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LEAK TIGHTNESS

Testing Methods
and Vacuum Technology

THEORY AND PRACTICE OF LEAK TESTING

About this preview

This demonstration preview presents selected pages from *Leak Tightness: Testing Methods and Vacuum Technology*. It offers a view of the book's scope, illustrations, calculations and technical presentation.

It is not the complete book. The 32-page preview contains the original front cover, 29 interior pages and two pages prepared for this preview.

Pages included

	<i>Preview</i>	<i>Book</i>
Introduction	3-5	2-4
Full table of contents	6	5
Planning a leak testing laboratory	7-17	31-41
Method selection and vacuum calculations	18-31	124-137
Ordering the complete edition	32	-

The contents list on preview page 6 describes the full book. Gaps between extracts are intentional. Original page numbers, equation numbers and cross-references have been retained; some references point to material outside this preview.

To order the complete English-language ebook or request the price and purchase details, please contact:

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The leak tightness of a product depends on its design, materials, manufacturing quality and service conditions. The reliability of a leak-tightness assessment also depends on preparation of the test object, the test pressure differential and the ability of the measurement system to detect an unacceptable leak. This book examines these issues in sequence, from selecting an acceptance limit and test method to calculating the result and deciding whether the product meets the requirement.

Leak testing observes the transfer of gas or liquid through the walls and joints of a product. To use this observation to assess product quality, the specified requirement must be related to the test conditions and measurement capability. This relationship governs the choice of method, surface preparation, connection arrangement and procedure for evaluating the result.

Particular attention must be paid to the buckling resistance of shells during evacuation. External pressure can cause buckling even in a structure capable of withstanding substantial internal pressure. Strength and buckling resistance must be assessed before the test conditions are specified.

The book comprises two parts. Part I addresses leak-tightness requirements, product preparation, test methods and evaluation of results. Part II shows how these principles apply to vacuum-system calculations, diagnosis of gas loads, equipment selection and practical case studies. Equations are accompanied by their conditions of applicability and definitions of the symbols.

The book draws on experience of testing equipment for the power generation, petrochemical, mechanical engineering and cryogenic industries. Practical examples show how physical principles manifest themselves in an actual installation and why

product preparation, test configuration and signal processing must be considered together [94, 95, 96, 97, 98, 99, 100].

Purpose and Structure of the Book

This book is intended for engineers, manufacturing specialists and practitioners who develop and perform leak tests. It covers the underlying physics, product preparation, laboratory arrangements, measurement configurations, calculations and evaluation of results.

The requirements for a particular product are established by the applicable codes and standards, design documentation and agreed test programme. The scope and applicable edition of each document must be established before a detailed test instruction is prepared. Conditions prescribed for one industry cannot automatically be transferred to another.

Development of a test procedure begins with a question: what transfer of fluid is still acceptable for this product, and how can it be represented under test conditions? The next steps are to select the tracer gas, specify the pressures on both sides of the wall and the temperature, establish the direction of the pressure differential and prepare the surface. Only then can the required system detection capability and decision rule be specified.

GOST R 50.05.01–2018 addresses testing of equipment and piping in nuclear power installations. Its provisions on preparation, verification of detection capability and documentation help explain the organisation of testing; specific test conditions and personnel requirements apply within the scope of that standard [86, Section 1].

Codes and standards connect a technical requirement with a procedure for verifying it. In developing a test, they provide a

basis for selecting the method, justifying the permissible leak rate and establishing the measurement conditions.

The test programme must account for the product design, pressure, temperature and service life. Metrological traceability is established by a documented, unbroken chain of calibrations linking the result to a reference, with each calibration contributing to the measurement uncertainty. Suitable measuring instruments and calibrated reference leaks are required. The procedure for verifying the test system and the decision rule must be specified in the test programme and recorded in the test report [85, 86, 87, 88, 89; 92; 131, clause 6.5.1].

Contents

Purpose and Structure of the Book 3

Part I Leak Testing 6

General Concepts, Terms and Definitions 6

Throughput Assessment and Leak Tightness Classes 15

Planning a Leak Testing Laboratory 31

Preparing Products for Leak Testing 42

Leak Testing Equipment and Materials 60

Helium Mass Spectrometer Leak Testing 65

Practical Aspects of Bubble Testing 104

Pressure Change Leak Testing 108

Evaluating and Recording Test Results 112

Laboratory Organisation and Competence 116

Selecting the Test Method and Conditions 124

Part II Practical Solutions in Vacuum Technology 125

Design Calculations for the Test System 125

Gas Sources and Surface Preparation 140

The Measurement Path and Validity of Readings 149

Residual Gas Analysis 171

Material Cleanliness and Vacuum Product Design 174

Comprehensive Vacuum Acceptance Testing 184

Cryogenic Systems and Vessels 191

Extended Systems and Difficult Leak Localisation 209

Vacuum under Operational Energy Loads 218

Molecular Flow Modelling 220

Automation and the Comprehensive Test Programme 223

Leak Detectors and Test Installations 235

Pressure Measurement and Vacuum Gauge Selection 279

Vacuum Pumps and Gas Path Preparation 301

Valves, Gas Lines and Seals 344

Equipment Maintenance and Personnel Training 357

Symbols for Physical Quantities 386

References 387

Conclusion 404

Planning a Leak Testing Laboratory

Laboratory layout affects measurement repeatability. Equipment placement, ventilation, cleanliness of connecting lines and tracer-gas handling must provide a stable background, safe working conditions and convenient access to the product.

Selecting the Room

Room dimensions are determined by the equipment and the largest test object. In addition to space for the rig, allow for walkways, connection work and safe servicing. See Figure 2.

Ventilation must remove released gases and vapours without creating air currents that interfere with sniffer testing. Air contamination and flow direction must be assessed in the actual working area.

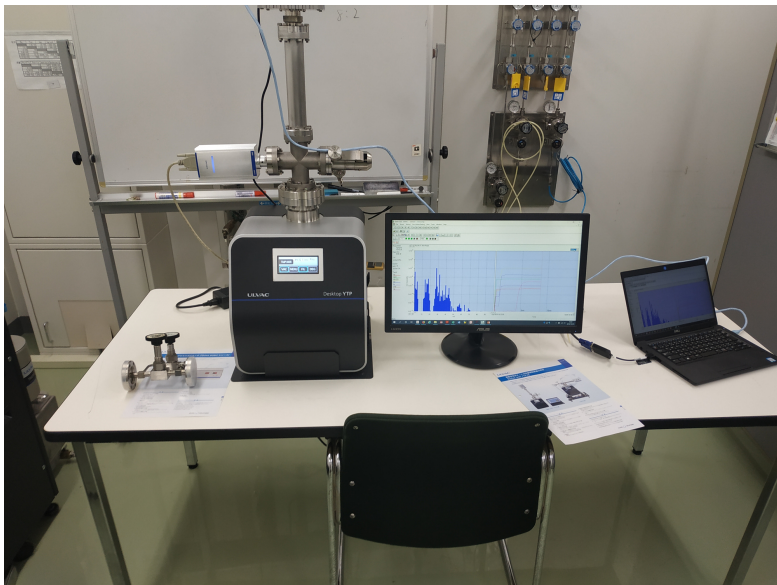


Figure 2 — Laboratory workstation with a vacuum system and computer-based recording. The measurement path, controls and data recording form a single working area.

Helium Discharge from the Test Room

Arrange helium discharge so that the gas cannot enter the measurement area. Increased helium concentration in the air raises the background and makes small leaks more difficult to locate. Discharge the gas through a dedicated line or route it to a recovery system; ventilation must prevent its return to the workstation.

Vacuum Pump Exhaust

Route vacuum pump exhaust away from the measurement area. Provide oil-mist separation for oil-sealed pumps. The flow resistance of the exhaust line must remain within the permissible limit: blockage or excessive length may increase the pressure at the pump outlet.

An oil-mist separator captures aerosol but does not remove helium from the exhaust. Filtration and gas discharge therefore serve different purposes and cannot replace one another.

Check exhaust-joint tightness and filter condition during maintenance. Locate discharge points so that gas cannot return through the ventilation intake, gas ballast or venting lines.

Clean Air or Nitrogen Supply

Use dry, clean gas for controlled venting and for purging where specified by the manufacturer. When using nitrogen, account for oxygen displacement: nitrogen supply does not replace room ventilation.

If the leak detector is designed for purging, supply clean gas to the designated port at the pressure and flow rate specified by the manufacturer. This helps reduce residual helium in the gas path. Do not connect nitrogen to an arbitrarily selected fitting.

After testing, discharge gas from the product and chamber through the designated line. Where necessary, purge with dry nitrogen or another compatible gas. Purge gas must also be removed from the working area: simply replacing helium with nitrogen does not prevent gas release into the room.

The background helium fraction in ordinary air is approximately 5×10^{-6} . Concentration and gas throughput have different dimensions. A sniffer reading depends on the sampled gas flow rate, instrument settings and calibration procedure; there is no universal correspondence between airborne background and throughput in $\text{Pa} \cdot \text{m}^3/\text{s}$. Air is not a substitute for a calibrated reference leak.

After a helium release, monitor the background and its stability at the workstation. If the background is elevated or changing, suspend measurements, eliminate the source and ventilate the area. Resume testing only after the background has recovered and the system detection capability has been verified.

Regularly check gas-line tightness, pressure-regulator operation and supply-gas cleanliness. Consider the condition of the gas supply when investigating an unstable background or an increase in leak-detector recovery time.

Electrical Supply

Provide the electrical supply, protective earthing and protective devices in accordance with the equipment documentation and electrical installation design. The design determines the protective-conductor cross-section; a single value cannot be applied to every instrument and installation method.

Select an uninterruptible power supply on the basis of apparent and active load power, pump starting currents, required backup duration and acceptable voltage waveform. Confirm

compatibility from the equipment documentation. The power rating and stored energy must be sufficient to save data and perform the specified safe shutdown, including necessary valve operations and operation of connected pumps.

Protection against interference and voltage deviations depends on the UPS topology. A UPS alone does not guarantee protection against every overload or short circuit; the power-supply design must include coordinated protective devices.

After power is restored, return the instrument to service in accordance with the manufacturer's instructions. Before resuming tests, check the vacuum operating conditions, background, retained settings and response to a check leak.

Lighting

Lighting must permit surface examination, reading of markings and reliable connection work. Use local lighting and, where necessary, optical magnification for small joints.

Specify workstation illuminance according to the visual task and applicable requirements. Additional local lighting aids examination of joints, but visual examination does not replace sensitive gas testing. When a leak is detected, examine the area and investigate the possible cause of the defect.

Safety

The layout and working arrangements must account for compressed gases, electrical equipment, hot surfaces and the substances used. Everyone performing the work must know the response to a malfunction and the emergency shutdown procedure.

A major hazard is the energy stored in compressed gas in cylinders and the test object. Secure cylinders, use compatible

pressure regulators and fittings, and limit pressure using the specified protective devices. Personnel must know the procedures for filling, isolation and safe depressurisation. Select personal protective equipment for the operations performed; it does not replace guarding and remote control.

When examining large installations, account for hot surfaces, rotating machinery, work at height and electrical circuits. Access to hazardous parts is permitted only after the specified protective measures and energy isolation have been implemented. Testing an operating installation requires a specifically developed safe arrangement; do not bring the spray nozzle or sniffer probe near exposed live parts.

Assess noise under the actual equipment operating conditions. Where necessary, reduce noise at source and provide vibration isolation and acoustic protection without compromising cooling or maintenance access.

Equipment Arrangement

Arrange equipment to follow the work sequence: delivery of the product, connection, testing and maintenance. The layout must provide for the following:

- Install the leak detector on a stable support in an approved operating orientation.
- Maintain clear access to controls, connections and components requiring servicing.
- Position the product so that the measurement line is short and does not impose unacceptable loads on its ports.
- Store fixtures and consumables separately from contaminated parts and used materials.

For a sensitive vacuum configuration, short, clean metal lines with adequate conductance are preferable. Polymer hoses are

acceptable only where their strength, outgassing and permeation have been shown to be suitable for the required detection limit. Include their length and cross-section in verification of the test system.

A restriction between the product and the pump can substantially reduce the effective pumping speed. For example, connecting a large pump inlet flange to a long, small-diameter bellows introduces substantial flow resistance. The pump may still meet its specified performance at its inlet, while the pumping speed at the product is much lower (Figure 3).

Gas Handling

The gas installation comprises the gas source, pressure-reducing equipment, isolation valves, supply lines and safe discharge lines. Check it as an integrated system:

- provide the air exchange specified by the ventilation design;
- check lines and connections for leakage;
- provide an accessible means of safely stopping the gas supply;
- keep the emergency response equipment selected for the area ready for use.

Secure cylinders against falling and protect them from excessive heat and mechanical damage. Use pressure regulators, valves, fittings and lines rated for the selected gas and pressure. The local operating instruction must define cylinder location, protective devices, connection, inspection and replacement, taking account of applicable requirements.



Figure 3 — Workstation with a helium leak detector and test fixtures. Access to connections and controls must be provided when arranging the station.

Additional Arrangements for Safe Working

Technical safeguards must be supported by personnel training and established working procedures:

- train personnel in handling gases, fixtures and measuring equipment;
- select personal protective equipment according to the operation and possible exposure;
- check equipment condition at the prescribed intervals and rectify identified faults before testing.

Separate the test hazard zone from workstations. Provide pressure limitation, controlled depressurisation and interlocks. Perform assembly and fault correction only after energy sources have been isolated and every compartment has been confirmed safe.

Vent a vacuum system in a controlled manner in accordance with the manufacturer's instructions. Sudden admission of gas can damage the instrument and cause flexible lines to move. Automatic venting is acceptable where it is part of the design and is correctly configured; protective functions must not be disabled without justification.

Arrange gas supply and discharge with regard to the area layout and cylinder-storage requirements. Monitor temperature and humidity within the limits required by the procedure and equipment. Retain documentation for instruments, reference leaks, fixtures and metrological procedures so that it can be linked to each test performed.

Determine the need for standby instruments from the laboratory's acceptable downtime and maintenance duration. A second leak detector can reduce downtime, but its presence does not by itself determine test reliability.

When checking workstation readiness, assess equipment accessibility, service connections and measurement conditions in sequence:

1. The area must allow the product to be moved safely, fixtures to be connected and equipment to be serviced.
2. Room and workstation surfaces must permit cleaning without recontaminating the measurement path.
3. Ventilation must provide air exchange and contaminant removal without returning tracer gas to the measurement location.

4. Provide water cooling where required by the equipment, with monitoring of cooling-water quality and flow rate.
5. Directed air currents must not reduce the demonstrated detection capability of sniffer testing.
6. Exhaust lines must carry gas to the designated discharge point within the permissible backpressure.
7. Store spare parts and tools so that working surfaces are protected from contamination and damage.
8. Work clothing and protective equipment must suit the task and the product cleanliness requirements.
9. Locate firefighting and emergency alarm equipment in accordance with the area's fire-safety requirements and keep access clear.
10. Lighting must suit the visual task and provide visibility of controls and connections.

After preparing the workstation, check the background and system response. Use these results to establish whether the specified leak can be detected under the actual room conditions.

Helium Background and Separation of Gas Flows

Separate the filling, measurement and gas-discharge areas wherever practicable. Choose ventilation flow directions so that helium released during product filling or discharged in pump exhaust does not reach the sniffer probe. Assess the effectiveness of this separation with the equipment operating through the normal sequence of operations.

Monitor both the mean background and its fluctuations over a single test. A stable elevated background may sometimes permit measurement of small increments, whereas a low but rapidly changing background can make them unreliable. Demonstrate readiness by detecting a check leak under actual working

conditions, rather than relying solely on the instrument reading with its inlet closed (Figure 4).

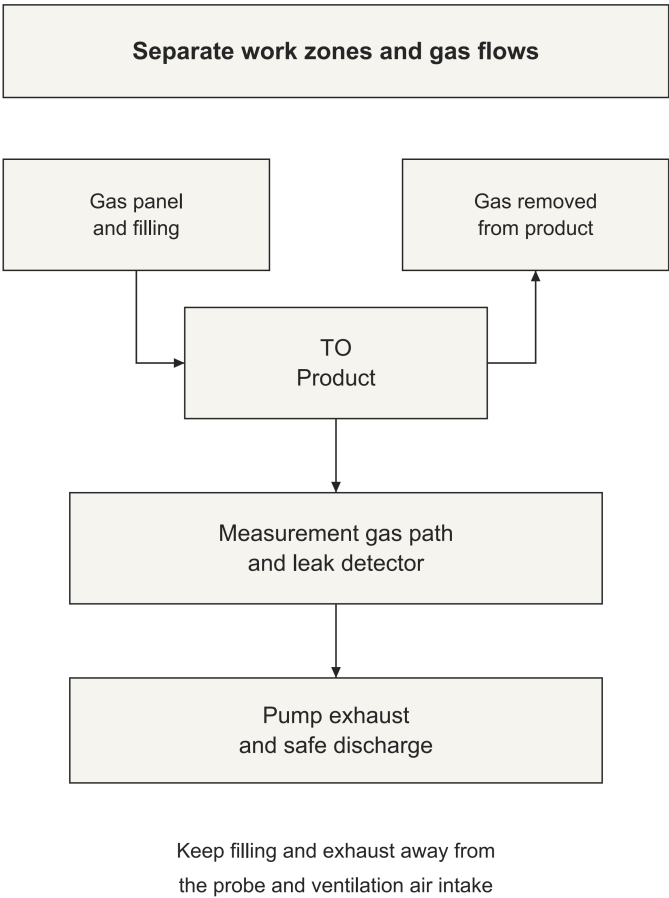
Before start-up, check cylinder restraints, pressure regulators, pressure limits, protective devices and the strength of every connected compartment. For shells subjected to evacuation, separately confirm buckling resistance under external pressure. A design assessment for internal gauge pressure does not replace this check. The approved programme for the specific product defines the test pressure, hold time and conditions for personnel access.

Monitoring Laboratory Conditions with LeakLab Atmo

Temperature affects the pressure of an enclosed gas, material permeability and the throughput of a reference leak. Humidity contributes to the gas load after a chamber has been opened. Ventilation changes the distribution of helium during spray and sniffer testing. Account for these conditions when preparing measurements and evaluating results.

LeakLab Atmo is intended to monitor CO₂, temperature and humidity, with provision for ventilation control. These data can assist comparison of laboratory test cycles. However, CO₂ measurement does not replace oxygen monitoring when inert gases or liquid nitrogen are used, and an ordinary environmental sensor does not constitute a safety gas analyser.

If the helium background rises towards the end of a shift, check the gas supply, supply-line leaks, discharge location and ventilation. Do not increase the rejection threshold to compensate for a high background: this changes the product requirement without eliminating the source of interference.



Check background under working conditions

Figure 4 — Functional separation of gas flows at the workstation

TO denotes the test object. The diagram shows functional separation of gas supply, measurement and discharge. Pump exhaust and gas removed from the product must not be directed towards the sniffer probe or ventilation intake. Pump outlet pressure is limited by the manufacturer’s instructions; excessive exhaust-line resistance is unacceptable.

Selecting the Test Method and Conditions

Table 5 — Selecting the test method and conditions

Technique	Preparation and loading	Checks during preparation and evaluation
Vacuum chamber	Dry product; test gas inside; vacuum outside	Leakage limit; product and chamber strength; external reference flow
External pressure chamber	Vacuum inside the product; gas outside	Shell buckling resistance; gas composition; complete coverage
Helium spray	Vacuum inside; local external application	Response time and leak location; quantitative measurement requires known gas composition and response
Helium sniffer	Gas inside; external sampling	Dynamic detection limit, stand-off distance, scanning speed and completeness of probe capture
Local vacuum chamber	Chamber over the area; tracer gas on the opposite side	Area overlap; seal tightness; response
Bubble testing	Gas pressure differential across the wall; indicator film or immersion	Liquid compatibility, detection capability, continuous observation and access to the entire area
Atmospheric accumulation	Closed enclosure around the filled product	Free volume, composition, time, mixing and losses

Technique	Preparation and loading	Checks during preparation and evaluation
Pressure change	Isolated volume after stabilisation	Temperature, volume, fixture background and pressure-measurement accuracy
Helium bombing of a sealed enclosure	External helium exposure followed by measurement	Stage durations, volume, flow model and gross leaks
Thermal vacuum technique	Agreed heating conditions and pressure differential	Temperature tolerance, background and detection capability at each test condition

Part II Practical Solutions in Vacuum Technology

In an actual installation, the signal depends on more than the leak itself. Piping conductance, surface outgassing, pump operation and the condition of the measurement path determine what the operator observes. Part II relates calculation models to worked examples and documented diagnostic cases. Numerical requirements from individual projects apply to the products and conditions described.

Design Calculations for the Test System

We begin test-system calculations with the gas balance: determine the permissible leakage for the available pumping capacity and other gas loads. We then assess gas-path conductance, response time and the influence of product geometry.

What a Leak Test Demonstrates

Leak Tightness Depends on Conditions

Consider a chamber that has successfully passed a laboratory test. After installation, its pressure is higher than calculated. A natural assumption is that transport has caused a leak. The chamber may, however, remain leak tight: a long pumping hose, a damp surface or a seal absent during factory testing may have raised the pressure. A statement about leak tightness and a statement about vacuum suitability therefore answer different questions.

The absence of a recorded response means that no leak was detected under those conditions within the demonstrated capability of the method. It does not prove zero transfer of matter or establish a precise upper bound on actual throughput without an adopted detection model. Transfer may also result from gas dissolution and diffusion through a continuous material, rather than a through-wall defect.

From the Requirement to Permissible Leakage

For a continuously pumped chamber, permissible leakage is derived from the gas balance. At the specified pressure, the pumping system must remove gas released from walls, seals and installed equipment, as well as gas entering through leaks. Under a steady-state approximation, the permissible leakage contribution is:

$$Q_{\text{leak,lim}} = S_{\text{eff}}(p_{\text{lim}} - p_{\text{ult}}) - Q_{\text{other}} \quad (53)$$

$Q_{\text{leak,lim}}$ is permissible total leakage throughput, $\text{Pa} \cdot \text{m}^3/\text{s}$; S_{eff} is effective pumping speed at the point considered, m^3/s ; p_{lim} is permissible pressure, Pa ; p_{ult} is the ultimate pressure defined by

the adopted pumping-system model, Pa; Q_{other} is the other gas load, $\text{Pa}\cdot\text{m}^3/\text{s}$.

The quantities in the equation must refer to one gas or to a mixture for which a single effective pumping speed is justified. Otherwise, construct a separate balance for each component. Define ultimate pressure and other gas loads so that the same source is not counted twice. If the right-hand side is negative, the target pressure cannot be achieved even without leaks: reduce outgassing or increase effective pumping speed [1, 2; 10].

Example 7 — Chamber with Limited Pumping Margin

Let effective pumping speed be $0.10 \text{ m}^3/\text{s}$, permissible pressure $1 \times 10^{-5} \text{ Pa}$ and other gas load $8 \times 10^{-7} \text{ Pa}\cdot\text{m}^3/\text{s}$. Neglect pump ultimate pressure. The total permissible throughput is $1 \times 10^{-6} \text{ Pa}\cdot\text{m}^3/\text{s}$, leaving $2 \times 10^{-7} \text{ Pa}\cdot\text{m}^3/\text{s}$ for leaks. Ignoring other gas sources and taking pressure multiplied by pumping speed as the leakage allowance would overestimate permissible leakage by a factor of five.

For a closed, unpumped volume, an initial estimate of permissible throughput follows Equation (10) in Part I, using volume, permissible pressure change and storage duration. The calculation assumes constant volume and temperature.

Equation (10) gives the permissible mean total gas influx over the interval considered. Subtract the other included gas sources to obtain the permissible leakage contribution specifically. If pressure differential changes, flow through the defect may also change. Account for temperature, outgassing and gas uptake in the relevant balance model.

Units and Conditions for Reporting Results

Pumping speed and leakage throughput frequently appear together but have different dimensions. Pumping speed is the gas volume accepted per unit time at the inlet pressure. In vacuum technology, throughput is conveniently expressed as pressure multiplied by volume per unit time. For the same number of molecules, gas volume at atmospheric pressure differs greatly from that under vacuum.

The ideal-gas state is described by:

$$pV = NkT = \nu RT \quad (54)$$

p is absolute pressure, Pa; V is volume, m^3 ; N is the number of molecules; k is the Boltzmann constant, 1.380649×10^{-23} J/K; T is absolute temperature, K; ν is amount of substance, mol; R is the universal gas constant, approximately 8.31446 J/(mol·K).

Example 8 — A Small Reading and a Large Number of Molecules

At 293.15 K, a throughput of 1×10^{-10} Pa· m^3 /s corresponds to approximately 2.47×10^{10} molecules per second. The display reading appears negligible, yet represents tens of billions of molecules. A small throughput becomes harmful when sustained over a long period, entering a small volume or carrying a substance that accumulates on a sensitive surface.

Converting Flow Rate to Reference Conditions

Volumetric flow rate referred to a reference pressure and temperature is obtained through the amount of substance:

$$\dot{V}_0 = \frac{Q}{p_0} \frac{T_0}{T} \quad (55)$$

Q is gas throughput at temperature T , Pa· m^3 /s; $\dot{V}_0$ is volumetric flow rate at reference conditions, m^3 /s; p_0 is reference absolute

pressure, Pa; T_0 is reference temperature, K; T is the temperature to which throughput Q refers, K.

When T and T_0 are equal, Equation (55) reduces to throughput divided by reference pressure. Always state reference conditions for volumetric flow rate: ‘cm³/s’ without pressure and temperature is ambiguous. At the same reference pressure, equal amounts of gas occupy volumes differing by approximately 7.3 % at 0 and 20 °C. Account for this difference when comparing results.

Specific Outgassing Rate

For material comparison, use throughput per unit surface area:

$$q_A = \frac{Q}{A} \quad (56)$$

q_A is specific outgassing rate, Pa·m³/(s·m²), equivalent to Pa·m/s; Q is total surface throughput, Pa·m³/s; A is surface area, m². All inputs must refer to the same temperature and specimen-preparation procedure.

For a porous material, the external geometric area may be much smaller than the internal surface area. When comparing specific outgassing rates, establish which area is used. State the area-determination method, specimen dimensions and preparation conditions in the report [8].

Gas Flow Regimes and Passage Conductance

Mean Free Path and Knudsen Number

At high gas density, collisions between molecules dominate over collisions with passage walls. As pressure decreases, mean free path increases. In molecular flow, gas transport is governed

primarily by passage geometry and molecule–surface interactions.

For the elastic hard-sphere model, mean free path is:

$$\lambda = \frac{kT}{\sqrt{2}\pi d_m^2 p} \quad (57)$$

k is the Boltzmann constant, 1.380649×10^{-23} J/K; λ is mean free path, m; d_m is effective molecular diameter in the selected model, m; p is pressure, Pa; T is temperature, K. Effective diameter is a collision-model parameter, not a universal geometric dimension of a molecule.

The ratio of mean free path to a characteristic passage dimension is the Knudsen number:

$$Kn = \frac{\lambda}{D} \quad (58)$$

λ is mean free path, m; D is the characteristic transverse passage dimension, m; Kn is the dimensionless Knudsen number. For $Kn \ll 1$, the continuum approximation applies; for $Kn \gg 1$, the free-molecular approximation applies. The transitional region lies between them. Knudsen number does not determine whether flow is laminar or turbulent: the Reynolds number is used for that assessment in continuum flow. Select the applicability limits of calculation formulas according to the required accuracy [1, 2; 27].

Example 9 — One Pipe and Different Flow Regimes

For an indicative estimate at 293 K, take λp for air as 6.8×10^{-3} Pa·m. In a pipe of diameter 0.02 m at 100 Pa, $Kn \approx 0.0034$; at 0.1 Pa, $Kn \approx 3.4$. The geometry is unchanged, but a single conductance equation is no longer suitable for the entire pump-down process.

A through-wall microcrack is more complex still. Atmospheric gas may be present at the inlet and high vacuum at the outlet. The flow regime changes along the passage. This is why conversion of helium throughput to air throughput using one factor requires justification beyond knowledge of molar masses alone.

Molecular Flow and the Role of Gas Mass

The mean thermal molecular speed is:

$$\bar{v} = \sqrt{\frac{8RT}{\pi M}} \quad (59)$$

$\bar{v}$ is mean speed, m/s; M is molar mass, kg/mol; R is the gas constant, J/(mol·K); T is temperature, K. At equal temperature, lighter molecules move faster than heavier molecules.

For a thin-wall aperture in molecular flow:

$$C_{\text{ap}} = \frac{A\bar{v}}{4} \quad (60)$$

$\bar{v}$ is mean thermal molecular speed, m/s; C_{ap} is aperture conductance, m³/s; A is aperture area, m². For a passage of finite length, multiply this value by the probability that a molecule passes from inlet to outlet:

$$C = \alpha C_{\text{ap}} \quad (61)$$

C is passage conductance, m³/s; C_{ap} is inlet-aperture conductance, m³/s; α is dimensionless transmission probability between zero and one. It depends on geometry and the wall-reflection model. A molecule may enter a pipe, reflect several times and return; entry alone does not imply transmission to the other side [2; 36; 72, 73, 74].

For the same passage at equal temperature, molecular-flow conductance for helium is approximately 2.69 times that for air.

This follows from the square root of the ratio of molar masses 0.02897 and 0.00400 kg/mol. The factor applies to molecular conductance; it is not a universal correction for every leak, seal or pressure.

Capillary Leak Model

For a long circular capillary, use Equation (6) in Part I. It describes laminar, isothermal ideal-gas flow with negligible wall slip and small inertial effects. Express all dimensions in metres, pressures in pascals and dynamic viscosity in Pa·s.

Equation (6) applies while its assumptions hold over the relevant part of the passage. It requires refinement for substantial rarefaction at the outlet, transition to molecular flow or significant gas acceleration. The fourth power of radius explains the strong geometric dependence: all else equal, increasing radius by 10 % increases throughput by approximately 46 %. A single measured throughput cannot, however, uniquely determine defect shape. Different combinations of passage length, width and tortuosity can produce the same result.

Effective Pumping Speed at the Product

Pumping Speed at the Flange and in the Chamber

A large pump does not guarantee a high pumping speed at the product. Adapters, valves, filters and hoses lie between them. For a pump and line in series, use Equation (17) in Part I; all characteristics must refer to the same gas and the relevant flow regime [1, 2].

Example 10 — Why Replacing the Pump Made Little Difference

A pump rated at 0.10 m³/s is connected to a chamber through a passage of conductance 0.010 m³/s. Effective pumping speed is

0.00909 m³/s. Replacing the pump with a 0.30 m³/s unit raises it to only 0.00968 m³/s. Despite a threefold increase in rated speed, effective speed at the product increases by only approximately 6.5 %. Shortening and widening the connecting line is more effective in this situation.

For sections in series, add reciprocal conductances; for parallel passages between the same nodes, add conductances directly. This representation requires each node to be described by a single pressure and each conductance to suit the gas and flow regime. For complex geometries where these conditions do not hold, use a spatial gas-transport model.

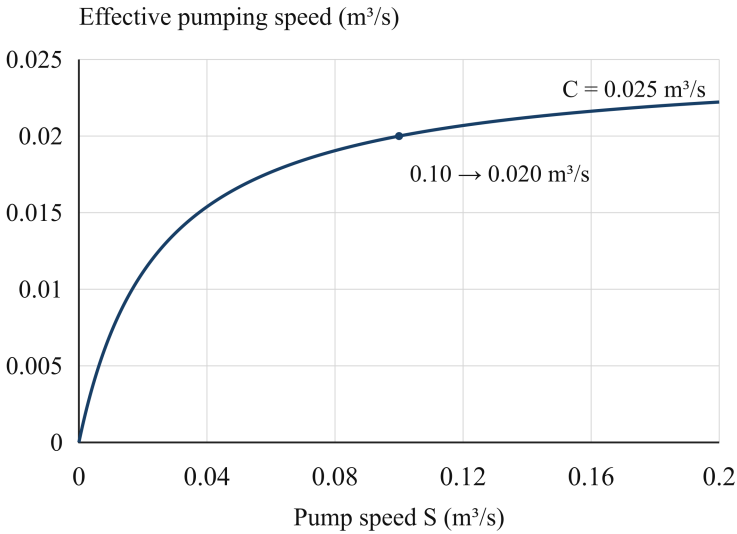
Plot 1 assumes a line conductance of 0.025 m³/s. With a pump speed of 0.10 m³/s, effective speed is 0.020 m³/s. Doubling pump speed gives approximately 0.0222 m³/s, an increase of only 11 %. The curve shows when increasing line conductance is more effective than choosing a faster pump. Where conductance depends on pressure, calculate it for the relevant conditions.

A Long Pipe

For a long, straight circular pipe with diffuse wall reflection in molecular flow:

$$C \approx \frac{\pi D^3 \bar{v}}{12L} \quad (62)$$

D is internal pipe diameter, m; L is length, m; $\bar{v}$ is mean molecular speed, m/s. The approximation applies when L is much greater than D. For short pipes, account for entrance resistance and a more accurate transmission probability.



Plot 1 — Effective pumping speed limited by a line conductance of 0.025 m³/s. Calculation for components in series.

In this model, conductance is proportional to the cube of diameter: doubling diameter increases conductance by a factor of approximately eight. Bends, corrugations, baffles, filters and valves generally reduce conductance relative to a smooth, straight pipe. Equation (62) therefore cannot be applied without correction to a corrugated hose or complex connection path. See Figure 27.



Figure 27 — Corrugated line connected to a nozzle. Corrugations, restrictions and transitions must be considered when assessing measurement-path conductance.

A Nearby Pump and a Long Gas Path

On site, the instrument is placed where space and power are available. A hose, adapters and valves remain between it and the product. The connection appears straightforward until the operator notices that the signal arrives too late or is weaker than expected (Figure 28).

In this situation, verify the complete assembled path. Introduce reference flow at a representative point in the product and observe the response with valves in their working positions. A check at the leak detector inlet alone does not reproduce connecting-line resistance. After shortening the line or changing the configuration, determine detection capability and response time again.

Low connection conductance may be the cause. Replacing a serviceable pump with a larger one may then be less effective than eliminating the restriction. Diagnosis therefore starts by tracing the tracer-gas path from product to analyser and checking the sections that restrict transport.



Figure 28 — Connecting line at the end assembly of a large vessel. Response assessment includes line length, cross-section and valve positions.

Flow Distribution between Pumps

If a chamber is connected simultaneously to a leak detector and an auxiliary pump, the throughput divides between them. Calculate the fraction reaching the measurement branch using

Equation (21) in Part I, accounting for the effective speed of each branch for the tracer gas.

An auxiliary pump shortens waiting time and accommodates an outgassing product, but also reduces the signal. Changing a valve position or connecting another pumping group therefore changes the sensitivity of the complete configuration. Position the external reference leak so that its gas follows the same path and divides between branches in the same proportion. The built-in leak primarily checks the instrument itself [21, 22].

Example 11 — Faster Does Not Always Mean Better Detection

Let the measurement branch have an effective speed of 0.001 m³/s and the auxiliary branch 0.009 m³/s. One tenth of the throughput reaches the leak detector. If the operator uses internal calibration and ignores this distribution, the reading may be mistaken for total product throughput. An external reference-leak check at the product determines the transfer factor experimentally.

Pump-Down Dynamics

Gas Balance in a Pumped Chamber

For a lumped volume at constant temperature and effective pumping speed, the balance is:

$$V \frac{dp}{dt} = Q_{\Sigma}(t) - S_{\text{eff}}(p - p_{\text{ult}}) \quad (63)$$

V is volume, m³; p is pressure, Pa; t is time, s; Q_{Σ} is total gas load, Pa·m³/s; S_{eff} is effective pumping speed, m³/s; p_{ult} is ultimate pressure in the adopted model, Pa. The lumped model assumes no significant spatial pressure differences within the volume.

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