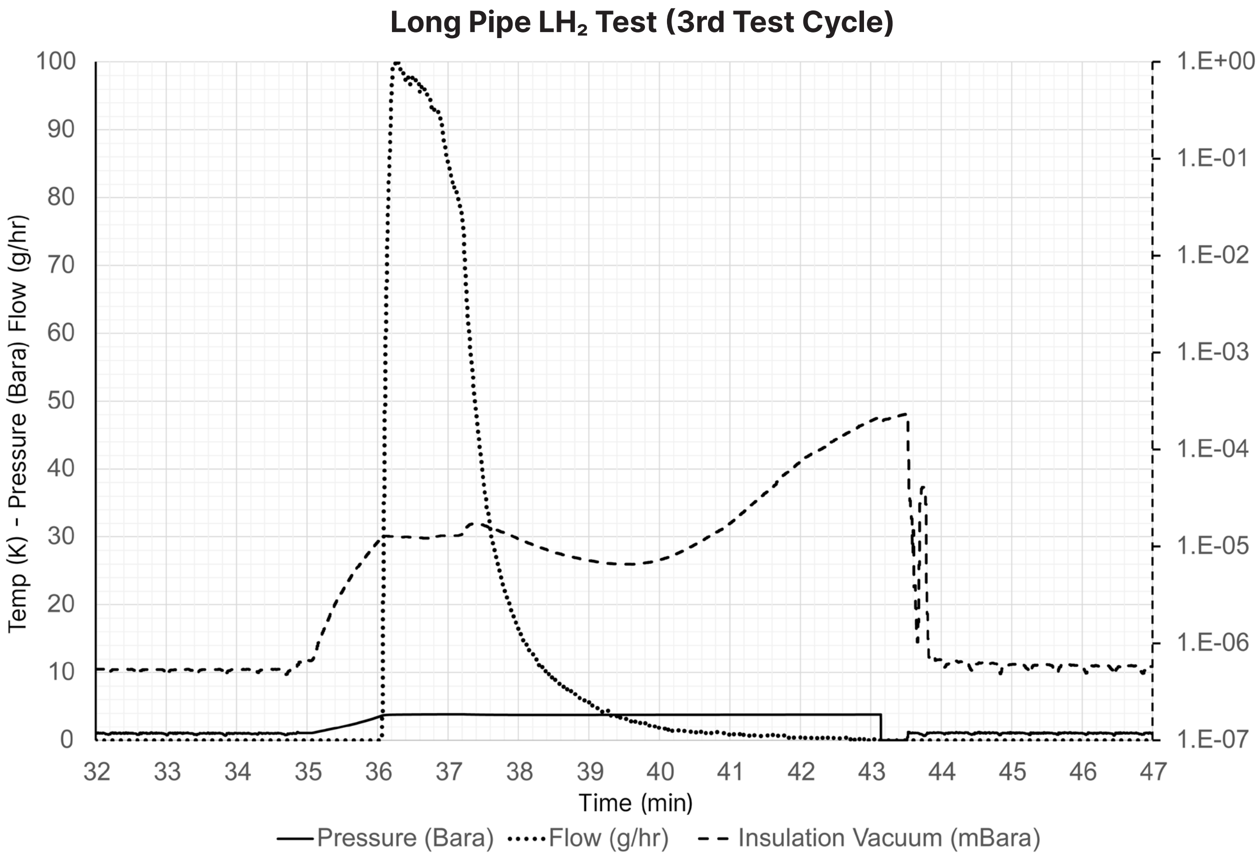
Following vacuum proofing, the pipes were subject to repeated LH_2 cooling cycles, during which the vacuum pressure, LH_2 boil-off flow rate, LH_2 pressure and downstream LH_2 temperature were measured. The two charts in figures 8 and 9 show the test data from one of the several cycles that each pipe was subjected to.

Figure 8. **Graph showing test parameters vs. time for the second LH_2 cycle on the short pipe.**



4.1. Results (Contd.)

Figure 9. **Graph showing test parameters vs. time for the third LH_2 cycle on the long pipe.**



Both test pipes maintained vacuum throughout the test. Shown in figures 8 and 9, neither vacuum dropped below 2×10^{-2} mBara, even after multiple LH_2 cycles, meaning the pipes exhibited minimal vacuum decay. The highest vacuum, achieved was 3.5×10^{-6} mBara and 4.5×10^{-7} mBara for the short and long pipes respectively, both of these occurred during the initial hydrogen flow through, demonstrating outstanding cryopumping behaviour.

The solid line in both graphs represents the pressure inside the inner pipe. When the hydrogen flow into the pipe is stopped, the pressure starts to increase as the hydrogen warms and begins to boil. The time it takes for a 4 bar internal pressure to be reached gives an indication of the heat leak performance of the pipe. The long pipe took 64 seconds to reach 4 bar, whereas the short pipe took 74 seconds. It should be noted that the downstream pipework was not insulated, therefore a proportion of the pressure rise would have been due to the LH_2 warming inside the downstream pipes.

Visually, neither of the pipes frosted or formed condensation during the tests. This indicates that the outer pipe surface maintained an ambient temperature for the duration of the tests.

4.2. Analysis

Cryopumping refers to the improvement in vacuum pressure as the inner pipe is cooled during initial LH_2 fill. Due to the cryopumping, these test pipes pulled the highest vacuum that had ever been recorded at the testing facility.

The thin walls of the inner copper tube mean due to a smaller volume of metal, compared with existing thick-walled stainless steel pipe systems, it's much faster to chill to -253°C before the hydrogen remains as a liquid inside the pipe. This, along with the cryopumping behaviour, means that the electroformed copper design is more efficient in terms of boil-off and therefore a lower volume of fuel is lost during both the fill and flow stages.

The heat leak, calculated from time and pressure readings with the known heat leaks of the two bayonet fittings subtracted, was shown to be 0.180W/m for the short pipe and 0.164W/m for the long pipe. This demonstrates a 2.8× lower heat leak than an existing market solution manufactured by Demaco. It should be noted that these values have a degree of uncertainty due to the limitations of measurement equipment in the test rig.

Table 1. **Comparison of vacuum jacketed cryogenic pipe systems**

	Electroformed Copper	**CryoWorks[4]**	**Demaco [5]**	**CryoFab [6]**
Mass per length (kg/m)	<1.6 (20mm ID)	6.67 (25mm ID)	3.5 (18mm ID)	5.5 (25mm ID)
LH_2 Heat leak (W/m)	0.16	0.42	0.45	0.40

Assuming low percentage errors in uncertainty, Ultima Forma's copper pipe design would provide significant efficiency savings of ground and vehicle based LH_2 fuel systems. To put this into perspective, a liquid hydrogen powered aircraft with 200m of cryogenic fuel lines would retain 2.8× more hydrogen as a liquid in a given timeframe, compared to the existing market solutions as shown in table 1. Therefore, less than 2.8× the energy would need to be spent in-flight to recondense the H_2 back to a liquid, increasing the aircraft's range. This highlights the need for further development of efficient LH_2 fuel systems.

For ground-based systems, the benefits would be around the consumption of hydrogen to fuel a vehicle, reducing the overall losses due to LH_2 boil off.

4.3. Scalability

The design and manufacturing process for this project were developed with scalability in mind. The manufacturing process steps used can be production automated, allowing for a lean quality assured production line. Ultima Forma currently uses a datalogging system to capture key parameters for all of the parameters in its manufacturing process. For larger scale production more automation is envisaged, employing machine learning for process improvement with minimal human interaction needed, akin to a modern car body manufacturing plant.

The pipe system is modular and so complex shapes can be formed from a single tool, with lengths of several metres possible. Electroforming is an electrolytic process, of which several are commonly used in the aerospace industry as medium-high volume manufacturing.

5. Going forwards

In November 2024, Ultima Forma presented the project results and findings to a group of industry stakeholders at the ATI Aerospace Innovation Showcase: Cryogenic Hydrogen Fuel Systems (26th November 2024) at the National Composites Centre. Representatives from the UK hydrogen supply chain were present. There was new interest in Ultima Forma's technology, with follow up discussions in progress.

A patent was filed in November 2024 (application number 2417322.1), pre-dating this report, which covers electroformed cryogenic pipe systems.

Ultima Forma has engaged with the CAA to brief them on the results from this study and to lay out a pathway towards certification.

The next steps are to partner on projects with industry and seek support from the ATI to progress the development of the technology showcased in this report.

The project team would like to hear from anyone working on LH_2 fuel systems to see how we can work together and tackle these demanding industry requirements.

The project has given the partners opportunities for further performance improvements that will be explored in future projects. The partners in this project will continue to respond to the needs of the aerospace Tier 1 suppliers and OEMs to develop these important new technology solutions for LH_2 propulsion systems.

6. Key Learnings & Conclusion

This project has seen the electroformed cryogenic double walled pipe system mature from TRL4 to TRL5. This unlocks further opportunities for funding to continue maturing the technology.

Significant data and knowledge was gathered during the course of this project, on both manufacturing techniques and testing.

The key learnings are as follows:

- Electroforming copper pipes is a viable and scalable manufacturing process, able to make efficient and lightweight cryogenic piping systems.
- Soldered joins on the outer pipe provide a hermetic seal, enough to pull and sustain a vacuum at 4.5×10^{-7} mBara. Furthermore, the vacuum did not decay after repeated LH_2 cycles.
- Thin-walled inner pipes create less LH_2 boil off during the initial chill-down stage of testing, compared to current stainless steel pipe designs.
- Ultima Forma's prototype design outperforms existing on-market solutions by a factor of at least 2×, with room for further improvements.
- The built-in expansion bellows being on the inside ease installation in an aircraft or ground based system as the outside geometry does not need to expand and contract to cope with the cryogenic temperature cycling, and therefore is easier to install in fixed interfaces.

Electroformed vacuum jacketed pipe systems for cryogenic applications offer a vast improvement over conventional systems in terms of mass per length efficiency. The heat leak of both test articles was also demonstrated to be better than that of existing market solutions when tested with liquid hydrogen.

The outcomes of this project have the potential to be a key way forward in the development of a cryogenic fuel systems for aviation.

A follow-up project is currently being planned, that would raise the TRL from 5 to 6, potentially by supplying a section of pipe to be integrated into Element's testing facility at Cotswold Airport.

7. References

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