TESTING OF HIGH RELIABILITY SEALS FOR SUBMERGED EQUIPMENT

Adrian Jarvis, Ian Watson (Huawei Marine Networks Co., Limited)

Email: adrian.jarvis@globalmarinesystems.com

Huawei Marine Networks, Co., Limited, c/o Global Marine Systems Ltd, Winsford Way, Chelmsford, CM2 5PD, UK

Abstract:

One of the greatest challenges for submerged equipment suppliers is protecting optical and electrical components from hydrogen (H_2) ingress generated as a consequence of either natural corrosion, magnetohydrodynamics (MHD) and/or electrolysis from Branching Unit (BU) Earths. Hydrogen (H_2) can cause attenuation in fibre, damage optical and electrical components and cause other issues like material embrittlement. The submarine equipment industry utilises many different sealing methods to reduce hydrogen penetration, such as shear seals and welding, to create hermetically sealed housings to accommodate optical and electrical components. One manufacturer has developed a sealing method for its products and successfully demonstrated its performance using a new testing methodology under in-service conditions.

Adopting a demountable end enclosure assembly containing the main sealing components helped simplify the manufacture of their products. This method of assembly required the application of high end vacuum sealing techniques using specialist seals and precision sealing surface, to ensure hermetic performance under both shallow and deep water applications.

Using unique test facilities, the manufacturer was able to hydrostatically test at 8km equivalent sea depth, whilst applying helium (He) gas across the seal interface and monitoring the leak rate. Unlike other housing test methodologies, this test provided a true indication of the level of hermeticity possible under in-service conditions. Testing achieved hermeticity levels better than 1×10^{-9}cc/s at a pressure differential of 5MPa across the sealing surfaces at a hydrostatic pressure of 83MPa.

1. INTRODUCTION

HMN has adopted a demountable end enclosure assembly to simplify the manufacture of their products. This requires a sealing method to resist possible hydrogen ingress.

This paper only considers the bulkhead seal inserted between the bulkhead and pressure housing, although similar technology is used at the penetrator/bulkhead interface.

This paper will show the detailed analysis and evaluation undertaken to ensure hermetic reliability of this interface.

2. THE ENEMY OF SUBMERGED EQUIPMENT – HYDROGEN

It is well known that hydrogen in and around mechanical, optical and electrical equipment can cause considerable problems, particularly if it is allowed to accumulate. Hydrogen entering fibre[1] can cause attenuation of the optical transmission signal, in materials it can make them brittle and in electronic components cause failure and damage. This type of failure can necessitate product recovery at considerable financial expense and reputation.

Hydrogen exists as a trace element in air (approximately 5ppm by volume) and under normal circumstances would be considered insignificant. In the presence of high reliability equipment even a small amount of hydrogen can cause significant problems.

Typical submerged equipment sealed to $2x10^{-8}$cc/s would expect to ingress approximately 20cc of hydrogen over 25 years through a combination of permeation/diffusion through material, internal outgassing and leakage.

Submerged equipment suppliers use techniques, such as getters, to capture hydrogen and moisture sealed in products during manufacture or generated through the 'out-gassing' of components and materials. These methods generally occupy space and are catalytic, thus requiring additional water by-product management. These approaches are well known and are not covered in this paper.

3. EXTERNAL SOURCES OF HYDROGEN

External sources of hydrogen are of concern, as they could penetrate the housing and overwhelm any internal preventative measures.

External hydrogen sources that could affect submerged equipment are well documented, however for information the main contenders are:

1. Natural Corrosion
2. Electrolysis
3. Magnetohydrodymanics (MHD)

All sources can act simultaneously and result is significant quantities of hydrogen generation, particularly around BU's.

Electrolysis is by far the most significant generator of hydrogen and is commonly the by-product of Branching Unit earths. They return the spur cable line current to Earth and are generally cathodic. Earth electrodes should be positioned sufficiently far away from submerged equipment to minimise this affect, however, it is still significant to cause problems if hermetic sealing is not sufficient.

4. CONSIDERATION OF TEST PRESSURE

Leak rate information published by other suppliers were analysed, reviewed and normalised to establish a helium gas permeation coefficient and compared against HMN's target (See Table 1).

Manufacturer	Helium Test Pressure (MPa)	Maximum Housing Permeation coefficient (mBar.litres/sec/Bar) $X10^{12}$
1	78.5	65
2	78.45	64
3	34.5	29
4	5.0	42
HMN	5.0	60

Table 1: Comparison of permeation coefficients

The permeation coefficient of the housing is simply the leak rate divided by the applied pressure. As leak rate is proportional to applied pressure, the permeation coefficient is constant for a given housing.

Based on historical information from recovered systems, hydrogen partial pressures of 2MPa have been found within cable terminations of repeaters.

Based on this it is sensible to use a 2.5 safety factor and adopt a working pressure of up to 5MPa for testing.

From table 1, it can be seen that using a test pressure of 5MPa is as valid as using a higher pressure. Higher test pressures are often used where concerns exist over hydrogen being generated through electrolysis on sea earth electrodes that are located on terminations or close to the main housing structures. In the case of HMN, the BU earth return is located 10m from the main trunk termination, thus levels of hydrogen are low and comparable to that of a repeater exposed to natural corrosion and MHD.

5. SEALING METHODS

The properties of hydrogen molecules make it difficult to prevent hydrogen ingress. The overall leak rate can be managed through the correct choice of materials and methods.

Different methods exist to prevent hydrogen entering submerged equipment, they include sealing the equipment through welding, using blocking compounds/gels and seals.

It is normal to use metal seals for hermetic systems, although other materials such as glazed ceramics, fused glass, etc., are useful in some circumstances.

The demountable system used by HMN results in a gap between the housing and bulkhead that hydrogen is free to exploit. Sealing this gap is the key factor in managing the hydrogen ingress into the product.

Welding was ruled out as it would not allow a demountable system. Although welding is a well-used method of manufacture, implementing a suitable joint for the material combination and ensuring compliance of the weld would require extensive preparation of the joint. Inspection of the weld quality is crucial to ensure no voids and ensure complete penetration and fill. Another side effect of welding is the Heat Affected Zone (HAZ) which provides an area of weakness for hydrogen to exploit in some material combinations, particularly under high stress concentrations.

6. SEAL SELECTION

To obtain the hermetic seal required to fulfil the design requirements, only a metal seal was considered suitable.

Plain and shear seals were examined, however they have limitations. A shear seal is often placed between knife edges and through the application of a pre-load allowed to flow, fill gaps and form an intimate bond. The shear seal is then reliant on constant sea pressure after deployment to maintain that seal[2]. It is important to carefully control the material extrusion to prevent contamination of the internal components and protect the critical knife edges and seal from damage. It is not suitable where movement or partial separation is possible, such as that experienced at high hydrostatic levels resulting from elastic distortion of the material, as this may lead to seal failure.

Following extensive consultancy within industry and tapping into the current technology used in high vacuum seals in safety critical industries, such as aerospace, space, motor sport (e.g. F1), subsea and oil and gas, HMN evaluated various seal designs that could satisfy the following criteria:

- High vacuum or high pressure sealing
- High reliability
- Simple installation
- Commercially available

7. SEAL EVALUATION

Following successful study it was decided that a spring energised metal seal would provide the best performance. The load characteristics ensured excellent sealing performance, resistance to hydrogen embrittlement through careful material selection and sufficient springback to ensure any bulkhead movement did not affect sealing performance. The springback ensures that should recovery of the equipment occur the sealing performance will be maintained.

For spring energised metal seals used in applications requiring a high vacuum sealing, it is crucial they are plated with an additional coating. This material is required to flow and fill any voids, scratches, etc. It can also move debris away from the seal line.

In order for the seal to work it is compressed between two flat, parallel surfaces to create a sealing interface. The combination of case and spring material selection ensures the seal is energised and able to maintain the correct load through elastic recovery or springback.

Using the equipment shown in figure 1, the displacement, load and leak rate characteristics of the seal could be evaluated.

Figure 1: Test equipment including hydraulic press, leak detector, helium source and data logger.

The equipment produced load versus displacement and load versus leak rate curves that were a helpful tool in determining if the seal performed and behaved as expected. Material inconsistencies and variations in plating are all observable and could be compared to reference curves.

A typical example of a failure is shown in Figure 2.

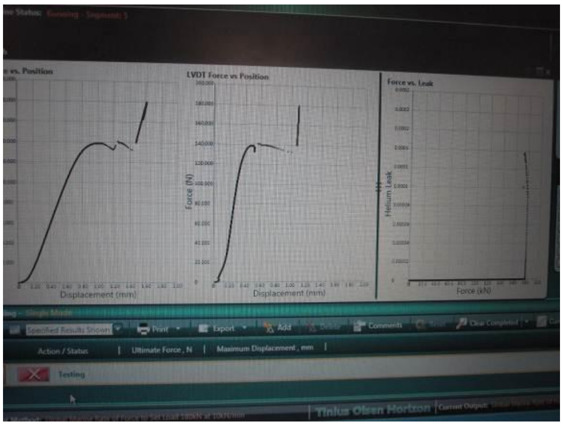


Figure 2: The two left hand graphs show a dip in load suggesting a failure. The right hand graph shows a catastrophic leak.

Further visual examination of the failure (See Figure 3) post-test, showed an area of concern.

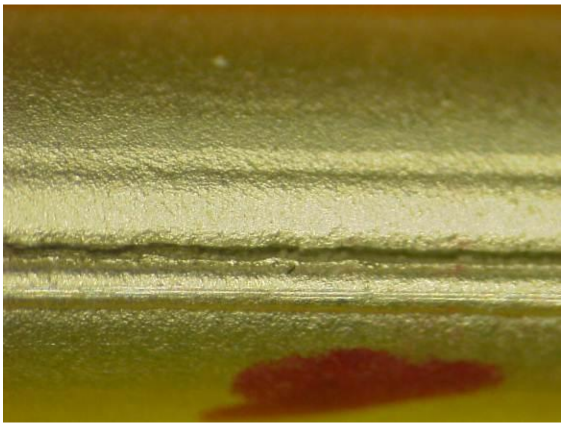


Figure 3: The photo reveals a possible tear in the plating

Subsequent metallurgical examination of the seal (See Figure 4) showed a fracture in the case material due to poor heat treatment control.

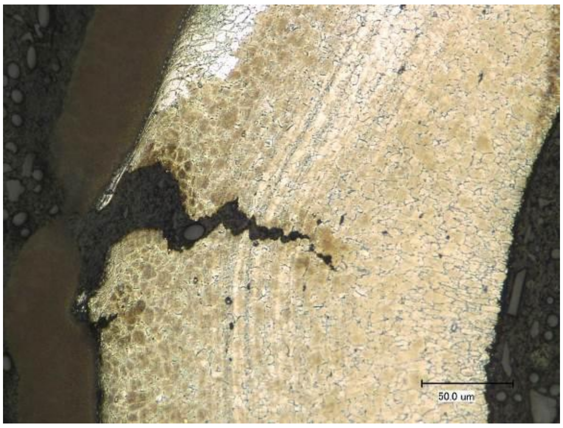


Figure 4: A failure in the case material has been found.

Another example of a problem included surface contamination in the plating material. By using electron microscopes (See Figure 5) and chemical analysis it was possible to discover what the material was, so that the source of contamination could be identified and procedures developed to remove it.

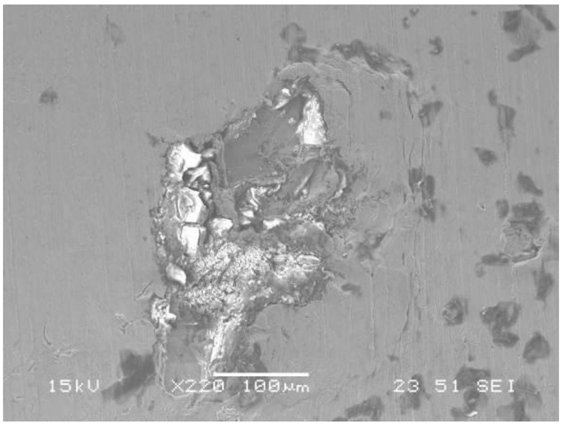


Figure 5: Aluminium Oxide contamination from a cleaning process

Observed fracture failures were investigated for possible hydrogen embrittlement (See Figures 6 & 7), although this was not found to be an issue.

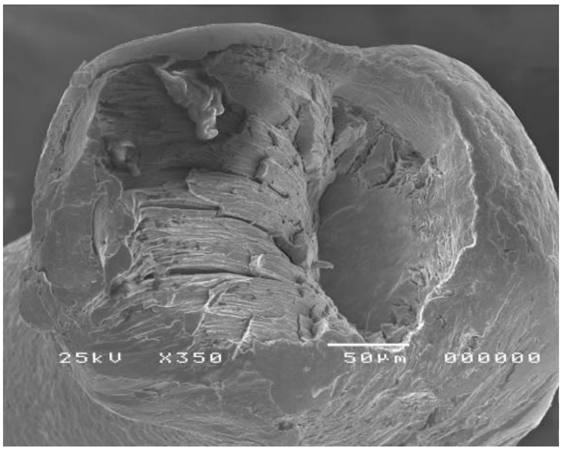


Figure 6: Typical green fracture

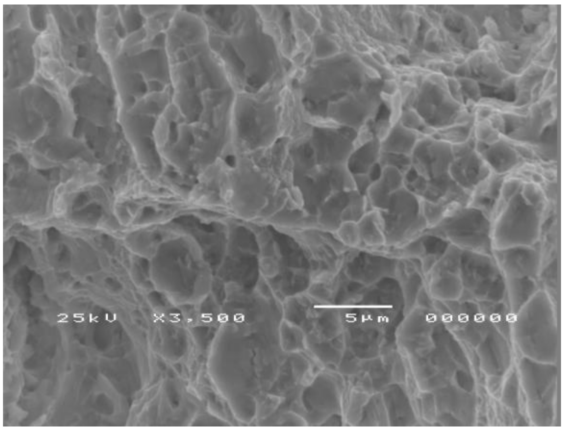


Figure 7: Typical fracture surface.

8. ESSENTIAL SURFACES

One aspect of the seal design outside the supplier's control is the quality of the sealing surface on the mating components. Working to the recommended surface finish, a repeatable manufacturing process was developed with our component suppliers and assessed to ensure the surface roughness and lay of the material was correct. Using a combination of stylus (see Figure 8) and laser (see Figure 9) measurements, a consistent and reliable process was proved.

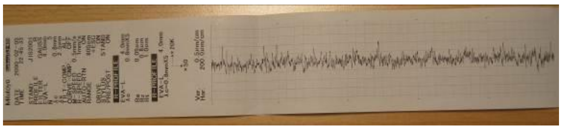


Figure 8: Stylus measurement of the Bulkhead main sealing surface.

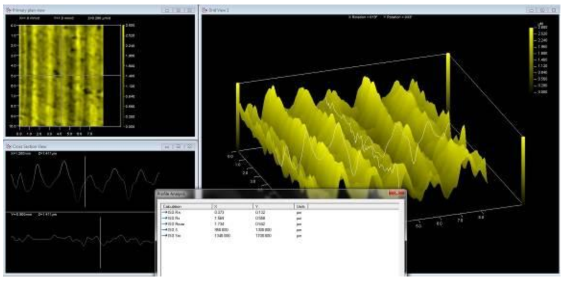


Figure 9: Laser scan measurement of the Bulkhead main sealing surface.

9. MANUFACTURING ISSUES

Manufacturing issues had to also be considered. It was initially considered the seating load for the seal would be applied using a load ring and bolts. The bolts would react against the load ring, compress the seal and hold it in position. However, it was later decided to use a hydraulic press, as this was found to push the bulkhead home in a more even and controlled manner. The press also provides an advantage as the load can be monitored to ensure the seal characteristics are correct and maintained during assembly.

A clean room environment is crucial for reliable sealing. Any contamination of the seal and component mating surfaces could compromise the seal. HMN has invested in a clean room and developed process to prevent this problem.

10. SEAL TESTING AND RESULTS

In order to validate the final seal selection, it was necessary to subject the design to a test that simulates 'in-service' conditions.

The test involved preparing a pressure housing and bulkhead, subjecting it to qualification standard testing, followed by a helium leak test at 83MPa. Helium was used as the trace gas for matters of safety. Hydrogen equivalent values were then calculated by multiplying the helium leak rate by $\sqrt{2}$, based on the molecular flow model[3].

A shortened and representative pressure housing was created with additional ports machined at each end, either side of the metal seal to allow gas to be introduced on one side, whilst allowing any leaks to be detected via a connection to a helium leak detector on the other side. A centre section of material was deliberately left in the pressure housing to ensure each end of the final test vessel could be isolated from each other, so that either individual or combined leak rates could be obtained.

A standard bulkhead was used. The penetrator used for optical and electrical connections was not fitted, but the corresponding hole was sealed. This had no effect on the overall mechanical properties of the bulkhead and the testing of the penetrator features and interface is not considered here.

Each end was fitted separately for ease of assembly. Each bulkhead was fitted with 2 O-rings to provide a water seal, and the spring energised metal seal was placed in the seal groove pressure housing.

Each bulkhead was pressed into position until the correct seating loaded was achieved. The load displacement curve and background helium leak rate was monitored throughout (See Figure 10). When the seating load was achieved, a leak test was performed. Helium was introduced at 5MPa with a target leak rate of < 1 x 10^{-9}cc/s per seal required before it was considered a pass.

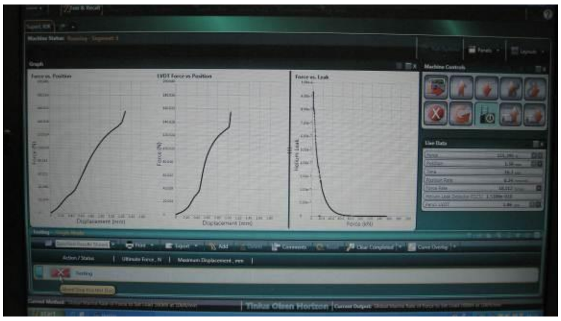


Figure 10: Load v's displacement of press and bulkhead, plus leak rate v's load

The retaining ring and bolts were fitted (See Figure 11) and the pressure from the hydraulic press released. The leak test was repeated.

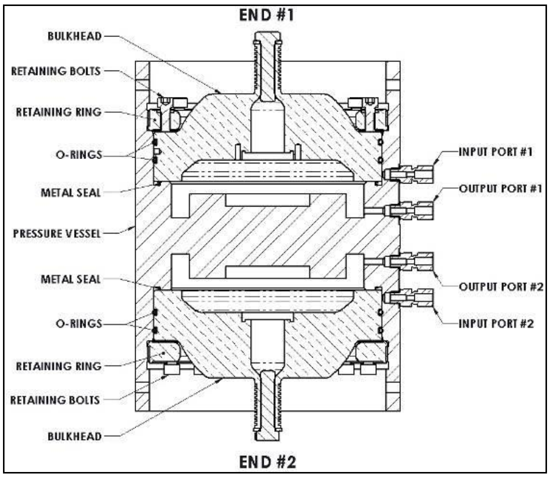


Figure 11: Test assembly section view

The sample was then subjected to a number of qualification tests. After each test, a leak test was performed on each bulkhead.

The tests in order of application were:

1. Temperature cycling to +50 to -20°C with 10 hour dwells for 5 cycles.

2. Bump to 50g, 6ms, half sine, 167 times each of 6 directions, total 1000 times.

3. Vibration to 10-150Hz, 5g, 1oct/min, 3 principle axis, 30 min per axis.

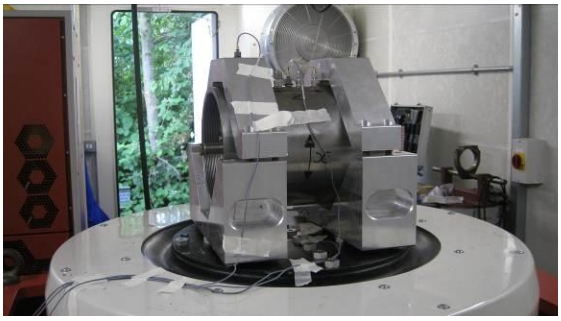
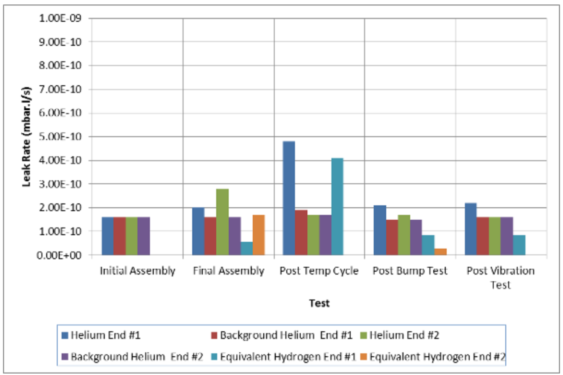


Figure 12: Bump and vibration testing

The result of the leak testing was as follows:

Leak Rate	Helium End #1	Background Helium End #1	Helium End #2	Background Helium End #2	Equivalent Hydrogen End #1	Equivalent Hydrogen End #2
	mbar.l/s	mbar.l/s	mbar.l/s	mbar.l/s	mbar.l/s	mbar.l/s
Test Type						
Initial Assembly	1.60E-10	1.60E-10	1.60E-10	1.60E-10	0.00E+00	0.00E+00
Final Assembly	2.00E-10	1.60E-10	2.80E-10	1.60E-10	5.66E-11	1.70E-10
Post Temp Cycle	4.80E-10	1.90E-10	1.70E-10	1.70E-10	4.10E-10	0.00E+00
Post Bump Test	2.10E-10	1.50E-10	1.70E-10	1.50E-10	8.49E-11	2.83E-11
Post Vibration Test	2.20E-10	1.60E-10	1.60E-10	1.60E-10	8.49E-11	0.00E+00

Table 2: Qualification test leak rates



Graph 1: Qualification test leak rates

It can be seen that the helium leak rates are well within the target of 1 x 10^{-9}cc/s (9.87 x 10^{-10}mbar.l/s). The spike in End #1 after temperature cycling was due to residue helium entering the test environment due to rapid depressurization of End #2 which was not allowed to clear, but sufficiently low enough for evaluation.

11. IN-SERVICE SIMULATION TEST

Following environmental testing a full hydrostatic pressure test at 83MPa was conducted. Global Marine's 16 inch pressure vessel is able to pressurise to an equivalent sea depth of 8km and provide connection ports through the lid.

Figure 14: Test sample is attached and connected to the pressure vessel lid

The assembly was attached to the underside of the pressure vessel lid and pipes connected to the ports (See Figure 13), through the lid to the gas supply and leak detector.

The connections allowed the gas to be pressurised with helium at both ends either individually or combined (See Figure 15).

Figure 15: Test sample is connected to the helium leak detector (left) and helium source (right)

The test began by applying 5MPa of helium to both ends simultaneously and monitoring the combined outputs. The water pressure was increased to 83MPa at a rate of 1MPa/min (See Figure 16 & 17) after which a total combined helium measurement (See Table 3) was taken. The sample was then held at pressure for 8 days.

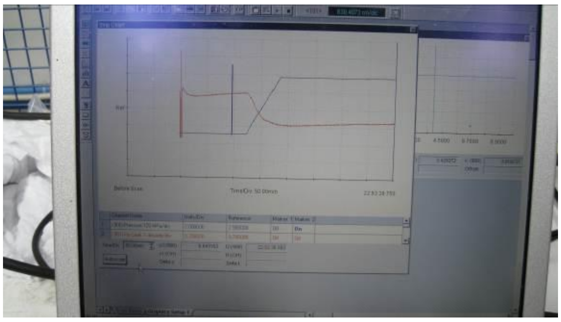


Figure 16: The graph shows pressure increase in blue and corresponding drop in helium leak rate in red

Readings were taken regularly to ensure no leaks.

Figure 17: Helium leak rate

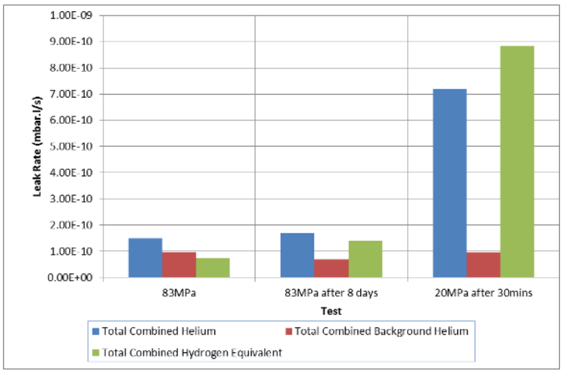
After 8 days the pressure was then removed at a rate of 1MPa/min until it was depressurised.

The final part of the test determined if the pressure could be re-applied to a lower level to see if hemeticity could be maintained. The pressure was increased until the pressure reached 20MPa and held for 30 mins. This part of the test was to see if the equipment could be redeployed and maintain leak rate performance. Pressure was then removed and the assembly recovered from the pressure vessel.

The results of these final tests are:

Sample	Total Combined Helium	Total Combined Background Helium	Total Combined Hydrogen Equivalent
	mbar.l/s	mbar.l/s	mbar.l/s
Test Type			
83MPa	1.50E-10	9.80E-11	7.35E-11
83MPa after 8 days	1.70E-10	7.00E-11	1.41E-10
20MPa after 30mins	7.20E-10	9.60E-11	8.82E-10

Table 3: In-service test leak rates



Graph 2: In-service test leak rates

It can be seen that the helium leak rates are well within the target of 1 x 10^{-9}cc/s (9.87 x 10^{-10}mbar.l/s).

As with both sets of results it is possible to subtract the background helium leak rate from the measured leak rate and then multiply it by √2 to provide an equivalent hydrogen leak rate.

12. DISCUSSIONS

It is clear that the seals selected achieved a leak rate better than 1 x 10^{-9}cc/s (9.87 x 10^{-10}mbar.l/s) of helium across both seals combined.

It should be noted that the background levels of helium are different between the qualification testing and the in-service testing. This affect is due to the environment the testing was conducted in. The qualification leak tests were performed in an enclosed laboratory area, and subject to frequent helium testing and discharges. This resulted in high levels of background helium that was absorbed through the leak detector test port o-ring external to the sample. This results in a high level of background helium. The in-service leak rate testing was performed in a large, open structure that allowed helium to escape more readily, hence the lower readings.

The background reading also gives an indication to the initial quality of the seal, as any significant leaks would prevent a vacuum from forming and would pull atmospheric helium (approximately 5ppm in air) into the detector which would be readily detectable.

Figure 16 provides an interesting view of how the application of hydrostatic pressure affects leak performance. This was expected as FEA analysis had shown compressive material movement. This closing of gaps and voids reduces available leak paths.

13. CONCLUSIONS

The testing revealed the development steps implemented by HMN achieved the design requirement of producing a hermetic seal that performed to the prescribed levels of better than 1 x 10^{-9}cc/s (9.87 x 10^{-10}mbar.l/s) for its wet plant bulkhead housing interface.

The tests also showed:

1) The pressure housing, bulkheads and seal design worked as expected.

2) As the pressure increases the sealing of the assembly improves.

3) The springback in the seal allows the equipment to be recovered and redeployed whilst maintaining an hermetic seal.

4) The test equipment can be used to verify seal performance at extreme environmental and hydrostatic conditions.

5) The sealing solution is transferable to other critical interfaces, such as the penetrator/bulkhead.

14. REFERENCES

[1] J M Jacobs (Corning), The Impact of Hydrogen on Optical Fibers, White Paper, 2004

[2] A Roth, Vacuum Sealing Technologies, American Vacuum Society, AIP Press, 1994

[3] American Society for Non-destructive Testing, Non-destructive Testing, Volume 1 - Leak Testing, Second Edition, 1985

15. ACKNOWLEDGEMENTS

The author would like to express his gratitude to the following:

Global Marine Systems Ltd

Mussett Engineering

Scantron Ltd

Elements Sheffield (formally Sheffield Testing Laboratories Ltd)

Peter Frost (formally Global Marine Systems Ltd)

David Walters (Consultant)