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BEIS Contract Connections Final Report
Connections Technology for Hydrogen Pipelines

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The project subcontractors were: Smartflow Couplings Ltd, the National Physics Laboratory, Engineering Marine Services Ltd and Peritus International.

Contents

Abbreviations and Technical Terms

API	American Petroleum Institute
CNC	Computer Numerical Control
FEA	Finite Element Analysis
HAPP	Hydrogen Transport Advisory Pipeline Panel
HDPE	High Density Polyethylene
ID	Internal Diameter
MASiP	Mobile Automated Spiral Intelligent Pipe
NPL	National Physics Laboratory
OD	Outside Diameter
QC	Quality Control
SMYS	Specified Minimum Yield Strength

Dolly	Hardened steel section used to form the Stem into the HDPE liner pipe
End Fitting	The whole arrangement including Stem, Flange, O-rings, Sleeve/Clamp.
Stem	The inner sealing member swaged into HDPE liner pipe with CNC machined 'teeth'
Swaging	The process of expanding the stem into the HDPE liner.

1. Executive Summary

The creation of an industrial hydrogen fuel transport and storage system will require a new approach to pipeline construction to reduce the risk factors involved.

Existing pipeline technology is based on connecting prefabricated 12m pipe segments using manual girth welding. This approach introduces a risk factor when hydrogen is transported or stored at high pressure in the form of fatigue fracture from hydrogen embrittlement. SPS have developed MASiP technology to offer a completely different approach with a lower risk factor. Girth welds are avoided altogether and the use of integrated forming winding technology to manufacture pipe continuously in the field with a polymer liner, that prevents direct contact of high-pressure hydrogen with the steel reinforcement. This creates a more flexible pipeline that has different handling characteristics to conventional pipe. It also requires cold working technology for end fittings.

This project has studied the feasibility of using cold working technology in a scaled-up demonstrator pipeline and the feasibility of designing pipe handling to exploit the increased flexibility of the pipe structure.

The heart of the cold work connection technology is to expand an inner steel fitting, the "stem" to a larger diameter so that specially designed sealing teeth engage with the polymer liner of the pipe system. Current technology limits this approach to smaller diameter pipelines below 8-inches diameter.

The project has addressed key uncertainties regarding the introduction of a cold worked swaging technology. These are (1) developing an engineering methodology for stem tooth design and embedment (2) variations in dimensions that frustrate alignment and quality control (3) external backing requirements for an internal swage and (4) concepts available for larger pipe diameters. The pipe parameters including cold worked connections were used to commission specialist industry pipeline analysis of the handling and support system needed for the 1km scale demonstrator. The results of the swaging tests, design improvements and handling design show that it is feasible to use cold working technology for larger diameter pipe with a good level of quality control in the layout designed for the demonstrator.

The project has advanced the technology readiness level for swaged connections for larger diameter pipes from TRL 4 to TRL 6, developing an engineering methodology using coupon tests and finite element analysis and verifying that with full scale pipe section tests. There are number of industry firsts that the project has achieved: -

- Developing a thorough engineering methodology for the swaging process and tooth design has not been done before and allows much more reliability to come into the design and quality control process;

- Digitising the measurement and alignment process allows field installation of end connections;

- The ability to handle pipe installation with 40D bend flexibility for larger diameter pipe is a huge potential saving for the industry, which currently introduces separate cold bend stations to achieve 40D bends.

The project has also addressed how pipe handling will be designed to exploit the flexibility of the pipe and what the best approach would be for the layout of a 1km scale demonstrator and for 100km pipelines and has engaged with industry feedback. There are uncertainties and safety risk factors associated with building large diameter pipelines – especially for hydrogen transport. A potential solution is to use bundles of 12-inch diameter pipes (to make up an equivalent 36-inch pipe) which provides flexibility and contingency. This can enable higher operating and storage pressures with reduced risk factors and operational benefits. Fabricating conventional pipe bundles in a factory has difficulties but MASiP technology is ready to go to make pipe bundles in the field. A key requirement for commercial roll out to 100km scale will be to demonstrate pipe bundles at scale. A bundle approach could also allow a CO2 return pipeline for industrial connections if appropriate.

Industry feedback has been very positive from both UK energy majors like BP, Shell and Cadent but also internationally connecting with future pipeline projects in India, Sweden, and Oman. This demonstrates the potential of the MASiP technology to create high value UK jobs and become a major export success.

The location of our trial site means that a full scale demonstrator at stage 2 can be used to raise awareness in industry in that region generally about how to go about introducing hydrogen for fuel supply.

This project has advanced MASiP technology such that it is now ready to be used in full scale demonstration.

2. Introduction

2.1 Aims and Objectives

The primary objective of the BEIS IFS Programme is to support the development of fuel switching and fuel switch enabling technologies for UK industry with a focus on low carbon fuels. Further to this, the aim of this project is to provide evidence and commercial viability of pipelines fuel-switching technologies and validation of industrial decarbonisation policy to reach the UK's Net Zero targets.

Hydrogen embrittlement is a well-known risk factor for conventional girth welded steel pipeline systems. Incorporating an inner polymer liner to seal the fluid and protect reinforcing steel from direct fluid contact considerably reduces this risk. However, this requires using cold worked connection technology to seal the polymer liner which introduces uncertainties – especially for larger diameter pipelines. There are also uncertainties regarding how the MASiP pipe system can be handled in longer lengths given its different flexibility and bending characteristics.

The key uncertainties which this project aimed to address are as follows: -

- The engineering methodology of the cold work sealing system
- Digital quality control system for quality control
- Pipe handling process and support design for longer pipe lengths?
- Pipeline layout for a full-scale hydrogen pipeline demonstrator

2.2 MASiP Pipeline System

The MASiP pipeline system incorporates a polymer liner pipe which is reinforced by high strength steel strip in a patented configuration which is fabricated in the field using a mobile pipe manufacturing machine. The end connection consists of a toothed steel stem which is internally expanded, or swaged, to form a permanent mechanical seal.

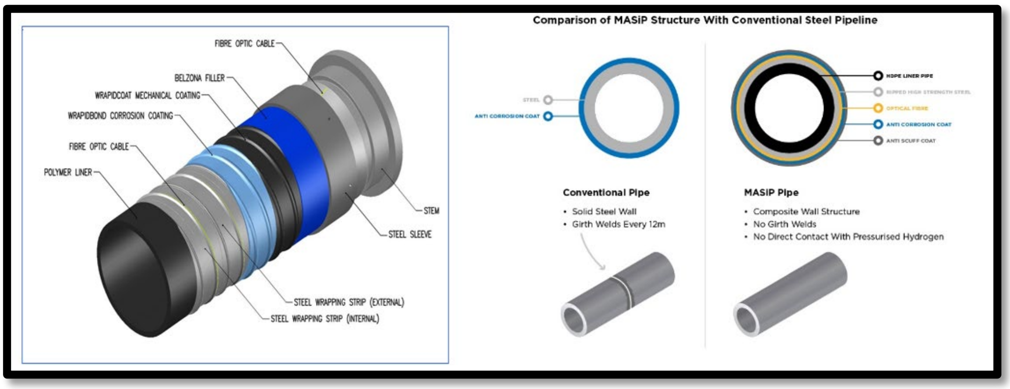

Figure 2-1 – MASiP Pipe Structure

The cold work swaging process is an internal swage which consists of expanding the ring of teeth in the stem into the polymer liner pipe using a solid dolly or otherwise.

Figure 2-2 - MASiP In Field Pipe Manufacturing System in North Yorkshire

The stem has sharp teeth machined into its outer diameter. It is first inserted into the polymer liner of the pipe and then expanded by a controlled amount. The dolly is a larger diameter solid steel cylinder – and drawing it through the stem cold forms the stem to a larger diameter and embeds the teeth into the polymer liner ID.

2.3 Project Logic Plan

The project plan logic was first to develop an improved engineering understanding and methodology for the core of the cold work sealing process – tooth penetration into the polymer liner by swaging. This made use of testing, finite element analysis and microscopy.

Improved measurement and fitting processes were developed for the swaging process emphasising digital data collection for improved quality control. These were tested with full scale pipe manufacture and testing at 12-inch pipe diameter. Alternative concepts of stem activation were explored for very large diameter pipe.

Pipe handling and construction was analysed using industry specialist analysis software Orcaflex, to understand pipe handling for a 50m trial section of pipeline. These elements will be taken forward for a larger scale pipeline to test the readiness of MASiP pipe for longer pipe construction and pipe bundling. Options of bundling 8-inch to 16-inch diameter pipe sizes as an alternative to building very large diameter pipes at 36-inch or 48-inch diameter was considered.

Finally, this has been brought together with Fibre optic feasibility work under another BEIS IFS feasibility study into an outline concept design for a kilometre scale pipeline demonstrator layout with a Gannt chart and cost estimation.

3 Engineering Methodology for Cold Work Connections

3.1 Stem Tooth Embedment- Laboratory Tests

The basic aspect of swaging that makes it work is the embedment of the teeth into the polymer. The National Physics Laboratory (NPL) were engaged to develop a physics-based model of the tooth embedment progress as the basis for an engineering methodology for scale up and automation. A model was developed as a finite element model written in Abacus with special routines to refine the mesh at the tip of the tooth. This is the first time this approach has been used for swaging and provides an engineering basis for any scaled-up designs of the swaging process. Laboratory tests were carried out on test coupons of three sizes of teeth each tested with three types of backing material.

	1mm tooth depth	2mm tooth depth	4mm tooth depth
Rubber backing	√	√	√
Nylon backing	√	√	√
Epoxy backing	√	√	√

Table 3-1 - Conditions Matrix

A series of coupon tests were designed and manufactured to embed teeth of different depth and with different backing material stiffnesses into the polymer pipe liner material on a controlled test machine at NPL. The conditions in Table 3-1 were explored.

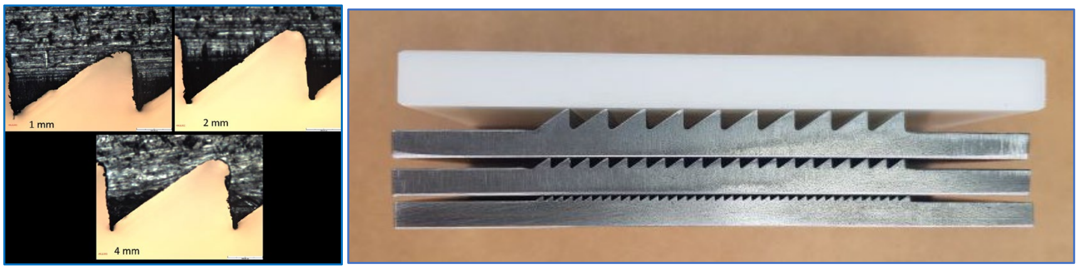

Figure 3-1 - Test Coupons used for Tooth Penetration Tests with NPL Tip Profiling

The tooth sharpness was measured with high accuracy by NPL on the coupons provided and this was used as an input parameter for the Finite Element Analysis. Figure 3-1 shows the test coupons with a flat slab of HDPE into which the teeth were embedded with the tip profiling. Each of the teeth conditions in the condition's matrix were then set up on the NPL test machine and compression platens applied a controlled loading to measure the tooth penetration distance and force.

After the tests the residual imprint of tooth penetration was characterised using profiling microscopy.

3.2 Ring Testing

The NPL work concentrated in understanding tooth embedment under laboratory conditions using test coupons designed and made for this programme. Ring tests were designed and made to take this investigation to the next stage with a full-scale ring that had the right thickness as a full stem but a shorter length so that better comparisons could be made. A separate report SFC-BFS-001-RPT-037 by our sub-contractor Smartflow gives the detailed evaluation of the rings and a brief summary is presented below. The ring test design and test setup is shown in Table 3-3 and Figure 3-6.

	1mm tooth depth	2mm tooth depth	4mm tooth depth
Rubber backing	√	√	√
Nylon backing	√	√	√
Epoxy backing	√	√	√

Table 3-2 - Ring test configurations

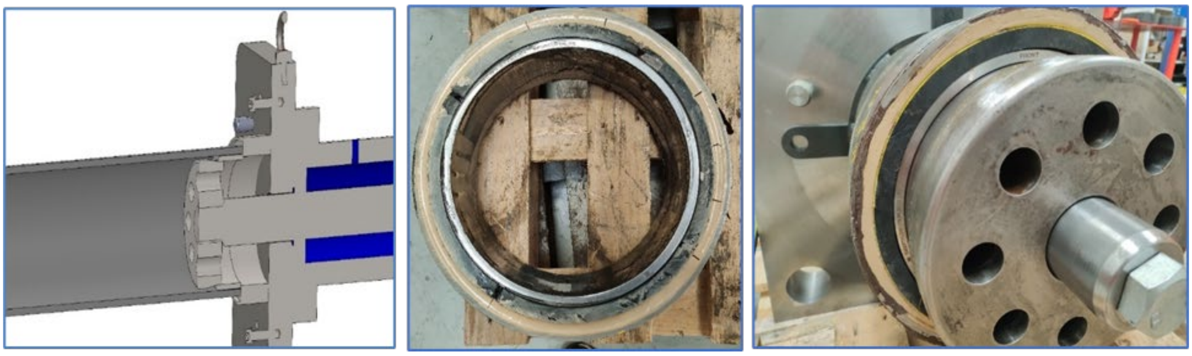

Figure 3-2 - Swaging ring design and test arrangement

3.3 Full Scale Pipe Testing

A full-scale pipe test was performed to directly test the teeth. Each end of the pipe was swaged with stems that had been machined with 1.2mm deep teeth- considered as a possible optimum. The outer sleeve was extended to cover to whole pipe to remove axial extension of the pipe from the equation

The set up and alignment procedures in the quality control section were followed. The swaging pressure was measured during the swage as a quality control measure as part of the digital quality control process and this is described in Section 5 of this report.

The pressure was increased until a failure was observed. In this test pipe design the axial extension of MASiP pipe was overwritten as it were by applying a steel sleeve over the entire length of the test pipe. This enabled the test result to focus on the teeth penetration from the trial swage.

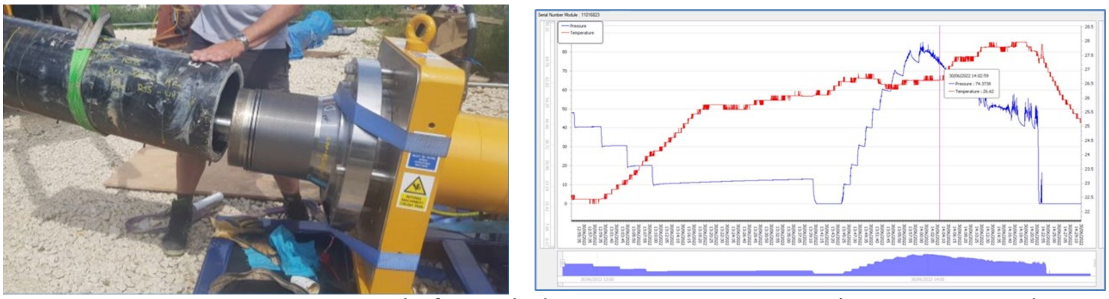

Figure 3-3 - Test swaging trial of 12inch diameter pipe section with pressure test data

The pressure test was conducted using water as the pressurising medium and this showed no failure up to 80 barg pressure as illustrated in the pressure chart result shown in Figure 3-8.

4 Swage Reliability and Quality Control

4.1 Alignment and Digital Measurement Systems

An alignment frame was designed and built to make the swaging process more manageable, more mobile, and amenable to using the robot arm high precision measurements. A hydraulically activated tilter assembly with a 7 degree range significantly improved the ability to insert the stem to avoid small misalignments which can cause jamming. This is mounted on the small skid shown in Figure 4-1.

Figure 4-1 – Mobile Alignment frame and Swaging Assembly

The digital Faro Arm was used to take measurements of the liner pipe internal diameter, tooth outside diameter and Stem outside diameter. Diagram of the measurements taken is presented in Figure 4-2.

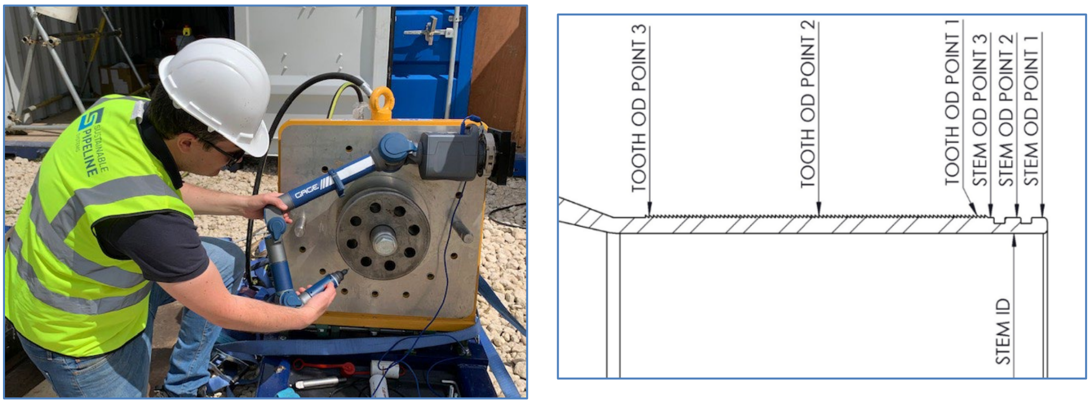

Figure 4-2 – Robot Faro Arm digital measurements and measurement point QC plan

Examples of digital QC dimensional measurements from the Robot Faro Arm are shown in Table 4-1 showing the accuracy that is achieved. This is a factor of 100x improvement on manual measurements.

A laser measurement system was required to measure tooth depth. This is an important final QC check that enables and tooth damage of inaccurate machining to be checked in the field just before swaging. The laser system will measure tooth profile and as there are a large number of teeth it can be programmed as a production tool to measure the statistics of tooth depth.

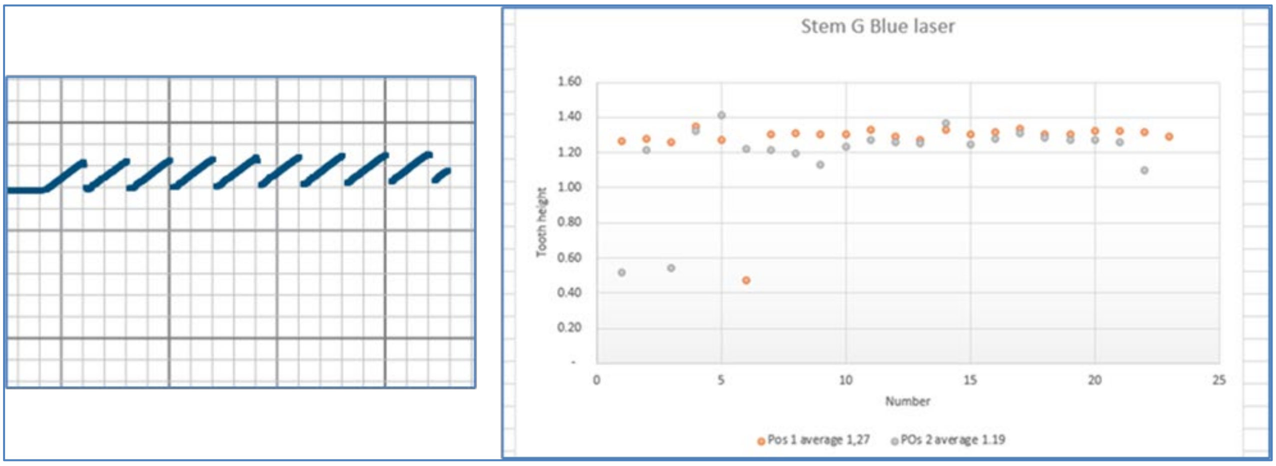

Figure 4-3 - Laser profile of Tooth Depth and statistics from scans across the stem at different positions

4.2 Swaging Process Control

After the dolly and stem are installed the swage process itself was monitored using a digital pressure transducer to record the pressure profile to create the swage. The plateau region defines the swage quality.

4.3 Digital Quality Control Conclusions

This is all brought together in a single Quality Control Sheet

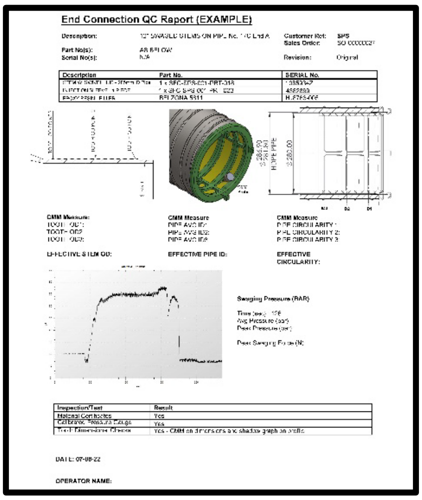

Figure 4-4 – Quality Control Sheet

Item	Supplier Documentation	Measurements When Received	Measurements when Swage Performed
Steel stem OD & ID	√	√	√
Liner pipe ID	√	√	√
Outer collar OD&ID	√	√	√
Dolly OD and length	√	√	√
Stem teeth profile	√	√	
Pressure during swage			√

Table 4-1 – Summary of Quality Control Package

The key quality control conclusions were that digital measurements of stem ID, tooth OD, tooth depth liner ID and dolly considerably improves the reliability and quality assurance of the swaging of end fittings for larger diameter pipe. Digital systems improve mobile use in the field.

5 Pipe Handling Feasibility for Longer Pipelines

In order to determine the feasibility of building a full-scale demonstrator using the MASiP pipe system with swaged end fittings, there are a number of pipe handling uncertainties that need to be resolved. These are: -

- Determining and proving the flexibility of MASiP pipe by including a 40D bend section in the full scale design and demonstrate the ability of pipeline system to be handled and installed into a curved trench in a single operation from the MASiP machine;

- Determine the reaction forces into the machine from making a long length of pipe with a defined touchdown point;

- Design, fabricate and install pipe supports needed for field manufacture and pipeline installation.

In order to address these uncertainties pipe tests were conducted with 10m long pipe section and a trial circa 50m pipe length was designed to fit the site available and then modelled using the standard pipeline industry analysis tool Orcaflex.

A full 3D finite element model was built of the MASiP pipe in bending and used to calculate the safe bending limits of the pipe. This showed that 40D bends could be used and the local strain distribution in the reinforcement strips was within allowable levels.

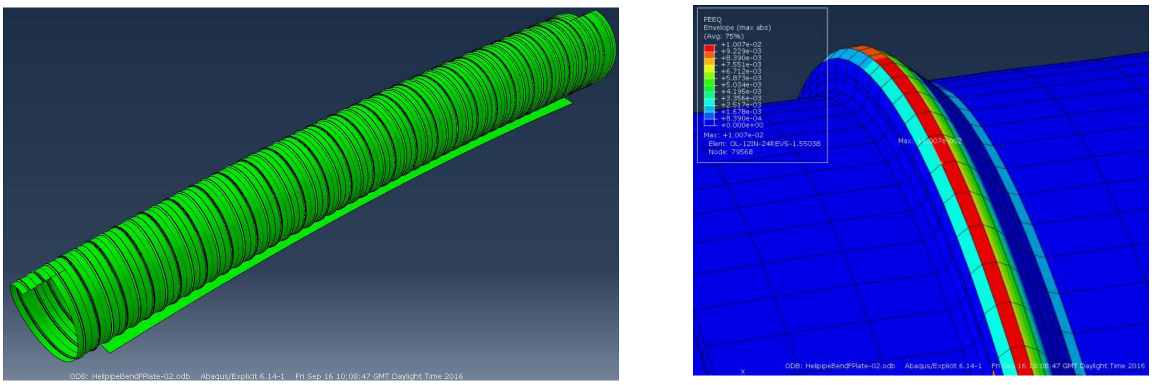

Figure 6-1 - 3D finite element analysis of bending on pipe steel reinforcement

This was tested by bending a 10m pipe section on a bending rig and measuring the pipe response.

Figure 6-2 - Pipe bending and handling tests using 10m pipe section

No damage was found from these tests with 12-inch diameter pipe, and which validated the finite element analysis. This allowed the input parameters to be developed and used in industry standard pipe handling design software using a specialist engineering pipeline contractor.

Detailed evaluation of the forces and the pipeline installation method has enabled support systems to be designed to exploit the flexibility of MASiP pipe and show how the pipe can be taken directly from the pipe manufacturing machine into a trench. Figure 6-3 indicates the whole model setup.

This work has resolved the uncertainties with regards the handling approach and bending design for a larger scale demonstration to the extent that this is possible without a larger scale demonstration.

6 Dissemination and Market Awareness

A presentation on the end fitting work of this project was given to the August 24th 2022 meeting of the Hydrogen Advisory Pipeline Panel (HAPP).

The members of HAPP are shown in Figure 7-1.

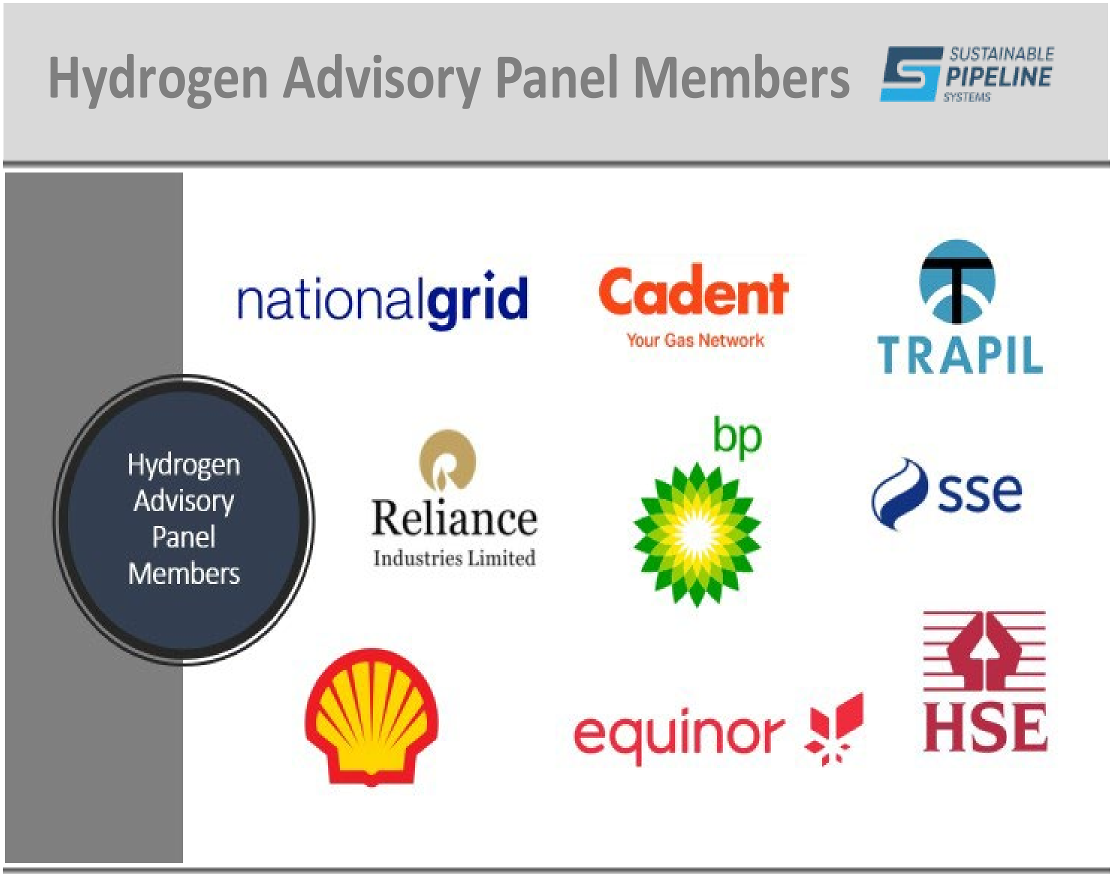

Figure 7-1 - Members of HAPP for August 24th Meeting

This provided a very good opportunity to disseminate key results from the project to leading energy companies internationally as well as in the UK. A questionnaire was developed to obtain more focussed feedback on future hydrogen pipeline projects and has given feedback on pipeline demonstrator design that has been built into the layout development.

7 Project Management

The project had a short timeframe for the amount of work needed especially when supplier delivery timeframes for hardware are considered.

To keep project, focus a draft final milestone report was started at the outset of the project and this was added to on a monthly basis as the project work was undertaken.

There were also weekly meetings of the project team, including subcontractors and the risk register was regularly updated.

This approach provided a flexible but focussed means for both the project manager and the project monitor to manage the project progress.

The project objective of showing the feasibility of cold work connections and pipe handling for direct manufacture into a trench were achieved within time and within budget.

8 Hydrogen Pipeline Demonstrator Design Development

The layout of the current pipeline trial is presented in Figure 9-1.

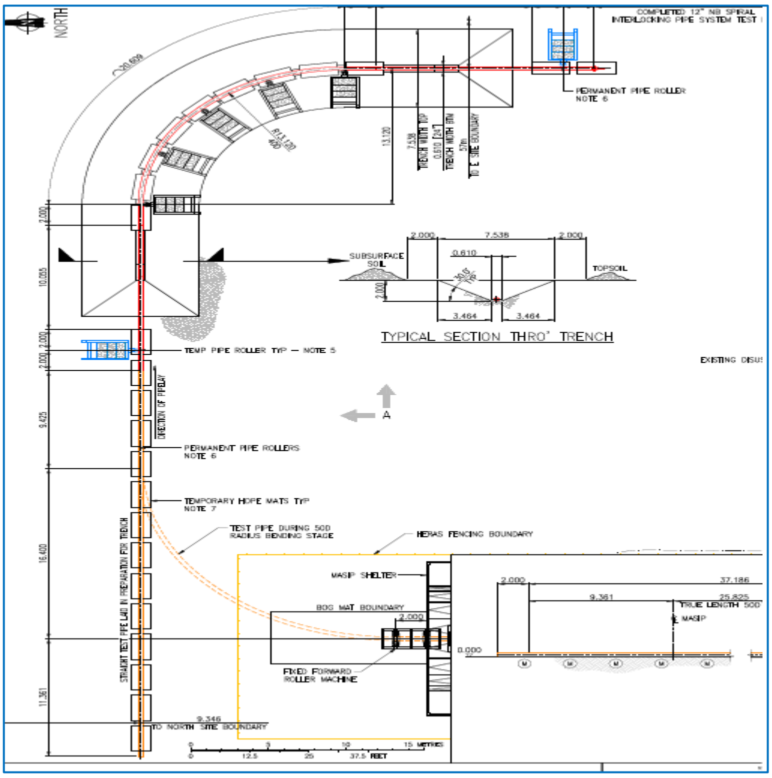

Figure 9-1 – Circa. 50m current Pipeline Demonstrator Layout

8.1 Conclusions and Recommendations

It has been found that cold worked connections technology is feasible for larger diameter pipe and a reliable and digitised quality control system has been developed which can work with the automated in field pipe manufacturing processes of MASiP technology. It has also been found that pipe handling design methodologies can be used to design specific pipe layouts exploiting MASiP pipe flexibility.

It is concluded that MASiP large diameter flexible pipe technology can be used for hydrogen pipeline construction and operation and that this will reduce the risk factor of introducing hydrogen as an industrial fuel and will also speed up and reduce the costs of deployment.

It is recommended that optimised cold worked connections technology be implemented on hydrogen pipelines and that this be demonstrated at kilometre scale to ready for roll out deployment in a full MASiP pipeline operating system