FIELD AND LABORATORY MEASUREMENTS WITH HYDROGEN PERMEATION MEASUREMENT DEVICES

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ABSTRACT

In oil and gas production, corrosion caused by hydrogen sulfide can result in hydrogen induced cracking in susceptible steels. Hydrogen induced cracking is dependent upon the concentration of hydrogen in the steel matrix, and, therefore, the hydrogen flux through the steel. In a previous paper, Paper 471 published at Corrosion 2000, we reported the application of a novel, non-intrusive, rapidly portable, detector for this purpose, generically called "the hydrogen collection method." This paper examines the performance of this method under various field and laboratory conditions to assure the validity of the data. Comparisons are made with five other field and laboratory tools.

INTRODUCTION

A new corrosion inhibition program was initiated to prevent hydrogen induced cracking (HIC) and general corrosion in an extensive wet sour gas transportation system. Since hydrogen damage was the critical aspect to be controlled, the development of an accurate method to determine hydrogen flux through the pipe wall was essential.^{1,2} Two other methods had been attempted to determine the effectiveness of the inhibitor program, but neither was entirely definitive: (a) Perform fluid sampling

at the gas plant to assure that the inhibitor chemistry was present. (b) Monitor the further development of HIC damage at selected bell-holes.

Method (a) proved to be problematic. While it proved possible to easily detect the presence of the diesel solvent from the inhibitor formulation, it proved much more difficult to verify by analytical methods whether or not the inhibitor itself was present. Further it was impossible to determine analytically if the concentration of inhibitor reaching the gas plants was sufficient to prevent HIC. The quantity of diesel reaching the gas plants was less than that predicted by theoretical modeling.

Method (b) was encouraging. It indicated that any crack growth was below the limits measurable by conventional ultrasonic inspection over the test period. However, these were long term data that could not be readily related to variations in inhibitor injection or other process parameters.

The need for a real time hydrogen permeation monitor for the gas transmission system and associated plants was clearly established.

In addition to the need for hydrogen permeation monitoring in the gas transmission system, a need developed to evaluate the success of an inhibitor program in a gas stream in a crude processing plant. Again, the object of the inhibition program was to reduce HIC and stress oriented hydrogen induced cracking (SOHIC) damage.

This paper reviews the performance of six commercial, proprietary, or developmental hydrogen permeation monitors in field and laboratory settings.

HYDROGEN MONITORS EVALUATED

Field work on the wet sour gas transmission system was performed with two different types of hydrogen permeation monitors. The first was a novel, non-intrusive, rapidly portable, detector, known as Hydrosteel^M, jointly developed by Ion Science Limited, Saudi Aramco, and Cambridge University.³ This probe uses the "hydrogen collection method." The second was an in-house, developmental proprietary intrusive electrochemical probe.⁴

Field work on the gas system in a crude processing plant was undertaken with the non-intrusive hydrogen collection probe, a commercially available non-intrusive electrochemical cell, the in-house, proprietary, intrusive electrochemical probe, and a commercially available intrusive pressure monitor.

Work in laboratory settings evaluated the hydrogen collection system, the in-house proprietary electrochemical probe, developmental pressure probes, third party proprietary electrochemical cells, and a commercial electrochemical cell.

[™] Hydrosteel: Manufactured and marketed by Ion Science Limited, Fowlmere, Cambridge, England.

Hydrogen Collection Method

The hydrogen collection method consists of a collector, that continuously captures hydrogen emanating from the steel pipework, and a hand-held detector module, that continuously draws the captured hydrogen into the detector and records data.^{1-3,5,6} The unit is shown in Figure 1. The collector is non-intrusive and is attached to a pipe or vessel surface using magnets or, more permanently, through a strap system. This allows the collector to be attached in almost any location within the plant giving it great flexibility. The lack of any liquids in the collector head enables the collector to be attached at any position around the pipe or vessel circumference without any restrictions. A low voltage, pneumatic pump, draws the air stream from the collector plate across the sensing face of a detector. The detector current is amplified and output to a digital display and data storage facility. The tool is certified to BASEEFA (BS EN 50020:1995) intrinsic safety standards (EEx ia IIC T4).

Electrochemical Cells

The general design features of the Devanathan cell are described in literature.^{7,8} Essentially, hydrogen is oxidized in an electrochemical cell operating at a fixed potential and the resultant current quantified to derive the amount of hydrogen. The solution within the measurement cell is most often a weak sodium hydroxide solution, 0.1 N NaOH, but other solutions such as concentrated sulfuric acid may also be used in some designs.

The proprietary intrusive electrochemical probe is a Devanathan type probe using a steel specimen made from HIC resistant steel to minimize trapping in the probe sensing face. The exit face of the steel specimen is palladium coated. The electrolyte is a dilute sodium hydroxide solution. Various body designs have been fabricated to facilitate use with laboratory autoclaves or field insertion through a standard 2-inch access fitting. In field locations, the probe was coupled through a safety barrier to a data logger and solar cell power system. Data were downloadable from the data logger to a laptop computer.

The external, third party, electrochemical cell is a Devanathan cell strapped onto the external surface of the test material. The test material exit surface is palladium coated. This is a complex process requiring surface preparation followed by the deposition of an electroless nickel layer followed by electroplated palladium. Data are evaluated using a proprietary program to eliminate background noise.

The commercial electrochemical cell is a non-intrusive Devanathan cell that can be strapped to the pipework in question. Prior to placement, the pipe surface was prepared by removing the paint system. A 0.010-inch (0.254 mm) thick palladium foil was placed between the cell and the pipe, a couplant being used between the pipe and the foil. Both the supplied paraffin wax and silicone grease were at used at different times as the couplant in field. In the laboratory, a steel coupon was used in an autoclave such that one side was exposed to the test environment and the rear side was palladium coated and provided the surface for attachment of the electrochemical cell.

Pressure Probes

Pressure probes monitor the increase in pressure due to the diffusion of hydrogen through a test membrane into an evacuated or atmospheric pressure space. Two types of pressure probes were used. In field tests, a commercial probe of the generic "finger" design was installed. This had a direct pressure gauge readout. In the laboratory, two identical developmental probes were used. Monitoring was via a precision pressure transducer. An automated pressure release system vented the probe when the pressure exceeded a predetermined value.

HYDROGEN PERMEATION MEASUREMENTS

The critical hydrogen permeation flux required to initiate HIC has frequently been presented in other publications as an "absolute" value. However, considering Fick's first law, under steady state conditions, permeation flux is defined by the relationship:

$$J_{\infty} = \mathrm{Dc}_0/\mathrm{L}$$
 (i)

where, J_{∞} is the steady state flux (milliliters/cm²/s), D is the hydrogen diffusion coefficient (cm²/s), c₀ is the hydrogen concentration at the inner pipe surface (cm³ of molecular hydrogen at 0°C and 1 bar per cm³ of steel), and L is the membrane (or pipe wall) thickness (cm).⁶

From Equation (i), it is apparent that the permeation flux is inversely proportional to membrane thickness. Various workers also report that for different steels the hydrogen diffusion coefficient, D, can vary.^{9,10} Therefore, hydrogen flux, per se, is not an absolute measure but is dependent on factors such as pipe wall thickness, steel composition, and even measurement technique. Data obtained from measurements made with an intrusive probe based on a thin steel membrane would be expected to be different to measurements made through a pipe wall in the field by an external detection device.

One way to compare data derived from different measurement techniques is to normalize them to some arbitrary wall thickness using the relationship of Equation (i). It must be noted that in some cases the above equation may be too simplistic. As the membrane thickness decreases, hydrogen entry and exit effects at the membrane surface can be assumed to become proportionally larger, and at some point will cause deviation from the linearity suggested by Equation (i), above. Further discussion of this issue is beyond the scope of this paper. However, as a first approximation, comparisons based simply on Fick's law provide a method for us to compare differing data sets.

FIELD DATA

Gas Transmission System

The hydrogen collection monitor was used to determine hydrogen flux rates along the length of a pipeline in the sour gas transmission system and in the destination gas plant.^{1,2} Data derived using the

hydrogen collection method in the gas plant were compared with data derived using the proprietary intrusive electrochemical cell.

Along the length of the pipeline, the hydrogen permeation rate was found to be less than 2 pl.cm⁻².sec⁻¹. The line terminated at the gas plant in a pig trap that was provided to accommodate recovery of cleaning pigs and in-line inspection (ILI) tools used for pipeline inspection. In the gas plant, readings were taken as shown in Figure 2. Upstream of the pig trap, readings were also found to be less than 2 pl.cm⁻².sec⁻¹. Between the mainline take-off and kicker line take-off, a hydrogen flux of 5 pl.cm⁻².sec⁻¹ was recorded. Between the kicker line and the end of the pig trap, a hydrogen flux of 8 pl.cm⁻².sec⁻¹ was measured. All readings were detectable only at the 6 o'clock location on the piping system.

The proprietary intrusive hydrogen probe⁴ was mounted at the 4:30 o'clock location, upstream of the pig trap, at the same position along the line as the first external measurement at 6 o'clock. With the intrusive probe, the steady-state reading was in the region of 4 pl.cm⁻².s⁻¹.

As a first order approximation, a constant hydrogen diffusion coefficient (D) can be assumed for the pipe material and the intrusive probe membrane. The membrane thickness (L) was 0.75 mm for the intrusive probe, and the pipe thickness (L) 9.42 mm. Using Equation (i), the expected reading on the external monitoring device in the same location would be of the order of 0.3 pl.cm⁻².s⁻¹, which is less than the minimum flux detectable by this version of the hydrogen collection system. At the exact location, no hydrogen activity was detected by the external probe. Two metres downstream, in the pig trap where there was less flow, an external hydrogen flux of 5 pl.cm⁻².sec⁻¹ was recorded. The readings obtained on the two different probes are to a first approximation, comparable and of the same order.

In order to provide additional confidence in the validity of the data, it is reasonable to ask if the reading variation seen along the pig trap is sensible. The line upstream of the pig trap is a 36-inch diameter line. After entering the pig trap, the main line exit is also a 36-inch line. About half way down the pig trap is the kicker line. This line is a small diameter line. It was found to be flowing gas while the field readings were being taken. Because of the flow difference between the 36-inch main line and the very much smaller kicker line, the flow in the pig trap will be much slower, possibly allowing drop out of water and certainly supplying less inhibitor to that part of the system. Accordingly, a reading that shows greater activity in the pig trap between the main line and the kicker line is quite reasonable.

This argument can be easily extended to the end of the pig trap where there would be no flow. The even higher reading in the dead-end of the pig trap makes intuitive sense. All readings, however, are less than the critical threshold permeation flux of 30 pl.cm⁻².s⁻¹ established for the system^{1,2} and indicate that the inhibitor program is satisfactorily doing its job.

Long-term data were collected on the inhibited pipeline system using the proprietary intrusive electrochemical probe. Readings were in general agreement with the range of data reported above. However, as with all intrusive probes, there is a stabilization period of a few days after the new probe is inserted into the line and the stable corrosion product films develop on the sensing element face. Using the continual data logging facility of this probe, it was possible to track changes in the performance of the inhibitor system. An example of the data is shown in Figure 3. With this developmental intrusive

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probe, some initial software problems were encountered with its data logging system. However, the utility of continual monitoring was demonstrated successfully over a two-month trial period.

Gas Oil Separation Plant (GOSP) Flare Line

The field data developed for the sour gas pipeline system by both the hydrogen collection method and the intrusive electrochemical probe were in good agreement. However, both data sets were near-zero readings. In order to verify that the hydrogen collection method could reliably and repeatably record higher readings in field locations, tests were performed on a system that could be reasonably expected to experience higher corrosion rates: an internally-uncoated flare line system. This line operates between 30 and 100 psi (0.2 - 0.6 MPa) with sour fluids. Exact conditions are unknown due to the uncertainty in which systems are being routed to the flare.

Hydrogen flux readings around the pipe. Spot measurements were taken at 12, 3, 6 and 9 o'clock around the horizontal pipe as shown in Table 1. Hydrogen activity was only detectable in the 5 to 7 o'clock locations where a repeatable measurement of 64 $pl.cm^{-2}.sec^{-1}$ was obtained. The logical conclusion is that this was the only water-wetted part of the pipe. This illustrates how critical the selection of monitoring location is when evaluating corrosion, especially by hydrogen permeation techniques.

<u>Hydrogen flux readings along the pipe</u>. A second series of readings was taken from sites at regular intervals of about 0.3 m (1 ft) along a 10-metre length of pipe, exclusively at the 6 o'clock position. Results are presented in Figure 4. The striking features of these readings were (A) the repeatability and (B) the variation between locations.

With regards to repeatability, it was possible to return to the sites of significant readings and obtain further readings with only small variation. Furthermore, sites where no flux was indicated consistently yielded zero readings upon re-testing. Table 1 also bears out the repeatability of tests at a specific 6 o'clock site of moderate hydrogen flux; there was a difference of only 5% between the highest reading and lowest reading. The possible reasons for the range of readings along the pipe are variations in water pooling inside the pipe, variations in surface films, and possibly variations in hydrogen traps in the steel matrix itself.

Crude Processing Plant Gas System

Four hydrogen permeation methods were used with the objective of establishing the effectiveness of an inhibitor system in a gas system containing hydrogen sulfide, carbon dioxide, and possibly glycol carry-over that was experiencing HIC and SOHIC.

A non-intrusive, commercial Devanathan cell design interfaced through a palladium foil and sealed with a couplant was installed at three fixed locations. Challenges were encountered in physically installing the cells in the desired locations. The placement of the cell solution and couplant were both difficult. Because of the pipe's low surface temperature (about 15°C), the petroleum wax couplant was replaced with silicone grease, and this helped considerably. Unfortunately, one out of the three cells

never operated satisfactorily, a second cell provided readings for a short while but failed after a mild rain. Examination of the probe found wiring to be heavily corroded. The third cell operated satisfactorily for some months.

Unfortunately, readings were not obtained with the developmental, proprietary intrusive electrochemical probe because it was damaged on installation. The 2-inch access fitting had been improperly installed resulting in a reduced diameter hole through the pipe wall. This reduced size hole resulted in probe damage on insertion into the line.

An intrusive, commercial pressure probe was installed in the system. The probe lacked sensitivity and did not record any activity even when readings were obtained on the commercial electrochemical probe during the short time that it functioned.

The hydrogen collection method was used for a rapid survey of the plant. Multiple locations in the corrosion circuit were investigated within a period of a few hours. At the time of the investigation, each location was found to be well inhibited. Work is continuing to develop a permanently installed version of the probe for deployment in the plant.

LABORATORY DATA

Need for data

The hydrogen collection monitor operated flawlessly throughout the field trials. However, the lack of access to more than one corrosive site limited our knowledge of the performance of the monitor. A qualitative field calibration system was developed to ensure the responsiveness of the monitor, and this was later augmented with the development of a quantitative field calibration system by the manufacturer. Unfortunately, it has not been possible to date to temporarily suspend inhibitor treatments so that baseline data could be obtained on uninhibited process streams and pipelines.

A laboratory test program was established to evaluate the performance of the hydrogen collection monitor. The objectives were to evaluate the responsiveness and repeatability of measurements taken with the monitor, the influence of surface coating systems on hydrogen collection monitor readings, and to compare data between different hydrogen permeation monitoring tools.

The influence of surface coatings is of interest because unlike the other monitoring systems that require extensive surface preparation and often the deposition of palladium films, the hydrogen collection monitor can be magnetically attached over organic coatings in place. This is a significant benefit in field operations because it disposes of the need to remove protective coatings and to reinstate afterwards. Thus, multiple readings can be taken at points around the equipment of interest. However, this feature is only useful if the presence of coatings has a neutral effect on the magnitude of the data collected. Tests with coatings were performed to investigate if they had any effects on the magnitude of the reading.

Test Methods

Three laboratory test methods were used: the responsiveness test, multiport cell tests,⁴ and large-scale pipe sample tests.

In the responsiveness test, a 2-mm steel plate was electrochemically charged with hydrogen.

In the multiport cell tests, the test environment used was a standardized acidified sour brine. Multiple probe ports were positioned circumferentially around a vertical cylindrical stainless steel vessel. Additionally, the base plate of the cylinder was fabricated from a 13-mm thick, HIC resistant carbon steel plate to allow the attachment of the hydrogen collection monitor externally to the vessel. The multiple ports allowed access to mount hydrogen monitors: the proprietary developmental hydrogen pressure probe, the commercial electrochemical probe, and the proprietary electrochemical probe. Each of these used a palladium coated, thin steel membrane, 0.75 to 0.82 mm thick, to interface with the solution. Elevated temperature experiments were controlled ($\pm 0.5^{\circ}$ C) by an electric immersion heater and recorded. Results were logged in a computer. Experiments ran from two days to one week.

In the full-scale pipe sample tests, hydrogen permeation probes were attached externally to 36" (0.914 m) diameter pipe spools, 6-mm wall thickness, recovered from the field. A range of sour production environments was evaluated.

Responsiveness

Responsiveness can be considered from two aspects.

- How well does the monitor react to changes that occur at its immediate sensing face?
- How appropriately does it react to changes in the system?

In regards to the first aspect, Figure 5 illustrates the speed of the probe response. The collector was attached to a 2-mm thick mild steel plate that was electrochemically charged with hydrogen at a constant rate. After approximately 750 seconds, the collector was detached from the surface. The probe response is approximately 30 seconds to clear from the reading to zero. This process is reversed at time = 1350 s. The probe response is approximately 30 seconds to rebuild from zero to 90% of the stable reading on reattachment.

In regards to the second aspect, the hydrogen collection monitor examines hydrogen transport through the actual process pipe or vessel of interest. Therefore, the rate of reaction of the probe to process change is dependent on the thickness of the membrane itself. This will be true for any nonintrusive externally mounted monitor.

Figure 6 demonstrates the difference in responsiveness of the hydrogen collection system attached to a thick test plate versus an externally mounted Devanathan probe mounted on a thin membrane. The thin membrane shows process changes much more quickly. This would be significant if output from the hydrogen monitor were used to control a process parameter such as inhibitor addition on a minute

by minute basis, but it is insignificant if inhibitor adjustments are made on a per shift basis or less frequently.

Correlation Between Probes

Figure 6 data generated by the multiport cell experiments also shows the correlation between stable plateau readings. Stable levels of both techniques were similar, with the commercial electrochemical cell most often being a little lower. In other cases, the reading from the commercial electrochemical cell would be seen to decay after reaching a similar maximum to the hydrogen collection monitor stable reading. An example of this is shown in Figure 7.

Similar readings were obtained between the proprietary electrochemical probe and hydrogen collection monitor. An example of these data is shown in Figure 8.

The developmental laboratory pressure probes trended experimental artifacts well but proved to be hard to calibrate, thus exact comparisons between data sets was not possible. Further improvements in the calibration of the pressure probes is presently underway.

In the full-scale test program on pipe spools in a laboratory environment, the hydrogen collection monitor was compared with a proprietary electrochemical cell at a third-party laboratory. The hydrogen collection monitor performed very well throughout the test period which spanned more than four months. Stable readings were obtained and compared excellently in magnitude with data from wet electrochemical Devanathan cells that were used alongside. Figure 9 presents an example of data from the two test techniques.

When the Devanathan cell functioned, the results were essentially the same. However, the proprietary third-party Devanathan cells were problematic. The data presented for these cells is routinely smoothed by a custom-designed computer filtering program. The unrefined data are extremely noisy. The Devanathan cell is prone to significant variations in performance with temperature. Slight mechanical shocks, such as the performance of ultrasonic inspection, interrupt the stability of the Devanathan cell. The Devanathan cell was also affected by a ground loop current. The cells required rebuilding every two weeks.

Reproducibility of Data

In order to perform experiments on coatings, a consistent and reproducible test environment had to be developed and generated. This required considerable experimentation. Differences in experimental environment were established by the use of multiple probes in the multiport system. The standardized environment provided a tight band of responses in multiple repetitive tests as presented in Figure 10.

Effect of Coatings on Data

Experiments were performed on a steel plate coated with 5-7 mils (130-170 μ m) dry film thickness aluminum pigmented alkyd, and on a steel plate coated with 25 mils (635 μ m) of fusion bonded epoxy. The former coating is a typical above ground plant coating while the later is a typical below ground pipeline coating for new construction.

Results are shown in Figures 11, and 12. As shown in Figure 11, neither the alkyd nor the fusion bonded epoxy had any effect on the steady state hydrogen flux measured. Figure 12 shows the effect on the responsiveness of the probe. The thick-film fusion bonded epoxy may increase the time to reach the stable flux a little. However, this effect has no practical importance in field measurements, as discussed further below. The conclusion is that hydrogen collection monitor measurements made on a coated surface are valid.

INTRUSIVE AND NON-INTRUSIVE CONSIDERATIONS

The physical mounting of the probe in the field has a significant effect upon the collection and interpretation of the data. Probes may be classified as intrusive or non-intrusive.

Intrusive probes are most commonly mounted through some sort of pressure-safe access fitting following any of the classic designs in the oil and gas industry. Intrusive probes whether they be electrochemical or pressure based, measure hydrogen permeation through an artificial barrier. This may be a thin test membrane of carbon steel. Because the membrane is thin, it will react quickly to process changes happening within the system. However, because the membrane is not exactly the same material as the pipeline itself, the resultant permeation data may not be truly representative of the behavior of the mechanical equipment. The intrusive probe is thus more a measure of the environment than the mechanical system. The use of intrusive probes requires considerable preplanning and knowledge of the exact location that is of most interest to study. In the case of electrochemical intrusive probes depend upon a corrodible membrane. Upon insertion of a new probe into a system, the probe will initially corrode at a very high rate until stable surface films are formed. Data generated by a new probe are not representative of the system until several days have passed and a quasi-steady state established. Intrusive probes are also susceptible to mechanical damage during field installation.

The non-intrusive probes in the present study include the hydrogen collection method and externally mounted electrochemical probes. Non-intrusive probes in general react slower to process changes because of the thickness of the pipe or vessel wall upon which they are mounted. However, permeation data that are collected relate directly to the mechanical system and therefore could be applied more usefully in HIC prediction programs. With readily portable non-intrusive systems such as the hydrogen collection method, multiple points on the outside of a system can be screened by a handheld roving unit before establishing a fixed monitoring location. There is no need to weld access fittings to a sour service system. Data collected by rapid techniques such as the hydrogen collection system are immediately applicable to the system under study because the pipe or vessel wall itself forms the corrodible membrane and has been in place under quasi-steady state conditions often for many years.

SUMMARY AND CONCLUSIONS

- The non-intrusive hydrogen collection method provided reproducible data from reproducible environments in both laboratory and field settings. In field locations, readings could be obtained quickly, allowing multiple sites to be examined.
- The collection of hydrogen permeation data through organic coatings used on pipelines and in plants has no practical significance on data generated by the hydrogen collection method.
- Commercial non-intrusive electrochemical cells were difficult to install and maintain in the field. Problems were encountered in sealing the cells to the pipe or test coupon surface. In the field, two out of three cells failed within a very short time of installation. Evaluation of one failed cell found the internal wiring to have experienced corrosion. After considerable problems with the commercial probe, further field and laboratory readings were abandoned.
- A proprietary third party non-intrusive electrochemical probe provided reliable data but the data needed extensive processing to be useful. Probe set-up required extensive surface preparation and each probe was entirely rebuilt every two weeks. The probe was liable to failure from tiny mechanical shocks and was also subject to ground loop problems.
- Commercially available pressure probes were too insensitive to pick up variations in system performance. Developmental proprietary probes were much more responsive but were extremely difficult to calibrate.
- A proprietary intrusive electrochemical probe performed well under normal ambient temperatures.

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UNIT CONVERSION

 $1 \text{ uA/cm}^2 = 127 \text{ picolitres/cm}^2/\text{s}$ at 25°C and 1 bar pressure.

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Position on Pipe (o'clock)	$\frac{\text{Hydrogen Flux}}{(10^{-12} \text{ litre.cm}^2 \text{ sec}^{-1})}$
12	0
3	0
6	64
6	67
6	64
9	0

Table 1: Hydrogen Flux Readings Around Flare Header in Gas Oil Separation Plant (GOSP)

Figure 1: Hydrogen collection method



Figure 2: Hydrogen flux readings at gas plant





Figure 3: Intrusive probe data, inhibited gas pipeline



Figure 4: Hydrogen flux, GOSP flare header

Figure 5: Effect of collector detachment from, and reattachment to plate face emanating steady state hydrogen flux





Figure 7, Comparison between hydrogen collection monitor and commercial electrochemical probe



Figure 6: Correlation between hydrogen collection method and commercial electrochemical probe



Figure 8: Comparison between hydrogen collection method and proprietary electrochemical probe



Figure 9: Hydrogen collection method (solid line) versus proprietary third party electrochemical cell (cross hatched)

Figure 10: Reproducible hydrogen flux band, measured through a 13 mm membrane







Experimental parameter, x



Figure 12: Comparison between Alkyd and FBE coating systems