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Next generation composite pipeline technologies enabling industrial fuel switching to hydrogen (H2-IFS)

Final Report

Prepared by

HIVE Composites Ltd
Advanced Technology Innovation Centre
Loughborough University Science & Enterprise Park
5 Oakwood Drive
Loughborough
Leicestershire
LE11 3QF

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1 Executive Summary

Pipelines will be the principal means of distributing hydrogen to industry. However, hydrogen causes embrittlement in steel pipes, reducing the safety of new and existing assets. This project set out to investigate the feasibility of next-generation Thermoplastic Composite Pipes (TCP) using pre-treated tape to provide performance close to that of welded pipes yet manufactured many times faster.

Composite material technologies are becoming a mainstream solution for transport of aggressive media and are set for significant growth due to their resistance to corrosion/hydrogen-embrittlement. To provide the required infrastructure at reduced cost and increased rate of deployment there is a need to manufacture TCP quickly (economically, higher production), safely and with the required in-service performance thereby supporting the transition to zero carbon emission industry.

Within this project Hive have successfully:

- Selected materials for the liner, reinforcement tapes, adhesives and barrier layers
- Sourced all the materials to Hive requirements
- Tested these materials to determine short term and long-term performance
- Designed the layup of the reinforcement layers to achieve the desired pressure
- Designed the prototype manufacturing equipment and commissioned this equipment
- Developed the equipment to manufacture small quantities on a commercial production facility
- Manufactured 120 metres of pipes of various designs and layups for testing and valuation
- Tested the permeation performance of the manufactured pipes
- Tested the burst performance of the pipes

The tape aging and testing identified a suitable reinforcement tape that is least affected by the exposure to water at 60C.

The data generated to date shows that the adhesive selected is insensitive to exposure duration at 60C over the timeframes tested.

The burst pressure of the pipes tested (average of 174 bar for the prototype pipes manufactured at Hive) is in the expected range and is more than 4 times higher than a typical working pressure required for a hydrogen distribution pipe at ambient temperature. This can be easily altered up and down in relation to the number of tapes {and their wind angles} applied to the pipe. Further tests will be performed at 60C.

This project has provided essential data to be able to move to the next stage of the development and qualification of this novel TCP concept.

Pipe fittings have been designed and improved. Finite Element Analysis (FEA) has been performed to reduce stress concentrations between pipe and fitting. This is beneficial for both laboratory and field fittings. It increases the pressure rating of the pipe (by ensuring failures occur in the pipe) as well as reducing likelihood of fitting-induced pipe failure.

Hive will be applying for a Phase 2 BEIS Industrial Fuel Switching project and are currently assembling the project team. The aim will be to be further enhance the piping materials and ancillaries and to perform a comprehensive qualification process that will be required for the appropriate standards (e.g. API 15S, API 17J, DNV F-119, IGEM/TD/19, ASME B31.12) and to demonstrate ease of install through a 5km field trial at a suitable site.

2 Background

Technologies are urgently required that enable industry to switch from fossil fuels to hydrogen and to deliver a decarbonised UK industrial sector. Pipelines will be the principal means of distributing the hydrogen to industrial and domestic users in both the UK and international markets. However, hydrogen causes embrittlement in steel pipes, reducing the safety of new and existing assets.

To reduce disruption and to improve the time taken to install, steel pipes can be replaced by thermoplastic composite pipe for hydrogen applications. These thermoplastic composite pipes (TCP) can be manufactured in lengths exceeding 2km and can be spooled onto a drum, then simply unspooled for fast installation. They are typically employed in the oil and gas industries and are attractive to the end user because of their ease of installation. Thermoplastic materials are also recyclable at end of life.

Current manufacturing methods for high quality thermoplastic composite pipes are laborious, energy intensive, slow, and require the pipe to be reprocessed several times until it is sufficiently strong for the end user. This limits a typical TCP manufacturer to an annual production capacity of about 200 km.

For high-quality pipe, the manufacturing process starts with an extruded liner onto which fibre reinforced thermoplastic tapes are helically wound from contrarotating heads. These tapes are continually welded onto the pipe as it passes down the length of the manufacturing line. The welding could take place at the winding head (with lasers) or downstream (with heating tunnels/ovens). The laser systems are expensive, energy intensive and have H&S issues. When welding takes place downstream of the winding, the pipe passes through a heated tunnel which can cause excessive heat buildup and pipe collapse (or the process has to be frequently stopped to allow cool down). These heating units take up additional floor space and limit the number of winding heads, typically to 4 or 6.

This project will develop materials and manufacture pipe sections to demonstrate that our thermoplastic composite pipes can be manufactured at rates that are five times faster than existing methods, do not require reprocessing (no reduction in properties from respooling) and reduce the energy to manufacture the pipeline by 83%. A key advantage of this methodology is to increase annual production from 200 km to over 1000 km and to significantly reduce the costs to manufacture., the energy consumption during manufacture and provide a solution that is resistant to hydrogen embrittlement.

3 Introduction to Hive Composites

Hive is an independent, director owned company based on Loughborough University's Science and Enterprise Park and have access to the University's staff and facilities. The company has their own R&D laboratory where it can manufacture and test prototype composite materials and structures.

Hive utilise the latest CAD and FEA design software and have well established networks with universities, and specialist supply chain partners such material suppliers, moulders and test houses etc

Hive Composites Ltd staff have considerable experience in conceiving, designing, developing, and testing lightweight engineering structures across a wide range of industries. In relation to thermoplastic composites HIVE staff have been involved in several major, class leading projects including:

- Continuous manufacture of Spoolable high pressure oil and gas pipelines to API 15S and DNV F119 using patent applied for thermoplastic composite tape technology

- Lightweight, thermoplastic composite sandwich panels for truck bodies, caravans, scaffold decks, flooring, road mats, luggage containers etc composite road mats for HGV lightweight semitrailers and HGV's
- Manufacturer of the world's first thermoplastic composite rigid inflatable boat and 10M wind turbine blade using liquid thermoplastic PBT resins
- Design and development of the world's first 13.6m thermoplastic composite semitrailer
- Diaphragm forming of thermoplastic composite applications
- Development of comingled thermoplastic composite fabrics

4 Project aims and objectives

The overall aim of this project was to develop a new form of spoolable, high pressure thermoplastic composite pipes (TCP) to enable fuel switching to hydrogen for industrial processes where steel pipelines are no longer suitable (i.e. cannot be repurposed) or for delivering locally generated green hydrogen. This involves developing the materials and multi-layer TCP pipe constructions that are permeation resistance, avoid gas explosions due to electrostatic discharge and contain the internal pressure. Pipes have been designed to meet the relevant standards (e.g. IGEM/TD/19) using our new manufacturing concept. Fibre-reinforced polymer pipelines offer significant benefits over steel pipelines regarding performance, whole life costs and whole life emissions. A TCP pipeline is typically constructed including an inner non-permeable barrier tube that transports the fluid (pressurized gas or liquid), a protective layer over the barrier tube, an interface layer over the protective layer, multiple glass or carbon fibre composite layers, an outer pressure barrier layer, and an outer protective layer. The TCP has improved burst and collapse pressure ratings, increased tensile strength, compression strength, and load carrying capacity, compared to non-reinforced, non-metallic pipelines.

Spoolable, high pressure thermoplastic composite pipelines exist for traditional oil/gas pipelines: however, limited work has been undertaken for transporting hydrogen (small molecule, high permeation potential) and to assess the long-term performance of the pipe materials and the possible collapse of the liner in the event of rapid decompression of the pipeline. The current methods of manufacture of TCP require significant energy for fusing the layers together and the speed of manufacture is restricted by heat-up and cooling rates.

The innovations this project will deliver over the 2 phases are:

- polymer inner liners with enhanced hydrogen permeation resistance and electrostatic discharge levels of conductivity using nano fillers (graphene, metals etc) and liner metallisation techniques
- TCP reinforcing tape materials which will bond to the inner liner to provide the necessary operating pressure rating – removes the need for heating
- outer polymer coating layer to protect the pipe from external damage and to enhance the permeation resistance of the pipe.
- improved joint designs
- to manufacture a series of prototype TCP pipes for testing in line with API 15S or IGEM/TD/19 coupled with short and long term accelerated permeation and electrostatic discharge tests

This is a disruptive approach to the manufacture of TCP product and to the dynamics of the hydrogen pipe sector.

5 Industry challenge

The UK has ambitious Government-set, net-zero emission targets by 2050. To meet these, it is vital that we build a clean, safe energy network. The transition to net-zero emissions must be fair for everyone, including billpayers, workers and our most vulnerable people. Only then can the economic and social benefits of a greener future be enjoyed by all.

For hydrogen to achieve widespread adoption across industry, it must be made and delivered to the sites in a reliable and cost-effective manner. One main challenge is developing the large-scale transport and infrastructure solutions required to supply industry with the necessary quantities of hydrogen needed. Industry and the distribution networks need to ensure the necessary hydrogen infrastructure is in place.

Large quantities of hydrogen could be transported via pipeline from production sites, while smaller quantities could be transported by truck. In addition, some industrial locations could develop the necessary infrastructure to support on-site hydrogen production, particularly if a renewable energy supply is within proximity. All these solutions require pipeline technologies.

A zero-carbon economy requires significant growth in low-cost, efficient infrastructure. Pipelines will be the principal means of distributing the hydrogen between generation, storage and users in the industrial sector. However, hydrogen causes embrittlement in traditional steel pipes meaning that existing assets may not be able to be repurposed for hydrogen distribution. Steel pipelines designed to carry hydrogen cost more than other gas pipelines because of the measures required to combat the embrittlement.

Potential pipeline solutions include using fibre reinforced polymer pipelines for hydrogen distribution. Non-metallic thermoplastic Composite Pipes (TCPs) are currently manufactured either from fully fused thermoplastic composite tape or from dry wrapping of reinforcing fibre around the thermoplastic liner. In both cases the reinforcement is helically wrapped around a liner. For welded pipe, the manufacturing line is long because of additional heating ovens; or expensive lasers (with H&S issues) are used to reduce space. At the end of the line, the pipes are spooled. Repeated spooling causes ovalisation which is removed prior to the next manufacturing pass. All this re-processing reduces quality and reduces annual production capacity.

Lower-cost pipes are manufactured without welding (with dry, unprotected fibre). Whilst they perform reasonably (80% of welded) during virgin burst tests, the potential for reinforcement movement (and fibre abrasion) during spooling and in-field is severe and several of these products have been known to fail in operation.

6 Social Value

Hive is an ambitious commercial company committed to creating new jobs and developing much-needed skills in the composite materials sector. We are committed to strengthening supply chains and skills for industrial decarbonisation around the UK. The UK is at the forefront of developing scientific research into new composite materials. This is an important technology that has huge potential for the future of high value manufacturing in the UK. With potential accelerated organic growth in the established composites-using sectors like infrastructure, aerospace, motorsport, and renewables, together with the emergence of substantial new markets for composites products in sectors such as automotive, rail, oil and gas, the UK has the opportunity to grow its current £2.3bn composite product market to £12.bn by 2030 (Ref: UK Composites).

The UK Manufacturing Review 2017-2018 identified a weakness in the UK industry supply chain as one of the main reasons for the skills shortage in the composites sector. The supply chain is not ready to switch from metal to composites on several levels. This project will enable Hive to encourage vertical integration of the complete composites supply chain in the UK by further anchoring of specialist skills and UK component manufacturing. Our investment in building and adapting the UK supply chain will secure more composites manufacturing in the UK, and prioritise local manufacturing rather than importing, in turn attracting local engineering talent into the composites industry.

Hive have recently employed 2 graduate engineers from Loughborough University, and we are training them in composite design, manufacture and testing. Award of the Phase 2 project will enable more opportunities for further graduate engineer appointments.

Job creation during project:

- Job safeguarding: 2 jobs during the phase 1 project
- Job creation during project/s: create at least 3-4 new jobs during phase 2 project
- Job creation after project/s: for UK manufacturing sector create >75 jobs over 12-year period through upskilling/reskilling/re-employment and reduction in offshoring of material development

Education: working alongside Loughborough University to develop commercially relevant technical education and training. One staff member (Gerry Boyce) is a visiting Professor at Loughborough University and lectures on polymeric materials

In addition to job and skills creation across the feasibility and demonstration project, we will have positive impact on foundations for the UK industrial strategy to increase productivity, to include the needs of a wide sector of society in UK job creation, sustainable industry and education, and to make the most of our potential via:

- Ideas; economy will be helped through our internal R&D investment
- Infrastructure; upgrade to the UK's infrastructure by investing in low-cost, high-quality hydrogen supply pipelines;
- Business-Environment; grow an innovation-led business by partnering with government and academia to increase materials sector productivity;
- Places; prosperous communities by building on Leicestershire Economic Partnership strategies to develop an East-Midlands-based thermoplastic-centre-of-excellence
- Safety; proving durable and safety driven composite pipeline solutions with the potential for embedded health monitoring to build confidence in the safe use of hydrogen in industrial environments. The project will comply with all relevant health, safety, and environmental regulations.
- Environment; supporting and enabling sustainable industrial operations using reduced cost solutions compared to traditional TCP and using recyclable thermoplastic materials

7 Technology overview

Hydrogen is predicted to be $2.5 trillion business by 2050 (Hydrogen Council). Green Hydrogen (electrolysis of water using renewable electricity) has more potential for decentralized production compared to ‘Blue Hydrogen’ (Natural gas-based hydrogen production with carbon capture and storage) and requires new, cost-effective, and reliable pipelines.

Composite material technologies are becoming a mainstream solution for transport of aggressive media and are set for significant growth due to their resistance to corrosion/hydrogen-embrittlement.

The installation costs for TCP are about >20% less than that of steel pipelines because the TCP can be obtained in spooled sections that are much longer than steel, minimizing welding requirements and eliminating many joints which are often the weakest link. To provide the required infrastructure at reduced cost and increased rate of deployment there is a need to manufacture TCP quickly (economically, higher production), safely and with the required in-service performance thereby supporting the transition to zero carbon emission industry.

Our technology/innovation will develop the next generation TCP using pre-treated tape to provide performance close to that of welded pipes yet manufactured several times faster and optimised for rapid deployment in the hydrogen infrastructure developments in industrial applications. The pipes have the potential to incorporate distributed optical fibres to detect potential damage (i.e. earth moving equipment operating nearby) as well as remote condition monitoring of the assets.

Hive have performed proof of concept coupon level testing to demonstrate the bond strength of the tapes and are experienced in the design and manufacture of 'traditional' TCP. In this project we have developed the essential data and processing parameters for the ground-breaking TCP materials and manufacturing process ready for scale-up and demonstration in a subsequent project.

The current traditional TCP solutions (reduced burst pressure over time, costly to manufacture) are limiting the potential of this ground-breaking solution. We have developed a unique material solution that fills a gap in the market not being addressed by other TCP providers and manufactured prototype pipe sections. Our solution has the potential to:

- Encompass the functionality of off-the-shelf tapes with SoA surface treatments and adhesives
- Dramatically reduce the time-to-manufacture and the cost of TCP pipes
- Surpass the long-term functionality of current dry-wound TCP
- Be optimised for the challenges of hydrogen containment (permeation resistant liners etc)
- Be recyclable at end of life (i.e. thermoplastic)
- Enable uptake of TCP technology for hydrogen infrastructure at lower Total Cost of Ownership
- Support the growth of a global low-carbon-hydrogen-economy for industry

Once commercialised, our next-generation TCP materials & products will stimulate the clean-energy sector.

8 Project activities

The project was split into the following work packages:

1- **Tape and liner selection** - Establish product performance and tape specification and obtain samples tapes from different manufacturers; Establish liner materials/system and obtain samples.
2- **Surface treatment and adhesives** - Evaluate the surface chemistry of the untreated thermoplastic composite tapes; treat the thermoplastic composite tape samples; Test the treated thermoplastic composite tapes. Determine surface energy with respect to process variables. Evaluate the performance of the surface treatment options between two thermoplastic composite tapes

3- **Coupon test programme - environmental effects (hydrogen compatibility, permeation, ageing, temperature, load, spool strain) -** Using the same samples as Work Package 2, test the effect of temperature load and strain on the long-term performance of the bond, tapes and liner; Evaluate the performance of the environmentally aged samples. Measure permeation resistance to hydrogen of the liner system developed. Design simulated spooling rig and measure spooling performance of materials.
4- **Pipe manufacture -** devise system to apply adhesive to a pipe manufacturing station; Design hardware for manufacture of pipe sections at prototype level. Manufacture 1m sections of pipes using the optimal adhesives and surface treatments.
5- **Pipe test programme -** Manufacture a pipe burst test rig. Burst test the conditioned pipes. Measure permeation performance of pipe sections. Design and build test frame to measure spooling performance. .
6- **Project Management**

Some details of the materials used, design, construction methods etc are confidential and hence some of the details, test results have not been included in this report.

8.1 Materials selection and testing

At an early stage in the project candidate materials were identified for the liners and tapes.

An extruded Polyethylene liner was selected (low cost, easily manufacture) and various options for materials and ways of including the permeation barrier within the pipe sections have been evaluated.

The tapes were manufactured from glass reinforced polyethylene with corona treated surfaces and a selection of adhesives applied. The corona treatment was applied by a third-party company. The rolls of tapes are shown in Figure 1.

Figure 1 Glass and polymer tapes

Hive have established a tape exposure and testing facility. To understand the long-term performance of the reinforcement materials, the tapes and adhesion samples are aged in air and water at 60C and then tested after 10, 100, 500, 1000, 5000 and 10000 hours of aging – in the timescale of this project tests have been performed on materials up to 1000 hours of exposure. The test fixtures for testing of the tapes before and after aging is shown in Figure 2 and the exposure baths for the tapes in Figure 3. The tapes were tested in tension using capstan grips where a 2-3m strip of tape is would around drums at either end to minimise stress concentrations (which can cause premature failure of the samples). The gauge length of the test sample is monitored using a contacting extensometer to measure local strain.

Figure 2 Test fixtures for testing of tapes

Figure 3 Test arrangement for aging of tapes

An example of the data generated on aged tapes is given in Figure 4 up to 1000 hours exposure – this data has been anonymised as it is confidential to Hive. The data shows that the tape least affected by the exposure to water at 60C is Tape A. The testing at 5000 hours and 10000 hours will be performed in due course as these intervals require 7- and 14-months exposure respectively. This will enable the data to be extrapolated to longer durations to predict the performance of the materials to service intervals of 20-30 years.

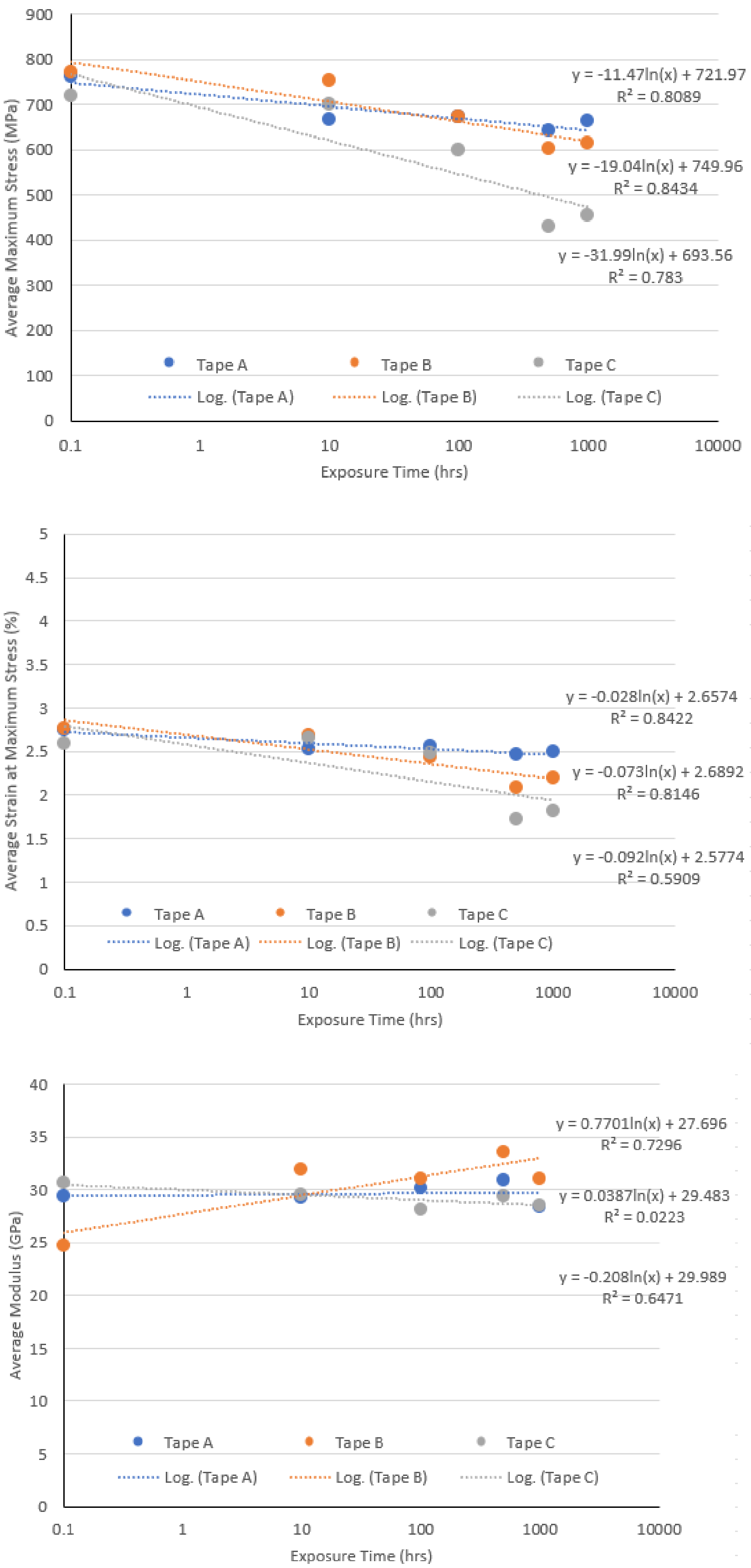

Figure 4 Data on tape performance after aging for 3 tapes tested

Several tests were performed on the tapes and the adhesives to develop the processing parameters required and performance data.

For the lap shear samples (Figure 5), tape coupons were cut using a blade into 100x25mm dimensions according to the ASTM D5868-01(2014) standard of Test Method for Lap Shear Adhesion for Fibre Reinforced Plastic (FRP) Bonding. To assemble the joints, the samples were placed onto the hydraulic press and a 100kPa pressure was applied for 5 seconds, following the procedure for the adhesive bonded samples. The tape and adhesive samples were tested in a Zwick Z150 test machine (Figure 6).

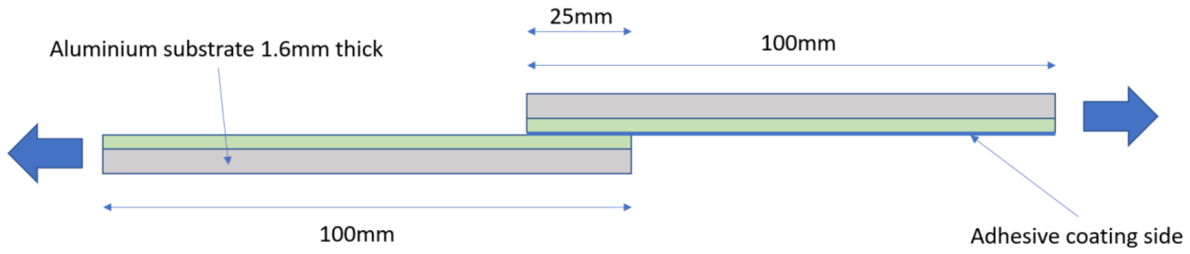

Figure 5 Lap shear test sample

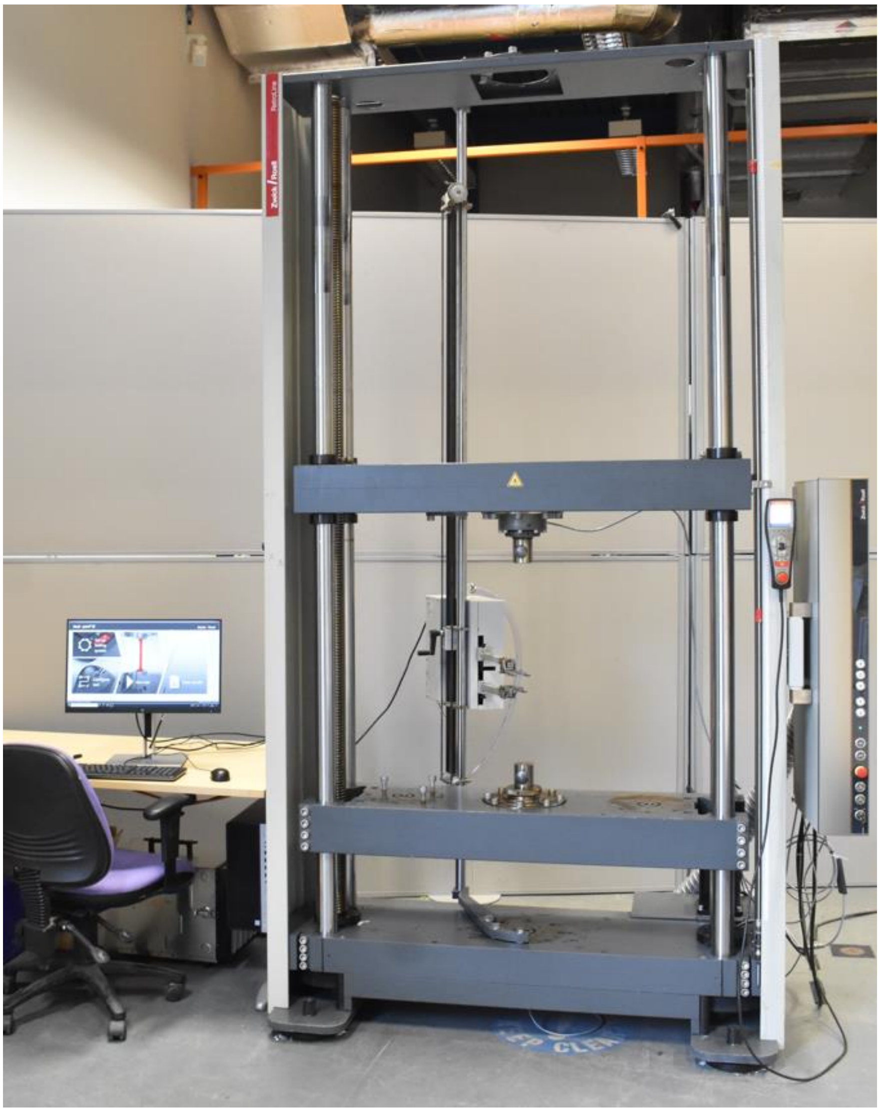

Figure 6 Test machine for tape and adhesive testing

Figure 7 Test arrangement for lap shear testing

A T-peel samples was designed to enable peel properties of the tapes to be measured after exposure to air at 60C. A schematic of the test sample is given in Figure 8 and the test arrangement in Figure 9.

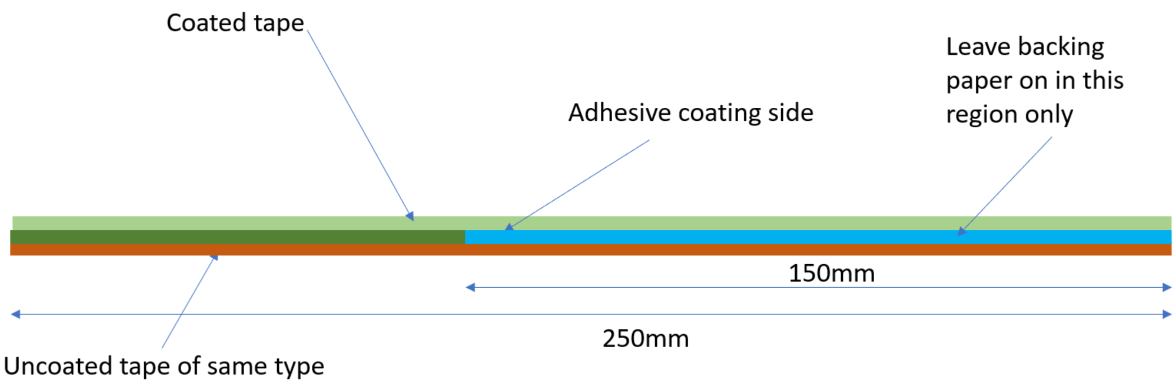

Figure 8 T peel test sample

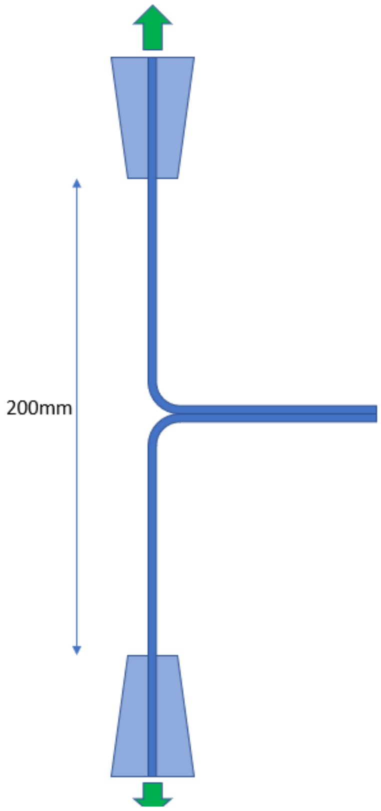

Figure 9 Test arrangement for T peel tests

The force to peel the samples apart was measured during the tests and an example plot is given in Figure 10. As the width of the test sample varies, the force per unit width is calculated and an example of this data is given in Figure 11. The average peel force and average peel force per unit width was calculated between a crosshead displacement of 25mm and 175mm when the peel behaviour was stable.

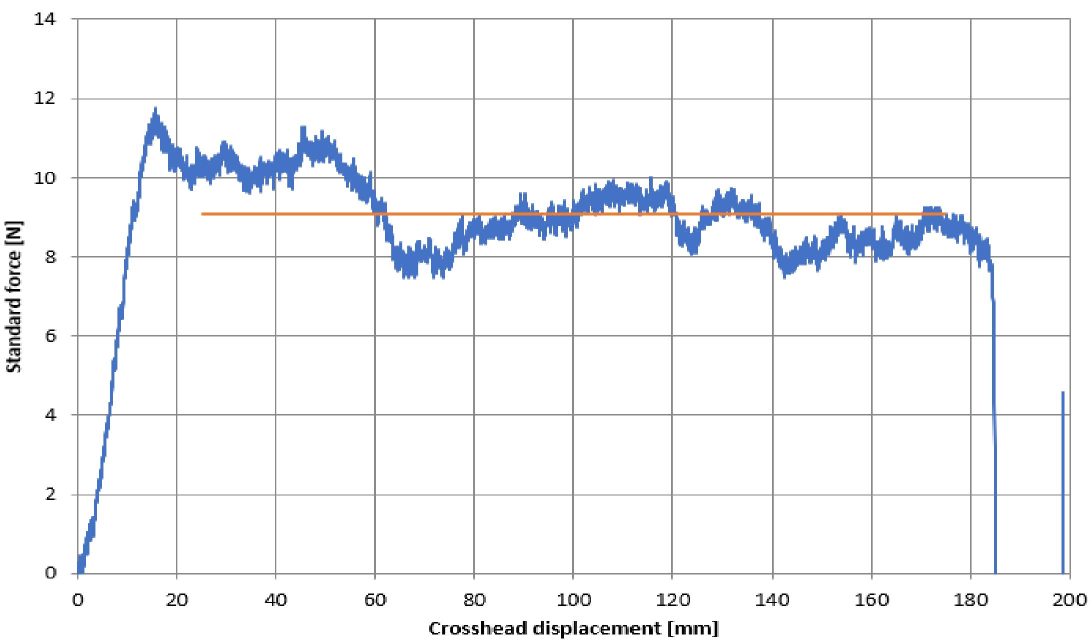

Figure 10 Force vs crosshead displacement for a typical T peel test

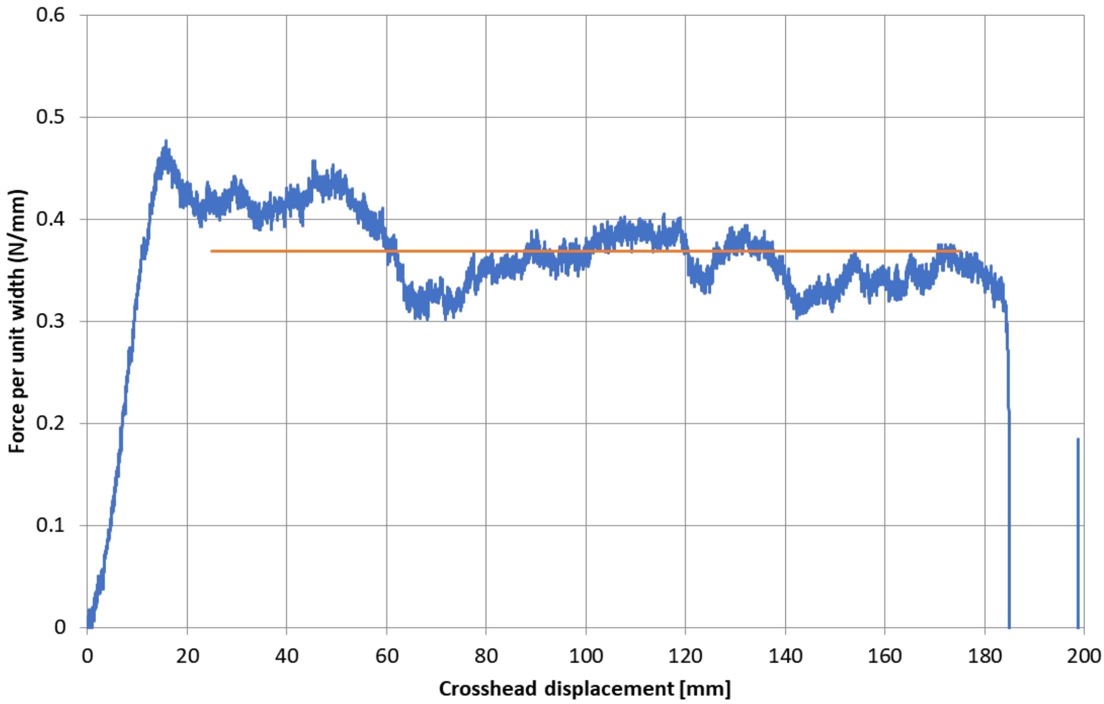

Figure 11 Force per unit width vs crosshead displacement for a typical T peel test

The average of the peel force vs exposure duration is given in Figure 12 and the average of the peel force per unit width vs exposure duration is given in Figure 13. All data is plotted against log exposure time.

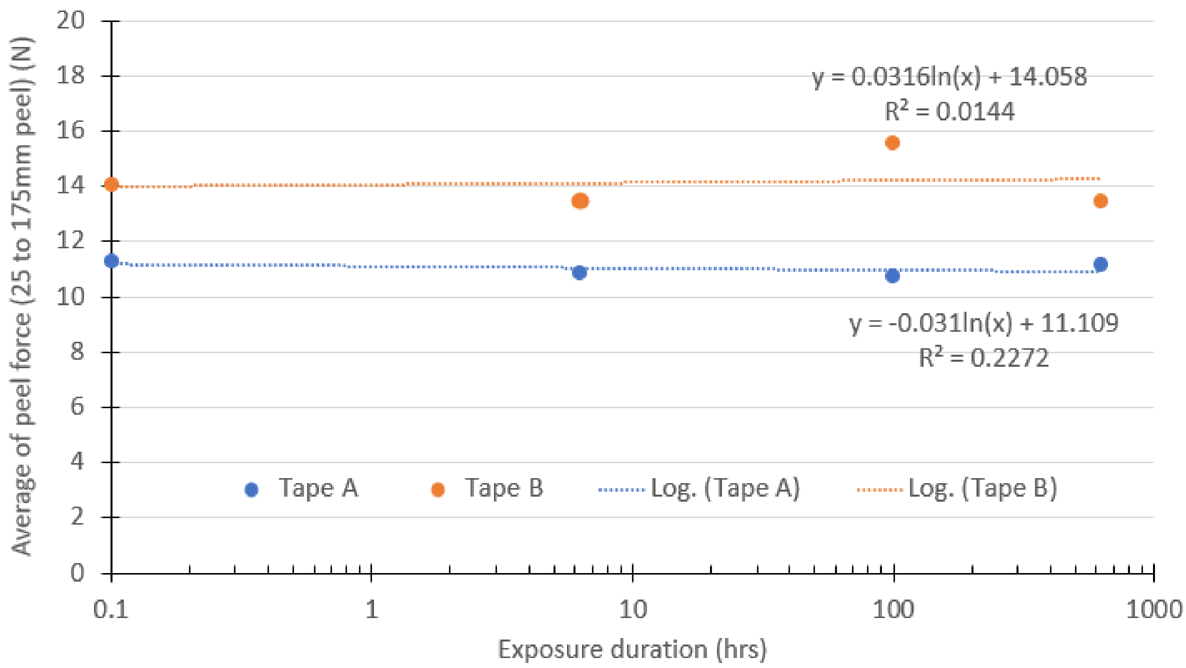

Figure 12 Average peel force vs exposure duration

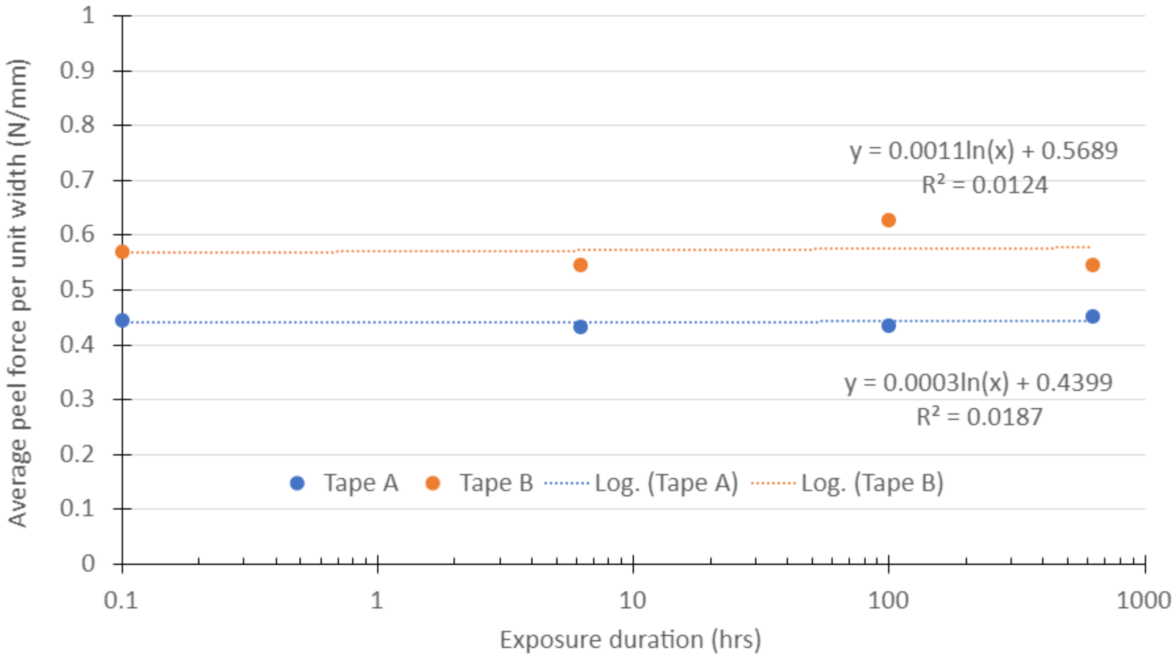

Figure 13 Average peel force per unit width vs exposure duration

The data generated to date shows that the adhesive is insensitive to exposure duration at 60C over the timeframes tested.

For the tapes and adhesion samples, testing has been performed up to 1,000 during IFS Phase 1 (with results extrapolated to predict performance after 5,000 and 10,000 hours) but testing will continue to record performance at these milestones.

Key to the performance of the hydrogen pipes is the ability to contain the hydrogen with minimal permeation through the pipe wall. As part of the project an extensive State of Art review was performed to assess the suitability of various materials either as a homogeneous liner or materials for use as a barrier layer within a hybrid liner construction.

Candidate materials we used to manufacture liner samples which were then tested for their permeation resistance. The standard permeation test arrangement (as per ISO 15105-1 Pressure Sensor Method) has been redesigned for our specific pipe samples. Images are shown in Figure 14.

Figure 14 Test arrangement for permeation testing

Hydrogen molecules diffuse through thermoplastics due to the concentration difference between the high hydrogen concentration inside of the tank/pipe and the lower concentration in the external environment and involves sorption, diffusion and permeation. Solubility of a gas in a polymer is based on chemical interactions whereas diffusion is a purely physical movement of molecules.

Permeation is the passage of fluid from one side of a polymer sample to the other. In its simplest form, it can be measured as a permeation rate in grams or cm3 of fluid passage per hour (or other time period) but this depends on the geometry of the sample (thickness and fluid contact area). To factor these variables out and provide a number which becomes a property dependent on the material, gas, temperature, and pressure, and not the form of the sample, the permeation rate is converted to a permeation coefficient (Q). This means that the results from Lab A should be comparable to those from Lab B, irrespective of the sample details, provided the gas, temperature, pressure and method of measurement employed, are identical. The passage of fluid also depends on two other variables; how quickly the permeant molecules move within the polymer, which is diffusion, and the quantity of permeant dissolved in the material surface, which is solubility. These two factors are also converted into coefficients: diffusion coefficient (D) and solubility coefficient (s).

The relationship between these coefficients is:

$$Q=D.s$$

Q and D are measured from the permeation test and s is then calculated from the above expression.

Permeation testing itself follows the methodology in ISO 15105-1 Pressure Sensor Method and produces a pressure build-up of the permeated gas on the low-pressure side of the sample, Figure 20.

This yields the permeation rate (dq/dt) from the slope of the linear portion of the output and hence the permeation coefficient (knowing the sample thickness and permeation area, which are fixed), as well as the diffusion coefficient from the initial transient stage by measuring the time lag (τ). The solubility coefficient can then be calculated, knowing both the permeation and diffusion coefficients.

The permeation data is summarised in Table 1 - this data has been anonymised as it is confidential to Hive.

Table 1 Permeation and diffusion coefficients for H2 at 50 bar and 60 °C

Sample	Permeation coefficient Q (cm2/s/bar)	Diffusion coefficient D (cm2/s)	Solubility coefficient s (/bar)
Type 1	479×10^{-10}	4.46×10^{-7}	107×10^{-3}
Type 2	99.0×10^{-10}	-	-
Type 3	5.70×10^{-10}	4.60×10^{-7}	1.24×10^{-3}
Type 5	263×10^{-10}	49.7×10^{-7}	6.19×10^{-3}
Type 7	6.86×10^{-10}	2.04×10^{-7}	3.36×10^{-3}

8.2 Manufacture of pipe samples

The materials needed to manufacture pipe samples consist of inner liners, barrier layers and adhesively coated tapes. The materials used for making these pipes are shown in Figure 15.

Figure 15 Materials required for pipe manufacture

Hive had previously acquired a second-hand R&D filament winding machine that was ideal for the manufacture of prototype pipe samples, but which had not been setup or commissioned. As part of this project Hive staff commissioned the filament winding machine, experimented with the control parameters required to lay down the tape materials as required and developed the hardware required to deliver the tapes onto the liners. An example of an early trial setup is shown in Figure 16 and the evolved arrangement in Figure 17.

Figure 16 Early trials using filament winding machine for pipe manufacture

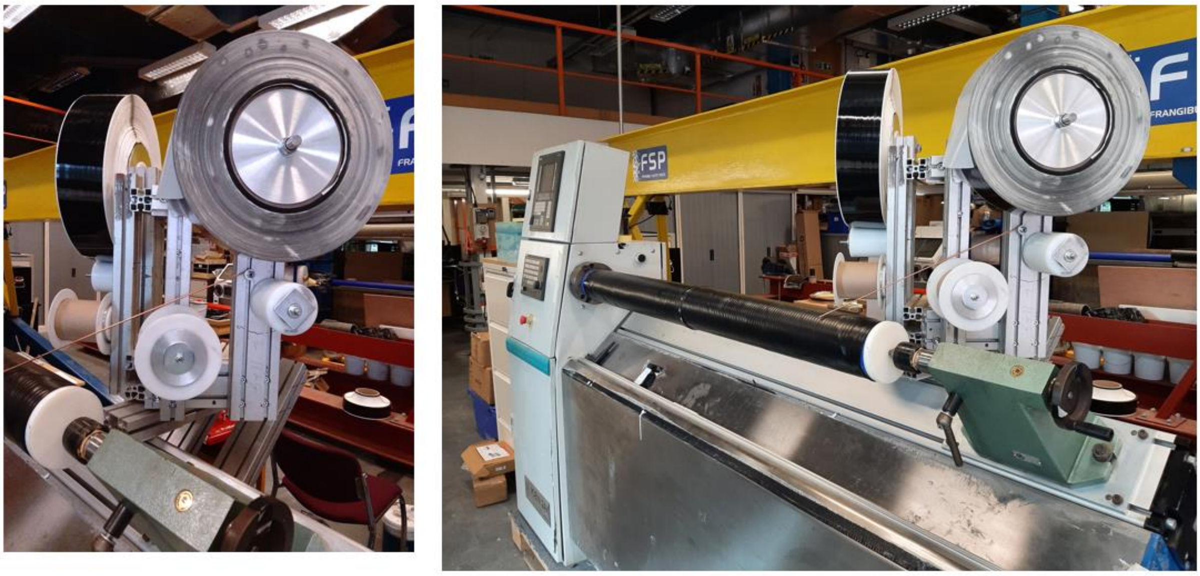

Figure 17 Final version of filament winding machine for pipe manufacture

The larger volume samples were made under subcontract on a commercial machine. Hive worked closely with the subcontract company to optimise the procedure for the manufacture of these pipe lengths. A total of 120 metres of pipe were manufactured for burst tests and other tests. Images of the manufacture of these samples is given in Figure 18.

Figure 18 Pipe manufacture on a commercial machine

The finished pipe samples are shown in Figure 19.

Figure 19 Pipe samples manufactured

Hive has also invested in non-destructive testing (NDT) of the pipe samples. This can be used on as-manufactured pipes as well as on pipes after burst testing to assess the mechanism of failure. Some images of the NDT system are given in Figure 20.

Figure 20 NDT system for assessment of pipe samples

8.3 Burst testing of pipes

To enable the pipe sections manufactured to be tested, bespoke fittings needed to be designed and manufactured. These are designed to seal onto the inner bore of the pipe (i.e. the inner plug needs to be a tight fit inside the pipe and to incorporate O-rings) and outer split collets then compress the pipe onto the inner plug by pulling the two flanges together using M36 bolts. Images of the fixtures designed and manufactured for this project are shown in Figure 21 and Figure 22.

Figure 21 The manufactured flange assembly

The pipes tested were all 4" SDR17 pipes with a test length (before fittings were attached) of between 1.3 and 1.5m.

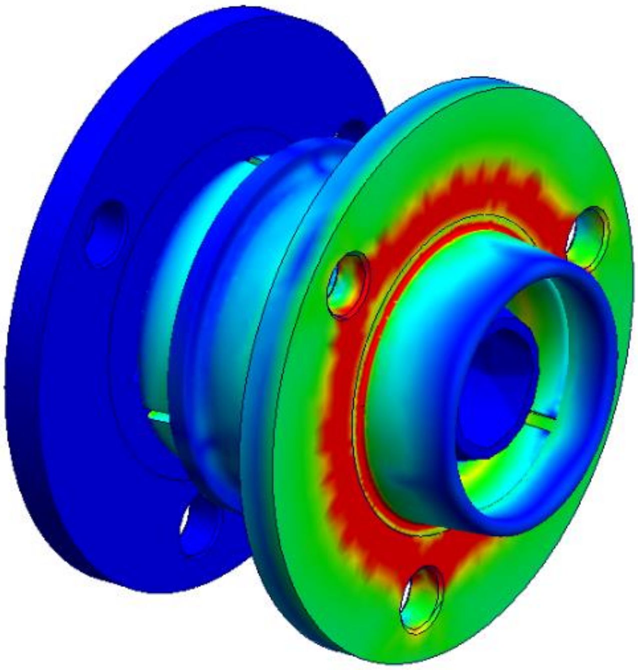

Figure 22 FE model of flange assembly

To contain the pipe samples during pressure tests that could go up to 400bar, a bespoke chamber was built into which the pipe samples are placed during testing. This is shown in Figure 23. The chamber is insulated and has heaters that mean pipes can be tested at 65C.

Figure 23 Chamber for burst tests

A pipe sample being assembled and about to undergo a burst test is shown in Figures 24 and 25. Equipment used in the burst testing is shown in Figure 26.

Figure 24 Pipe samples prepared for burst testing

Figure 25 Pipe sample prepared for burst testing

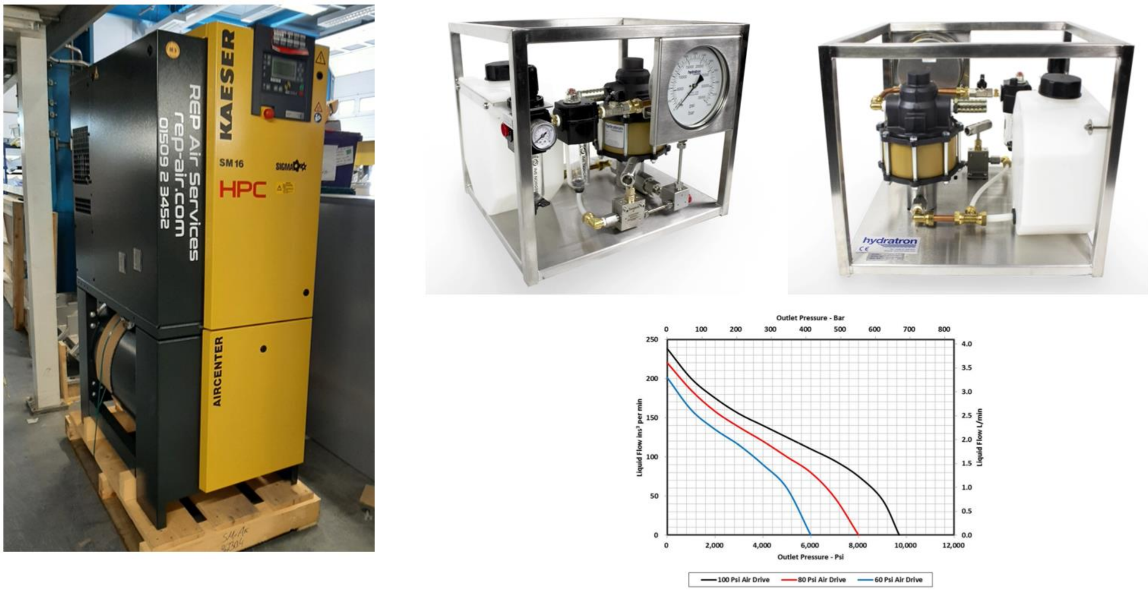

Figure 26 Selection of equipment used in burst testing

Examples of typical failures in the pipe samples are given in Figure 27.

Figure 27 Failure in prototype pipe sample after burst test

The burst pressure of the pipes tested (average of 174 bar for the prototype pipes manufactured at

Hive) is in the expected range and is more than 4 times higher than a typical working pressure required for a hydrogen distribution pipe at ambient temperature. Further tests will be performed at 60C in due course. This project has provided essential data to be able to move to the next stage of the development and qualification of this novel TCP concept.

Failures in the pipes can occur where the pipe exits the flanges and can be induced by the flange design. Hence the true burst pressure can be higher than that measured. As part of this feasibility project, we have performed finite element analysis (FEA) of several proprietary designs of flange fittings for both laboratory and field joints to reduce stress concentrations where the pipes exit the fittings. This has provided useful information for the redesign of both the laboratory and field fittings. Some images from the FEA study are given below. Results of this exercise will result in new IP for Hive either in the form of a patent, registered design, or trade secret.

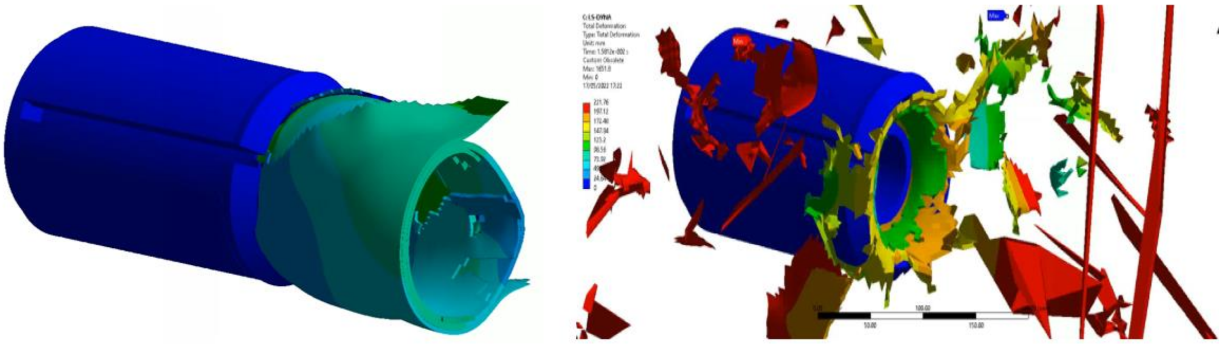

Figure 28 FEA of flange design and pipe failures

9 Project Results

9.1 Commercial viability

Hydrogen is predicted to be $2.5 trillion business by 2050 (Hydrogen Council - a global trade group including BP, Total and Shell). In Europe, a consortium of gas transmission companies has plans to create a 14,300-mile network by 2040 using 70% repurposed natural gas pipelines, augmented by 30% new lines. Goldman Sachs estimate that pipeline configuration projects could cost around $100 billion by 2050 ($30 billion for new pipelines).

In 2019, global reinforced thermoplastic pipe market was $5.86bn (https://bit.ly/2VGTCjE). Addressable annual revenue as supplier of TCP was $785m with a total install of 4663km. Materials (of which this project is focusing) accounts for 78% of net cost (21% gross margin), so total available revenue for our tape product was $485m in 2019.

Hive will be creating a new market segment (with our proprietary TCP technologies) and will address the hydrogen pipeline configuration projects, targeting a modest 0.25% of the tapes ($12m) and 0.05% of TCP products market in 2030 (£15m).

Now is the ideal time to develop more cost-effective pipeline technologies to be ready for the infrastructure developments that will be needed in the near future.

The business need is to improve the production rate of TCP manufacturing whilst producing a structurally efficient product for hydrogen distribution within industrial infrastructure with the performance of fully welded TCP; to reduce the overall manufacturing floor space; to reduce energy cost of manufacturing TCP.

Our disruptive technology has begun to demonstrate that we can:

- Encompass the functionality of off-the-shelf tapes (glass/Polyolefins) with State of Art (SoA) surface treatments (plasma/corona) and adhesives
- Demonstrate at small scale the potential for a dramatic reduction In the time to manufacture and cost of TCP pipes
- Surpass the long-term functionality of current dry-wound TCP

With further development and demonstration (Phase 2 project) we will:

- Enable uptake of TCP technology for hydrogen infrastructure at lower Total Cost of Ownership (TCO)
- Support the growth of a global low-carbon-economy
- Demonstrate the carbon emission reduction benefits of the technology (lower energy, faster manufacturing, recyclable materials…)

Economic benefits to customers will include:

- affordable, high-quality pipe (combination of high-performance bonded-pipe and low-cost, no-heat manufacturing)
- reduced product variability by removing heat build-up and hot spots; reduced factory rent from elimination of space-occupying heaters
- significant reduction in manufacturing energy cost from elimination of heaters
- faster production from high-speed winding (no need to wait for weld)
- ability to accurately predict product longevity and provide confidence on product lifespan
- UK designed/manufactured products supporting the UK manufacturing sector (11% of GVA, 45% of UK exports, directly employs 2.7 million people pre-Covid) with financial benefits

distributed across the UK supply chain (global tape manufacturers, UK-based coupling suppliers, extruders, polymer manufacturers, tooling die engineers, PLC control developers...)

9.2 Technical feasibility

Over 500 km of composite oil and gas pipelines have now been installed offshore and onshore which has validated all the key aspects of adopting this technology including joints, inspection and maintenance, cost effectiveness, durability and reliability, ease of transportation and installation etc

One of the key performance requirements for TCP for hydrogen is the permeation performance of the materials and structures. Only five studies were identified quantifying the leakage rates from the transport of hydrogen in pipelines [Ref:H2 Emission Potential Literature Review - BEIS Research Paper 22]. There were no detailed studies specific to the UK.

Several studies found that that leakage rates measured empirically in studies of plastic pipework were found to be lower than would be predicted by theoretical permeabilities and that GHG emissions from hydrogen transport via pipeline are likely to be small compared to the rest of the hydrogen value chain, as GHG emissions will be mostly due to electricity consumption by equipment such as compressors. GHG emissions from hydrogen transport by pipeline also vary depending on the pressure at which the gas is transported.

Our project has shown that a hybrid pipe construction using low-cost PE materials combined with a barrier layer significantly reduces the hydrogen permeation through the pipe wall whilst keeping per metre cost to a minimum.

It is important that we demonstrate in a follow-on Phase 2 project that a thermoplastic composite pipeline:

- can be manufactured at the required production rates
- exhibits minimal hydrogen permeation through thickness
- exhibits no trapped hydrogen within the composite pipe (which could cause delamination and/or blistering of the pipe when decompressed)
- includes end to end pipe connectors (vented and/or unvented)
- has demonstrated long term performance.

These are the main goals of our next Phase 2 project.

10 Phase 2 IFS Project

A follow-on Phase 2 project is now needed to build on this successful project and to:

- secure public trust (build-in resilience) of TCP through demonstrating product longevity such as fatigue issues associated with unbonded reinforcement.
- meet carbon emission commitments through elimination of high-energy thermal welding
- tackle shortages of key raw materials by producing a more structurally efficient TCP, increasing long-term design confidence, reducing safety factor and reducing materials use.

The aim of the Phase 2 project will be to perform a comprehensive qualification process that will be required for the appropriate standards (e.g. API 15S, API 17J, DNV F-119, IGEM/TD/19) and to demonstrate ease of install through a 5km field trial at a site to be selected.

The phase 2 project will:

- manufacture and instal a spoolable, thermoplastic composite, high pressure (up to 40Bar) hydrogen pipeline. This will involve testing and certifying the thermoplastic composite pipe and joints to appropriate standards such as API 15S, API 17J, DNV F-119 or IGEM/TD/19.
- enable the scale-up of a UK based manufacturing supply chain for the pipes and fitting including the tape coating lines, pipe manufacturing facilities to grow the UK capability in this sector. This will include:
  - co-extruded polymer liners with barrier layers
  - Thermoplastic composite tapes which have been surface treated and coated with a compliant adhesive
  - High speed manufacture of thermoplastic composite pipelines
  - cross head extrusion of outer polymer coating for environmental protection
  - design, development, testing and certification of metallic joints/connectors
  - manufacture and installation of up to 5 km of thermoplastic composite pipeline for off grid transmission of hydrogen.
- demonstrate recycling of the pipes at end of life (circular economy)
- demonstrate lower energy input in manufacture and transport and enabling this sector to move towards net zero.

11 Conclusions

There are currently two types of commercial TCP products: dry-wound tapes/fibres; and fully fused/welded tapes. The dry wound system has a reduced burst pressure performance which significantly reduces further over time due to friction damage of the reinforcing layers. The fully fused system requires significant heat which: reduces manufacturing rate; increases production floor space, H&S, energy use, manufactured cost and product variability.

Our project was to assess the feasibility of a new form of TCP utilising the functionality of off-the-shelf tapes with SoA surface treatments and adhesives and to prove the burst pressure performance and permeation performance.

Suitable pre-treatments and adhesives have been developed and the manufacturing process for this novel TCP product has been proven at the prototype (Hive developed equipment) and at the larger scale. In this project we focussed on glass-reinforced-polyethylene tapes (low surface energy=difficult to bond) but are the most suitable for cost-effective TCP. The adhesion needs to provide flexibility to allow spooling and movement of the composite plies during operation whilst maintaining shape and allowing high levels of load transfer to achieve excellent long-term pressure resistance. This trade-off between strength and flexibility is a key challenge to overcome from pre-treatment and adhesives development.

The tape aging and testing shows that the tape least affected by the exposure to water at 60C is Tape A. The testing to 5000 hours and 10000 hours will enable the data to be extrapolated to longer durations assuming the same degradation mechanisms continue.

The data generated to date shows that the adhesive selected is insensitive to exposure duration at 60C over the timeframes tested.

For the tapes and adhesion samples, testing has been performed up to 1,000 during IFS Phase 1 (with results extrapolated to predict performance after 5,000 and 10,000 hours) but testing will continue to record performance at these milestones.

The project also developed the manufacturing process for the tapes and pipes at a laboratory scale and manufactured 120 metres of prototype pipes or various materials and constructions and tested them.

The burst pressure of the pipes tested (average of 174 bar for the prototype pipes manufactured at Hive) is in the expected range and is more than 4 times higher than a typical working pressure required for a hydrogen distribution pipe at ambient temperature. Further tests will be performed at 60C in due course. This project has provided essential data to be able to move to the next stage of the development and qualification of this novel TCP concept.

Regarding pipe flange design, FEA has been performed to reduce stress concentrations where the pipes exit the fittings. This is useful for both the laboratory and field fittings.

Hive will be applying for a Phase 2 BEIS Industrial Fuel Switching project and are currently assembling the project team. The aim will be to be to perform a comprehensive qualification process that will be required for the appropriate standards (e.g. API 15S, API 17J, DNV F-119, IGEM/TD/19) and to demonstrate ease of install through a 5km field trial at a site to be selected.