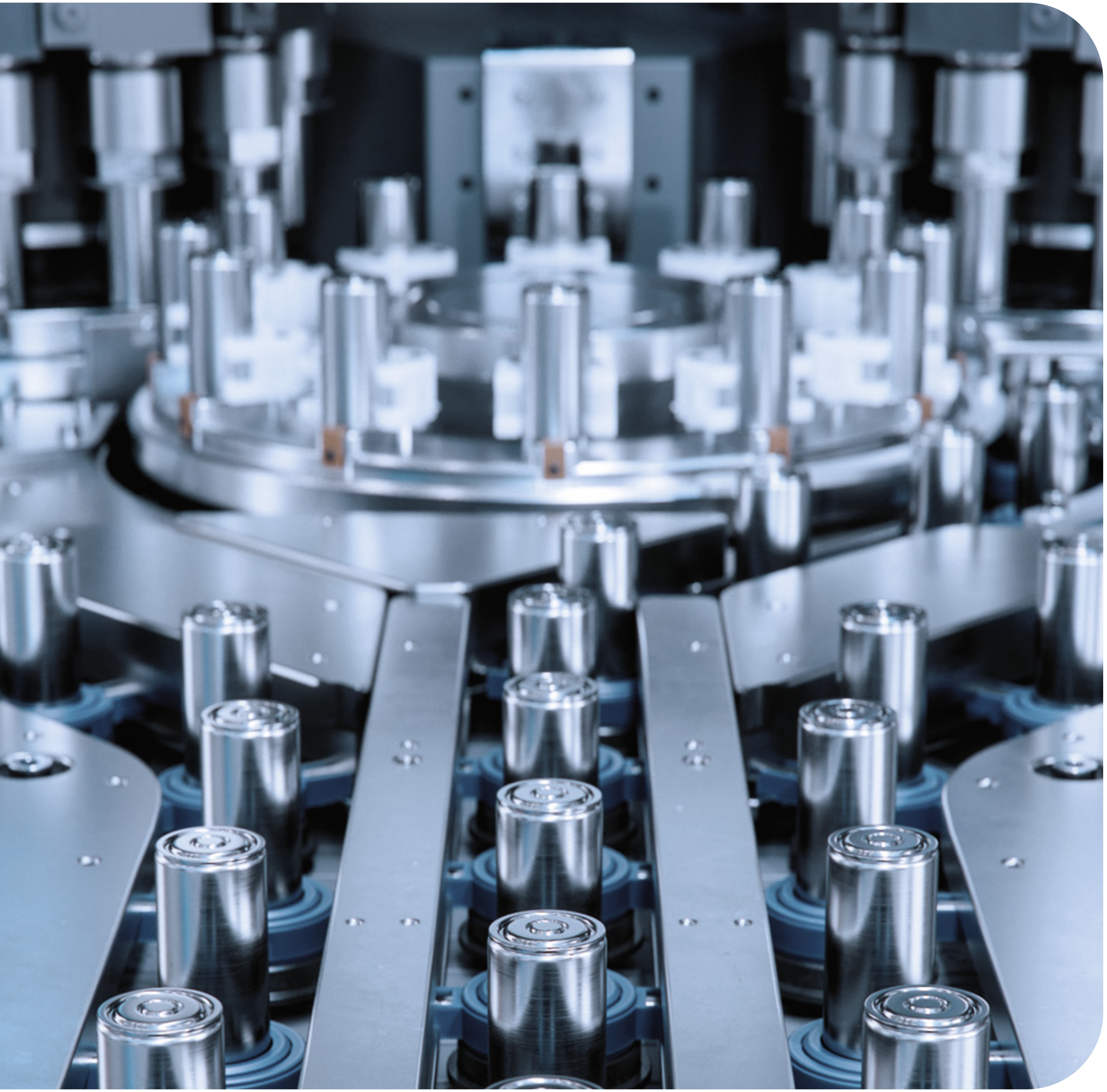

WHITEPAPER

23 Tips to Notably Improve Your Battery Production

Optimization Opportunities for:

- ✓ Electrode Production
- ✓ Battery Cell Assembly
- ✓ End-of-Line Testing
- ✓ Solid-State Battery Production

INFICON

Dear Reader,

The battery industry is growing – and with it, the demands on quality, cost efficiency, and process reliability. Staying competitive as kWh prices fall means keeping your manufacturing processes under tighter control – step by step, and increasingly automated.

This whitepaper gives you 23 dedicated tips for getting the data and metrics you need to make informed process decisions. The focus is on four key areas of cell production: electrode manufacturing, cell assembly, end-of-line testing, and – as a dedicated chapter – All-Solid-State Batteries, whose solid-state electrolytes call for entirely new approaches to leak testing.

Whether it's vacuum monitoring during electrode drying, reliable leak testing of already-filled cells using Direct Electrolyte Leak Testing, or the specific challenges of semi-solid-state and all-solid-state cells: these 23 tips show you where there's still room to optimize in your production.

Your INFICON Team

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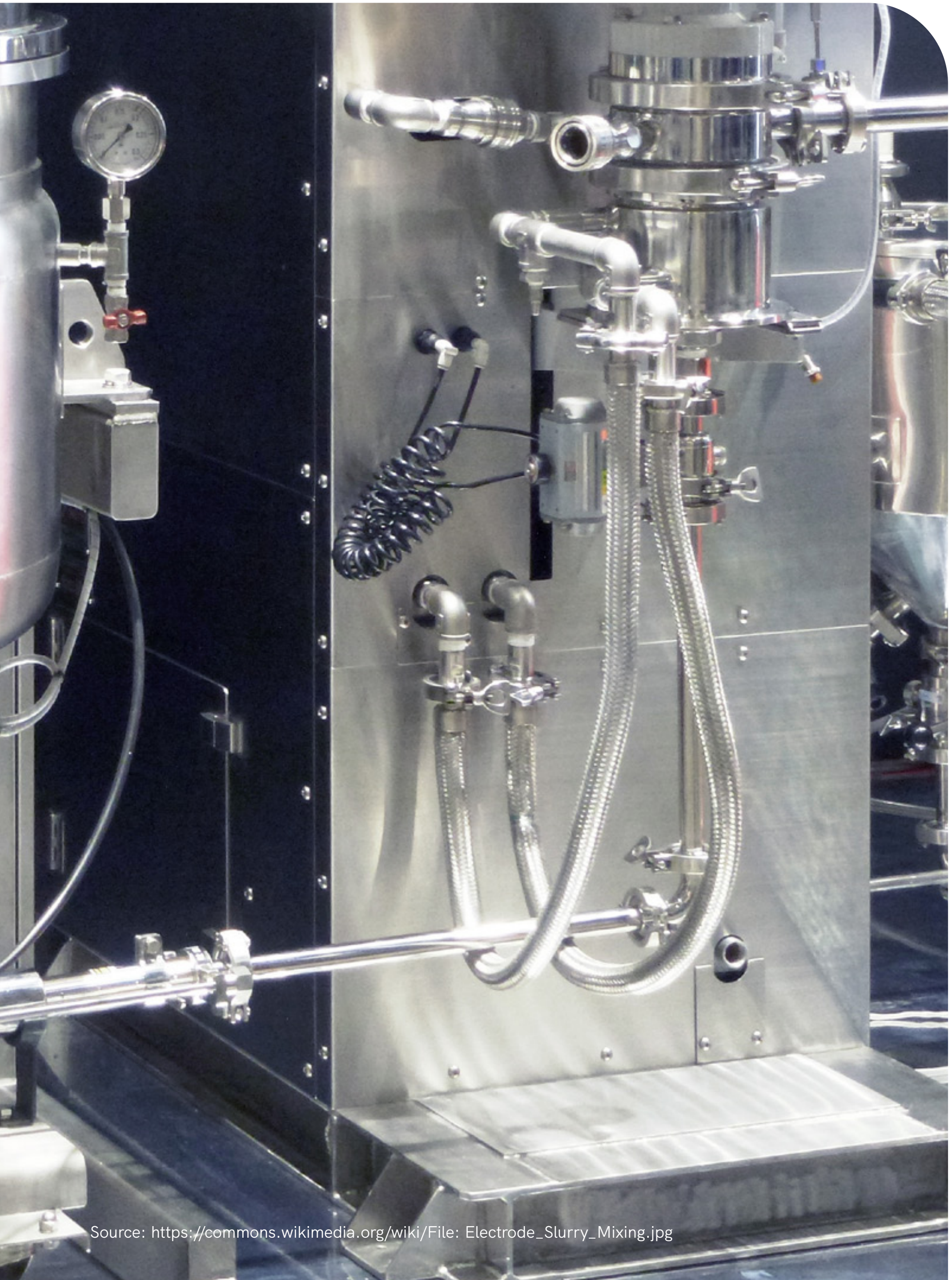


Source: https://commons.wikimedia.org/wiki/File: Electrode_Slurry_Mixing.jpg

1. Four Tips to Optimize Your Electrode Production

In the electrode manufacturing process, there are a number of process steps that must take place in a vacuum, from colloid mill pretreatment to vacuum chamber drying. Monitoring of air quality and humidity is also essential during electrode slurry mixing if you want to achieve consistently high quality.

However, by no means have all battery manufacturers decided to monitor and control their electrode production in a meaningful and economically advantageous way. The following four tips highlight what you can do to notably improve your electrode production.

1.1 Prevent contamination of the slurry through accurate process monitoring and control.

The uniformity of the electrode and the quality of the battery depend on how well you manage to control critical process variables during slurry mixing. In addition to variables such as viscosity and density, monitoring air quality is also critical, as you want to prevent impurities from contaminating the electrode slurry.

It is therefore advisable to use gas analyzers in this process step to monitor not only air quality, but also other important process parameters, such as humidity.

1.2 Control the vacuum level for highest process efficiency during electrode baking.

Tunnel electrode baking systems use different vacuum levels in their various chambers. However, if you want to fully utilize the capacity of your system, you need to avoid unnecessary wait times - and move electrodes to the next drying step as quick as possible. This requires fast and accurate measurement if the required vacuum level has been reached.

Pirani gauges provide an economically viable way to monitor at all times whether the various vacuum levels required in the drying process have already been achieved. For even better performance, use Pirani CDG combination gauges in the baking lines.

The high accuracy and fast response of the measurement with a capacitance gauge (CDG) can noticeably increase the process efficiency and provide an economically viable way to monitor at all times whether the various vacuum levels required in the drying process have already been achieved.

Pirani Capacitance Membrane Gauge (PCG55x)

1.3 Monitor residual moisture in the drying process, optimally determine the drying endpoint and save energy.

In anode production, there is a vacuum drying process, and together with the air, the moisture is also evacuated. Here it is important to ensure that no residual moisture affects the result.

Nevertheless, most manufacturers still do not monitor the residual moisture and therefore, cannot reliably determine the endpoint of the drying process. But it is precisely here that consistent monitoring is worthwhile.

Gas analyzers benefit the drying process through continuous process monitoring and quality control, which can result in significant energy savings. Because the drying process is so energy-intensive, it makes a significant difference whether you can always accurately determine its endpoint or whether the vacuum drying process will be extended unnecessarily.

1.4 Increase the uptime of your production by choosing vacuum gauges that are resistant to common contaminants.

It's unavoidable: the electrode manufacturing process produces impurities, for example in the form of particles from the metal powder for electrode coating and outgassing solvents.

For Pirani gauges, particles and solvents can cause significant problems and failures are not uncommon, for example due to filament burn out. Robustness is therefore an important criterion for the gauges used in your system.

When sourcing a vacuum gauge, look for a Pirani gauge that is specially protected against the ingress of contaminants - resulting in a correspondingly long lifetime for the filaments and saving you from costly production interruptions.

Another line of defense is an optional center ring with a sinter filter that can be attached between the gauge and the vacuum system. This is another way to reduce metal particle ingress and extend the life of your Pirani gauges.

Pirani standard gauge PSG5xx

2. Seven Tips to Improve The Battery Cell Assembly

Lithium-ion battery cells must be leak-proof if they are to retain their functionality and capacity over a long period. In addition, some process steps take place under different vacuum conditions. Vacuum controls and consistent leak tests on battery cells can significantly increase the quality of your production and yield. The following seven tips describe which methods and devices are best suited for which assembly step. A special highlight is the unique method developed by INFICON to reliably test cells for leaks even after they have been filled: the direct electrolyte leak detection method.

2.1 No more scrapping cases and wasting electrolyte when filling by testing your hard case battery cells for leaks beforehand.

Testing your lithium-ion battery cells with solid cases for leaks before you fill them with electrolyte is an excellent way to avoid having to scrap housings and stop wasting electrolyte.

For this leak test before filling the cell, a vacuum leak test with helium as the test gas is recommended. The procedure: First, evacuate the assembled battery cell and fill it with helium. Now place the battery cell in a vacuum chamber, which is also evacuated, for testing. Any leaks will cause helium test gas to escape into the vacuum of the chamber. A leak detector immediately detects the escaping helium as a quantitative indicator of a leak, resulting in the highest throughput and maximum uptime in battery production.

Scrapped round cells from an assembly line for lithium ion batteries.

Testing hard case battery cells in a vacuum chamber.

2.2 Reliable vacuum gauges increase repeatability and uptime during helium leak testing.

For helium leak testing, you need a vacuum chamber. The pressure in the vacuum chamber changes from atmospheric pressure to a pressure of 0.1 mbar during the measurement process. It is important not to expose the helium leak detector to excessive pressure and to control the pressure conditions closely. A Pirani gauge or a Pirani combination gauge is well suited for this wide pressure range between 0.1 mbar and 1 bar.

Usually, the helium leak test takes place directly after welding the battery cell housing. However, this leaves many particles in the cell, which can easily contaminate a Pirani gauge and cause the filament to burn out. It is therefore worthwhile to select the Pirani gauge carefully, particularly one that has an internal protective chamber to keep particles away from the filament.

In addition, consider an optional center ring with a sinter filter that is mounted between the gauge and the helium test chamber to prevent particles from entering the hot filament.

Pirani gauge (PSG5xx) or a Pirani combination gauge (PCG5xx) in use.

2.3 Fully automatic drying of battery cells requires fast and accurate real-time pressure monitoring.

Before filling battery cells with electrolyte, you must remove any residual moisture from them. For this, a continuous drying furnace is used. The different stages of the drying furnace operate at different vacuum levels. In addition, the moving parts cause constant pressure fluctuations. Exposure to the atmosphere and accurate opening and closing of valves depends on fast and accurate control by a powerful vacuum gauge. For best results,choose a Pirani and capacitance combination gauge (Pirani/CDG) that offers you faster and more accurate pressure measurement in the range of 50 - 1500 mbar.

Basically, water vapor and particles from the welding process can lead to a high failure rate with a Pirani sensor. A Pirani gauge is designed specifically to protect the filament against water vapor and particles is your best choice. And if you mount a center ring with sinter filter between the gauge and the vacuum system, you additionally reduce the amount of penetrating particles - which further extends the service life of the gauge.

2.4 Accurately control the pressure in the filling system to avoid unwanted moisture absorption.

At the beginning of the filling process, the battery cells are evacuated to a vacuum level of 30 - 63 mbar. If there are leaks in the filling system, the evacuation could draw moisture from the environment into the filling system. One indicator that the filling system is drawing in (moist) air is rising pressure. This is why it is so important to use highly accurate pressure gauges here.If you control the pressure with a diaphragm capacitance gauge, you will always be able to clearly distinguish between a real pressure rise and a mere instability of the sensor signal - and reliably prevent moisture ingress. In principle, the accuracy of a conventional Pirani sensor is ±15 %. A diaphragm capacitance gauge on the other hand, has an accuracy of ±0.2 %. The ultra pure ceramic sensor in a capacitance diaphragm gauge can withstand the possible corrosion from the solvent in the electrolyte, the sensor lifetime can be much longer than a normal Pirani gauge.

2.5 Precise control of the evacuation pressure ensures stable process conditions and a high yield.

Precise control of the evacuation pressure during the electrolyte filling process can create repeatable conditions and achieve a high yield.If the pressure is too high, there is still too much air in the cell, which prevents good filling. But if the pressure is too low, the solvents contained in the electrolyte will begin to evaporate and the composition of your electrolyte will change. Choosing to use a diaphragm **capacitance gauge** offers you high accuracy while also being highly resistant to contamination. This ensures a long lifetime for the gauge sensor.

Capacitance diaphragm meter (SKY® CDG025D) in use.

2.6 Real time gas process monitoring provides protection from any explosive gas mixtures in your filling process.

Battery cells are filled with electrolytes in a vacuum. However, these electrolytes contain a variety of solvents and when these evaporate, highly dangerous gases are produced that can pose an explosion hazard. Using gas analyzers to monitor your electrolyte filling in a vacuum is a critical step to ensure the safety of employees and production lines. Gas analyzers provide predictive process monitoring and control for maximum protection against potentially explosive gas mixtures in the filling process.

INFICON Transpector® gas analyzer for process monitoring and control.

2.7 Test already filled cells before formation to reduce safety risks and not waste your capacity.

If you leak test your filled battery cells even before formation, it will ensure that only leak-proof cells make it to formation. In this way, the fundamental safety risk associated with formation is reduced, and you no longer waste formation capacity and effort. At this point, it is worth retesting pretested hard case battery cells (see TIP 1 in this section) to ensure that the filling opening has also been properly sealed.For soft deformable pouch cells, now is the right time to consider leak testing.

INFICON has developed a unique method that allows such a leak test on already filled battery cells. The new method finds leaks by directly detecting escaping electrolyte. The procedure: The filled and sealed battery cells are placed in a vacuum test chamber. When the chamber is evacuated, the electrolyte escapes through any leaks. The solvent contained in the electrolyte also escapes in the process; it evaporates in the vacuum and is detected by a highly sensitive sensor. With this direct electrolyte leak detection method from INFICON, you can detect leaks down to the micrometer range.

Fire damage to a lithium-ion battery.

Testing of filled battery cells with INFICON's unique direct electrolyte leak detection method. The red light indicates that a leak has been detected.

For leak testing of soft, sensitive pouch cells during R&D or in pilot production, a special, flexible test chamber is available that allows non-destructive testing in a vacuum. The pouch cells are placed between two membrane layers that conform to the shape of the cells and prevent them from inflating.

For mass production testing, customized chambers should also be used for simultaneous testing of multiple cells.

3. Nine Tips for Optimal End-of-Line Battery Cell Testing

In your production of lithium-ion cells, end-of-line leak testing is the final and crucial step for quality control to prevent moisture from entering the cells for many years. Among other things, our following six tips describe why the unique Direct Electrolyte Leak Testing method provides reliability and accuracy that surpasses traditional methods, such as pressure or helium bombing.

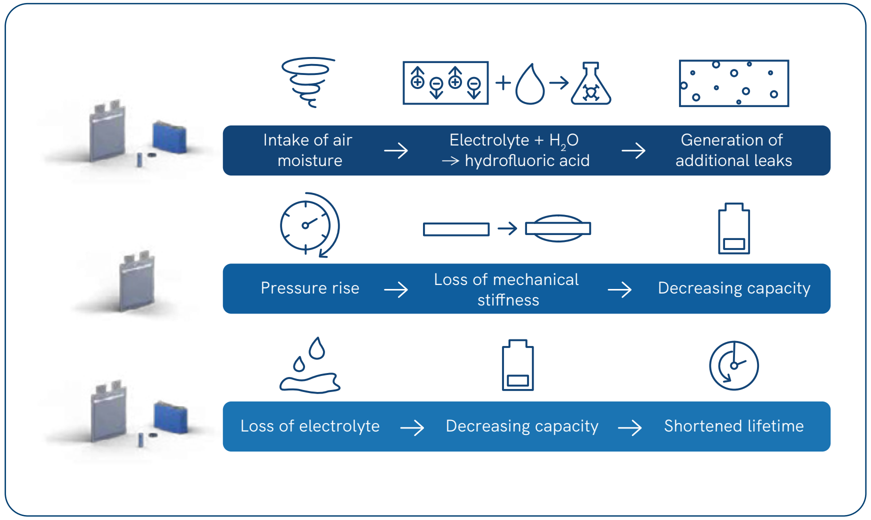
This method can achieve the same pace as series production by testing several cells simultaneously to realize quality assurance for every single manufactured cell, regardless of its design.

3.1 Avoid rapidly decreasing capacity and extend the life of your battery cells by consistently (properly) checking them for leaks.

With all lithium-ion battery cell designs - whether they are round, prismatic, button or pouch cells - it is important to prevent the loss of electrolyte so that capacity is not reduced over time.

It is perhaps even more critical to eliminate any absorption of moisture. In particular, battery cells sealed at negative pressure (under pressure) can draw in moist air through leaks. The moisture in the air reacts with the electrolyte in the cell to form hydrofluoric acid, which attacks the battery cell and causes additional leaks.

This way even the smallest defects can quickly become larger and explains why reliable end-of-line testing is so important in your battery cell production.



Three failure modes of lithium-ion battery cells.

3.2 Direct electrolyte leak testing is the only reliable method to find leaks down to the micrometer range.

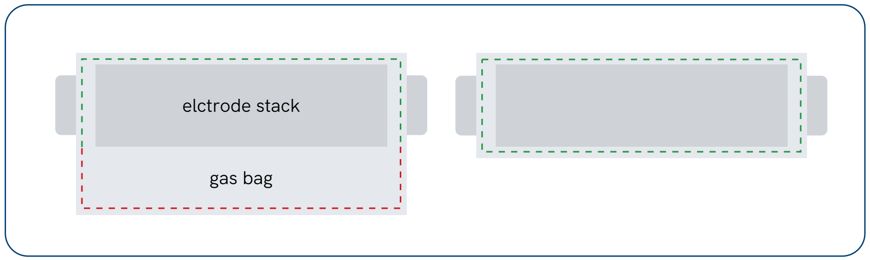
If lithium-ion cells have very small leaks in the micrometer range, these leaks are blocked by the liquid electrolyte itself - so air cannot penetrate. The maximum size of a leak that can still be blocked by the electrolyte depends on the specific properties of the electrolyte and on the pressure conditions inside the cells. Pressure testing methods or even helium bombing with subsequent vacuum leak testing might initially appear to be attractive solutions. Unfortunately, none of these methods finds leaks down to the blocking limit. This is because these micrometer leaks correspond to gas leakage rates in the range of 10^{-6} mbar·l/s.Pressure tests are, at best, only capable of finding leaks in the range of 10^{-3} mbar·l/s.

In helium bombing, the test parts are first stored in a helium atmosphere under high pressure. If a test part leaks, helium penetrates into its interior. During the subsequent vacuum test, this helium escapes again, is detected and is evidence of the leak. Bombing is a proven method for finding gas leaks in hermetically sealed parts widely used for leak testing of airbag ignitors for example. It is entirely unsuited for test parts filled with liquid - as in our battery cell scenario. Helium ingressing through a leak rises inside the cell like a gas bubble in sparkling water. Preventing the helium from escaping to the outside again during the test in a vacuum. Even if all liquid has soaked into the cell stack, chances are that the liquid electrolyte wetted any microleaks during filling so that these leaks are clogged now but will dry off later.

With its Direct Electrolyte Leak Testing, INFICON has developed the very first method to test ready-filled lithium-ion battery cells for leakage. Instead of first pressurizing the cell with helium, as is the case with bombing, the method uses a vacuum test to detect leaking electrolyte directly: in the form of the solvent that escapes and evaporates in the vacuum chamber. This new method can also be used to detect leaks down to the micrometer range on ready-filled battery cells - up to the required gas leak rates in the range of 10^{-6} mbar·l/s.

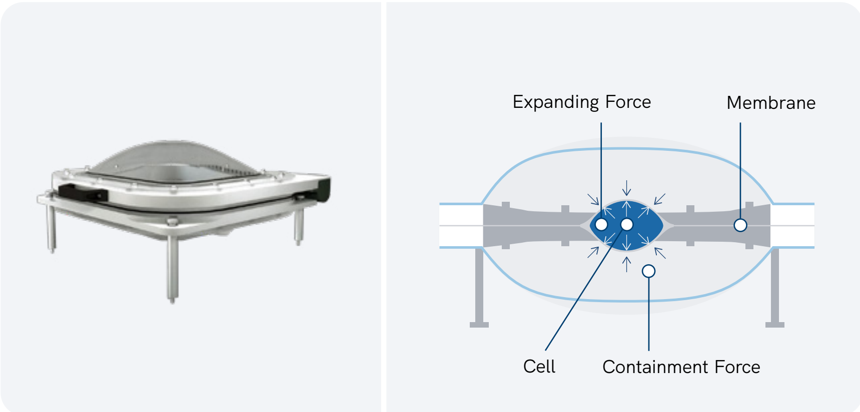
3.3 Test soft pouch cells after formation.

Soft pouch battery cells are sealed in a vacuum. During formation, gas is generated inside the pouch cells. This gas collects in a gas bag connected to the cell. After formation, the excess gas is removed, the gas bag is cut off, and the cell is finally sealed. The only way to ensure the tightness of this final seal is to perform a leak test after formation. Additionally, because leaks can occur simply by handling pouch cells, it is crucial to leak test at the end of the manufacturing process.



Pouch cell before (left) and after formation (right).

Testing pouch cells without damaging them can be challenging as pouch cells inflate in a conventional vacuum chamber, which stresses their seals. For R&D and pilot production testing, INFICON has developed a special test chamber for its unique Direct Electrolyte Leak Testing process. A flexible chamber, which consists of two layers of a flexible material, supports the pouch cells during testing and prevents them from inflating. For mass production and testing of batches of pouch cells, a larger chamber with special holders may be used that also support the pouches and prevent them from inflating.

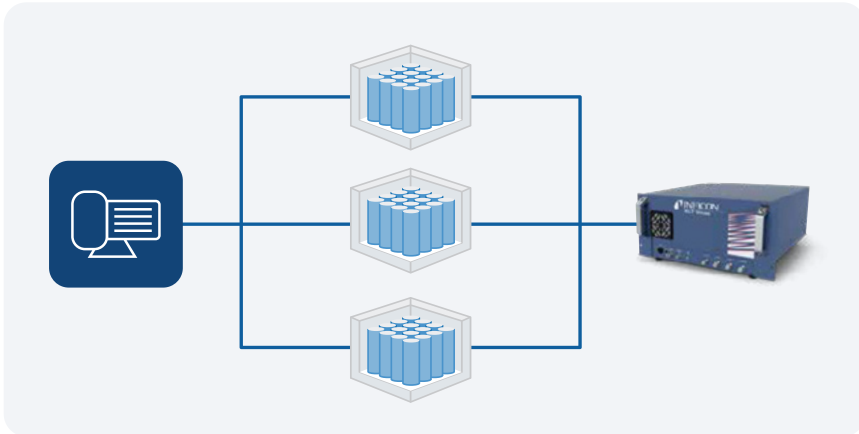


INFICON FTC3000 flexible chamber enables non-destructive testing in a vacuum, even for pouch cells.

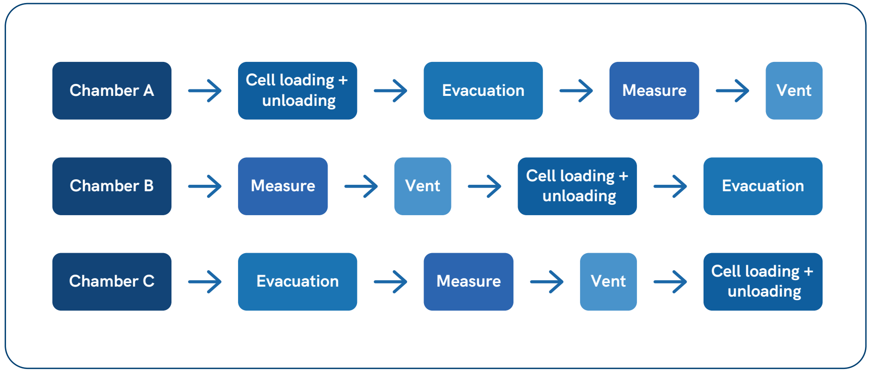
3.4 Testing at the pace of your production - with short cycle times

For quality assurance in mass production, a 100% inline test of all battery cells should be implemented. Automated leak test stations must operate at the pace of your production. There are a number of measures you can take to optimize the cycle time for direct electrolyte leak testing. One factor is choosing a vacuum chamber - with the smallest possible dead volume (the difference between chamber volume and test part volume) to minimize evacuation time. The use of particularly powerful external vacuum pumps also greatly accelerates evacuation and shortens the cycle time.

You can also clean the cells of electrolyte residues before the test cycle, for example by laser cleaning. Connecting several vacuum chambers to a leak tester will also significantly shorten the cycle time. In multi-chamber test stations, process steps such as charging or evacuating a chamber no longer lead to waiting times so that your electrolyte leak tester is almost constantly in measuring mode.



Multi-chamber test stations



Typical cycle times for industrial electrolyte leak testing with the ELT3000 PLUS from INFICON.

3.5 Batch testing for highest throughput in mass production

In high-volume production, where high throughput is required, batch testing is most economical. With batch leak testing, you test a larger number of battery cells in one test cycle. As a result, the effective testing time for each individual cell is reduced to a fraction. Choose the size of your batches so that most of the tested batches are leak-free and only a small number contains leaking cells.

After all, if a leak is detected in a particular batch, further testing is required at a downstream leak test station (which may also be automated).

In retesting, cut the batch size in half until the leaking cell is identified. Two examples: For batches of 16, this requires four additional testing steps; for batches of 64, it requires six. Which batch size is optimal for your case depends on the typical defect rate in your production.

After all, the total number of tests required should naturally remain as small as possible in batch testing.

3.6 The key to success is proper calibration of your leak testers - with certified calibration leaks.

Calibrating your test equipment regularly is the only way to ensure that your readings are correct and your tests are reliable at all times. However, master parts are not a substitute for a calibration leak. This is because master parts may not exhibit stable leak rates over time. In addition, the leak rate of master parts cannot be certified.

Calibration leaks, on the other hand, are supplied with a certificate indicating the leak rate of the calibration leak and providing traceability to national standards. This is the only way to meet the requirements of ISO 9001.

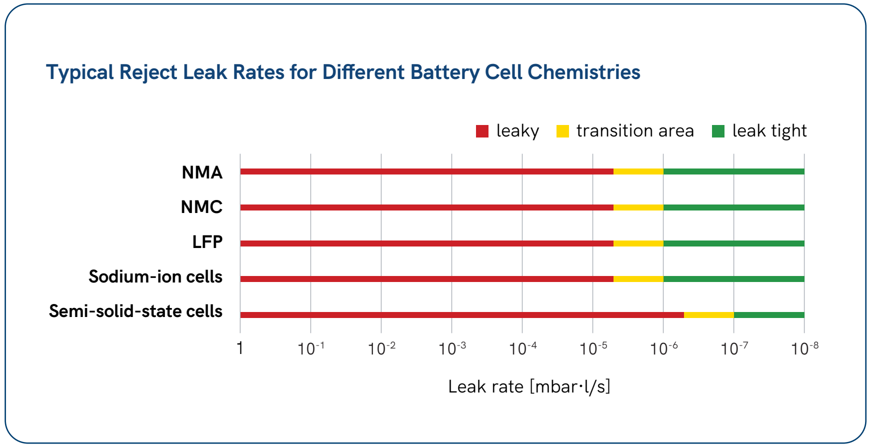
Calibration of the ELT battery leak detector family with a certified E-check calibration leak.

3.7 Semi-solid-state battery cells require leak testing for smaller leak rates

Semi-solid-state batteries replace the liquid electrolyte of a conventional lithium-ion or sodium-ion cell with a gel-like one. This changes the cell's energy density and thermal behavior, but it does not change the underlying requirement: the cell still has to remain leak-tight over its service life to limit electrolyte and capacity loss. What does change is the physical behavior of a leak. A gel-like electrolyte escapes more slowly through a leak than a liquid one, which has direct implications for the sensitivity, cycle time and chamber design of a leak-testing setup.

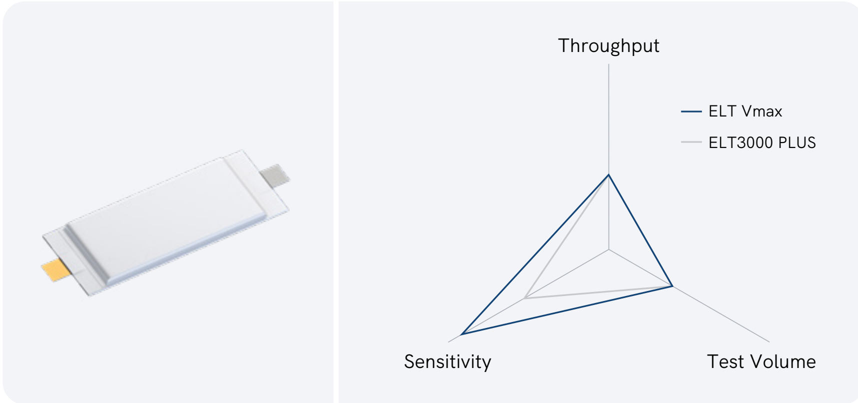
The distinguishing feature of semi-solid-state lithium-ion cells is their electrolyte: a gel rather than a liquid. Because a gel escapes more slowly through a leak in a vacuum chamber than a liquid does, a leak-testing method needs a sensitivity margin beyond what is strictly required for liquid-electrolyte cells in order to still identify critical leaks within a normal production cycle.

While NMC, NMA as well as sodium-ion chemistries are typically tested against $1 \cdot 10^{-6}$ mbar l/s to $5 \cdot 10^{-6}$ mbar·l/s helium equivalent leak rates, semi-solid-state cells require reject leak rate as low as $1 \cdot 10^{-7}$ mbar·l/s to $5 \cdot 10^{-7}$ mbar·l/s (all stated as helium equivalent leak rates).



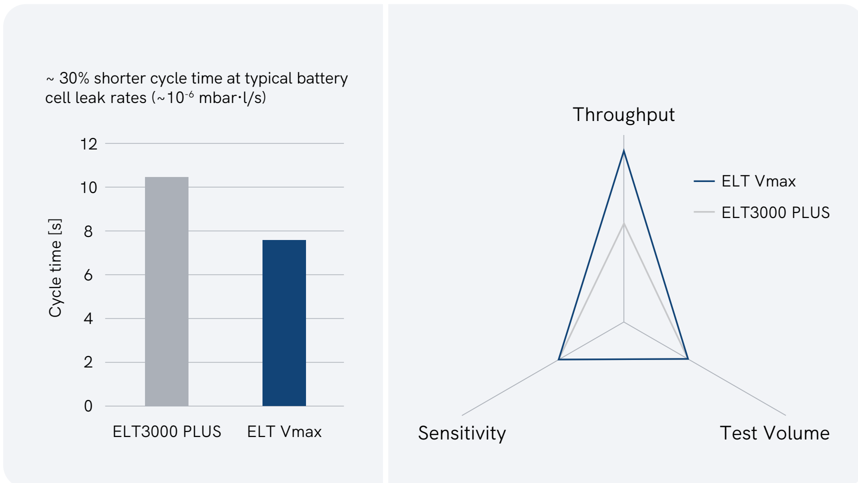
Comparison of leak testing thresholds for different chemistries of cells.

Direct electrolyte leak testing, in which the evaporating electrolyte solvent itself acts as the tracer gas, is one method capable of providing this margin. The latest generation of its ELT Vmax reaches a limit leak rate of $5 \cdot 10^{-8}$ mbar·l/s and is ideal for testing for these significantly smaller leak rates.

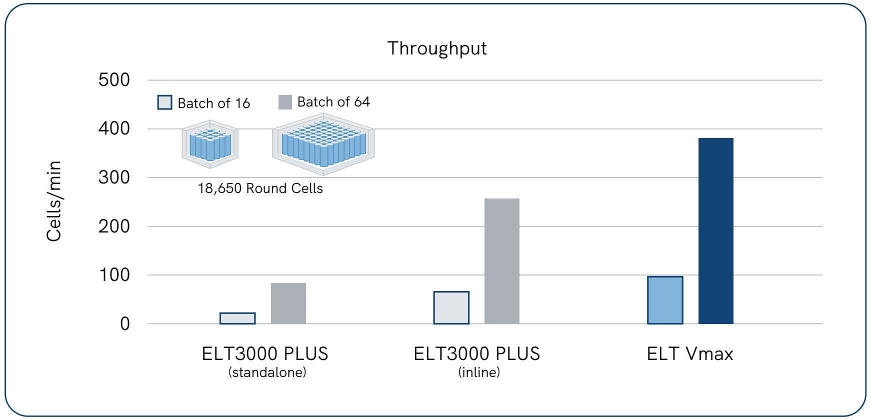


3.8 Additional sensitivity allows for faster testing cycles

A leak-testing method with sensitivity well beyond the required detection limit can extrapolate the signal rise earlier in the measurement, which shortens the cycle time without reducing detection reliability- if the employed leak detector shows excellent repeatability between measurements.

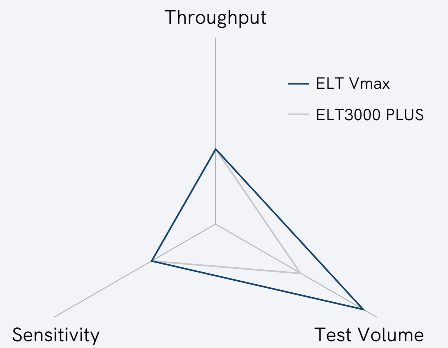


Example: reported cycle-time reduction between two generations of a direct electrolyte leak tester, measured at typical battery-cell leak rates.



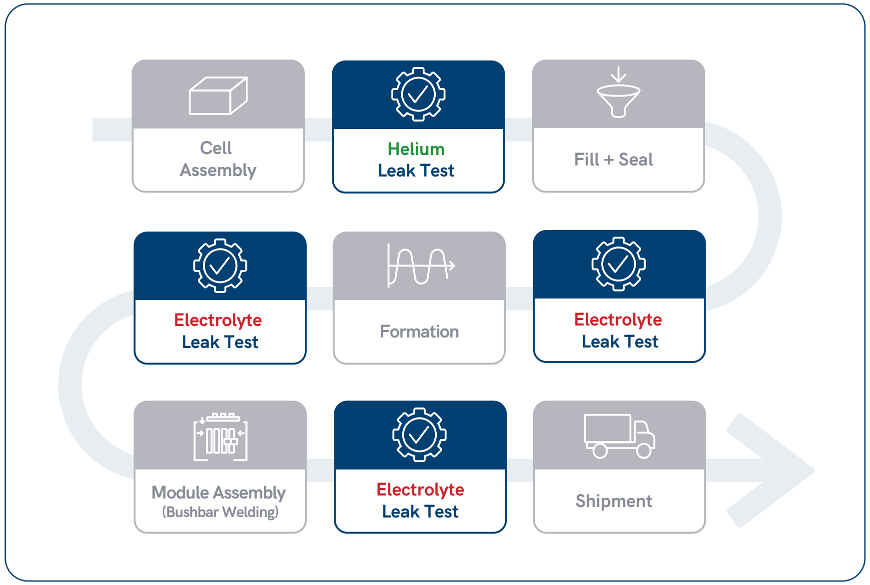
3.9 Higher sensitivity enables larger testing volumes

The smallest leak rate a vacuum-based test can resolve depends on the dead volume of the chamber: a larger free volume around the test part raises the smallest detectable leak rate. A leak detector with higher sensitivity can therefore be operated with a chamber of larger dead volume and still reach the leak rates of around 10^{-6} mbar·l/s specified for battery cells. Larger chambers are required for particularly large cells, batch testing of larger numbers of cells and even enables the testing of complete battery modules.



New for battery modules: leak testing after busbar welding, at module level

This is relevant because cells within a module are connected in parallel or series through a busbar that is welded to the electrical contacts of each cell. This welding step carries a risk of damaging the cell housing, particularly for soft pouch cells, and testing for such damage after module assembly has generally not been standard practice. As pouch cells move into production, a module-level leak test is one way to verify that the assembly process has not compromised cell integrity before shipment.



Example process flow showing where a leak test can be added at the module level, after busbar welding.

4. Three Tips for Ideal Leak Testing in All-Solid-State Battery Production

All-solid-state batteries (ASSBs) replace the liquid or gel electrolyte of conventional lithium-ion and semi-solid-state cells with a solid ionic conductor — typically a sulfide-, oxide-, or polymer-based material.

The change affects energy density, thermal behavior, and the failure mode associated with electrolyte leakage, and it has attracted substantial development effort across the industry. It also changes what leak testing means for these cells: the methods established for liquid- and gel-electrolyte batteries rely on detecting an escaping liquid or vapor, and an ASSB cell contains neither.

The following three tips outline why established leak-test methods do not transfer to ASSB cells, examine one commonly proposed alternative, and describe an approach currently used for this purpose.

4.1 All-Solid-State Battery leak testing requires new testing methods.

In a conventional lithium-ion or semi-solid-state cell, a defect in the housing eventually allows liquid electrolyte or its solvent to escape and evaporate in a surrounding vacuum — the physical basis for direct electrolyte leak testing.

An all-solid-state cell contains no liquid electrolyte or solvent that can outgas in this way: the ionic conductor is a solid. A defect in the housing of an ASSB cell therefore produces no vapor signal for a mass spectrometer to detect, and direct electrolyte leak testing, reliable as it is for liquid- and gel-electrolyte cells, does not apply to this cell architecture.

	LIQUID- / GEL-ELECTROLYTE CELL	ALL-SOLID-STATE CELL
Electrolyte state	Liquid or gel	Solid ionic conductor
Behavior at a housing defect	Humid air enters the cell (forming HF) Solvent vapor escapes and evaporates in vacuum	Humid air enters the cell (forming H_2S for sulfide-based chemistries) No liquid or vapor is available to escape
Direct electrolyte leak testing applicable?	Yes — detects evaporating solvent	No — no solvent vapor is generated

Direct electrolyte leak testing depends on a solvent that can outgas in vacuum. An all-solid-state cell does not contain one.

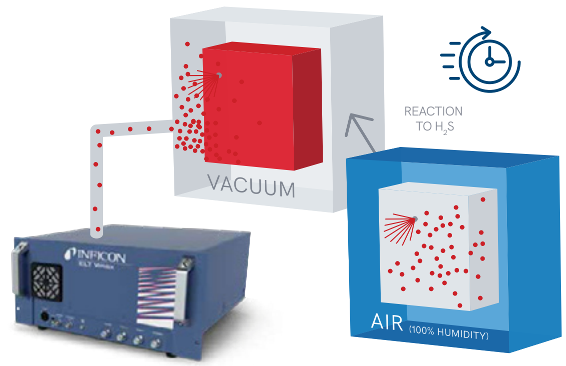
This does not make leak-tightness less important. Sulfide-based solid electrolytes — the chemistry with the highest ionic conductivity among current solid-electrolyte candidates, and a leading option for automotive applications — are highly sensitive to moisture. Humidity entering through even a microscopic defect reacts with the sulfide material, degrading ionic conductivity and generating hydrogen sulfide (H_2S) gas inside the cell. A cell that passes visual inspection and initial electrical testing can still contain a defect that shortens its service life or creates a safety hazard later.

A production-viable ASSB leak test therefore needs a detection principle that does not depend on a liquid or vapor already present inside the cell.

4.2 H_2S detection is not a suitable leak testing approach.

One method that has been proposed exploits the same moisture-sulfide reaction responsible for degrading a defective cell: expose sealed cells to humidified air under pressure (for example, around 5 bar for 30 minutes), allow any moisture entering through a defect to react with the sulfide electrolyte and form H_2S, then test under vacuum for H_2S escaping from the cell.

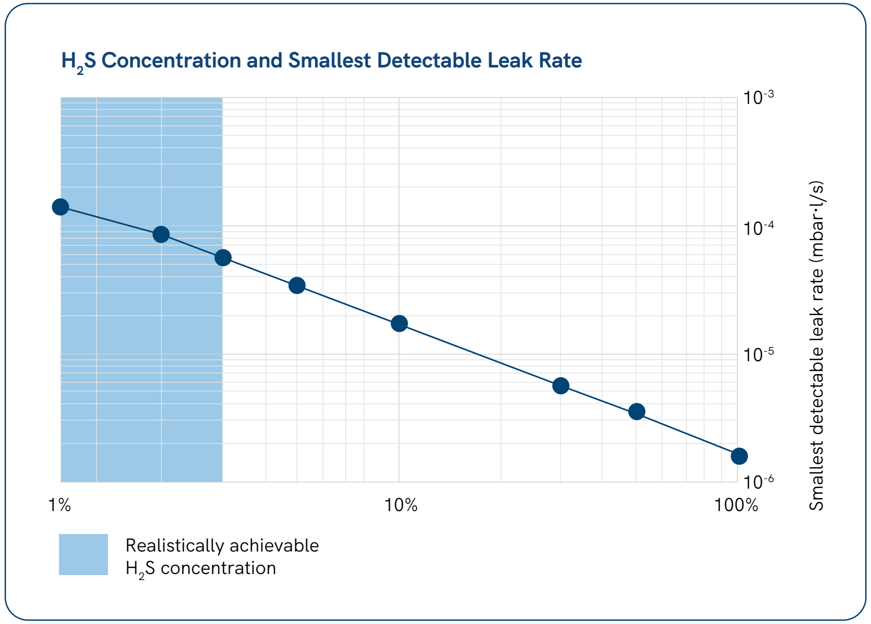
The approach uses the failure mechanism itself as the detection signal. In practice, several factors limit its use as a production quality gate.



Humidity bombing and subsequent H_2S detection

In a mass spectrometer, H_2S produces a signal at mass 34, which overlaps with the signal from oxygen — present in air at roughly 21% concentration and left over as residual background on parts and inside the test chamber. This limits the smallest detectable leak rate for H_2S to around $2 \cdot 10^{-6}$ mbar·l/s, and only if the gas escaping the cell were 100% H_2S. In practice, the H_2S concentration that can accumulate in a defective cell during bombing is limited by the moisture content of air (about 2% at 20°C) and the kinetics of the water–sulfide reaction; published research puts realistic H_2S concentrations in the cell headspace at roughly 1–5%.

At these concentrations, the smallest detectable leak rate is only around $3 \cdot 10^{-5}$ to $1.7 \cdot 10^{-4}$ mbar·l/s — well short of the low 10^{-6} mbar·l/s sensitivity generally specified for ASSB leak testing.



Smallest detectable leak rate as a function of H_2S concentration in the cell headspace. Realistic bombing conditions (1–5%) fall well short of typical ASSB sensitivity requirements.

The usable range is narrowed further by leak size itself. Very small leaks (around $1 \cdot 10^{-6}$ mbar·l/s) generate an equilibrium H_2S concentration of only a few parts per million — too low to distinguish from the air background. At the other end, large leaks ($1 \cdot 10^{-4}$ mbar·l/s and above) can empty the cell's small internal volume so quickly that the H_2S has already escaped before the measurement phase begins, so the defect can be missed entirely. Only a comparatively narrow band of medium-sized leaks falls within a workable detection window.

The H_2S concentration generated during bombing also depends on bombing duration, temperature and pressure, as well as on the surface area of electrolyte exposed to moisture and the cell's internal volume — factors that vary with electrode surface roughness, porosity and cell design, and are not tightly controlled from cell to cell. As a result, the same physical defect can produce different readings on different test cycles, which limits its usefulness as a repeatable quality gate.

Humidity bombing also introduces moisture into the production environment, which runs counter to the humidity control that ASSB manufacturing generally requires, and H_2S itself is toxic — its immediately dangerous concentration is around 50 ppm — adding safety and regulatory considerations.

The method is limited to sulfide-based electrolytes; it provides no detection mechanism for oxide- or polymer-based ASSB chemistries.

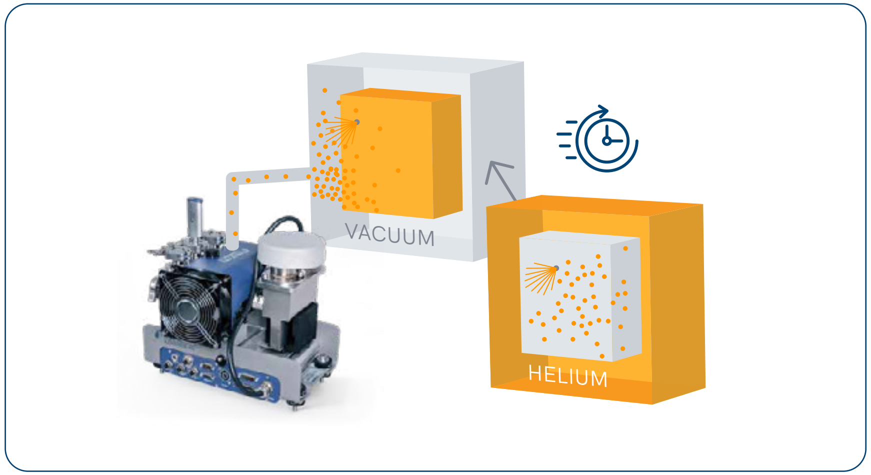
4.3 Helium bombing reliably detects leaks in all-solid-state cells.

Helium bombing follows a similar sequence to H_2S bombing — cells are placed in a pressure vessel and exposed to a tracer gas (typically helium) at elevated pressure for a defined duration, then transferred to a vacuum chamber for detection — but the tracer gas is supplied externally rather than generated by a reaction inside the cell.

Helium, the smallest noble gas, penetrates a defect and accumulates inside the cell during bombing; a helium-specific mass spectrometer then measures any helium escaping under vacuum. Because the method does not depend on any liquid, vapor, or reactive species inside the cell, its applicability does not depend on whether the ASSB uses a sulfide-, oxide-, or polymer-based solid electrolyte.

This is not a new or unproven method: helium bombing has been used for decades to test other sealed, safety-critical components with very low tolerance for leakage, including automotive airbag gas generators and igniters.

Applying an established, well-characterized method to ASSB cells avoids relying on a detection principle — like H_2S generation — whose behavior in this specific application remains difficult to control.

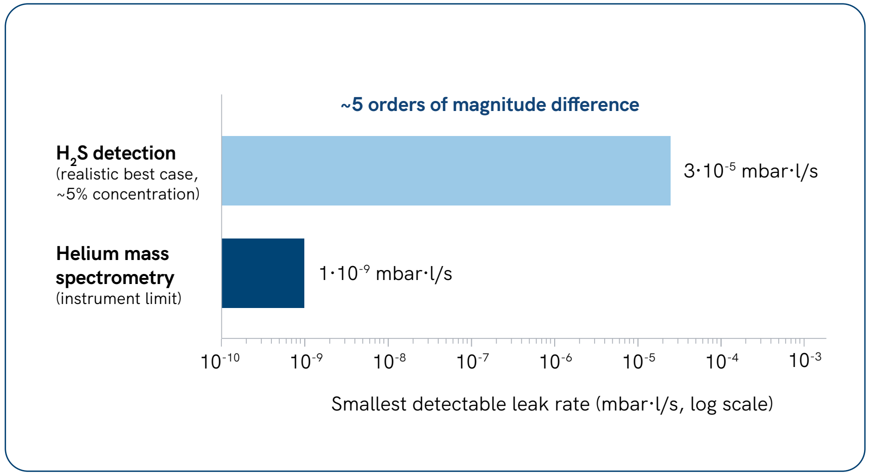


Helium bombing and subsequent H_2S detection

The amount of helium absorbed by a defective cell during bombing follows well-understood physics — Henry's Law and Fick's law of diffusion — so for a given defect size, bombing pressure and duration, the resulting helium concentration inside the cell is consistent from one cell to the next. This gives helium bombing a repeatability that H_2S bombing lacks: the same defect produces essentially the same signal on repeated tests. Sensitivity is also considerably higher, in part because helium's natural background concentration in air is very low (about 5 ppm), unlike oxygen.

Mass spectrometric helium detectors can resolve leak rates several orders of magnitude finer than H_2S detection; instruments with a stated sensitivity down to $1 \cdot 10^{-9}$ mbar·l/s are available, meaning that even a modest 1% helium fill fraction inside the cell after bombing can still correspond to a detectable leak rate around $1 \cdot 10^{-7}$ mbar·l/s.

Higher instrument sensitivity also permits shorter bombing times, since less helium needs to accumulate to produce a measurable signal.



Reported order-of-magnitude difference in achievable sensitivity between H_2S detection under realistic bombing conditions and helium mass spectrometry.

As with any bombing method, the small internal volume of an ASSB cell means a sufficiently large defect can empty the accumulated tracer gas rapidly, potentially during chamber evacuation and before the measurement phase starts.

Process parameters such as bombing pressure, bombing duration, and evacuation timing need to be set so that both fine and gross defects remain detectable; this constraint applies to helium bombing as much as to H_2S bombing.

Because helium is chemically inert, non-toxic, and non-flammable, it also avoids the safety and regulatory overhead associated with handling H_2S as a process gas.

As an example of currently available equipment, INFICON offers the **LDS3000** helium leak detector for integration into automated ASSB production lines and the mobile **UL3000** for pilot lines and R&D use; other manufacturers offer helium leak detectors based on comparable operating principles.

5. Appendix

5.1 Legal Notice

Issued by INFICON GmbH, Cologne (www.inficon.com)

Note: All links to external websites contained in this whitepaper were correct at the time of writing. However, the content and destination addresses of these links may change at any time without notice.

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5.2 Illustration credits

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5.3 About INFICON

INFICON is a leading provider of innovative instrumentation, critical sensor technologies, and Smart Manufacturing/Industry 4.0 software solutions that enhance productivity and quality of tools, processes and complete factories. These analysis, measurement and control products are essential for gas leak detection in air conditioning/refrigeration, and automotive manufacturing — including the leak testing of lithium-ion and next-generation battery cells described in this whitepaper. They are vital to equipment manufacturers and end-users in the complex fabrication of semiconductors and thin film coatings for optics, flat panel displays, solar cells and industrial vacuum coating applications.

Other users of vacuum-based processes include the life sciences, research, aerospace, packaging, heat treatment, laser cutting and many other industrial processes. INFICON also leverages its expertise in vacuum technology to provide unique, toxic chemical analysis products for emergency response, security, and environmental monitoring.

INFICON is headquartered in Switzerland and has world-class manufacturing facilities in Europe, the United States and China, as well as subsidiaries in China, Denmark, Finland, France, Germany, Italy, Japan, Korea, Liechtenstein, Malaysia, Mexico, Singapore, Sweden, Switzerland, Taiwan, the United Kingdom and the United States. INFICON registered shares (IFCN) are listed on the SIX Swiss Exchange.

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