E-Book

E-mobility: Leak Testing for Electric and Fuel Cell Vehicles

Test tasks in the industrial production of BEV/PHEV/FCV vehicles: for the production of drive batteries, electric motors and fuel cells

Contents

Foreword

The requirements for leak testing of alternative drives and their individual components are as complex as the product itself. Critical components include batteries (filled with electrolytes), media circuits (with water-glycol or hydrogen), and electrical components (with high voltages/currents). These place the highest demands on quality assurance in manufacturing and thus, also on leak testing.
At Robert Bosch Manufacturing Solutions GmbH, we have been involved with high-precision leak testing technology for many years. One important finding is that theoretical considerations such as physical principles of thermodynamics and simulations are an initial direction for selecting the appropriate test method. Ultimately, however, this is not sufficient. For example, simply answering the question of the hole size at which liquid starts to leak is anything but trivial. Material and hole geometry, as well as thermodynamic boundary conditions such as temperature, pressure and viscosity, play a major role here.
In addition to the actual leakage limit value to be tested for, whether this is specified by standards or other considerations for product quality, the correct test method must be selected. The costs for a leakage test must always be evaluated as well. In a first step, simple and inexpensive compressed air-based methods such as a pressure decay or mass flow leak test are often used. However, this document makes it clear - and I can only confirm this from my own experience - that the leakage limits to be tested tend to require a trace gas analysis. With the new testing technologies presented here, economical solutions can be found, especially for industrial production with corresponding requirements for cycle time and process capability.
In addition to the actual general challenges in leak testing, this e-book shows various testing technologies and important examples of experience. It also provides a good insight into the field of alternative drives.

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Stuttgart, March 2021, Robert Bosch Manufacturing Solutions GmbH

Introduction

Leak testing: essential in the production of traction batteries and fuel cells

Electromobility is becoming more significant every year. As the number of Battery Electric Vehicles and Plug-in Hybrid Electric Vehicles grows, so does the number of traction batteries required. Ensuring their quality becomes a central task for car manufacturers and suppliers. Fuel cell electric vehicles (FCEVs) also need batteries to supply power to the electric motors that drive them - although ones with significantly less capacity. In any case, careful leak testing is essential for the hydrogen tanks and fuel cells of FCEVs.

During the production of traction batteries, consistent leak testing of all relevant components is crucial. This is because consumers, in the age of alternative, zero-emission drives, do not want their automobiles to catch fire. Nor are they ready to invest large sums in a new battery after a few years in order to regain the necessary capacity and an acceptable range. With traction batteries, it is important to ensure at every stage of production that the electrolyte in the battery cells does not leak out or come into contact with water under any circumstances - not even with the moisture in the air -This is because there is a risk that the water will react with the electrolyte of the cell to form hydrofluoric acid. In addition, because of the risk of short circuits, water must not enter the battery modules or packs from the outside. And because a battery should never overheat, the cooling circuit for the traction battery must also be leak-proof and protected from the loss of the cooling medium.

Lithium-ion batteries in hybrid vehicles.

Traction batteries represent both potential sources of danger as well as wear parts that are critical to the success of BEV/PHEV vehicles. In the field of hydrogen technology for FCEV vehicles, safety and leak tightness are indispensable in any case. Any manufacturer of alternative drives who would like to meet the demands of their customers in the long term cannot avoid suitable leak testing methods in their manufacturing processes. Quality assurance is essential.

A Toyota fuel cell vehicle.

This whitepaper gives a detailed overview as to which requirements are relevant and at which stage in the industrial production processing of BEV, PHEV and FCEV vehicles, and which leak testing methods are suitable for a specific application. One finding: Only modern tracer gas methods are able to ensure the essential gastightness of alternative drive components.

1 Electromobility is the future

There was a new record set in 2019: More than 2.1 million BEV and PHEV vehicles were sold worldwide, which was 40 percent more than in the previous year, with 2018 having already set a new record. These are the figures from the "Global EV Outlook 2020" of the International Energy Agency (IEA), an OECD organization based in Paris. The move toward zero-emission mobility is wanted and promoted, particularly on the political level,It is being driven just as much by official climate targets as by explicit quota regulations. On the other hand, China, for example, has almost halved its subsidies for buyers in 2019 - electric vehicles are gaining acceptance there even without high subsidies. The People's Republic is home to approximately 47 percent of all BEV/PHEV vehicles in the world, followed by markets such as Europe and the United States. And while the global passenger car market weakened overall in 2019, there was clear growth in electric vehicles. In China, for example, BEV/PHEV vehicles already accounted for 4.9 percent of all passenger car registrations in 2019, while in Europe their market share was 3.5 percent. The figures emerging for 2020 paint a similar picture. While the Corona pandemic is slowing down the global passenger car economy, BEV/PHEV vehicles can hold their own with at least stable, if not increasing, sales figures.

US automakers are also driving growth in the electric vehicle market.In addition to investments in production capacities for BEV and PHEV vehicles, in-house production of lithium-ion batteries is also playing a growing role. For example, Ultium Cells, the joint venture between General Motors and South Korea's LG Chem, is currently building a lithium-ion battery manufacturing plant in Lordstown, Ohio. And its plant in Spring Hill, Tennessee, is General Motors' third factory to equip for electric vehicle production. Even Ford's new CEO Jim Farley is publicly considering building his own battery cell manufacturing facility to gain more flexibility in the face of Ford's rapidly growing production numbers. A BEV pioneer like Tesla has been relying on its own battery cell production for some time now - although the huge Tesla Gigafactory 1 near Sparks, Nevada, has currently only reached 30 percent of its final planned production capacity. Another trend paving the way for the new technology is the ever-decreasing price for battery capacity. Today a kilowatt hour of storage capacity can be had for just US$156 whereas in 2010 it still cost US$1,100,At the same time, the total capacity of batteries installed in BEV and PHEV vehicles is increasing. While in 2018 it was still 37 kWh on average for the entire class of light electric commercial vehicles, today it is already 44 kWh. Today in most markets, purely battery-electric powered passenger cars today already have storage capacities in the range between 50 and 70 kWh, which helps them achieve a corresponding range.

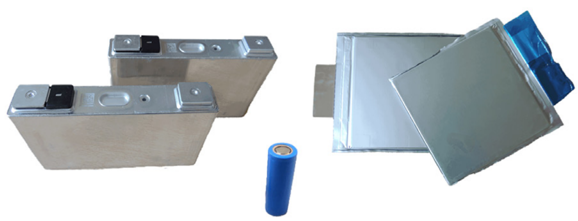
In parallel with the purely battery-electric drives, the topic of fuel cells is also back on the agenda. The essential energy storage system for an FCEV vehicle is its hydrogen tank. In the fuel cell, the hydrogen that is carried along reacts with atmospheric oxygen to form water. A comparatively small traction battery stores the resulting electricity and feeds the electric motors that drive the vehicle. Despite higher energy costs, FCEVs also have advantages over battery-electric BEVs, such as a greater range and far shorter refueling stops. This makes fuel cell technology an interesting CO_2-free drive alternative for large passenger cars and commercial vehicles.

At present, not least of all Asian manufacturers, such as Honda, Hyundai and Toyota, believe in the future of the technology and are offering FCEV passenger cars. For example, of the new model generation of the Toyota Mirai already presented, 30,000 units are to be produced annually from 2021 onwards - a tenfold increase in current production capacity. Supplier Robert Bosch also manufactures fuel cell components at its Homburg/Saar site and plans to bring a new "Bosch Stack" on the market by 2022, not least of all to power heavier and commercial vehicles. Bosch expects that, by 2030, as much as 20 percent of all electric vehicles worldwide will generate their drive power from fuel cells.

2 The heart of BEV/PHEV vehicles: the traction battery

2.1 From battery cells to battery modules and packs up to traction batteries

In classic automobiles, the combustion engine could be considered the "heart” of the vehicle. In BEV/PHEV vehicles, however, this function is fulfilled less by the electric motor than by the traction battery. At present, the traction battery accounts for between 25 and 30 percent of the added value of the entire vehicle, although the price of batteries has fallen steadily over the years and is likely to continue to do so in the future. The smallest manufacturing unit in the traction battery is the electrolyte-filled battery cell in which the energy is stored. Currently, there are three different designs for battery cells. We are all familiar with the cylindrical round cells (typically 18650 or 26650) from our

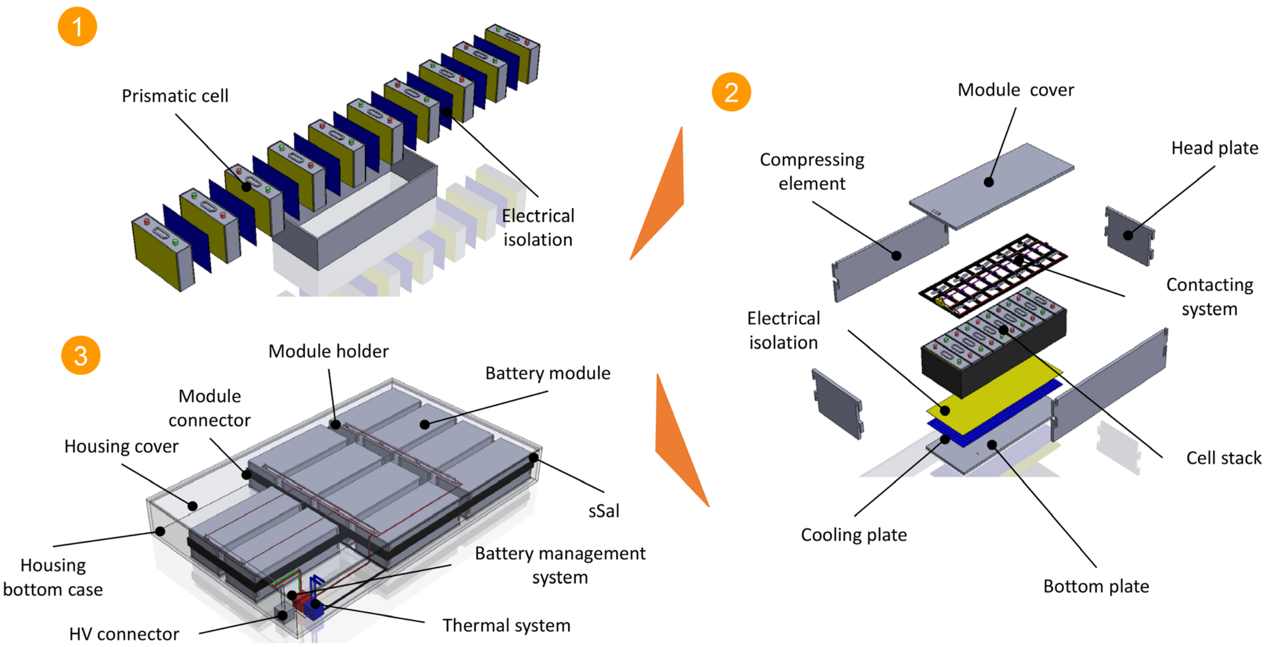


Different geometries for battery cells (from left to right): prismatic cells, round cells (cylindrical cells), soft pouch cells.

everyday life. Round cells and prismatic cells both feature a stable housing, while pouch cells have a flexible housing resembling a pouch.
At the downstream end of the manufacturing chain, the individual cells are initially combined into battery modules and these, in turn, are joined together to form battery packs. At the end of the manufacturing process, these battery packs are jointly placed into a single housing. At every stage of production, it is important to ensure that the electrolyte in the battery cells never leaks out or comes into contact with water or humidity. This requirement for gastightness can only be met by modern tracer gas methods.

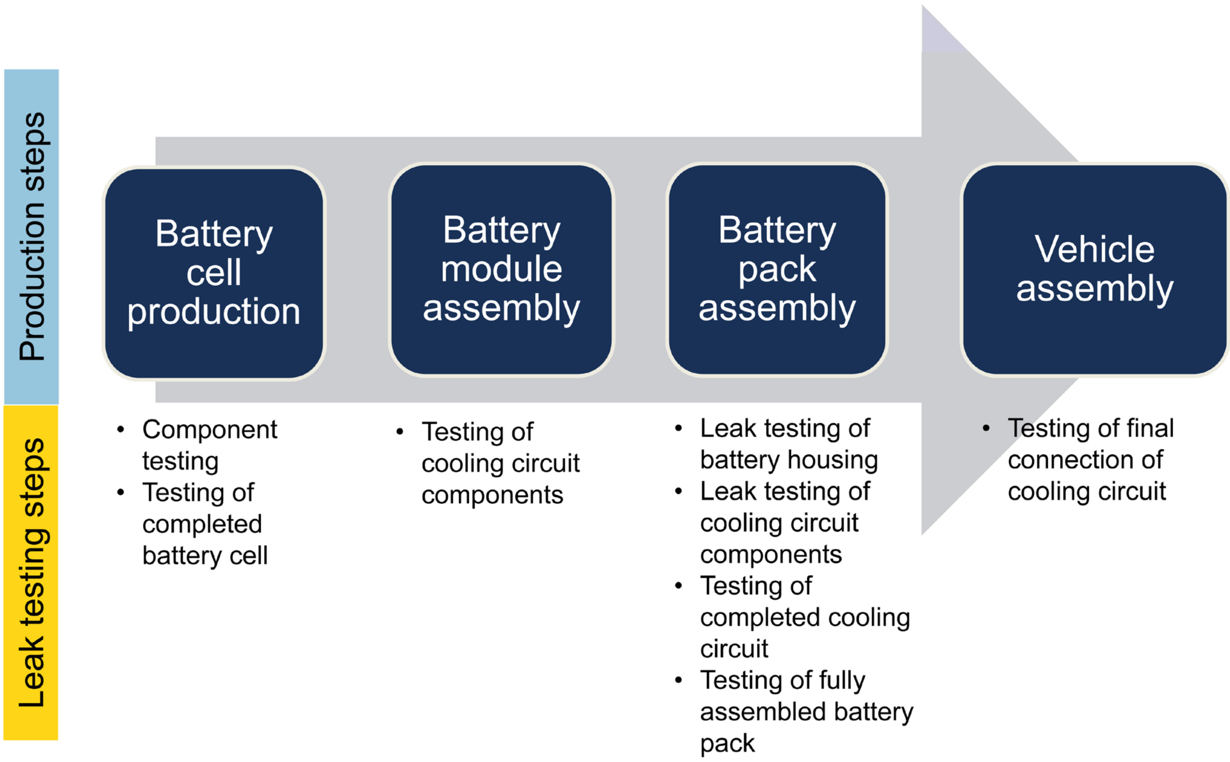
2.2 Fire risk and thermal runaway

Reliable leak testing of battery cells is necessary because of the readily flammable electrolyte that they contain: Leaking electrolyte poses the risk of burning vehicles and may even lead ato fire-related total losses. Permeating humidity, on the other hand, is associated with a short circuit risk and also reduces the service life of the battery. The current status of the overseas manufacture of battery cells is also problematic. because, damage to battery cells during long transport routes from Asia is not uncommon. This damage may have fatal consequences -



Value chain in battery production. (Source: RWTH Aachen, PEM) even during transport. Due to being a fire hazard, lithium-ion batteries and cells, for example, are no longer allowed to be transported as cargo in passenger aircraft. Aircraft crashes due to burning cargo have prompted various aviation supervisory authorities to disallow these batteries on aircraft. At the same time, carriers like FedEx are using special cargo foam systems for the targeted extinction of fires in containers with battery cells on board cargo aircraft. More frequent incidents of completely destroyed ship containers are known as well. The "thermal runaway" of a single battery cell - triggered, for example, by a local short circuit of the internal electrodes - may cause the burning electrolyte to heat up the entire ship container to temperatures of up to 1,100 °C, eventually causing it to explode.

One of the most serious risks associated with lithium-ion batteries is their flammability.



Leak testing at different stages of the value-added chain.

2.3 Incoming goods test for battery cells

Against this background, it is not surprising that many experts and scientists - for example the Institute for Power Electronics and Electrical Drives (ISEA) at RWTH Aachen University - take the view that it is of great importance to design an efficient incoming goods test so that German manufacturers and suppliers can detect faulty cells before they are assembled.

2.4 Leak tightness of battery modules and packs

The subsequent value-added processes also require a wide variety of leak testing. Initially, battery cells are assembled into battery modules which are then merged into battery packs. Some OEMs are already performing these production steps themselves, while others purchase their complete battery packs from Tier 1 suppliers.

Both battery modules as well as battery packs typically include several cooling channels which are operated either with a water-glycol mixture or with refrigerant from the AC system of the vehicle. Usually, the power electronics controlling the battery operation in the vehicle are also cooled in one of these two ways. Leak proofing of these systems is critical because, on the one hand, cooling of the batteries must be guaranteed in the long term and, on the other hand, leakage of the cooling medium could lead to short circuits.

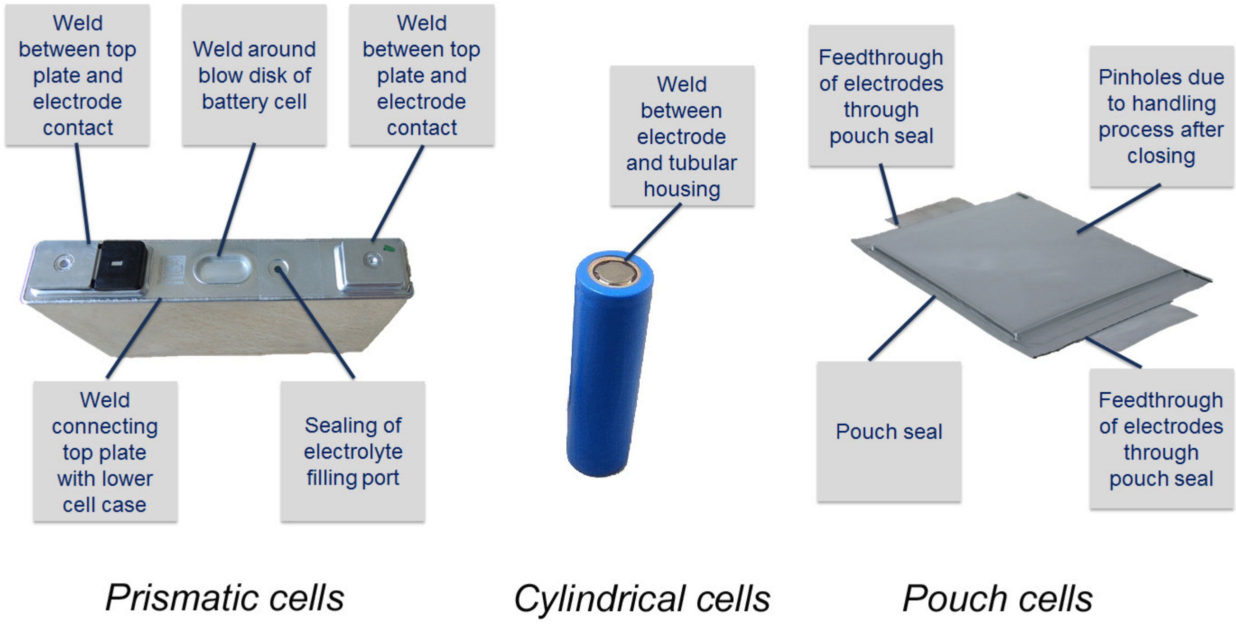
Why a cell must be leak-proof: prismatic cell (left) and soft pouch cell (right).

2.5 Ensuring battery service life

Even more crucial than the question of the possible short-circuit and fire risk could prove to be the problem of the shortened service life of the traction battery in the everyday life of BEV/PHEV vehicles. After all, who is going to pay for the replacement of a battery when it has lost most of its capacity due to poor workmanship? Where can the commuter turn to when he/she is unable to cover 60 miles, even on a full battery charge? Who bears the risk of shortened battery life: the customer, the dealer, the vehicle manufacturer or its supplier? One way or another, an expensive traction battery with a short service life would quickly result in customer dissatisfaction. The sustainability target of a traction battery is currently estimated at approximately 80 percent of the remaining storage capacity after 10,000 charging cycles. So, there is no way around it, the triumph of electromobility clearly invites new challenges for quality assurance. At every stage of production, it is important to guarantee that the electrolyte in the battery cells does not leak or come into contact with water and humidity. In other words, the battery must be gastight. Only modern, sensitive tracer gas methods will enable car manufacturers and suppliers to meet this standard for gastightness.

3 Test methods for battery cells

When an electrolyte reacts with water, hydrofluoric acid is formed, which destroys the battery cell. At the end of the service life of a cell - many manufacturers expect 10 years - the water concentration in the electrolyte must therefore be as low as possible. The loss of electrolyte must also be kept to a minimum throughout the service life. This is necessary because harmful heavy metals are dissolved in the electrolyte. The exact level of the tolerable leak rate depends on several factors, including the pressure conditions in the battery cell, the required service life of the cell and its volume. In soft pouch cells, for example, an underpressure of 50 to 500 mbar absolute prevails after their formation, so that the electrolyte wets the anode and cathode well and to enable mechanical stability of the cell. Prismatic, button and round cells with



Trouble spots for the different cell types.

a solid housing are usually filled at atmospheric pressure so that there is no pressure difference. The leak rates that are still tolerable are accordingly higher. In general, the limit leak rates to be tested for are of the order of 10^{-6} mbar·l/s. Due to the low leak rate allowance, tracer gas-based methods are the method of choice for leak testing in battery cell manufacturing.

3.1 Failure models for the different cell types

Each of the three designs – prismatic, round and pouch cell – has its own trouble spots. Prismatic cells, for example, are sealed at atmospheric pressure or at a slight underpressure (-20 mbar). Formatting often results in gaseous reaction products, so that there may be a slight overpressure in the cell after the formatting process. Any leak may cause air and humidity to enter the cell and may eventually lead to a discharge of electrolyte. The failure patterns for the prismatic cells identifies several potential leak locations. These include the weld seams between the cover plate and the two electrode contacts, as well as the rupture disc welded there; the weld seam between the cover plate and the lower housing part; as well as the sealing of the opening for the electrolyte filling. In round cells, the leakage-prone areas are located on the crimped connections between the cylindrical housing and the electrodes attached to the ends of the cylinder. The soft, bag-like pouch cells are at risk of leakage from the bag's gaskets, from leaks at the two electrode feedthroughs – which in this context are usually called current collectors – and from the needle-shaped holes that might be caused by post-closing handling processes.

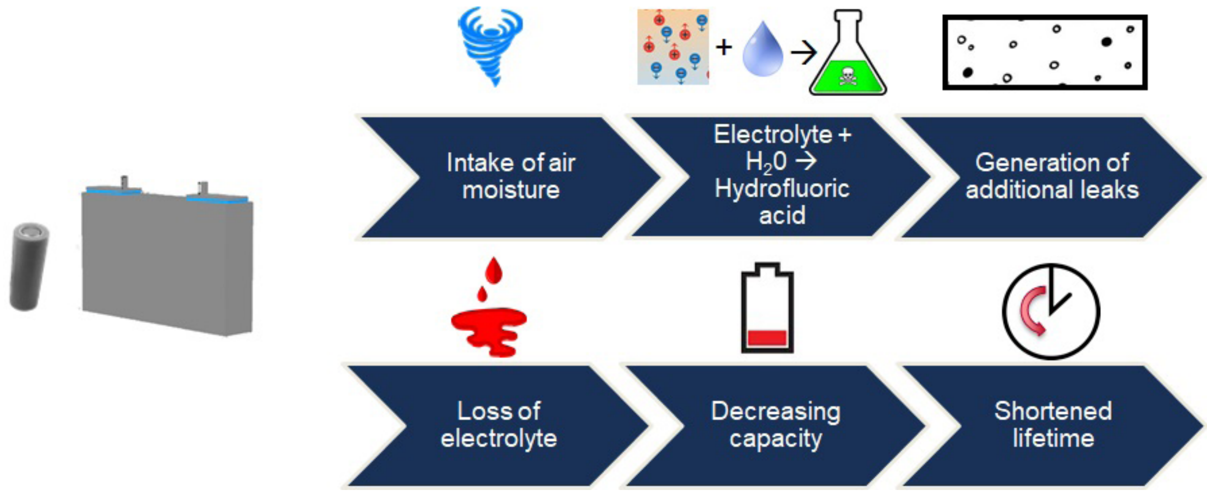
3.2 Leak rate requirements by cell type

So what requirements do the different battery cell designs place on the limit leak rate that should be tested for when leak testing?In the case of prismatic and round cells, a small amount of air remains in the cell even after it has been filled with electrolyte under atmospheric pressure. Thus, if air with a certain amount of moisture enters the cell, there may be a large contact area with the electrolyte through which the water can go into solution. However, the exchange with the ambient air occurs only by diffusion, and thus very slowly, due to the almost non-existent pressure difference.

In the case of pouch cells, a leak causes air to be drawn in by the underpressure inside, but the surface of the electrolyte coming into contact with water remains small and for fine leaks is limited exclusively to the leakage channel.

3.2.1 Required leak rate for hardcase cells (prismatic, button and round cells)

If, after ten years, the concentration of undesirable water dissolved in the electrolyte is to be as low as possible, then permissible leak rates (depending on the maximum tolerable moisture content and cell geometry) are in the range of 10^{-6} to 10^{-8} mbar·l/s. When testing in a vacuum, a pressure difference of approximately 1 bar is artificially created, thus generating a greater leak rate for the same hole size. Therefore, the vacuum method usually tests for leak rates in the range of 10^{-6} mbar·l/s.



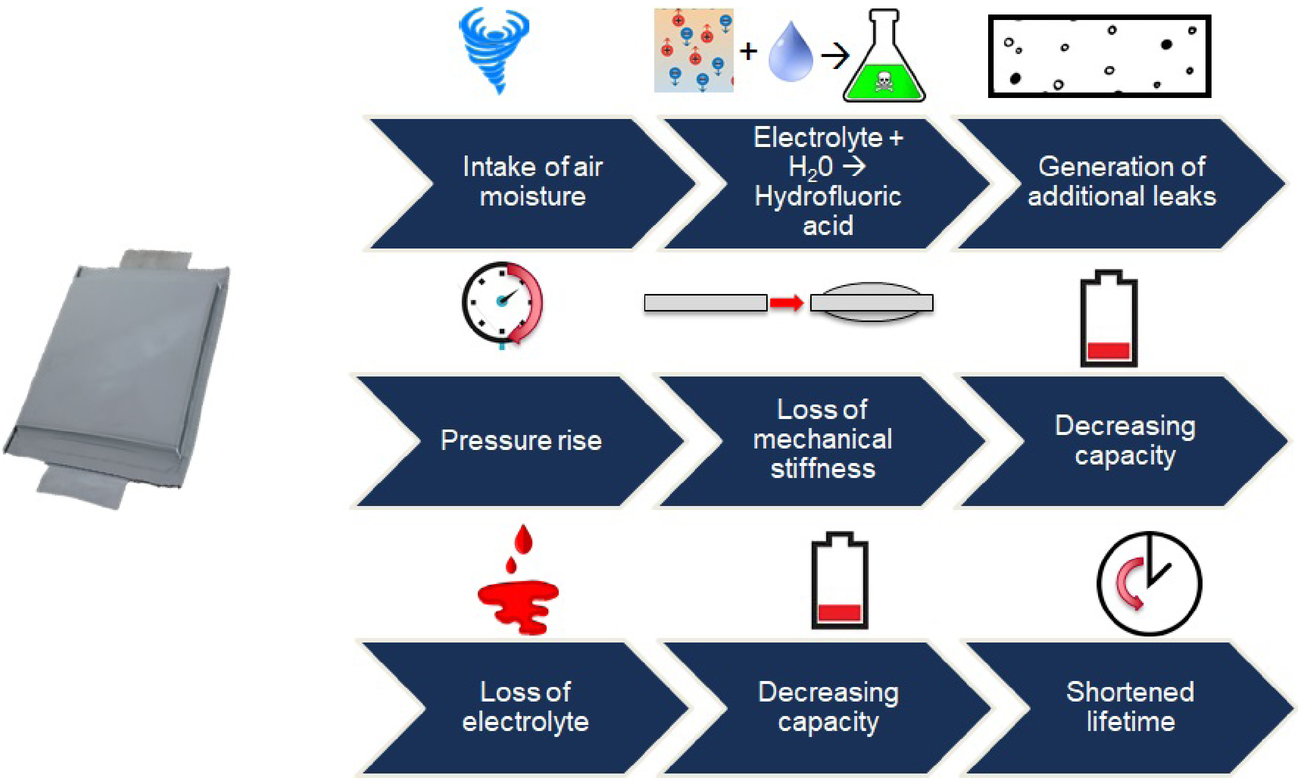
Two failure models for solid cells, whether prismatic or round.

3.2.2 Required leak rate for pouch cells

For pouch cells, it is useful to differentiate between two failure models. If there is a large, so-called gross leak, then the penetrating air will affect the required underpressure in the cell. One of the leak-proofing requirements for pouch cells is for the underpressure to still exist after ten years, i.e., for the internal pressure to be less than 1,000 mbar. This results in an exceptionally stringent requirement for the limit leak rate: it may only be 10^{-9} mbar·l/s. The second failure model for pouch cells results in less stringent requirements. If a needle-shaped leak occurs, the contact surface of the air and the electrolyte is relatively small, and the unwanted water concentration in the electrolyte rises slowly as a result. For the water concentration to be less than 80 ppm after 10 years of service life, a needle-shaped capillary leak must have a diameter of less than 1 µm. This corresponds to a limit leak rate in the range of 10^{-8} mbar·l/s.

In-depth SAE paper

"Methods for Leak Testing Lithium-Ion Batteries to Assure Quality with Proposed Rejection Limit Standards" is an SAE paper by Dr. Daniel Wetzig, Research Manager at INFICON. It examines the leakage scenarios for the various types of lithium-ion cells and discusses - based on INFICON experience - which limit leak rates are useful for their testing: www.sae.org/publications/technical-papers/content/2020-01-0448/



Three failure models for soft pouch cells.

However, these two theoretical limit leak rates for pouch cells do not come into play in practice, since capillaries "block" with electrolyte above a limiting diameter of a few µm (depending on the internal pressure and material combination). That means that they fill completely with electrolyte, which, due to its surface tension and wetting behavior, does not leak from the end of the capillary. In practice, this means that neither electrolyte can escape from leaks smaller than this limit diameter, nor can air and thus, no humidity can enter either. At the very small contact area - a circular area with a diameter of a few µm - between moist air and the electrolyte at the end of a leak channel, very small amounts of water can enter by diffusion, but the magnitude is so small that the amounts can be neglected.

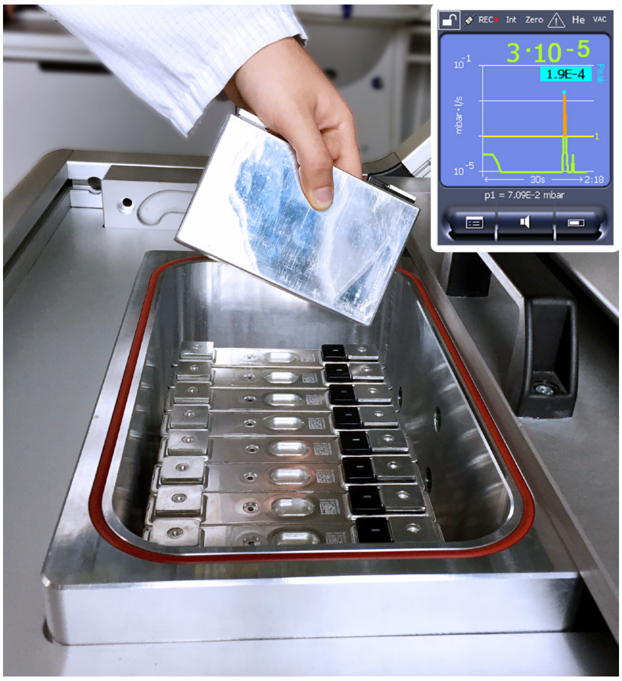
3.3 Preliminary testing of cell housings

Many manufacturers of battery cells are already performing leak testing on the housings of the cells. For this purpose, the solid housings of prismatic and round cells are evacuated and subsequently refilled with 100 percent helium

Failure case	Max. permissible hole size	Corresponding helium leak rate
Absorption of moisture < 80 ppm	(1µm)	~ 10^{-8} mbar·l/s
No significant increase in pressure over 10 yrs	(<< 1µm)	< 10^{-9} mbar·l/s
Blocking of the leakage channel ➔ No penetration by atmospheric moisture, no leakage of electrolyte	(2 ... 5 µm)	~ 10^{-6} mbar·l/s

Derivation of the limit leak rates to be tested.

and sealed. The cell is then placed in a vacuum test chamber, the chamber is evacuated and the amount of helium leaking from the battery cell over a given period of time is measured. After the leak rate has been determined, the helium can be recovered from the cell. For this housing test, one usually works with a limit leak rate of 10^{-6} mbar·l/s. To reduce the helium requirement, it is also possible to lower the helium concentration, provided that the tracer gas is mixed with either dry air or nitrogen.



Preliminary test of unfilled prismatic cells.

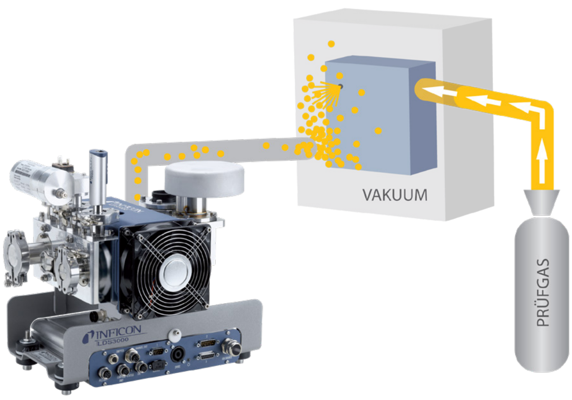


Diagram for helium testing in a vacuum chamber.

Leakage channel diameter (hole size)	Helium leak rate in vacuum testing
10 µm	$3{\cdot}10^{-4}$ mbar·l/s
5 µm	$2{\cdot}10^{-5}$ mbar·l/s
2 µm	$5{\cdot}10^{-7}$ mbar·l/s

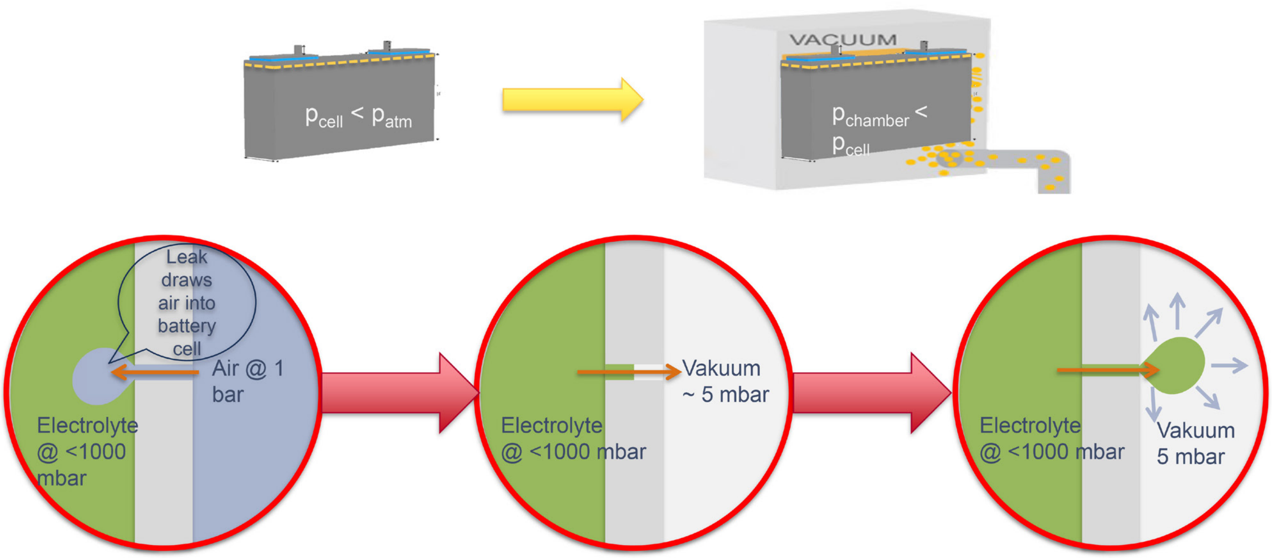
Relationship between the leakage channel diameter and the helium leak rate for prismatic and round cells when tested in a vacuum, assuming a cell wall thickness of 2 mm.

3.4 Leak testing on ready-filled battery cells

Even if a cell with a rigid case has been subjected to preliminary testing, it is still always possible that the filling nozzle, for example, is leaking. In the case of soft pouch cells, preliminary testing is hardly possible anyway. This makes it necessary to test the ready-filled battery cells for leak tightness. However, this test is not a trivial task. Until now, the only methods available for this purpose were either not sensitive enough, too unreliable, or both. For example, the pressure test, whose minimum detectable leak rate is 10^{-4} mbar·l/s in the very best case, is far too insensitive for the required test of a leak rate of 10^{-6} mbar·l/s, which is a hundred times lower. In addition, pressure testing always carries the risk that even the smallest temperature fluctuations will falsify the results, especially with larger test part volumes. And although the so-called helium bombing has sufficient sensitivity, successful testing with bombing depends decisively on the location of the battery cell and the exact position of the leakage point. INFICON has now found a remedy for the first time by means of a specially developed detection method. This completely new method uses the electrolyte solvent in the ready-filled cell as the tracer gas.

3.4.1 Direct leak detection using electrolyte solvent

To be able to reliably test all three types of cells for leak tightness, even after they have been finally filled, INFICON has developed a method

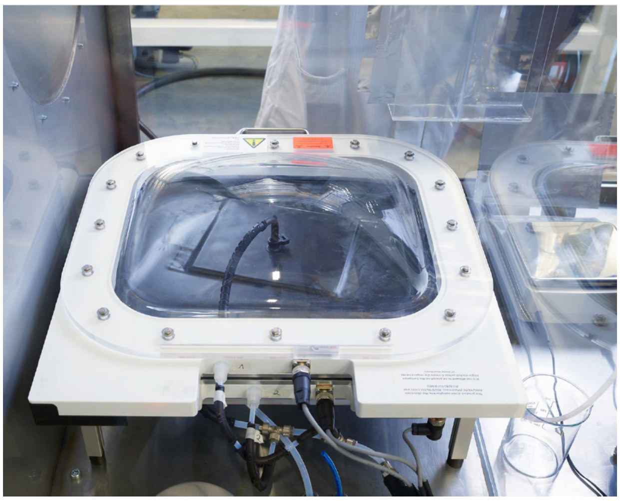


Direct detection of leaking, gaseous electrolyte in a vacuum.

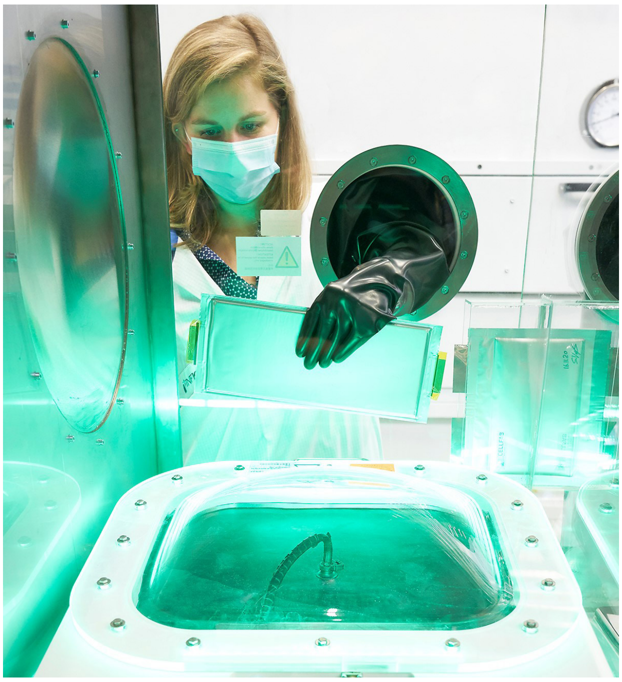
that directly detects any leaks in lithium-ion battery cells. With this new method, leaking electrolyte solvent serves as the tracer gas. In this way, the INFICON ELT3000 tester can identify leaks in lithium-ion cells down to a helium-equivalent leak rate of $1 \cdot 10^{-6}$ mbar·l/s, which corresponds to a leak diameter of a few microns. For battery cell types with a solid case, a rigid vacuum chamber is suitable.

For fragile pouch cells, INFICON has developed and patented a flexible film vacuum chamber that fits snugly against the pouch cells during testing. As a carrier layer, the foil protects the cells from any damage in the vacuum.

Once the vacuum is generated, electrolyte solvent escapes into the chamber from potential leaks. Because the air pressure there is only a few mbar absolute, the solvent evaporates immediately in the vacuum chamber, allowing it to be detected as a gas by the ELT3000's mass spectrometer. The ELT3000 directly detects all common electrolyte solvents, such as DMC, DEC, EMC and PP. The instrument is designed in such a way that it is just as suitable for use at manual work places in the development department as for the simultaneous testing of several cells in automated production lines. The pure measurement time is approximately 10 seconds; the pump-down time depends on the chamber and pump size used.



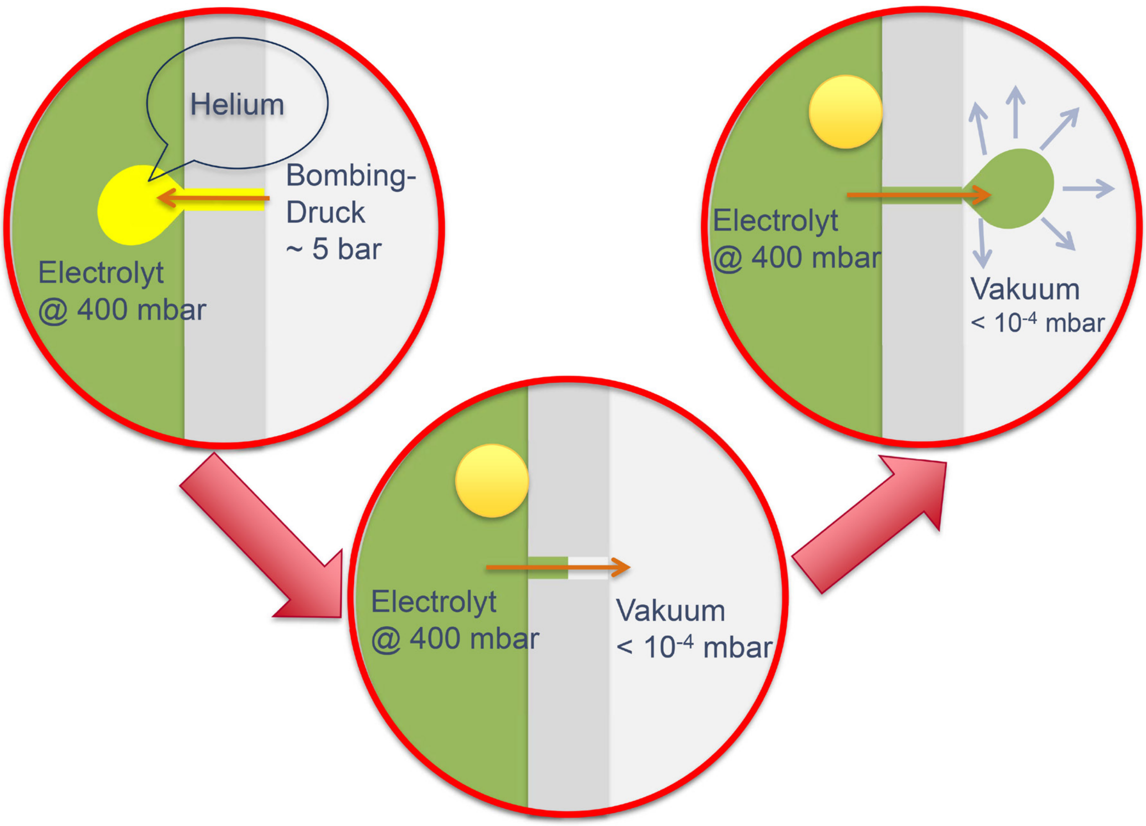
Flexible film vacuum chamber prevents damage to delicate pouch cells.



Manual loading before the vacuum test.

3.4.2 Direct detection is superior to pressure methods and helium bombing

With its mass spectrometer technology, the new battery cell tester from INFICON is able to detect leaks 1,000 times smaller than conventional pressure measurement methods - this is essential for the targeted 10-year cell service life.
In this particular battery cell testing application scenario, the ELT3000 is also far more reliable than a method such as helium bombing. In bombing, the battery cell is first placed in a vacuum chamber and then exposed to a helium atmosphere under positive pressure. This is to allow the tracer gas, helium, to enter the cell through any leaks. The helium is then detected in a final step when it escapes again through the leak.
However, the exact leak location and the position of the battery cell are crucial for the success of the bombing method: If the leak is located on the underside of the cell, for example, the final vacuum test cannot reliably detect the tracer gas because the light helium in the battery cell

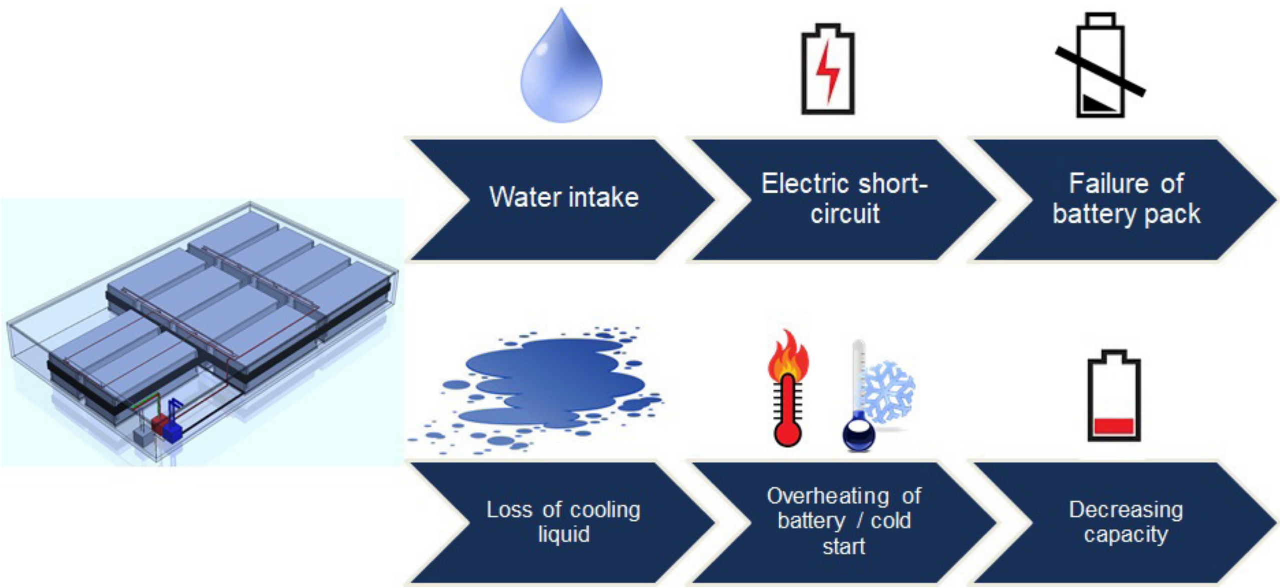


Why helium bombing is not suitable for leak testing battery cells.

rises to the top and sometimes does not even escape from the leak at the bottom. The new direct test method does not have these problems: When testing ready-filled lithium-ion battery cells, it combines accuracy and reliability, whether using prismatic, round or pouch cells.

4 Requirements for battery pack housings

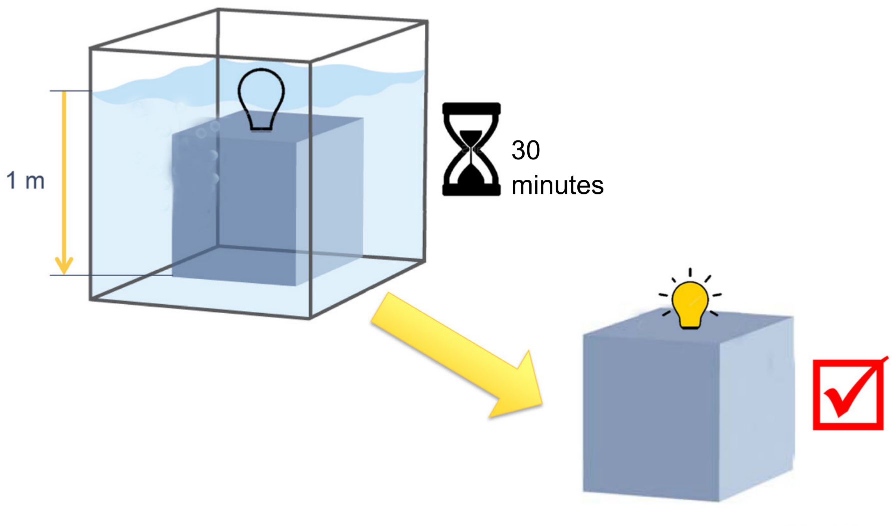
Battery pack housings require specific leak-proofing requirements since they must protect the modules and cells inside of them from water. Depending on where in the vehicle it is installed, a housing must meet the requirements for protection classes such as IP67 or IP69K. The latter becomes relevant if the housing is potentially exposed to the jet of a high-pressure cleaner. However, if another base plate is installed under the traction battery of the vehicle, it is sufficient if the housing of the battery pack meets the requirements of protection class IP67. The specific limit leak rate for which testing should be carried out again depends on the material from which the housing is made. Steel and plastics are comparatively uncritical, while aluminum has particularly high requirements.



Two failure mechanisms in battery packs.

Tech Spot 1: IP67 - The enclosure material determines the limit leak rate

Housings for current-carrying components are often designed according to protection class IP67, whether they are housings for lithium-ion batteries, power control units, electric motors or electronic modules. Testing according to IP67 requires that, after an immersion bath of 30 minutes at a depth of 1 meter, the component must have retained its full functionality. In some cases, this means that no water of any kind may have penetrated into the component. Looking at the IP67 requirements in more detail, two things become clear. First, the required limit leak rates can usually only be tested for using modern tracer gas methods. Second, the housing material itself has a significant influence on leak-proofing requirements because water droplets detach more easily from some materials than from others, and thus enter the housing through a leakage channel.

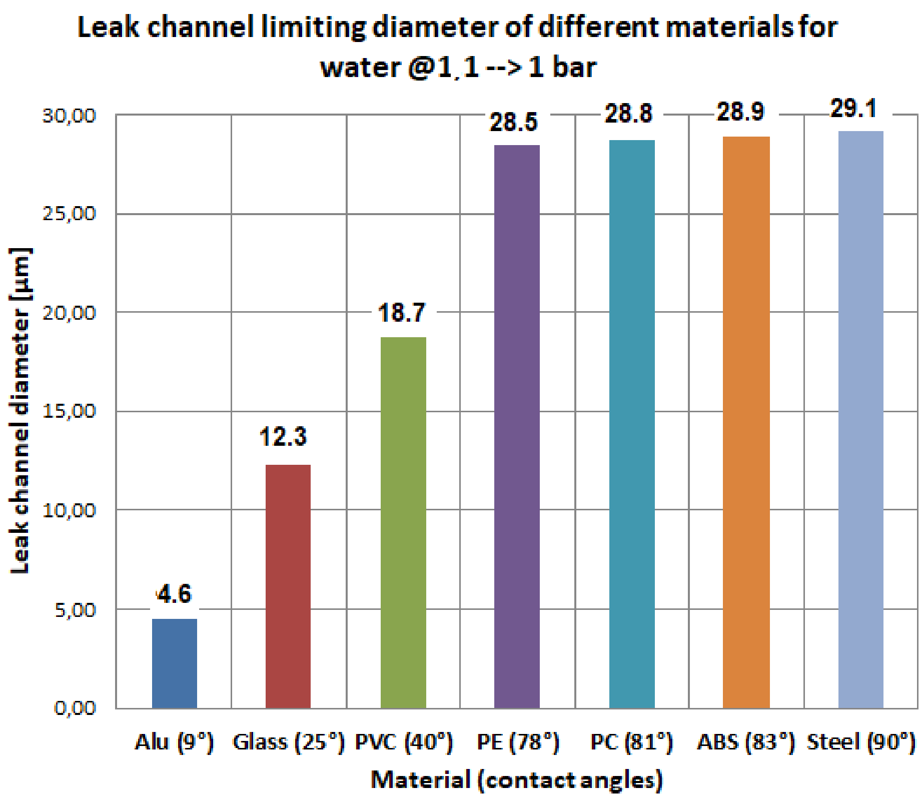


Definition IP67.

The housing material determines the limit leak rate

Tests with glass capillaries of a defined length and diameter illustrate when a water droplet penetrates a leakage channel at the differential pressure of 0.1 bar as required by IP67. If a glass leakage channel has a length of 10 mm and a diameter of 20 µm, this leak size corresponds to a helium limit leak rate of $2 \cdot 10^{-4}$ mbar·l/s (0.01 sccm). If such a glass capillary is used in the experiment at these pressure conditions, then the first drop of water soon appears, but it does not detach until after a period of more than 30 minutes. In theory, the water pressure of 0.1 bar is then in equilibrium with the forces that cause the water to adhere to the surface of the 10 mm long leakage channel when the glass capillary has a diameter of 12 µm. Experiments have shown that within 30 min, even with a diameter of 15 µm, no more droplets form.

In general, water droplets detach comparatively poorly from glass because the water adheres well to its surface. Water droplets adhere slightly better to other materials such as steel or ABS



Limit diameter for water penetration when tested according to IP67 (100 mbar overpressure) for various materials.

than to glass. Before a leak here leads to water penetrating a housing under a differential pressure of 0.1 bar, the leakage channel diameter must be a little larger. If housings made of steel or ABS are to be watertight according to IP67, it is recommended to test for a limit leak rate of approximately $1 \cdot 10^{-3}$ mbar·l/s (0.06 sccm). Housings made of aluminum, on the other hand, have greater leak-proofing requirements. Here, water droplets only adhere to the material at a very small leakage diameter. Accordingly, an aluminum housing, for complete watertightness in the half-hour IP67 scenario, must be tested against a hundred times lower limit leak rate, in the range of 10^{-5} mbar·l/s (0.01..0.05 sccm).

A few drops of water or none at all?

After the defined immersion process, protection class IP67 requires unchanged, complete functionality. What it does not explicitly require is that no water at all penetrate the component during a 30-minute immersion bath at a pressure difference of 0.1 bar. If a manufacturer decides that it can tolerate the penetration of a few drops of water, because it does not affect the functionality of the component, the manufacturer can accordingly choose other, not as low leak rates for the test. For example, if a component has an ABS or steel housing with a polymer gasket, testing for a limit leak rate of $5 \cdot 10^{-3}$ mbar·l/s (approximately 0.3 sccm) will ensure that only isolated drops will penetrate. For complete watertightness, however, testing against $1 \cdot 10^{-3}$ mbar·l/s (approximately 0.06 sccm) is required.

Glass Capillary	220 x 33	150 x 43	75 x 27	40 x 22	15 x 30	[µm x mm]
Air leak rate	56	9	1	0.1	0.001	[sccm]
Air leak rate	1.01E+00	1.69E-01	1.69E-02	1.69E-03	6.91E-05	[mbar*l/s]
Helium leak rate	9.51E-01	1.58E-01	1.58E-02	1.58E-03	6.42E-05	[mbar*l/s]
Drop interval	~ 1	~ 1.5 – 2	~ 60	~ 120 – 180	---	[sec]
Drops after 30 minutes	~ 1800	~1200 – 900	~ 30	~ 15 – 10	---	

Relationship between the gas leak rate and the water leak rate.

Tracer gas beats pressure decay test

In practice, leak rates on the order of 10^{-3} mbar·l/s (0.06 sccm) represent the limit of what can be detected with a conventional pressure decay test under ideal conditions. For their leak testing in production, many manufacturers therefore only resort to limit leak rates of up to 10^{-2} mbar·l/s (or up to 1 sccm) and, when testing for gross leaks, to the pressure decay test, which tends to be less reliable. This is because, especially with large component volumes, the measurement of the pressure change is strongly affected by even the smallest temperature fluctuations during the testing process. This cannot be fully compensated for in pressure decay testing - and can very easily lead to false positive or false negative results. Therefore, for all limit leak rates in the range 10^{-3} mbar·l/s or less (<0.06 sccm), the more reliable tracer gas-based methods are more suitable because they are free from temperature influences. The choice of a specific test method also depends on the pressure differential that a part can tolerate. Many parts designed to meet protection class IP67 can withstand only fairly small pressure differentials of 0.1 or 0.2 bar. Otherwise, the component or its gaskets would be damaged.

4.1 Preliminary housing testing in a vacuum or accumulation chamber

In contrast, a cast aluminum housing that has not yet been assembled can withstand high pressure differences. Helium leak testing in the vacuum chamber is therefore a suitable method for the preliminary testing of the leak tightness of such an aluminum housing. In addition to its sensitivity, the great advantage of the vacuum method is its high speed: A modular leak tester, such as the LDS3000, permits particularly short cycle times in the production line. In the vacuum method, the test part is first evacuated and then filled with the tracer gas helium at a pressure of 1 bar or greater. A vacuum is then generated around the test part in the vacuum chamber. In this way, escaping helium can be detected immediately. Alternatively, a pressure of up to 6 bar can be used, but the helium concentration is then reduced to 15 percent. In any case, with the vacuum method, the pressure difference is so great that the limit leak rate against which testing must be carried out is increased by a factor of approximately 10. Thus, for the complete watertightness of an aluminum housing, testing is not carried out in the vacuum chamber for a limit leak rate in the range of 10^{-5} mbar·l/s (0.01...0.05 sccm), but rather 10^{-4} mbar·l/s (0.1....0.5 sccm). However, the basic relationship between the properties of the material with regard to its adhesion to water and the corresponding limit leak rate to be tested for remains effectively unchanged in the vacuum test. Steel and plastics are the least demanding while aluminum is particularly demanding.

The testing sequence also differs, depending on the material. In the case of housings made of comparatively easily deformable plastic, it is not possible to evacuate them completely at the start of the test. If the housing is evacuated at all, then only down to the maximum tolerable underpressure. The moderately evacuated housings are then charged with tracer gas to the maximum tolerated positive pressure. When measuring the escaping tracer gas, it should be noted that the tracer gas concentration is lower than in a completely evacuated housing, since the helium mixes with the residual air present in the component. Accordingly, the actual leak rate measured is lower and must always be given the necessary correction factor.

The fastest and most accurate way to test a component for leak tightness on the production line is to test for helium in a vacuum chamber. Another option for the integral leak testing of both assembled and unassembled housings is accumulation testing, although this requires somewhat longer cycle times. A simple accumulation chamber is used to determine whether tracer gas is escaping from the inside of the test part. Fans ensure that escaping tracer gas is distributed in the chamber and accumulates there to be detected by the stationary sensor. The LDS3000 AQ from INFICON is used in such test systems. As tracer gases, it uses either helium or the cost-effective forming gas, a non-combustible mixture of 5 percent hydrogen and 95 percent nitrogen. Despite the low detection limit of 10^{-5} mbar·l/s (approx. 0.03 sccm), with a correspondingly low dead volume of the chamber, the costs of accumulation testing with the LDS3000 AQ are similarly low as those for simple air testing. Accordingly, the accumulation test is suitable for housings made of plastic or steel. For the more demanding aluminum housings, which are to be tested for a limit leak rate of 10^{-5} mbar·l/s (0.03 sccm), vacuum testing is still required.

Accumulation leak testing with LDS3000 AQ leak detector

4.2 Automated robotic sniffer leak detection

For example, if a manufacturer wants to test the integrity of the gaskets on an already assembled battery pack, vacuum testing is not an option, because too high a differential pressure could damage the gaskets and underpressure could destroy the installed capacitors. For testing on finished battery packs and already assembled housings, tracer gas-based sniffer leak detection is recommended instead. Either the measuring tip of the sniffer leak detector is located on a robot arm that travels along all the connection points between the bottom of the housing and the cover, or an tester manually guides a measuring tip over the trouble spots of the housing. In principle, a distinction is made between static leak testing - the sniffer tip remains over a defined point for a few seconds (before moving on to the next) - and dynamic leak testing. In the latter case, the robot arm or the human tester moves the sniffer tip in a continuous motion over the surface, for example, along a weld seam or an installed gasket.

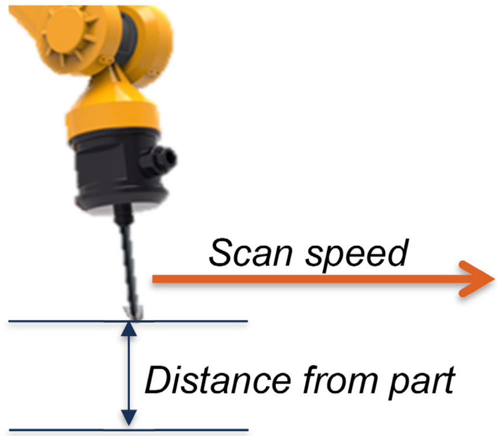
In both static and dynamic sniffer leak detection, the smallest possible safety distance between the sniffer tip and the test part surface is desirable, especially in automated testing with the robot arm. This is because, although the sniffer tip must never touch the component, it must still be able to reliably detect an escaping tracer gas cloud. Component tolerances and the accessibility of potential leakage points are limiting factors here. In addition, a robotic testing system should, in any case, be located in a shielded area so that escaping tracer gas clouds cannot blow away - ideally, the Plexiglas safety enclosure of the robotic station also protects against air movements in the production area.

Diagram for robotic sniffer leak detection using the modular LDS3000 plus XL sniffer adapter.

In addition to the smallest possible safety distance of the sniffer tip, the feed speed also plays a decisive role in dynamic robotic sniffer leak detection. In order to be able to perform robotic leak testing with a high degree of reliability, it is therefore essential that the sniffer leak detector draws in the air to be tested at a high gas flow rate. Conventional sniffer leak detectors usually operate with a gas flow of only 60 sccm, making dynamic robotic sniffer leak detection completely impossible.

INFICON offers the Protec® P3000XL and the XL3000flex, two leak detectors with a very high gas flow rate of 3000 sccm. They have been specifically developed for fast and robotic leak testing. The Protec P3000XL operates with helium and is suitable for dynamic robotic testing of medium limit leak rates up to the order of 10^{-4} mbar·l/s (down to 0.01 sccm). With static robotic sniffing and the smallest possible distance to the test part, the instrument detects leaks of up to 10^{-5} mbar·l/s in practice. However, the XL3000flex is even more sensitive. This instrument is therefore recommended for the dynamic robotic sniffing of limit leak rates in the range of less than $1 \cdot 10^{-4}$ mbar·l/s (0.06 sccm). The XL3000flex can be operated either with helium as the tracer gas or with the cost-effective forming gas. BUS interfaces allow the XL3000flex to be easily integrated into a wide variety of production environments.

Dynamic robotic sniffer leak detection is used for the leak testing of fully assembled battery packs. First, the component is evacuated to a certain degree and then a tracer gas overpressure of only 0.1 bar is generated in it. A robot arm then automatically guides the tracer gas sensor along the gaskets of the battery pack to detect any leaking tracer gas. In this scenario, any leakage channel consists of the housing material, usually aluminum, on one side and the polymer for the gasket on the other. Accordingly, the limit leak rate for which the gasket is to be tested should also be averaged between the leak rates that are typical for the material. Thus, for this test scenario, a limit leak rate in the range of 10^{-4} mbar·l/s (0.01... 0.05 sccm) is sufficient, even though pure aluminum material would require testing in the range of 10^{-5} mbar·l/s (0.001...0.005 sccm).



Two limiting factors for robotic sniffer leak detection.

	Evacuation pressure	Post-fill tracer gas concentration	Leak rate correction factor[2]
1.1 bar (100 mbar)	Without evacuation	9%	0.09
	at 0.9 bar	18%	0.18
1.2 bar (200 mbar)	Without evacuation	17%	0.17
	at 0.8 bar	33%	0.33
1.3 bar (300 mbar)	Without evacuation	23%	0.23
	at 0.7 bar	46%	0.46
1.4 bar (400 mbar)	Without evacuation	29%	0.29
	at 0.6 bar	57%	0.57
1.5 bar (500 mbar)	Without evacuation	33%	0.33
	at 0.5 bar	67%	0.67

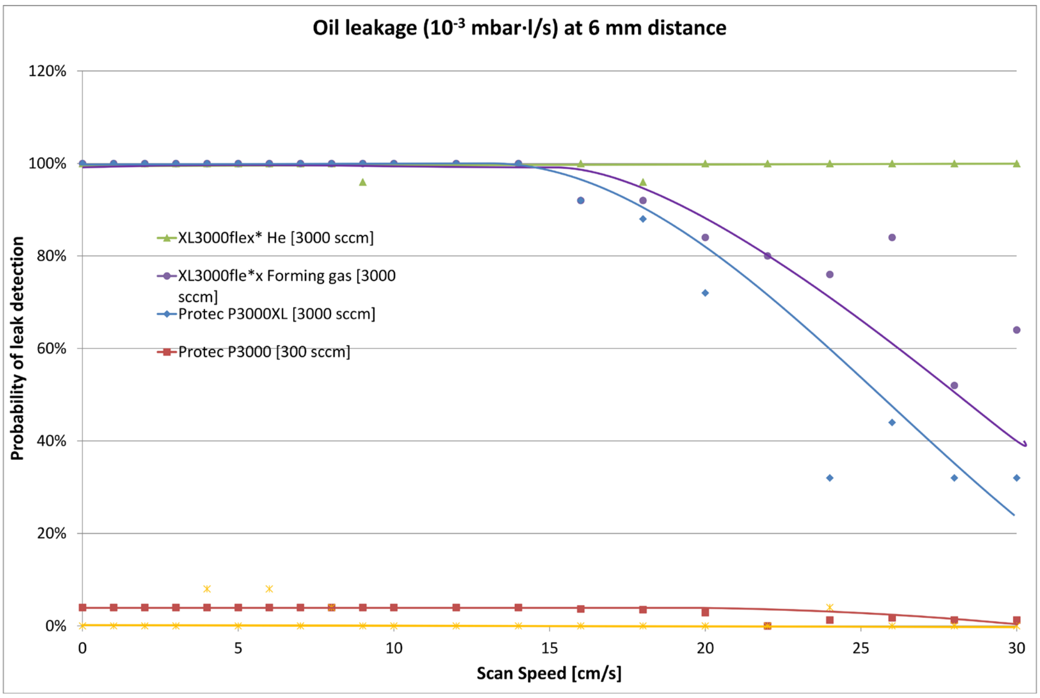
1) Max. differential pressure
2) Real leak rate to displayed leak rate.

Tracer gas concentration influences the leak rate measurement

Tech Spot 2: Why high gas flow is crucial in robotic sniffer leak testing

Dynamic sniffer leak detection should accomplish two things at once: First, it should check a larger area of the test part for any leaks; second, it should do this at the greatest possible speed. Unfortunately, both goals are not easy to reconcile with each other. This is because the lower the leak rate, the slower the cloud of escaping tracer gas is distributed at a leak location.

Many conventional sniffer leak detectors draw gas in at their sniffer tips with a particle flow rate in the range of only 60 to 300 sccm. This can sometimes be sufficient if the sniffer tip is handled carefully by hand, for example, if there are only a few test points and the sniffer tip is only moved slowly and close to the surface. However, dynamic robotic sniffer leak detection has much greater requirements.



Dynamic robotic sniffer leak detection for oil leaks, for a leak rate of 10^{-3} mbar·l/s.

Test series show what effect the scan or advance speed of the probe has, for example, when testing for a leak rate of $1 \cdot 10^{-3}$ mbar·l/s (0.06 sccm) (using the example of a test leak of $1 \cdot 10^{-3}$ mbar·l/s at a safety distance of 6 mm from the test part - see figure on Page 31). The sobering result: Conventional, commercially available sniffer leak detectors, which draw in gas at a flow rate of only 60 sccm, completely fail in such a scenario. The probability that a leak of $1 \cdot 10^{-3}$ mbar·l/s (0.06 sccm) will be found by such instruments is zero. Even instruments that operate with a particle flow rate of 300 sccm are unsuitable for this application.
Only instruments such as the Protec P3000XL and the XL3000flex, which were specifically designed for a flow rate of 3000 sccm, meet the requirements of dynamic robotic sniffer leak testing. If the robotic arm guides the measuring tip of these instruments over the surface of the test specimen at a speed of less than approximately 14 cm/s (5.5 in/sec), leaks up to the limit leak rate of $1 \cdot 10^{-3}$ mbar·l/s (0.06 sccm) are detected and pinpointed 100 percent of the time. At a test speed of more than 14 cm/s (5.5 in/sec), the detection probability of the Protec P3000XL slowly decreases, while the XL3000flex can still detect the leak completely reliably even at a speed of 30 cm/s (12 in/sec) - provided that helium is used as the tracer gas.

If this test is performed with an even lower limit leak rate of $1 \cdot 10^{-4}$ mbar·l/s (0.006 sccm), the indispensability of a high gas flow is confirmed. Again, it is only the instruments with a gas flow rate of 3000 sccm that can detect the leak 100 percent of the time. However, this requires reducing the advance speed of the measuring tip to a maximum of 8 cm/s for the Protec P3000XL and 10 cm/s (4 in/sec) for the XL3000flex.

4.3 Manual sniffer leak detection with forming gas

If the sniffer leak detection is to be performed manually rather than automatically, for example, during the pilot production of the housings, then an instrument such as the Sensistor Sentrac from INFICON is also suitable for this purpose. The Sensistor Sentrac® uses the less expensive forming gas as the tracer gas and still meets the somewhat greater leak-proofing requirements of aluminum housings with polymer gaskets in the range of 10^{-4} mbar·l/s (0.01... 0.05 sccm). Even if a tester still performs the sniffer leak detection manually in pilot production, automation with instruments such as the Protec P3000XL or the XL3000flex is usually recommended in line production.If rework on housings is then required, the manual procedure with the Sensistor Sentrac can again be used to check the results.

Sensistor Sentrac - manual sniffer leak detector for forming gas.

5 Leak tightness of cooling components

The reliable cooling of a traction battery affects its operating safety as well as its service life. Batteries heat up in the driving mode and while charging. It is therefore important to provide reliable cooling for the battery cells, as well as for the electronic control unit (ECU) of the traction battery. Generally, two different cooling systems are used: passive air cooling and active liquid cooling. In the latter case, a distinction must again be made according to the liquid medium. There are water-glycol mixtures or refrigerants, such as R1234yf. The cooling channels through which the coolant is passed in active cooling are typically made of aluminum or copper. The purpose of leak testing the cooling components is not only to ensure effective cooling of the battery. If water or refrigerant leaks out, a short circuit in the cells and modules of the battery can occur.

5.1 Glycol-water cooling or refrigerant

In a BEV vehicle, such as the Tesla Model S, round cells of Type 18650 are combined into battery modules. Sixteen of these modules form

one battery pack. The cooling coil routing the water-glycol mixture through a battery module runs in an S-shaped path through various layers of round cells. In the battery of the Model S, 16 of these modules are combined into one battery pack. This battery architecture is currently very popular in China, also.
One example of a module architecture with prismatic cells is the BMW i3. In this case, the cells

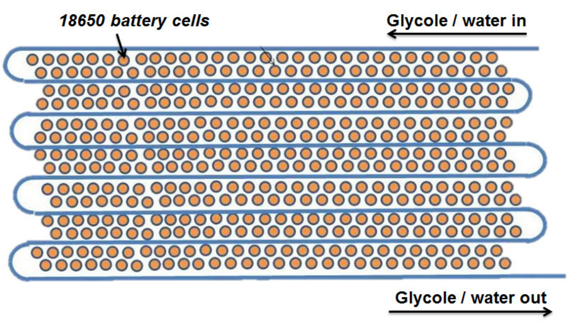


Diagram for the cooling of round cells and an illustration of a cooling coil.

are layered between a larger number of cooling plates, which in turn are connected to a base plate pervaded by refrigerant pipes. The battery module is cooled via a bypass from the vehicle's AC system and thus ultimately by a refrigerant.

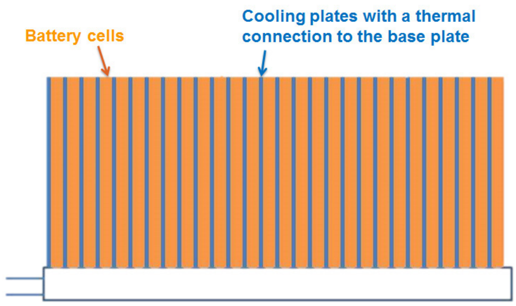


Diagram for the cooling of prismatic cells.

5.2 Leak-proofing requirements for the cooling circuit components

The specific leak-proofing requirements depend on the cooling medium. For a water-glycol mixture - the more common approach - the limit leak rate is 10^{-3} mbar·l/s (0.1...0.5 sccm). For a refrigerant such as R1234yf, because of its easy combustibility, it should even be tested for a leak rate of approximately 10^{-5} mbar·l/s (0.001....0.005 sccm). A limit leak rate of 10^{-3} mbar·l/s (0.1...0.5 sccm) might mislead one to use a simple pressure decay test to determine the watertightness of a component. But unfortunately, the pressure decay test is not suited for this application. By their very nature, cooling circuit components, such as cooling plates and heat exchangers, are extremely susceptible to temperature fluctuations - as the temperature changes, the measured air pressure in the test component changes as well. A temperature fluctuation of only 0.1 °C can already falsify the results of the pressure decay test by a factor of 100.

Instead, it often makes more sense to test cooling circuit components in a simple accumulation chamber. In this process, escaping tracer gas collects in the test chamber where it can be detected after a few seconds. Instead of helium, it is also possible to use a particularly inexpensive forming gas, an incombustible mixture of 95 percent nitrogen and 5 percent hydrogen. This is made possible by a new leak detector from INFICON, the LDS3000 AQ. It detects liquid leaks using the simple accumulation method as reliably as only the more complex helium vacuum test could in the past. The detection limit of the instrument is in the range of 10^{-5} mbar·l/s. And the testing costs are just as low as for a simple air test. Vacuum testing with helium does, however, hold one advantage as it allows shorter cycle times than the accumulation test.

5.3 Sniffer leak detection during battery installation

Once the battery cells have been manufactured, filled with electrolyte and combined into battery modules, which in turn have been grouped into battery packs, these battery packs still have to be installed in the electric vehicle. This means that vehicle manufacturers will also find themselves confronted with leak testing tasks involving the cooling circuit. After the traction battery has been installed, the OEM must test the connections to the water-glycol circuit or in the refrigerant circuit for leak tightness.

The exact limit leak rate for cooling with a refrigerant is dependent on its specifications. The allowable leak rate, usually expressed in units of g/a or oz/yr, ranges between 2 and 5 g of the respective refrigerant per year (0.07 and 0.18 oz/yr), which corresponds to a helium leak rate in the range of 10^{-5} mbar·l/s (0.001…. 0.005 sccm). There are, however, leak detectors which are able to use the respective refrigerant itself as a tracer gas during sniffer leak detection and thus directly detect escaping refrigerant. The INFICON Ecotec E3000 is one such multi-gas leak detector, where users can select the refrigerant required for their situation from a library of all relevant refrigerants. Sniff-

Ecotec E3000 multi-gas leak detector for the detection of glycol and refrigerant.

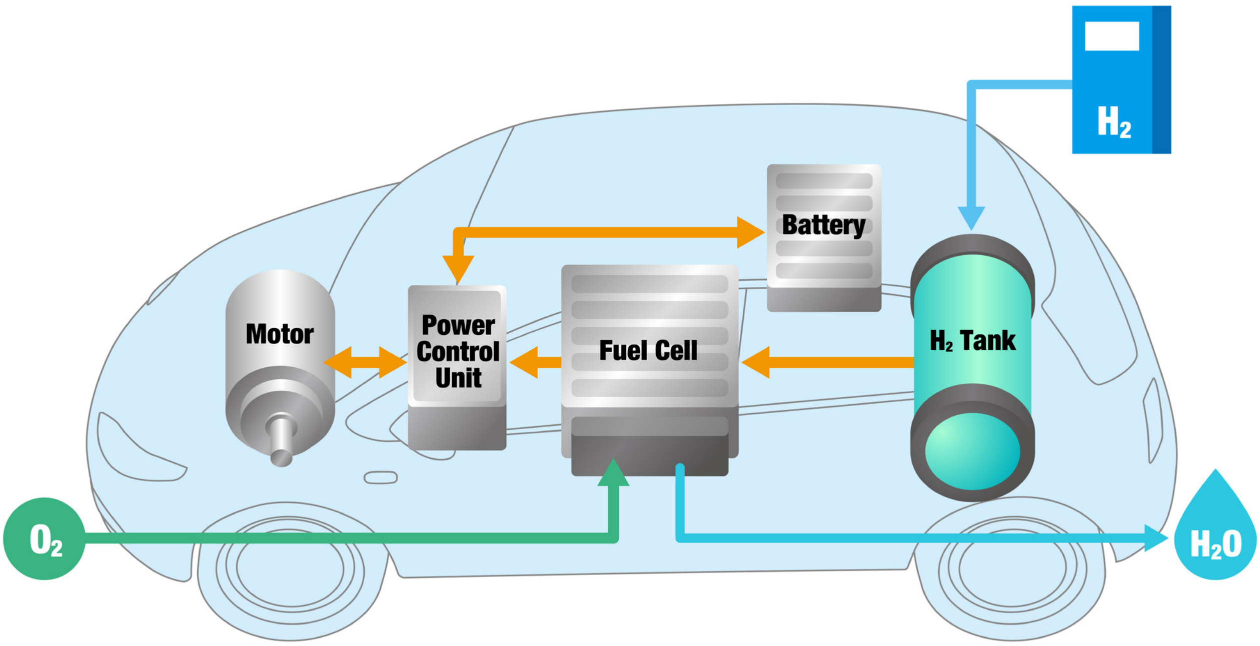
er leak detection is the only option available for testing the filling valve for leak tightness after it has been closed.

The leak tightness of a water-glycol cooling circuit must be tested for a limit leak rate of 10^{-3} mbar·l/s (0.1…0.5 sccm). This can be done either by sniffer leak detection with forming gas (and the Sensistor Sentrac) or by sniffer leak detection with helium (and with instruments such as the Protec P3000XL or the INFICON XL3000flex), with a tracer gas concentration of 5 percent being sufficient for the helium method. Both of the latter instruments work with a particularly high gas flow rate of 3000 sccm. As described in Tech Spot 2: Why high gas flow is critical in robotic sniffer leak testing, this is the prerequisite for automated sniffer leak detection.

Compared to the P3000XL, the XL3000flex has even higher reliability under production conditions. This instrument is suitable for harsh production environments, allows high process speeds and detects leaks even with an elevated tracer gas background.

6 Fuel Cell Electric Vehicles (FCEV) and their components

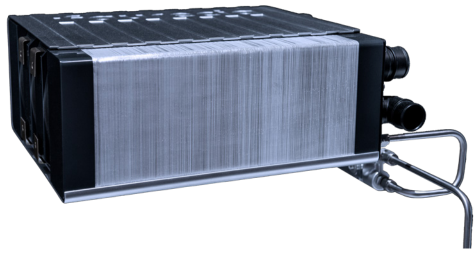
The Fuel Cell Electric Vehicle (FCEV) genre has many components for which there are the same leak-proofing requirements as for battery-electric EV vehicles. This is because both are ultimately driven by the same electric motors. The lithium-ion batteries that supply these electric



Layout of a fuel cell vehicle (FCEV).

motors with power are also identical fundamentally, but these batteries are much smaller in fuel cell vehicles and have a lower storage capacity. This is because in the FCEV, they serve only as buffer batteries. Their task is to temporarily store electrical energy so that the fuel cell can always be operated at the optimum operating point. The various test tasks for the traction batteries are basically the same as those already described in Chapters 3. Test methods for battery cells and 4. Requirements for the housings of battery packs. The specific leak-proofing requirements for electric motors will be discussed later, in Chapter 8.1 Electrical and electronic components.

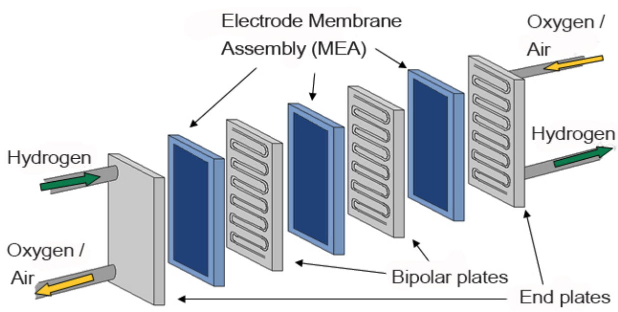
What fundamentally distinguishes FCEV vehicles from BEV vehicles is that they generate their own electrical energy. They carry hydrogen in a tank, from which they generate electricity in a galvanic cell - the fuel cell. The only exhaust gas produced by this controlled reaction of hydrogen and atmospheric oxygen is ecologically completely harmless water vapor. So while the testing requirements for the electrical components and batteries in a fuel cell vehicle are the same as for a BEV or PHEV vehicle, FCEV vehicles have the added challenge of the many leak-proofing requirements for the fuel cell components. The hydrogen tanks, hydrogen lines and hydrogen recirculation in FCEV vehicles also require leak testing - these will be discussed in Chapter 7. Hydrogen tanks and lines.



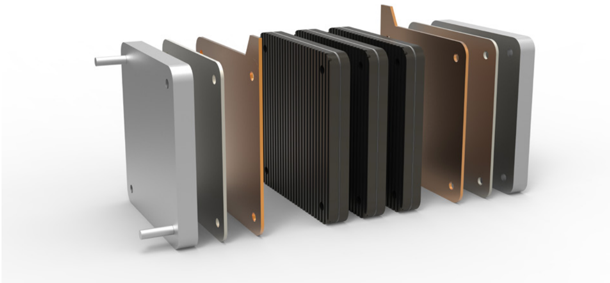
Assembled fuel cell stack.

6.1 Bipolar plates for fuel cells

Fuel cell stacks are the heart of fuel cell vehicles. These fuel cell stacks consist of two end plates with several bipolar plates sandwiched between them. The bipolar plates are each separated by membrane electrode assemblies (MEAs). As electrically conductive plates, bipolar plates have the function of connecting the anode of one cell to the cathode of the other cell. Each



Layout of a fuel cell stack.



Bipolar plates - three different channels for three different media.

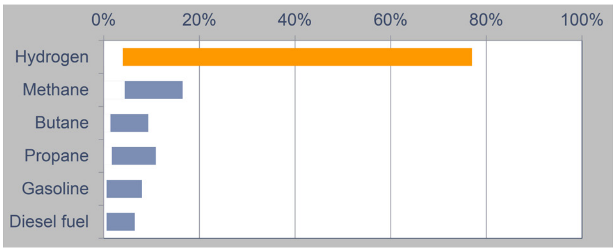
bipolar plate contains two cavities for the process gases hydrogen and atmospheric oxygen, as well as an internal cooling loop. Starting from the cavities of the process gas flow, the process gases hydrogen and atmospheric oxygen are directed over a large area to the membrane of the membrane electrode unit via the so-called flow field. The corresponding high-temperature cooling circuit has the task of maintaining an optimum process temperature for the entire fuel cell system.

Essentially, there are four failure modes for a fuel cell:

a. The leakage or loss of - combustible - hydrogen.
b. A leakage of hydrogen followed by a subsequent uncontrolled reaction with oxygen, either through so-called crossover leaks between the anode and the cathode, or through overboard leaks at gaskets.
c. Loss of coolant, with loss of efficiency and damage to the fuel cell stack.
d. Leakage of hydrogen into the cooling circuit, which, on the one hand has a corrosive effect and, on the other hand, impairs the efficiency of the cooling or even damages the pump, due to the gas bubbles in the coolant.

H_2 Hydrogen leakage	Air leakage	Coolant leakage
Hydrogen path to the outside • Undersupply of fuel cell • Flammable gas concentration	**Air path to the outside** • Undersupply of fuel cell	**Cooling path to the outside** • Overheating of fuel cell • Electric shortage
Hydrogen path into air path • uncontrolled reaction of H2 and O2 • Widening of defect	**Air path into hydrogen path** • uncontrolled reaction of H2 and O2 • Widening of defect	**Cooling path into air path** • Blocking the gas path • Undersupply of fuel cell
Hydrogen path into cooling channel • Gas bubbles in coolant • Corrosion of pump • Pump damage • Overheating of fuel cell	**Air path into cooling channel** • Gas bubbles in coolant • Pump damage • Overheating of fuel cell	**Cooling path into hydrogen path** • Blocking the gas path • Undersupply of fuel cell

Failure mechanisms for a fuel cell.

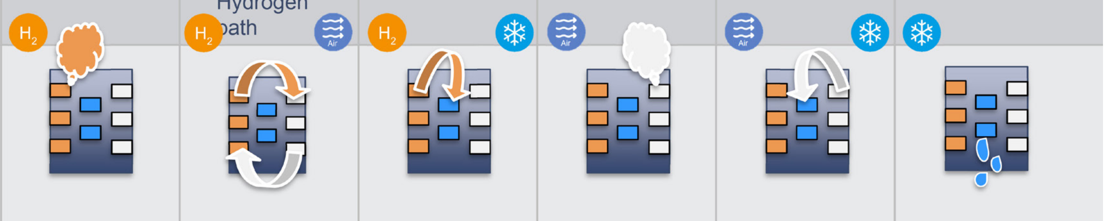


Flammability limits of different fuels.

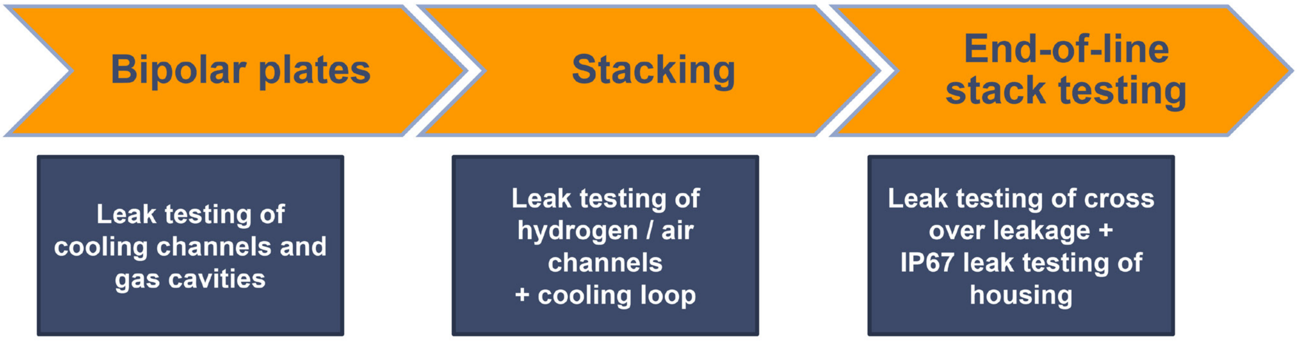
Different leak rate requirements result from the different failure scenarios. Hydrogen leakage - both to the outside and into the cooling channel - should typically be checked for leak rates in the range of 10^{-4} to 10^{-6} mbar· l/s. As a general rule, however, hydrogen leak rates should be as low as possible, if only because hydrogen is ignitable over a wide range of concentrations: between 4 and 73 percent hydrogen in air. Thus, it may well make sense to select the limit leak rate one degree of magnitude lower and to test for 10^{-7} mbar· l/s.

6.2 The refrigerant loop for the bipolar plate

The refrigerant in the high-temperature cooling circuit that runs through the bipolar plates must have low conductivity to avoid short circuits. This is why deionized water with an antifreeze additive is usually used as the cooling fluid here. To avoid leakage of this liquid from the cooling channel, leak testing for limit leak rates in the range of 10^{-3} to 10^{-4} mbar·l/s (0.1...0.01 sccm) is recommended. This is the usual order of magnitude for liquid leak tightness because leaks of this size are then sealed by the water itself. In the line production of bipolar plates, vacuum testing with helium is also the method of choice because it allows short cycle times and high throughput. In vacuum testing, the cooling channel is first evacuated, then filled with helium and

Leak testing steps	1	2	3	4	5	6
Failure to prevent	Hydrogen leakage to the outside	Cross-over leakage • Hydrogen to Air path • Air to Hydrogen path	Hydrogen leakage into the cooling path	Air leakage to the outside	Air leakage into the cooling path	Cooling leakage to the outside
						
Typical leak rates	• „as low as possible“ • Typically 10^{-3} ... 10^{-5} mbar·l/s • Some publications ask for 10^{-7} mbar·l/s					10^{-4} ... 10^{-3} mbar·l/s

Test scenarios in the testing of bipolar plates.



Testing steps in the production of fuel cell stacks.

then sealed again. Once the bipolar plate to be tested is placed in the vacuum chamber and the chamber is evacuated, a helium leak detector, such as the INFICON LDS3000, detects any helium that escapes from the cooling channel into the vacuum of the chamber. The helium used can, of course, be recovered each time after the conclusion of the testing process.

In addition to the high-temperature cooling circuit that flows through the bipolar plates, FCEV vehicles also have one or more low-temperature cooling circuits that keep electrical components, such as the drive, converter and power electronics, in temperature ranges below 60 °C. They are operated with a conventional water-glycol mixture and must also be tested for liquid leak tightness.

6.3 Testing bipolar plates for hydrogen leakage

When testing bipolar plates for hydrogen leakage, the vacuum method is also used. For this purpose, the hydrogen cavity of the bipolar plate is sealed, evacuated and filled with helium. In an evacuated vacuum chamber, a leak detector, such as the LDS3000, can then in turn detect escaping helium at limit leak rates of 10^{-6} or 10^{-7} mbar· l/s. If no helium is detectable, it is certain that there are no leaks from the hydrogen cavity to the outside or into the cooling channel. If a leak is detected, further investigation of the cause is possible. This takes advantage of the fact that the hydrogen cavity of the bipolar plate is still filled with helium and sealed after the initial test in the vacuum chamber. However, only the cooling channel of the bipolar plate is now connected to a vacuum pump. This allows the

LDS3000 to detect whether helium enters the vacuum of the cooling channel. If not, the originally identified leak led to the outside.

6.4 End-of-line testing of complete fuel cell stacks

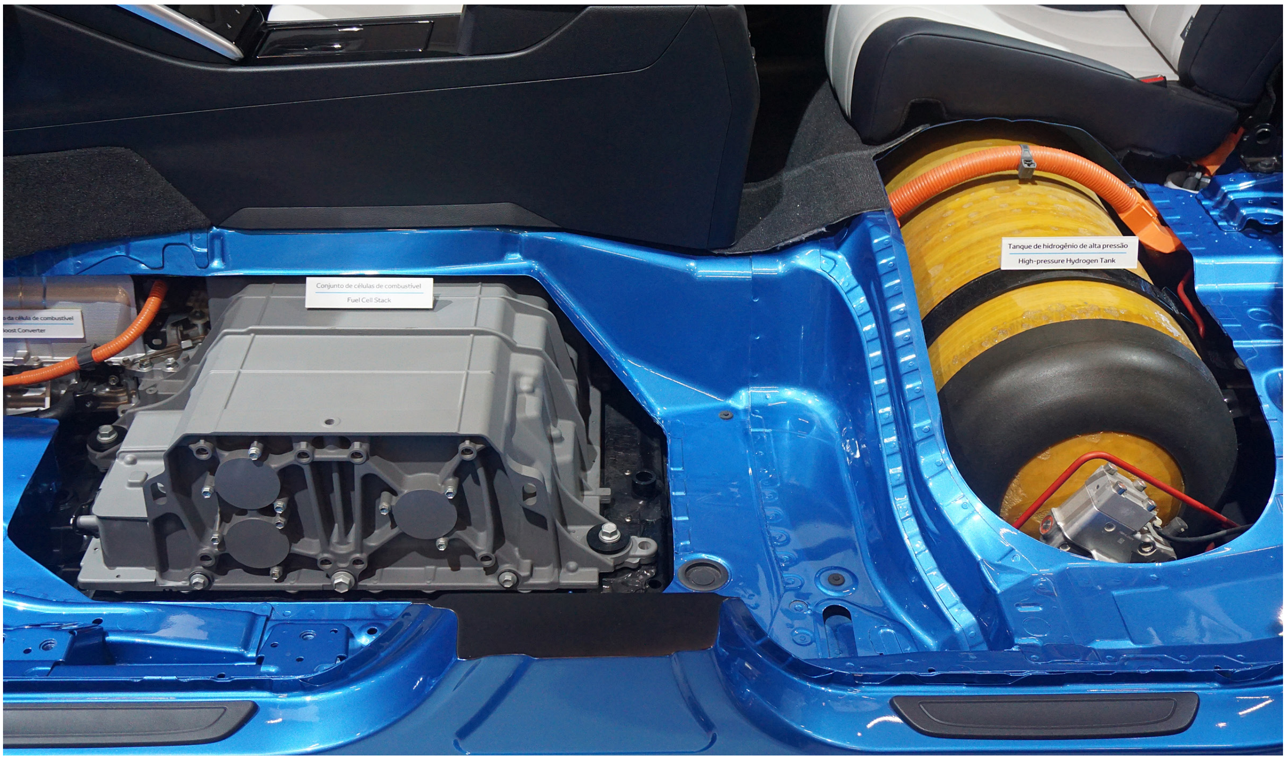
After the bipolar plates have been assembled into complete fuel cell stacks, end-of-line tests for possible hydrogen leaks are performed, although tests can also be useful after the preceding intermediate steps. Typical limit leak rates for the leak testing of assembled bipolar plates are in the range between 10^{-3} and 10^{-5} mbar·l/s (0.1...0.005 sccm). In individual cases, however, limit leak rates as low as the 10^{-7} mbar·l/s have been discussed. For all of these tests on assembled fuel cell stacks, helium is also used as the tracer gas, if only because testing with hydrogen carries the risk that the fuel cell will start to operate unintentionally and produce electricity. Also for safety reasons, hydrogen should not be used as a tracer gas, since a gross leak in the hydrogen circuit could quickly lead to hydrogen concentrations of more than 4 percent in air and thus to an ignitable mixture. Additional leak testing is required on components such as the media distribution plate of a fuel cell (which conducts hydrogen, air, and refrigerant), its various valves, pumps, and its hydrogen recirculation system. Because hydrogen and atmospheric oxygen do not completely react with each other at the membrane electrode units of the bipolar plates, the gases - after passing through water separators - are recirculated and reused in the fuel cell. Again, ideally, hydrogen-carrying components should be tested for the lowest possible leak rates of up to 10^{-6} or 10^{-7} mbar· l/s.

Sniffer test on a fuel cell stack.

7 Hydrogen tanks and lines

7.1 Standards and permeation limits

The hydrogen tanks installed in fuel cell vehicles are usually so-called Type IV tanks made of composite materials. The purpose of these pressurized tanks is to be able to carry a larger quantity of hydrogen gas in the vehicle. The strength of a Type IV tank is typically provided by a carbon fiber structure; these tanks are



Hydrogen tank installed in a Toyota Mirai.

lined with a polymer layer. Type IV pressurized hydrogen tanks for passenger cars are typically designed to withstand operating pressures up to 700 bar (or 10,153 psi), while the much larger hydrogen tanks of buses are designed to only withstand operating pressures of up to 350 bar (5,076 psi). A fuel cell production passenger car, such as the Toyota Mirai, has two tanks, each with a volume of approximately 60 l (15,85 gallons), while hydrogen buses use tanks with volumes between 1,300 and 1,700 l (340 to 450 gallons).

The leak tightness and leak rate requirements for the hydrogen tanks of fuel cell vehicles result from a number of international standards that define the maximum permeation rates for these tanks. These are standards such as ISO15869 B.16, EU406-2010 4.2.12.3. and ECE R134 5.3.3.

For continuous operation, ISO 15869 B.16 defines a permeation rate for hydrogen gas of less than 2 cm³ per hour and liter of tank capacity at a pressure of 350 bar / 5,000 psi (as is typical in buses). At a pressure of 700 bar / 10,000 psi (i.e., for passenger car tanks), the permeation rate may be 2.8 cm³ per hour and liter of tank capacity.

The standard EU406-2010 4.2.12.3 specifies that the permeation rate must be less than

6 Ncm³ per hour and liter of tank capacity in continuous operation.

And the standard ECE R134 5.3.3. (c) specifies that, if the measured permeation rate is greater than 0.005 mg/s (corresponds to 3.6 Nml/min 0 = 3.6 sccm), local leak testing is necessary to ensure that the total value of 0.005 mg/s (3.6 Nml/min = 3.6 sccm) is not exceeded at any individual leakage point.

7.2 Leak rates are based on permeation rates

The permeation rate of a hydrogen tank is to be equated with a leak rate in its leak testing. For a passenger car hydrogen tank with a capacity of 30 l (~ 8 gallons) and a pressure of 700 bar (~ 10,000 psi), this results in, converted according to the permeation limit values of ISO 15869 B.16, a helium limit leak rate of $2.3 \cdot 10^{-2}$ mbar·l/s (1.4 sccm). With the same tank size and only 350 bar (~ 5,000 psi) pressure, the limit leak rate would be even somewhat lower at $1.6 \cdot 10^{-2}$ mbar·l/s (1 sccm). For a passenger car tank with 30 l (~ 8 gallons), the standard EU406-2010 4.2.12.3. provides for a limit leak rate equivalent to $5 \cdot 10^{-2}$ mbar·l/s (3 sccm). According to ECE R134 5.3.3. (c), the maximum permissible limit leak rate is finally $6 \cdot 10^{-2}$ mbar·l/s (3.6 sccm).

In reality, however, hydrogen tanks are often not only tested according to the standards - and thus in the range of 10^{-2} mbar·l/s (1...3 sccm) - but even for leak rates in the range of 10^{-3} mbar·l/s (0.1...0.5 sccm). This is because the actual permeability of the materials used for hydrogen tanks is often an order of magnitude lower than required by the standards.

7.3 Accumulation testing for hydrogen tanks

Only when the required fittings and valves are attached to a hydrogen tank does the original tank body become what is known as the tank module. Both the vacuum leak testing with helium as well as the accumulation test with forming gas are suitable for the preliminary testing of the tank bodies. Because the number of items in production is currently often not so high that a more complex vacuum test would be worthwhile due to its shorter cycle times, the accumulation test currently plays an even greater role. This applies not least of all to the large hydrogen tanks on buses. These typically have volumes of up to 1,700 l and are tested in accumulation chambers with a chamber volume of up to 4,000 l. Because of the lower tracer gas costs, such a test item is filled with the less expensive forming gas - but at a pressure of 700 bar

(~10,000 psi).This operating pressure that is twice as great would also be suitable for a burst test (which, however, is carried out beforehand with water). But the high tracer gas pressure is also necessary for the accumulation test, because the otherwise significantly lower leak rates in the rather large accumulation chamber would not be detectable. Because of the high test pressure, there is an emergency outlet in the accumulation chamber that opens when there is excess pressure.

7.4 Vacuum testing for hydrogen tanks

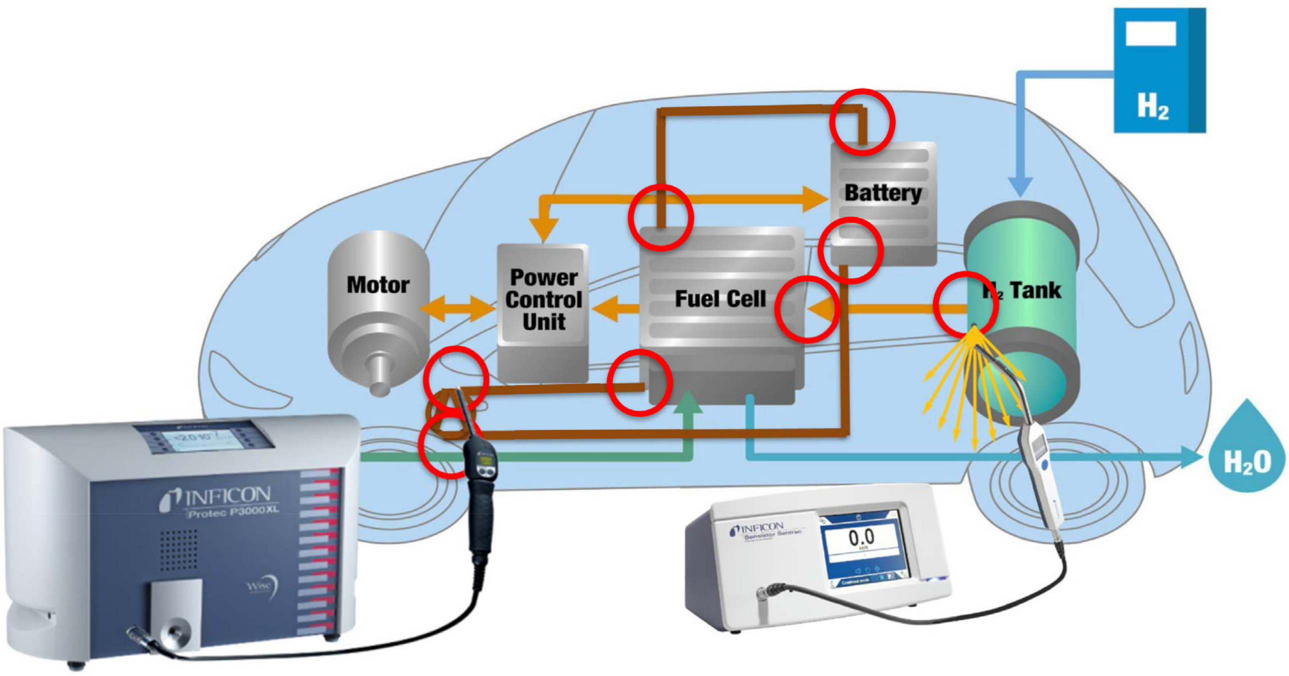
If the hydrogen tanks for buses with a higher throughput are to be checked, or if the smaller tanks for passenger cars are to be checked for leak tightness, the vacuum test with helium can generally also be used. However, for the large hydrogen tanks in buses, this also requires corresponding investments in pump sets that are able to quickly evacuate the large volume of the vacuum chamber and thus realize the fundamental speed advantage over the accumulation test. Since the vacuum chamber itself has to be much more leak-proof than a simple accumulation chamber, no emergency outlet can be installed here. Instead, it is necessary to equip the vacuum chamber with a safety cage that prevents damage if the tank bursts. Due to the general sensitivity of the vacuum method, however, it is possible to significantly reduce the helium concentration in the tracer gas or, alternatively, to fill the test item with a lower pressure than the operating pressure, both of which reduce the use of helium. At the same time, the limit leak rate that must be checked for is also reduced. If the helium concentration in the tracer gas is reduced to 1 percent, for example, the requirement for the limit leak rate increases accordingly by two orders of magnitude: Instead of $5 \cdot 10^{-2}$ mbar·l/s (3 sccm), the hydrogen tank is to be checked for $5 \cdot 10^{-4}$ mbar·l/s (0.03 sccm).

7.5 Sniffer leak detection on completed tanks with all the fittings

Even after assembling the tank body with all the fittings - filling and outlet valves, as well as pressure sensors - leak testing is still required.

Sniffer leak detection on the fittings of a hydrogen tank.

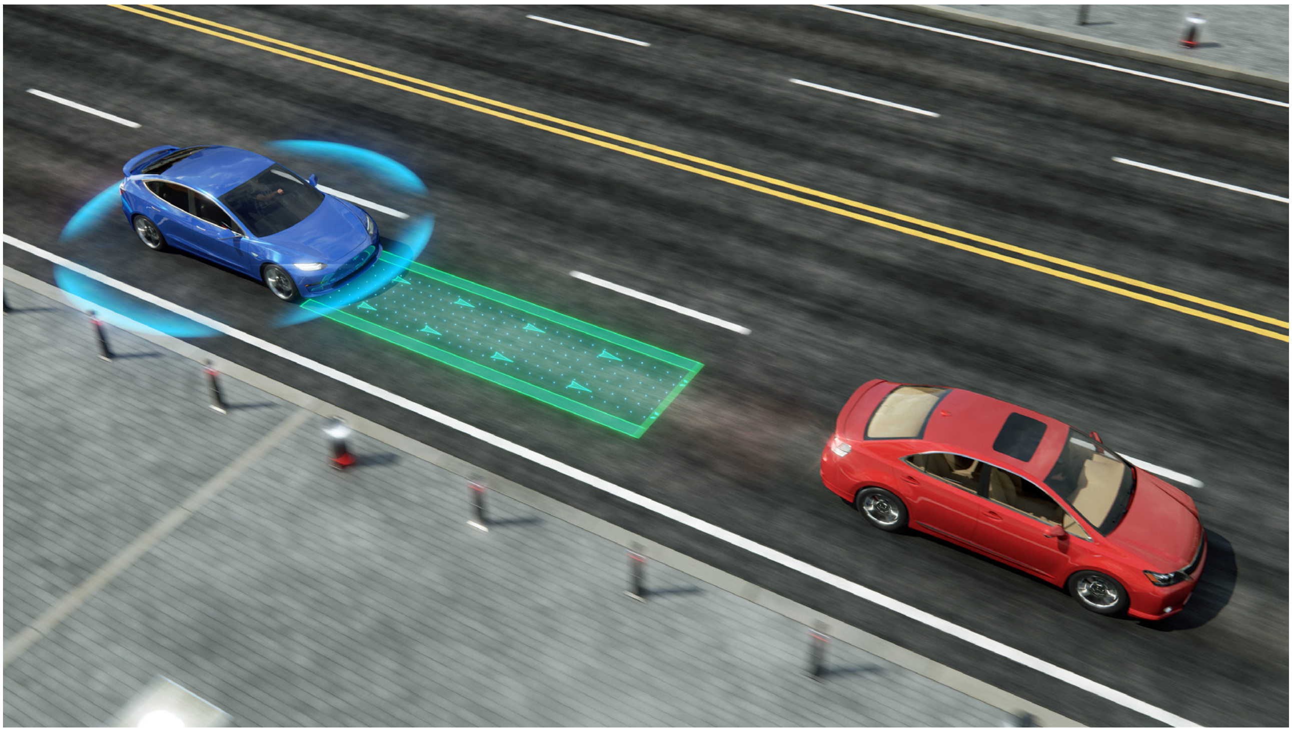
However, the so-called sniffer leak detection is usually used here. The test part - the finished tank - is filled with tracer gas (either helium or forming gas) and sealed. A sniffer tip is then moved along the surface of the tank - either completely or concentrated on the trouble spots. Basically, a distinction is made between manual sniffer leak detection and automatic robotic sniffing. Here, instead of a human tester, a programmed robotic arm guides the sniffer tip over the surface of the test specimen. As described in Tech Spot 2: Why high gas flow is crucial in robotic sniffer leak testing, gas flow plays a decisive role, especially in dynamic sniffer leak detection with a continuously moving sniffer tip. Leak detectors from INFICON, such as the Protec P3000XL and the XL3000flex, operate with a very high gas flow of 3000 sccm - they were specially developed for fast and robotic leak testing. Typical limit leak rates for these end-of-line tests on finished hydrogen tanks, which can be performed with helium or forming gas, are in the range of $5 \cdot 10^{-2}$ mbar·l/s (3 sccm).



Leak testing during installation of components in the vehicle.

8 Electrical and electronic components

The principal enemy of all electrical and electronic components in a vehicle is, by its very nature, water. Accordingly, the watertightness of the housings for these components is an important requirement - usually it is a matter of ensuring that they are in accordance with protection class IP67. The close relationship between the housing material and the resulting requirements for the limit leak rate for which testing must be carried out has already been described in Tech Spot 1: IP67 - The housing material determines the limit leak rate. In addition to the general requirements for the watertightness of housings, which is essential for the power control units and the electronic modules of vehicles, there are also leak-proofing requirements for their cooling circuits in the case of electric motors. In the case of Advanced Driver Automation Systems (ADAS), on the other hand, gastightness is essential for their sensors, among other things, in order to ensure long-term functional reliability.



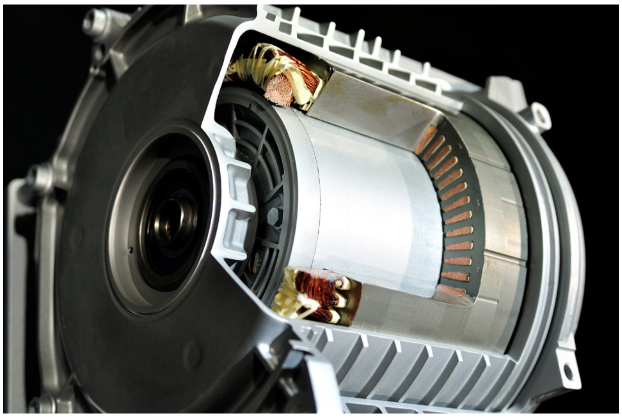
Autonomous or semi-autonomous driving requires functionally reliable environmental sensors.

8.1 Sensors and control modules

So far, sensors have often been tested using the less sensitive and strongly temperature-dependent pressure decay test. If the temperature rises during the pressure decay test, this will hide potential leaks, while a drop in temperature will lead to misidentified leaks and false alarms. With the demands on autonomous vehicles, however, the demands on the reliability of their ADAS systems and the leak tightness of their radar (radio detection and ranging) and lidar (light detection and ranging) sensors increase. A Six Sigma approach that tolerates 3.4 errors in a million cases is unimaginable in the ADAS context. Manufacturers of ADAS components follow a zero-defect strategy - with a thousand times greater reliability. Accordingly, sensors with radar or lidar technology must not only be water-tight, but also gastight so that no air humidity can penetrate into them. This means that other leak test methods are required. Manufacturers therefore test their radar and lidar sensors using a helium vacuum test for leak rates in the range of 10^{-6} to 10^{-7} mbar·l/s. Helium vacuum tests are also used for glass feedthroughs through which cables are fed into a housing.

Control modules compensate for pressure when the outside temperature changes (which is, for example, seasonal), often via a waterproof Gore-Tex® membrane. The tracer gas-based accumulation method is used here for quality assurance. The control module is first pressurized with helium at an overpressure of up to a maximum of 100 mbar, so that the tracer gas penetrates through the membrane into the control module. Subsequently, the helium can escape again through any leak into an accumulation chamber with a slight underpressure, where it accumulates. In this way, the leak is detectable.

8.2 Electric drive motors



Electric drive motor for EVs.

All vehicles with alternative drives ultimately use electric motors. It is essential to check these drive motors both to make sure that water does not enter them from the outside and to make sure that there are no leaks in their water-filled cooling jacket - either to the outside or into the motor. Even during normal vehicle use, electric motors are exposed to water, whether from environmental influences, such as rain, or from the water jet of a high-pressure cleaner, for example, in a car wash. Accordingly, the housings must meet the requirements of ingress protection classes IP67 to IP69. This results in the need to test plastic or steel housings for limit leak rates in the range of 10^{-3} mbar·l/s (0.1...0.5 sccm) and the more demanding aluminum housings for 10^{-5} mbar·l/s (0.001...0.005 sccm) (at 100 mbar differential pressure).

In addition, more and more electric motors are using active water cooling to keep the motor at a constant ideal temperature so that it operates at maximum efficiency. The coolant is usually a water-glycol mixture. The leak tightness of the water cooling jacket is important so that water does not penetrate the electrical components of the engine and cause short circuits. At the same time, however, the coolant must not leak out of the circuit and get lost. The typical leak-proofing requirement for the cooling water circuit of an electric drive motor is in the range of 10^{-3} mbar·l/s (0.1...0.5 sccm).

8.3 Vacuum or accumulation testing for motor housings

Because the components in the cooling water circuit are designed for rapid heat transfer, leak testing methods, such as air or pressure decay testing, are principally overkill, as they are far too sensitive to temperature fluctuations. That is why tracer gas-based methods are used for these tasks.

To test the watertightness of the housings of electric motors, not only vacuum testing with helium is suitable for materials such as steel or plastic, but also the accumulation method, in which a non-flammable mixture of 5 percent hydrogen and 95 percent nitrogen, the so-called forming gas, is used as the tracer gas in addition to helium. Forming gas is less expensive than helium, and the simple accumulation chamber is also less costly than a vacuum chamber. In accumulation testing, the housing is evacuated, filled with tracer gas at approximately 5 bar (the maximum permissible pressure for the housing) and then closed. The housing filled with tracer gas is placed in an accumulation chamber, where any tracer gas escaping through leaks accumulates and can be detected by a test instrument such as the INFICON LDS3000 AQ. The speed of the gradual increase in concentration of the tracer gas in the chamber is a measure of the leak rate. For aluminum housings, however, which have to be tested for leak rates in the range of 10^{-5} mbar·l/s (0.001...0.005sccm) (at a differential pressure of 1000 mbar), testing with the vacuum method is recommended. Although it is more complex, it also has the advantages of being more sensitive and allowing shorter cycle times than an accumulation test.

8.4 Leak testing of the water cooling jacket

The same procedure is used to test the water cooling jacket of an electric motor housing. The only difference is that only the cavity of the cooling jacket is filled with the tracer gas at approx. 2 to 3 bar (or at the maximum permissible pressure). Because the leak rate requirements depend on the material, the accumulation method can be used for steel and plastic housings, either with helium or forming gas. The limit leak rate here is 10^{-3} mbar·l/s (0.1...0.5 sccm). The more demanding aluminum housings are instead tested in a vacuum chamber with helium for leak rates in the range of 10^{-5} mbar·l/s (0.001...0.005 sccm) (at a differential pressure of 1000 mbar).

9 About INFICON

When it comes to development, production and sales of instruments and equipment for leak testing, INFICON is one of the leading companies. INFICON leak testing equipment is used in demanding industrial processes in production and quality control. INFICON leak detectors cover a wide variety of leak testing applications. The main customers of INFICON are manufacturers, as well as service companies for the RAC industry, the automotive industry, the semiconductor industry and manufacturers of leak testing systems. With its years of experience in leak testing and leak detection, INFICON now also supports the food industry and with its patented Contura S400.

INFICON now looks back on more than 50 years of experience in leak detection technology. INFICON handles worldwide sales through production facilities in Cologne (Germany), Balzers (Liechtenstein), Linköping (Sweden), Syracuse (USA) and Shanghai (China), as well as sales offices in all the major industrialized countries and an expanded network of sales partners. In fiscal year 2020, INFICON AG and its approximately 1100 employees achieved worldwide sales of approximately US$398 million. INFICON's registered shares (IFCN) are traded on the SIX Swiss Exchange.

10 Additional sources of information on leak testing of automotive components

10.1 Document series on specific leak testing tasks

INFICON offers a large number of documents that describe how specific automotive components can be efficiently leak tested during production. You will learn which leak rates are useful, which methods are suitable and how the testing is performed. All PDFs in this **document series** are available for free download from the INFICON website.

A selection:

Battery cells

https://bit.ly/2NiqkaO

Battery packs

https://bit.ly/3acgYq4

Electric drive motors

https://bit.ly/2Z5vcD9

Bipolar plates for fuel cells

https://bit.ly/3a8iwBt

Hydrogen tanks

https://bit.ly/3pbfgd0

10.2 Further training at the INFICON ACADEMY

The purpose of our INFICON ACADEMY is to qualify your employees. Through our seminars, we would like to help you increase the efficiency of your leak testing. Our comprehensive Seminar program is deliberately designed to be manufacturer-neutral. We will teach you the basics of leak testing, provide an overview of common measurement methods, and present a wide variety of applications in different industries.

The diverse seminar program includes specific events regarding the following:
» Leak testing of batteries and e-vehicles
» Leak testing of fuel cells and FCVs
» Robotic testing systems.

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