



SURFACE VEHICLE RECOMMENDED PRACTICE

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Liquid Leak Tightness Standards for Propulsion Battery Packs Recommended Practice

RATIONALE

As the market adoption of electrified vehicles (EVs) like plug-in hybrids (PHEVs) and battery electric vehicles (BEVs) accelerates, ensuring their battery pack watertightness becomes increasingly critical. These Rechargeable Energy Storage Systems, RESS (battery packs), are often positioned in areas vulnerable to water exposure, be it rainfall/snowmelt or low levels of standing water. Naturally, EV users expect a high degree of confidence that such exposure won't lead to harmful water ingress.

While the prevalent functional test for water intrusion, as IEC 60529's IPX7 level, offers regulatory compliance, its destructive nature renders it unsuitable for regular production testing. Therefore, alternative methods are needed to assess EV battery packs' water intrusion resistance during nondestructive in-line or lab evaluations.

The proposed practices align with the Equivalent Channel (EC) selection methodology defined in SAE J3277, enabling their application for nondestructive water intrusion testing of battery packs in both production and lab settings.

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1. SCOPE

This recommended practice (RP) establishes nondestructive in-line production test methods for evaluating the water leak tightness of propulsion battery packs. It aims to achieve results equivalent to the IEC 60529 standard's IPX7 level using the Selected Equivalent Channel (EC) method defined in SAE J3277. This RP provides guidance for system setup, tooling design, validation, and leak test procedures. It acknowledges the limitations of certain battery pack designs and recommends appropriate air or tracer gas leak tightness technologies.

Specifically, this RP covers nondestructive end-of-line leak testing for:

- Battery pack assembly: Ensuring protection against water ingress into the battery pack.
- Coolant system: Verifying the integrity of the coolant system and preventing coolant leaks into the battery pack.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J3277 Liquid Leak Tightness Evaluation Methodology for EV Battery Packs Informational Report

2.1.2 IEC Publications

Available from International Electrotechnical Commission, 3, rue de Verambe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +41-22-919-02-11, www.iec.ch.

IEC 60529 ED. 2.1 B:2001, Degrees of protection provided by enclosures (IP Code) CONSOLIDATED EDITION, issued 2013.

2.1.3 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, Ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

ISO 1219-1:2012 Fluid power systems and components - Graphical symbols and circuit diagrams - Part 1: Graphical symbols for conventional use and data-processing applications

ISO 6469-1:2019 Electrically propelled road vehicles - Safety specifications - Part 1: Rechargeable energy storage system (RESS)

2.1.4 ISO/IEC Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, Ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

Available from International Electrotechnical Commission, 3, rue de Verambe, P.O. Box 131, 1211 Geneva 20, Switzerland, Tel: +41-22-919-02-11, www.iec.ch.

ISO/IEC 17025:2017 General requirements for the competence of testing and calibration laboratories

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1715 Hybrid Electric (HEV) and Electric Vehicle (EV) Terminology

SAE J1715/2 Battery Terminology

SAE J2464 Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing

SAE J2973 Fuel Components and Systems Leak Tightness Specifications and Test Practices (or Methods)

Gorti, V. and Sagi, H., "Simplifying the Approach to Specify and Measure Product Seal Integrity and Leak Tightness," SAE Technical Paper 2006-01-0379, 2006, <https://doi.org/10.4271/2006-01-0379>.

2.2.2 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, 1, Ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, Tel: +41 22 749 01 11, www.iso.org.

ISO 19453-6:2020(E) Road vehicles - Environmental conditions and testing for electrical and electronic equipment for drive system of electric propulsion vehicles - Part 6: Traction battery packs and systems, published 2020.

2.2.3 Other Publications

NOAA Air Resources Laboratory. (2019, December 4). *Moisture Calculator*. READY Tools. <https://www.ready.noaa.gov/READYmoistcal.php>.

National Institute of Standards and Technology. (n.d.). *Thermophysical Properties of Fluid Systems*. NIST Chemistry WebBook, SRD 69. <https://webbook.nist.gov/chemistry/fluid/>.

2.3 Related Regulations

GB 38031-2020 Electric Vehicles Traction Battery Safety Requirements, China regulation

GB 18384-2020 Electrical Vehicle Safety Requirements, China regulation

3. DEFINITIONS

3.1 EQUIVALENT MICRO-GEOMETRY (EMG)

Maximum allowed single leak path geometry (diameter [d] and length [L]) that will not allow continuous leakage that exceeds the regulatory or customer requirements. Two types of EMGs are commercially available which represent the two extreme conditions for a potential real-life defect/leak. One is a Sharp Edge Orifice where the L/d is small (such as laser drilled hole on a thin film). The second is a Micro-Channel type (Equivalent Channel) with a larger L/d ratio. The Equivalent Channel represents a more likely defect in a battery pack enclosure and is also a more conservative selection when performing a production leak testing. Therefore, this recommended practice uses the Equivalent Channel as the selected Equivalent Micro-Geometry.

3.2 EQUIVALENT CHANNEL (EC)

A smooth and round micro-channel where $L \gg d$ ($L/d \sim 100$). Diameter is specified in micron-meters (microns). Roundness and diameter imperfection must be held to $\pm 10\%$ of diameter across that micro-channel length. Tolerance on EC diameter must be held to $\pm 1 \mu\text{m}$ for diameters less than $20 \mu\text{m}$ or $\pm 2 \mu\text{m}$ for diameters larger than $20 \mu\text{m}$. Length is specified in millimeters (mm); tolerance is $\pm 0.25 \text{ mm}$. Flow curves of various ECs with test air in the viscous (continuum) flow regimes are included in SAE J3277 Appendix C. EC flow rates will vary due to common dimensional tolerances and manufacturing methods. However, flow rates to be within $\pm 10\%$ at the test conditions as shown in SAE J3277 Appendix C.

3.3 FLOW REGIMES

Flow regimes are estimated by using the Knudsen (Kn) dimensionless number which is the ratio of the mean free flow path in meters to the EC diameter in meters. Four flow regimes are recognized: (1) Viscous (Continuum) flow regime where $\text{Kn} < 0.01$, (2) Slip flow regime where $0.01 < \text{Kn} < 1$, (3) Transitional flow regime where $0.1 < \text{Kn} < 1$, and (4) Molecular flow regime where $\text{Kn} > 1$. The actual flow regime is dependent on gas mixture/type, inlet and outlet pressure, and EC diameter. Flow data in SAE J3277 Appendix C are taken at Viscous flow regime and be different at other flow regimes.

3.4 LEAK

A hole or void in the wall of a Unit Device Under Test (UUT DUT), capable of passing liquid or vapor water (or liquid coolant) from outside of the battery pack (or from coolant channel) to its interior volume of the battery pack under action of pressure differential existing across the leak at operating condition. Leak is an unintended defect of the battery pack integrity.

3.5 STP - STANDARD TEMPERATURE AND PRESSURE

The pressure and temperature to which an actual compressible fluid's volumetric flow rate is normalized to yield the same mass flow at actual pressure and temperature of that fluid. This standard uses standard pressure of 101.325 KPa Absolute Pressure and 20°C as STP conditions.

3.6 LEAKAGE RATE (LEAK-FLOW RATE)

The flow rate of a liquid or gas through a leak at a given temperature as a result of a specified pressure differential across the leak. Leak flow rates are expressed in numerous measurement units. It is recommended to use SI measurement units for volumetric (as cc/min, cc/s) or mass flow rates (as mg/min, mg/s). Sometimes leak flow rates are described as SCCM or SCC/s which are actual volumetric flow rates normalized to Standard Temperature and Pressure conditions (STP) to yield same mass flow rate. There is no "one standard" for STP and different STP conditions can result in flow rate variations up to 8% for a given leak flow rate.

3.7 TRACER GAS LEAK TESTING

Leak testing utilizing gas that its normal concentration in the atmosphere is low, as few parts per million (ppm). The device test volume is filled with tracer gas, and once leakage exists, it is detectable by instruments capable of measuring this gas concentration, such as mass spectrometer. Common industrial tracer gas is Helium (He), normally its concentration in the air is 4 to 6 ppm. Since He is an inert gas, it is safe to use. He has a mole weight of 4, and its viscosity is higher than air. Other common tracer gas is Nitrogen/Hydrogen at 95%/5% concentration.

3.8 FUNCTIONAL LEAK TIGHTNESS REQUIREMENT

The Water Ingress Protection level that a battery pack must comply to meet regulatory and/or design requirements, e.g., IPX7 per IEC 60529 ED. 2.1 B:2001. Another example of a functional requirement is "no-sustainable coolant leakage into the battery pack headspace." The functional requirements are agreed upon between OEM and supplier.

The functional requirements, especially water immersion tests of charged battery packs, are not practical and may post risks of failures, for 100% in-line battery packs testing on the production line.

3.9 PRODUCTION LEAK TIGHTNESS REQUIREMENT (or LEAK TIGHTNESS SPECIFICATION)

The maximum allowed Equivalent Channel size which will enable the battery pack or its subsystem to meet its Functional Leak Tightness Requirements to be used during in-line product production (or validation) leak testing.

SAE J3277 provides the method to develop maximum size of EC as a quality assurance measure with agreed threshold of acceptance.

3.10 VIRTUAL LEAK

A leak that does not have a true leak path from the inside to outside but appears to the test instrument as a leak. Typically, virtual leaks are small narrow gaps, cracks, threads, or hidden crevices that take a long time to be pressurized or evacuated and identified as false positives.

3.11 INGRESS PROTECTION, IPX7

To meet the IPX7 water resistance requirements of IEC 60529 ED. 2.1 B:2001 and ISO 6469-1:2019, a product must withstand immersion in 1 m of water for 30 minutes without harmful water ingress. For battery packs specifically, this depth is measured from the bottom of the pack as mounted in the vehicle. However, for taller packs exceeding 0.85 m, the water level is set 0.15 m above the highest point.

NOTE 1: Filtered tap water is used for testing unless otherwise is agreed between OEM and Supplier.

NOTE 2: The temperature difference between the pack's internal air and the water must not exceed 5 °C.

NOTE 3: Minimal water condensation during or after the test due to air humidity is not considered ingress for battery packs.

NOTE 4: Strict safety precautions are mandatory when immersing energized battery packs in water.

3.12 HEADSPACE

The entrapped air volume (at STP condition) inside the battery pack. It is actually the empty battery pack internal volume less the sealed components volume, measured in liters for battery pack assemblies.

4. TERMINOLOGY

4.1 Unit Under Test (UUT), Device Under Test (DUT)

The battery pack assembly (or cooling system) under test.

5. MEASUREMENT UNITS - DEFINITIONS

5.1 Flow Measurement Units

5.1.1 mL/min, Volumetric flow (Q) in 10^{-3} L/min (or cc/min, ccm) should be specified with the gas type, pressure, and temperature at which it is measured.

NOTE 1: If the temperature is not specified, it is assumed to be 20 °C. The temperature effect on actual flow is in absolute temperature, which has a smaller influence and sometimes is not mentioned in leakage measurements.

NOTE 2: If gas type is not mentioned, it is assumed to be air or nitrogen.

NOTE 3: Since gas is a compressible fluid, its volumetric flow will change across the leak flow path due to changes in gas density.

5.1.2 Mg/min, Mass Flow ($\dot{m}$) in 10^{-3} g/min (or 10^{-6} Kg/min).

NOTE: Mass Flow is unchanged across the leak flow path at steady state conditions (mass conservation law).

- 5.1.3 SCCM/SCCS, Actual Volumetric flow (at a given pressure, temperature, and gas type) in mL/min or mL/s normalized to STP conditions to yield the same mass flow of that given gas. This is a popular flow measurement unit but is not an SI recognized measurement unit.

NOTE: Time-based units that are part of the flow measurement units can be minutes or seconds.

- 5.1.4 mbar*liter/s, Actual volumetric flow normalized to its pressure (PressureXVolume Flow, or PXQ). Flow rate of 1 Atm-cc/s at 20 °C can be interpreted to be 1 sccs of the same gas.

NOTE: This measurement unit is common with Helium (or other tracer gas) Mass Spectrometers.

5.2 Pressure (P) Units

- 5.2.1 Absolute Pressure (P-abs) Pressure units relative to 0 pressure, noted as KPa-ABS (psia, psi absolute).

- 5.2.2 Gage Pressure (P-g) Pressure units relative to existing barometric pressure, which varies and is noted as KPa-gauge, KPa-g (psig, psi gauge).

5.3 Measurement Uncertainties (per ISO/IEC 17025:2017 Definitions of Uncertainties)

- EC Diameters (microns): $\pm 0.25 \mu\text{m}$
- EC length: $\pm 0.5 \text{ mm}$
- Flow measurements: $\pm 1\%$ of reading
- Pressure measurement: $\pm 0.5 \%$ of reading
- Temperature measurement: $\pm 2 \text{ K}$

6. LEAK TESTING OF BATTERY PACK ASSEMBLIES

Battery pack leak tightness requirement (EC Size or Leakage rate) to meet desired water ingress protection level as IPX7. Pressure and test method to be agreed by OEM and Supplier. Measured data for pass/fail decisions should be saved for traceability as agreed by OEM and Supplier and in compliance with regulatory requirements. Common nondestructive production leak testing technologies for battery pack leak testing for in-line quality assurance are:

- Air Leak Testing - Micro-Flow (vacuum or pressure test inside the battery pack)
- Air Leak Testing - Pressure Decay-Pressure Differential Sensor
- Tracer Gas - Accumulation method
- Tracer Gas Robotic Sniffing

NOTE: It may be challenging to test components (as air vents) that are attached to the battery-pack housing with these test methods and settings. An alternate inspection approach should be agreed upon between OEM and Supplier to test these specific components, once installed, for water ingress protection.

Air vents should be independently tested for water leakage and properly stored and handled prior to assembly at the battery pack.

First priority is leak testing the sealing surface between the battery-pack housing and the assembled component to ensure that the sealing is free of damage and therefore functional post battery-pack assembly.

If it is impossible to leak test the seal integrity between the assembled components (e.g., air vent), an operator independent assembly process monitoring is recommended (as assembly force signature monitoring, vision system, etc.).

CAUTION: Proper safety precautions shall be applied when testing energized/charged battery packs.

6.1 Air Leak Testing

6.1.1 Battery Pack Micro-Flow Mass Extraction

6.1.1.1 Method A: Direct Micro-Flow Measurement Battery Pack at Vacuum

Overview:

This direct measurement method simulates real-world pressure conditions by placing the battery pack under vacuum and measuring extracted air flow for leak detection. It offers a simple and robust setup and avoids the need for custom test enclosure and expensive tooling.

Key Steps (see Figure 1):

1. **Connect and evacuate:** Securely connect the pack to a vacuum source through its ports and evacuate to -9.8 kPa gage (see Figure 1, all valves open).
2. **Stabilization:** Close isolation and evacuation valves to allow internal pressure to stabilize. Leaks will draw air into the pack, and from it to the vacuum reservoir, measured by the micro-flow sensor.
3. **Test mode:** Direct all leaks through the sensor and compare the measured flow rate to a threshold based on the equivalent channel (EC) flow at -9.8 kPa. This determines pass/fail based on measured leak flow rate value.
4. **Disconnect the test system connectors and air-vent seals** to allow the battery pack to return to atmospheric condition.

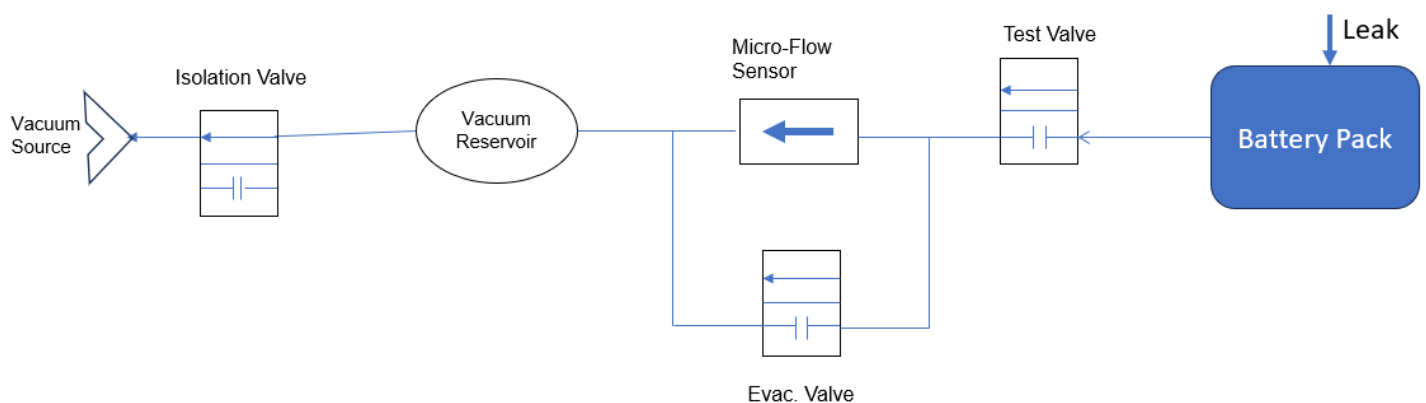


Figure 1 - Micro-flow Method A, pneumatic schematic - Direct vacuum applied to the battery pack.
The Micro-Flow Sensor includes a built-in micro-flow, pressure, and temperature sensors.
Schematic symbols are per ISO 1219-1:2012.