



SURFACE VEHICLE INFORMATION REPORT

J3277™

APR2024

Issued

2024-04

Liquid Leak Tightness Evaluation Methodology for EV Battery Packs Informational Report

RATIONALE

Vehicles using high voltage systems for electrified propulsion are expected to be introduced to the market in increasing quantities. These vehicles include, but are not limited to, plug-in electric vehicles (EV) and hybrid electric vehicles (HEV). These vehicles include Rechargeable Energy Storage Systems, RESS (battery packs) that might be mounted in locations that are exposed to water, either through rain/snow weather conditions or relatively low levels of standing water. Users of these vehicles are anticipated to have some amount of assurance that such water exposure will be unlikely to result in harmful water leakage into a battery pack. Common (and regulatory) functional test requirements for water ingress is per IEC 60529, IPX7 level, which is a destructive test and isn't applicable for an in-line production testing. This information report offers a method to convert these functional requirements into end-of line nondestructive quality assurance tests of battery packs.

TABLE OF CONTENTS

1.	SCOPE	3
2.	REFERENCES	3
2.1	Applicable Documents	3
2.1.1	SAE Publications	3
2.1.2	ISO Publications	3
2.1.3	IEC Publications	3
2.2	Related Publications	4
2.3	Related Regulations	4
3.	DEFINITIONS	4
4.	MEASUREMENT UNITS - DEFINITIONS	6
4.1	Flow Measurement Units	6
4.2	Pressure (P) Units	6
4.3	Measurement Instrument Uncertainties	6
5.	TERMINOLOGY	6
5.1	Unit Under Test (UUT)	6
6.	STEPS TO DEFINE EC SIZE (PRODUCTION LEAK TIGHTNESS REQUIREMENT)	7
7.	DEFINING EC SIZE - KEY PRODUCT PARAMETERS	7
7.1	Battery Pack Assembly	7
7.2	Battery Pack Cooling System Leakage	7
7.3	EV Battery Pack Design Parameters Important for Defining Applicable EC Geometry	7
8.	ANALYTICAL MODEL	8

SAE Executive Standards Committee Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2024 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, or used for text and data mining, AI training, or similar technologies, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
http://www.sae.org

SAE WEB ADDRESS:

Full document details: SAE J3277_202404

For more information on this standard, visit
https://www.sae.org/standards/content/J3277_202404/

Documents



Share Your Hub

8.1	Calculating the Amount of Water Battery Pack can Tolerate before Condensation	8
8.2	Theoretical Liquid Water Ingress Calculation Through Capillary Leak Path	9
8.3	EC Calculation of Water Ingress into the Example Battery Pack (per 7.2).....	9
9.	EMPIRICAL TESTING - FINDING ACTUAL EC SIZE.....	10
9.1	Testing and Test Protocol	10
9.2	Test Results Requirements	10
9.3	Testing for the Battery Pack Example.....	11
9.3.1	Water Ingress Test.....	11
9.3.2	Coolant Ingress Test.....	13
10.	APPLYING THE EC AS A PRODUCTION LEAK TIGHTNESS REQUIREMENT.....	18
11.	NOTES	19
11.1	Revision Indicator.....	19
APPENDIX A	ANALYTICAL MODEL	20
APPENDIX B	EXAMPLE DETAIL calculations.....	22
APPENDIX C	BATTERY PACK WATER INGRESS TEST DATA THROUGH SELECTED ECs	23
APPENDIX D	COOLANT LEAKAGE TEST DATA THROUGH SELECTED ECs (CAPILLARIES).....	25
Figure 1	Water ingress test setup, using a manifold with multiple test stations. The setup is inside an environmental chamber heated to test temperature. The EC (micro-tube made of silica) is encapsulated inside the EMG holder. Ingressed water is collected in the custom collection cup. Each test station has a manual isolation valve. (Reprinted with permission. ©Pfeiffer Vacuum Inc.).....	11
Figure 2	Water ingress versus EC diameter, with a power best-line fit. (Reprinted with permission. ©Pfeiffer Vacuum Inc.).....	12
Figure 3	Airflow to water ingress correlation per the data of Appendix C (Reprinted with permission. ©Pfeiffer Vacuum Inc.).....	13
Figure 4	Coolant leakage through EC setup. A manifold with 16 test channels, each with one manual isolation valve and EC encapsulated inside a Swagelok fitting with a collection cup and overflow cup. The manifold is inside an environmental chamber, heated to 65 °C. The sample collection cups were hand tightened and then loosened by a half turn to avoid pressure build up inside the collection cup. (Reprinted with permission. ©Inficon GmbH)	14
Figure 5	Total average coolant mass loss rate in mg/hour (Reprinted with permission. ©Inficon GmbH)	15
Figure 6A	Air leakage rate of ECs (capillaries) before and after coolant test (Reprinted with permission. ©Inficon GmbH)	16
Figure 6B	Helium leakage rate of ECs (capillaries) before and after coolant test (Reprinted with permission. ©Inficon GmbH)	17
Table 1	EC test samples for the water ingress test for the battery example of 7.3	12
Table 2	EC test samples for the coolant ingress test for the battery example of 7.3	14

1. SCOPE

This technical information report (IR) presents a methodology to evaluate battery pack liquid leak tightness attributes to be used in a production line to satisfy the functional requirement for IPX7, water ingress requirement, and no sustainable coolant leakage for coolant circuits. The Equivalent Channel Method is used as a suggested production leak tightness requirement for a given battery pack design that will correlate and assure that the battery pack meets or exceeds its functional requirement. Obtaining the specific geometry of the Equivalent Channel (EC) for a given battery pack is done analytically and empirically in consideration of the product design limitations. This document is a precursor to J3277-1, which will present the practices to qualify that product leak tightness is equal or better than the maximum allowed EC for that product using applicable and commercially available leak test technologies.

This document may be applied to EV and HEV battery packs as tested during production, without harnesses or other accessories installed by the OEM during vehicle assembly.

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 J1715 Hybrid Electric Vehicle (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>.

2.1.2 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO 6469-1:2019 Electrically Propelled Road Vehicles - Safety Specifications - Part 1: Rechargeable Energy Storage System (RESS)

ISO 17025:2017 General Requirements for the Competence of Testing and Calibration Laboratories

ISO 19453-6:2020 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

2.1.3 IEC Publications

Available from IEC Central Office, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 02 11, www.iec.ch.

IEC 60529 Degrees of protection provided by enclosures (IP Code)

2.2 Related Publications

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

Moisture Calculator, NOAA - Air Resources Laboratories, <https://www.ready.noaa.gov/READYmoistcal.php>.

NIST Chemistry WebBook, SRD 69 Thermophysical Properties of Fluid Systems, www.nist.gov.

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 that 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 microchannel type (Equivalent Channel) with a larger L/d ratio. The EC represents a more likely defect in a Battery Pack enclosure and is also a more conservative selection when performing production leak testing. The OEM and Supplier may agree on the type of EMG to be used, especially for coolant leak tightness requirements. This IR uses the EC as the selected EMG.

3.2 EQUIVALENT CHANNEL (EC)

A smooth and round microchannel where $L > d$ ($L/d > \sim 100$). Diameters are specified in micron-meters (microns). Roundness and diameter imperfection must be held to $\pm 10\%$ of diameter across that microchannel length. Tolerance on EC diameter must be held to ± 1 micron for diameters less than 20 microns or ± 2 microns for diameters larger than 20 microns. Length is specified in millimeters (mm), tolerance is ± 0.25 mm. Examples of flow curves of various ECs with test air in the viscous (continuum) flow regimes are included in Appendices C and D. EC flow rates will vary due to common dimensional tolerances and manufacturing methods. However, flow rates are to be within $\pm 10\%$ of the average test conditions as specified in Appendices C and D.

3.3 FLOW REGIMES

Gas 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: Viscous (Continuum) flow regime, where $Kn < 0.01$; Slip flow regime, where $0.01 < Kn < 1$; Transitional flow regime, where $0.1 < Kn < 1$; and Molecular flow regime, where $Kn > 1$. The actual flow regime is dependent on gas mixture/type, inlet and outlet pressure, and EC diameter. The same EC geometry with the same pressure differential across it and gas temperature will exhibit different flow rates depending on its flow regime (Kn number) conditions.

3.4 LEAK

A hole or void in the wall of a Unit Under Test (UUT) 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 IR 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 is derived by a specified pressure differential across the leak for a given flow regime (or outlet pressure and EC diameter). Leak flow rates are expressed in numerous measurement units. It is recommended to use SI measurement units for volumetric (cc/min, cc/sec) or mass flow rates (mg/min, mg/sec). Sometimes leak flow rates are described as SCCM or SCC/Sec, which are actual volumetric flow rates normalized to Standard Temperature and Pressure (STP) conditions to yield the 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 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. Another example of a functional requirement is “no-sustainable coolant leakage into the battery pack headspace.” The functional requirements are agreed upon between the 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.

3.8 PRODUCTION LEAK TIGHTNESS REQUIREMENT (OR LEAK TIGHTNESS SPECIFICATION)

The maximum allowed EC size that will enable the battery pack or its sub-system to meet its Functional Leak Tightness Requirements to be used during in-line product production (or validation) leak testing.

This IR provides the method to develop maximum size of EC as a quality assurance measure with agreed threshold of acceptance per the steps outlined in Section 7.

3.9 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.

3.10 INGRESS PROTECTION, IPX7

To meet the IPX7 water resistance requirements of IEC 60529 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.

- Filtered tap water is used for testing unless otherwise agreed between the OEM and Supplier.
- The temperature difference between the pack's internal air and the water must not exceed 5 °C.
- Minimal water condensation during or after the test due to air humidity is not considered ingress for battery packs.
- Strict safety precautions are mandatory when immersing energized battery packs in water.

3.11 HEADSPACE

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

3.12 RELATIVE HUMIDITY (RH)

The amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature. The RH is also the % ratio of the vapor partial pressure (Pa) to the saturation vapor pressure (Pa) at the same temperature.

4. MEASUREMENT UNITS - DEFINITIONS

4.1 Flow Measurement Units

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

- a. 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.
- b. If gas type is not mentioned, it is assumed to be air or nitrogen.
- c. Since gas is a compressible fluid, its volumetric flow will change across the leak flow path due to changes in gas density.

4.1.2 Mg/min Mass Flow (m) in 10^{-3} grams per minute (or 10^{-6} kg/min).

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

4.1.3 SCCM/SCCS Actual Volumetric flow (at a given pressure, temperature, and gas type) in mL/min or mL/sec 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.

4.1.4 mbar*liter/sec actual volumetric flow normalized to its pressure (PressureXVolume Flow, or PXQ). A flow rate of 1 Atm-cc/sec 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.

4.2 Pressure (P) Units

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

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

4.3 Measurement Instrument Uncertainties

Per ISO 17025 definitions of uncertainties:

- EC diameter (microns): ± 0.25 micron
- EC length: ± 0.5 mm
- Flow measurements: $\pm 1\%$ of reading
- Pressure measurement: $\pm 0.5\%$ of reading
- Temperature measurement: ± 2 K

5. TERMINOLOGY

5.1 Unit Under Test (UUT)

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

6. STEPS TO DEFINE EC SIZE (PRODUCTION LEAK TIGHTNESS REQUIREMENT)

Step 1: Define specific battery pack properties, as demonstrated in the example of 7.3.

Step 2: Estimate EC size using an analytical model (see Section 8). It is demonstrated using the example Battery Pack selected per 7.3.

Note that analytical models will be used for initial estimation only due to the large uncertainty of these models' calculations.

Step 3: Use empirical lab testing to define the required EC size as a Production Leak Tightness requirement (see Section 9). It is demonstrated for the example Battery Pack used in this document.

7. DEFINING EC SIZE - KEY PRODUCT PARAMETERS

7.1 Battery Pack Assembly

The Functional Leak Tightness requirement for Battery Pack in this IR is IPX7.

NOTE: For more or less stringent requirements, the test pressure should be changed. However, the process of this IR can be applied to other Functional Leak Tightness requirements.

7.1.1 Different battery pack designs vary from each other. The critical parameters can be different headspace, wall thickness and material used, seal design, electronic components, cell sensitivity to presence of liquid water, and operating temperature.

7.1.2 Therefore, it is the responsibility of the OEM and Supplier to define the applicable EC size applicable for their battery pack. See 7.3 for an example of a battery pack, and the steps and approach may be used by the OEM and Supplier to define the EC size for their specific EV battery pack design.

7.1.3 To meet or exceed IPX7 requirements (see 3.9), a pressure of 1 m of water (9.8 kPa-gage) preferably (as applicable for a given design and leak testing technology) is to be applied from outside of the battery pack to inside.

7.2 Battery Pack Cooling System Leakage

Cooling system leakage into the battery pack headspace: A different size of EC (or Sharp Edge orifice) shall be defined separately as cooling system pressure is higher, and the battery pack is always exposed to coolant, causing more stringent requirements (or smaller diameter EC).

Functional Leak Tightness requirement of the cooling system: No sustainable coolant leakage into the battery pack headspace.

NOTE: The EC (or Sharp Edge orifice) size is dependent on the cooling liquid type used, coolant cleanliness (filtering), cooling system pressure and coolant temperature during normal or maximum operating conditions, and selected defect length. One of two types of defect are likely to happen: pin-hole minimal length (Sharp Edge orifice), or microcrack (microchannel, EC) with longer length. The Production Leak Tightness will be the largest EC (or Sharp Edge orifice) size that is self-plugged and will stop a leakage shortly (within a few hours) after exposure to coolant.

7.3 EV Battery Pack Design Parameters Important for Defining Applicable EC Geometry

Headspace: 40 L

Test pressure (outside to inside): 9.8 kPa-gage

Battery pack: wall thickness and material - 3 mm, material type - hydrophobic plastic (as Heptadecafluoro or FDTs)

Electronic components protection: conformal coating

Typical operating temperature inside the headspace during normal driving conditions: 40 °C (typical operation temperature, not the maximum temperature battery pack may operate)

Typical RH when produced: 50%

Maximum allowed water mass before performance degradation is noticed: Up to 100% RH. No liquid water accumulated inside the battery pack at normal operating temperature (40 °C) under 1 m of water for 30 minutes. A few water drops due to condensation (at lower temperature) are allowed.

NOTE: This is an example only and its purpose is to establish the development of EC geometry. The maximum allowed water mass shall be established experimentally and agreed upon between the OEM and Supplier.

Cooling system: Coolant is GLYSANTIN G48® (Ethylene Glycol with rust inhibitor additives) and water 50%-50% mixture by volume. Test pressure of 250 kPa-gage and 65 °C and typical wall thickness of 2 mm. Functional Leak Tightness requirement per 7.2.

8. ANALYTICAL MODEL

8.1 Calculating the Amount of Water Battery Pack can Tolerate before Condensation

The amount of water inside the battery pack before condensation that can occur can be calculated per Equation 1 below:

$$m_{water} = (\rho_{100\%} - \rho_{initial}) * V \quad (\text{Eq. 1})$$

where:

m_{water} = total amount of water mass, in mg, that can be absorbed before condensation starts

V = battery pack head space (internal volume) in liters

from the NOAA Moisture Calculator (see 2.2):

$\rho_{100\%}$ = water content in air (mg/L) at 100% RH at typical operating temperature (This is the point where condensation starts.)

$\rho_{initial}$ = water content in air (mg/L) at RH at initial production environment and room temperature of 20 °C

from the Battery Pack example (see 7.3) and Equation 1:

$V = 40.00 \text{ L}$

$\rho_{100\%} = 50.57 \text{ mg/L at } 40 \text{ °C}$

$\rho_{initial} = 8.59 \text{ mg/L at } 50\% \text{ RH and } 20 \text{ °C}$

Therefore, from Equation 1: $m_{water} = 1679 \text{ mg}$

Conclusion: The Battery Pack of this example can absorb water ingress of up to 1.679 g before condensation starts at typical operating temperature (40 °C).

NOTE: A more stringent approach is “no water ingress allowed” compared with the approach outlined in 8.1, which allowed some water ingress until the Battery Pack reaches 100% RH (condensation).

Using the “no water ingress allowed” approach will result in calculating the EC diameter for applied pressure of 9.8 kPa-gage, resulting in surface retention pressure (see Appendix A, Equation A8). That surface retention pressure will oppose the applied external pressure of 9.8 kPa-gage. That approach will yield a significantly smaller EC diameter, resulting in a leak flow rate that will be two magnitudes of order smaller. That stringent requirement for the battery pack will require more proper (and more expensive) seal design and production leak testing.

The final leak tightness approach shall be decided between the OEM and Supplier.

8.2 Theoretical Liquid Water Ingress Calculation Through Capillary Leak Path

As shown in Appendix A, the theoretical total amount of water (m in mg) that can ingress the battery pack in 30 minutes to meet the IPX7 requirement is:

$$m = 5.635741 * \frac{(DP+Ps)}{L} \frac{d^4}{128} \quad (\text{Eq. 2})$$

where:

m = total amount of water in mg

DP = pressure differential across the capillary path and is 9.8 kPa (1 m of water)

d = equivalent diameter of the capillary flow path in μm (micrometers)

L = length of the capillary flow path (μm)

Ps = pressure induced (kPa) due to surface tension effects (see Equation 3) and is negative for hydrophilic battery pack housing material (see Appendix A)

$$Ps = \frac{287.6 * \cos\theta}{d} \quad (\text{Eq. 3})$$

where:

θ = the contact angle between the liquid surface and the microchannel wall (see Figure A1). The contact angle is dependent on the battery pack wall material.

8.3 EC Calculation of Water Ingress into the Example Battery Pack (per 7.2)

We will calculate the EC diameter, d , to allow water ingress, m , in 30 minutes that equals to the total water mass the battery pack can contain before condensation starts as calculated in 8.1. For our battery pack example: $m = m_{\text{water}} = 1679 \text{ mg}$.

We will calculate the EC diameter from Equation 2 for two cases: first case where $Ps = 0$, or negligible surface tension pressure loss/gain, and second case where Ps is calculated per Equation 3.

The detailed calculation is shown in Appendix B.

For the first case, where $Ps = 0$, $d = 58.45 \mu\text{m}$

For the second case, where surface tension is not negligible, $d = 61.13 \mu\text{m}$

NOTE 1: The above model and its technical assumptions do not consider molecular phenomena and water impurities that can partially plug the EC and reduce its effective diameter.

NOTE 2: Therefore, for empirical testing of water ingress, the recommended EC will be: length = 3 mm, diameter range = from 50 to 125 μm