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Static Seals for Sealing Hydrogen: A Review

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Hydrogen has a potentially large role in the future of energy, either as a fuel, as an energy storage vehicle, or both. Based on the amount of research work and government funding in this area, such as the US Government's pledge of $7 billion for hydrogen hubs, it would be a good assumption that the role of hydrogen is set to grow for the foreseeable future. This is especially the case for so called green hydrogen, where hydrogen is produced by the electrolysis of water and the electricity used in the electrolysis is from a renewable energy source (e.g., wind, solar).

Due to its inherent properties, there has been some concern about the potential for leakage of hydrogen in this new process industry. This, of course, brings into focus the sealing of static bolted connections, i.e., bolted flange joints. The most common leakage tests for bolted flange connections use either helium (EN13555), methane (ASME B16.20) or nitrogen (DIN 3535), but not hydrogen. There are good reasons for choosing these gasses, particularly helium, which is safe and a small molecule which can be detected and measured by standard equipment such as a mass spectrometer.

Other literature has shown that leak rate of different gases cannot be judged and predicted by molecule size alone, therefore the conversion of leak rate using a standard test and test gas cannot be easily converted to a leak rate of hydrogen. Therefore, testing of gaskets with hydrogen has been required to make engineering decisions.

This paper will review recent public domain papers on sealing tests using hydrogen, especially those comparing hydrogen sealing rates to helium sealing rates. This paper will also include some recent hydrogen sealing testing commissioned at a third party test house using spiral wound gaskets with different fillers.

1 Introduction

Hydrogen is well placed to be a key part of any transition towards a cleaner and more sustainable energy economy. Decarbonization of processes such as electricity generation, steel making, and other industrial processes will likely utilize hydrogen as a key part of the process.

It would not be a valuable use of time to spend a large part of this paper discussing the place of hydrogen in upcoming energy transition when there are multiple conferences and publications in this field which cover this subject in more detail. Examples would be publications and events organized by the Fuel Cell and Hydrogen Energy Association [1] and Hydrogen Europe [2].

The chemical element hydrogen is part of many everyday chemicals and materials, including fossil fuels and polymers. Therefore, there is already an established global industry that uses hydrogen or chemicals containing hydrogen. One of the most common, as will be discussed below, is the petrochemical industry. This industry contributes significantly to the more than 100 Mt/y of hydrogen produced today, often by steam methane reforming. While this industry is established, it will likely have to move beyond its current grey hydrogen production and into blue and even to green hydrogen (see Figure 1 below).

While the science of the matter is still evolving, it currently appears that hydrogen is an indirect greenhouse gas [3]. This means that it indirectly contributes to global warming by impacting chain reactions in the troposphere and stratosphere [3]. In fact, one recent report has shown that hydrogen has a Global Warming Potential (GWP) over 100 years of at least eleven times that of carbon dioxide. By way of comparison the GWP of methane is >80 times that of carbon dioxide [4].

Therefore, as hydrogen use becomes more common in decarbonization, the control of fugitive emissions of hydrogen will become more important, including controlling flange leaks.

A common concern with the use of hydrogen is the safety issues surrounding its use. While appropriate safety precautions must be taken, hydrogen is arguably no more or less difficult to use than other flammable gases [5]. However, as the gas is flammable, the fugitive emissions can also present a risk.

Table 1: Comparison of flammability limit and explosive limit properties

	Flammability Limits in Air (vol %)	Explosion Limits in air (vol %)
Hydrogen (H_2)	4.0 - 74.0	18.8 - 59.0
Methane (CH_4)	5.3 - 15.0	5.7 - 14.0

Clearly from a test laboratory perspective, helium is a more preferred test media than hydrogen. There are a few reasons for this, including helium being inert and non-flammable and easily detected using a mass spectrometer. Typically, few modifications are needed to any test laboratory in order to use helium. In contrast, testing with hydrogen or methane would require significant safety related modifications to a test environment.

2 Materials and Methods

There are a number of test methods currently used in the industry, and a number of different gasket types that can be used to seal hydrogen, based on application conditions. These will be introduced below.

2.1 Colours of Hydrogen

In the simplest explanation, hydrogen is a colorless, odorless, tasteless, non-poisonous, and non-toxic gas. Therefore, the use of colors when describing hydrogen a potential source of confusion.

Colour	Fuel	Process	Products
Brown/Black	Coal	Steam reforming or gasification	$H_2 + CO_2$ (released)
White	N/A	Naturally occurring	H_2
Grey	Natural Gas	Steam reforming	$H_2 + CO_2$ (released)
Blue	Natural Gas	Steam reforming	$H_2 + CO_2$ (% captured and stored)
Turquoise	Natural Gas	Pyrolysis	$H_2 + C$ (solid)
Red	Nuclear Power	Catalytic splitting	$H_2 + O_2$
Purple/Pink	Nuclear Power	Electrolysis	$H_2 + O_2$
Yellow	Solar Power	Electrolysis	$H_2 + O_2$
Green	Renewable Electricity	Electrolysis	$H_2 + O_2$

Figure 1: Illustration of the colours of hydrogen and the processes involved [6]

From a chemist's perspective and assuming equal purity, one color of hydrogen is exactly the same as another. In Sealing Technology terms, one color of hydrogen should not be more difficult to seal than another.

The colour designation is often used to indicate the method of its production. What is more important to the sealing requirements, are the process conditions, which obviously differ depending on the colour and process. For example, grey hydrogen can be produced at >400°C and relatively high pressures, whereas green hydrogen from a Polymer Electrolyte Membrane (PEM) stack or alkaline stack will be produced at <100°C, at near ambient pressure.

Grey hydrogen is by far the most common in the world today and has been for many decades. Grey hydrogen accounts for >95% of the hydrogen manufactured today and is by definition made from fossil fuels, specifically natural gas, most typically inside a refinery using steam methane reforming. One refinery will have multiple steam methane reformers and the grey hydrogen will either be consumed within the refinery or collected as a feedstock for a process elsewhere.

Blue hydrogen is essentially grey hydrogen where the carbon consumed and/or produced in manufacturing is captured and prevented from being emitted to the atmosphere. Most commonly, this is through carbon capture and storage (CCS). This would commonly be achieved in brownfield sites by adding a sequestering unit to existing equipment.

Green hydrogen is hydrogen that is (typically) manufactured by the electrolysis of water into its constituent elements (hydrogen and oxygen) using renewable energy such as wind or solar. Electrolyzer stacks are being developed that are based on multiple evolving technologies, including PEM, Alkaline and Solid Oxide (SOEC).

Stacks fall into generally two types, higher temperature (500-900°C) technologies such as SOEC and occasionally Molten Carbonate Cells (MCEC) and lower/moderate temperature (75-200°C) technologies such as PEM and Alkaline.

2.2 Gasket Types

There are several situations where hydrogen can be used and therefore would need to be sealed. Examples include its manufacture by possibly steam methane reforming or electrolysis, subsequent compression, liquefaction, or storage. This means logically that a wide range of static seal (gasket) types would be used to seal hydrogen, but exactly which type of gasket would depend on the exact application conditions, particularly the temperature and pressure.

Steam methane reforming systems have been sealed by standard semi-metallic gaskets for decades. Typically, a Spiral Wound Gasket (SWG) with austenitic stainless steel winding wire and a graphite filler can be used successfully (figure 2).

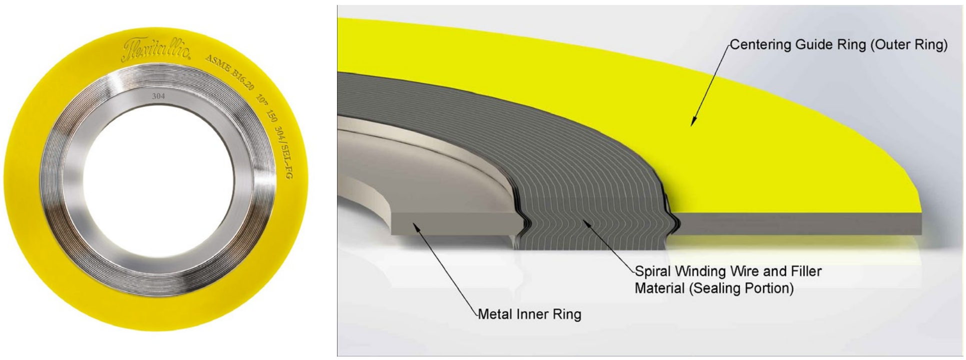

Figure 2: Illustration of a Spiral Wound Gasket. Front view (left) and cross section (right)

SWGs can be manufactured with a variety of conformable filler materials. Exfoliated graphite (also known as Flexible Graphite) is the most common filler for SWGs. However, other filler materials are used in other applications where there are different operating conditions, and these different operating conditions may be encountered in different parts of the Hydrogen industry. Some new sealing data will be presented below in Section 4.

An illustration of a Kammprofile gasket, discussed in section 3.5 below is shown in figure 3.

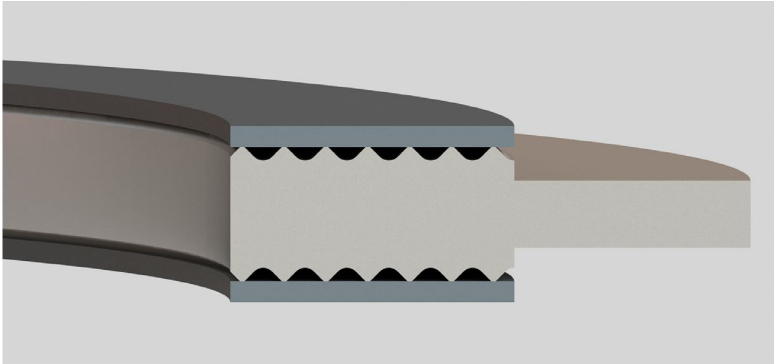

Figure 3: A cross section iillustration of a Kammprofile gasket, with a serrated metal core and outer ring, plus a soft sealing material as a facing

In electrolysis for green hydrogen using PEM or Alkaline stacks, the temperature is relatively moderate, therefore high-quality rubber and PTFE gaskets can be used. For sealing SOEC systems, which operate at temperatures between 500 and 900°C, a key issue can be the low stress available to seal due to both the temperature and the nature of the ceramic components used. This can lead to some challenging sealing situations. In SOEC systems, typical seals are either glass or vermiculite based.

2.3 Testing Methods

The most common leakage tests for gaskets in bolted flange assemblies include CEN EN13555 [7], which uses helium as the test gas, ASME B16.20 [8] (methane) and DIN3535 [9] (nitrogen). None of these tests mandate the use of hydrogen. It should also be noted that there is little mechanical similarity between these tests, and it is hard to compare results from one test with results from another.

There are good and practical reasons for choosing these gases, particularly helium, which is a safe test gas, it is nonflammable and non-toxic. Furthermore, it is the smallest molecule. It is true that hydrogen is the smallest atom, but hydrogen exists in diatomic form as H_2 which is larger than helium, which exists in the atomic form.

It has been shown from earlier papers [10] that molecule size is not the only factor which effects leakage rates, and the conversion of leakage rate from one gas to another is not universally understood.

However, the type of gas flow that leads to leakage could be laminar flow, molecular flow, or a mixed mode. Therefore, depending on the type of gas flow, the relative rates for different gases can vary and the rates themselves are different for each mode [11]. The experimental investigation of gas flow and leakage is not the purpose of this paper, but it remains an area of industry interest.

2.3.1 EN13555 Testing Methodology

This section is simply a summary of the test methodology, full details are in the standard [7]. The EN13555 sealing test is typically carried out on a Amtec Temes *fl.ai1* test machine, the test is pre-programmed into the software.

In the test, helium leakage is measured at successive gasket stresses which change according to the specification. Typically, the stress is successively raised, and drops back after each new, higher stress, with a 40 bar helium leakage test at each step. Data is presented graphically and in tabular form.

Graphically, leakage vs gasket stress is presented (for example Figure 7 below). The leakage axis is logarithmic, with horizontal lines at each decade. The black dots represent actual leakage tests. The dots are joined sequentially with the course of the test.

The software interpolates the minimum load required to reach a certain sealing class (eg a leak rate of 0.01 mg/m/s, which is designated L 0.01) and this is given in a table and shown as a yellow dot on the graph (figure 7) at each decade of leakage. The table shows data for stress required on assembly to reach a certain leakage class ($Q_{min(L)}$ or loading) and in service ($Q_{smin(L)}$ or unloading).

This $Q_{(min)L}$ term is defined in EN13555 [7] Section 3.2 as the minimum gasket surface pressure, on assembly, required at the ambient temperature in order to seat the gasket into the flange facing roughness and close the internal leakage channels so that the tightness class to the required level (L) for the internal test pressure. The term $Q_{smin(L)}$ is defined as the minimum surface pressure required for leakage rate class L after off loading.

3 Review of Published Data

In recent years several third-party test laboratories have expanded their test capabilities to include leakage testing with hydrogen [12, 13, 14]. Comparisons can only be made from the plots made available in the publications. Sometimes estimations must be made from observing the plots as exact leak rate data may not be noted on the chart (it is not normal for this information to be noted on the chart) and from the $Q_{(min)L}$ table (also typically not shown but always recorded during the test). For data gathered in house, this leak rate data is available, as is the minimum required gasket stress in assembly, $Q_{(min)L}$.

It should be noted that some of this data has previously been reviewed [15], but since the publication of that paper, further data has become available for inclusion.

3.1 Aramid Fibre/Rubber Compressed Sheet gaskets

Aramid fibre and rubber compressed sheets have been known for many years, and their predecessor formulations date back over 120 years. In 2022, Übermesser et al published some data on the sealing of these types of materials using hydrogen and helium [16]. This testing used a flange connection using the principles of

VDI2440/2200 [17]. The authors concluded that at two gasket stresses, using their test conditions, there were no significant differences between the sealing of helium and the sealing of hydrogen.

Berger [18] completed some hydrogen compatibility tests on these types of gaskets and some graphite sheet gaskets and concluded that no notable changes in gasket material properties could be observed with storage in hydrogen. Berger also completed some leakage testing of three grades of sheet material with hydrogen and nitrogen using the principles of DIN 28090-02 [19]. In all cases, the mass leak rate for nitrogen was higher than for hydrogen. Also, the order of performance for the three grades was the same for both gasses, which is still a useful conclusion.

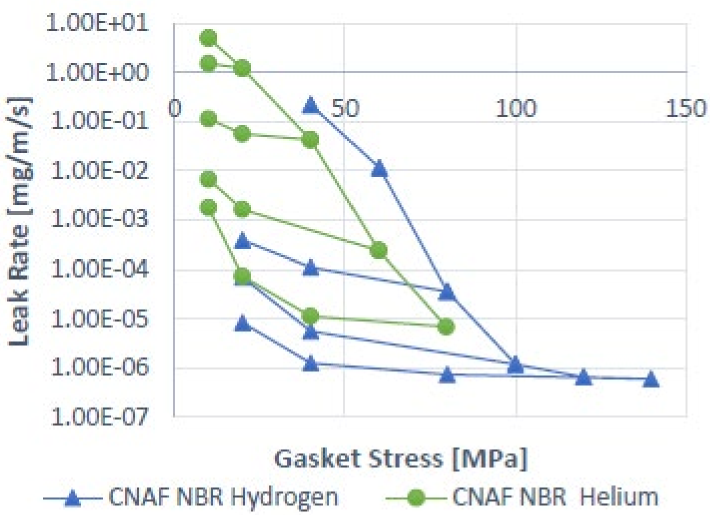

Figure 4: EN13555 sealing plot for Aramid Fiber/Rubber compressed sheet gasket

In a different publication, General and Norman [20] tested an un-named material using EN13555 testing using both hydrogen and helium. Figure 22 in this publication (figure 4 here) shows a direct comparison between leakage tests with these two gasses. Unfortunately, the data for helium is only shown to 80MPa while the data for hydrogen is shown to 160 MPa. While the leakage curves are somewhat similar, the leak rate for hydrogen appears to be consistently lower. This lower leakage rate with hydrogen is probably approximately the difference from the helium data than would be expected from normal experimental variation.

General and Norman also tested some ASME B16.21 sheet materials, specifically a FKM gasket and some ePTFE (discussed in section 3.3 below). Unfortunately, no reference was made to their source or physical properties.

In order to compare the hydrogen sealing data of FKM from Gordon and General, we completed a sealing test of a representative FKM gasket [15] and determined that (bearing in mind some assumptions) the performance was similar in hydrogen and helium.

3.2 ePTFE Gaskets

Expanded PTFE (ePTFE) is a specific form of PTFE that can be formed into a useful sheet gasket material, it is especially useful for low stress situations and aggressive chemicals. This material was developed by W. L. Gore [21], however the key patents have expired, and this type of material is now manufactured by a small number of other manufacturers.

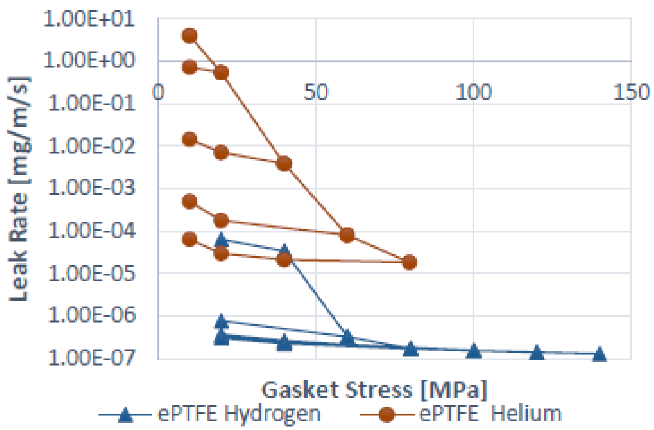

Figure 5: EN13555 sealing plot for ePTFE gaskets [20]

General and Norman [20] also included a comparison of hydrogen and helium sealing for an ePTFE sheet. Unfortunately, they provided no source information on the grade of ePTFE used. Figure 23 of their paper (figure 5 here) shows that the leakage rate for helium is as much as two orders of magnitude higher than the leakage rate with hydrogen. This is a very significant difference that is unlikely to be explained by test error or variation.

Teadit have published a product information sheet [22] showing hydrogen sealing data for their ePTFE grade 24 SH (figure 6). It was possible to compare this data to data published helium leakage data on gasketdata.org [23], shown in figure 7. Figures 6 and 7 show that sealing for hydrogen is again better than sealing of helium.

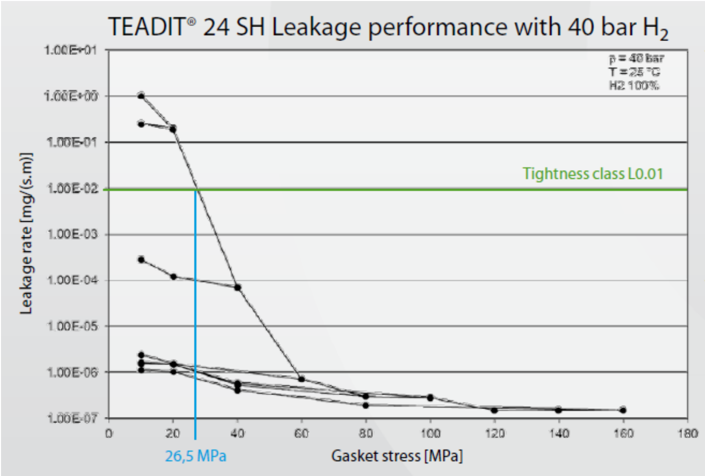

Figure 6: EN13555 Sealing plot for ePTFE [22]

The $Q_{(min)L}$ data for L 0.001 are similar, 26 MPa for hydrogen and 30 MPa for Helium, but at gasket stresses greater than 60 MPa the sealing of hydrogen is better.

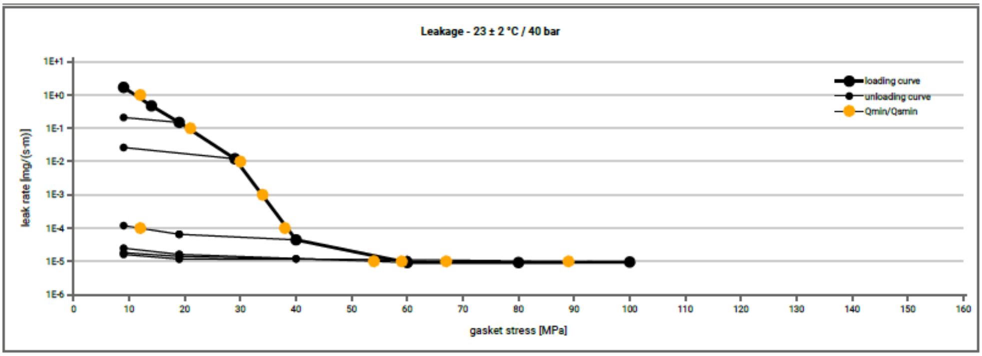

Figure 7: EN13555 Sealing plot for ePTFE [23]

At this point it is not clear why there is a difference between hydrogen and helium sealing performance with ePTFE gaskets. This difference has been shown by two independent studies.

3.3 Graphite Sheet Gaskets

Berger [18] also discussed graphite gaskets and showed that testing of graphite gaskets gave a similar pattern of results to the results for aramid fibre / rubber compressed sheet gaskets. Nitrogen mass leak rates were again higher than hydrogen leak rates. Different results were recorded for different sheets and the order was the same, as observed above.

SGL Carbon have published a comprehensive document on hydrogen stability (compatibility) and sealing for their range of graphite gasket materials [24]. They provide hydrogen sealing curves for a number of their grades of materials, including some testing at different internal pressures and a comparison of hydrogen and helium leakage curves for Sigraflex Hochdruck Pro (figure 8).

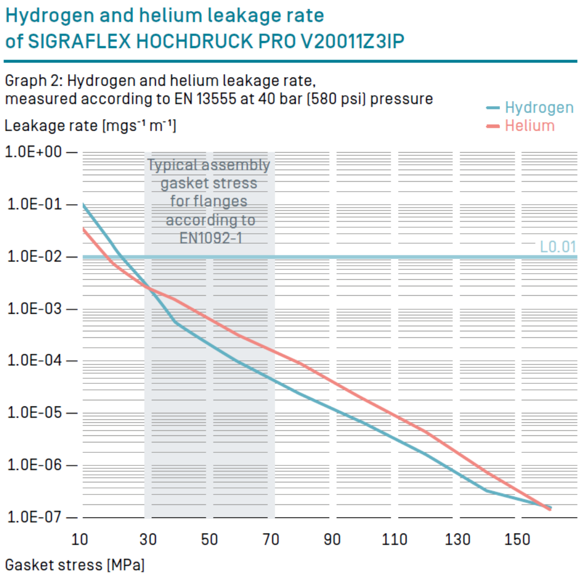

Figure 8: EN13555 Hydrogen sealing plot for a Graphite Sheet Gasket

Their conclusion is that at gasket stresses of above 40MPa the leakage of hydrogen is less than the leakage of helium. However, the difference is not large. They further conclude that helium data could be used to perform flange tightness calculations such as EN1591-1. They also provide some long-term sealing plots in accordance with DIN28090-1 and -2 [19] (using nitrogen as a test gas) and conclude that over a 10,000 hour test, graphite can provide a reliable and consistent seal.

The same publication [24] discussed chemical resistance of graphite with hydrogen. The publication states that graphite is chemically resistant in hydrogen from -269°C to 900°C. Starting at temperatures above 900°C, it is possible that the graphite can begin to degrade when the carbon atoms of the graphite can react to form methane gas.

This publication [24] also discusses hydrogen embrittlement of metals and concludes that austenitic stainless steels such as 316L and 304 are less prone to degradation and are the standard (preferred) materials in hydrogen technologies. This conclusion is also pertinent to spiral wound gaskets and kammprofile gaskets.

3.4 Kammprofile Gaskets

Kammprofile gaskets are well known gaskets and are included in standards such as ASME B16.20 [8] and EN 1092 [25]. They consist of a metallic core and a soft facing or sealing material (figure 3). The sealing material is often a similar grade of Flexible Graphite to that used in sheet gaskets and SWGs. Other facings are used when the application conditions require it.

General and Norman [20] discussed the sealing of Kammprofiles in their publication. Figure 19 in this paper (figure 9 here) is an EN13555 plot of a graphite faced Kammprofile comparing sealing hydrogen and helium and Figure 20 is a similar plot for ePTFE faced Kammprofiles.

In both cases there is no discernible difference in the sealing performance in hydrogen and helium.

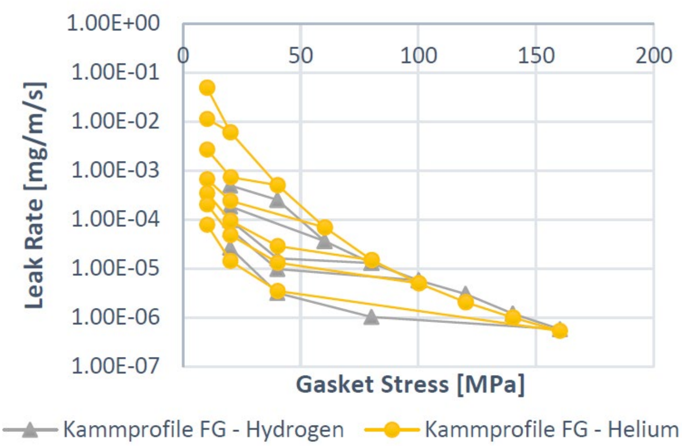

Figure 9: EN13555 Hydrogen sealing plots for graphite faced Kammprofile gaskets.

3.5 Spiral Wound Gaskets

Spiral Wound Gaskets are well known gaskets, they are included in standards such as ASME B16.20 [8] and EN1092 [25]. The sealing element comprises a profiled and wound metal, typically but not exclusively, a stainless steel, co-wound with a soft sealing material, the soft sealing material is often flexible exfoliated graphite, but other fillers can be used depending on the application conditions. These other fillers include PTFE, mica and vermiculite-based fillers.

General and Norman [20] presented sealing data for hydrogen and helium on graphite SWGs. They compared construction of gasket, Low Emission (LE) vs “Standard” constructions. While the LE gasket sealed more effectively than the standard construction, the difference between hydrogen and helium sealing was not discernible in either case.

In house manufactured SWGs were included in a previous publication [15], however, some new data has been gathered and the information will be presented in the following section.

4 Spiral Wound Gasket Sealing Data

The information published previously [15] investigated different types of filler, that data will be presented here, along with new data on a PTFE filled SWG. In all cases, the SWGs were made in our Houston facility and a stack of ten sequentially produced gaskets was used for the testing. Each gasket was wound with 316 stainless steel winding wire and fitted with a 316L stainless steel inner ring and a carbon steel outer ring.

Four different fillers were tested in total. A high quality, oxidation resistant flexible graphite, our proprietary high temperature vermiculite-based filer, our proprietary lower temperature vermiculite-based filler and a pure un-sintered PTFE filler.

Helium sealing tests were carried out in our Houston Test lab using the EN13555 sealing method, using an automated multifunctional test rig (Ametc TEMES fl.ai1). Hydrogen sealing testing was carried out at Amtec NA [26] using a similar rig but with modifications for hydrogen testing.

It should be remembered that SWGs manufacturers typically recommend a minimum gasket stress of 69MPa (converted from 10,000psi) and this should be considered when viewing EN13555 test plots, which typically start at 5 MPa gasket stress. The maximum tested gasket stress is typically 160 MPa, which is usually driven by the load available on the Amtec TEMES fl.ai1, which is 1 MN.

4.1 Graphite Filled SWGs

The previously reviewed leakage plots for graphite filled SWGs with different test gases are slightly different (Figures 3 & 6 in reference [15], the hydrogen plot is figure 10 here). The lowest leak rate is recorded at 160 MPa for helium is 3 x 10^{-5} mg/m/s and for hydrogen it is 4.3 x 10^{-6} mg/m/s. For helium the $Q_{min(L)}$ 0.001, which represents the minimum gasket stress in assembly, is 59 MPa and for hydrogen it is 54 MPa which is relatively similar, and lower than the typical minimum required stress to seal for a SWG of 69 MPa. See table 3.

This suggests similar sealing of hydrogen and helium at moderate stresses, and better sealing in hydrogen at high stresses. The unloading curves are also very similar.

4.2 Vermiculite Filled SWGs

While it is understood that the high temperature vermiculite filler was not intended for ambient temperature use, it is a worthwhile test to carry out in the context of this review. The high temperature (HT) vermiculite based SWG filler has a very similar lowest leakage rate (at 160 MPa) in both cases, the lowest leakage rate was 3.0 x 10^{-7} mg/m/s for the helium and 1.7 x 10^{-7} mg/m/s for hydrogen.

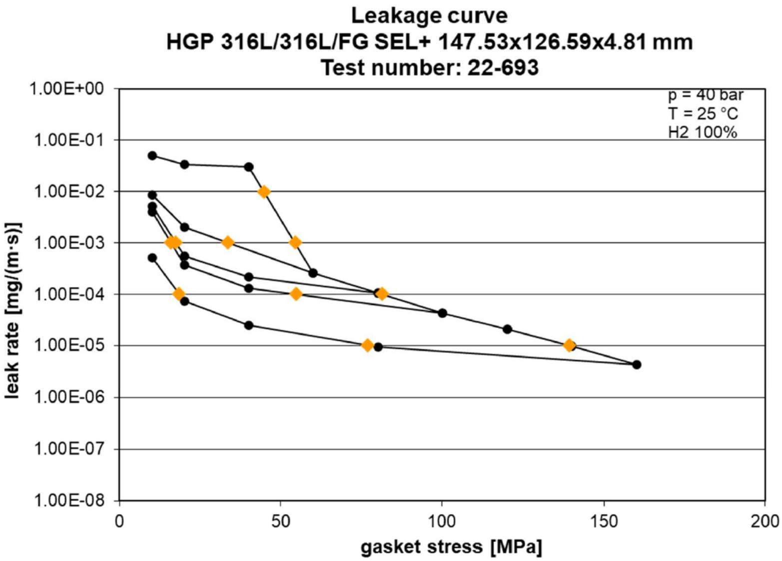

Figure 10: EN13555 Hydrogen sealing plot for the LT vermiculite (CR235) SWG

The Tightness Class L0.001 in helium was 87 (compared to 59 for graphite), in hydrogen this tightness class was achieved at 28 MPa, which is extremely low (good). In fact, a tightness class of 0.000001 was achieved at 75 MPa in Hydrogen (this level was not achieved in helium). This suggests the high temperature vermiculite has some ambient sealing advantages in hydrogen, compared to graphite.

The lower temperature (LT) rated vermiculite filler has a different proprietary formulation to the high temperature version and will not go through significant thermal changes within its operating window. The data shows it has a very attractive sealing curve, especially with hydrogen as the test gas, see Figure 11. The lowest leak rate when tested with hydrogen is 1.2 x 10^{-7} mg/m/s (compared to 2.3 x 10^{-6} mg/m/s when tested with helium), See Table 2.

The LT vermiculite filled gasket reaches high tightness levels at a stress less than the nominal minimum recommended assembly stress for both test gases. A tightness class of 0.001 was achieved at 58 MPa with helium and 60 MPa with hydrogen. A lower tightness class of 0.00001 was achieved at 83 MPa with helium and 60 MPa with hydrogen as the test gas. Both of these stress levels are around the nominal minimum load to seal for SWGs (10,000 psi / 69 MPa). See table 3.

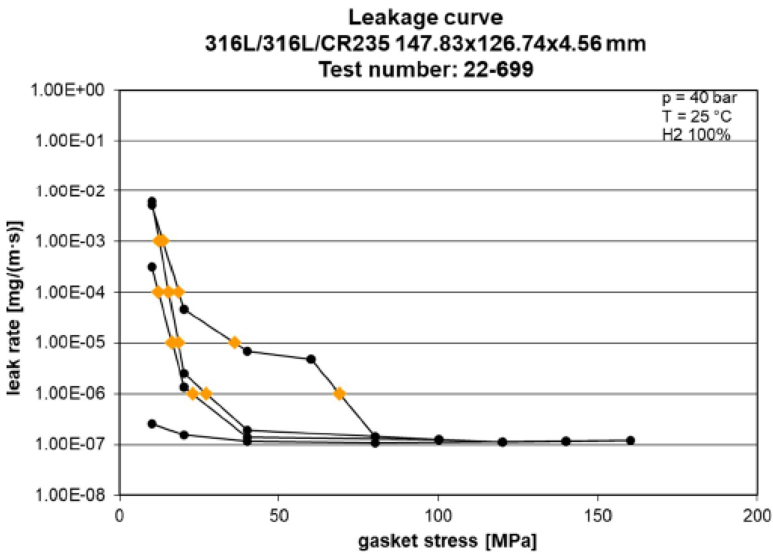

Figure 11: EN13555 Hydrogen sealing plot for the LT vermiculite (CR235) SWG

Interestingly, the LT vermiculite filler has a leak rate which is slightly lower than the high temperature vermiculite filler at 160 MPa and an order of magnitude better than graphite in these SWGs in hydrogen.

Furthermore, the unload lines from the hydrogen sealing test for the low temperature vermiculite filler are very flat until at 40MPa or below. The $Q_{smin(L)}$ in every case is below 30 MPa, which is potentially advantageous.

4.3 PTFE Filled SWGs

As with previous testing, helium leakage tests were carried out in-house and hydrogen testing was carried out at a third party (Amtec NA) [26]. Figure 11 is reproduced from the second of these reports [26]. The lowest leak rate was recorded at 160 MPa and was 6.0 x 10^{-8} mg/m/s for helium and 3.4 x 10^{-7} mg/m/s for hydrogen. This is a very low leak rate in both helium and hydrogen.

The minimum stress required to achieve a tightness class of 0.001 as reported above was achieved at below 20 MPa for hydrogen. The same low stress to seal was found with helium, see table 3.

During the unloading cycles, the leakage of the PTFE SWGs stayed very low (Figure 11) and the $Q_{smin(L)}$ in every case is very low, lower than SWGs with other fillers.

4.4 Summary of SWG Performance

Table 2 and Table 3 show a summary of the sealing properties of SWGs with different fillers, where both helium and hydrogen are used as the test gas. In Table 3

L=0.001 was chosen as it is tighter than the VDI requirements and the results for this tightness class are often close to the minimum stress to seal for a SWG.

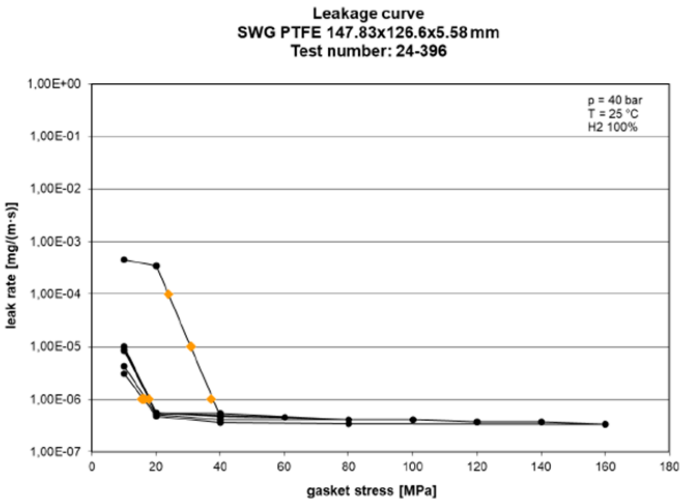

Figure 11: EN13555 Hydrogen sealing test for a PTFE filled SWG.

Table 2 shows that in terms of sealing at higher stresses (160 MPa) all of the gaskets are generally good, but the graphite filled SWG stands out as the least good in hydrogen by approximately an order of magnitude. This is true for the graphite gasket tested with helium also. Both of the Vermiculite filled SWGs perform better than graphite in both test gasses. The PTFE filled SWG is the best in helium and similar to both vermiculite filled SWGs when the test gas is hydrogen. However, as previously stated, all of these results are good. This is confirmed using different data in table 3, below.

TABLE 2: Leak rate at 160 MPa for different SWG fillers (mg/m/s)

SWG Filler	Test Gas	
	Helium	Hydrogen
Graphite	3.1×10^{-5}	4.3×10^{-6}
HT Vermiculite	3.0×10^{-7}	1.7×10^{-7}
LT Vermiculite	2.3×10^{-6}	1.2×10^{-7}
PTFE	6.0×10^{-8}	3.4×10^{-7}

In terms of minimum load to seal in the assembly condition, L = 0.001, all of the SWGs are slightly better when hydrogen was the test gas. Almost every case this tightness class was achieved at lower than the typical recommended stress to seal for a SWG.

In all cases, the unloading portion of the EN13555 leak test was good and the $Q_{smin(L)}$ values were low. In the interest of brevity these are not shown here. In each case the unload lines were flat until 40MPa or lower was reached.

TABLE 3: Stress (MPa) required to achieve tightness class L = 0.001

SWG Filler	Test Gas	
	Helium	Hydrogen
Graphite	59	54
HT Vermiculite	87	28
LT Vermiculite	58	<60
PTFE	<20	<20

One final consideration when sealing hydrogen is fire safety. One of the most common tests for gaskets is the API 6FB fire test [27]. Only a few sheet gaskets are considered fire safe, while many kammprofiles and SWGs are. PTFE SWGs are not generally considered fire safe, including in this API 6FB test. However, graphite [28] and vermiculite filled SWGs (both LT and HT) [29, 30] pass this fire test.

5 Discussion

It is clear that hydrogen will form an important part of the energy transition and of multiple industries in the upcoming decades. Therefore, it is important that the sealing of hydrogen is well understood, across a range of application conditions and for a range of gasket styles and types.

From the data collated from many sources and presented above, it can be observed that many, if not all, of the common conformable sealing materials used today are compatible with hydrogen and therefore suitable for sealing hydrogen.

It can generally be observed that the leakage rates of helium and hydrogen are relatively similar.

Previous work has shown that aramid fiber sheets, elastomeric sheets and ePTFE sheets can seal well in both hydrogen and helium.

As one would expect, very low leakage values are achieved for many types of gasket including graphite and ePTFE. Semi-metallic gaskets such as kammprofiles and SWGs also provide very good seals with hydrogen leak rates as low as 1.2 x 10-7 mg/m/s at 160 MPa for a low temperature vermiculite filled SWG. This is better than the standard graphite filled SWG.

If fire safety is a concern when sealing hydrogen, then graphite or vermiculite SWGs or kammprofiles are considered fire safe, using the API 6FB test standard.

6 Conclusion

Work reviewed here has shown that many common sealing materials can be considered resistant to hydrogen, this includes many soft sealing materials, including common sheet gaskets, and semi metallic gaskets where austenitic stainless steels are commonly used.

Based on the results reviewed, it appears that for many types of gaskets, the sealing performance is similar in hydrogen and helium. This is not the case for nitrogen or methane, as discussed in an earlier publication [15].

Therefore, while some specific applications may require hydrogen testing, the bulk of the data reviewed here suggests that most engineering decisions can safely be made helium leakage data.

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