TECHNICAL WHITE PAPER

Calibrated Leak Technology White Paper

An Industry Encyclopedia from Principles to Practice

Leak Rate · Flow Regimes · Processes · Metrology · Application Methodology · Solutions

RealMeter Instruments (Shanghai) Co., Ltd.

V2.6 Final Edition · Four Parts, Sixteen Chapters · July 2026

Abstract: From first principles, this paper presents the physics, processes, metrology and application methodology of calibrated leaks — leak-rate language, three flow regimes, the full process spectrum, lifetime physics, uncertainty, leak-test methodology, quantitative semiconductor RGA, system-level air-tightness accuracy, and the Three-Reference helium-reduction paradigm — concluding with solutions and field data across all leak rates, all pressures and all gases.

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Compilation note: This book is compiled from the technical content system of the RealMeter Leak Research Institute. Parts I–III cover industry-generic knowledge (physics, metrology, methodology); Part IV presents RealMeter's technical solutions. All RealMeter product parameters are cited from the 2026 RealMeter® Calibrated Leak Product Handbook & Configuration Guide (Revised Edition) and publicly released materials.

Contents

Preface

The calibrated leak is a "small but weighty" industry: the device is the size of a thumb, yet it carries the pass/fail judgment of the entire manufacturing world. For decades, the knowledge of this industry has been scattered across metrology specifications, vacuum textbooks, leak-detector manuals and the experience of veteran engineers — no book has ever strung together a complete path "from entry level to deep understanding." This book attempts to fill that gap.

Structure: Part I (Cognition, Ch. 1–3) builds the language and the physics: what leak rate is, how units convert, and what happens inside a leak. Part II (Principles, Ch. 4–7) builds judgment: the process spectrum, lifetime physics, valves and dead volume, uncertainty and traceability. Part III (Applications, Ch. 8–12) builds methodology: leak-test methods, quantitative semiconductor RGA, system-level air-tightness accuracy, the helium-reduction paradigm, selection and FAQ. Part IV (Solutions, Ch. 13–16) presents one answer: what emerges when this knowledge system is fully engineered. The appendices provide quick-reference tools.

How to use this book: New engineers should read sequentially from Chapter 1 — the first three chapters will give you a more solid foundation than most three-year practitioners. Production process and quality engineers may jump to Chapters 8–12: the Four-Piece Kit, the bypass method and Three-Reference helium reduction are usable tomorrow. Metrology and audit personnel: Chapter 7 and Appendix D are written for you. Procurement and decision-makers: the "rules" and "four questions" in Chapters 4, 11 and 12 can be written directly into tender documents.

One promise: For every physical conclusion, we show the derivation; for every product parameter, we cite the source; for every capability boundary, we state it honestly (including what we ourselves cannot do). We believe this is the only way a white paper earns trust.

PART I

Cognition | Understanding the Leak

Chapter 1 What Is a Calibrated Leak: The "Yardstick" of Leak Testing

> **What this chapter answers:** why calibrated leaks exist, where they sit in the measurement system, and how they relate to real leak points on workpieces. After this chapter, you should be able to explain to any non-specialist colleague: without a calibrated leak, every OK / NG decision on the production line loses its basis.

1.1 A Decision Made Every Second

On production lines for power batteries, automotive air conditioning, semiconductors and medical devices, thousands of such judgments are made every second: does this part leak or not? OK — release; NG — reject. The judgment is made by a leak detector: a helium mass-spectrometer leak detector, a differential-pressure air-tightness tester, or a halogen leak detector. But the detector itself cannot "know" how large a leak counts as rejectable — it is merely an instrument that amplifies a gas signal into a number. What truly answers "how big counts as leaking" is a thumb-sized device: the **calibrated leak**.

Its role is exactly that of a weight on a balance, or of a standard voltage source when calibrating a multimeter: the instrument gives a reading, the standard tells whether the reading is trustworthy. **The leak detector is the scale; the calibrated leak is the weight.** If the weight is wrong, the more precise the scale, the more confidently it errs. The two costliest quality accidents on a production line — false rejects (good parts scrapped) and missed rejects (defective parts shipped) — when traced to the end, point in a remarkable proportion of cases to the same root cause: the yardstick itself is untrustworthy, or its working conditions were not used correctly.

1.2 Definition: A Metrologically Characterized "Standard Source"

> **Definition 1-1 (Calibrated leak — also known as calibrated leak standard or reference leak)**
>
> A calibrated leak is a reference device that provides a known and stable leak rate under specified working conditions (gas species, inlet pressure, outlet pressure, temperature), calibrated and certified by a metrological institution. The Chinese national metrology specification JJF 1833—2020, *Calibration Specification for Vacuum Helium Leaks*, defines a vacuum helium leak as "an element that provides a known helium flow rate, used to calibrate the sensitivity of helium mass-spectrometer leak detectors," and divides leaks by structure into two classes: **channel-type leaks** (the leak element is a real geometric channel, e.g. capillary, orifice, crushed-metal) and **permeation leaks** (with quartz glass or similar as the permeation element)[1].

The definition contains three indispensable keywords — they form the essential difference between a "standard source" and an arbitrary pinhole:

Table 1-1 The three elements of a standard source: why a random drilled hole is not a calibrated leak

Element	Meaning	Counter-example (what a random hole does)

Repeatable	Same output today, tomorrow and next year under identical conditions — even after temperature swings, vibration and shipping	Channel drifts with temperature and creeps over time; readings differ month to month
Traceable	The leak-rate value is traceable through an unbroken calibration chain to the national primary standard, with known uncertainty at every link	The rate is merely "the vendor's rough figure," unprovable
Verifiable	A certificate states the calibration conditions and uncertainty; a third party can re-verify to the same specification	No certificate, or a certificate without stated conditions — nothing to check against

These three elements are also the undercurrent of the whole book: every later chapter — flow-regime physics (Ch. 3), the process spectrum (Ch. 4), lifetime physics (Ch. 5), uncertainty (Ch. 7) — is essentially answering "how to push the three elements to their limits."

1.3 Position in the Measurement System

The calibrated leak sits in the exact middle of a complete chain of trust. Upstream lies metrology; downstream lies product quality:

- **Upstream**, it is the calibrated party: its leak rate is assigned by a calibration facility (flow-meter method, fixed-quantity gas method, or comparison method) and traced to the national primary standard[1];
- **Downstream**, it is the assigning party: the detector's sensitivity and the line's reject threshold are anchored by it.

The calibrated leak therefore has a property rarely seen in other measuring instruments: **its error is amplified twice** — first copied into the detector's systematic error, then copied into every product judgment. A calibrated leak with a +20% rate deviation, unknown to its user, keeps an entire production line running day and night against a wrong threshold. This is why metrology specifications impose hard requirements on the annual stability of calibrated leaks (JJF 1833—2020 requires ≤ 3%/year) and on calibration-facility uncertainty (relative expanded uncertainty better than 10%, k = 2)[1] — and why this book devotes a full chapter each to "decay" and to "uncertainty."

1.4 Leak ≠ Leak Point ≠ Orifice Diameter: The Equivalent Leak Channel

Three concepts are constantly conflated in the field and must be separated:

Table 1-2 The three most easily confused concepts

Concept	Definition	Key point
Calibrated leak	A deliberately manufactured, metrologically calibrated standard source	An intentional "good leak" — the more stable, the more valuable
Leak point	An objectively existing defect channel on the workpiece (crack, weld porosity, sealing-face notch)	Almost never a round hole; often not reproducible

Equivalent channel	The leak point's gas-transport capability at a given pressure difference and gas, expressed as that of a geometric channel	The only engineerable object that can be compared and calibrated

The key insight: **leak testing measures "leak rate," never "orifice diameter."** A 50 μm crack and a 5 mm capillary are, for sealing purposes, the same problem as long as they transport gas equally under the same conditions. A calibrated leak provides precisely such a stable, controllable, reproducible **equivalent leak channel** — used to "impersonate" the critical defect on the workpiece (the OK / NG judgment and helium-reduction systems of Ch. 10–11 are built on this). Every conversion of "what hole diameter does this leak correspond to" is meaningless without specifying gas species, pressure and flow regime (Ch. 3 gives a rigorous treatment).

1.5 The Traceability Chain: From National Primary Standard to Line Judgment

How does the leak-rate value reach your production line, step by step? The figure below shows the complete chain:

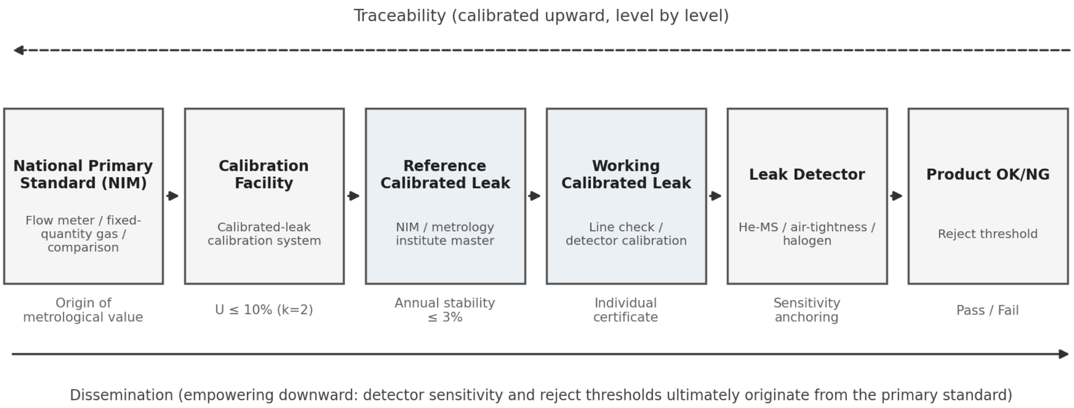

Figure 1-1 The leak-rate traceability chain: traced upward, disseminated downward (illustrative)

Every link has a name: the primary leak-rate standard maintained by the National Institute of Metrology (NIM) → calibration facilities at metrology institutes at various levels (JJF 1833—2020: flow-meter / fixed-quantity gas facilities must have relative expanded uncertainty better than 10%, k = 2; comparison facilities better than 20%) [1] → **reference calibrated leaks** (master standards used by institutes to establish their standards, each with a national-level certificate) → **working calibrated leaks** (for daily line checks and detector calibration) → detector readings → product OK / NG judgment.

This chain explains two phenomena familiar in the industry:

- **"Certificates with different stated conditions give numbers that don't match"**: every link is bound to working conditions (gas, pressure, temperature, outlet conditions); change conditions at any link and every downstream number is distorted;
- **"Establishing a standard is the institute's business — and also the leak manufacturer's"**: a reference calibrated leak must itself be an extremely stable product, holding its value between two calibrations (typically 12 months); annual stability, temperature coefficient and shipping robustness directly determine

the quality of the established standard. Chapter 15 presents a complete standard-establishing leak set conforming to JJF 1833—2020.

1.6 A Taxonomy of Calibrated Leaks

The calibrated leak is not a single product but a multi-dimensional family. Master the following six classification dimensions and you hold the "map coordinates" of this book:

Table 1-3 Six classification dimensions of calibrated leaks

Dimension	Categories	Physical / engineering significance
① Structural principle	Channel-type (capillary, orifice, crushed, microchannel) / permeation (quartz membrane, etc.)	Determines tempco, pressure rating, media compatibility (Ch. 3, 4)
② Gas supply	Reservoir-type (built-in gas volume) / passive (external supply)	Reservoir leaks work standalone but decay (§3.8); passive leaks never decay and can simulate any condition
③ Outlet condition	Vacuum leak (into vacuum) / positive-pressure leak (into atmosphere)	One leak, two ratings; §2.5 gives the conversion conditions
④ Medium	Single gas / gas mixture / isotopes / liquids (water, dodecane, DMC, etc.)	Gases follow conductance models; liquids follow evaporation–transport models (Ch. 3 & 6)
⑤ Test method	He-MS / differential-pressure / hydrogen / halogen-refrigerant / RGA / MFC micro-flow	Each method imposes different requirements on the leak (Ch. 8)
⑥ Form factor	Reservoir / probe / micro-size (down to Φ2.0 mm class) / built-in / adjustable	Form serves installation space and in-situ calibration (Ch. 14)

Reservoir vs passive is the first choice to make in the field, so build the intuition early: **a reservoir-type leak is like a "self-inking standard stamp"** — open the valve and it works; portable, independent, ideal for detector calibration and metrological traceability. **A passive leak is like a "standardized precision capillary"** — driven by the local gas supply, it can precisely simulate workpiece leakage at any pressure, and is the foundation of OK / NG judgment systems and helium-reduction schemes (Ch. 10, 11). Neither is better; they simply have different applicable boundaries.

1.7 Why This Industry Is Upgrading

Over the past decade, four industry-level changes have pushed the calibrated leak from "accessory of the leak detector" to "foundation of the quality system":

Table 1-4 Industrial upgrading and its new demands on calibrated leaks

Driver	Change in testing demand	Requirement on leaks
Mass production of EV batteries	High-takt He / H_2 testing of cases and cooling systems	Shock resistance, high-frequency checks, OK/NG three-piece simulation sets, helium reduction

Structural helium shortage	Pure He → low-concentration He (1% ~ 50%)	Three-Reference simulation references that stay decidable at low concentration (Ch. 11)
Semiconductor & UHV	RGA quantification, isotope / mixture calibration	Zero-dead-volume valves, all-metal sealing, ultra-low background (Ch. 6)
Maturing metrology system	JJF 1833—2020, JJG (military) 165—2024 and others in force[1][2]	Reference-grade leak sets, uncertainty budgets, standardized certificates

1.8 Summary

- The calibrated leak is the "weight" of the leak-testing world: detector readings and line reject thresholds ultimately trace back to it;
- The three elements of a standard source — repeatable, traceable, verifiable — are the meta-standard for evaluating any leak;
- Leak testing measures leak rate (equivalent-channel capability), not orifice diameter;
- Every link of the traceability chain is bound to working conditions; "conditions fixed in writing" is the premise of all subsequent work;
- Six classification dimensions (principle / supply / outlet / medium / method / form) form the map coordinates of this book.

The next chapter settles the most fundamental — and most error-prone — language problem of this industry: the units and magnitudes of leak rate.

Chapter 2 The Language of Leak Rate: Units, Magnitudes and Intuition

> **What this chapter answers:** how the dozen or so leak-rate units on the market convert into one another, which of the numbers you see daily are "the same quantity expressed differently," and how to judge the magnitude of a leak rate within three seconds. This chapter is the dictionary of the whole book.

2.1 What Leak Rate Measures: pV per Unit Time

Leak rate is neither hole size nor gas volume, but the **product of pressure and volume transported through the leak channel per unit time**:

$$Q = \frac{d(pV)}{dt} \tag{2-1}$$

Q — leak rate; pV — the pressure × volume product of the transported gas (a measure of "amount of gas"). Under isothermal conditions, pV is proportional to the number of molecules, so leak rate is essentially "how many molecules pass per unit time."

Why not use volume flow directly? Because gas is compressible: 0.01 cm^3/s on the high-pressure side may expand to 10 L/s on the low-pressure side. Only pV is invariant along the path (at constant temperature) — this is why vacuum technology worldwide uses "pressure × volume / time" as the base dimension of leak rate. All the units below are merely different pV conventions.

2.2 The Unit Family: One Quantity, Five Dialects

Table 2-1 Mainstream leak-rate units and conversions (based on 1 $Pa \cdot m^3/s$)

Unit	Equal to 1 $Pa \cdot m^3/s$ ×	Main user communities
$Pa \cdot m^3/s$	1	SI; Chinese national standards; vacuum community
mbar·L/s	10	European leak-detector convention; vacuum industry daily unit
atm·cc/s	9.87	American convention; semiconductor & hermetic-package community
Torr·L/s	7.50	Vacuum engineering (older literature)
sccm (std. cc/min)	592	Gas flow, MFC community
g/y (grams per year)	medium-dependent	Refrigeration & automotive A/C regulations

The three most useful relations to memorize:

- **1 $Pa \cdot m^3/s$ = 10 mbar·L/s ≈ 9.87 atm·cc/s** — the "trio" of the vacuum community, numerically interchangeable within ±1.3% for engineering estimates;
- **1 mbar·L/s ≈ 59.2 sccm ≈ 0.987 std.cc/s** — the bridge between vacuum and flow communities;

- **1 atm·cc/s ≈ 1.013 mbar·L/s** — semiconductor literature mostly uses atm·cc/s; it can be read as mbar·L/s directly, with the difference absorbed in rounding.

g/y is a special dialect: it is a **mass flow**, whose conversion to pV flow depends on the molar mass of the medium:

$$Q\,[\mathrm{g/y}] = Q\,[\mathrm{mbar\cdot L/s}] \times \frac{365 \times 86400}{22.413 \times 10^3} \times \frac{273}{273+t} \times \frac{m}{1.013} \tag{2-2}$$

m — molar mass (g/mol); t — temperature (°C); 22.413 L/mol is the standard molar volume; the 273/(273+t) factor corrects the volume from t °C to 0 °C; 1.013 converts mbar to atm. For R134a (m = 102 g/mol): 1 mbar·L/s ≈ 1.3×10^5 g/y, i.e. 1 g/y ≈ 7.6×10^{-6} mbar·L/s — thus the "a few grams per year" regulatory language of the refrigeration industry connects with the "10^{-5} ~ 10^{-6} class" technical language of the vacuum industry.

2.3 Magnitude Intuition: Anchoring Leak Rates to Time

Numbers alone build no intuition; time does. How long does a leak of a given rate take to leak one standard cubic centimeter (1 std.cc ≈ 1 mL of gas at 0 °C, 1 atm)?

Table 2-2 Time for one std.cc to escape at various leak rates (fastest mental anchor)

Leak rate / mbar·L/s	Time for 1 std.cc	Typical scenario
10^{-2} ~ 10^{-3}	~100 s ~ 17 min	Coarse air-tightness check, large-flow MFC calibration
10^{-4} ~ 10^{-5}	2.8 h ~ 1.16 days	Battery cases, A/C lines — the industrial main battlefield
10^{-5} ~ 10^{-6}	1.16 ~ 11.6 days	High-sealing relays, compressor assemblies
10^{-7} ~ 10^{-8}	116 days ~ 3.2 years	Hermetic packages, sensor cavities
10^{-9} ~ 10^{-10}	3.2 ~ 32 years	UHV devices, space components
10^{-11} ~ 10^{-13}	320 years ~ 320,000 years	Metrology class: reference calibrated leaks, extreme-sealing verification

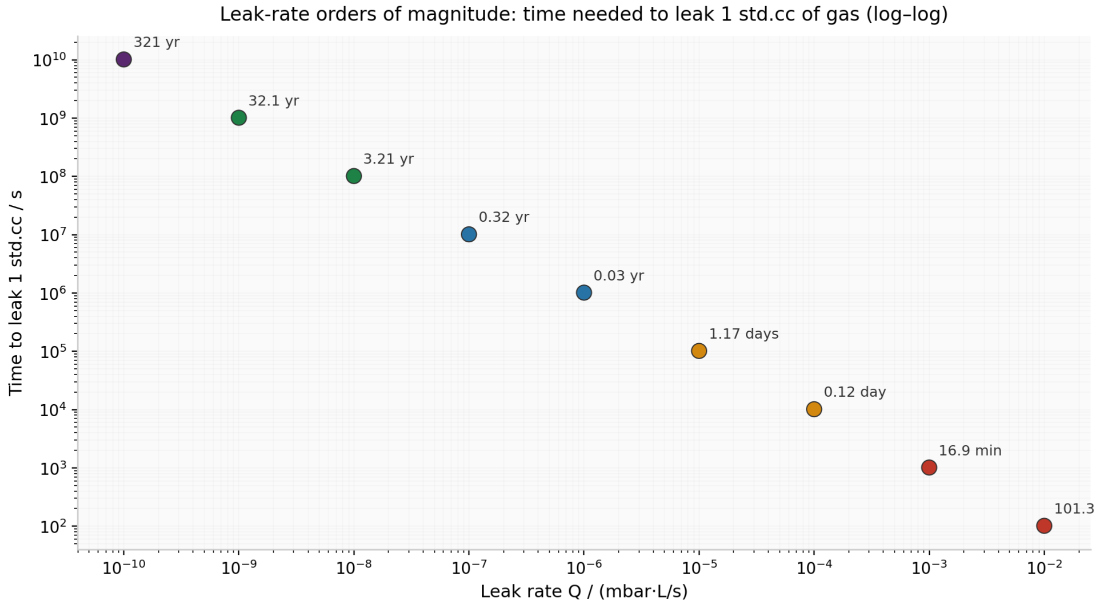

Figure 2-1 Time for one std.cc to escape at each leak-rate order of magnitude (log–log)

Three intuitions to carry away: ① each order of magnitude is a tenfold world — the difference between 10^{-5} and 10^{-6} is not 10%, but ten times the time; ② everyday language is misleading — a "slight leak" of 10^{-3} is a hundred billion times a "metrology-class leak" of 10^{-13}; ③ **small leaks do not mean small risk**: a 3.5×10^{-6} mbar·L/s hydrogen calibrated leak releases only ~0.3 mL of hydrogen per day, far below any combustion-concern threshold — magnitudes must be discussed together with gas species and environment.

2.4 Reading Certificates: Vacuum vs Atmosphere Outlet, Gauge vs Absolute Pressure

Two pairs of conditions on a certificate change the numerical value of the "same" leak; they are the most frequent sources of field disputes.

First pair: vacuum outlet vs atmosphere outlet. The same channel into vacuum (outlet ≈ 0) vs into atmosphere (outlet ≈ 1 atm) gives different rates — in molecular flow the difference is small (rate ∝ Δp: 11 bar vs 10 bar, about 10%); in viscous flow it can be large (rate $\propto p_1^2 - p_2^2$: $11^2 - 1^2$ vs $11^2 - 0$, about 0.8% at 11 bar, but 25% at 2 bar). Certificates must state the outlet condition; between the two ratings, use the flow-regime formulas of Chapter 3 to convert, never "approximately the same."

> **Rule 2-1:** For any reading with the outlet to atmosphere, first check the inlet absolute pressure. With inlet above ~10 bar absolute (~9 bar gauge), viscous-flow differences between the two outlet ratings stay within 1%; in low-pressure scenarios (e.g. 2 bar absolute) they can exceed 25%. Before comparing numbers from two certificates, align gas species, inlet pressure, outlet condition and temperature — all four.

Second pair: gauge vs absolute pressure. Field pressure gauges read gauge pressure; physical formulas use absolute pressure. A part tested at 20 kPa gauge is at ~121 kPa absolute; a 1% error in absolute pressure terms is not 0.2 kPa but 1.2 kPa. All calculations in this book use absolute pressure; all field settings must add one atmosphere (~101.3 kPa) before use.

2.5 Flow-Rate Units and Temperature Reference: sccm Is Not ccm

The MFC and calibration communities distinguish "standard-state volume flow" (sccm: volume per minute reduced to 0 °C, 1 atm) from "actual volume flow" (ccm: at actual temperature and pressure). They differ by the temperature/pressure correction factor: 1 ccm measured at 23 °C equals ~0.92 sccm. Certificate conversions and calibration-system settings must state the reference temperature — the default in this book is 0 °C (273.15 K), and 23 °C measurements are explicitly marked when used.

2.6 Three Deadly Misconceptions

Misconception 1: treating mbar·L/s as "hole diameter." The same 10^{-5} mbar·L/s may correspond to completely different physical channels for different gases, pressures and structures — leak rate is a transport capability, not a geometric size (§1.4).

Misconception 2: converting between gases with one fixed factor. The truth: in molecular flow Q(He) ≈ 2.65 × Q(air) (light molecules leak faster, the 1/√M law of Eq. 3-3), while in viscous flow Q(air) ≈ 1.06 × Q(He) (inverse viscosity ratio, Eq. 3-2) — the two factors, 2.65 and 0.94 (= 1/1.06), differ by nearly a factor of three and point in *opposite* directions. Gas-conversion factors depend on the flow regime, which depends on pressure and orifice size — see §3.6; this is the most underestimated pit in the industry.

Misconception 3: comparing certificate values without conditions. Two certificates both saying "1×10^{-5} mbar·L/s" may differ by tens of percent in actual behavior if one is vacuum-outlet He and the other atmosphere-outlet N_2 — the four conditions (gas, inlet pressure, outlet, temperature) must be aligned before comparison (Rule 2-1).

2.7 Summary

- Leak rate is pV per unit time: 1 Pa·m³/s = 10 mbar·L/s ≈ 9.87 atm·cc/s, and 1 mbar·L/s ≈ 59.2 sccm;
- g/y is a mass-flow dialect requiring molar-mass conversion (Eq. 2-2);
- Magnitude intuition: time for one std.cc — 10^{-5} ≈ 1 day, 10^{-9} ≈ 3 years;
- Certificates are read against four conditions: gas, inlet pressure, outlet, temperature — vacuum/atmosphere outlet and gauge/absolute pressure are the two most common traps;
- Gas conversion depends on flow regime (He 2.65× vs air 1.06×, opposite directions) — full treatment in Ch. 3.

With the language in place, the next chapter opens the leak itself: what determines its output — the three flow regimes, and the temperature effects that quietly rewrite the numbers.

Chapter 3 Physics Inside a Leak: Three Flow Regimes and Temperature Effects

> **What this chapter answers:** what actually happens to gas inside a leak channel; why the same leak gives different numbers under different pressures, gases and temperatures; and why "temperature coefficient" is the first hard indicator distinguishing leak technologies. This chapter is the physical foundation of the whole book.

3.1 One Number Divides Three Worlds: The Knudsen Number

Gas flowing through a microchannel exhibits three completely different personalities, depending on the ratio of the molecular mean free path λ (the average distance a molecule travels between collisions) to the characteristic channel size d — the **Knudsen number** Kn = λ / d:

$$Kn = \frac{\lambda}{d}, \qquad \lambda \approx \frac{68\ \text{nm}}{p\ [\text{atm}]}\ (\text{air}, 23\ ^\circ\text{C}) \tag{3-1}$$

- **Kn ≪ 1 (viscous flow)**: molecules collide mostly with each other; gas behaves as a continuous fluid, "squeezed" through by pressure, following Poiseuille's law;
- **Kn ≫ 1 (molecular flow)**: molecules collide mostly with the walls; each molecule passes independently, with no collective behavior;
- **0.01 < Kn < 1 (transitional flow)**: both mechanisms coexist; the hardest to compute and the most error-prone region in engineering.

Concrete feel: for a leak with d = 5 μm at 1 atm inlet, Kn ≈ 0.014 (viscous side); pump the inlet down to 100 Pa and λ grows a thousandfold, Kn ≈ 13 (molecular side). **The same physical leak may switch flow regimes as operating pressure changes — this is the physical root of "numbers that don't match" when rating conditions differ** (echoing Rule 2-1). For extremely fine channels of 50 nm, the flow is already molecular even near atmospheric pressure.

3.2 Viscous Flow: Q ∝ ($p_1^2 - p_2^2$), Sensitive to the Fourth Power of Diameter

$$Q_{\text{vis}} = \frac{\pi d^4}{256 \eta L} \left(p_1^2 - p_2^2\right) \tag{3-2}$$

d — channel diameter; L — length; η — gas viscosity; p_1, p_2 — inlet / outlet absolute pressures.

Three engineering corollaries: ① **d^4 sensitivity** — a 1% change in diameter shifts the rate by 4%; this is the fundamental difficulty of making stable leaks, and the reason metal-crushed and drawn-glass processes struggle with consistency; ② rate depends on the **pressure difference of squares** — doubling inlet pressure nearly quadruples the rate, which is why rating pressure must be pinned down; ③ rate is inversely proportional to viscosity η — for the same channel, gases with higher viscosity (air 18.5 μPa·s) leak *slower* than lower-viscosity hydrogen (8.9 μPa·s), and helium (19.6 μPa·s) leaks slowest of the three.

3.3 Molecular Flow: Q ∝ Δp / √M, Light Molecules Run Faster

$$Q_{\text{mol}} = \frac{\pi d^3}{12L}\bar{v}\,(p_1 - p_2), \qquad \bar{v} \propto \sqrt{\frac{T}{M}} \tag{3-3}$$

$\bar{v}$ — mean molecular thermal speed; M — molar mass; T — absolute temperature.

Key corollary: in molecular flow the rate is inversely proportional to √M — **for the same channel, the smaller the molecular mass, the faster the leak**. He (M = 4) vs N_2 (M = 28): the molecular-flow rate ratio is √(28/4) ≈ 2.65. This is the physical reason helium is the premier tracer gas: for the same defect, the helium signal is 2.65 times the air signal (and its background in air is only 5.2 ppm, so the signal-to-noise ratio is overwhelming). Note the d^3 scaling here (vs d^4 in viscous flow): geometry matters differently across regimes — the basis of the "process yardsticks" in Chapter 4.

3.4 Transitional Flow: Add the Two, Never Use Just One

$$Q_{\text{total}} = Q_{\text{vis}} + Q_{\text{mol}} \times Z(Kn) \tag{3-4}$$

Z(Kn) — a transition correction factor (empirical form, e.g. the Knudsen interpolation); in engineering it is often sufficient to add the two components directly and validate against measurement.

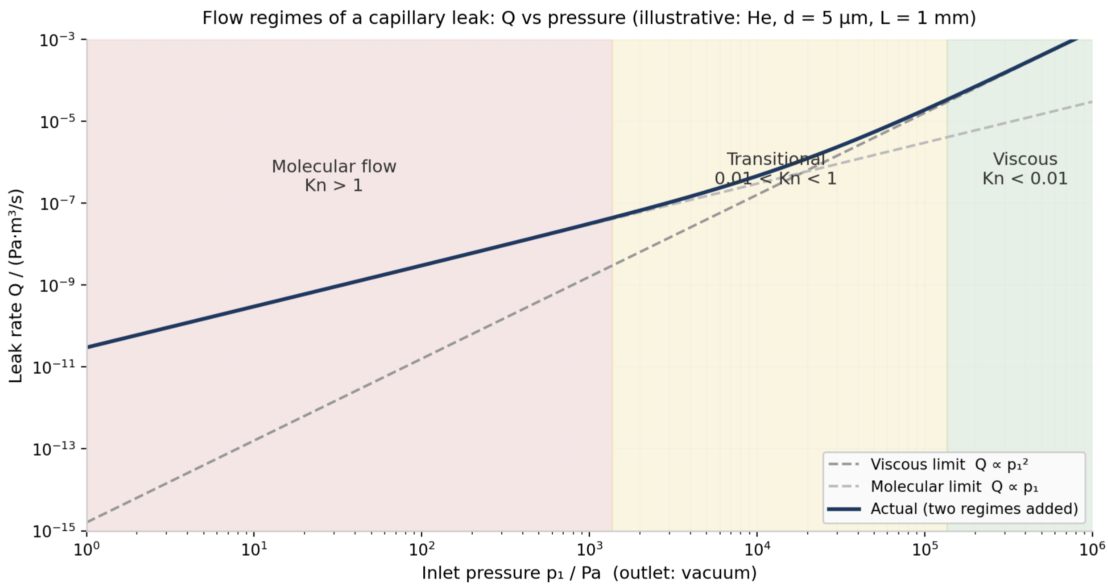

Figure 3-1 Flow regimes of a capillary leak and the Q–p relation: in the transitional region the actual rate (solid) sits above both single-regime limits

The danger of the transitional region: the apparent "pressure exponent" drifts between 1 and 2, and gas-conversion factors lie between the viscous and molecular limits without a universal value. Whenever you see "rate vs pressure is neither linear nor quadratic," you are in the transitional region — at that point, **only a full-range calibrated leak, or a computational model validated by full-range data, can give trustworthy ratings**. RealMeter's RMI-Cal™ conductance-simulation engine is built on precisely this class of models (Ch. 13).

3.5 Temperature Effects: Three Mechanisms, Three Personalities

Temperature is the invisible hand that rewrites leak rates daily. The three structural families behave completely differently:

Table 3-1 Temperature sensitivity of the three leak families (first-order)

Family	Dominant mechanism	Typical tempco	Engineering consequence
Channel-type (molecular flow)	Molecular thermal speed $\bar{v} \propto \sqrt{T}$	≈ +0.17 %/°C (theoretical, Eq. 3-5)	Nearly negligible in general industry
Channel-type (viscous flow)	Gas viscosity η rises with T	≈ −0.24 ~ −0.6 %/°C	Matters in precision calibration
Permeation (quartz membrane)	Arrhenius permeation activation	≈ +3 ~ +4 %/°C	5 °C swing = 20% drift; temperature control mandatory

$$\frac{1}{Q}\frac{dQ}{dT}\Big|_{\text{mol}} = \frac{1}{2T} \approx +0.17\ \%/\text{K}\ (T = 296\ \text{K}) \tag{3-5}$$

$$\frac{1}{Q}\frac{dQ}{dT}\Big|_{\text{vis}} = -\frac{1}{\eta}\frac{d\eta}{dT} \approx -0.24\ \%/\text{K (theoretical floor for air at 296 K)} \tag{3-6}$$

$$Q_{\text{perm}} = Q_0 \exp\left[-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \Rightarrow \text{ typically } +3 \sim +4\ \%/\text{K} \tag{3-7}$$

Eq. (3-6) is the theoretical lower bound for viscous flow; with structural corrections, real metal-channel leaks measure about −0.6 %/°C. Eq. (3-7) is the Arrhenius form for permeation: Ea — activation energy.

The engineering conclusion writes itself: **temperature coefficient is the sharpest single indicator separating leak technologies.** A production floor without climate control swings ±5 °C day and night: a permeation leak drifts ±20%, while a metal-channel leak drifts less than ±1% (viscous) or ±0.85% (molecular) — whether a daily OK / NG judgment needs temperature compensation depends entirely on this number. This is why the selection chapter (Ch. 12) makes "tempco ≤ 0.2 %/°C" a hard threshold for line duty.

3.6 Gas Conversion: One Table, Two Regimes

The rigorous answer to Misconception 2 of §2.6 — rate ratios between gases for the same channel (using He → N_2 and He → H_2 as examples):

Table 3-2 Gas conversion factors for the same channel in the two limiting regimes

Conversion	Molecular flow (1/√M)	Viscous flow (η ratio)	Note
He → N_2 (air)	× 0.38 (÷ 2.65)	× 1.06	Directions opposite; transitional region in between

He → H_2	× 0.71 (÷ 1.41)	× 2.2	Hydrogen testing needs regime confirmation even more

Rule 3-1: Never convert between gases with a single fixed factor. Determine the flow regime from the rating pressure and channel size first (Eq. 3-1); use the table factors at the two limits, and use a superposition model or measured calibration in the transitional region. Any helium-to-hydrogen conversion must be validated by experiment.

3.7 Liquid-Medium Leaks: Evaporation–Transport, Not Flow

Water, dodecane, DMC and other liquid-media "leaks" do not flow — the liquid evaporates at the channel inlet, vapor is transported along the channel, and condenses at the outlet. The rate depends on saturated vapor pressure and channel conductance, and is far more temperature-sensitive (the vapor-pressure curve is steep): dodecane runs ~12 %/°C, so a ±0.5 °C temperature-control error alone means ~6% rate drift. Such leaks are mainly used for liquid-cooling-plate and refrigerant-circuit simulation; Ch. 6 (§6.5) and Ch. 9 (§9.5) discuss their rating and use.

3.8 Decay of Reservoir-Type Leaks: An Exactly Computable Loss

A reservoir-type (self-contained) leak is a small gas tank leaking through a calibrated channel: as gas leaves, pressure falls, and the rate falls with it — this is "decay," not a fault but an inherent property. With initial rate Q_0, reservoir pressure p and volume V:

$$\text{Relative annual decay} \approx \frac{Q_0}{pV} \times 3.15 \times 10^7\ \text{s} \quad (3\text{-}8)$$

$$\text{Molecular flow (Q} \propto \text{p):} \quad Q(t) = Q_0\, e^{-t/\tau},\ \tau = \frac{pV}{Q_0}\ \ \text{(exponential)} \quad (3\text{-}9)$$

$$\text{Viscous flow (Q} \propto \text{p}^2\text{):} \quad Q(t) = \frac{Q_0}{(1 + t/\tau)^2}\ \ \text{(hyperbolic)} \quad (3\text{-}10)$$

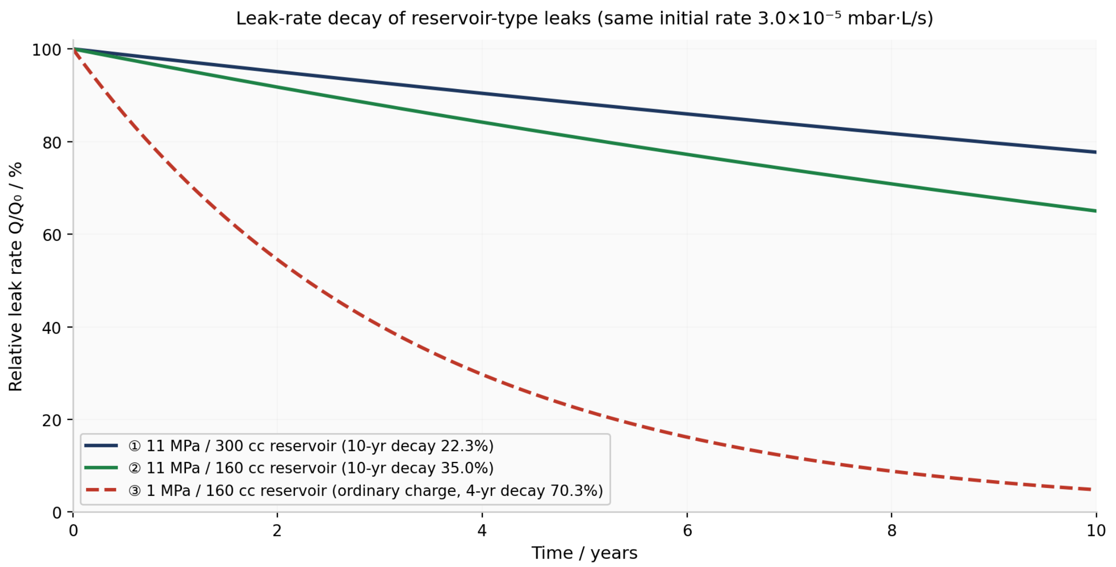

Figure 3-2 Decay of three reservoir configurations at the same initial rate: raise charge pressure and enlarge the volume — decay can be designed down by an order of magnitude

Reading the figure: ① 11 MPa / 300 cc — only 22.3% decay in ten years; ② 11 MPa / 160 cc — 35.0% in ten years; ③ 1 MPa / 160 cc (ordinary charge) — 70.3% gone in just four years. **Decay is not destiny; it is design** (the day-by-day iteration behind this figure is equivalent to the closed-form solutions of Eqs. 3-9 / 3-10): high-pressure charging and enlarged volume push annual decay below 3%, satisfying the JJF 1833—2020 stability requirement; low-pressure small-volume products are disqualified at birth. When choosing a reservoir leak, ask for the decay-curve calculation before the certificate (Ch. 12).

3.9 Summary

- Kn = λ/d divides three regimes: viscous (d^4, Δp^2, η-dependent), molecular (d^3, Δp, $1/\sqrt{M}$), transitional (superposition, no universal conversion factors);
- The same leak switches regimes with pressure — the physical root of mismatched ratings across conditions;
- Tempco: molecular +0.17 %/°C, viscous ≈ −0.6 %/°C, permeation +3~4 %/°C — the sharpest separator of technologies;
- Gas conversion: He 2.65× faster than air in molecular flow, 6% slower in viscous flow — determine the regime first (Rule 3-1);
- Reservoir-leak decay is computable (Eq. 3-8~3-10): high pressure + large volume is the only way to keep annual decay under control.

With physics in hand, Part II uses this yardstick to measure every process route in the industry: who can make stable channels, and who cannot.

PART II

Principles | Understanding the Processes

Chapter 4 The Full Process Spectrum of Calibrated Leaks

> **What this chapter answers:** what process routes exist in the industry, and the physical principle, capability boundary and failure mode of each. This chapter evaluates no vendor — it only measures every process with the physical yardsticks of Chapter 3. After reading, you will understand why some leaks are "fragile and precious," while others can be dropped, frozen, and worked at 40 MPa.

4.1 Four Physical Yardsticks for Judging a Process

Chapter 3 told us that a leak's macroscopic behavior is governed by four physical quantities. To judge any process, simply ask how well it controls these four:

Table 4-1 Four physical yardsticks: from formulas to process metrics

Yardstick	Formula origin	Corresponding engineering metric
Orifice d (and its consistency)	Eq. (3-2): $Q \propto d^4$; Eq. (3-3): $Q \propto d^3$	Rate tolerance, batch consistency, customizability
Channel regularity	Ideal circular-tube assumption	Directionality, clog resistance, computability
Material & seal background	Permeation, adsorption, outgassing	Minimum achievable rate, media purity, tempco
Structural strength	Pressure, shock, thermal cycling	Pressure rating, drop resistance, temperature range, lifetime

The orifice item deserves quantification. From $Q \propto d^4$, the relation between rate tolerance and orifice tolerance:

$$\frac{\Delta Q}{Q} = 4\,\frac{\Delta d}{d} \quad \Rightarrow \quad \pm 10\% \text{ rate tolerance requires } \pm 2.4\% \text{ orifice tolerance; } \pm 20\% \text{ req} \tag{4-1}$$

For a 5 μm orifice, ±2.4% means diameter control within ±120 nm. **Leak manufacturing is, at its core, a contest of sub-micron geometric control** — every process difference below ultimately lands on this point.

4.2 Drawn-Glass Capillary: The First-Generation Mainstream

Principle: a glass tube is fused with a metal wire (or glass rod) and drawn thin; the micro-gap formed by the differential thermal expansion of glass and metal on cooling serves as the leak channel. **Capability:** typical rates $10^{-4} \sim 10^{-7}$ mbar·L/s, pressure generally < 1 MPa. **Failure modes:** first, the gap is an annular taper rather than a circular tube — orifice varies along the axis, forward and reverse conductance differ, i.e. the rate is **directional** (§4.9, §5.4); second, glass brittleness means it fears drops, freezing and pressure shocks, with short field life; third, the gap geometry is not designable — target rates are achieved by "draw a batch, measure a batch, pick a few," with consistency left to luck.

4.3 Crushed-Metal: Simple but Uncontrollable

Principle: a fine metal tube (or metal foil sandwiching a wire) is repeatedly crushed, measured, crushed again, until the rate falls into the target band. **Capability:** typical rates 10^{-1} ~ 10^{-6} mbar·L/s, pressure generally < 2 MPa. **Failure modes:** the crushed channel is a crescent-section product of trial and error — directional as well; metal creeps slowly under stress, so the rate drifts over time; die wear translates directly into batch variation. Its merits are low cost and large rates, so it survives in coarse testing — but "adjustable, computable, reproducible" is out of the question.

4.4 Quartz Permeation Membrane: The Old King of Tiny Leaks

Principle: small molecules such as He undergo a "dissolve–diffuse–desorb" permeation through quartz glass; the rate is set by membrane area and thickness. **Capability:** can reach 10^{-9} ~ 10^{-12} class — long the mainstream choice for built-in calibration leaks of helium detectors. **Failure modes:** first, tempco as high as ~ +4 %/°C (the Arrhenius mechanism of Eq. 3-7): a 5 °C workshop swing means ~20% drift, so a temperature-correction table is mandatory; second, the differential pressure across the membrane is limited (the membrane is the weak point) and glass is brittle; third, **the medium is locked** — only small molecules like He and H_2 permeate; N_2, Ar, refrigerants and mixtures are all excluded; fourth, quartz permeation of He is itself a ~10^{-10} atm·cc/s "background" — going smaller means drowning in your own background (§5.2).

4.5 Powder-Sintered and Porous Media

Principle: metal or ceramic powder is sintered into a porous body; conductance comes from the statistical average of a vast number of parallel micro-pores. **Capability:** suits larger rates of 10^{-1} ~ 10^{-4}, decent pressure tolerance. **Failure modes:** wide pore-size distribution — consistency is statistical, not geometric; the huge internal surface area makes **adsorption / desorption significant** (§5.3), so humidity and contamination slowly drift the rate; cannot scale down across orders of magnitude.

4.6 Critical-Flow Nozzle: A Special Solution for Large Flows

Principle: when the downstream/upstream pressure ratio falls below the critical ratio (~0.528 for air), the throat reaches sonic speed; flow depends only on upstream pressure and throat area, independent of downstream. **Capability:** the correct solution for large-flow (sccm to L/s) gas-flow standards, widely used in MFC calibration. **Failure modes:** requires a sufficient pressure ratio to stay "critical" — fails at low pressure differences; cannot be made small; sensitive to upstream cleanliness. It is a flow-metrology device rather than a leak-testing standard — a distant cousin of this book's protagonist.

4.7 MEMS Etching: A Semiconductor-Mindset Attempt

Principle: microchannels are photolithographically etched into a silicon wafer and bonded into a package. **Capability:** geometrically controllable and batch-replicable in principle — a hot direction in academia and startups. **Failure modes:** silicon brittleness and the sealing background of anodic glass bonding limit pressure rating and minimum rate; adhesives and solders in packaging introduce outgassing and permeation; batch-to-batch consistency and long-term stability data remain insufficient. A direction worth watching, but the road "from wafer to production-line yardstick" is not yet finished.

4.8 Metal-Based Microchannel: Turning Leaks from "Craft" into "Design"

The six processes above share a common fate: **the rate is a result "made, then measured," not a design "computed, then built."** The metal-based microchannel process (RealMeter RMI-MTC™) inverts the logic: geometrically defined circular microchannels are machined directly into a metal body (orifice continuously controllable from 50 nm to 200 μm); target diameter and length are computed from the conductance formulas (Eq. 3-2, 3-3, 3-4) first, then built to the drawing. Measured against the four yardsticks:

1. **Orifice and consistency:** geometry is a design value; rate tolerance starts at ±10%, available at ±5% or tighter on request (the ±2.4% orifice tolerance of Eq. 4-1 is routine for CNC machining) — batch consistency no longer depends on selection;
2. **Channel regularity:** near-ideal circular tube ⇒ **no directionality**, clog-resistant (no throttling throat in a uniform bore), computable across all regimes;
3. **Material background:** metal body + all-metal sealing (permeation < 10^{-15} atm·cc/s, §5.2) — no organic materials introduced;
4. **Mechanical strength:** monolithic metal structure ⇒ passive leaks rated to 40 MPa, passing a 1.2 m × 5-cycle drop test, operating temperature −20 ~ +65 °C[3].

The result is a combination no traditional process can achieve simultaneously: **all leak rates (100 mL/s ~ 10^{-13} Pa·m³/s) × all pressures (0.1 Pa ~ 40 MPa) × all media (any non-corrosive gas / mixture / liquid) × rate and specified pressure customized together**. This is not leadership in any single metric — it is a generational change across all four yardsticks.

4.9 Comparison of the Seven Processes

Table 4-2 Process spectrum comparison (typical magnitudes, for selection reference)

Process	Rate range / mbar·L/s	Pressure limit	Tempco	Directionality	Media	Inherent limitation
Drawn-glass	10^{-4} ~ 10^{-7}	< 1 MPa	~ ±0.3 %/°C	Yes	General, contamination-sensitive	Gap not designable; fragile
Crushed-metal	10^{-1} ~ 10^{-6}	< 2 MPa	~ ±0.5 %/°C	Yes	General	Trial-and-error; creep drift
Quartz permeation	10^{-9} ~ 10^{-12}	< 0.2 MPa class	~ +4 %/°C	No (permeation)	He / H_2 only	Large tempco; locked medium; fragile membrane

Powder-sintered	10^{-1} ~ 10^{-4}	~ 5 MPa	~ ±0.8 %/°C	No	General, humidity-sensitive	Statistical consistency; adsorption drift
Critical-flow nozzle	Large-flow only	~ 20 MPa	~ ±0.3 %/°C	No	General	Needs pressure ratio; not a leak standard
MEMS-etched	10^{-6} ~ 10^{-9} class	< 1 MPa	~ ±0.3 %/°C	No	Packaging-limited	Packaging background; strength; limited track record
Metal microchannel	**10^{2} ~ 10^{-13} (all)**	**40 MPa**	**+0.1 %/°C (mol.) / −0.6 %/°C (visc.)**	**No**	**All media**	——

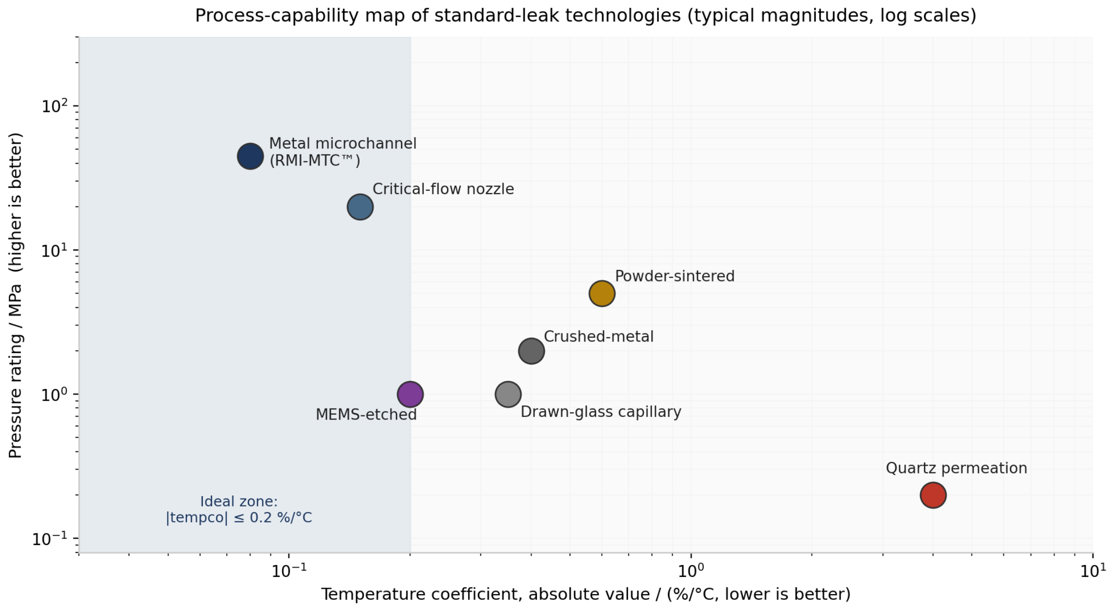

Figure 4-1 Process-capability map: temperature coefficient (lower left is better) × pressure rating (higher is better)

How to read the map: the further left (small tempco) and the further up (high pressure rating), the stronger the process. The seven processes stratify naturally — this is not any vendor's marketing conclusion but a direct corollary of Chapter 3 physics: tempco is set by flow regime and material mechanism; pressure rating is set by structure and sealing.

> **Rule 4-1 (one-minute test for true microchannels):** Reverse-mount the leak and re-measure at the same pressure difference. An ideal circular tube has strictly equal forward and reverse conductance; drawn-glass and crushed-metal channels, being geometrically asymmetric, must show a difference. **Non-directionality is the simplest and hardest-to-fake fingerprint of the microchannel process.**

4.10 Summary

- Four yardsticks suffice to judge any process: orifice control (d^4/d^3), channel regularity, material background, mechanical strength;
- The shared fate of the six traditional processes is "rate by trial and selection"; the essence of microchannel is "rate by design, computation and replication";
- Tempco and pressure rating are products of physical mechanism, not of marketing;
- The bidirectional rate-equality test is a one-minute criterion for identifying ideal circular channels.

Process determines a leak's "nature"; the next chapter discusses its "nurture": clogging, background, adsorption, creep — every enemy a leak faces over its lifetime.

Chapter 5 Lifetime Physics of Leaks

> **What this chapter answers:** why a calibrated leak "dies" — the physical causes of rate drift, abnormal readings and total failure — and how to engineer a ten-year lifetime from both design and usage ends. §3.8 covered reservoir-leak decay; this chapter covers the remaining lifetime threats — seal background, adsorption/outgassing, directionality, mechanical/thermal damage (the mechanism and defense of clogging are folded into the §5.1 list and §5.6) — closing with a "failure mode × process route" matrix that maps every route's spectrum of deaths.

5.1 The Threat List: Five Ways a Leak Dies

Table 5-1 Overview of lifetime threats

Threat	Physical mechanism	Macroscopic symptom	Defense strategy
Decay (reservoir)	Finite stored pV; decay rate Q/(pV) (Eq. 3-9/3-10)	Rate slowly declines year by year	High pressure + large volume; refill or replace; passive design eliminates it
Clogging	Particles wedge and self-lock at a throat (tapered / crushed throats have one naturally); oil mist and water vapor form Kelvin-condensed liquid bridges (the smaller the pore, the easier the dew)	Rate drops sharply or vanishes	Uniform bore without a throat + inlet interception; clean, dry gas (defense at both ends: §5.6)
Seal background	Seal permeation / micro-leaks superimposed on nominal rate	Tiny rates unmeasurable, unmakeable	All-metal sealing (§5.2)
Adsorption / outgassing	Desorption of surface layers forms a "phantom leak rate"	Inflated readings, slow background recovery	Low-surface-energy materials, bakeout, short paths
Mechanical / thermal damage	Drops, vibration, freeze–thaw, pressure shock	Abrupt geometry or seal change; rate jumps	Monolithic metal structure; wide-temperature verification

In reading this list, one classification axis matters more than the count of five — **classify by where the cause of death resides**. On one side is **external intrusion**: particles and liquid films breaching the filter element from outside — triggered at the usage end, the only death the user can actively defend against. On the other side is **endogenous failure**: causes written into the genes of material and geometry, which no amount of careful usage can rewrite. Endogenous failure falls into two families — **endogenous clogging** (the material "grows" its own blockage: progressive oxide narrowing, surface poisoning of the permeation interface, pore creep, spalling aging products) and **structural destruction** (fracture, relaxation-springback, thermal instability — rewriting the rate directly or through distortion). In field statistics, about 90% ~ 99% of conventional-process failures belong to these two endogenous families (the §5.6 matrix unfolds along this axis); external intrusion is only the small remainder. Recognizing this axis tells you, in every section that follows, whether a "defense strategy" belongs at the design end or the usage end.

5.2 Seal Background: Who Drowned 10^{-12}

Making a channel-type leak nominally rated 10^{-12} atm·cc/s: the real difficulty is not "making such a small channel" but "proving that the measured 10^{-12} comes entirely from the channel itself." A leak's total output is the channel rate plus system background:

$$Q_{\text{meas}} = Q_{\text{channel}} + Q_{\text{seal permeation}} + Q_{\text{interface micro-leak}} + Q_{\text{outgassing}} \tag{5-1}$$

Engineering rule (same SNR logic as Ch. 3): **the sum of all background terms should be below 1/10 of the nominal rate**. Self-permeation magnitudes of common sealing schemes:

Table 5-2 Typical self-permeation of sealing schemes

Sealing scheme	Self-permeation / atm·cc/s	Leak lower limit (10:1 rule)
Epoxy / resin bonding	~ 10^{-9}	10^{-8}
Elastomer (O-ring / gasket)	~ 10^{-8} ~ 10^{-7}	10^{-7}
Quartz-glass package (He permeation)	~ 10^{-10}	10^{-9}
All-metal fused sealing (RMI-Metal™)	< 10^{-15}	10^{-14} class with margin

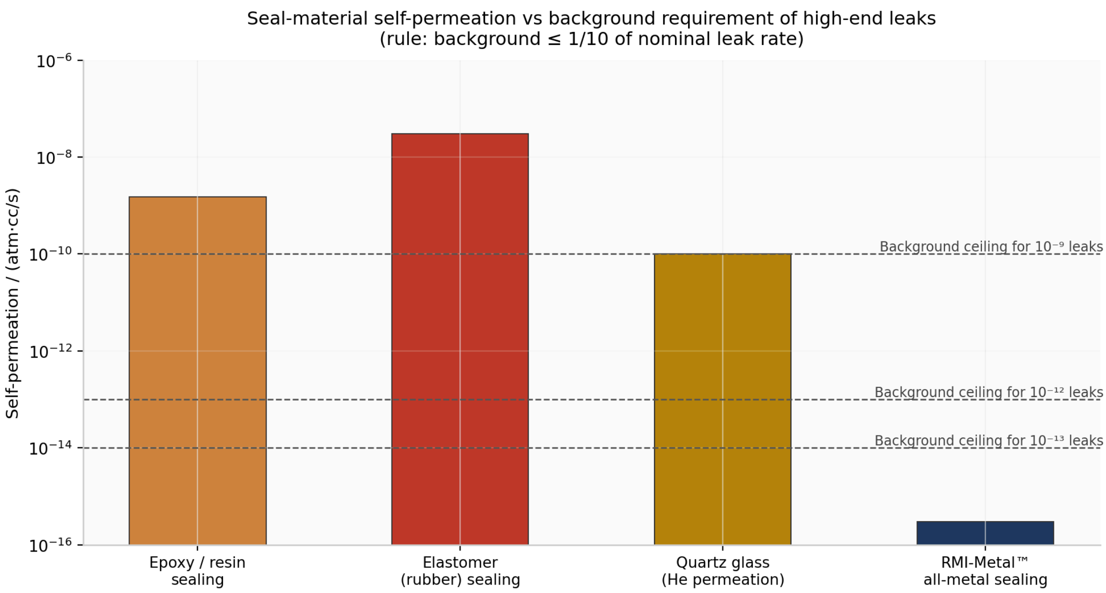

Figure 5-1 Seal-material self-permeation vs the background requirement of high-end leaks

This figure explains an industry fact: **why channel-type He leaks of 10^{-11} ~ 10^{-13} Pa·m³/s (10^{-10} ~ 10^{-12} mbar·L/s) were long available only as permeation membranes** — not because channels couldn't be made, but because conventional seals (10^{-9} ~ 10^{-10}) sit exactly in that range and drown the channel signal. Every order of magnitude the seal background is pushed down unlocks one more order of magnitude in the leak's lower limit.

That is why the figure "all-metal sealing < 10^{-15} atm·cc/s" (5~6 orders of magnitude ahead of conventional sealing[3]) is the entry ticket to high-end leaks — and the premise on which the $10^{-11}/10^{-12}/10^{-13}$ series of Chapter 13 can exist.

5.3 Adsorption and Outgassing: The Invisible "Phantom Leak"

Every solid surface exposed to gas carries an adsorbed molecular layer. An order-of-magnitude estimate: one monolayer on 1 cm² holds ~10^{15} molecules, i.e. a gas quantity of:

$$pV = Nk_{\mathrm{B}}T \approx 10^{15} \times 1.38 \times 10^{-23} \times 296 \approx 4 \times 10^{-6}\ \mathrm{Pa \cdot m^3} \ = \ 4 \times 10^{-3}\ \mathrm{Pa \cdot L} \quad (5\text{-}2)$$

These molecules desorb slowly under vacuum, acting as a "phantom leak": for a 10 L vacuum system targeting a 10^{-6} Pa background, full desorption of just 1 cm² of monolayer raises the pressure by 4×10^{-4} Pa — an overshoot of ~400× (more than two orders of magnitude). This is the daily reality of RGA / UHV work: **the biggest "leak" in the system is often not a leak at all, but a surface**. The defense strategy follows directly:

Defense therefore follows directly:

- **Materials:** no adhesives, no polymer seals; all-metal construction plus electropolishing to cut specific surface area;
- **Structure:** valve and leak integrated into one body, eliminating assembly interfaces (every interface is a pocket that traps gas);
- **Usage:** bake out UHV systems; pre-evacuate a calibrated leak before connection so the atmospheric adsorbed layer is not carried in.

Adsorption has a subtler incarnation: **stratification and memory in gas mixtures** — heavy components adsorb into and release from organic seals and dead corners at different rates than light ones, so a mixture leak's output composition drifts over time. This is the same root as the "memory effect" of dead volume in §6.2.

5.4 Directionality: An Overlooked Authenticity Test

The conductance of an ideal circular tube depends only on geometry and flow regime, never on flow direction — mounted forward or reversed, the rate is strictly equal. Tapered gaps and crushed channels, being geometrically asymmetric (sudden contraction at the inlet, gradual expansion at the outlet), can differ by a visible ratio, in extreme cases by a factor of two. Directionality causes two practical harms:

- if calibration and use occur in different orientations, the rate is simply wrong;
- if a leak is accidentally reverse-mounted in the field, readings distort without any warning.

Directionality is therefore both a usage trap and a process touchstone (Rule 4-1): **equal bidirectional rates are the most direct and hardest-to-fake evidence of a "near-ideal circular tube."** Add this one action to acceptance inspection (measure forward, measure reversed): five minutes of cost, enormous information.

5.5 Mechanical and Thermal Damage: The Daily Violence of the Factory Floor

The difference between a laboratory leak and a production-line leak is that the latter lives amid vibration, drops, temperature swings and oil mist. The physical essence of damage is **geometric mutation**: channel cracks, loosened seal interfaces, displaced capillaries — each directly rewrites d or the seal background, and the rate jumps irreversibly. Mechanical tolerance must therefore be a design specification, not a usage caution:

- Monolithic metal structure (no adhesives, no glass) eliminates brittle failure modes at the root;
- Quantified verification: e.g. rate unchanged after a 1.2 m × 5-cycle drop test, unchanged after −20 °C snap freezing (Ch. 15 presents measured data and video references[3]);
- Wide-temperature design: operating −20 ~ +65 °C, tolerating −30 °C freezing, so the leak can follow the workpiece into real conditions rather than a greenhouse.

One account is often left out of the ledger: **the most dangerous outcome of structural destruction is not death but distortion**. A shattered glass leak is discovered and replaced the same day — an explicit failure costs one leak; but a channel leak that "works wounded" after geometric relaxation or micro-deformation does not stop breathing — it only quietly changes its rate, handing the line a wrong reference while looking healthy for months. Covert distortion corrupts every judgment the line makes (this is the microscopic mechanism of the "blind judging" in Ch. 10). In rating mechanical endurance, therefore, "survives the drop" is only the passing grade; "rate unchanged on re-measurement after the drop" is the full score — which is exactly why quantified verification (the previous item) must demand re-measurement data.

> **Rule 5-1:** To judge a leak's lifetime, don't ask "how long will it last" — ask four things: decay rate (Q/(pV)), anti-clog structure (is there a throat), seal background (how many orders of magnitude below the nominal rate), and mechanical verification (re-measured data after drop / freeze tests). The first two are computable; the last two are visible.

5.6 The Failure Matrix: A "Map of Deaths" for Four Process Routes

Overlaying Chapter 4's process routes with this chapter's failure mechanisms yields a complete failure matrix. Three reading conventions first:

- **Filter elements are a constant, not a variable:** precision filtration (against dust and liquid) is standard across all processes and broadly equal in protective capability — it creates no differentiation. The differences lie only in "whether the channel itself is vulnerable" and "what other endogenous failures remain." Filter placement follows the contamination path: passive leaks are guarded at both ends; reservoir leaks, whose sealed reservoir leaves the outlet as the only ingress path, are guarded at the outlet only;
- **The denominator must be stated:** in field statistics, roughly 90% ~ 99% of conventional-process failures belong to **the two endogenous families — endogenous clogging and structural destruction** (including rate distortion and secondary clogging caused by structural destruction); external intrusion is the smaller share. Once microchannel construction structurally deletes the two endogenous families, the residual cause of death is almost solely "external contamination breaching the filter element." The two statements do not

contradict — their denominators differ: one is the failure composition of conventional processes, the other the residual composition after the microchannel reset;

- **This matrix disparages no process:** every route has its application window and its historical contribution. The matrix's value is making the full failure spectrum visible so that selection becomes an informed decision — the very premise of process improvement;
- **"Permeation leaks don't clog" is only half true:** a permeation membrane has no through-channel — helium dissolves into the glass and diffuses through the bulk — so particle clogging simply has no site to occur (matrix row 1); that has been the scheme's founding merit for decades. But backstreaming pump oil and hydrocarbon vapors film the membrane surface and rewrite helium solubility and the interfacial gradient — "surface poisoning," its equivalent way to die (row 3). Meanwhile, the "channel-type clogs easily" reputation belongs to the old throat-bearing processes (tapered gaps and crushed crescents carry a natural sharp throat where a particle self-locks) — a uniform circular bore has no throat, particles either pass or stop at the inlet face, and with filter elements, intrusive clogging has been downgraded to a low-probability, preventable event. In short: **channel types fear "particle clogging"; permeation types fear "surface poisoning" — both sides carry contamination sensitivity, only in different forms.**

Failure mode × process route matrix (immune / low / medium / high = leading cause of death)

Failure mode	Failure attribute	Permeation (glass membrane)	Drawn-glass capillary	Crushed-metal capillary	Microchannel (RMI-MTC™)
Particle clogging	External intrusion	**Immune** (no through-channel)	High (tapered throat self-locks)	High (crescent throat self-locks)	Low (throat-free + dual filters; preventable)
Liquid-film / oil-mist blockage	External intrusion	Medium (surface filming, see next row)	Medium (capillary condensation)	Medium (capillary condensation)	Low (filtered + bakeable)
Surface poisoning (permeation interface)	Endogenous clogging	**High** (films rewrite solubility)	—— (n/a)	—— (n/a)	—— (n/a)
Mechanical fracture (drop / torque / thermal shock)	Structural destruction	**High** (glass brittleness; leading killer)	**High** (glass brittleness)	Low	Low (monolithic metal; §15.2 data)
Thermal drift (in-use error)	Structural destruction (thermal instability)	High (3 ~ 4 %/°C, exponential)	Low (< 0.5 %/°C)	Low (~0.1 %/°C)	Low (0.1 %/°C, wide-temp verified)
Hysteresis / relaxation / memory	Structural destruction	High (helium memory in glass; sluggish switching)	Medium (asymmetric geometry)	High (cold-work relaxation)	Low (stable geometry; bidirectional identity)

Seal material / aging drift	Endogenous clogging + structural destruction	Medium (membrane aging)	Medium (package interfaces)	Medium (progressive oxidation clogging)	Low (all-metal seal < 10^{-15} atm·cc/s)

The defense of intrusive clogging has two ends. **Design end:** a uniform circular bore has no throat — a particle either passes through or is stopped at the inlet face (where a protective filter can sit); this is the geometric essence of "clog resistance." Dust/water protection at the inlet (e.g. a dust-and-water cap for vacuum duty) keeps interception outside the channel. Liquid-phase condensation obeys the same geometry — oil mist and water vapor condense capillarily inside micro-pores (Kelvin effect: the smaller the pore, the lower the saturation vapor pressure, the easier a liquid bridge forms), and a throat-free, bakeable structure makes it reversible. **Usage end:** filter and dry the gas supply (oil content < 0.01 mg/m³ class), avoid liquid carryover, seal ports during storage. A rule of thumb: **any leak that demands "handle with care, store at constant temperature, dedicated gas supply" is a leak whose unfinished design homework has been dumped on the user.**

The last column reveals a structural fact: the microchannel leak's failure modes **converge**. The whole family of endogenous failures — brittleness, thermal drift, hysteresis, seal aging — is physically deleted by the monolithic metal structure, uniform geometry and all-metal sealing, leaving almost a single residual cause of death: external contamination breaching the filter. The nature of death thereby changes: **conventional leaks mostly die of "illness" (failures written into their structural genes), while the microchannel leak can only be "killed" (contamination imported from outside)** — the weapon sits in the user's plumbing, not in the leak. High-volume after-sales data agree with this model: in production-line supply to leading battery-makers, the microchannel leak's field failure rate is 1 ~ 2 orders of magnitude below conventional processes, with service life several times longer — "long life" thus turns from a claim into a decomposable mechanism. One closing sentence: **a leak's leading cause of death is not "clogging" but "breaking" — endogenous clogging and structural destruction cannot be written into a usage procedure; they can only be written into the design drawings.**

5.7 Summary

- A leak dies in five ways: decay, clogging, background drowning, adsorption/outgassing, mechanical/thermal damage — each with a clear mechanism and defense;
- The first principle of clog defense is "uniform bore without a throat + interception outside the channel";
- The ceiling of tiny leak rates is set by seal background (the 10:1 rule); all-metal sealing (< 10^{-15} atm·cc/s) is the premise for 10^{-11}~10^{-13} channel-type leaks;
- Monolayer desorption (~4×10^{-3} Pa·L per cm²) is the biggest "phantom leak" in UHV / RGA scenarios;
- The bidirectional re-measurement is a five-minute acceptance action with enormous information value;
- The failure matrix (§5.6): a leak's leading cause of death is not "clogging" but "breaking" — endogenous clogging and structural destruction account for 90% ~ 99% of conventional failures and belong in design drawings, not usage procedures; with both endogenous families structurally removed, the microchannel leak's residual death is external intrusion alone — hence a 1~2-order-of-magnitude lower failure rate;

The next chapter widens the view from the leak body to its "accessory": the valve. A dead volume the size of a fingernail is enough to overturn everything this chapter has carefully engineered.

Chapter 6 Valves, Dead Volume and System Integration

> **What this chapter answers:** why a valve is not an "accessory" of the leak but part of the system; how dead volume quantitatively consumes gas, shocks vacuum and creates memory effects; why a mixture leak's partial rates are not simple mole percentages; and why liquid-medium leaks carry tempcos of ~10 %/°C.

6.1 Dead Volume: The "Hidden Gas Cell" Inside the Valve

> **Definition 6-1 (Dead volume)**
>
> The volume of gas sealed inside the valve seat, flow path and fittings when the valve is closed. It is released instantly at every opening and trapped at every closing — undesigned, unnoticed, yet participating in every measurement.

Dead volumes of conventional calibrated-leak valves are typically 0.01 ~ 0.1 cc (10 ~ 100 μL). That sounds negligible — the following three calculations will change your mind.

6.2 The Three Costs of Dead Volume (Quantified)

Cost one: cycle loss. Every time the valve opens, the high-pressure gas in the dead volume is vented:

$$\Delta G = V_{\text{dead}} \times p \qquad (6\text{-}1)$$

With V_{dead} = 0.1 cc and 10 MPa (100 atm) charge: loss per cycle = 0.1 × 100 = 10 atm·cc ≈ 10 mL of standard gas. A reservoir leak cycled 100 times wastes 1 L of standard gas for nothing — money for ordinary He, an unacceptable waste for Xe, Kr or ^{3}He isotopes. Compress the dead volume to 0.098 μL and the same conditions cost 0.0098 atm·cc per cycle — about 1 mL per 100 cycles, negligible (Fig. 6-1).

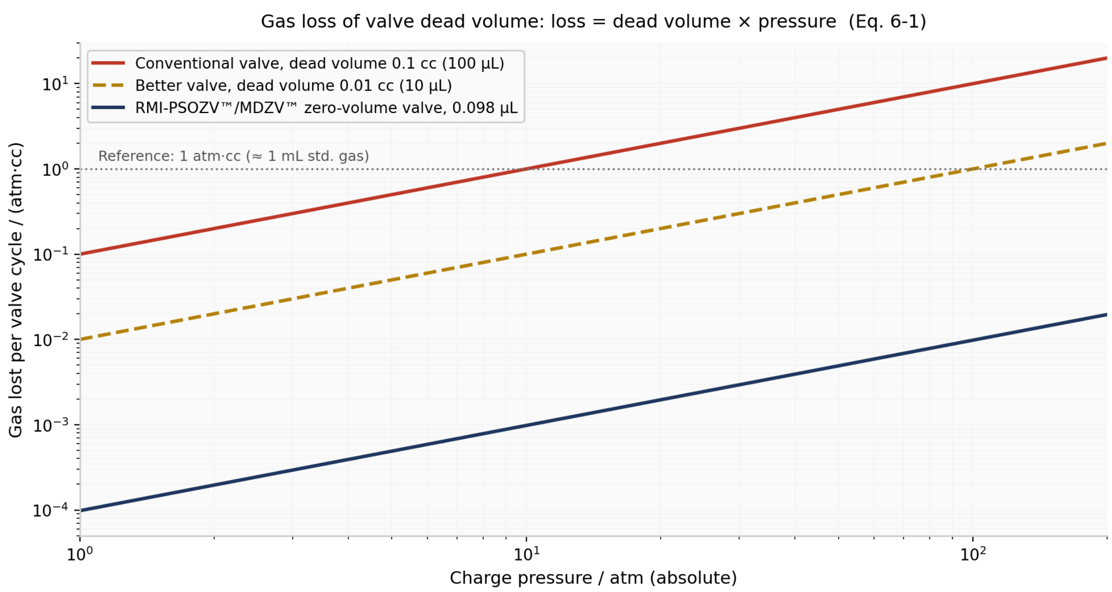

Figure 6-1 Cycle loss of valve dead volume: loss = dead volume × pressure (Eq. 6-1, log scales)

Cost two: vacuum shock. The high-pressure gas trapped in the dead volume rushes into the vacuum system the instant the valve opens. Estimate: 0.1 cc × 100 atm = 10 atm·cc ≈ 10^3 Pa·L, dumped into a 100 L chamber at 10^{-3} Pa background — an instantaneous pressure jump of +10 Pa, i.e. 10^4 times the background: at best the signal is buried for minutes, at worst a protective shutdown. This is why "an ordinary leak must be pre-evacuated before connecting to an RGA," and the physical basis of the zero-volume valve's claim "no shock no matter how long it has been closed": 0.098 μL × 100 atm ≈ 0.01 atm·cc ≈ 1 Pa·L — an instantaneous increment of only ~10^{-2} Pa in the same scenario, three orders of magnitude below the conventional valve. This theoretical ledger is backed by public measurements: with an RGA system at a base vacuum of 4×10^{-6} hPa, opening a PSOZV™ zero-volume-valve leak whose reservoir holds helium at 100 bar raised the system pressure only to 3×10^{-5} hPa — an increment of about $+2.6\times10^{-3}$ Pa, less than one order of magnitude — with no disturbance to the turbopump or filament; a conventional-valve leak under the same conditions makes the pressure jump by several orders of magnitude and can even trip the turbopump into protective restart[15]. The measured increment sits in the same 10^{-3} ~ 10^{-2} Pa range as the estimate — theory and measurement agree.

Cost three: memory effect. Dead volume is a "slow gas cell": gas from the previous use (especially heavy mixture components and water vapor) is adsorbed and trapped inside, then slowly released in the next measurement, forming false backgrounds and composition drift. It directly lengthens the system's **background recovery time** — on a high-takt line, every second of recovery time is throughput. Shrink the dead volume by three orders of magnitude and the memory gas shrinks in proportion — that is the quantitative explanation of "fast background recovery."

6.3 The Zero-Volume Valve: From 100 μL Down to 0.098 μL

The zero-volume valve aims to push dead volume an order of magnitude below the physical norm. Taking RMI-PSOZV™/MDZV™ as an example, the dead space is Φ0.5 mm × 0.5 mm:

$$V_{\text{dead}} = \pi \left(\frac{0.5}{2}\right)^2 \times 0.5\ \text{mm}^3 \approx 0.098\ \text{mm}^3 = 0.098\ \mu\text{L} \tag{6-2}$$

That is 2 ~ 3 orders of magnitude below the 10 ~ 100 μL of conventional valves, and all three calculations of §6.2 shrink in proportion[3]. The two form factors divide the work:

- **MDZV™ manual zero-volume valve:** metrology and laboratory scenarios — human-operated, minimal and reliable;
- **PSOZV™ normally-closed pneumatic zero-volume valve:** automation scenarios. The value of normally-closed design is **active fool-proofing** — forgetting to close the valve is the number-one human cause of gas loss in reservoir leaks; a normally-closed valve deletes "will someone forget" from the risk list and, combined with automation takt, achieves near-zero natural decay — especially significant for expensive isotope gases (Xe, Kr, ^{3}He).

> **Rule 6-1:** When evaluating a valved leak, ask for three numbers: the dead volume (determines cycle loss and vacuum shock), normally-open or normally-closed (determines human risk), and whether valve and leak are integrated (determines interface micro-leaks and added dead volume). A valve dead volume < 0.1 μL is a hard threshold for three scenarios: large-rate reservoir leaks, UHV / RGA, and expensive gases.

6.4 The Physics of Partial Rates in Gas-Mixture Leaks

RGA calibration and semiconductor process monitoring make heavy use of gas-mixture calibrated leaks (e.g. 1% each of H_2/He/N_2/Kr/Xe balance Ar, or 1 ppm Kr/Xe balance N_2). There is a widely misunderstood physical point here: **in molecular flow, components transport independently, and the partial-rate ratio does not equal the mole-fraction ratio**. From Eq. (3-3), the partial rate of component i:

$$Q_i \;\propto\; \frac{x_i\,p}{\sqrt{M_i}} \quad\Rightarrow\quad \frac{Q_i}{Q_{\text{total}}} = \frac{x_i/\sqrt{M_i}}{\sum_j x_j/\sqrt{M_j}} \tag{6-3}$$

An example: 1% He + 99% Ar. In molecular flow the He share of the total rate is

$$\frac{Q_{\text{He}}}{Q_{\text{total}}} = \frac{0.01/\sqrt{4}}{0.01/\sqrt{4}+0.99/\sqrt{40}} = \frac{0.005}{0.005+0.1565} \approx 3.1\% \tag{6-4}$$

Helium at 1% concentration contributes 3.1% of the rate — the light component is "amplified." Three engineering corollaries:

- A mixture leak's "rate" must state its basis: **the partial rate of a component (P basis, e.g. 95P = major-component partial rate) or the total rate (T basis, 95T)**. Get the basis wrong and the whole calibration is wrong[7];
- In viscous flow there is no √M amplification (components are "bound" together by viscosity) — the same mixture leak outputs different compositions in the two regimes: flow regime decides everything, again;
- Light components escape faster from the reservoir, so the stored composition slowly "gets heavier" over long storage — another reason to watch the decay basis of reservoir-type mixture leaks.

6.5 Liquid-Medium Leaks: The Evaporation–Transport Model

Semiconductor outgassing analysis, EUV carbon-contamination monitoring and aerospace mass-based acceptance all need liquid-medium standard sources (water, n-dodecane $C_{12}H_{26}$, DMC, PFTBA, etc.). Their physics differs fundamentally from gas leaks: **the liquid evaporates first; the vapor is then transported through the channel** — the rate is dominated by vapor pressure:

$$Q_{\text{liq}} \;\propto\; p_{\text{vap}}(T)\cdot C(T,\,M) \tag{6-5}$$

Vapor pressure depends on temperature exponentially (Clausius–Clapeyron), so liquid leaks carry tempcos of several percent per degree — for n-dodecane, ~12 %/°C (exponential)[8]. Three usage rules follow:

- **Temperature control is a necessity:** a ±0.5 °C control error alone means ~6% rate drift; liquid leaks must be used within ±0.5 °C of the certificate temperature, or corrected strictly by the exponential curve;
- **A large tempco is not a defect but a physical property:** it is set by the medium's enthalpy of vaporization — no vendor can "improve" it; what can be improved is measuring the correction curve accurately and making the zero-volume valve normally closed (to avoid pointless vapor loss);
- **The value of long-chain alkanes:** dodecane (M = 170), tetradecane/hexadecane and other high-mass media fill the gap in RGA high-m/z calibration and EUV heavy-hydrocarbon contamination quantification — a category no gas leak can in principle replace.

6.6 Summary

- The three costs of dead volume are quantifiable: cycle loss $\Delta G = V \cdot p$; vacuum shock (0.1 cc × 100 atm can spike a 100 L chamber by +10 Pa); memory effect lengthening background recovery;
- The zero-volume valve (0.098 μL) shrinks all three costs by 2~3 orders of magnitude; the normally-closed pneumatic valve eliminates "forgot to close," the largest human risk;
- Mixture partial rates ≠ mole fractions: in molecular flow light components are amplified by $1/\sqrt{M}$ (1% He contributes 3.1% of the rate); certificates must state the P/T basis;
- Liquid-leak rates are set by vapor pressure; a ~10 %/°C tempco is a property, not a defect — temperature control and exponential correction are prerequisites for use.

With the physics and hardware of leaks complete, the next chapter enters metrology: how to grade a leak's "accuracy" in the language of uncertainty, and how China's leak-rate values travel from the national primary standard into your hand.

Chapter 7 Uncertainty and Metrological Traceability

> **What this chapter answers:** how a calibrated leak's "accuracy" is scientifically expressed and proven. This chapter provides the minimum necessary knowledge of GUM uncertainty evaluation, a ready-to-use uncertainty budget example for leak calibration, a complete map of China's leak-rate metrology specifications, and a five-element checklist for reading any leak certificate. This chapter is the touchstone for metrology-institute readers and auditors.

Before uncertainty proper, three concepts that are constantly conflated must be separated — they describe three different qualities of a leak, and no axis can substitute for another:

Three orthogonal axes of leak quality

Concept	The question it answers	Determined by	Typical expression
Machining precision	Is it made right? (conformance)	Process and simulation capability: is the rate a "designed parameter" or an "emergent result"	Manufacturing tolerance, e.g. ±10%
Uncertainty	Is it measured right? (knowledge of the value)	The measurement system: upper-level standard, method, the artifact's behavior during calibration	U = 8% (k = 2)
Stability	Does it drift slowly? (time axis)	The leak itself: decay rate, tempco, damage resistance (Ch. 5)	0.1% ~ 1% per year

The axes are orthogonal but mutually supporting: however high the machining precision, without low-uncertainty calibration it cannot be proven to a third party; however precise the calibration, poor stability voids the value within months. The most frequent customer-side confusion is **taking the manufacturing tolerance for the uncertainty** — a leak made to 5×10^{-6} mbar·L/s ±10% and then calibrated carries a certificate reading "measured 5.12×10^{-6}, U = 8% (k = 2)": the ±10% describes manufacturing capability (the scatter of hits around the bull's-eye), the 8% describes how precisely the hit's position is known. The two numbers mean entirely different things and must never be interchanged in contracts or acceptance documents.

> **Example · what machining precision actually is:** a passive simulation leak under the following working constraints — pure He, inlet test pressure 4.2 MPa, outlet into vacuum, target rate 5×10^{-6} mbar·L/s. The microchannel process, paired with RMI-Cal™ conductance simulation, delivers 5×10^{-6} ±10% in one pass: the superposition model of Eq. (3-4) computes the diameter and length first; machining and actual calibration follow. For "rate-emergent" processes (crushing, permeation), the rate only "grows out" after forming; hitting both constraints — the specified pressure and the specified rate — simultaneously is extremely difficult, and the industry resorts to batch production followed by grading and selection. That is the essential divide of machining precision: **whether the leak rate is a designed parameter or an emergent result**.

7.1 A Leak Rate Without Uncertainty Is Not a Quantity

"This leak is 1.0×10^{-6} Pa·m³/s" — metrologically, that sentence is incomplete. It lacks uncertainty: by how much the value might deviate, with what confidence. The correct expression is "Q = 1.0×10^{-6} Pa·m³/s, U = 10% (k = 2)," meaning: with ~95% confidence, the true value lies within $[0.90, 1.10]\times10^{-6}$. The difference between the two sentences is the difference between a "number" and a "quantity value." **Uncertainty is not a cover for error but a score for measurement quality** — the smaller it is, the stronger the measurement system behind the leak.

7.2 The GUM Framework for Uncertainty Evaluation

The internationally accepted method is specified by the GUM (*Guide to the Expression of Uncertainty in Measurement*, adopted in China as JJF 1059.1—2012[11]), in three steps:

1. **Build the measurement model**: output Y = f(X_1, X_2, …). A typical model for leak calibration: calibrated rate = standard value × signal ratio × temperature correction × pressure correction × flow-regime correction;
2. **Evaluate the standard uncertainty of each input**: Type A (statistics of repeated measurements, $u = s/\sqrt{n}$) and Type B (certificates, instrument specifications, assumed distributions — rectangular: $u = a/\sqrt{3}$; normal: $u = a/2$);
3. **Combine and expand**:

$$u_c = \sqrt{\sum_i (c_i u_i)^2}, \qquad U = k \cdot u_c \quad (k = 2 \approx 95\%) \tag{7-1}$$

c_i — sensitivity coefficient (the factor by which the output changes per unit change of the input). The sensitivity coefficient of the temperature-correction term is the temperature coefficient itself — this is why 0.1 %/°C and 4 %/°C are worlds apart in a budget table.

7.3 An Uncertainty Budget for Leak Calibration (Example)

Take the calibration of a 10^{-6}-class He calibrated leak by the comparison method; a typical budget is shown in Table 7-1 (values are illustrative; actual evaluation rests with the laboratory):

Table 7-1 Uncertainty budget example: leak-rate calibration by comparison (relative values)

Component	Type	Source and evaluation	u_i / %
Upper-level calibrated-leak value	B	Upper certificate U = 8% (k=2) → u = 4.0	4.0
Comparison repeatability	A	n = 10 comparisons, s/√n	1.5
Intermediate stability	B	Estimated drift between calibrations	2.9
Readout / instrument linearity	B	MS linear range	1.0

Temperature effect	B	Control ±2.5 °C × tempco 0.1 %/°C, rectangular ÷√3 (a 4 %/°C permeation leak would reach 5.8)	0.15
Pressure measurement	B	Pressure-gauge indication error	0.3

$$u_c = \sqrt{4.0^2 + 1.5^2 + 2.9^2 + 1.0^2 + 0.15^2 + 0.3^2} \approx 5.3\,\% \;\Rightarrow\; U \approx 11\,\%\,(k=2) \tag{7-2}$$

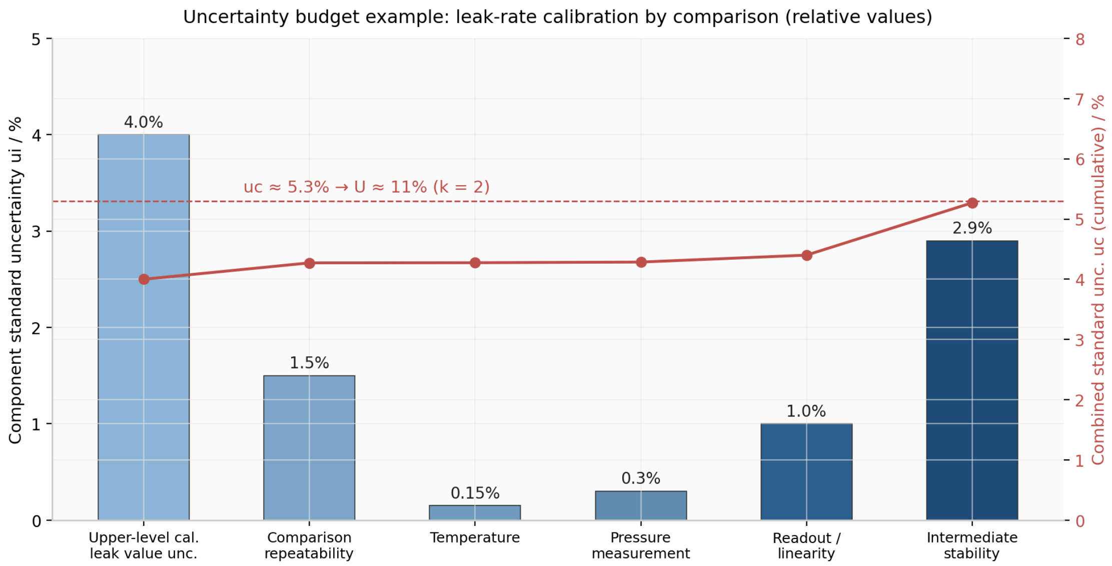

Figure 7-1 Pareto view of the uncertainty budget: attack the dominant components first

How to read a budget matters more than how to compute one: **find the dominant components first, then decide what to compress.** In this example, "upper-level standard value" and "intermediate stability" contribute nearly 90% of the variance — meaning: refining the detector readout is useless; the only two upgrade paths are a better upper-level standard (move up the traceability chain) and a more stable leak (compress the "intermediate stability" term by design). Swap in a permeation tempco of 4 %/°C and the temperature term alone (u = 4×2.5/√3 ≈ 5.8%) lifts u_c to nearly 8% — **tempco is squared in uncertainty combination**: the engineering echo of §3.5.

7.4 Map of China's Leak-Rate Metrology Specifications

The industry's most confused point: **specifications for "leaks" and for "leak detectors" are two separate systems**. One table sorts them out:

Table 7-2 Map of China's leak-rate metrology specifications (current, as of 2026)

Code	Title and object	Scope	Key points
JJF 1833—2020	Calibration Specification for Vacuum Helium Leaks (object: **leaks**)	$(1\times10^{-10} \sim 1\times10^{-4})$ Pa·m³/s	Channel/permeation classification; facility U ≤ 10% (flow-meter / fixed-quantity gas), ≤ 20% (comparison); annual stability ≤ 3%[1]

JJF 1627—2017	Calibration Specification for Calibrated Leaks (Soap-Film Flowmeter Method) (object: **leaks**)	1 mL/min ~ 10 L/min; inlet 1 kPa ~ 1.5 MPa, outlet to atmosphere	A primary method for positive-pressure / air-tightness leaks[6]
JJG (Mil.) 165—2024	Verification Regulation for Vacuum Calibrated Leaks (defense system)	Verification of vacuum calibrated leaks	Effective 2025-01-01; RealMeter (Shanghai) is a participating drafter[2]
JJF 1986—2022	Calibration Specification for Differential-Pressure Air Leak Testers (object: **testers**)	Test pressure ≤ 700 kPa; leak rate (0~100) mL/min	Leak-rate error ±10%; measurement standards include digital pressure gauges and **calibrated leaks**[9]
JJF 1964—2022	Calibration Specification for Halogen Leak Detectors (object: **detectors**)	Detectable rates (10^{-6} ~ 10^{-5}) Pa·m³/s	Basis for calibrating refrigerant leak detectors[10]

The strategic meaning of this map: the detector specifications (1986, 1964) both designate calibrated leaks as the measurement standard — **the leak is the intersection of the two systems**; if leaks are wrong, the calibration of both detector classes collapses. Meanwhile the leak specifications (1833, 1627, Mil. 165) write "channel/permeation," "annual stability" and "uncertainty" into mandatory language — precisely the projection of this book's Chapters 3~5 physics onto the regulatory level.

7.5 Standard Establishment and Traceability on the User Side

To establish a vacuum-helium-leak calibration facility, a metrology institute needs a **reference calibrated-leak set** covering all orders of magnitude, each piece individually traceable. A typical JJF 1833—2020-compliant configuration (full measured list in §15.3): six leaks covering (3×10^{-10} ~ 3×10^{-5}) Pa·m³/s, one per decade; annual stability 0.1% ~ 1.0% (specification requires ≤ 3%); tempco 0.1 %/°C; each piece traceable to national-level institutes such as NIM; recalibration cycle 12 months[3]. Air-tightness and refrigerant media have their corresponding standard-establishing sets (JJF 1627 / JJF 1964 systems).

The enterprise-side logic follows: **working leaks follow reference leaks; reference leaks follow the national primary standard**. Recommended asset-management actions:

- Line working leaks: per-shift check (Q_0 signal drift monitoring), annual external calibration;
- Reference leaks: fixed purpose, fixed conditions, dedicated custodian, 12-month recalibration;
- Certificate archive: four elements verifiable — rate value, uncertainty, calibration conditions, traceability institute.

A clarification on the certificate system (stated once for the whole book)

Leak manufacturing and metrological accreditation are two different things. As a manufacturer, RealMeter issues a factory test certificate for every leak shipped; RealMeter calibrated leaks, measured by national metrology institutions, have been procured by multiple metrology institutes/stations as reference calibrated leaks (master standards) for establishing their standards, and RealMeter joined the drafting of JJG (Mil.) 165—2024 as a participating unit[2]. Where customers need CNAS / ISO 17025 calibration certificates, these are issued by metrology institutes (sent out by RealMeter or by the customer). All statements about "certificates" and "traceability" in this book follow this convention.

7.6 How to Read a Certificate: The Five-Element Checklist

For any calibrated-leak certificate, check the following in order — 30 seconds tells you whether it is usable:

Table 7-3 Five-element checklist for leak certificates

Element	What to check	Common defects
① Medium & basis	Gas species, concentration; mixtures must state the P/T basis (§6.4)	"Air" without concentration; missing mixture basis
② Inlet pressure	Value + absolute/gauge + unit (§2.4)	"5 bar" without stating absolute or gauge
③ Outlet condition	Vacuum / atmosphere / specified back-pressure (§2.5)	Missing, or mismatched with the usage scenario
④ Temperature & correction	Calibration temperature, tempco, standard state (0 °C convention for sccm)	No tempco; no basis for use away from 23 °C
⑤ Uncertainty & traceability	U value with k, traceability institute, recalibration date	Only the word "pass," no uncertainty

Rule 7-1: If any of the five elements is missing, the certificate is as good as absent on your floor — because you cannot reproduce its value "on the same basis." When comparing two parties' certificates at acceptance, align the five elements first, then the numbers.

Reading a real extreme-class certificate against these five elements (a 10^{-12} Pa·m³/s-class He leak, National Primary Vacuum Metrology Station of the defense industry, July 2026): rate value, U_r = 22% (k = 2), outlet into vacuum, helium medium, upper-level standard with validity date — every element present. The full example is Table 15-1 in §15.1.

7.7 Summary

- Leak rate + uncertainty (U, k=2) is the only complete expression of a quantity value;
- Read the budget by dominant components: in leak scenarios, "upper-level standard value" and "intermediate stability" typically contribute 90% of variance — stability is a leak manufacturer's core competence;
- Tempco is squared in uncertainty combination — 0.1 %/°C vs 4 %/°C is a world of difference in the budget;
- Two specification systems: leak specifications (JJF 1833 / 1627 / Mil. 165) and detector specifications (JJF 1986 / 1964), with leaks at the intersection;
- Missing any of the five certificate elements (medium & basis / inlet pressure / outlet / temperature / uncertainty & traceability) renders a certificate unusable.

Part II is complete: process (Ch. 4), lifetime (Ch. 5), system (Ch. 6), metrology (Ch. 7) — four pieces forming a complete knowledge system for judging any leak. Part III takes this system to the field: leak-test methodology, quantitative RGA, system-level air-tightness accuracy, the helium-reduction paradigm and selection methodology.

PART III

Applications | Using Leaks Right

Chapter 8 Overview of Leak-Test Methodology

> **What this chapter answers:** given a sealing requirement, which test method should you choose? This chapter maps the principles, sensitivity boundaries and speed/cost profiles of mainstream methods, together with the specific demands each method places on calibrated leaks. Choose the wrong method, and no leak, however good, can save you.

8.1 One Map: Sensitivity × Cost

Choosing a leak-test method is essentially finding the intersection between "minimum detectable leak rate" and "cost / takt per part":

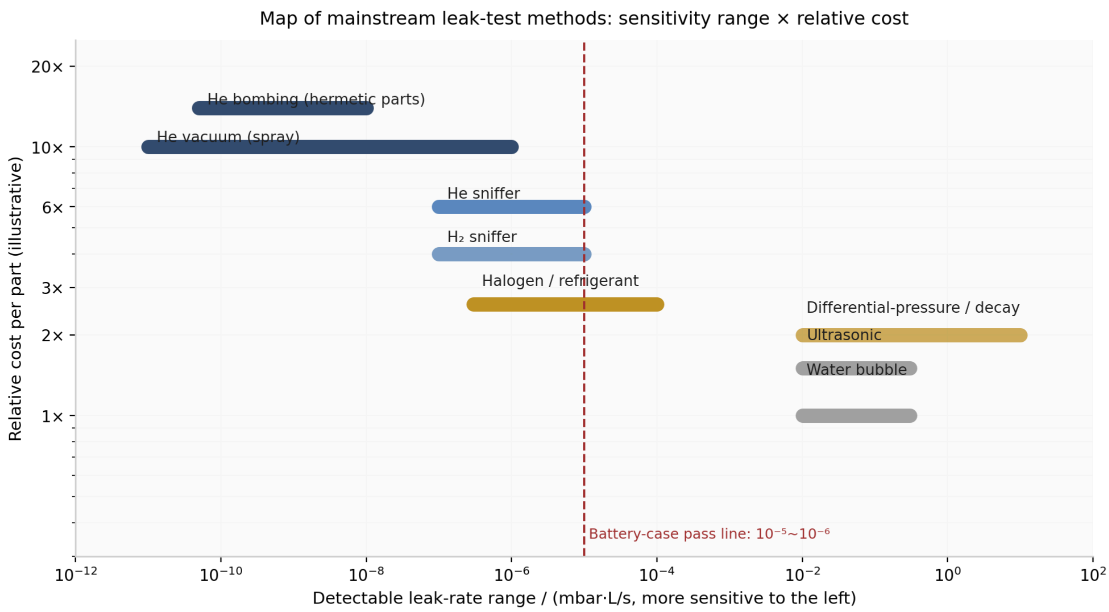

Figure 8-1 Map of mainstream leak-test methods: sensitivity range × relative cost per part

Three principles for reading the map: **first, sensitivity needs margin** — the method's detectable floor should sit 1~2 orders of magnitude below the reject threshold (for a 10^{-5} threshold, the method should reach 10^{-6}~10^{-7}); **second, cost jumps in steps** — crossing from pressure decay to helium testing lifts equipment and per-part cost by a tier, so "can pressure decay solve this?" is always the first question; **third, no method does everything** — high-end lines normally combine: pressure decay to screen gross leaks + helium for fine leaks.

8.2 Helium Mass-Spectrometer Leak Testing: Vacuum / Sniffer / Bombing

A helium leak detector uses a small magnetic-sector mass spectrometer to exclusively "count" ions of mass number 4. The reasons for choosing helium as tracer are textbook material themselves: extremely low natural abundance (only 5.2 ppm in air — clean background), small and penetrating molecules, inert and safe. The three basic modes impose very different demands on leaks:

Table 8-1 The three modes of helium mass-spectrometer leak testing

Mode	Principle	Sensitivity & traits	Requirements on calibrated leaks
Vacuum method (spray / hood)	Part evacuated and connected to detector; helium sprayed or hooded outside	Most sensitive (10^{-11} class); locates leak points	Reservoir-type vacuum leaks (sensitivity calibration); positive-pressure leaks for sniffer calibration
Sniffer method (pressurized part)	Part charged with He (or He mixture); sniffer probe scans outside	10^{-5} ~ 10^{-7} class; line workhorse; locates leaks	**Passive simulation leaks at same pressure and medium as the part** (OK/NG pieces)
Bombing method (hermetic devices)	Device pressurized in a high-pressure He tank, then measured for released He in a vacuum chamber	Dedicated to hermetic packages (10^{-9} ~ 10^{-11}); gross + fine steps	Vacuum calibrated leaks; equivalent standard rate per MIL-STD-type methods

The sniffer method is the most used — and most misused — mode on production lines: readings depend strongly on probe-to-leak distance, scan speed and ambient He background — **it is a "relative comparator," not an "absolute meter."** That is exactly why a sniffer line's judgment system must be built with calibrated-leak simulation pieces under identical conditions (the Four-Piece Kit of Ch. 10 and the Three-Reference Verification of Ch. 11 both grow from here).

8.3 Differential-Pressure and Pressure-Decay Air-Tightness: ΔP = Q·Δt / V

Air-tightness testing needs no tracer gas: the test volume is charged with air / N_2 to test pressure, stabilized, and the pressure change is monitored. From the definition of leak rate (Eq. 2-1) and the gas law, the pressure drop caused by leakage is:

$$\Delta P = \frac{Q \cdot \Delta t}{V} \qquad \Rightarrow \qquad Q = \frac{\Delta P \cdot V}{\Delta t} \tag{8-1}$$

V — test volume including plumbing (m³); Δt — test time (s); ΔP — pressure drop (Pa). Example: V = 2 L, 10 Pa drop in 10 s → Q = 2×10^{-3} Pa·m³/s = 2×10^{-2} mbar·L/s ≈ 1.2 sccm.

Eq. (8-1) is the "Newton's second law" of the air-tightness industry, and it reveals the method's three inherent properties:

1. **Sensitivity ∝ time / volume**: for the same threshold, a tenfold larger volume means either tenfold waiting time or tenfold worse sensitivity — large-volume parts are the method's natural difficulty;
2. **It measures a volume-normalized rate**: the same part on a different fixture (changed volume) changes the rate corresponding to the same ΔP;
3. **Everything that moves pressure is an interferer**: temperature (Eq. 10-1), adiabatic effects, fixture elastic deformation — the entry point to all of Chapter 10.

The differential-pressure configuration (a differential sensor between the part under test and a reference volume) suppresses temperature and charge-pressure fluctuations by "dual-channel common-mode rejection" and is the mainstream machine type; the direct-decay configuration is simpler but more sensitive to supply and environment. JJF 1986—2022 regulates the calibration of differential-pressure air leak testers (test pressure ≤ 700 kPa, leak rate 0~100 mL/min), one of whose measurement standards is the calibrated leak[9].

8.4 Hydrogen, Halogen and Other Methods

Hydrogen testing: uses 5% H_2 + 95% N_2 (non-flammable mixture) as tracer with a semiconductor-sensor sniffer; sensitivity 10^{-5} ~ 10^{-7} class, far lower cost than helium, no helium-resource dependency — an important alternative on the helium-reduction path; its leak requirements mirror He sniffer testing (H_2/N_2 simulation leaks at same pressure and medium). **Halogen / refrigerant testing**: uses the refrigerant itself (R134a, R1234yf, etc.) as tracer — the refrigeration industry's regulatory-compliance tool (JJF 1964—2022, detectable 10^{-6} ~ 10^{-5} Pa·m³/s[10]); since the medium is the product's working fluid, leaks must be calibrated with the real refrigerant and certified on the g/y basis (Eq. 2-2). **Water-bubble and ultrasonic**: coarse screening above the 10^{-2} ~ 10^{-3} class — intuitive and cheap, commonly used as "gross-leak interception" before helium testing.

8.5 RGA Quantification and Micro-Flow Calibration: Two "Instrument-Level" Scenarios (Map First; Ch. 9 Expands)

Two scenarios do not test products directly but are the high-end battlefield of calibrated leaks: **first, residual gas analyzer (RGA) quantification** — semiconductor and UHV systems use RGAs to monitor process atmospheres and outgassing composition; quantitative calibration needs standard sources of known partial pressure / partial rate: single gases, mixtures (component partial rates, §6.4), isotopes (^3He, D_2, $^{18}O_2$, etc.), even liquid-medium vapors (§6.5). Such scenarios are extremely sensitive to valve dead volume and background (the zero-volume valve is a hard threshold, Rule 6-1). **Second, mass-flow-controller (MFC) calibration**: calibrated leak rates of sccm ~ L/min class serve as flow references, positive-pressure outlet; the soap-film flowmeter method of JJF 1627—2017 is one traceability path[6]. A positioning note is worthwhile here: calibrated leaks and MFCs are complementary, not competing — an MFC is an active control element (regulating flow in real time), while a calibrated leak is a passive reference (a known, stable, traceable flow truth). Use the former to run the process and the latter to calibrate the former — the same division of labor as a variable-frequency drive and a standard resistor.

8.6 Method-Selection Quick Reference

Table 8-2 Leak-test method selection at a glance

Requirement profile	First-choice method	Calibrated-leak form
Threshold ≥ 10^{-3} mbar·L/s; fast takt, low cost	Differential / decay air-tightness	Passive air-tightness leaks (Air / N_2, same pressure and volume simulation)
Threshold 10^{-5} ~ 10^{-7}; leak location needed	He / H_2 sniffer	Passive simulation leak sets (OK / NG / Q_0)
Threshold ≤ 10^{-7}, or hermetic devices	He vacuum / bombing	Reservoir-type vacuum leaks (incl. built-in calibration leaks)

Refrigeration regulatory compliance	Halogen / refrigerant testing	Refrigerant calibrated leaks (g/y basis)
RGA quantification / semiconductor process monitoring	—— (instrument calibration)	Single-gas / mixture / isotope / liquid leaks + zero-volume valves
MFC and flow calibration	—— (flow reference)	sccm-class positive-pressure calibrated leaks

8.7 Summary

- Method selection = sensitivity margin (1~2 orders below threshold) × cost/takt constraints; high-end lines normally combine "decay for gross + helium for fine";
- The He sniffer is a relative comparator — its judgment system must be built with calibrated leaks under identical conditions;
- The first formula of air-tightness, $\Delta P = Q \cdot \Delta t / V$: sensitivity is bought with time and volume; temperature is the number-one interferer;
- Every method has its leak-form requirements — leak selection starts from "the test method," not from "the rate number."

The next chapter enters the instrument-level main battlefield, and the chapter of heaviest strategic significance: quantitative RGA calibration for semiconductors — from qualitative to quantitative, equipping China's high-end manufacturing with "eyes that can measure."

Chapter 9 From Qualitative to Quantitative: Semiconductor RGA Calibration

What this chapter answers: contamination tolerance in advanced semiconductor processes has entered the ppb and even ppt regime, and the residual gas analyzer (RGA) is the only "eye" inside the vacuum chamber — but without a calibration system, that eye sees trends, not numbers. This chapter systematically presents the methodology for moving RGA from qualitative to absolute quantitative, the role of calibrated leaks in it, and the strategic significance of this scenario for the self-reliance of high-end manufacturing.

9.1 Why Semiconductors Deserve a Chapter of Their Own

The core processes of advanced nodes — PVD, CVD, ALD, plasma etch, ion implantation, EUV lithography — all run in vacuum. Each node generation tightens the requirement on vacuum-background purity by roughly an order of magnitude:

Table 9-1 Typical vacuum-background requirements of key semiconductor processes[13]

Process step	Typical vacuum / mbar	Key monitored gases	Contamination tolerance
PVD metal deposition	$10^{-8} \sim 10^{-9}$	Ar, H_2O, O_2, N_2	H_2O < 1 ppb
CVD dielectric deposition	$10^{-6} \sim 10^{-8}$	SiH_4, NH_3, by-products	Cross-contamination < 10 ppb
ALD high-k dielectric	$10^{-7} \sim 10^{-9}$	H_2O, TMA, carrier gas	H_2O < 0.1 ppb
Plasma etch	$10^{-3} \sim 10^{-5}$	CF_4, SF_6, BCl_3, by-products	Endpoint detection ±1%
Plasma etch	$10^{-3} \sim 10^{-5}$	CF_4, SF_6, BCl_3, by-products	Endpoint detection ±1%
EUV lithography	$10^{-8} \sim 10^{-10}$	H_2, Xe, Sn vapor	Mirror contamination < 1 ppt

The meaning of this table: **at the deepest level, the competition of advanced manufacturing is a competition of trace-contamination metrology capability.** ppm-level contamination can scrap an entire wafer lot, and the only instrument that can simultaneously resolve multiple gas species and their partial pressures in vacuum is the RGA (quadrupole residual gas analyzer). The RGA is the "eye" of high-end equipment; and all the argumentation of this book's first eight chapters condenses into one sentence: **eyes need a yardstick, and the yardstick must be traceable.** Vacuum acceptance of semiconductor tools, contamination monitoring of process chambers, incoming inspection of high-purity materials, root-cause tracing in failure analysis — these links have long depended on imported calibration means. Making the RGA calibration system self-reliant fills in the lowest-level piece of the "metrology foundation" for high-end manufacturing. That is why this chapter stands alone — and why it is the largest growth market of the calibrated-leak industry over the next decade.

9.2 RGA Quantification Principle and Three Evolution Stages

The quantitative basis of an RGA is the linear relation between ion current and partial pressure:

$$I_g = S_g \cdot P_g \tag{9-1}$$

I_g — ion current of gas g's characteristic peak (A); P_g — partial pressure (mbar); S_g — sensitivity factor (A/mbar), jointly determined by electron energy, ion-source geometry, quadrupole transmission function and detector gain, and drifting with filament aging and contamination.

Eq. (9-1) is structurally identical to Eq. (8-1) of air-tightness testing: **instruments output "signals"; between signal and "quantity value" stands a coefficient that must be calibrated periodically.** The three stages of RGA application are essentially the history of calibrating that coefficient:

Table 9-2 Three evolution stages of RGA application[13]

Stage	Capability	Limitation / breakthrough
① Qualitative monitoring (1970s~90s)	Watch the water peak (m/z 18) and air peaks (28/32) to judge vacuum health	"Is something wrong" — no numbers
② Semi-quantitative (1990s~2010s)	Built-in gas library + sensitivity factors; rough quantification of common gases	Error ±30% ~ ±100%; blind to organic vapors and trace impurities
③ Absolute quantification (2010s~)	In-situ calibration with calibrated leaks, permanent gases → organic vapors → ppm traces	**The calibration system decides accuracy**: liquid and mixture leaks fill the blind zones

Core insight: An RGA's quantitative accuracy depends not on the instrument itself but on the quality and coverage of its calibration system. Without reliable calibrated leaks, an RGA remains forever a "trend watcher"; with precise, traceable calibration tools, it becomes a "metrological sensor" for process control.

9.3 The Four Calibration Methods

First, the sensitivity-factor method. Connect a pure-gas calibrated leak of known rate to the system, record the ion current at steady flow, and solve directly for $S_g = I_g / P_g$. Two engineering points: the zero-volume valve lets calibration run in-situ on production tools without shocking the vacuum (Ch. 6); annual decay below the 0.2% class makes calibration results portable and reusable.

Second, the calibrated-leak comparison method. For target sources that cannot be measured directly, compare signals against a known leak at the same pumping speed:

$$Q_{\text{test}} = Q_{\text{ref}} \times \frac{I_{\text{test}}}{I_{\text{ref}}} \tag{9-2}$$

For extremely low rates (< 10^{-11} Pa·m³/s), use the static accumulation method: isolate the pumps and measure the rate of pressure rise in volume V:

$$Q = V \times \frac{\mathrm{d}P}{\mathrm{d}t} \tag{9-3}$$

Note that Eq. (9-3) is the same formula as Eq. (8-1) of air-tightness testing — **vacuum accumulation and positive-pressure decay are physical mirror images**: the recurring theme of this book that "leak rate has only one physics."

Third, fragmentation-pattern analysis. In mixtures, every mass peak is a linear superposition of multiple components:

$$H_M = \sum_g S_g \, \alpha_{Mg} \, P_g \tag{9-4}$$

α_Mg — fragmentation factor of gas g at mass number M. The main peaks of CO / N_2 / C_2H_4 overlap completely at m/z 28; separation must rely on fragment differences (CO at m/z 12, C_2H_4 at m/z 27) — and calibrating the fragmentation-factor database requires mixture calibrated leaks of precisely known composition as input.

Fourth, the liquid-medium quantification breakthrough. Water vapor, photoresist solvents (DMC), pump-oil tracers (PFTBA) and n-alkanes (organic-contamination fingerprints) have long been the RGA's "organic-vapor blind zone": vapor pressure varies exponentially with temperature, gas-phase standards are lacking, and the high-m/z region has no response reference. Microchannel controlled-release liquid leaks (liquid–vapor equilibrium + microchannel flow-resistance release), combined with known temperature coefficients (9~12 %/°C, §6.5), turn the blind zone into a quantifiable one (±10% class) — PFTBA fragments spanning m/z 69~671 are the recognized gold standard for high-mass calibration[13].

9.4 Trace Calibration: Two-Stage Dilution and the Natural Mass Ruler

Advanced processes need the ability to verify "ppb-level impurities in the process background." The two-stage dilution architecture of ppm-class mixture leaks provides the answer: Kr/Xe at 1 ppm in the source gas (first-stage dilution), with the ratio of total leak rate to system pumping speed further suppressing the partial pressure (second stage):

$$P_{\mathrm{Kr}} = \frac{Q_{\mathrm{total}} \times C_{\mathrm{Kr}}}{S_{\mathrm{eff}}} \tag{9-5}$$

Q_total — total leak rate; C_Kr — Kr mole fraction in the source; S_eff — effective pumping speed. What the RGA "sees" of Kr is set by the ratio of Kr partial rate to pumping speed.

Table 9-3 Two-stage dilution: Kr partial pressure under different rate–speed combinations[13]

Total rate / mbar·L/s	Kr source conc.	Kr partial rate / mbar·L/s	Pumping speed / L/s	Kr partial pressure / mbar	Relative level
10^{-3}	1 ppm	10^{-9}	100	10^{-11}	~100 ppm
10^{-3}	1 ppm	10^{-9}	1000	10^{-12}	~10 ppm
10^{-6}	1 ppm	10^{-12}	100	10^{-14}	~100 ppb
10^{-6}	1 ppm	10^{-12}	1000	10^{-15}	~10 ppb
10^{-9}	1 ppm	10^{-15}	1000	10^{-18}	~10 ppt

Note: "relative level" is the Kr partial pressure as a fraction of a typical 10^{-7} mbar system background (e.g. $10^{-11}/10^{-7}$ = 100 ppm).

One table spanning six orders of magnitude — the "input end" of trace verification thus becomes traceable. The other half of the problem is **mass discrimination**: quadrupole transmission efficiency varies with mass number, and the response at m/z 132 can differ by orders of magnitude from m/z 28. The natural multi-isotope abundances of Kr (78~86 amu) and Xe (124~136 amu) are "mass rulers written into physical constants": comparing measured isotope ratios against theoretical values yields the transmission correction factor at each mass, building a cross-mass sensitivity response curve (Fig. 9-1).

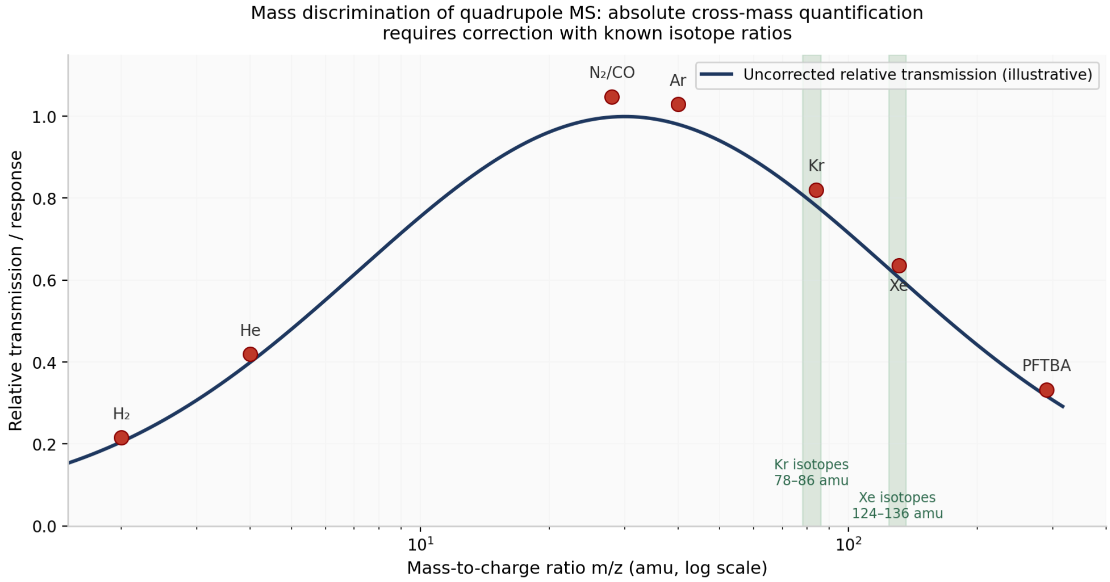

Figure 9-1 Quadrupole mass discrimination and the natural Kr / Xe mass ruler (illustrative)

Case · PFTBA: the tuning ruler for the high-mass region. Perfluorotributylamine ($C_{12}F_{27}N$, M = 671) produces characteristic fragment peaks (m/z 69, 219, 502, among others) spanning the whole mass axis, and is the industry's accepted mass-spectrometer tuning medium. A PFTBA liquid calibrated leak provides controlled injection (typically 3.13×10^{-6} mbar·L/s, ≈ 2.7 g/y mass consumption), serving both as a high-mass sensitivity anchor for the RGA and as a direct check of mass-axis and relative-fragment-abundance fidelity. It complements the Kr / Xe isotope ruler: PFTBA answers "are peak positions and spectral shape right," while the isotopes solve "how transmission efficiency varies with mass"[20].

9.5 Full-Chain Scenario Map and Coverage

Table 9-4 RGA calibration scenarios across the semiconductor chain and leak configurations[13]

Stage	Calibration task	Leak configuration
Tool manufacturing & acceptance	Ultimate-vacuum "gas fingerprint," detector sensitivity, pump-speed verification, material outgassing rate	He / N_2 / Ar / H_2O single-gas leaks + mixture leaks
PVD	Ar working-gas purity, <1 ppb water-vapor quantification	Ar leak (m/z 40 sensitivity) + H_2O liquid leak

CVD / ALD	Precursor residue, post-clean baseline recovery, H_2O precursor residue	N_2 / Ar references + ppm mixtures + H_2O leak
Plasma etch	Endpoint detection ±1% (e.g. m/z 69 CF_3^+ response)	Ar / CF_4-type mixture simulation leaks
Lithography / EUV	Photoresist volatiles quantification, Xe residue, post-purge trace verification	DMC liquid leak + Xe leak + 1 ppm Kr/Xe mixture
Chamber-clean verification	Wet-to-dry time optimization, water-peak quantitative tracking	Ar / N_2 fingerprints + H_2O leak
Material incoming inspection	ppb-level impurities in high-purity gases, moisture in specialty gases	ppm-class mixture leaks + H_2O leak
Packaging / failure analysis	In-package atmosphere, moisture, contaminant spectral library	He / N_2 / Ar + H_2O / organic-vapor leaks

Calibration coverage assessed by stage: tool vacuum acceptance > 95%, PVD > 95%, lithography / clean verification > 90%, packaging & test > 95%, material incoming > 90%; CVD / ALD / etch / implantation, which involve reactive specialty gases, about 65% ~ 70% — reasons in the next section[13].

Scenario focus · Water vapor: from "estimate" to "quantified." Water vapor accounts for over 90% of residual gas in UHV systems, yet has long been the hardest component to quantify — strong adsorption and phase-change behavior made water-vapor standard sources scarce, and the customary H_2 / Ar lookup-table estimate of the water peak carries 50% ~ 100% error[19]. H_2O calibrated leaks (distilled-water medium + passivated microchannel + zero-volume valve) turn the water peak into an absolutely quantifiable, in-situ-calibrated target. Three usage points follow directly from the physics: tempco ≈ 9.5 %/°C (exponential — requires a stable-temperature environment or strict mathematical correction, §6.5); ~24 h of initial pump-down after first use or venting to establish desorption equilibrium (~10 min in routine use); typical rate range 10^{-6} ~ 10^{-8} Pa·m³/s. Applications: quantitative desorption kinetics of materials, bake-out endpoint determination (a quantitative model linking water-peak partial pressure to injected flow), and PVD / CVD process-moisture verification — this is how the H_2O entries of Table 9-4 are realized in practice[19].

Scenario focus · Quantitative monitoring of HHC contamination in EUV lithography. Heavy-hydrocarbon (HHC) contamination inside EUV chambers causes carbon deposition on collector mirrors and shortens their lifetime; the RGA identifies mass numbers but lacks sensitivity factors for heavy alkanes, so no contamination rate can be derived. C_{12} / C_{14} / C_{16} n-alkane calibrated leaks (typical rates 10^{-6} ~ 10^{-9} Pa·m³/s) establish a linear "ion current ↔ mass flow" relationship for the RGA (72-hour continuous monitoring: linearity $R^2 > 0.98$, versus $R^2 \approx 0.80$ ~ 0.90 for conventional needle valves), turning contamination level from "guessing from spectra" into real-time quantification — mirror lifetime becomes a predictable parameter[20]. Three practical points: tempco ≈ 12 %/°C (exponential correction, §6.5); ~2 h initial pump-down; ~10 min to thermal equilibrium in normal use — the fastest-responding family among liquid media.

Scenario focus · "Medium repatriation" for battery-electrolyte leak testing. Helium molecules and viscous electrolyte penetrate defects very differently, so converting helium-test results into equivalent electrolyte leakage is systematically distorted. A DMC (dimethyl carbonate, a principal electrolyte solvent) calibrated leak provides a stable evaporation rate on the order of 2×10^{-5} mbar·L/s with the real medium, letting the leak detector's rejection threshold be calibrated directly on the DMC signal — the medium mismatch disappears[20]. Note the division of labor: helium testing answers "is the enclosure sealed" (the Ch. 11 helium-reduction scheme applies there in full), while DMC calibration answers "what is the real electrolyte leak rate" — complementary, not substitutive. DMC tempco ≈ 9.0 %/°C; temperature control and correction follow §6.5.

9.6 Technical Boundaries: An Honest List and the Complementary Architecture

A responsible white paper must state its boundaries. **Reactive / corrosive / highly toxic specialty gases — SiH_4, AsH_3, PH_3, WF_6, TMA, Cl_2, HBr, NF_3, F_2 — cannot currently be made into stable calibrated leaks** — the reason lies in gas physics itself (decomposition inside microchannels, lethal safety risks, channel corrosion, strong adsorption), not in process capability; even in the markets with the most advanced calibrated-leak technology, such leaks are equally scarce or nonexistent. "Surrogate-gas calibration" serves trend judgment only within a narrow window (single mass number, no overlapping peaks, no memory effect) and introduces 20% ~ 100% systematic error — **tactically usable, strategically undependable**.

The industry's mature solution is a cross-sensor complementary architecture: direct measurement of specialty gases goes to FTIR, OES and electrochemical sensors; the RGA returns to its "environmental watchdog" role — process-fingerprint baselines, cross-contamination monitoring, clean verification, and indirect inference via correlated parameters (e.g. for WF_6, watch not m/z 298 but the by-product SiF_4 at m/z 85). In this architecture, the calibrated leak's task is to **keep the RGA's long-term response stable** — precisely the value zone of low-decay, zero-dead-volume leaks. Best practices for consistency: sensitivity factors recalibrated every 3~6 months, in-situ first, mixtures for cross-checking the high-mass region, liquid media calibrated specifically every 6 months[13].

9.7 Strategic Significance: Completing the Metrology Foundation for High-End Manufacturing

Putting this chapter back in the big picture: self-reliance in semiconductor equipment ultimately comes down to "every tool's vacuum performance being credibly verified at shipment, and every wafer's process environment being credibly monitored." The credibility of verification and monitoring, in turn, ultimately comes down to whether the calibration system is self-reliant and traceable. For a long time, high-end calibration leaks and RGA quantification methods were bundled inside imported supply systems; once the microchannel process made "all media (single gases / mixtures / isotopes / liquids), all leak rates (10^{-3} ~ 10^{-10} mbar·L/s), in-situ zero-shock calibration" a routine domestic supply, **the last mile of upgrading RGA from a "reference tool" to a "metrological instrument" — the calibration link — was opened**. As fabs expand and nodes advance (below 2 nm pushing tolerances toward ppt), this market grows not linearly but multiplicatively with "verification stations × calibration frequency." The directions are equally clear: lower concentrations (ppb → ppt mixtures), wider mass range (> 500 amu precursors), materials-science breakthroughs for reactive-gas calibration, and automated periodic calibration integrated with RGA software.

9.8 Summary

- At its base, advanced-process competition is trace-contamination metrology competition: ppb/ppt tolerances demand the RGA upgrade from "trend watcher" to "metrological sensor";
- RGA quantitative accuracy is set by the calibration system: sensitivity-factor method, comparison method (Eq. 9-2/9-3, mirror image of pressure decay), fragmentation-pattern method (Eq. 9-4), liquid-medium breakthrough;
- ppm mixtures + two-stage dilution (Eq. 9-5) deliver ppb → ppt trace inputs; multi-isotope Kr / Xe is the natural mass ruler;
- The impossibility of calibrated leaks for reactive specialty gases is a global physical boundary — honest boundary marking plus a cross-sensor complementary architecture is the responsible technical route;
- A self-reliant RGA calibration system = a key piece of the metrology foundation for high-end manufacturing, and the calibrated leak's largest growth market of the next decade.

The next chapter returns to the main battlefield of production-line application: system-level accuracy of air-tightness testing.

Chapter 10 System-Level Accuracy of Air-Tightness Testing

> **What this chapter answers:** why a differential-pressure air leak tester with "0.1 Pa datasheet accuracy" still swings daily between false rejects and missed rejects on the line. This chapter gives a sobering derivation (how a 1 °C drift eats ~400 Pa), a proven system-level solution (the Golden-Part Four-Piece Kit + bypass method), and the final verification path that speaks in GR&R.

10.1 Why an "Allowable ΔP" Cannot Be the Criterion

From Eq. (8-1), judging leakage = judging pressure drop. The problem: **pressure is not changed by leakage alone**. For a sealed volume, the gas law gives the direct effect of temperature on pressure:

$$\frac{\Delta P_T}{P} = \frac{\Delta T}{T} \tag{10-1}$$

Insert typical line conditions: test pressure 20 kPa gauge (~121 kPa absolute), ambient 27 °C (300 K), a 1 °C drift of part or environment within the test cycle:

$$\Delta P_T = P \cdot \frac{\Delta T}{T} = 121\ \mathrm{kPa} \times \frac{1}{300} \approx 400\ \mathrm{Pa} \tag{10-2}$$

A 1 °C temperature drift ≈ a 400 Pa pressure drift. And what is a typical decision ΔP in air-tightness testing? Tens of Pa. In other words, **temperature noise is an order of magnitude larger than the leak signal** — any practice of "set an allowable ΔP and judge OK/NG" is physically equivalent to measuring microns with a thermally expanding ruler. The differential-pressure architecture (common-mode comparison between reference and test part) cancels slowly varying common-mode temperature fields, but not two residuals: the **temperature difference** between test and reference parts (uneven incoming temperatures, hot parts fresh off the line), and the **asymmetry of adiabatic effects** (gas heats on charge compression, then loses heat to the walls, pressure settling exponentially with a time constant of seconds — Fig. 10-1).

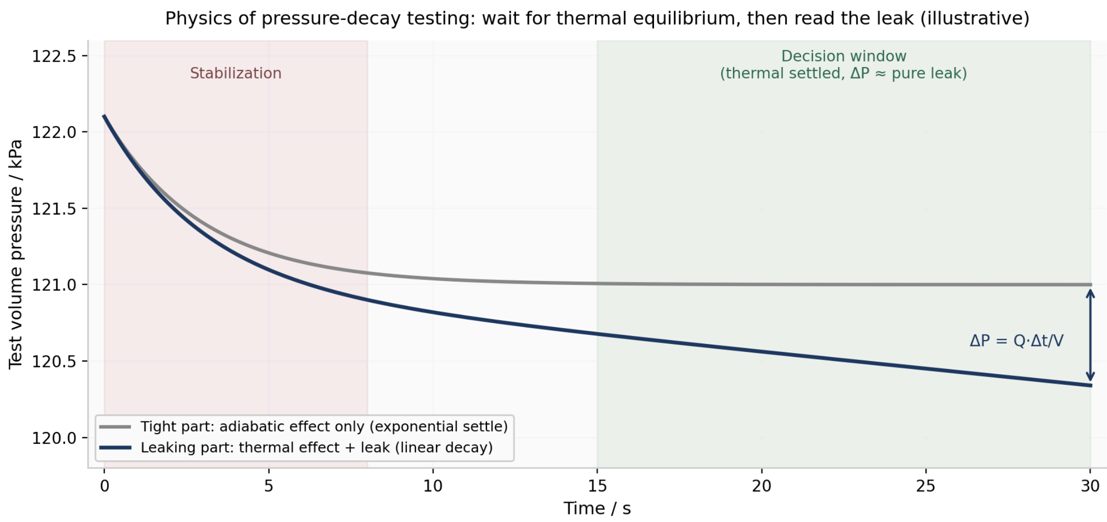

Figure 10-1 Pressure composition in decay testing: adiabatic effect (exponential settle) + leak (linear decay) — the decision window must come after thermal equilibrium

Table 10-1 Error-source budget for air-tightness testing (magnitude impression: 20 kPa gauge, 2 L part, 10 s test)

Error source	Mechanism	Typical magnitude	Countermeasure
Ambient / part temperature difference	Eq. (10-1), ΔP = P·ΔT/T	1 °C → ~400 Pa	Climate zone, incoming-temperature management, differential common mode
Adiabatic compression	Charge heating → heat loss to walls	Hundreds of Pa, exponential over seconds	Sufficient stabilization time (Fig. 10-1 decision window)
Fixture / part elastic deformation	Volume changes with pressure, V shifts	Structure-dependent; can exceed leak signal	Rigid fixtures, stops, identical reference part
Sensor zero drift & resolution	The differential sensor itself	0.1 ~ several Pa	Periodic calibration (JJF 1986—2022[9])
Volume calibration error	V in Q = ΔP·V/Δt is inaccurate	Several percent (relative)	Calibrate V with a calibrated leak, never estimate from drawings

Conclusion: **ΔP-based judgment is essentially "substituting physical assumptions for verification"** — assuming uniform temperature, assuming known volume, assuming completed thermal equilibrium. All three assumptions hold in the laboratory and are doubtful on the line. The way out is not a pricier sensor but making "judgment capability" a daily-verifiable system: the Golden-Part Four-Piece Kit.

The same cognitive traps exist on the helium side, more insidiously. **First, what a leak detector displays is not a leak rate but an ion current** — filament aging can make the same leak rate produce signals differing severalfold; the reading only acquires physical meaning through a calibration factor (CF), and an uncalibrated reading is a number without dimensions. **Second, single-point calibration cannot cover the full range** — ion-source contamination drifts the capture efficiency differently at each magnitude, and system conductance changes with flow regime (viscous for large leaks, molecular for small ones, Ch. 3), so extrapolated "linearity" across decades is a dangerous assumption. **Third, a 100% He leak cannot be rescaled to a low-concentration**

condition — partial pressure is not total pressure, and a mixture transports through micro-orifices differently from pure helium (§6.4); low-concentration testing must be verified with same-concentration simulation leaks under real conditions. All three point to one rule: **calibrate near the threshold, verify under real working conditions** — the Three-Reference Verification of the next chapter is exactly this rule, systematized.

10.2 From Instrument Accuracy to System Accuracy: A Shift of View

The datasheet's "accuracy 0.1% FS" describes a sensor; what the line needs is **judgment**. The gap between the two is opened by four links: tooling, environment, part condition, operation. System-level thinking splits leak judgment into three layers, each verified with a different standard piece:

- **Machine level**: is the tester itself still accurate? — verified daily with an external / built-in calibrated leak (Q_0 check piece);
- **Fixture level**: tester + fixture + plumbing + program parameters — can the assembled system still resolve a borderline leak? — verified with OK / NG simulation dummy parts;
- **System level**: is judgment stable across continuous production? — verified by periodic re-testing of boundary pieces and GR&R statistics.

One common counter-example of the three-layer architecture must be named: **a line that relies solely on the tester's "self-check" is essentially a black box**. The self-check calibrates the instrument against a built-in leak, yet the built-in leak's own drift is verified by no one — using an unverified ruler to verify the ruler is a circular argument; and a built-in leak usually provides a single rate point, so single-point fitting extrapolated to other magnitudes is unreliable (cognitive trap no. 2 at the end of §10.1). The credible practice is a **dual evidence chain**: a reservoir-type leak verifies the instrument itself (machine level — "is the gauge right"), while passive simulation leaks verify the system under real pressure, real medium and real takt (fixture / system level — "is the job right"). If the former fails, the instrument is flying blind; if the latter is missing, the whole line is judging blind. Neither is dispensable.

10.3 The Golden-Part Four-Piece Kit: Building the Judgment System into the Fixture

The Four-Piece Kit is the minimal complete configuration for system-level verification[7]:

Table 10-2 Composition and roles of the Golden-Part Four-Piece Kit

Piece	Physical composition	Verification goal & frequency
Q_0 check piece	Calibrated leak (rate = reject threshold or sensitivity class)	Per shift / daily check: instrument reading-drift monitor; machine level
OK dummy	Golden part + built-in / side-connected calibrated leak, total rate = (1/3 ~ 1/2) × threshold	Fixture level: must judge OK stably (false-reject guard)
NG dummy	Golden part + calibrated leak, total rate = (2 ~ 3) × threshold	Fixture level: must judge NG stably (missed-reject guard)

Golden part	A reference part confirmed leak-free by helium testing (or equivalent sealed dummy)	Carrier and reference for OK / NG dummies

The logical loop of the kit: **the OK piece guards the false-reject line, the NG piece guards the missed-reject line, Q_0 guards instrument drift, and the golden part provides a trustworthy carrier.** Run all four pieces at the start of each day, and the "today's health" of the judgment system is immediately known — turning the physical dilemma of §10.1 from "assumptions" into "daily measurement." Two engineering details: first, the OK/NG dummy leaks should be built into or side-connected inside the golden part, so that leak path, volume and temperature response match the real part (five identical conditions of simulation: same volume, pressure, medium, temperature, takt[7]); second, the stability of the leaks themselves is the premise of the kit's credibility — if a dummy's leak drifts with temperature (permeation +4 %/°C) or decays off, the referee's ruler changes by itself; this is why the kit prefers channel-type low-tempco leaks (Table 3-2).

Terminology note: the Q_0 + OK + NG pieces form the core verification logic; the golden part is their realistic carrier in pressure-decay scenarios (making leak path, volume and temperature response identical to real parts). In tracer-gas (helium) testing, the same verification system is called the **Three-Reference Verification** — with the same decision criteria: GR&R ≤ 15% + three-tier separation (Ch. 11). OK / NG dummy rates are (1/3~1/2) Q_0 and (2~3) Q_0 throughout this book.

10.4 The Connection-Method Accuracy Ladder and the Bypass SOP

How a calibrated leak is connected to the test system directly decides the credibility of the verification value. Four connection methods form a ladder from low to high fidelity:

Table 10-3 Accuracy ladder of leak-connection methods

Method	How it is done	Main error	Applicability
① Direct quick-plug	Leak plugged into the instrument's calibration port	Completely decoupled from the fixture	Instrument-only verification (machine level)
② Line tee-in	Leak connected into the charging line	Path differs from the part	Coarse verification
③ Built into dummy	Leak embedded inside a golden-part dummy	Dummy fabrication needed	Standard practice for OK/NG dummies
④ Bypass method	Leak connected across the test volume via a bypass valve; opened mid-test to inject a known leak	Minimal (real part, real plumbing, real takt)	Highest grade of system verification and volume calibration

Bypass-method SOP (system-level accuracy verification and equivalent-volume calibration):

1. Clamp a real part; charge and stabilize per the normal program;
2. After entering the test segment, open the bypass valve to inject the calibrated leak of known rate Q_0 in parallel;
3. Read the incremental pressure change ΔP_0, and solve for the system's equivalent volume from Eq. (8-1): $V = Q_0 \cdot \Delta t / \Delta P_0$;

4. Close the bypass valve to restore normal operation. This V contains all real plumbing, fixture and part — far better than any drawing estimate;
5. Repeat periodically: drift of V is an early signal of system state changes.

> **Rule 10-1:** The credibility of air-tightness judgment depends not on sensor digits but on "whether the system can stably separate the OK dummy from the NG dummy today." Daily Four-Piece verification + periodic bypass volume calibration is the lowest-cost path that turns ΔP judgment from physical assumption into engineering evidence.

10.5 Closing with GR&R: Statistical Proof of the Judgment System

Once the system is built, prove it metrologically: take samples near the boundary (OK dummy, NG dummy and borderline parts), run repeated measurements by multiple operators, and perform a GR&R (gage repeatability & reproducibility) analysis; for attribute judgment (OK/NG), run an attribute agreement analysis (Kappa). Common industry thresholds: variable GR&R ≤ 10% acceptable, 10~30% risk-dependent, > 30% unusable; for OK/NG judgment systems, the more direct engineering criterion is **GR&R ≤ 15% + three-tier separation** (OK, Q_0, NG readings clearly tiered without overlap, §11.3). A GR&R report is also the language most accepted by OEMs and auditors — **the Four-Piece Kit is the daily thermometer; GR&R is the periodic health check**.

10.6 Summary

- A 1 °C drift ≈ 400 Pa pressure drift (Eq. 10-2), an order of magnitude above typical decision ΔP — a naked ΔP criterion is physically untenable;
- Judgment is verified in three layers: machine (Q_0 checks), fixture (OK/NG dummies), system (GR&R);
- OK guards false rejects, NG guards missed rejects, Q_0 guards drift, the golden part carries — the Four-Piece Kit is the minimal complete configuration;
- The bypass method tops the accuracy ladder: back-calibrating the system's equivalent volume with a known leak — real part, real plumbing, real takt;
- The kit's dummy leaks must themselves be stable (low tempco, predictable decay) — otherwise the referee changes first.

This chapter solved system accuracy for "air testing"; the next chapter solves the cost dilemma of "helium testing": in the era of helium at 300+ RMB/m³, how to cut helium usage by one to two orders of magnitude without losing judgment capability.

Chapter 11 The Helium-Reduction Paradigm: Equivalent-Orifice Relative Comparison and Three-Reference Verification

> **What this chapter answers:** under the 2026 helium supply crisis, how to cut helium usage to 1/10 or even 1% **without losing judgment capability**. This chapter offers a three-layer answer: the physics first principle at the cognition layer (equivalent-orifice comparison), Three-Reference Verification (Q_0 + OK + NG) at the method layer, and the stepwise concentration-reduction iteration (finding the Minimum Working Concentration, MWC) at the engineering layer — with an honest disclosure of applicability boundaries. This is the book's most methodology-intensive chapter, and the mainstream direction of helium-testing lines for the next decade[12].

11.1 The Helium Crisis and Three Mindsets

In March 2026, escalating geopolitical conflict in the Middle East severely damaged facilities at Ras Laffan Industrial City in Qatar — the world's second-largest helium production base — with repairs expected to take 3~5 years; together with the United States, Qatar forms the two pillars of global helium supply (30%~39% of the world total). Chinese landed prices for industrial-grade helium soared from 50~70 RMB/m³ in 2025 to 300~400 RMB/m³ in April 2026, a 5~10-fold increase. China's helium consumption relies on imports for about 90%, of which 54%~66% comes from Qatar — even those willing to pay the premium may not secure a stable quota[12]. "Reducing helium consumption per test" has upgraded from a cost-optimization option to an industrial-survival option.

Under the crisis, the industry shows three mindsets:

Table 11-1 Three mindsets in the leak-testing industry

Mindset	State of mind	The problem
Pure-He fundamentalists	"Pure helium is the only standard; any concentration cut means risk"	The belief is unverified — pure helium itself cannot guarantee reliability (§11.3)
Reluctant reducers	Already down to 80%, 60% He, but "honest in body, not in faith," planning to return to pure He once prices fall	The unease comes from "no verification," not from "lower concentration" — they never ran three-reference verification at 80% He, nor did they at 100% He
Three-Reference verifiers	"Verification passed = system reliable, regardless of concentration"	The correct cognition — needs promotion

The key cognitive shift: **from "concentration determines reliability" to "verification determines reliability."** "80% He is less reliable than 100% He" is an untested assumption — the correct comparison is "80% He + three-reference verification = reliability confirmed" versus "100% He + no verification = reliability unknown." Concentration anxiety is unsolvable (helium prices are beyond your control); verification anxiety is solvable (three references, a few minutes per shift).

11.2 The Physics First Principle: The Four-Layer Framework of Equivalent-Orifice Comparison

All air-tightness and leak testing does exactly one thing: **compare the size of the equivalent leak channel on the workpiece** (§1.4). Split this judgment into four layers and the industry's misconceptions become visible at a glance:

Table 11-2 The four-layer framework of leak testing

Layer	Content	Variable?	Industry misconception
Physical reality	The workpiece's equivalent orifice d_0	Immutable	Ignored
Purpose	Judge $d > d_0$ (NG) or $d < d_0$ (OK)	Immutable	Distorted into "precise measurement"
Means	Tracer gas: 100% He / 1% He / Air / N_2	Replaceable	"Only pure helium works"
Reading	The mbar·L/s number on the instrument	Varies with means	The number is mistaken for physical reality

Whether you charge 100% helium or 1% helium, the physical orifice on the workpiece does not change by a single micron — leak rate Q is a function of gas species, pressure difference, temperature and flow regime (Eq. 3-1 ~ 3-4), not an intrinsic property of the leak channel; switching concentration only changes the mixture's mean molar mass and effective partial pressure. **The industry's core misconception is mistaking the fourth layer (the reading) for the first layer (physical reality), and mistaking one option in the third layer (100% He) for the only option.**

A long-overlooked fact: **air leak testers proved long ago that non-helium gases can reliably compare orifices**. A differential-pressure air tester uses compressed air (containing only ~5 ppm helium) as medium, has no mass spectrometer, and still judges Pass/Fail stably on production lines (Ch. 10). From air testing → low-concentration helium testing → pure-helium testing is a continuous spectrum, not a black-and-white boundary — if testing's essence were "absolute accuracy of the instrument reading," air testers could not work at all; they do work, which means the essence is "sufficient discrimination." The ultimate output of line testing is a binary Pass/Fail; the core need is **judgment consistency**, not **absolute accuracy**.

Under ideal conditions, this judgment can be written as clean mathematics. The helium-test signal (sniffer or vacuum method) for a leak Q is:

$$S = k \cdot c \cdot Q \tag{11-1}$$

S — instrument signal (rate reading); k — instrument sensitivity coefficient (transmission, ionization, amplification); c — helium concentration in the tracer gas; Q — total leak rate of the workpiece's leak point.

Measure the workpiece and the calibrated leak under the **same concentration** of tracer gas (same source), and take the signal ratio:

$$R = \frac{S_{\text{part}}}{S_{\text{leak}}} = \frac{k \cdot c \cdot Q_{\text{part}}}{k \cdot c \cdot Q_{\text{leak}}} \approx \frac{Q_{\text{part}}}{Q_{\text{leak}}} \tag{11-2}$$

In the ratio R, k and c cancel **approximately** — this is the ideal model of judgment. But note: it is only a zero-order approximation; the deviation sources and engineering countermeasures follow in §11.3.

> **Principle 11-1 (Equivalent-orifice comparison):** The essence of leak judgment is "comparing sizes," not "reading numbers." The "size" here means the **rate of the equivalent leak channel** (§1.4) — what is compared is the channel's gas-transport capability, not its geometric shape, and certainly not the absolute instrument reading. The ratio R (Eq. 11-2) gives the ideal model: with workpiece and calibrated leak measured at the same concentration on the same instrument, sensitivity k and concentration c cancel approximately; dropping helium concentration from 100% to 1% leaves judgment capability unchanged in principle. **But the engineering implementation of this principle does not rely on the cancellation being exact — real systems exhibit flow-regime nonlinearity, system drift and concentration fluctuation (§11.3); the final basis of judgment is three-reference measured verification (GR&R ≤ 15% + three-tier separation), not theoretical derivation.** Note the applicability domain: this principle covers all "judgment" scenarios (OK / NG); metrology and traceability scenarios (Ch. 7) are tasked with "reading numbers," where absolute measurement still requires full sensitivity and standard concentration — judgment by comparison, metrology by traceability; do not mix the two.

11.3 From Mathematical Cancellation to Engineering Comparison: Three-Reference Verification

Early versions of the helium-reduction argument (including this book up to V1.2) stated the cancellation in Eq. (11-2) as "exact." Deep engineering practice has shown this statement **over-idealized**; it needs correction. Real systems exhibit three classes of deviation:

- **Flow-regime nonlinearity**: when He concentration drops from 100% to 1%, the mixture's mean molar mass changes from 4 to about 28. In molecular flow (Kn ≫ 1) conductance scales as 1/√M and the signal scales roughly linearly with concentration; but in transitional flow (0.01 < Kn < 1) the viscous component is not negligible, and mixture viscosity follows complex nonlinear mixing rules — the signal may fall by 80× or 120× instead of exactly 100×, and workpieces of different orifice sizes may even behave inconsistently as they cross regimes;
- **System non-idealities**: filament aging, electronics temperature drift and vacuum-background fluctuation make k not strictly constant;
- **Concentration non-constancy**: dynamic consumption from the mixing tank and line adsorption/desorption make c not strictly constant.

The methodology must therefore complete three turns: **from "mathematical cancellation" to "engineering comparison"** — no longer pursuing a proof that the concentration term cancels exactly; three-reference measured verification replaces mathematical cancellation as the basis of judgment. **From "single-piece Q_0 calibration" to "Three-Reference Verification"** — Q_0 + OK + NG verified together, ensuring the system works reliably in its actual state of the day. **From "theoretically determined concentration" to "iterating to the MWC"** — not presuming 1% must work; use the stepwise concentration-reduction method to find each scenario's optimal concentration by measurement (§11.4). This correction does not weaken the scheme's reliability — it strengthens its honesty and operability.

Three-Reference Verification (Q_0 + OK + NG) is the gold standard of leak testing — whether at 100% He or 1% He, whether or not helium is reduced:

Table 11-3 Composition and roles of the three references (analogy: calibrating the scale daily)

Reference	Leak rate	Verification goal	Scale analogy
Q_0 threshold piece	= reject threshold	Anchor the Pass/Fail boundary	1 kg weight — does the scale read 1 kg?
OK piece	(1/3 ~ 1/2) Q_0	Verify "no false rejects" (good parts not killed)	0.5 kg weight — surely it won't read 1.2 kg?
NG piece	(2 ~ 3) Q_0	Verify "no missed rejects" (bad parts always caught)	2 kg weight — surely it won't read 0.8 kg?

Run all three references at the start of each day / shift — this is the correct way to open a leak-testing line. **Only two conditions decide system usability: ① system GR&R ≤ 15% (the common measurement-system-analysis standard); ② three-tier separation (OK, Q_0, NG readings clearly tiered, no overlap). When both hold, the system works — whether on 100% He, 1% He, or air.** The discrimination ratio (measured reading ratio) is a natural consequence of the two conditions rather than an independent constraint: with the conventional choices OK = (1/3~1/2)Q_0 and NG = (2~3)Q_0, even at SNR as low as 3 the discrimination ratio typically stays between 2~5; GR&R ≤ 15% keeps within-tier fluctuation far below the inter-tier gap, leaving no "gray zone" between tiers (Fig. 11-1).

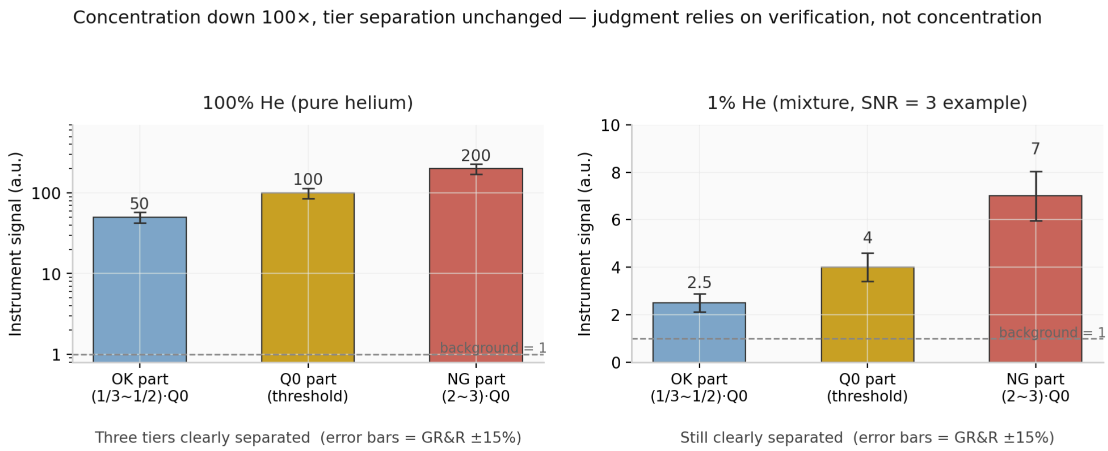

Figure 11-1 Three-tier separation: concentration down from 100% to 1% (signal down 100×), yet with GR&R ≤ 15% the OK / Q_0 / NG tiers remain clearly separated (SNR = 3 example: background 1, readings 2.5 / 4 / 7, discrimination ratio 2.8) — judgment relies on verification, not concentration

This is the dividend of the paradigm shift: **the traditional "absolute metrology" paradigm demands SNR ≥ 10 (the rate value must be known precisely); the "size comparison" paradigm needs only SNR ≥ 3 ~ 5, provided GR&R ≤ 15%** — from "precise measurement" to "sufficient discrimination," the threshold drops dramatically.

There is also a frequently inverted positioning of Three-Reference Verification: **it is not an accessory of helium reduction — it is the best practice even under pure helium**. 100% He solves only the single dimension of "signal strength," while test reliability is a system engineering of instrument, environment, operation and standards — instrument sensitivity drift (filament aging, electronics drift — concentration-independent), environmental background spikes after gross leaks (pure He makes gross leaks dump *more* helium and pollute *worse*), calibrated-leak self-drift (permeation leaks decay 1%~5%/year — concentration-independent), fixture and operation differences, vacuum-system micro-leaks: none of these five problem classes disappears automatically under pure helium. Thought experiment: two lines both on 100% He — line A, which never verifies, may "fly blind" for months after 30% filament aging, shipping batches of missed rejects unnoticed; line B, verifying daily, would spot an 18% drift of the Q_0 reading on day three and act immediately. **The problem has never been concentration; it is whether you verify.** Helium reduction is an extension of Three-Reference Verification — since you should verify daily anyway, finding the lowest workable concentration along the way is pure cost saving: **what helium reduction cuts is cost, not quality.**

11.4 Stepwise Concentration Reduction: Finding the Minimum Working Concentration (MWC)

The Minimum Working Concentration (MWC) is not computed — it is measured, through three-reference verification. The procedure: first establish baseline readings of the three references at 100% He and record the discrimination ratio (Step 0); then step down through 50% → 20% → 10% → 5% → 2% → 1%, re-running the full three-reference verification at each level — if the three tiers stay clearly separated, keep descending; if tiers overlap or GR&R > 15%, stop, and **MWC = the previous level**. Every part–equipment combination finds its own optimum this way — the methodological upgrade from "guessing 1%" to "scientifically finding the optimum." Two execution details: first, the iteration must run at the **target takt** — verify with the same integration time as the line's actual takt (minimum detectable rate depends on integration time; a 3~5 s/part ultra-fast line has different margin than a tens-of-seconds conventional line, though even the fastest lines retain large margin in industrial helium testing); second, record environmental parameters such as temperature and humidity alongside.

Reference starting concentrations by threshold magnitude (iteration starting points, not conclusions):

Table 11-4 Graded helium-reduction reference (final concentration determined by three-reference verification at target takt)

Threshold class	Typical applications	Reference starting conc.	Notes
10^{-4} mbar·L/s	Automotive A/C lines, ordinary refrigeration parts, general industrial seals	1% ~ 3%	Huge margin; no pressure at any takt
10^{-5} mbar·L/s	Battery cases, refrigeration compressors, medium-seal industrial parts	1% ~ 5%	Core application range; the economic "sweet spot"

10^{-6} mbar·L/s	High-seal relays, some medical devices, aerospace critical seals	10% ~ 20%	Higher concentration needed to pass verification; still saves 80%~90% vs pure He

Low concentration carries a counter-intuitive dividend: the **active noise-reduction effect**. On pure-He lines, test exhaust (about 60%~70% of total emissions), joint and seal micro-leaks, part-surface desorption and calibration exhaust can push the workshop's local helium background from the natural 5 ppm to hundreds or even thousands of ppm; switching to a 1% mixture cuts the absolute helium emitted per test by ~100×, total workshop He emissions by ~99%, and the background returns to natural levels. The "memory effect" after gross-leak parts (helium adsorbed on mass-spectrometer chamber walls releasing slowly, conventionally requiring minutes to tens of minutes of clean-up waiting) shrinks to seconds under the mixture scheme, since the absolute helium flushed in drops by two orders of magnitude — no shutdown needed. In SNR = signal / noise: the numerator (signal) falls with concentration, but the denominator (ambient He interference) falls even more — **at sites with severe ambient helium pollution, the effective SNR may actually rise rather than fall**. This is the scheme's core insight: "counter-intuitive" yet "physically rigorous."

A simple flow-regime guide: **molecular flow** ($Kn \gg 1$) — signal-vs-concentration is approximately linear, but three-reference verification is still mandatory; **transitional flow** ($0.01 < Kn < 1$) — possibly nonlinear, verification absolutely required; **viscous flow** ($Kn < 0.01$) — significantly nonlinear, helium reduction not recommended. All flow-regime effects are absorbed by three-reference comparison — every step of concentration iteration trusts measurement, not theory.

11.5 The Cost Ledger: Starting from 300 RMB/m³

Helium cost ≈ usage × concentration (at fixed recovery rate, Fig. 11-2):

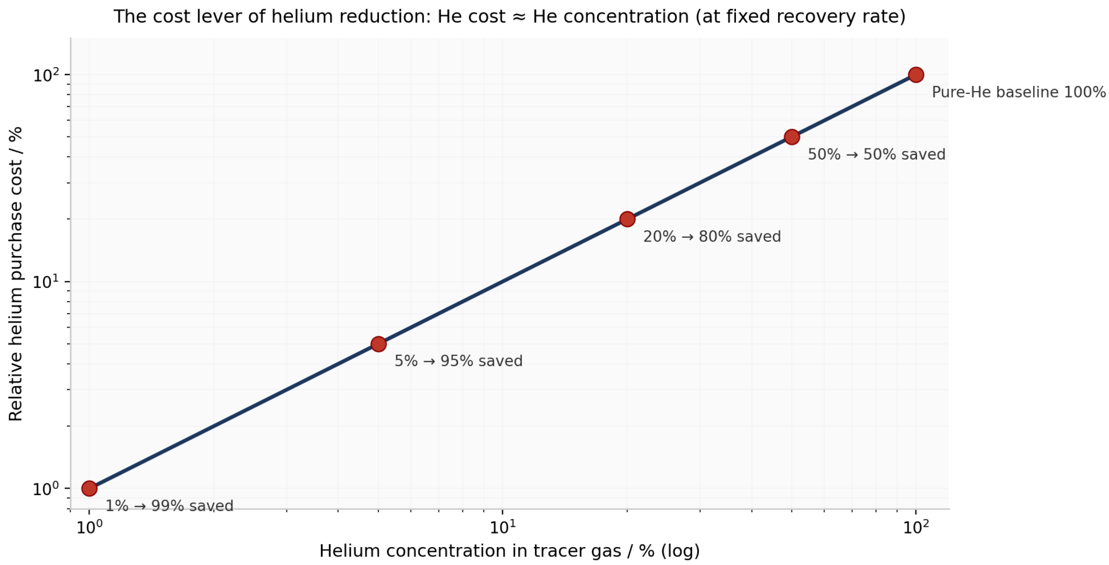

Figure 11-2 The cost lever of helium reduction: helium cost is proportional to concentration (at fixed recovery rate)

A concrete ledger (battery-pack helium-testing line, 5~6 million parts/year, industry operating-data caliber[12]): the pure-He scheme consumes ~300 cylinders/year (50 L × 20 MPa, ~3,000 RMB/cylinder), ~900,000 RMB/year of helium; at 10% concentration, consumption falls to ~30 cylinders, ~90,000 RMB — **annual savings of about 800,000 RMB** — while the one-time investment for Three-Reference Verification is only

10,000~30,000 RMB (Q_0 calibrated leak + OK / NG dummy fabrication), and mixing equipment costs far less than recovery systems. The hidden gains are equally substantial: daily three-reference verification eliminates batch misjudgment from systematic drift (false-alarm rates can drop by 50%+); post-gross-leak clearing time falls from minutes to seconds, lifting effective takt by 3%~8%; per-shift three-reference calibration records give quality audits evidence (satisfying IATF 16949 and similar systems); and low consumption is itself a supply-chain risk hedge.

The ledger has a second dimension — the total cost of ownership (TCO) of the standard itself. The hidden expenses of conventional permeation / glass-process leaks are spread over three items: transport losses and accidental scrap from fragility, frequent recalibration trips with line-down waiting, and batch misjudgment caused by drift. Leaks with low decay (0.1% ~ 2.5%/year, §16.3), proven drop/freeze performance (§15.2 measurements), and wide-temperature, no-special-storage operation stretch the recalibration cycle reliably to 12 months (the §15.3 apparatus example) and remove "handle with kid gloves" from daily work. These savings are not denominated in helium, but they reach the income statement just the same. At selection time, replacing "unit price" with "TCO = purchase price + recalibration fees × years + scrap rate × replacement cost + misjudgment risk cost" often reverses the conclusion.

Helium reduction is not a point technology but a three-factor product of "concentration × recovery × judgment method" — and the judgment-method factor (Three-Reference Verification) happens to be the cheapest and purest cognitive lever of the three. The bigger picture: when industrial helium testing cuts helium usage to 10% of before, the same import volume supports more than 10× the testing demand, domestic limited capacity becomes "enough," and the helium crisis is dissolved on the demand side — a "demand-side revolution" that also gives China the chance to become the definer of low-concentration helium-testing standards[12].

11.6 Applicability Boundaries and Honest Disclosure

An honest white paper must state its boundaries clearly. Applicability by test method:

Table 11-5 Applicability of helium reduction by test method

Method	Applicability	Core requirement	Notes
Vacuum method	Most thoroughly proven	Chamber sealing, sufficient pumping speed	Dual benefit of He reduction (signal ↓, background ↓↓)
Positive-pressure accumulation	Fully feasible	Sealed accumulation chamber, time control	Essentially similar to vacuum method; common in the battery-pack industry
Sniffer method	Feasible but higher bar	Intake flow must be constant (MFC / constant-flow pump)	Ambient He background fixed at ~5 ppm: reducing He does not reduce noise, SNR falls strictly; MWC usually higher than vacuum method
Pressure decay / differential	**Not applicable**	——	Air is the medium; no tracer-concentration concept (its system-level verification is Ch. 10)

- **Dual-track system**: industries that mandate absolute-rate reporting (aerospace GJB, medical devices, etc.): use low-concentration Three-Reference Verification for daily production, and retain pure-He capability for type tests or customer acceptance reports;

- **Magnitude boundaries**: 10^{-4} ~ 10^{-5} mbar·L/s (vacuum / accumulation methods) — mature and reliable; 10^{-6} class — feasible after careful verification; 10^{-7} and below — outside the scope claimed by this scheme;
- **Temperature effects**: low-tempco leaks (0.1 %/°C class) are negligible in general industrial environments (±2 °C), but the workpiece's own rate may vary with temperature (polymer seal thermal expansion, etc.); environments swinging > 10 °C warrant a temperature-sensitivity test;
- **Concentration-fluctuation control**: size the mixing tank > 200× single-cycle consumption, install online concentration monitoring, zone the supply for multi-station lines, qualify 2+ gas-mixture suppliers;
- **Response time**: signal buildup lengthens at low concentration — leave stabilization margin in takt design;
- **Three hard specs for simulation leaks**: rate and specified pressure customized together (threshold = target), low tempco (no climate control on lines), shock and drop resistance (line environment); and the leak must match the workpiece in **concentration, pressure and medium** — mixture simulation leaks are customized to the site's actual concentration and certified on the total-rate basis (§6.4 P/T basis); a "fake same-source" pair (pure-He leak vs mixture-charged workpiece) voids the ratio. Methodology ultimately lands back on device physics (Ch. 3~5).

> **Rule 11-1:** The correct order of helium reduction: first build Three-Reference Verification (worth doing at any concentration — pure He included); then iterate to the MWC by measurement (never pick a concentration by guess); control the background in parallel (protect SNR); and finally add recovery (tail-helium purification and reuse). Get the order wrong, and the money is wasted.

11.7 Summary

- The essence of leak testing is comparing equivalent orifices: gas is only the tracer medium, the reading only the means' response; the only invariant is d_0 (four-layer framework, Table 11-2); air testers long ago proved non-helium gases can compare orifices reliably;
- The ratio R = Q_part / Q_leak is a zero-order approximation (Eq. 11-2) — flow-regime nonlinearity, system drift and concentration fluctuation defeat "exact cancellation"; engineering judgment rests on three-reference measured verification, not mathematics;
- Three-Reference Verification (Q_0 + OK (1/3~1/2)Q_0 + NG (2~3)Q_0) is the gold standard: the only usability criteria are GR&R ≤ 15% + three-tier separation, independent of helium concentration; unverified pure helium is "flying blind" just the same;
- The paradigm dividend: SNR ≥ 3~5 suffices (absolute metrology demands ≥ 10); low concentration also actively reduces noise — at heavily polluted sites SNR may rise rather than fall;
- The MWC is found by stepwise iteration (100% → 50% → 20% → 10% → 5% → 2% → 1%); reference starts: 1%~3% for 10^{-4} class, 1%~5% for 10^{-5} class, 10%~20% for 10^{-6} class;
- Battery-pack ledger: ~800,000 RMB/year saved on helium, against a one-time 10,000~30,000 RMB for three references — what helium reduction cuts is cost, not quality;
- Boundaries: vacuum / accumulation methods fully feasible; sniffer needs constant intake flow and gains no noise reduction; pressure decay not applicable; dual-track for absolute-reporting industries; 10^{-7} class not claimed.

The final chapter of Part III returns to the most everyday question: given a requirement, how to choose the right leak step by step — and the pitfalls we have stepped into over the years.

Chapter 12 Selection Methodology and Common Pitfalls

> **What this chapter answers:** given a leak-testing requirement, how to converge step by step onto the right leak (and certificate); plus the fifteen most frequent mistakes in the industry. This chapter is the book's "practical terminus" — print it out and pin it at the desks of your procurement and process engineers.

12.1 The Five-Step Selection Method

Selection is essentially fixing the "four working-condition elements + form" of Chapter 2. Converge in the following five steps, each mapping to earlier chapters:

Table 12-1 The five-step selection method

Step	Question to answer	Chapters & key points
① Fix the medium	What gas? Pure / mixture / refrigerant / liquid? Concentration and P/T basis?	§6.4 mixture basis; §6.5 liquid media; refrigerant g/y (Eq. 2-4)
② Fix the rate	What is the reject threshold? Sensitivity verification or OK/NG simulation?	Threshold × (1/3~1/2) for OK pieces, × (2~3) for NG pieces (§10.3)
③ Fix the pressure	Inlet pressure (absolute!), outlet condition (vacuum / atmosphere)?	§2.4 gauge vs absolute; §2.5 positive/vacuum bases (Rule 2-1)
④ Fix the form	Reservoir or passive? Fittings and mounting space? Valve needed?	§1.6 taxonomy; Ch. 6 three valve questions (Rule 6-1)
⑤ Fix the certificate	Factory certificate / institute calibration certificate? Uncertainty requirement?	Ch. 7 five-element check (Rule 7-1)

After the five steps, what you get is not a model number but a line of "working-condition language" — e.g. "N_2, 2.0×10^{-4} Pa·m³/s, inlet 6 bar absolute, outlet atmosphere, passive, VCR 1/4." Any serious leak manufacturer should quote price and lead time from that line. A requirement that cannot be stated this way will repay, with interest at acceptance time, every cent saved on the quotation.

12.2 Reservoir or Passive: A Decision Table

Table 12-2 Reservoir / passive decision table

Scenario profile	Recommendation	Rationale
Detector sensitivity calibration, metrological traceability, mobile checks	Reservoir	Self-contained supply, portable, complete certificates; decay managed via Eq. (3-9/3-10)
Line OK/NG dummies, Four-Piece Kit, helium-reduction simulation	Passive	Zero decay, same source and pressure as the workpiece, customizable to any pressure/medium
Reservoir need at large rates (> 10^{-3} mbar·L/s)	Reservoir + zero-volume valve	Dead-volume loss and decay are amplified at high pressure and large rates (Rule 6-1)

RGA / UHV / expensive isotopes	Reservoir (zero-volume valve) or passive	Background and gas-loss hard constraints
High-pressure (> 10 bar) condition simulation	Passive	Microchannel passive pieces withstand 40 MPa; reservoir systems are a separate family

12.3 Decoding the Ordering Logic: Five Promises in One Code

A proper ordering code should decode segment by segment (illustrative structure): medium – leak rate – inlet pressure – fitting – certificate level. At acceptance, check each segment against the certificate's five elements (Table 7-3): if the code says "6 bar absolute" while the certificate says "6 bar gauge," the one-atmosphere gap is an order-of-magnitude error on the low-pressure side (§2.4). **Code, nameplate and certificate telling one consistent story is the first formality of incoming acceptance.**

12.4 Customization Flow and Lead-Time Expectations

One meaning of the microchannel process is "customization as the norm": specified pressure + specified rate + specified medium, with geometry computed first by conductance simulation (Eq. 3-4), then machined, then actually calibrated and certified. Reasonable expectations: routine customization delivers in ~3~5 working days; extreme specs (below 10^{-12}, 40 MPa, special media) need technical review. **The touchstone for whether a manufacturer truly owns the process: can they accept "pressure and rate customized together" — instead of only letting you pick from a shelf list.**

12.5 Top-Fifteen FAQ

1. **How long does a leak last?** Passive channel-type: no natural lifetime limit (periodic recalibration suffices). Reservoir: watch Q/(pV) (§3.8); high-pressure large-volume products can hold annual decay to 0.1%~2%.
2. **Can an inaccurate leak be repaired?** For microchannel leaks, most cases are clogging or contamination — clean, unclog and recalibrate; geometric damage is irreparable. Glass pieces are essentially irreparable.
3. **Dropped it once — still usable?** Glass / quartz pieces: write off by default. For drop-verified monolithic metal leaks (e.g. 1.2 m × 5 cycles), simply re-measure the rate to confirm.
4. **Certificate expired — still usable?** The value loses traceability: usable only as a "reference piece," not a "standard"; recalibration restores status.
5. **Why don't the new leak's readings match the old one's?** Check the five elements first (Table 7-3): medium, pressure basis, outlet condition, temperature, uncertainty — eight times out of ten it is a basis mismatch, not a broken leak.
6. **Are lower workshop readings in winter normal?** Check the tempco sign: viscous-dominated air-tightness leaks gain rate when colder; molecular-flow-dominated helium leaks lose rate (Table 3-2), ~0.1~0.6 %/°C in magnitude — correct first, suspect the instrument later.
7. **Why does a permeation leak need a temperature-correction table?** The +3~4 %/°C Arrhenius mechanism (§3.7): without correction you carry a built-in drift of a dozen-plus percent per month.

8. **Can a calibrated leak serve as a product leak point?** Not in reverse: the leak is the "standard source," the workpiece leak point is the "object under test"; simulate the critical defect with OK/NG dummies (§10.3).
9. **How bad is mixing up sccm and mbar·L/s?** A factor of 59.2 (Eq. 2-3). Write units in full when specifying; convert first at acceptance.
10. **What if someone forgets to close a reservoir leak's valve?** Continuous discharge shortens life — choose normally-closed valves or build check habits (§6.3).
11. **Are hydrogen calibrated leaks dangerous?** At micro rates they release ~0.3 mL/day, far below any safety-concern limit (§2.3 magnitude intuition); ordinary ventilation suffices.
12. **Why are field readings at 5 MPa wrong with a 10 MPa certificate?** In viscous flow $Q \propto p^2$ (Eq. 3-2): halving pressure quarters the rate. Order for the use pressure; never redeploy across pressures.
13. **Which "rate" does a mixture leak's rate mean?** Always ask: P basis (a component's partial rate) or T basis (total rate) — they differ by $\sqrt{M}$ weighting (§6.4).
14. **What should a metrology institute buy to establish its standard?** A reference-leak set: covering 5~6 orders of magnitude, each piece traceable to national level, annual stability and uncertainty meeting JJF 1833—2020 (§7.5).
15. **How to quickly judge a leak manufacturer's real level?** Four questions: What is the tempco (and can they explain it by flow regime)? Are bidirectional rates equal (Rule 4-1)? Can they customize pressure and rate together? Do they dare show drop / freeze–thaw re-test data?

12.6 Summary

- Five-step selection: medium → rate → pressure (absolute) → form → certificate, producing one complete "working-condition sentence";
- Reservoir vs passive by scenario: traceability calibration → reservoir; line simulation → passive;
- Code = nameplate = certificate: consistency is the first acceptance formality;
- "Can pressure and rate be customized together" is the touchstone of process authenticity;
- The fifteen questions cover 80% of field disputes — most disputes are basis problems, not product-quality problems.

Part III is complete. The reader now owns the full equipment from physics to methodology. Part IV shows what a product matrix and technology system look like when one factory fully masters and engineers this knowledge system.

PART IV

Solutions | The RealMeter Answer

Chapter 13 Four Core Technology Platforms: Answers to the Physics of the Previous Twelve Chapters

> **What this chapter answers:** the previous twelve chapters built a complete set of physical yardsticks for evaluating calibrated leaks. This chapter answers: what technology system grows when those yardsticks are engineered to their limits. Every technology maps back to a physical problem posed earlier — this is a "problem–answer" structure, not a product-promotion structure.

13.1 The Logic of Answering: A Problem List

Table 13-1 Physics problems of Ch. 1–12 and their corresponding technologies

Problem posed earlier	Where	Technology answer
The orifice must be a "design value," not a "luck value" (d^4/d^3 sensitivity)	Ch. 3, §4.1	RMI-MTC™ microchannel capillary process
Only an ideal circular tube is non-directional, clog-resistant and computable across all regimes	§4.9 Rule 4-1, §5.6	RMI-MTC™ (equal bidirectional rates)
Seal background sets the lower limit of tiny rates (the 10:1 rule)	§5.2, Eq. (5-1)	RMI-Metal™ all-metal sealing < 10^{-15} atm·cc/s
Adsorption/outgassing is the "phantom leak" of UHV / RGA	§5.3, Eq. (5-2)	RMI-Metal™ + integrated design (no adhesives, no assembly interfaces)
The three costs of dead volume: loss, shock, memory	Ch. 6, Eq. (6-1)	RMI-PSOZV™ / MDZV™ zero-volume valves (0.098 μL)
Mixture partial rates and all-regime conversion must be computable	Eq. (3-4), §6.4	RMI-Cal™ conductance-simulation engine
Reservoir decay rate ∝ Q/(pV): the lifetime contest is a pressure contest	§3.8 Rule 3-2	High-pressure reservoirs (≤ 12 MPa) + normally-closed zero-volume valve fool-proofing
Tempco is set by flow regime — how low can it go?	§3.7 Table 3-2	Measured: +0.1 %/°C (molecular-flow reservoir), −0.6 %/°C (viscous-flow passive) — theory delivered

13.2 RMI-MTC™ Microchannel Capillary Process: From Craft to Design

Geometrically defined microchannels are machined directly into a metal body, with orifice continuously controllable from 50 nm to 200 μm — computed first from the conductance formulas (Eq. 3-2, 3-3, 3-4), then machined[3]. Against the four yardsticks of Chapter 4:

- **Orifice as design value:** pressure and rate customized together (e.g. "2.3×10^{-7} Pa·m³/s at 34 bar gauge"); tolerance from ±10%, available at ±5% or tighter — the ±2.4% orifice tolerance of Eq. (4-1) is routine for

CNC micro-machining;

- **Ideal circular tube:** non-directional rate (direct evidence for Rule 4-1); uniform bore without a throat, hence clog-resistant (§5.6); all-regime behavior fully described by Eq. (3-4);
- **Mechanical strength:** monolithic metal structure — passive leaks rated 40 MPa, enduring repeated 400-bar pressure shocks, passing a 1.2 m × 5-cycle drop test, operating temperature −20 ~ +65 °C (withstanding −30 °C freezing)[3];
- **Tempco delivers theory:** reservoir (molecular-flow dominated) +0.1 %/°C; passive (viscous-flow dominated) −0.6 %/°C — exactly the magnitudes predicted by Eqs. (3-5)/(3-6), an order of magnitude below permeation membranes (Table 3-2).

13.3 RMI-Metal™ All-Metal Sealing: Pressing the Background Down to 10^{-15}

Seal background < 1×10^{-15} atm·cc/s — 5~6 orders of magnitude ahead of conventional sealing processes (10^{-9} class)[3]. Re-read this number through §5.2's 10:1 rule: it means background is no longer a constraint on any foreseeable rate spec — the lower limit of channel-type leaks advances to the 10^{-12} atm·cc/s (10^{-13} Pa·m³/s) class. Meanwhile, the adhesive-free, polymer-free, integrated structure eliminates adsorption/outgassing paths (§5.3) — the entry condition for semiconductor RGA, UHV and isotope scenarios.

13.4 RMI-PSOZV™ / MDZV™ Zero-Volume Valves: 0.098 μL of System Engineering

Dead space Φ0.5 mm × 0.5 mm = 0.098 μL, rewriting all three ledgers of Chapter 6[3]:

- **Cycle loss:** conventional valve 0.1 cc × 100 atm = 10 cc/cycle; zero-volume valve ~0.01 cc/cycle — about 1 cc lost per 100 cycles, negligible (Eq. 6-1, Fig. 6-1);
- **Vacuum shock:** no matter how long it has been closed, the instantaneous release at opening does not shock HV / RGA systems — in-situ calibration on production tools becomes possible (§9.3);
- **Minimized decay:** gas is lost only while open; combined with the normally-closed pneumatic design (PSOZV™), the largest human risk — "forgot to close" — is actively eliminated; for expensive isotopes (Xe, Kr, ^{3}He), near-zero natural decay is achieved. Measured examples: MDZV™ H_2 leak (160 cc, He 1.60×10^{-6} Pa·m³/s @ 10.8 bar, multi-pressure calibration points), annual decay < 2.5% (at 60 uses × 60 min per year); PSOZV™ mixture leak (Xe-132 / Kr-84 isotope set), annual decay < 1%[3].

13.5 RMI-Cal™ Digital Conductance Engine: From "Trial and Error" to "Computed First"

RMI-Cal™ is a gas-properties library plus a conductance-simulation algorithm (the engineering implementation of the superposition model of Eq. 3-4): inputs are medium (pure gas / mixture / liquid), inlet pressure and target rate; outputs are orifice and length machining parameters; mixture partial rates are computed per Eq. (6-3) with automatic P/T basis conversion; liquid media follow the vapor-pressure model (Eq. 6-5). It turns customization from "repeated crushing trials" into "simulate first, machine second, then actually calibrate," compressing delivery from traditional weeks to **3~5 working days** (CNAS certificate +1 week)[3]. To the user, its most tangible form is the ordering-code matrix — medium, rate, pressure, fitting, valve, certificate encoded segment by segment (§16.1): one line of code is a complete working-condition contract. It should be said that RMI-Cal™'s theoretical foundation is no mystery — it is precisely the open physics of Chapter 3: the flow-regime criterion (Kn), the viscous / molecular-flow formulas and the $1/\sqrt{M}$ conversion form the computational core, and the gas-properties library supplies viscosity and molecular-weight data. Its value lies in turning this physics into executable, reviewable, batch-capable engineering computation, not in any black-box secret.

13.6 The Closed Loop: How the Four Technologies Enable Each Other

Individually, each technology solves one class of physical problem; together they form a closed loop: **RMI-Cal™ makes it "computed right" (design layer) → RMI-MTC™ makes it "built right" (manufacturing layer) → RMI-Metal™ makes it "sealed tight" (background layer) → RMI-PSOZV™/MDZV™ makes it "lasting in use" (system layer)**. Missing any link, the extreme specs collapse: without metal sealing, microchannels cannot reach 10^{-13}; without zero-volume valves, the high-pressure reservoir's decay advantage drains away in use; without the simulation engine, all-media customization falls back to trial and error. This is the structural reason "all leak rates × all pressures × all media" coverage can hold simultaneously.

Chapter 14 The Full-Scenario Product Matrix

> **What this chapter answers:** how the four technologies map onto products: covering all leak rates (100 mL/s ~ 10^{-13} Pa·m³/s), all pressures (0.1 Pa ~ 40 MPa), all gases (any non-corrosive gas / mixture / isotope / liquid) — and how this matrix answers the scenario requirements of Ch. 8–12 one by one[3].

14.1 Matrix Overview: Four Dimensions of Full Coverage

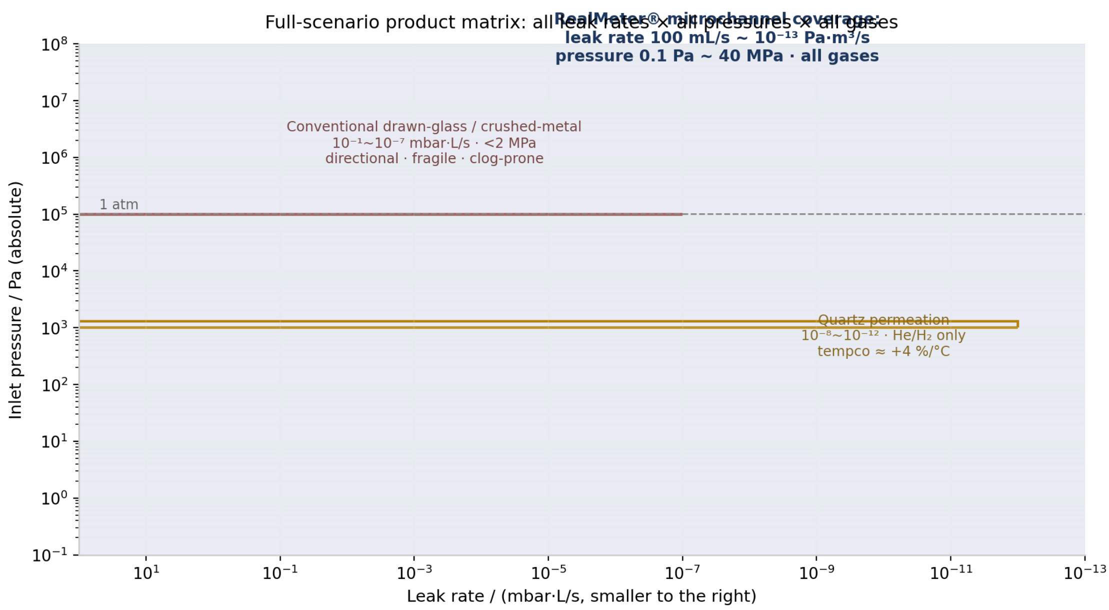

Figure 14-1 Full-scenario product matrix: all leak rates × all pressures × all gases

The physical significance of full coverage: the three axes of the figure correspond to Chapter 3's three variables (rate ← flow regime, pressure ← driving force, medium ← molecular properties). "Full coverage" means there are no physical blind zones in the product space — every scenario from Ch. 8 to Ch. 12 has a landing point in the matrix.

Table 14-1 Overview of product families (representative parameters, subject to the latest handbook)

Family	Representative capability	Typical scenario
Passive simulation leaks	All media (single / mixture / isotope / liquid); 0.1 Pa ~ 40 MPa; customized rate + pressure together	Line OK/NG dummies, Four-Piece Kit, helium-reduction simulation (Ch. 10, 11)
Reservoir-type calibrated leaks	≤ 12 MPa charge, 160~300 cc; He tempco +0.1 %/°C; annual decay 0.1% ~ 2%	Detector calibration, metrological traceability (Ch. 7)
Zero-volume-valve leak series	MDZV™ manual / PSOZV™ normally-closed pneumatic, dead volume 0.098 μL	RGA / UHV / expensive isotopes (Ch. 6, 9)

Vacuum / positive-pressure calibrated leaks	Dual bases: vacuum outlet / atmosphere outlet (§2.5)	He vacuum detectors, sniffer calibration (Ch. 8)
Air / N_2 air-tightness leaks	Viscous-dominated, tempco −0.6 %/°C; sccm class	Differential / decay tester calibration (Ch. 10; JJF 1986)
Refrigerant calibrated leaks	R134a / R1234yf etc., g/y basis (Eq. 2-4)	Refrigeration regulatory compliance (Ch. 8; JJF 1964)
Reference calibrated-leak sets	5~6 orders of magnitude coverage, individually traceable to national level	Metrology institutes establishing standards (§7.5; JJF 1833)

14.2 Extreme-Spec Products: Answers to the Physical Frontiers

10^{-11} ~ 10^{-13} Pa·m³/s microchannel He calibrated leaks (the product form of Chapter 5's physics): what pressed the channel-type lower limit down by three orders of magnitude was precisely the all-metal sealing background (< 10^{-15} atm·cc/s, §13.3). The value of this spec: reference calibration of the most sensitive helium detectors, bombing-method hermetic-package testing, metrology institute standard establishment[5]. **40 MPa passive simulation leaks**: hydrogen-energy and high-pressure vessel scenarios — pressure no longer an excuse for judgment failure. **Mixture / isotope leaks**: 1 ppm Kr/Xe balance N_2 (two-stage dilution source, §9.4); multi-component H_2/He/N_2/Kr/Xe balance Ar (mass-discrimination correction, §9.4); ^{3}He, D_2, $^{18}O_2$ isotopes (scientific and nuclear applications); all certified on explicit P/T bases (§6.4). **Liquid-medium leaks**: n-dodecane, DMC, PFTBA (§6.5, §9.3), filling the RGA high-m/z calibration gap.

14.3 Coverage Answers by Scenario

Table 14-2 Scenario requirements of Ch. 8–12 and their matrix answers

Scenario requirement	**Where**	**Matrix answer**
EV battery line: high-takt, high-frequency checks, shock resistance	Ch. 8, 10	Line OK/NG dummies, Four-Piece Kit, helium-reduction simulation (Ch. 10, 11)
Semiconductor RGA: quantitative calibration, isotopes, mixtures, liquids	Ch. 9	Zero-volume-valve series + full-media leaks + ppm mixtures
Metrology institutes: establishing standards per JJF 1833—2020	Ch. 7	Reference calibrated-leak sets (Ch. 15 presents the example)
Refrigeration / A/C: g/y compliance, −0.6 %/°C tempco	Ch. 8, 10	Refrigerant leaks + air-tightness simulation pieces
Hydrogen energy: high pressure, safety	Ch. 8	40 MPa passive H_2 simulation leaks
Helium reduction: mixed-gas judgment at 1% ~ 50% concentration	Ch. 11	Mixture simulation leaks (same concentration, pressure, medium as the workpiece)

14.4 Summary

- The product matrix = the engineering projection of Chapter 3's three variables: all leak rates (100 mL/s ~ 10^{-13} Pa·m³/s) × all pressures (0.1 Pa ~ 40 MPa) × all gases;
- Extreme specs each have a physical source: 10^{-13} from all-metal sealing background; 40 MPa from monolithic metal strength; all-media from the simulation engine + channel process;
- Every scenario requirement of Ch. 8–12 has a landing point in the matrix.

Products are what specifications say; evidence is what data shows. The next chapter: field data.

Chapter 15 Field Data: Turning Specifications into Evidence

> **What this chapter answers:** can specs be believed? This chapter presents verifiable evidence: metrological evidence (institute reference-leak sets with full NIM traceability, a 10^{-12} Pa·m³/s-class national-station certificate, participation in drafting national military standards), extreme-condition re-measurement data (freezing, drops), third-party field cases, and outgoing repeatability records. The principle: every number must be reproducible by a third party.

15.1 Metrological Evidence

- **Participation in drafting JJG (Mil.) 165—2024, *Verification Regulation for Vacuum Calibrated Leaks*** (effective 2025-01-01)[2];
- **Reference leaks procured by multiple metrology institutes/stations as master standards for establishing their own standards**: He calibrated leaks of 10^{-10}, 10^{-11}, 10^{-12} mbar·L/s classes and H_2 calibrated leaks, with calibration certificates from the National Primary Vacuum Metrology Station of the defense industry — the deepest endorsement of a leak manufacturer is to have its products used as someone else's yardstick[3];
- **Long-term stability data**: tracking batches of reference leaks over multiple recalibration cycles, with year-to-year changes within the certificates' stated uncertainty (data continuously archived, available for review on-site).

A concrete certificate from July 2026[16]:

Table 15-1 Example certificate elements at the 10^{-12} Pa·m³/s class (National Primary Vacuum Metrology Station of the defense industry, 2026-07)[16]

Element	Content
Object	Reservoir-type He calibrated leak RM51X-121711V0/6 (outlet into vacuum)
Result	$Q = 8.12\times10^{-12}$ Pa·m³/s (calibration gas: helium)
Expanded uncertainty	$U_r = 22\%$ ($k = 2$)
Upper-level standard	(5×10^{-13} ~ 5×10^{-5}) Pa·m³/s gas micro-flow standard apparatus: dynamic comparison U_r = 14%, static accumulation comparison U_r = 18% ($k = 2$); Certificate [2017] Guo-Fang-Ji-Biao Top No. C249, valid through 2027-12-19
Primary traceability gauges	Spinning-rotor gauge (SRG), capacitance diaphragm gauge (CDG), etc.

This certificate is also Chapter 7's uncertainty language instantiated at the extreme class: the 22% relative uncertainty is not process sloppiness — 10^{-12} Pa·m³/s already approaches the boundary of the national metrology system, whose own upper-level apparatus carries U_r = 14% ~ 18%, and the calibrated value cannot beat its source. Read the other way: **that a certificate with uncertainty and a complete traceability chain can be issued at this magnitude at all means the domestic value-transfer system has closed the loop for 10^{-12} Pa·m³/s-class microchannel leaks.**

A common customer question deserves a note in passing: the same leak receives different uncertainties from different institutes — the value is governed chiefly by the capability of the measuring apparatus (the upper-level-standard component of the Chapter 7 budget). The National Primary Vacuum Metrology Station of the defense industry can assign 3% ~ 5%; the National Institute of Metrology routinely assigns 10%; regional institutes typically 15%. RealMeter's in-house certified values (5.5% at the 10^{-5} mbar·L/s class, ±8% over 10^{-6} ~ 10^{-9} mbar·L/s) sit in between, resting on repeated comparisons against the company's reference-leak sets and on process priors. All of this presupposes a good leak in the first place — short-term instability feeds directly into the repeatability component: **with a poor leak, no apparatus, however capable, can assign a small uncertainty.**

15.2 Extreme-Condition Re-measurement Data

The quantified form of §5.5 "mechanical and thermal damage" — public demonstration records[14]:

Table 15-2 Extreme-performance test records

Object	Treatment	Nominal (before)	Re-measured (after)
Passive He leak	−20 °C freezer, 1 night + violent drop test	4.75×10^{-5} mbar·L/s (2 bar gauge)	4.80 ~ 4.90×10^{-5} mbar·L/s (retention 101% ~ 103%)
Reservoir He leak	−20 °C freezer, 1 week + violent drop test (ΔT ≈ 40 °C)	1.16×10^{-7} mbar·L/s	1.10×10^{-7} mbar·L/s (retention ~95%)

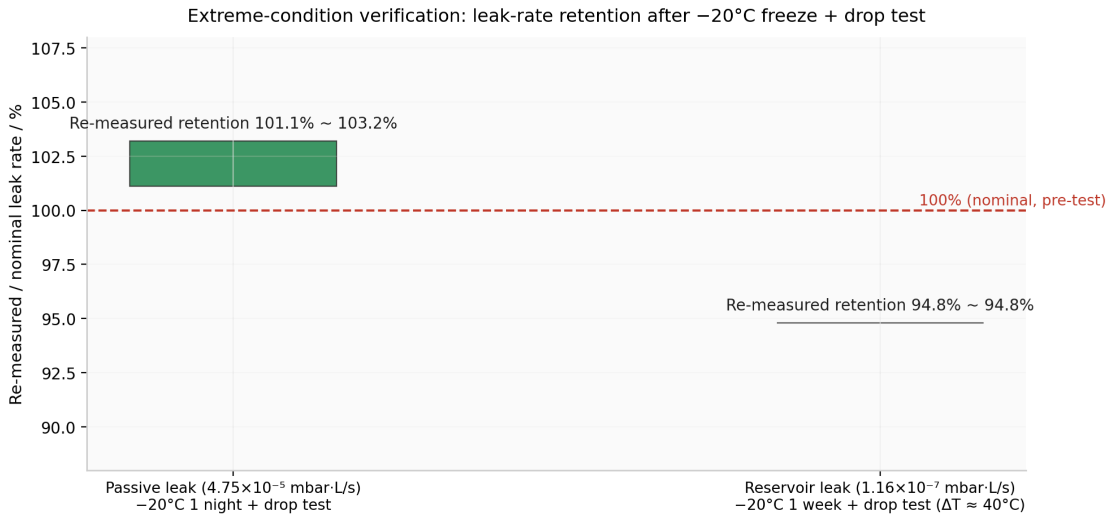

Figure 15-1 Rate retention after −20 °C freezing + 1.2 m drop tests (re-measured vs nominal)

- **Passive leak** (4.75×10^{-5} mbar·L/s): after one night at −20 °C + 1.2 m drop, re-measured retention 101.1% ~ 103.2% (within the certificate uncertainty);
- **Reservoir leak** (1.16×10^{-7} mbar·L/s): after one week at −20 °C + drop test, re-measured 1.10×10^{-7} mbar·L/s (retention ~95%); the ~5% change is explainable by tempco (+0.1 %/°C × 40 °C ≈ −4%) under the ~40 °C non-climate-controlled re-test conditions.

The point of such data is not "dropping is fun" but the quantifiable verification logic of Chapter 5: **a leak's robustness should not be a usage caution but a design specification with re-measured evidence.** A further piece of hardware-endurance evidence is the vacuum-shock measurement — opening a zero-volume-valve leak disturbs an RGA system's pressure by less than one order of magnitude; the data are in §6.2[15].

15.3 Third-Party Reports and Field Cases

Cases across key industries (desensitized):

- **Metrology:** a provincial institute's reference-leak set (6 pieces covering 3×10^{-10} ~ 3×10^{-5} Pa·m³/s), passing JJF 1833—2020 standard-establishment assessment, in service beyond two recalibration cycles;
- **Power batteries:** a head battery-maker's helium-reduction retrofit (100% → 10% He), Three-Reference Verification passing GR&R ≤ 15%, annual helium cost reduced by ~90% (Ch. 11 ledger);
- **Semiconductors:** a PVD tool maker's RGA in-situ calibration scheme (Ar + H_2O + ppm Kr/Xe combination), reducing vacuum-acceptance time per tool by ~40%;
- **Refrigeration:** a compressor maker's R134a leak replacement of permeation references — temperature-compensation table abolished, winter/summer judgment difference disappearing (Table 3-2 physics delivered).

The metrology case above is now documented in full public detail (a municipal institute of metrology and testing, 2026)[18]:

Table 15-3 Reference-leak set for a vacuum helium-leak standard apparatus (JJF 1833—2020 system)[18]

Model	Target rate / Pa·m³/s	Measured / Pa·m³/s	NIM cert. no.	Annual decay
TLS-5P	3.0×10^{-5}	3.01×10^{-5}	RGyz2025-07108	~0.8%
TLS-6P	3.0×10^{-6}	3.01×10^{-6}	RGyz2025-07109	< 1.0%
TLS-7P	3.0×10^{-7}	3.14×10^{-7}	RGyz2025-07110	< 0.7%
TLS-8P	3.0×10^{-8}	3.14×10^{-8}	RGyz2025-07111	~0.3%
TLS-9P	3.0×10^{-9}	2.97×10^{-9}	RGyz2025-07112	< 0.1%
TLS-10P	3.0×10^{-10}	3.04×10^{-10}	RGyz2025-07107	< 0.1%

Common specifications: 100% He; channel-type (microchannel); KF25 outlet; −20 ~ +65 °C; tempco 0.1 %/°C; uncertainty ±10% (k = 2); 12-month recalibration; all six calibrated and traced by the National Institute of Metrology (NIM), China.

Against JJF 1833—2020 §6.2.1 (the apparatus shall carry multiple calibrated leaks covering every decade of its range, with stability better than 3%/year): this set covers 3×10^{-10} ~ 3×10^{-5} Pa·m³/s — six decades, one leak per decade — with annual decay of 0.1% ~ 1.0%, an order of magnitude better than required. The piece-to-piece decay differences are a textbook display of the decay law Q/(pV) of Eq. (3-10): higher-rate models carry larger reservoirs (300 ~ 1000 cc for TLS-5P / 6P; 100 cc for TLS-9P / 10P), keeping even the high-rate end below 1%/year. **Establishing a standard is not buying six leaks — it is buying a value echelon that has every decade covered and every piece surviving annual recalibration.**

Outgoing-repeatability evidence, also public: a 1.0 mL/min @ 20 kPa air-tightness Air calibrated leak underwent 32 consecutive repeatability runs before shipment, with flow fluctuation within the rated specification; the full test video and data record are openly accessible[17]. Such "N-run consecutive re-tests" should become a routine acceptance action for air-tightness leaks — it maps directly onto Chapter 10's system-level logic: a single-point calibrated value is only the entry ticket; consecutive repeatability is the evidence of production-line credibility.

15.4 Summary

- The depth order of evidence: metrological endorsement (institutes procuring as master standards) > extreme-condition re-measurement data > third-party reports > specifications;
- All extreme-condition verification follows Chapter 5's logic: quantified conditions, re-measured results, physical explanation of deviations;
- Field cases close the loop with Parts II–III methodologies (Ch. 7, 10, 11 physics delivered in the field).

The final chapter: the service system — how to make this knowledge and evidence reproducible for every customer.

Chapter 16 Service and Quality Assurance System

> **What this chapter answers:** what else a customer buys besides the device itself. This chapter presents the service closed loop from ordering to retirement, and the quality documents delivered with each product.

16.1 Customization Service: One Code Is One Contract

The ordering-code matrix (medium – rate – pressure – fitting – valve – certificate) is the engineering interface of the RMI-Cal™ engine (§13.5): the customer states working conditions, simulation outputs parameters, machining builds to drawing, actual calibration issues the certificate — code, nameplate and certificate tell one story (§12.3). Routine customization: 3~5 working days; CNAS / institute certificates: +1 week[3].

16.2 Technical Support: Beyond Selling Devices

- **Application-method design:** Four-Piece Kit configuration, bypass-method SOP, helium-reduction scheme design (Three-Reference + stepwise concentration iteration, Ch. 10, 11);
- **Metrology support:** standard-establishing configuration consulting (reference-leak sets), uncertainty-budget templates (§7.3), recalibration management;
- **RGA quantification support:** calibration-scheme design, mixture / liquid selection, sensitivity-factor workflows (Ch. 9);
- **Knowledge output:** this book, plus the RealMeter Leak Research Institute's public technical content (white papers, cases, videos[7][14]).

16.3 Quality Commitments and After-Sales

- Factory test certificate with every unit; CNAS / institute calibration certificates on request;
- Clogging / contamination repair + recalibration service (Chapter 5's "maintainable design" delivered);
- Reservoir-leak decay tracking and refill service (Chapter 3's decay prediction delivered);
- Warranty terms and response-time commitments per contract.

16.4 Closing: A Book's Promise, An Industry's Direction

From the definition of leak rate (Eq. 2-1) to Three-Reference helium reduction (Ch. 11), this book has tried to prove one thing: **every judgment in leak testing can and should be anchored in physics and metrology** — judgment is comparing sizes, not reading numbers; verification makes it trustworthy. The calibrated-leak industry is small, yet it holds the scale of a much larger manufacturing world. May this book help everyone in this line of work: understand leaks, choose leaks right, use leaks well.

RealMeter Leak Research Institute
July 2026, Shanghai

Appendix A Leak-Rate Unit Conversion Card

Table A-1 Leak-rate unit conversions (0 °C standard state; engineering rounding)

Unit	**= 1 Pa·m³/s ×**	**= 1 mbar·L/s ×**	**Notes**
Pa·m³/s	1	0.1	SI base
mbar·L/s	10	1	Vacuum-industry daily unit
atm·cc/s	9.869	0.9869	American / semiconductor convention
Torr·L/s	7.501	0.7501	Older vacuum literature
sccm (0 °C)	592.2	59.22	Air-tightness / MFC; mind the standard state
std.cc/s	9.869	0.9869	"1 mbar·L/s ≈ 1 cc per second"
mol/s	4.403×10^{-5}	4.403×10^{-6}	22.414 L/mol (0 °C)
g/y	molar-mass dependent, Eq. (2-4)	same	Refrigerant regulatory basis

Magnitude intuition: 10^{-5} mbar·L/s ≈ 1.16 days per cc; 10^{-7} ≈ 116 days; 10^{-9} ≈ 31.7 years; 10^{-13} ≈ 317,000 years.

Appendix B Core Formula Cards

Table B-1 Index of core formulas

Formula	Content	No.	Use
Leak-rate definition	$Q = d(pV)/dt$	(2-1)	Starting point of all conversions
sccm conversion	$1\ Pa·m^3/s = 592.2$ sccm	(2-3)	Daily use in air-tightness
g/y conversion	X mbar·L/s → g/y (with molar mass)	(2-4)	Refrigerant regulations
Knudsen number	$Kn = \lambda/d$	(3-1)	Flow-regime criterion
Viscous conductance	$Q = \pi d^4(p_1^2-p_2^2)/(256\eta L)$	(3-2)	High-pressure / air-tightness duty
Molecular conductance	$Q = (1/6)\sqrt{(2\pi RT/M)}·d^3/L·\Delta p$	(3-3)	Vacuum duty
Superposition model	$Q \approx Q_{mol} + Q_{vis}$	(3-4)	Basis of custom simulation
Tempco	Molecular +1/(2T); viscous $-(1/\eta)d\eta/dT$	(3-5)(3-6)	Temperature-drift correction
Reservoir decay	Exponential (molecular) / hyperbolic (viscous); rate ∝ Q/(pV)	(3-8)~(3-10)	Lifetime prediction
Seal background	$Q_{meas} = Q_{channel} + Q_{perm} + Q_{micro} + Q_{outgas}$	(5-1)	Feasibility of tiny rates
Dead-volume loss	$\Delta G = V_{dead} \times p$	(6-1)	Valve selection
Mixture partial rate	$Q_i/Q = (x_i/\sqrt{M_i})/\Sigma(x_j/\sqrt{M_j})$	(6-3)	Mixture basis
Pressure decay	$Q = \Delta P·V/\Delta t$	(8-1)	First formula of air-tightness
Temperature–pressure	$\Delta P = P·\Delta T/T$ (1 °C ≈ 400 Pa @ 121 kPa)	(10-1)(10-2)	Main error source of air-tightness
Equivalent-orifice comparison	$R \approx Q_{part}/Q_{leak}$ (zero-order; judgment by three-reference measurement)	(11-2)	Helium-reduction methodology
RGA quantification	$I = S·P$; comparison; accumulation $Q = V·dP/dt$	(9-1)~(9-3)	RGA calibration
Two-stage dilution	$P_{Kr} = Q_{total}·C_{Kr}/S_{eff}$	(9-5)	ppb/ppt trace inputs
Uncertainty	$u_c = \sqrt{\Sigma(c_i u_i)^2}$; $U = k·u_c$ (k=2)	(7-1)	Metrological expression

Appendix C Glossary

Table C-1 Core terminology at a glance

Term	Definition
Calibrated leak	A metrologically calibrated reference device providing a known, stable leak rate under specified conditions
Channel-type / permeation	Leaks whose element is a geometric channel / relies on membrane permeation (JJF 1833 classification)
Reservoir / passive leak	Self-contained gas reservoir / externally fed
Vacuum / positive-pressure leak	Outlet to vacuum / to atmosphere (different bases, §2.5)
Leak rate	Gas quantity (pV flow) passing the channel per unit time, $Pa \cdot m^3/s$
Knudsen number Kn	Ratio of mean free path to channel size; flow-regime criterion
Viscous / molecular / transitional flow	$Kn<0.01$ / $Kn>1$ / in between
Temperature coefficient	Relative rate change per °C, set by the dominant flow regime / permeation mechanism
Decay	Rate decline of a reservoir leak as its reservoir pressure falls; rate $\propto Q/(pV)$
Dead volume	Gas volume trapped inside a closed valve (source of cycle loss / vacuum shock / memory effect)
Zero-volume valve	Valve with dead volume < 0.1 μL (RealMeter 0.098 μL)
Directionality	Unequal forward/reverse rates; an ideal circular tube has none
Seal background	Seal-material self-permeation / micro-leaks / outgassing superimposed on the nominal rate
Golden-Part Four-Piece Kit	Q_0 check piece + OK dummy + NG dummy + golden part
Bypass method	System-level verification: leak paralleled to the test volume via a bypass valve, injecting a known leak mid-test
Equivalent-orifice relative comparison	Leak judgment = comparing equivalent-channel sizes; the ratio is a zero-order approximation — engineering judgment rests on three-reference measured verification (§11.2~11.3)
Three-Reference Verification (Q_0+OK+NG)	Per-shift verification with threshold piece + OK $(1/3\sim1/2)Q_0$ + NG $(2\sim3)Q_0$; usability criteria: GR&R ≤ 15% + three-tier separation
MWC (Minimum Working Concentration)	Lowest usable helium concentration found by stepwise iteration — descend level by level with three-reference verification at each; stop when tiers overlap (§11.4)
P / T basis	Component partial rate / total rate basis for mixture leaks
Uncertainty U (k=2)	Half-width of the value interval at ~95% confidence
Traceability chain	National primary standard → calibration facility → reference leak → working leak → leak detector → product judgment

GR&R	Gage repeatability & reproducibility analysis — statistical verification of a judgment system

Appendix D List of Norms and Standards

Table D-1 Leak-rate metrology norms (current)

Code	Title	Object / scope
JJF 1833—2020	Calibration Specification for Vacuum Helium Leaks	Leaks; $(1\times10^{-10} \sim 1\times10^{-4})$ Pa·m³/s
JJF 1627—2017	Calibration Specification for Calibrated Leaks (Soap-Film Flowmeter Method)	Leaks; 1 mL/min ~ 10 L/min, 1 kPa ~ 1.5 MPa
JJG (Mil.) 165—2024	Verification Regulation for Vacuum Calibrated Leaks	Leaks; defense-industry system (RealMeter participated in drafting)
JJF 1986—2022	Calibration Specification for Differential-Pressure Air Leak Testers	Testers; ≤ 700 kPa, 0~100 mL/min
JJF 1964—2022	Calibration Specification for Halogen Leak Detectors	Detectors; $10^{-6} \sim 10^{-5}$ Pa·m³/s
JJF 1059.1—2012	Evaluation and Expression of Uncertainty in Measurement	General methodology (GUM)

Appendix E Index of Engineering Rules

Table E-1 The book's eleven engineering rules

Rule	Content	Source
Rule 2-1	With inlet > 10 bar absolute, positive-pressure rate ≈ vacuum rate (< 1%); at low pressure the two must be calibrated separately	§2.5
Rule 3-1	Gas-conversion factors must be bound to flow regime; serious practice is full-media calibration or conductance-model conversion	§3.6
Rule 3-2	The reservoir-lifetime contest is a reservoir-pressure contest: high pressure + large volume is the right answer	§3.8
Rule 4-1	One-minute test for true microchannels: equal bidirectional rates	§4.9
Rule 5-1	Four lifetime questions: decay rate, anti-clog structure, seal background, mechanical verification	§5.5
Rule 6-1	Three questions for valved leaks: dead volume, normally-open/closed, integrated or not	§6.3
Rule 7-1	A certificate missing any of the five elements is unusable; align elements first, numbers second, at acceptance	§7.6
Principle 11-1	Equivalent-orifice comparison: judgment is comparing sizes, not reading numbers; the ratio is a zero-order approximation — three-reference measurement is the engineering criterion	§11.2
Rule 10-1	Credibility of air-tightness judgment = whether the system stably separates OK / NG dummies today (Four-Piece Kit + bypass method)	§10.4
Rule 11-1	Helium-reduction order: build three-reference verification first, iterate to the MWC, control background in parallel, add recovery last	§11.6
Five-step selection	Medium → rate → pressure (absolute) → form → certificate	§12.1

The top-fifteen FAQ: §12.5. The certificate five-element checklist: Table 7-3.

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