



SURFACE VEHICLE RECOMMENDED PRACTICE

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RESS Cell Package Integrity Requirements and Tests

RATIONALE

The increasing adoption of electrified propulsion systems in vehicles, including plug-in electric vehicles (EVs) and hybrid electric vehicles (HEVs), has driven the demand for reliable energy storage solutions. These vehicles rely on Rechargeable Energy Storage Systems (RESS), which are comprised of multiple interconnected energy cells. The integrity of these RESS cells, particularly their Closure Integrity, is critical to ensuring the long-term safety and performance of the entire battery system. Given the critical nature of RESS Cell Closure Integrity, this recommended practice defines the necessary Closure Integrity (leak) requirements and provides guidelines for approved non-destructive leak testing methods, including the tooling and procedures required for these tests. This ensures that the RESS cell package remains free from electrolyte leakage and excessive moisture ingress, factors essential to the safety and operational efficiency of the vehicle.

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
2.1.4	Other Publications	4
2.2	Related Publications	4
2.2.1	SAE Publications	4
2.2.2	ISO Publications	4
2.2.3	Related Regulations	5
3.	DEFINITIONS	5
4.	SYMBOLS	7
5.	MEASUREMENT UNITS – DEFINITIONS	7
5.1	Flow Measurement Units	7
5.2	Pressure (P) Units	8
5.3	Measurement Uncertainties (per ISO 17025:2017 Definitions of Uncertainties)	8
6.	STEPS TO DEFINE EC SIZE (PRODUCTION LEAK TIGHTNESS REQUIREMENT)	8
7.	ANALYTICAL MODEL	8
7.1	Calculating EC Diameter for No Electrolyte Leakage	9
7.2	Calculating Moisture Ingress Due to Diffusion	9
7.3	Calculating Moisture Ingress Due to Effusion (Gas Flow)	10

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8.	EMPIRICAL TEST FOR RESS CELL LEAKAGE AND MOISTURE INGRESS	11
8.1	Test Facility and Protocol	11
8.2	Preparation of Test Cells	11
8.3	Control (Non-Leaking) Cells	11
8.4	Test (Leaking) Cells	12
8.5	Test Procedure and Data Analysis	12
9.	CELL INTEGRITY (LEAK) TESTING TECHNOLOGIES AND METHODS	13
9.1	Cell Production Test Phases	13
9.2	Empty Assembled Cell's Testing Technologies and Methods	14
9.2.1	Tracer Gas (He) Leak Test System - Cell Is Inside a Vacuum Chamber	14
9.2.2	Mass Extraction (Air) Leak Test System - Cell Is Inside a Vacuum Chamber	16
9.3	Electrolyte Filled and Sealed Cell's Testing Technologies and Methods	19
9.3.1	Mass Spectrometer (MS) Leak Test System - Sealed and Filled Cell Is Inside a Vacuum Chamber	19
10.	MEASUREMENT SYSTEM REPEATABILITY AND REPRODUCIBILITY (R&R)	21
11.	NOTES	22
11.1	Revision Indicator	22
APPENDIX A	NO ELECTROLYTE LEAKAGE- BLOCKAGE DUE TO SURFACE TENSION	23
APPENDIX B	CALCULATING MOISTURE INGRESS DUE TO DIFFUSION	25
APPENDIX C	CALCULATING MOISTURE INGRESS DUE TO EFFUSION (GAS FLOW)	27
Figure 1	Typical empty tracer gas (He) leak test schematic	15
Figure 2	Typical empty cell mass extraction (air) leak test schematic	17
Figure 3	Typical sealed cell MS test schematic	20

1. SCOPE

This recommended practice (RP) presents a methodology to evaluate RESS Cells Closure Integrity (Leak Tightness) requirement.

This RP applies to two types of RESS Cells, each containing liquid electrolyte: Lithium ion (Li-ion) Cells and Sodium ion (Na-ion) Cells.

The Equivalent Channel Method is used as a suggested cell closure integrity requirement for a given RESS Cell design during its production and product validation phases. The Closure Integrity requirements intended to assure no electrolyte leakage and no excessive moisture ingress during the usage of these cells as part of the RESS (Battery Pack), which is crucial to assure the safety and performance of these RESS.

This RP specifies non-destructive Integrity (leak) testing processes of the Cell Closure. It describes approved leak testing technologies, testing procedures, tooling requirements, and leak test systems validation/verification requirements.

This document may be applied to RESS Cell Closure Integrity testing during their initial product validation and their in-line 100% of production integrity/leak testing. This RP applies to RESS Cells with rigid packaging (cylindrical or prismatic) or flexible packaging (pouch).

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: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), www.sae.org.

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

SAE J3277-1 Liquid Leak Tightness Standards for Propulsion Battery Packs Recommended Practice

2.1.2 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, Tel: +41 22 749 01 11, www.iso.org/store.

ISO 1219-1:2012 Fluid power systems and components - Graphical symbols and circuit diagrams

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

2.1.3 IEC Publications

Available from IEC Secretariat, 3 rue de Varembé, PO Box 131, CH-1211 Geneva 20, Switzerland, Tel: +41 22 919 0211, www.iec.ch.

IEC 60529 Ed. 2.1 B:2001, Degrees of protection provided by enclosures (IP Code), consolidated edition, issued 2013

2.1.4 Other Publications

- [1] 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] Wetzig, D. and Reismann, M., "Methods for Leak Testing Lithium-Ion Batteries to Assure Quality with Proposed Rejection Limit Standards," SAE Technical Paper 2020-01-0448, 2020, <https://doi.org/10.4271/2020-01-0448>.
- [3] Wikipedia contributors, "Fick's laws of diffusion," Wikipedia, The Free Encyclopedia, https://en.wikipedia.org/w/index.php?title=Fick%27s_laws_of_diffusion&oldid=1346236275.
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- [5] The Engineering ToolBox, "Air - Diffusion Coefficients of Gases in Excess of Air," 2018, www.engineeringtoolbox.com/air-diffusion-coefficient-gas-mixture-temperature-d_2010.
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- [7] Czernia, D., "Mean Free Path Calculator," 2024, <https://www.omnicalculator.com/physics/mean-free-path#how-to-calculate-mean-free-path-mean-free-path-equation>.
- [8] Karniadakis, G.E. and Beskok, A., "Micro Flows: Fundamentals and Simulation," Springer-Verlag, New York, 2002.
- [9] Singh, S.P., Singh, J., Stallings, J., Burgess, G., and Saha, K., "Measurement and Analysis of Temperature and Pressure in High Altitude Air Shipments," Packag. Technol. Sci., 23: 35-46, 2010, <https://doi.org/10.1002/pts.877>.

2.2 Related Publications

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

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), 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)

2.2.2 ISO Publications

Available from International Organization for Standardization, ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, Tel: +41 22 749 01 11, www.iso.org/store.

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 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 cell and is also a more conservative selection when performing a production leak test. 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 $L \gg d$ ($L/d \gg 100$). Diameter is specified in micro-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 $\pm 10\%$ in 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 $0.01 < \text{Kn} < 0.1$, (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 from outside of the Cell Enclosure to its interior volume of the cell or passing electrolyte from the Cell to its environment, under action of pressure differential existing across the leak at operating condition. Leak is an unintended defect of the Cell Closure 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 mL/min, mL/s, or $\text{Pa} \cdot \text{m}^3/\text{s}$) or mass flow rates (as micro-gram/min).

3.7 TRACER GAS LEAK TESTING

Tracer gas leak testing is a deterministic, non-destructive method that uses gases such as helium (He) to detect leaks. The test volume is filled with a tracer gas, and if a leak is present, it can be identified by instruments like a mass spectrometer that measure the gas concentration. Helium is the most common tracer gas because its natural concentration in air is very low (about 5 ppm), it is inert and safe to use, and it has a low molecular weight of 4 with slightly higher viscosity than air. Another commonly used tracer gas mixture is 95% nitrogen and 5% hydrogen.

3.8 MASS EXTRACTION LEAK TESTING

Mass Extraction for leak testing is a deterministic, non-destructive test method that quantifies the mass flow rate of gas (usually air) escaping from or entering a sealed item under a vacuum. The mass extraction instrument utilizes a microflow sensor measuring amount of air extracted from an item under constant vacuum condition.

3.9 MASS SPECTROMETER (MS)

A mass spectrometer (MS) is an analytical instrument that measures the mass number or mass-to-charge ratio (m/z) of ions. This measurement allows scientists to determine the elemental composition, molecular structure, and quantity of chemical substances in a sample.

The technique, called mass spectrometry, involves converting sample molecules into gas-phase ions, sorting them based on their m/z ratio, and detecting them. Because different molecules and isotopes have unique masses, a mass spectrum (a plot of ion abundance versus m/z) acts as a “molecular fingerprint” for identification of leakage and/or gas analysis.

The leak test method utilizing MS is deterministic and non-destructive.

3.10 FUNCTIONAL LEAK TIGHTNESS REQUIREMENT

For Battery Cell functional requirements are “no electrolyte leakage out of the cell” or “no moisture ingress more than xg/year.”

The functional requirements are not practical for 100% in-line battery packs testing on the production line.

3.11 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.

3.12 VIRTUAL LEAK

A leak that does not have a true leak path from the inside to outside but appears to be 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.

3.13 INGRESS PROTECTION, IPX8

The RESS cell must meet moisture ingress protection and electrolyte liquid leakage requirements, or IPX8 as described in Sections 7 and 8 of this document.

3.14 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.

3.15 CALIBRATION

Calibration of leak test instruments (HMS, MS, Mass Extraction) is a process of comparing the instrument readings against known flow (leak) and pressure standards, qualified per ISO 17025, and adjusting the instruments accordingly if the measurement error exceeds its allowable limit. Calibration shall use same gas used during leak testing.

3.16 VERIFICATION

Verification is done periodically, using calibrated instruments, to verify that the system accepts known good cells (master parts) and rejects known cells with leaks (as with Calibrated Leak attached to the cell or chamber), where the leakage value is near the threshold limit. Verification testing shall use suitable fluid comparable to electrolyte and test parameters as used during actual leak testing.

4. SYMBOLS

HMS helium mass spectrometer

UUT (Unit Under Test), DUT (Device Under Test) the cell 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 micro-g/min

Mass Flow ($\dot{m}$) in 10^{-6} g/min (or 10^{-9} kg/min).

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

5.1.3 Pa*m³/s

Volumetric flow normalized to its pressure (PressureXVolume Flow, or PXQ) which is the flow rate that will increase the gas pressure of 1 m³ by 1 Pa within 1 second.

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

5.2 Pressure (P) Units

5.2.1 Absolute Pressure (P-abs)

Pressure units relative to 0 pressure, noted as KPa-abs (Kilopascal, 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 (Kilo-Pascal gauge, Kpa-g).

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

- EC Diameters (microns): $\pm 0.25 \mu\text{m}$
- EC Length: $\pm 0.5 \text{ mm}$
- Air Flow Measurements: $\pm 1\%$ of reading
- Helium Mass Spectrometer (HMS) Measurement Uncertainty: $\pm 10\%$
- Pressure Measurement: $\pm 0.5\%$ of reading.
- Temperature Measurement: $\pm 2 \text{ K}$

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

The following steps are required to define the EC size for a given RESS Cell design:

- Step 1: Use the analytical model to ESTIMATE to range of potential EC diameters to prevent Electrolyte and Solvents leakage and excessive moisture ingress as described in Section 7.
- Step 2: Define final EC diameter: Using the estimated range of EC, conduct a lab test with actual RESS cells that are known as acceptable and RESS cells that have defects introduced into the cell envelope before filling it with Electrolyte as described in Section 8.
- Step 3: For a given test method, use the defined EC to characterize gas flow rate at inlet and outlet pressure as be used during production leak testing.

7. ANALYTICAL MODEL

Recommended Analytical Steps:

1. Calculate the maximum microchannel diameter based on “No Electrolyte Leakage-Blockage” per the model described here.
2. For the calculated microchannel geometry in step 1, calculate the Moisture Ingress due to Diffusion. Use Moisture Ingress due to Effusion only if and as applicable. Combine both moisture ingress calculated rates. Both models are described below. Reducing the microchannel diameter if the amount of moisture ingresses exceeds the electrolyte chemistry maximum allowed moisture content.

7.1 Calculating EC Diameter for No Electrolyte Leakage

This model is based on the maximum operating pressure required to overcome the surface tension retaining pressure (P_c) and external pressure in order to generate an electrolyte (or electrolyte solvents) leakage from the cell into the surrounding environment. This model is known as Laplace model [7],[8] and is described in detail in Appendix A with an example.

The EC diameter d [m] is calculated based on Equation 1 from Appendix A:

$$d = 2 \cdot r = \frac{4 \cdot \gamma}{P_c} \quad (\text{Eq. 1})$$

where:

γ is the surface tension coefficient [N/m]

P_c is the capillary pressure [Pa-gage pressure]

7.2 Calculating Moisture Ingress Due to Diffusion

Diffusion Analytical Model Assumptions:

1. The impact of effusion (flow due to pressure differential) is negligible. This is true in cases where the micron size defect is blocked by electrolyte or contamination.
2. There are negligible driving forces due to chemical/electrostatic potential changes.
3. There is no water vapor accumulation inside the cell as the water molecule goes through an exothermic chemical reaction with the electrolyte, and the outcome of this reaction is a gas mixture. Therefore, water vapor concentration inside the cell is constant and similar to initial water vapor condition (near 0% RH).
4. Water vapor in barometric condition and vacuum is treated as an ideal gas.

The water vapor ingress due to diffusion through a micro-channel with a length z [m] and cross section area is based on Fick's first law of diffusion and ideal gas models and described with an example in Appendix B.

The vapor ingress rate $\frac{\delta m}{\delta t}$ [kg/s] is given in Equation 2 and is developed in Appendix B:

$$\frac{\delta m}{\delta t} = - \frac{D \cdot A}{R \cdot T} \cdot \frac{P_o - P_i}{Z} \quad (\text{Eq. 2})$$

where:

D is the diffusivity coefficient, and for water vapor in air at 20 °C and barometric condition is $0.242 \cdot 10^{-4}$ [m²/s]

A is the microchannel cross area [m²]

R is the water vapor gas constant [J/K/kg] and T is the absolute temperature [K]

P_o is water vapor partial pressure outside the cell (outside the battery pack, e.g., atmospheric condition), and P_i is the water vapor partial pressure inside the cell. Since the cell is packaged at extremely low humidity, we can assume $P_i=0$.

Z is the microchannel length typically wall thickness of the cell enclosure

See Appendix B for more details and a calculation example using Equation 2.