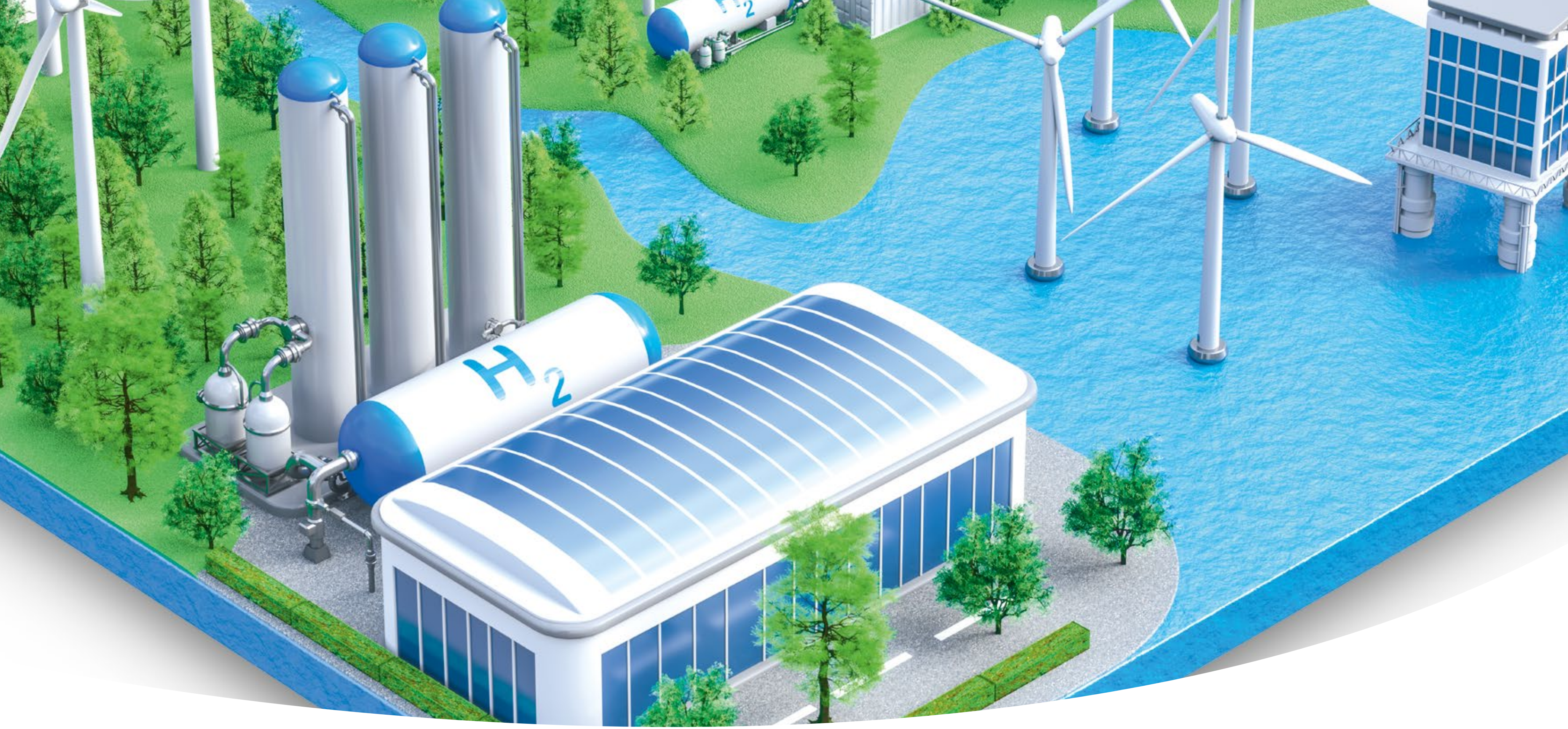


ELECTROLYZERS AND HYDROGEN: WHAT ARE THE REQUIREMENTS FOR SEALS IN RENEWABLE ENERGIES? A WHITEPAPER

ISSUE 2: ELECTROLYZERS AND HYDROGEN

INNOVATING TOGETHER

FREUDENBERG
SEALING TECHNOLOGIES

Content

Executive Summary

The hydrogen economy is experiencing rapid growth and is regarded as a key element of the energy transition. This development is being driven by the pressure to decarbonize, ensure energy security and meet the growing demand of the industry. At the same time, increasing technical and regulatory requirements are appearing along the entire hydrogen value chain – and seals are safety-critical components in these processes. They have to minimize permeation, resist high pressures, withstand explosive decompression (RGD), ensure media and temperature resistance, and provide reliable sealing over long operating periods.

This white paper provides a concise overview of the requirements, material and design recommendations, standards, and best practices for H_2 sealing solutions – specifically prepared for:

- Electrolysis (PEM, AEM, alkaline, SOEC)
- H_2 processing (compression, purification)
- Transport and storage (gas, cryogenic, filling stations)
- Utilization (fuel cell, H_2 ICE)

This process-specific information is supplemented by a checklist to assist with seal selection, an expert interview with Artur Mähne, and a comprehensive summary table that covers applications, materials, and designs.

"The requirements placed on seals in hydrogen systems are fundamentally different from those in conventional gas and liquid applications. They are used in temperatures ranging from -253 °C (cryogenic) to high-temperature environments in solid oxide electrolyzer cells (SOEC/SOFC fuel cells). The small size of molecular hydrogen (H_2) facilitates permeation. At the same time, high pressure fluctuations carry the risk of explosive decompression (RGD – Rapid Gas Compression), while media such as oxygen (O_2), potassium hydroxide (KOH), and sulfuric acid (H_2SO_4) cause the materials to age more rapidly.

Freudenberg Sealing Technologies has been a driver of innovation in the global sealing industry for decades. During this time, we learned that knowledge grows only when it is shared. Our close collaboration with our customers in the early stages of the technology and system development enables us to rigorously coordinate and refine the material selection, design concept, manufacturing, and testing methods for each specific process environment. By clearly focusing on safety, long service life, and the highest purity requirements, we create material innovations and sealing concepts that are safe, compliant, and sustainable.

With this white paper, we examine the application-specific challenges along the entire H_2 value chain. These range from material-based precision seals in electrolyzers and low-wear sealing systems for compressors with excellent PFAS-free sealing performance to integrated stack seals in fuel cells. We show which materials are used where, give industry experts opportunities to speak, and provide links to further information. Our aim is to support your professional work. We look forward to receiving your feedback so we can expand this series of white papers as needed."

Marcel Schreiner
Global Segment Director, Energy at Freudenberg Sealing Technologies

Marcel Schreiner

Which electrolysis processes dominate the hydrogen economy?

Hydrogen can be produced with various methods. For the sake of completeness, we should mention the conventional processes of steam reforming from natural gas (grey hydrogen) and methane pyrolysis (turquoise hydrogen). However, if the goal is to make a forward-looking contribution to reducing greenhouse gas emissions, the focus for large-scale H_2 production is on electrolysis. This method uses electric currents to split water molecules (H_2O) into their components: one oxygen molecule (O_2) and two hydrogen molecules (H_2). Here is a brief overview of the four most important electrolysis processes today:

Proton exchange membrane electrolysis (PEM)

PEM electrolysis uses a proton exchange membrane to split water into hydrogen and oxygen. This method exposes the seals in PEM electrolyzers to extreme conditions: they must withstand dynamic loads in an acidic environment under high differential pressures of up to around 35 bar, with even higher stack pressures expected in the future. Purity requirements (ensuring the absence of metal ions) are also critical for optimal sealing performance. The materials used must be resistant to continuous pressure changes and O_2 oxidation over a long period to ensure the electrolyzer's efficiency and durability.

Anion exchange membrane electrolysis (AEM)

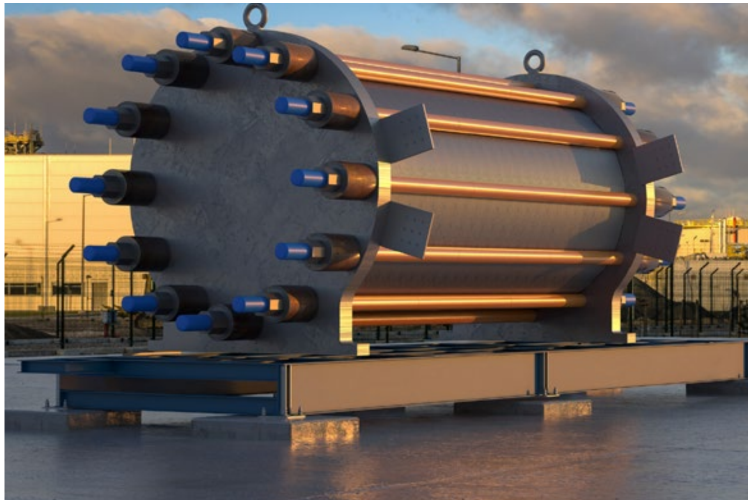
AEM electrolysis uses an anion exchange membrane to electrochemically separate water into hydrogen and oxygen. Here the seals operate in an alkaline environment (KOH). The greatest challenges for the seals lie in ensuring long-term stability in a corrosive environment at higher temperatures. One goal in AEM electrolysis is to use inexpensive catalysts free of platinum-group metals (PGM). This, in turn, plays a role in the selection of sealing materials.

Alkaline electrolysis (AEL)

Alkaline electrolysis (AEL) also uses electric current to split water into hydrogen and oxygen. While AEL is a well-established technology, it places high demands on the seals: AEL seals must be able to resist oxygen pressures of up to 40 bar as well as typical operating temperatures of up to 100 °C. To improve system efficiency, operating temperatures are increasingly being raised to as much as 150 °C. As a result, the materials used must meet stricter requirements for oxygen aging resistance and caustic resistance.

Solid oxide electrolyzer cell electrolysis (SOEC)

A SOEC (solid oxide electrolyzer cell) uses high-temperature electrolysis in a temperature range of 800–1000 °C to split water. This process reduces the decomposition voltage and makes it possible to achieve higher efficiencies than low-temperature methods. It can be used at industrial sites where large volumes of steam are produced at high temperatures. The seals required here also face challenges: The materials and seal designs must withstand the thermal corrosion and relaxation as well as the continuous start-stop cycles.



Electrolyser

What are the sealing requirements along the H_2 value chain?

The requirements for sealing solutions are defined by the media and temperatures involved in hydrogen production and processing, transport, storage, and use. This spectrum covers a broad range: from different electrolysis processes, compression, purification, transport and storage in gaseous, liquid form (cryogenic) or derivatives such as methanol or ammonia, all the way to the end use in fuel cell systems (FC - fuel cell) or hydrogen internal combustion engines (HICE). Let's zoom in:

Production: PEM, AEM, AEL, and SOEC electrolyzers

Operating parameters and risks

Permeation

H_2 permeation causes hydrogen losses and creates a safety risk. Low-permeability material formulations are effective in preventing this. They include CIIR (chlorobutyl rubber), HNBR (hydrogenated nitrile butadiene rubber), EPDM (ethylene propylene diene rubber), and FKM (fluoroelastomer). In this context, it is important to simulate and validate the material-specific permeation coefficients of the seals for each application..

Explosive decompression (RGD)

RGD-resistant materials are required wherever rapid pressure changes occur, for example in tank or compressor environments. These include EPDM, FVMQ (fluorosilicone rubber), and PVMQ (phenyl methyl silicone), among others. The materials used here must have a proven RGD resistance up to ≥ 700 bar.

Media resistance

PEM electrolysis requires seals to withstand dilute sulfuric acid and continuous exposure to O_2. In addition, highly pure materials must be used to ensure that no metal ions leach out and cause ionic contamination.

AEL electrolysis requires seals to withstand a 20-40 percent potassium hydroxide solution. The conventional temperature range (standard AEL) involves operating temperatures of 60–80 °C, an elevated temperature range (modern/optimized AEL) involves operations at 80–90 °C, and high-temperature alkaline electrolysis (advanced AEL) reaches operating temperatures of 100–120 °C. In research and development projects, the operating temperatures can even reach 150 °C. In addition, the oxygen pressure in this application is 35–40 bar. This means that the sealing materials are exposed to strong oxidation with the resulting accelerated material aging. EPDM has proven to be reliable in this area.

Thermal resistance

The sealing materials must also meet the strictest requirements in terms of temperature resistance. Environmental conditions range from <20 to 80 °C during the cold start of a PEM electrolyzer to >800 °C in SOEC applications. Furthermore, tempering processes must be optimized to prevent what is known as fuel cell poisoning. Seal geometry is another fundamental factor in ensuring perfect performance. The seals must pass compression set tests that take all load cases into account, including thermal cycles.

Material and design recommendations

PEM-Stacks

- FKM is ideal for O_2 pressure resistance.
- EPDM/FKM compounds are used in overmolded frames (bonded systems) for reliable assembly and sealing.
- Good to know: There are integrated stack frame seals with an L/C cross section that improve barrier performance under operating pressure. During assembly, the cross section has an innovative L-shape. When the electrolyzer starts operating, its internal pressure rises and activates the seal, which then takes on a C-shape. The increases the seal's contact pressure and turns it into a reliable barrier for gases and liquids.

AEM-Stacks

- Material purity and membrane compatibility are the priorities here.
- EPDM has proven effective in the alkaline environment of AEM stacks.

AEL-Stacks

- PTFE (polytetrafluoroethylene) and ePTFE seals (expanded PTFE) are resistant to the challenging continuous contact with oxygen and potassium hydroxide.
- Under suitable framework conditions, EPDM is a sustainable alternative.

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Processing: Compression, purification, and conditioning

Components and parameter spaces

Reciprocating compressors (H_2)

Reciprocating compressors operate in pressure ranges of 50–500 bar and 350–1000 bar. Small units are designed for a service life of more than 1,000 hours, whereas large units are expected to provide full performance for a period between 8,000 and 24,000 hours. The sealing systems used here (piston rings, rod seals, packings) must be low-wear and absolutely leak-tight and can already function without using PFAS.

Scroll compressors (compressors and vacuum pumps)

Scroll compressors and scroll vacuum pumps operate in pressure ranges of 1–2 bar and a temperature range of -35 to 110 °C. These traditionally use scroll seals (tip seals) made of special PFTE. However, there is a trend towards finding alternative PFAS-free materials.

Tribology and wear

Comprehensive test methods are required to minimize friction-driven interactions between surfaces in compressors, purification systems, and H_2 conditioning processes. These methods are used to test and optimize coefficients of friction and linear wear under realistic conditions. In these applications, fiber-reinforced thermoplastics such as PEEK (polyether ether ketone) and PPS compounds (high-performance thermoplastics) offer low friction and therefore low wear.

Good to know: Design tips

Multi-stage pressure drops of around 50 percent per packing stage along with spring-loaded segments ensure contact and optimize the gap closure. Cooling and dehumidification concepts can significantly reduce the heat input..

Transport and storage: Gas, LH_2, and refueling stations

Components and parameter spaces

Gas and high-pressure storage

These elements of the H_2 value chain are subject to the requirements in UN Regulation R134 with regard to the safety-related properties of hydrogen- and fuel-cell-powered vehicles (HFCVs) and their components. The applications involve O-rings, back-up rings, and valve tappets made of EPDM, FKM, and NBR (acrylonitrile butadiene rubber) that have proven resistance to RGD (rapid gas decompression).

H_2 liquid gas transport at -253 °C (cryogenic)

It is crucial for the materials and coating systems used here to remain ductile even at very low temperatures. For this reason, magnet systems and couplings require hydrogen-compatible surfaces that resist embrittlement as effectively as possible.

Refueling stations and refueling

Hydrogen refueling stations and refueling operations involve rapidly changing pressure profiles. RGD-safe elastomers that provide low permeation are used here as well. Regular maintenance intervals should be specified to ensure smooth system operation.

Utilization: fuel cells and hydrogen internal combustion engines (H_2 ICE))

Components and parameter spaces

Fuel cells – AFC, PEMFC, PAFC, DMFC, MCFC, SOFC

The six types of hydrogen fuel cells listed above are currently used worldwide. Their differences lie in the gases used, the types of electrolytes, the operating temperature, and their performance capacities. They can be adapted to different requirements. The operating temperatures for LT-PEMFC are 60–80 °C and for HT-PEMFC they are 120–180 °C. PAFC operates at 160–220 °C, MCFC at 620–650 °C, and SOFC at 800–1000 °C. Stack seals made of EPDM, FCPO, FKM, and LSR are used in these applications. It is important to select the materials according to the following properties: their compression set, permeation, and media resistance.

Good to know: For optimum service life and performance of the fuel cells, integrated seals at the interface between the bipolar plate and the gas diffusion layer improve the removal of liquid water from the reaction zones.

Hydrogen internal combustion engine (H_2-ICE))

The key advantages of manufacturing H_2 internal combustion engines are the robustness of the technology and the rapid market introduction. All the same, the following challenges must be resolved to ensure that these drive system operate safely: NH3 outgassing, the use of lubrication systems, and abnormal combustion. It is crucial to consider the prevailing temperature range and interaction of all the above-mentioned media when selecting the appropriate sealing systems.

Which seals are required in electrolyzers?

Basic functions and installation points in the stack

Frame seals and flat seals are installed between the cell frames and the bipolar plates. They are used for gas and electrolyte sealing, electrical insulation, pressure retention, and to ensure the purity of the so-called H_2/O_2 separation. The seals are typically manufactured as molded elastomer parts – for example from EPDM or FKM. At this time, flat seals made of PTFE and ePTFE are also used, particularly in alkaline environments.

Sub-seals, edge seals, and seals on the substrate provide sealing near the edges of the membrane electrode assembly (MEA), as well as on plastic frames and metal plates. Numerous variants are available for these seals: seals on plastic frames or on bipolar plates, and loose seals that are edge-bonded, overmolded, or press-fitted. O-rings and extruded sealing profiles are also used here. The selection always depends on the automation level, available installation space, surface pressure, and the specified service life of the components used.

Special high-pressure seals (PEM) are also used in PEM stacks. These seals can be groove-clamped and provided with retention features, for example. They have an L-to-C activating cross section that ensures secure positioning and pressure activation for increasing stack pressures.

Technology-dependent selection criteria

In PEM electrolysis, the pH value is 4–6, the oxygen side is oxidative, the temperature range is 60–120 °C and there are pressures of up to 35 bar. The use of FKM is recommended here due to its low H_2 permeation as well as its O_2oxidation resistance and temperature stability on the stack side. PTFE is normally used in areas with low bolt load and high purity requirements. During the installation, it is important to ensure the utmost cleanliness to minimize ion leaching.

The requirements placed on sealing solutions in AEL and AEM electrolysis are defined by potassium hydroxide solutions of 3–30 percent, temperatures of 60–150 °C, and pressures of up to 35 bar. The prevalent material groups here are EPDM because of its KOH resistance and PTFE/ePTFE because of its chemical resistance. If necessary, electrical insulation can be optimized by using additional frames or suitable sealing materials.

Key design recommendations

- Balance the clamping force against the internal pressure. Sealing grooves provide a force bypass and reduce overcompression and extrusion compared with flat seals that are flush with the flange face.
- Profiled elastomer cross sections significantly reduce the required bolt load – unlike so-called slab geometry.
- Perform a finite element analysis (FEA) and tests to verify the tolerance and pressure resistance.
- Consider seals early on and plan for them before defining the bipolar plate tool. The geometry, suitable material, purity, possible leaching, and the potential degree of automation all have to be decided on.
- Good to know: Standard parts are rarely sufficient – application-specific compounds and designs are generally required.

Which seals are required for H_2 compressors, pumps, storage, and transport?

Compressors

Packing seals made of graphite-filled PTFE are used in reciprocating and diaphragm compressors. To reduce leakage at rods and shafts, low-contact labyrinth seals are installed. PEEK back-up rings are used as extrusion protection devices at high pressures.

In turbo and centrifugal compressors, contactless dry gas seals have proven effective due to their low leakage rates and long service life.

As a general rule, the combination of materials and design in sealing solutions is decisive for the performance of the compression processes.

Pumps and pump peripherals

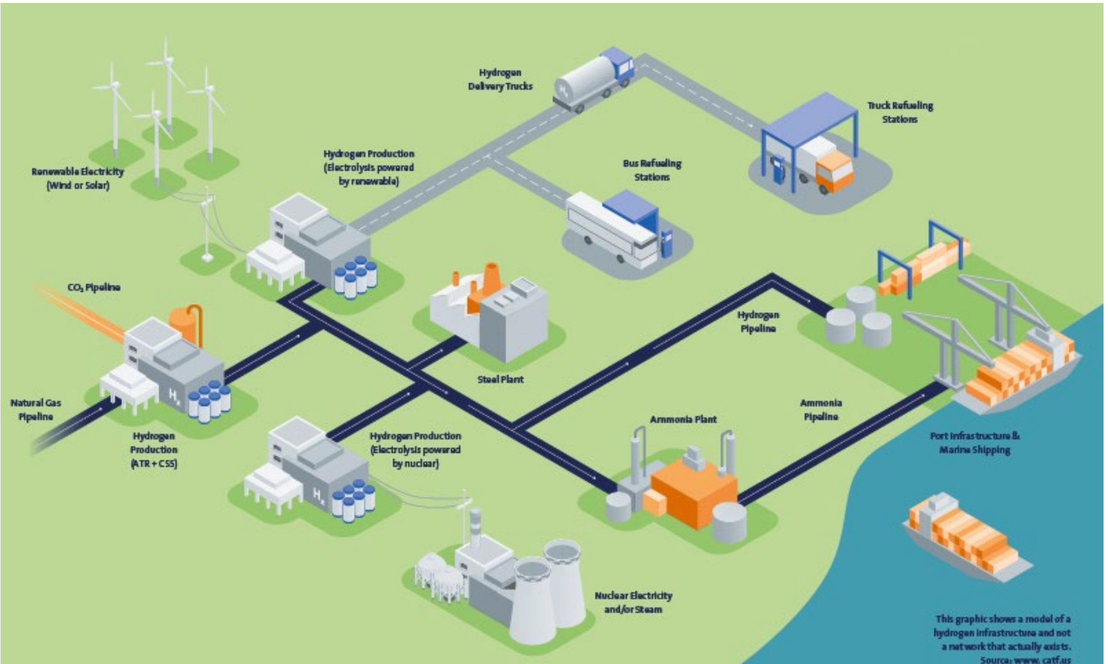
Mechanical seals that correspond to the relevant process media are used in these applications. In addition, gland packings made of graphite are required for rotating units. The seals withstand water and coolants as well as potassium hydroxide solution and CO_2-containing streams. Graphite packings and laminates have also proven effective at elevated temperatures and pressures.

Storage and transport

In addition to permeation, temperatures between -40 and +85 °C and pressures of up to 105 MPa define the operating parameters for compressed gaseous hydrogen. Depending on the medium and temperature, cover seals, O-rings, and O-ring/back-up ring combinations made of EPDM, FKM, and HNBR are installed here. These applications also employ spring-energized PTFE lip seals and metal seals.

Liquid hydrogen (LH_2) is stored and transported in cryogenic form at -253 °C. Elastomers are not suitable materials in this temperature range. Metal and plastic seals made of PTFE are preferred.

Pipe and fitting interfaces must be sealed to be ultra-tight, highly pure, and resistant to high pressure. Stainless steel and nickel alloys are utilized here in the form of VCR® fittings and metal face seals. Cone and thread fittings are also ideal for very high pressures. They provide metallic sealing and have low diffusion.



Which seals are required to convert electrical energy into storable energy carriers?

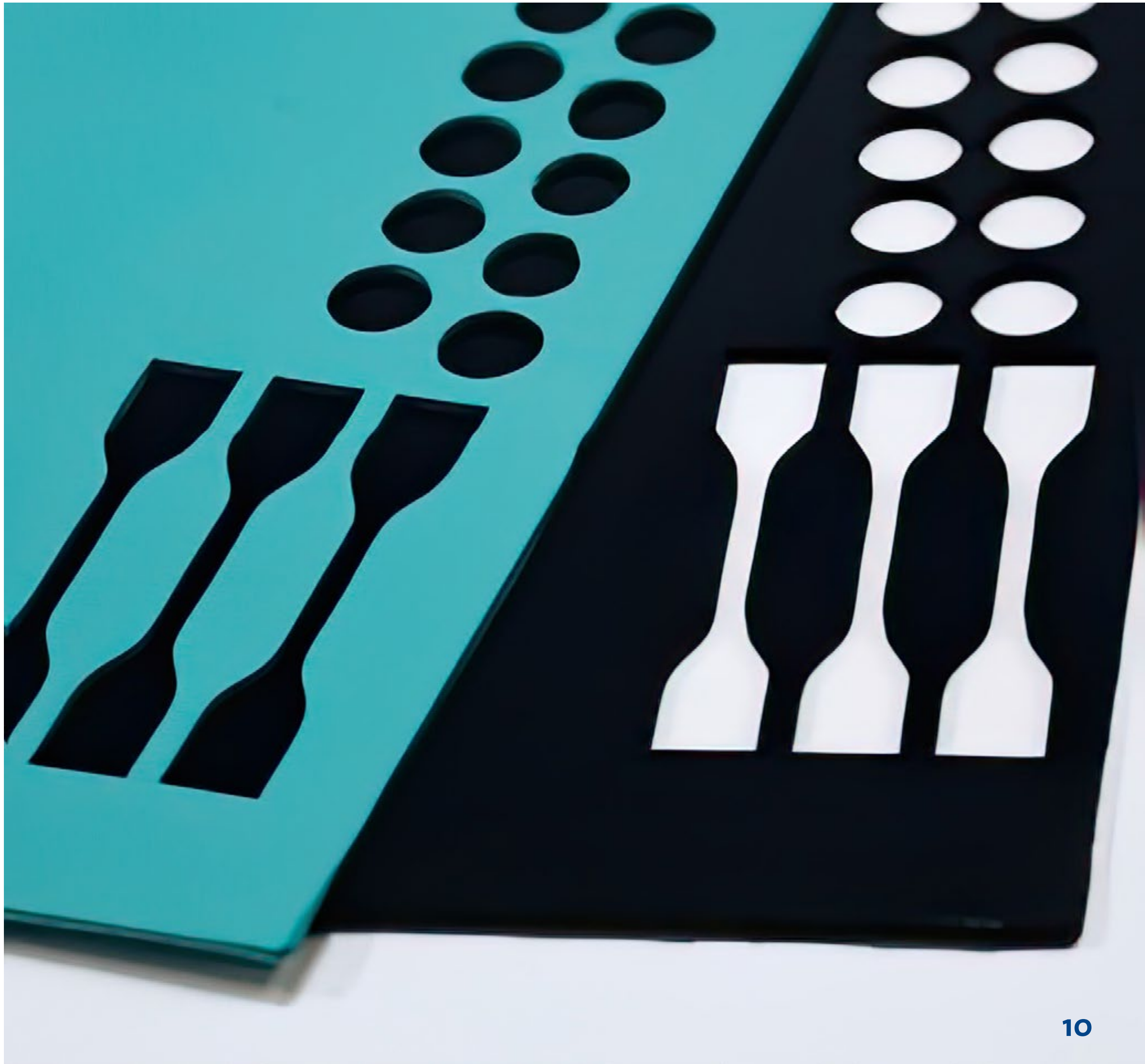
Sealing solutions for Power-to-X processes (PtX)

Syntheses and media

In the various processes for the production of ammonia (NH_3), methanol, e-fuels, and methane through methanation (CO/CO_2), the conditions sometimes involve high temperatures and pressures as well as corrosive environments. This is where static high-performance flat gaskets are used. The highly corrosive process sections require the use of PTFE-based sealing materials. Spiral-wound seals, camprofile serrated gaskets, and flexible graphite in the form of graphite laminates have also proven effective here.

Material selection

The process chemistry is the main determining factor for the PtX relevance of the materials used in these applications. Graphite is chemically stable even at high temperatures. PTFE and modified PTFE (PTFE/mod) offer universal chemical resistance as well as good creep and set levels in specialty grades.



Which seals are required for H2 refueling stations (HRS) and for refueling?

Requirements and standards

ISO 19880-1:2020 defines the minimum requirements for the design, operation, inspection, and service modalities of hydrogen refueling stations equipped with H35 and H70 dispensing nozzles. At these stations, vehicles can be refueled within a few minutes utilizing pre-cooling down to -40 °C.

Valves and safety elements for H70 dispensing nozzles

ISO 19880-3 defines the applicable testing and safety requirements for check valves, overflow valves, shut-off valves, and safety valves, as well as breakaway couplings. The sealing concepts in these applications often incorporate metallic sealing elements and RGD-resistant high-performance elastomers.

Dispenser hoses and couplings

ISO 19880-5 and ANSI/CSA HGV 4.2 define the internationally applicable safety requirements for high-pressure hoses with low permeation that are used at -40 °C. Metal-sealing interfaces are preferred here.

Question for the industry expert

Are there new production methods for seals in the hydrogen and electrolyzers sector, Mr. Mähne??

Artur Mähne is Global Segment Manager, Hydrogen Technologies, at Freudenberg Sealing Technologies. He reports: “Yes – and this across the entire H2 value chain. In recent years, we industrialized several production-ready manufacturing process chains for electrolyzer stacks, peripherals, and H2 infrastructure. We specifically designed our manufacturing and testing processes for scalability, media purity, low permeation, and high-pressure capability. In essence, this involves modern extrusion lines, precision injection molding and overmolding onto carriers, as well as large-format press capacities – all backed by our material and process expertise. We develop and analyze all formulations, material properties, bonding behavior, and purity assessments for sealing solutions by applying the finite element method (FEA). I will gladly go into more detail and present our manufacturing processes in three sections.

I will start with a process for injection molding and overmolding of seals onto carriers (for bipolar plates and metal or thermoplastic frames)

At Freudenberg Sealing Technologies, we master the direct molding of seals onto metallic bipolar plates, metallic frames, and thermoplastic carriers. In these applications, key aspects include defined adhesion through bonding agents, controlled groove filling, and the geometric activation of the seal.

For PEM stacks, we have developed a seal design with high-pressure capability that has already been validated for series production. This consists of a groove clamp with retention properties: an L-shaped cross section that is “activated” under operating pressure into a C-shaped barrier. This design is usually injection-molded and demonstrates the interaction between geometry, bonding, and process. In H2 and electrolysis applications, the benefits include a lower number of components, a higher degree of automation, better reproducibility of the compression position, and lower leakage and permeation.

Large-format presses for manufacturing XXL seals and large O-rings in all material classes

When it comes to large cell formats with diameters of 0.3–2 m and peripheral applications, we use powerful large presses to manufacture large-format frame seals, flat seals, and large O-rings – in line with the current scaling of electrolyzers toward MW/GW factories. Depending on the media window and bolt load, we produce molded EPDM and FKM elastomer parts. Our press capacity enables series production in high quantities. For H2 electrolysis, we offer the benefit of scalable surface sealing for large cells and covers, as well as robust tolerance absorption compatible with serial stacking and gigafactory cycle times.

Extrusion including an LCM (liquid curing method) line, for manufacturing profile and frame seals

We have specifically expanded our profile extrusion technology for hydrogen applications. For example, we developed a new extrusion line based on continuous production technology for delicate cross sections. We have the ability to vulcanize materials in a molten salt bath with optimized heat transfer and without exposure to air. This has allowed us to broaden the range of materials and cross-linking systems for large seals used in hydrogen applications, with a specific focus on reliability and durability. At the same time, our optimal process control has enabled us to significantly reduce manufacturing tolerances. This technology toolkit can be adapted with different extruders in LCM (liquid curing method) setups, making it possible for us to manufacture continuous stack profiles with tight tolerances, low creep tendency, and high chemical resistance. For alkaline electrolysis (AEL), we are producing extruded profiles for seals with diameters of up to 2m and well beyond. The fundamental advantage of these manufacturing processes for H2 electrolysis is that we can now manufacture large seals in optimized and customized high-performance materials with minimal tolerance variations and high precision. This is important for stack service lives of many tens of thousands of hours.

In closing, the bottom line is this: Yes, there are new manufacturing processes – and we are focusing on vertical integration and scaling. We are investing in standardization and global production capacities at our sites in Europe, China, and the United States. We are doing this with the goal of supplying H_2 seals reliably, sustainably, and locally for local markets in high volumes. Thanks to our material and process expertise, the concepts and methods described here are ready for series production – from AEL/AEM to PEM, and from stacks to H_2 infrastructure. This directly contributes to the safety, service life, and scalability of electrolyzers. At our company, one thing becomes clear every day: Material and process expertise are the "second half" of every innovation.

Artur Mähne

Is there a summary table for applications and typical use cases along with suitable material classes and seal designs?

There is now – and it addresses the question of which seal designs optimize the safety, durability, and efficiency across the entire hydrogen process chain.

The dynamic evolution of technologies for hydrogen generation has been accompanied by a sharply rising learning curve for materials and seal designs. Due to outstanding achievements in materials research and specialized H_2 seal designs, many established materials have evolved into highly safe precision sealing solutions. Advances in production and testing methods are making them increasingly sustainable, durable, and powerful. Which combinations are especially recommended? Here is an overview:

Application	Typical operating conditions	Material class and sealing solution
PEM electrolyzer – stack (O_2 side)	pH 4–6 (pure water, possibly slightly acidic), T < 60–150 °C, p up to ~35 bar high oxidation and cleanliness requirements	FKM as a stack seal (O_2 resistance, low H_2 permeation) Seal on plastic or metal frame/plate Seal on bipolar plate (overmolding)
PEM electrolyzer – high-pressure seal	high internal pressures, secure groove position, activation under load	Innovative seal profiles (L-shape) with retention features (press-in-place – PIP) or overmolded onto a carrier
AEL and AEM electrolyzer – stack (KOH environment)	3–30 wt % KOH T < 60–150 °C p up to ~35 bar electrical insulation depending on system design	EPDM seals with retention features (PIP) or overmolded onto a carrier produced by injection molding or extrusion. PTFE flat seals or films with low-creep tendency from mechanical production seal on plastic or metal frame (depending on automation)
Electrolyzer – peripheral and flange connections	low bolt load, purity, electrical insulation, variable T/P	EPDM and FKM O-rings PTFE flange seals
CGH_2 storage and transport (tanks and pipelines)	T ≈ -50...+85 °C p up to ~105 MPa permeation to be minimized	O-rings (EPDM/FKM/HNBR depending on medium and temperature) depending on application, with plastic back-up rings (PEEK, etc.)
Ultra-high-purity and high-pressure connections	UHP requirements (clean, low diffusion) vacuum (pressure, very low leakage)	VCR® metal face seal (stainless steel/nickel alloys); metal-to-metal sealing for UHP lines and components
H_2 compressors – reciprocating and diaphragm	high pressure, dynamic movement, wear, leakage minimization	packing seals (PTFE-filled, graphite) labyrinth sealsPEEK back-ups for extrusion protection
H_2 compressors – centrifugal	continuous rotation, high speed, low-energy sealing	dry gas seals (non-contact, thin gas film) very low leakage, low wear
Pumps and valves in PtX processes	corrosive media, high T/P, changing loads	mechanical seals, graphite packings, static spiral-wound seals/camprofile serrated gaskets, PTFE depending on medium/T
PtX syntheses (NH3, methanol, e-fuels)	aggressive chemicals thermal cycles, high pressures	graphite laminates/spiral-wound/camprofile serrated gaskets modified PTFE (chemical resistance, set behavior)
Threads and screwed connections (peripherals)	Up to 100 % H_2 reliable leakage protection at pipe threads	hydrogen-ready thread sealants (e.g. LOCTITE 55/567/577)
Material behavior – selection guidance	Permeation (H_2 diffuses strongly, RGD for rapid pressure changes	FKM tends to have lower H_2 permeation than EPDM/NBR HNBR/FKM/FFKM compounds show RGD resistance profile cross sections/sealing grooves reduce assembly force and extrusion

The Hydrogen Rainbow

All hydrogen is not the same. Although it is colorless in its natural form, we differentiate it into separate color classes based on its mode of production. Whether it is green, yellow or gray, we explain what it stands for.

White

This is the natural hydrogen that exists in the environment. It is mostly found in layers of rock deep in the earth. It can be extracted with **hydraulic fracturing or thermal fracking**.

CO_2-neutral: No
Thermal fracking is only CO_2-neutral if renewable energy is exclusively used in the process.

Yellow

Here the electric current for the electrolysis comes from the **mix of power sources** available today.

CO_2-neutral: No
Since the global electric power mix was only about 30% renewable in 2023, it is not (yet) carbon-neutral.

Orange

Biomass is used for the production of this type of hydrogen. The process can take place in two ways. Either by heating the biomass and then filtering the hydrogen out of the resulting gases. Or with electrolysis, with the electricity coming solely from waste incineration facilities.

CO_2-neutral: No
CO_2 is one of the gases released as biomass is incinerated.

Purple

The hydrogen is extracted with electrolysis. Electricity from **nuclear power** is exclusively used in this case.

CO_2-neutral: No
While the production with nuclear power is CO_2-neutral, carbon dioxide is emitted over the lifecycle of nuclear electric power, in the mining of uranium or the processing of nuclear fuel, for example.

Green

The electricity for the electrolysis comes exclusively from **renewable energy sources** such as photovoltaics and wind energy.

CO_2-neutral: Yes
The hydrogen is only produced using a CO_2-neutral and environmentally friendly process.

Turquoise

Methane is used instead of water in the production of this type of hydrogen. Methane is broken down into solid carbon and hydrogen with methane pyrolysis.

CO_2-neutral: Yes
Solid carbon is produced instead of CO_2. The material can then be reused.

Blue

This hydrogen is produced with the steam reformation of **natural gas**. The methane reacts with water vapor.

CO_2-neutral: No.
The resulting CO_2 is not released into the atmosphere but rather compressed underground.

Brown

To produce this kind of hydrogen, **brown coal** is transformed into a synthetic gas under high temperatures and controlled oxygen input.

CO_2-neutral: No
The synthetic gas mainly consists of H_2 and CO_2.

Gray

This type of hydrogen is extracted from **natural gas**. Using steam reformation, methane is transformed into hydrogen and carbon dioxide. This is how most hydrogen is produced worldwide.

CO_2-neutral: No
The ratio of hydrogen to carbon dioxide is 1:10 in natural gas, mirroring the proportion of the hydrogen that is generated and the CO_2 that is released.

Black

Much like brown hydrogen, coal is the base material for the production of hydrogen. Instead of brown coal, **hard coal** is used here. The coal is gasified and broken down into hydrogen and carbon monoxide.

CO_2-neutral: No
As is the case with brown hydrogen, this process releases substantial quantities of CO_2.

Which materials are suitable for each type of seal?

The material selection always follows the medium–temperature–pressure cycle and takes the service life and purity into account. The following rule-based guidance does not claim to be exhaustive.

Elastomers for O-rings, frame seals, molded seals, and profilese

- EPDM: resistant to KOH and water, good low-temperature flexibility; suitable for AEL/AEM and for peripherals in the electrolysis environment; has higher H_2 permeation than FKM. Caution is required in direct contact with oxygen.
- FKM: withstands O_2 oxidation and high temperatures; resistant to deionized water (DI water) and acidic environments; suitable for PEM stacks and peripheral valves and seats; low H_2 permeation. RGD-resistant materials are available for applications with pressure fluctuations.
- HNBR/NBR: good mechanical strength; widely used for gases; oil-resistant. RGD-resistant materials are available for applications with pressure fluctuations.
- FFKM: maximum chemical resistance; suitable for critical PtX process steps and for high temperatures

Fluoropolymers and thermoplastics for flat seals, sealing lips, and back-ups

- PTFE, ePTFE, and modified PTFE: nearly universal chemical resistance; prone to creep, should be placed in main load area; low permeation. This makes them ideal for KOH, CO_2, and flange seals in stacks and fittings.
- PEEK: ideally suited for back-up rings and spring energizers. These thermoplastics offer high rigidity and temperature resistance. At the same time, they provide good extrusion protection in high-pressure applications.

Which seal geometries are needed where in hydrogen technology?

Static seal geometries for flanges, housings, and stacks

Electrolysis stacks

Here the selection depends on the degree of assembly automation, the production volumes, surface pressure, and tolerance conditions. Sealing profiles for frames and bipolar plates, PIP seals, O-rings, and extruded profiles are usually installed here. Profiled elastomer cross sections reduce the assembly effort. In PEM electrolysis, high-pressure geometries with retention features and pressure-activating cross sections provide optimum performance.

Process and PtX plants

In these applications, the focus is on spiral-wound seals and camprofile serrated gaskets made of graphite laminate. In addition, PTFE flat seals are used for high temperatures and pressures as well as for corrosive media.

Ultra-pure and high-pressure environments

Metallic sealing profiles with high dimensional accuracy ensure optimum sealing performance here. VCR® metal seals and RTJ, C-ring, and E-ring seals deliver minimal leakage and permeation rates.

Dynamic seal geometries for compressors, valves, and control elements

Centrifugal compressors

Contact-free dry gas seal profiles are proven sealing solutions for this type of compressor.

Piston and diaphragm compressors

These applications use packings, labyrinth seals, and PEEK back-ups.

Valves and regulators

Spring-energized PTFE lip seals are prevalent in the high-pressure and low-temperature environments of these applications. They are supplemented by EPDM, FKM, and HNBR profiles with back-ups.

Hydrogen refueling stations

Metallic PTFE-seated valves that comply with ISO 19880-3 are suitable for these application areas, as are hose systems designed for use at temperatures as low as -40 °C.

Which norms and standardizations must be met by seals in the hydrogen value chain?

When it comes to hydrogen technologies, the standards landscape is currently undergoing dynamic development. Many standards are being revised or newly developed at this time. In general, global norms and standardization are essential for the hydrogen economy to ensure the integrity and performance of sealing systems under widely varying pressure and temperature conditions. Which legal framework conditions apply where? The following frameworks cover the key regulatory and normative requirements for seals and sealed assemblies across the entire H_2 value chain – from electrolyzers, pressure equipment and pipelines, transport and H_2 refueling, all the way to onboard systems. As the Chinese hydrogen market is developing with significant momentum, we will begin with three GB standards that apply in China and then broaden the focus to global guidelines. Here is an overview:

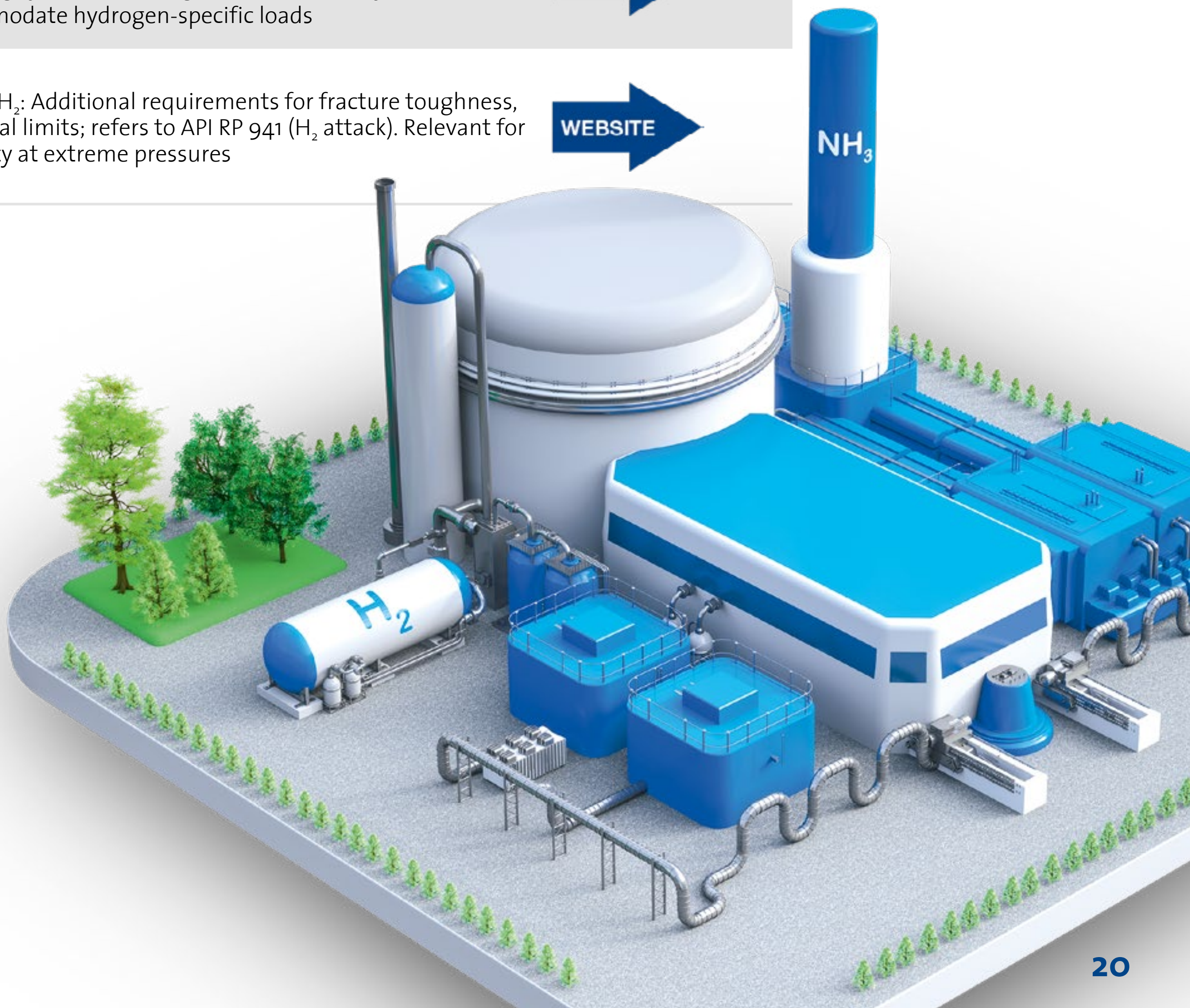
Segment	Standard/ regulation	Region	What it covers (briefly) / relevance to seals	
H_2 purity classes	GB/T 40060-2021	China	Pure hydrogen, high-purity hydrogen, and ultra-high-purity hydrogen (English version)	WEBSITE
H_2 storage	GB/T 37244-2018	China	Technical requirements for the storage and transport of liquid hydrogen (English version)	WEBSITE
H_2 as a fuel	GB/T 3634.2-201	China	Fuel specification for vehicles with proton exchange membrane fuel cells – hydrogen (English version)	WEBSITE

Standards and regulations – EU and global

Segment	Standard/regulation	Region	What it covers (briefly) / relevance to seals	
Electrolyzers (safety/design)	ISO 22734 (currently replaced by ISO 22734 1:2025) "Hydrogen generators using water electrolysis"	Global	Design, safety, and performance requirements for water electrolyzers (PEM, AEM, alkaline). Seal-related topics: media and pressure resistance, leakage, material compatibility, testing in the system	WEBSITE
H_2 systems in areas at risk of explosions	IEC 60079 series (e.g. 60079-0 "General requirements"; supplemented by the IECEx certification system)	Global: (IEC/IECEx) EU: über EN IEC 60079	Basic requirements for equipment in areas at risk of explosions (prevention of ignition sources, marking) – relevant for components, valves, and seals installed in or on electrolyzers (materials, surfaces, temperature classes) IECEx provides the conformity assessment scheme.	WEBSITE
Explosion protection – product law	ATEX Equipment Directive 2014/34/EU	EU/EEA	Conformity/CE for equipment and protective systems in areas at risk of explosions – including sealing systems and housings with explosion protection levels; harmonized EN standards listed in the OJ. [eur-lex.europa.eu]	WEBSITE
Explosion protection – occupational safety	ATEX Workplace Directive 1999/92/EC	EU/EEA	Zoning, minimum workplace requirements; influences the selection and design of seals and valves in plant environments	WEBSITE
Pressure equipment	Pressure Equipment Directive (PED) 2014/68/EU	EU/EEA	Fundamental safety requirements for pressure equipment/assemblies (vessels, pipelines, fittings); seals are pressurized components / safety-relevant (material requirements, testing, CE marking)	WEBSITE
Hydrogen safety guideline	ISO/TR 15916 "Basic considerations for the safety of hydrogen systems"	Global	Safety principles for H_2 systems (properties, hazards, risk issues, material/leakage aspects) – helpful for selecting and specifying sealing materials	WEBSITE
"Green" certification/proof framework (EU import, RFNBO)	Delegated regulations (EU) 2023/1184 and 2023/1185 (RED II/III – RFNBO supplement, GHG methodology)	EU	Methodology and criteria for renewable H_2, including additionality, temporal and geographical correlation, and GHG balancing – affects material and process requirements (e.g. cleanliness/leakage in seals) for certifiability	WEBSITE

Standards and regulations for pipelines, piping, and pressure vessels

Segment	Standard/regulation	Region	Relevance
H_2 pipelines & piping	ASME B31.12 "Hydrogen Piping and Pipelines"	USA / international application	Design/manufacture/testing for gaseous and liquefied H_2 (industrial piping and pipelines). Includes rules for materials, welds, and testing – sealing systems for flanges and expansion joints must be able to accommodate hydrogen-specific loads WEBSITE
Pressure vessels (H_2 service)	ASME BPVC sect. VIII; div. 3, art. KD-10 (special H_2 requirements)	USA / international application	High-pressure H_2: Additional requirements for fracture toughness, fatigue, material limits; refers to API RP 941 (H_2 attack). Relevant for sealing integrity at extreme pressures WEBSITE



Standards and regulations for storage systems and cylinders (stationary and mobile), and material compatibility

Segment	Standard/regulation	Region	Relevance	
Material compatibility (cylinders/valves)	ISO 11114-1 (metallic materials) ISO 11114-2 (non-metallic materials) ISO 11114-4 (H_2 embrittlement – selection tests)	Global	Assessment of the compatibility of cylinder and valve materials with H_2 (embrittlement, chemical interaction). Important for seals, liners, and valve seats	WEBSITE
Steel and composite cylinders	ISO 9809-1 (seamless steel), ISO 11119 series (composite, types 2–4)	Global	Design, manufacture, and testing of H_2 pressure vessels; requirements for valves, sealing surfaces, and tests influence the sealing concepts	WEBSITE
Cryogenic vessels (LH_2)	(LH_2) ISO 21009-1 (static vacuum-insulated – design and tests)	Global	Requirements for LH_2 tanks (strength, leak-tightness, testing, materials) – essential for seals in cold/vacuum-insulated environments	WEBSITE

Standards and regulations
for transport by road and rail, by sea and air, and for transportable pressure equipment

Segment	Standard/regulation	Region	Relevance	
Road transport (ADR)	ADR 2025 (UN ECE) – incl. UN 1966 LH2, class 2	Europe/ other signatory states	Classification, packaging, tanks, operation – technical requirements and testing for tanks, connections, and sealing systems (cold, vibration, pressure)	WEBSITE
Transportable pressure equipment	TPED 2010/35/EU	EU/EEA	Uniform legal framework for the design, conformity, and recurring inspections (cylinders, MEGCs, tanks) – including "π" marking. Sealing components must comply with testing intervals/ standards	WEBSITE

Standards and regulations for H_2 refueling infrastructure (HRS) – station, components, fuel

Segment	Standard/regulation	Region	Relevance	
H_2 refueling stations (general requirements)	ISO 19880 1:2020	Global	Minimum requirements for the design, installation, operation, inspection, and maintenance of HRS (dispensing, compressor, storage, pre-cooling). Critical: leakage limits, leak-tightness tests, hose/valve performance	WEBSITE
Valves in HRS	ISO 19880 3:2018	Global	Safety performance and test methods for high-pressure gas valves (up to H70) – leak-tightness under pressure and cycling requirements.	WEBSITE
Hoses and hose assemblies	ISO 19880 5 (2019; 2nd ed. 2025)	Global	Requirements for hoses up to 70 MPa (materials, design, testing – permeation, cycling, flexing). Parallel in NA: CSA/ANSI HGV 4.22	WEBSITE
Fuel quality of H_2	ISO 14687 (2019 ed.; second edition 2025) EN 17124:2022 (EU)	Global / EU	Specification (limit values) for H_2 purity (PEM fuel cells) – direct requirements for material purity/leachables of seals in order to avoid contamination	WEBSITE
Nozzle/coupling standard	ISO 17268 (2020; in multi-part form in 2025), for 35/70 MPa	Global	Design/safety features of nozzle and receptacle, incl. sealing surfaces, locking, materials, test methods	WEBSITE
Refueling protocol	SAE J2601 (LD, 35/70 MPa)	USA/International	Pressure and temperature profiles, end-of-fill targets (T20/30/40); requirements for pre-cooling sealing systems, hose leak-tightness under rapid cycling	WEBSITE
U.S. protection standards: Fire protection	NFPA 2 (Hydrogen Technologies Code) & NFPA 55 (gases/cryogenics)	USA	Distances, ventilation, emergency shutdowns, materials, testing – for stations, storage, pipelines, and fittings/seals	WEBSITE

Standards and regulations for vehicles and onboard systems

Segment	Standard/regulation	Region	Relevance	
Vehicle fuel systems	SAE J2579 (reaffirmed 2023)	USA/International	Requirements for the design, operation, and verification of H_2 storage and handling systems in vehicles (leak-tightness, crash leakage, service life)	WEBSITE
Onboard containers	ISO 19881 – Road vehicle fuel containers, supplementary	Global	Requirements for pressure vessels/piping – interfaces with vehicle couplings/sealing faces (note: often anchored in OEM/type-approval standards)	WEBSITE

Standards and regulations
for cross sections: certification, documentation, and global recognition

Topic	Framework/Source	Key point	
H_2 certification – fundamentals	Hydrogen certification 101 (IEA H2 TCP/ IPHE)	Terminology, roles (scheme owner, certification, issuing, accreditation bodies), chain of custody (mass balance vs. book & claim), mutual recognition – important for cross-border trade and consistent requirements for materials and processes (e.g. cleanliness of seals)	WEBSITE
Standardization and digital documentation	H2 global policy brief “Standardizing Hydrogen Certification”	Harmonization steps, role of ISO/WD/TS 19870 (GHG methodology), Digital Product Passport/blockchain for traceability – supports conformity of components/materials in supply chains	WEBSITE
GHG methodology for H_2	ISO/TS 19870 (in progress; derived from IPHE methodology)	Uniform methodology for determining greenhouse gas emissions from production, conditioning, and transport – important for documentation (RFNBO, CBAM) and therefore indirectly for material and process selections (e.g. low-leaching sealing materials)	WEBSITE

Where can I get industry news in the hydrogen technologies sector?

There is an immense range of information sources available along the hydrogen value chain and categorization is strongly recommended. Here we will list three platforms that we value, followed by a structured overview of many additional information sources. Let's get started:

China Daily – Hydrogen technology section – China's hydrogen market; technological advances, large-scale projects, and international cooperation; prepared for an international expert audience.

WEBSITE

CORDIS – EU research news on hydrogen

EU portal for research projects and innovations in hydrogen, including storage and sealing technologies.

WEBSITE

The Energy and Resources Institute (TERI) – leading energy research institute in India; regular updates on H_2 technologies..

WEBSITE

Daily Industry News – editorially curated

Hydrogen Insight – daily updates on projects, auctions, industrial offtakes, and regulations (EU/global))

WEBSITE

H_2 View – broad coverage (mobility, industry, politics) plus monthly magazine and webinars; good coverage of Europe and Asia

WEBSITE

FuelCellsWorks – very frequent output (daily, global), from OEM news and infrastructure to weekly reviews related to China k

WEBSITE

Hydrogen Economist (PE Media) – background analyses & outlook pieces (paywall, but strong classification)

WEBSITE

Euronews – Hydrogen – EU-focused articles with regulatory relevance (ACER, market realities) (ACER, Markt-Realität)

WEBSITE

Policy, regulation, and funding programs (Europe/Global)

IEA – Global Hydrogen Review 2025 incl. the new Hydrogen Tracker (policy database with more than 1,000 measures, project and cost layers). Ideal for a "single source of truth" perspective.

WEBSITE

Clean Hydrogen Partnership (EU) – official news on calls, projects & hydrogen valleys; published 2026 call for €105 million

WEBSITE

European Hydrogen Bank (EHB) – auction results and lessons learned; second round: many withdrawals due to completion guarantee & uncertainty of demandt

WEBSITE

Hydrogen Europe – news/analyses on EU policy (EHB, Innovation Fund, Hydrogen Mechanism) – a good lobby/industry perspective

WEBSITE

IPHE – International Partnership for Hydrogen and Fuel Cells in the Economy – government network; governance updates & international initiatives

WEBSITE

European Hydrogen Observatory – editorial EU news (projects, H_2 airports, large-scale plants).

WEBSITE

Market prices, data, and analyses

S&P Global Commodity Insights (Platts) – price indices, pump price assessments, news/analyses; also the organization behind World Hydrogen Leaders (events)

WEBSITE

Argus Media – Hydrogen & Future Fuels – global price/cost models, policy news, offtake databases

WEBSITE

BloombergNEF – realistic supply outlooks (e.g. share of "likely achievable" capacity by 2030) & cost trajectories

WEBSITE

Project and Technology Tracker – useful for pipeline and competitive monitoring

IEA Hydrogen Tracker & Projects Database – interactive maps, project status (from concept to operation), infrastructure & cost; usable under CC-BY.

WEBSITE

IEA Projects Dataset @ KAPSARC – machine-readable access (data exports), helpful for individual evaluations

WEBSITE

Hydrogen Monitor (Hydrogen Europe) – annual EU market status incl. funding landscape, permitting, target achievement

WEBSITE

Official Reference Reports – published annually and semiannually

IEA – Global Hydrogen Review 2025 – global status of demand, supply, policy, investment; supplemented by the online tracker

WEBSITE

Hydrogen Council – Global Hydrogen Compass 2025 – industry perspective & capital curve; >500 mature projects, >$110 billion committed (context and case studies)

WEBSITE

How do I stay up to date?

To avoid losing track amid the high volume of information sources, we recommend a convenient setup:

1. Weekly strategy updates

a. Read: IEA Hydrogen Tracker (policy/project layer) + Hydrogen Council Compass (industry perspective).

iea.org

hydrogencouncil.com

2. Daily alerts (Outlook/RSS):

a. Hydrogen Insight, H_2 View, FuelCellsWorks

search terms:
– electrolyzer FID
– offtake ammonia/methanol
– EHB
– Hydrogen Bank
– Hydrogen Valleys

hydrogeninsight.com

H_2-view.com

3. Monatliche Preis/Markt-Sanity-Checks

a Monthly price/market sanity checks

b. **https://www.spglobal.com/energy/en/commodity/energy-transition/hydrogen**

c. **https://www.argusmedia.com/en/commodities/hydrogen**

A practical checklist:
What information do I need to select seals along the hydrogen process chain?

With this checklist, we help you systematically capture the key parameters needed for optimal seal selection. The individual questions relate to environmental and operating conditions, highlight requirements in terms of media resistance, seal geometry, and maintenance intervals. They conclude with questions on safety requirements and legal frameworks. We wish you every success in working with our checklist!

CHECKLISTE

Media

- ☐ Are my seals used in an acidic or alkaline environment?
- ☐ Do my seals need to withstand potassium hydroxide/caustic potash?
- ☐ Is my hydrogen in gaseous or cryogenic form?
- ☐ Do the seals need to resist oils and coolants?
- ☐ Which purity requirements apply?
- ☐ What is the maximum permissible leakage rate?
- ☐ What is the maximum permissible permeation rate?
- ☐ Which compatibilities must be ensured?

Geometry/hardware

- ☐ What are the best-suited flange geometries and qualities?
- ☐ Which groove and seat geometries are required?
- ☐ What is the quality of the surfaces to be sealed?
- ☐ Which manufacturing process (extrusion/LCM/overmolding) is advisable?

Leakage and operating life

- ☐ How is the permissible leakage rate defined?
- ☐ How are the CSR limits defined?
- ☐ What is the target service life (e.g. 100,000h in electrolysis)?
- ☐ Which maintenance intervals are required?
- ☐ What is the structure of the spare-parts logistics – how quickly must spare parts be available?

Safety and standards

- ☐ Which ATEX requirements (ATEX zones) must be met?
- ☐ How is the RGD risk defined?
- ☐ Which test protocols are required and where are they documented?
- ☐ Is ISO 22734 conformity ensured?
- ☐ For vehicles: is UN R134 complied with?

Conclusion and Outlook

Experimental curiosity is accelerating the development of forward-looking solutions, especially in the energy sector. This inventive spirit also fuels continuous advancement in materials, manufacturing processes and sealing solutions at Freudenberg Sealing Technologies. Because one thing is clear: Seals are the decisive factors that enable efficiency, safety, and predictable life cycle costs in hydrogen systems. They are the technology drivers that make it possible to achieve the targeted cost and scaling effects.

This white paper helps you stay up to date on sealing solutions for the hydrogen process chain. At the same time, we offer important insights into how innovative technologies can help you move toward climate neutrality. We would be pleased to continue developing this white paper together with you and look forward to your feedback.

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Glossar – Werkstoffklassen und Markennamen

ACER	Agency for the Cooperation of Energy Regulators
AEL electrolysis	alkaline electrolysis
AEM electrolysis	anion exchange membrane electrolysis
ASME	American Society of Mechanical Engineers – Norms and standardization
ATEX	Explosion protection directives
Fuel cell stack	modular arrangement of individual standardized fuel cells
CCC	Component Cleanliness Code
CIIR	chlorobutyl rubber
Cryogenic	extremely low temperatures (-150 to -273 °C)
DIAvent Light®	pressure equalization element
EHB	European Hydrogen Bank
EPDM	ethylene propylene diene rubber
ePTFE	expanded polytetrafluoroethylene
FKM	fluororubber
FVMQ	fluorosilicone rubber
H_2	hydrogen
H_2 ICE	hydrogen internal combustion engine
HFCV	hydrogen- and fuel-cell-powered vehicles
HNBR	hydrogenated nitrile butadiene rubber
HRS	hydrogen refueling station

Hydrogen Mechanism	EU energy platform
IEA	International Energy Agency
IECEx	conformity assessment scheme
KOH	potassium hydroxide
KOH (aq)	caustic potash
L/C cross section	plate seal that improves barrier performance under operating pressure
LCM	Liquid Curing Method (extrusion process)
LOCTITE	thread sealant
NBR	nitrile rubber – nitrile butadiene rubber
NH_3	ammonia
PEM electrolysis	proton exchange membrane electrolysis
PTFE	polytetrafluoroethylene
PtX	Power-to-X/process for converting electrical power into fuels or energy carriers
PVMQ	phenyl methyl silicone
RGD	explosive decompression
S&P	Standard & Poor's/rating agency
SOEC electrolysis	solid oxide electrolyzer cell electrolysis
TRL	technology readiness level
UHP	ultra-high performance

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