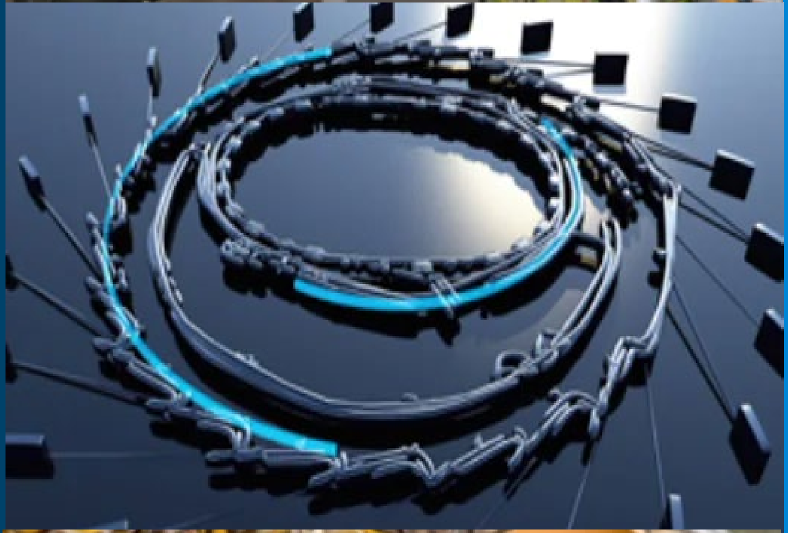
Creating, Measuring and Maintaining High and Ultra-high Vacuum: **Session 1**

CAARI-SNEAP Conference: November 2022



Agilent
Trusted Answers

John Screech
Sr Applications Engineer
Agilent Vacuum Products Division (VPD)

Introduction to UHV

Ultra-High Vacuum Seminar: Part 1 of 2 Session Series

John Screech, Senior Applications Engineer, Agilent Technologies, Vacuum Products Division

This class provides the basics for understanding the nature of ultra-high vacuum (UHV) which is a key enabling condition for many types of scientific inquiry and experimentation. Topics in Session One will include an introduction to high vacuum and ultra-high vacuum, including the relationship between Pumping Speed, Throughput, Gas Load and Conductance. A description of the working principles of vacuum pumps and gauges used in rough, high and ultra-high vacuum will also be discussed. The curriculum for this 90 minute class is excerpted from Agilent's one-day UHV Seminar and is intended to provide an introduction to ultra-high vacuum systems and practice for scientists, engineers and technicians. Attendees will receive a printed copy of the slide deck and are encouraged to add notes to this useful resource.

		Kincaid (Hybrid)	Quarter	Palomino	Arabian	Pioneer III	Pioneer IV
Wednesday, 11/2	8:45 AM	PS-AR-01					
	9:30 AM						
	10:00 AM	IBTM-02	MA-01	SP-08	RE-08	NBAT-01	SD-03
	11:30 AM						
	12:30 PM	MA-04	NST-03	SP-09	IBTM-04	NBAT-02	RE-03
	2:00 PM						
	2:30 PM	AMP-02	MA-06	WKS-VAC1	IBTM-05	TD-01	RE-04
	4:00 PM						
	4:15 PM	Lab Tour					
	6:30 PM	Networking Dinner - Triangle Ballroom/Event Lawn					

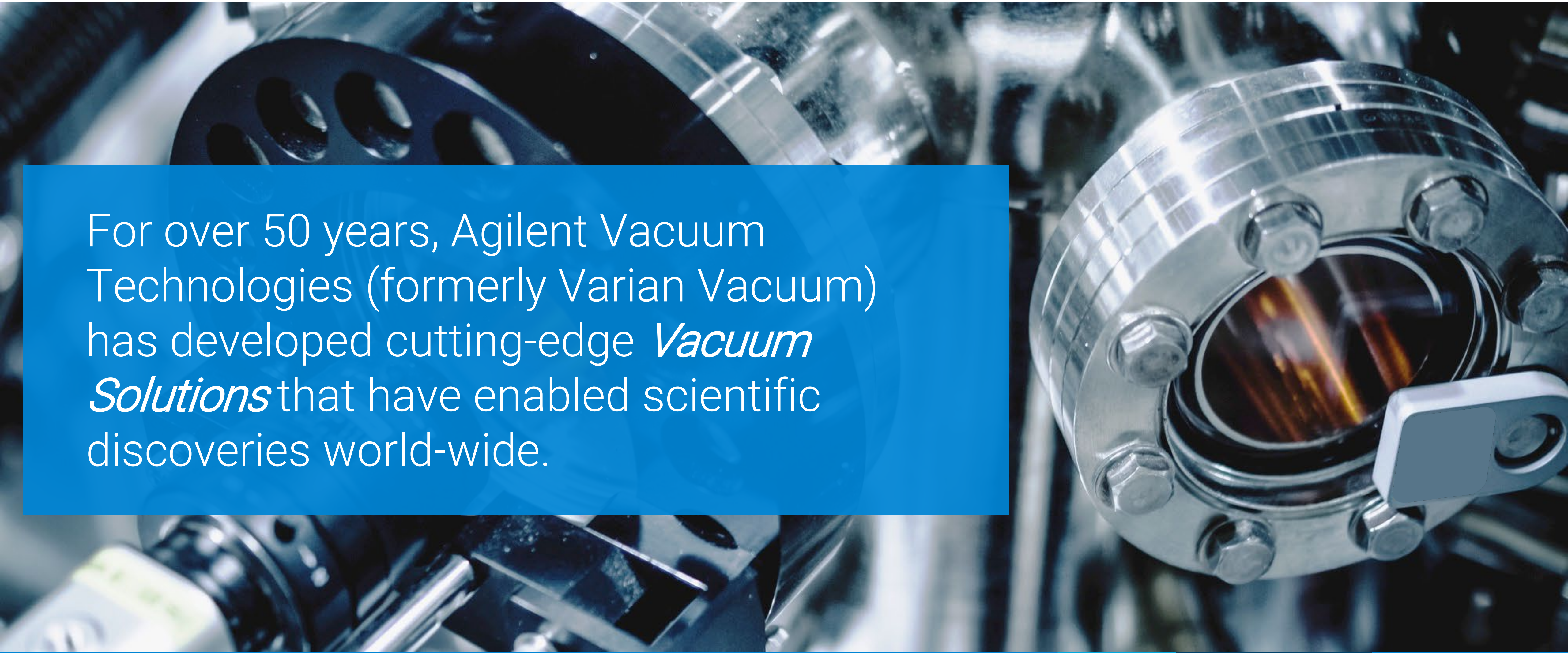
You Can Achieve Your Ideal Ultra or Extreme High Vacuum Pressure Easily with Agilent.

Join the comprehensive **2-part Ultra-High Vacuum Workshop**:

- **Part 1:** *Nov. 2nd (Wed.) 2:30 – 4 pm*
- **Part 2:** *Nov. 3rd (Thurs.) 10:30 am – 12 pm*

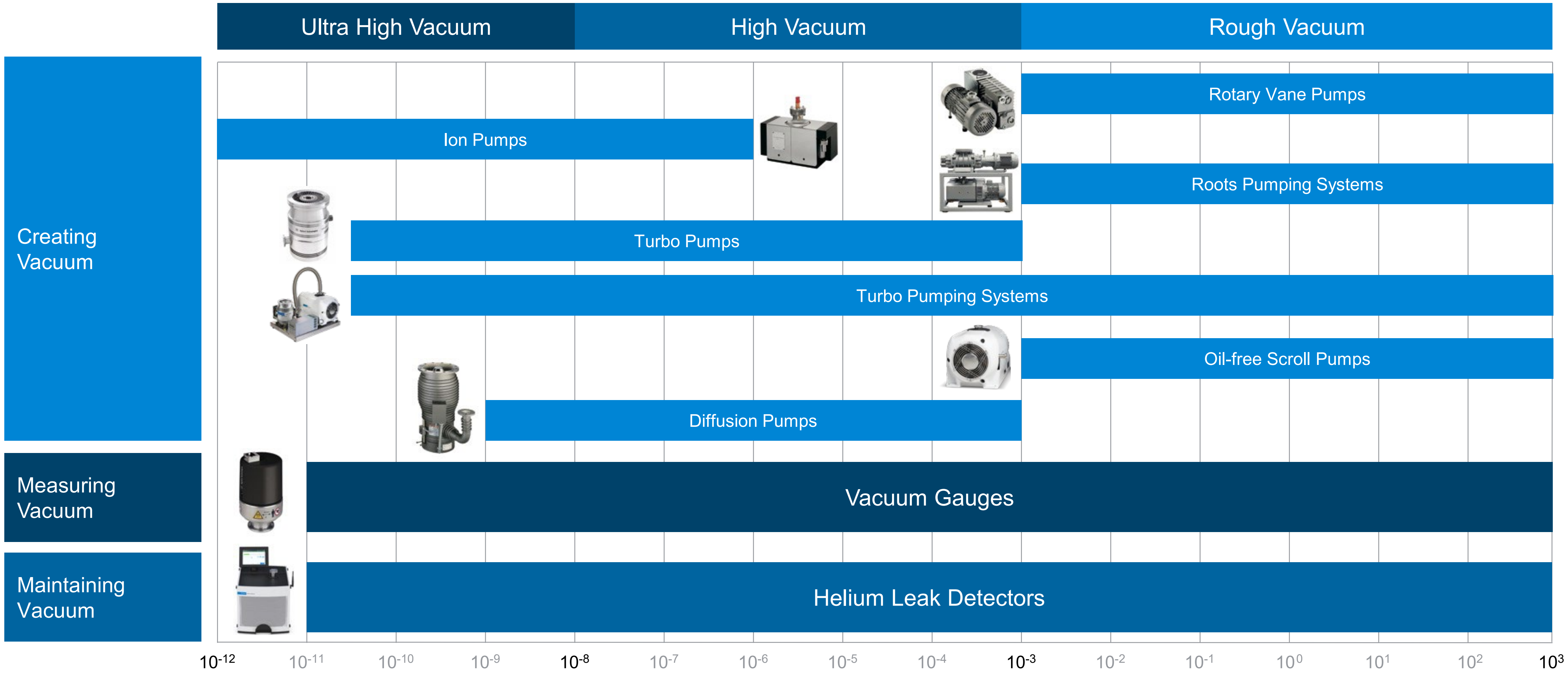
And schedule a complimentary in-person consultation with our vacuum experts to discuss your application challenges. Limited availability, book your spot now by scanning the code or go to https://calendly.com/agilent-vacuum/carri-sneap-2022

Agilent Vacuum Technologies



For over 50 years, Agilent Vacuum Technologies (formerly Varian Vacuum) has developed cutting-edge *Vacuum Solutions* that have enabled scientific discoveries world-wide.

Agilent Vacuum at a Glance



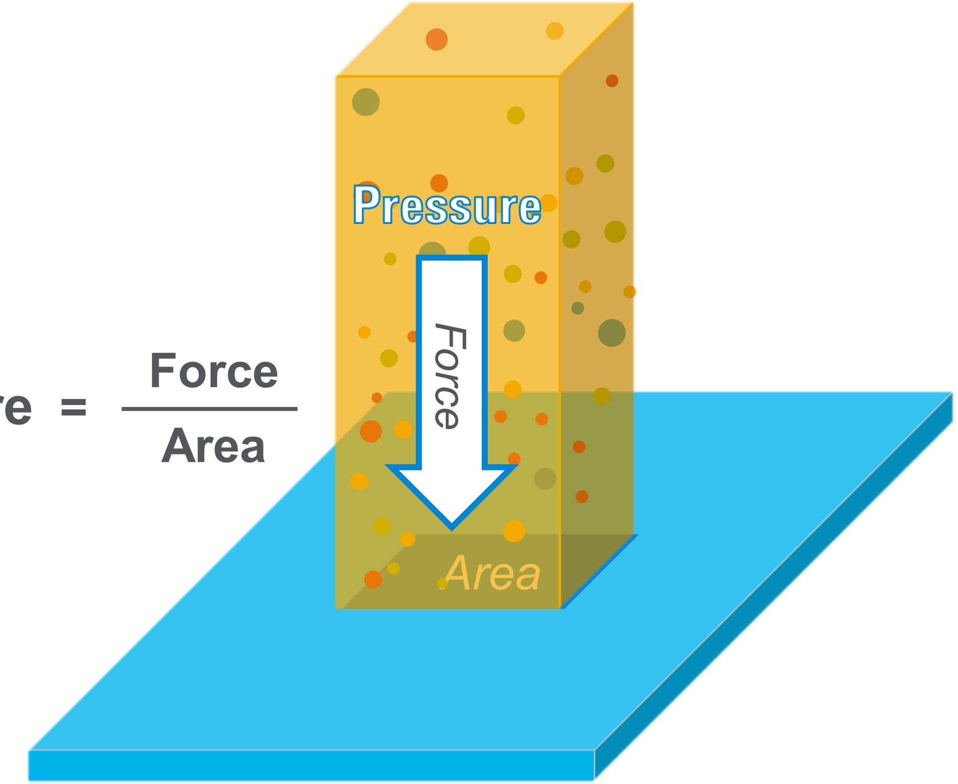
Topics: Session 1

- Introduction
  - What is Pressure & Why we need Vacuum
  - Pumping Speed, Throughput, Gas Load & Conductance
  - Viscous and Molecular Flow
- Creating & Measuring Rough Vacuum
  - Rough Vacuum Pumps
  - Mechanical & Thermal Vacuum Gauges
- Creating High Vacuum
  - High Vacuum Pumps

Pressure (P) Made Simple

Pressure can be defined as the Force exerted by gas molecules striking a surface Area.

$$\textbf{Pressure} = \frac{\textbf{Force}}{\textbf{Area}}$$



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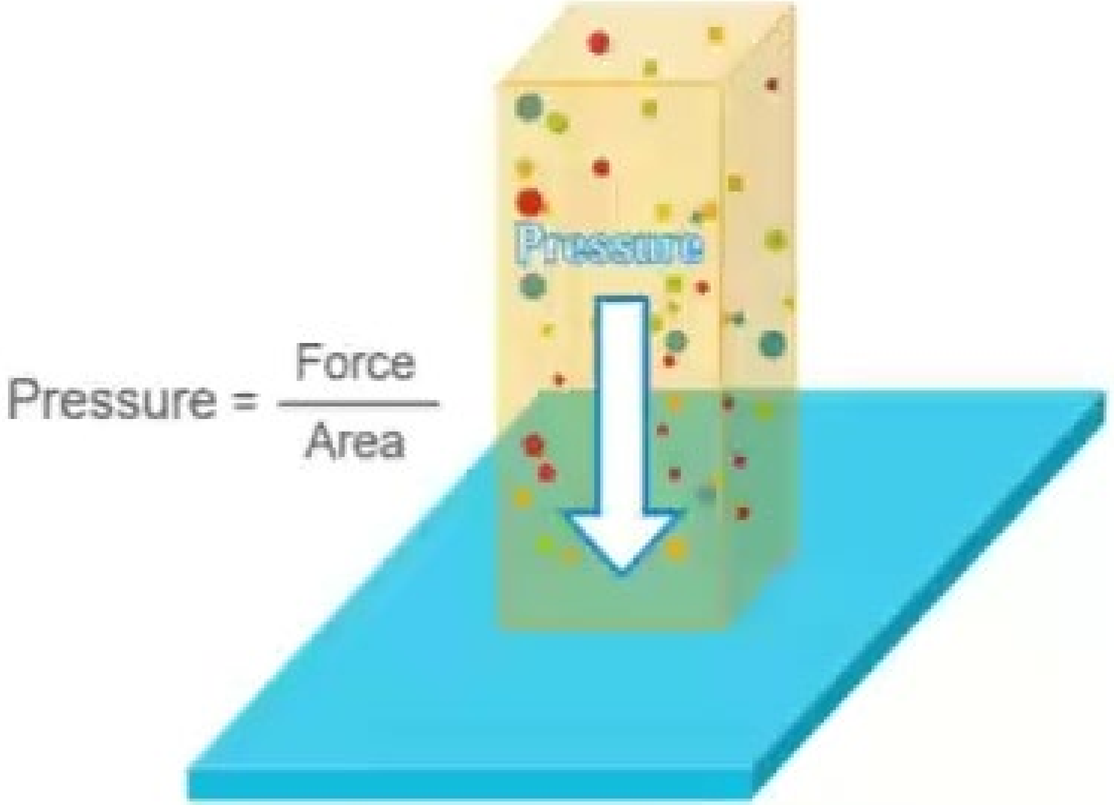


WHY We Need Vacuum?

Move Particles over Long Distances

- avoid signal 'loss' from collisions with background gas molecules

Create & Maintain 'Clean' Surfaces

- facilitate deposition onto pristine surfaces
- re-create spacelike conditions

Prevent Electrical Breakdown

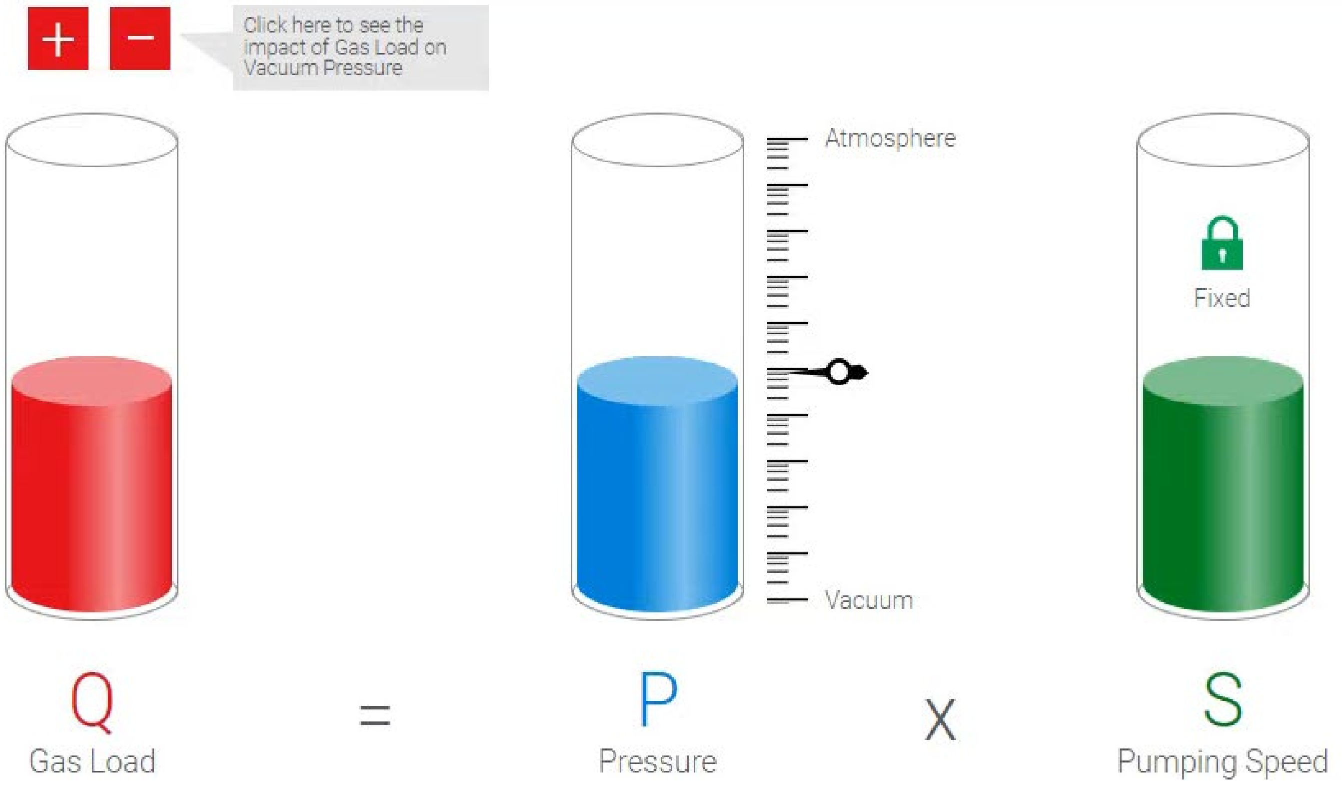
- maintain large electric potentials without 'arcing'

Create the Conditions for Gas Flow

- create conditions that promote the transfer of He from high-pressure to low-pressure region

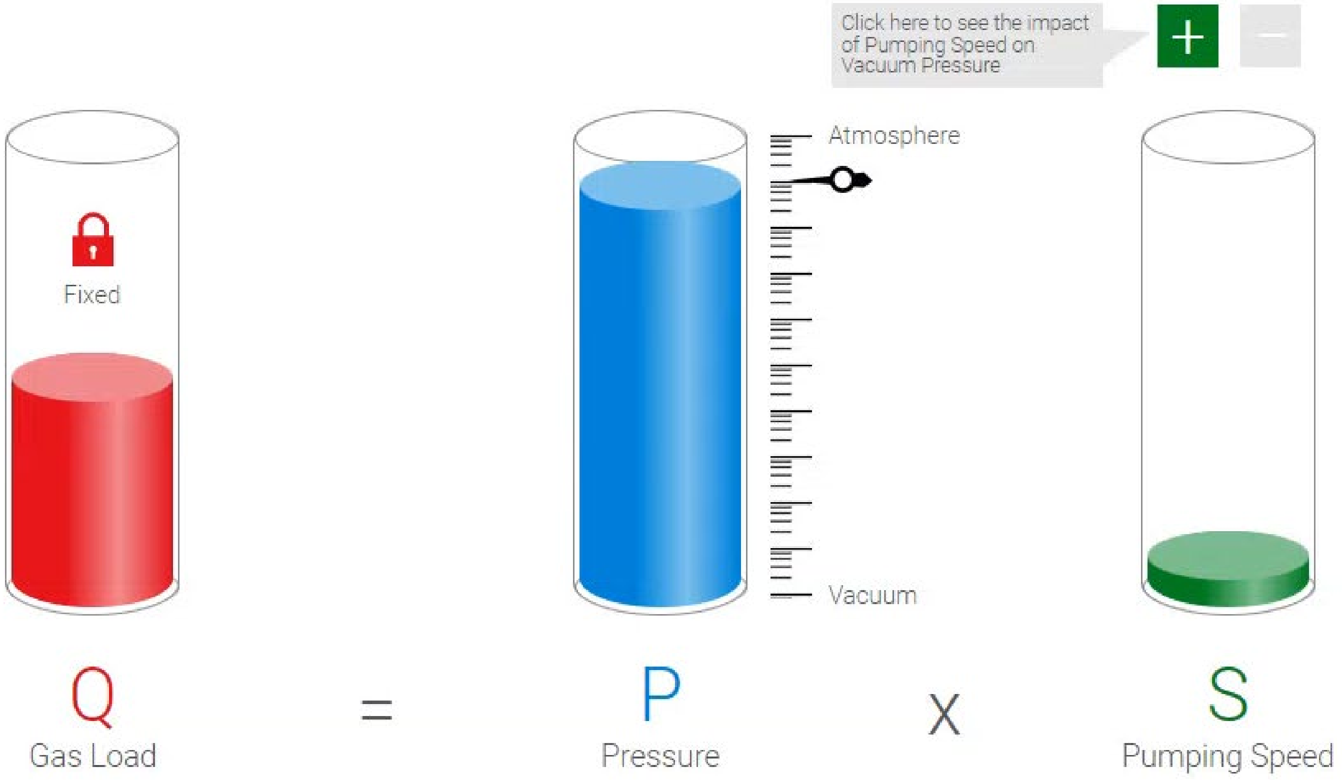
Vacuum Made Simple: Q = P x S

If Pumping Speed (S) is fixed then Pressure (P) is *directly* proportional to Gas Load (Q).



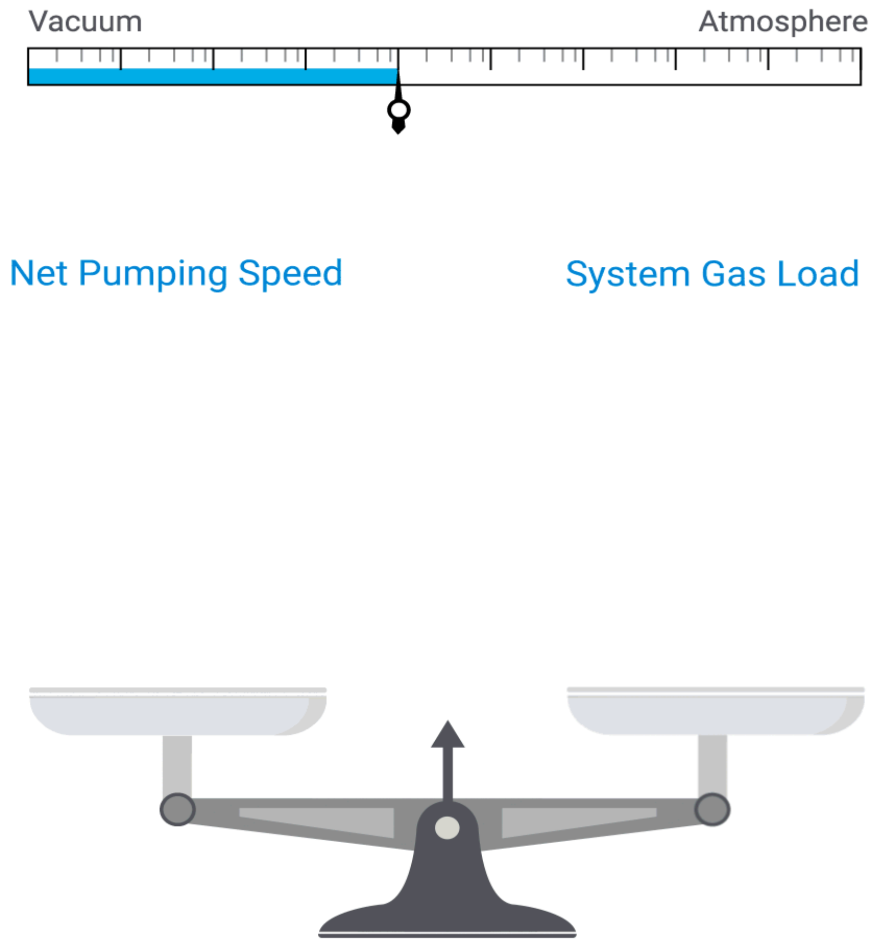
Vacuum Made Simple: Q = P x S

If Gas Load (Q) is fixed then Pressure (P) is *inversely* proportional to Pumping Speed (S).



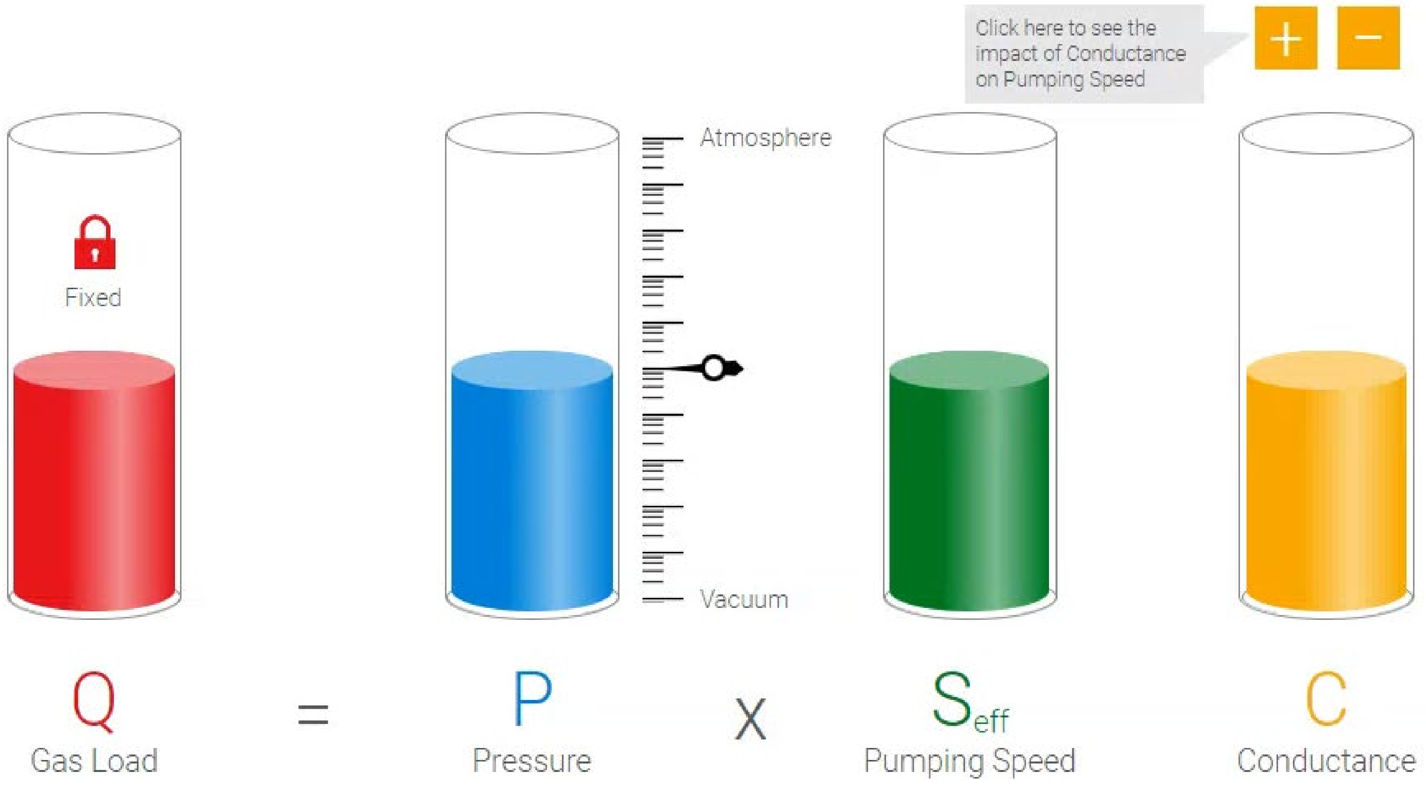
Ultimate Pressure

Ultimate Pressure of vacuum system represents the BALANCE between Effective (net) Pumping Speed and Total System Gas Load.



Vacuum Made Simple: Q = P x S

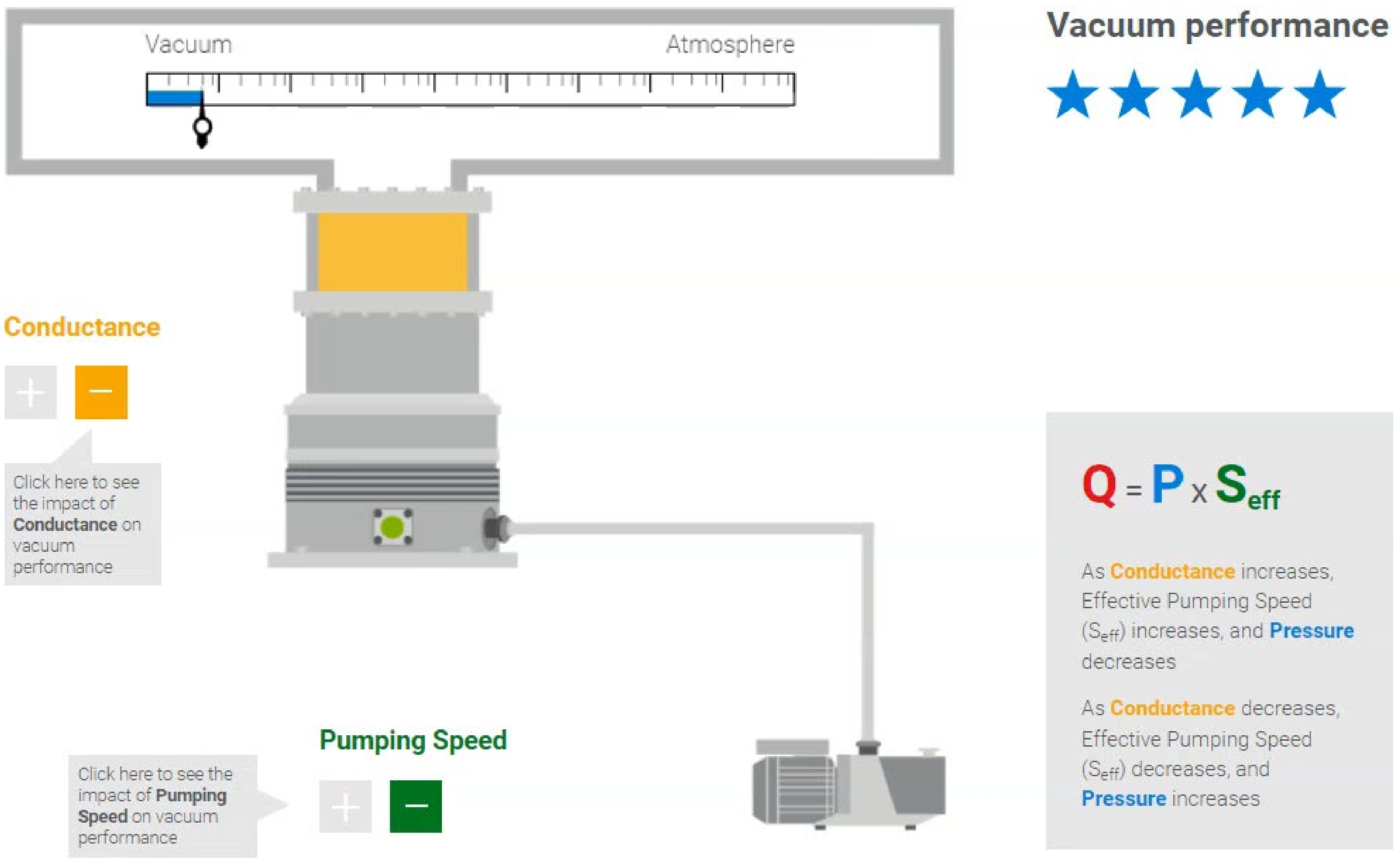
Effective Pumping Speed (S_{eff}) includes the *negative* influence of Conductance (C).



Conductance, Pumping Speed & Pressure

A **large vacuum pump** with **poor conductance** will result in **poor vacuum performance** (higher ultimate pressure).

Impact of conductance on effective pumping speed



$Q = P \times S_{eff}$

As **Conductance** increases, Effective Pumping Speed (S_{eff}) increases, and **Pressure** decreases

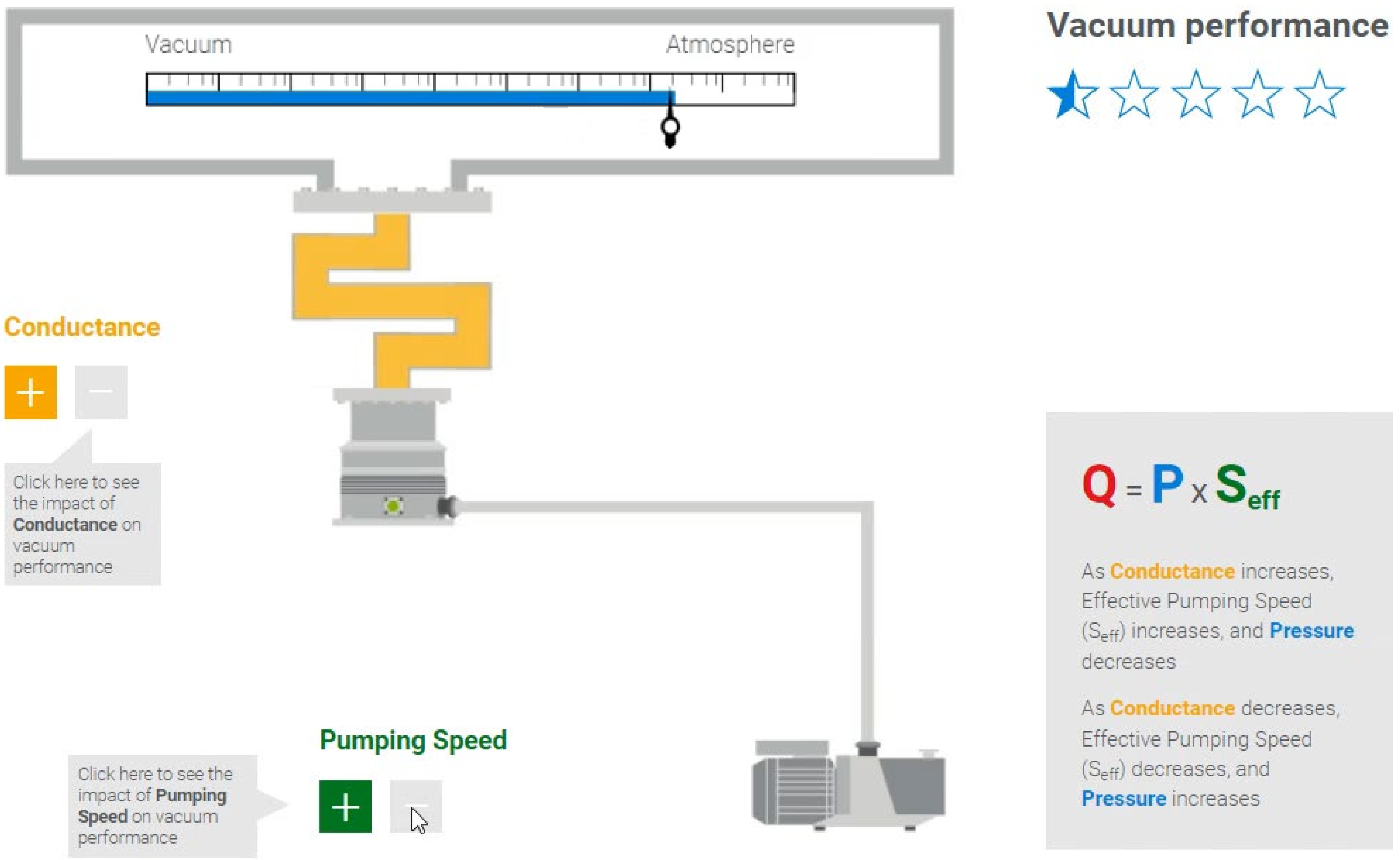
As **Conductance** decreases, Effective Pumping Speed (S_{eff}) decreases, and **Pressure** increases

Conductance, Pumping Speed & Pressure

A **large vacuum pump** with **poor conductance** will result in **poor vacuum performance** (higher ultimate pressure).

If a vacuum system is **CONDUCTANCE LIMITED**, increasing the **pump size** will have a **negligible effect** on ultimate pressure.

Impact of conductance on effective pumping speed



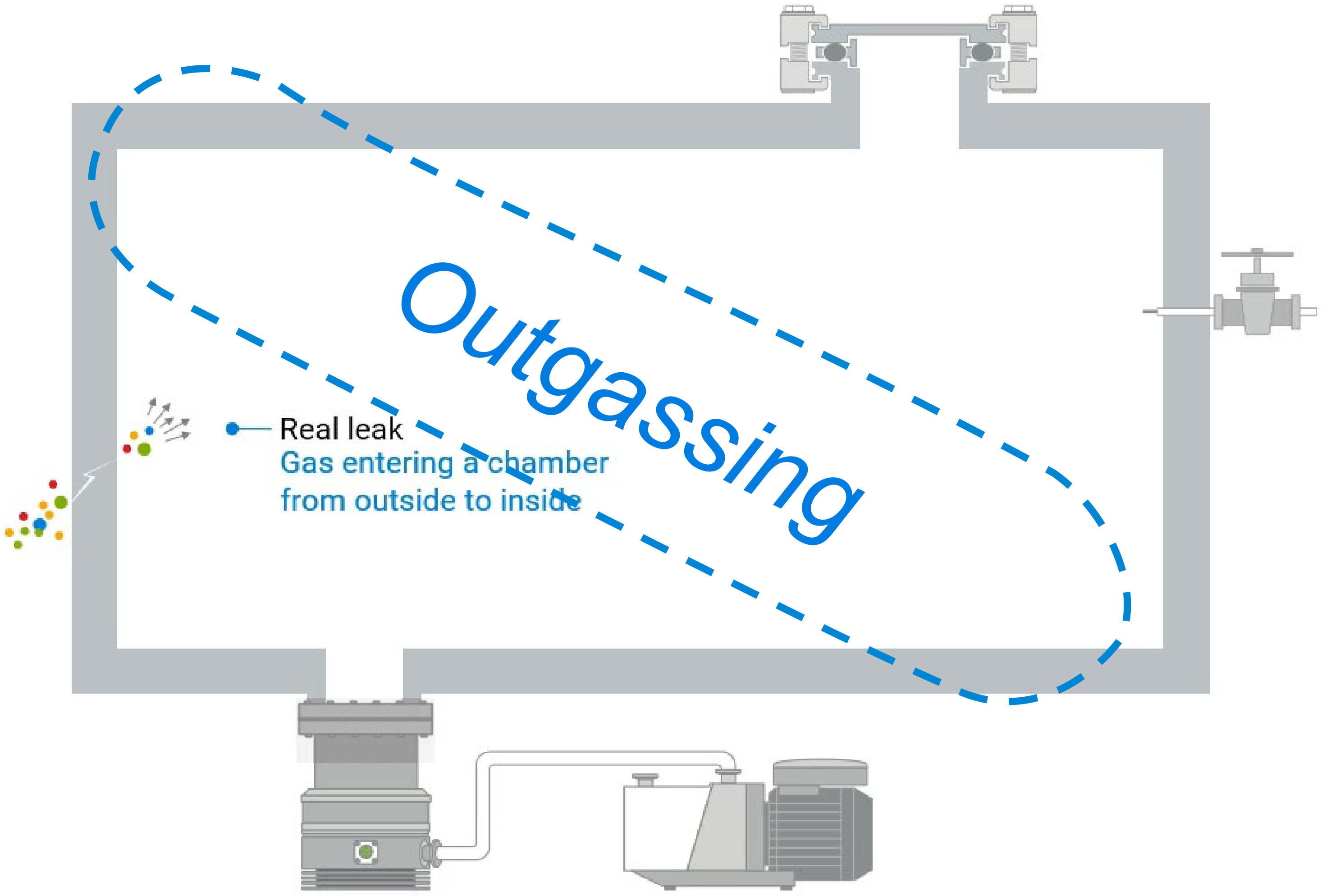
$Q = P \times S_{eff}$

As **Conductance** increases, Effective Pumping Speed (S_{eff}) increases, and **Pressure** decreases

As **Conductance** decreases, Effective Pumping Speed (S_{eff}) decreases, and **Pressure** increases

Total System Gas Load

Total System Gas Load includes **Real Leaks, Outgassing** (Desorption, Diffusion, Trapped Gas), **Permeation, Process Gas**, and **Backstreaming**.

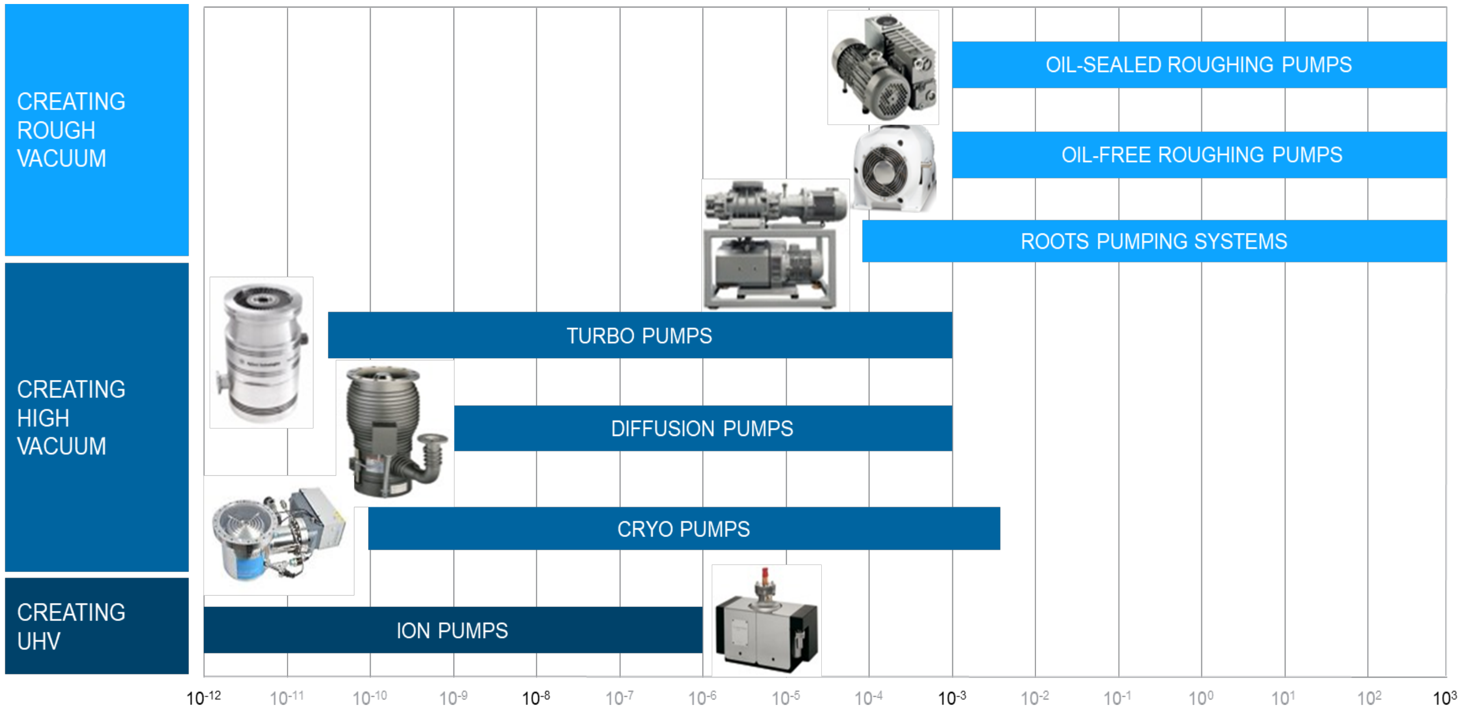


Vacuum Pressure Ranges

We typically describe levels of vacuum by the range of pressures:

- **Rough Vacuum**: Atmosphere to 10^{-3} Torr
- **High Vacuum**: 10^{-3} Torr to 10^{-8} Torr
- **Ultra-High Vacuum**: 10^{-8} Torr to 10^{-12} Torr

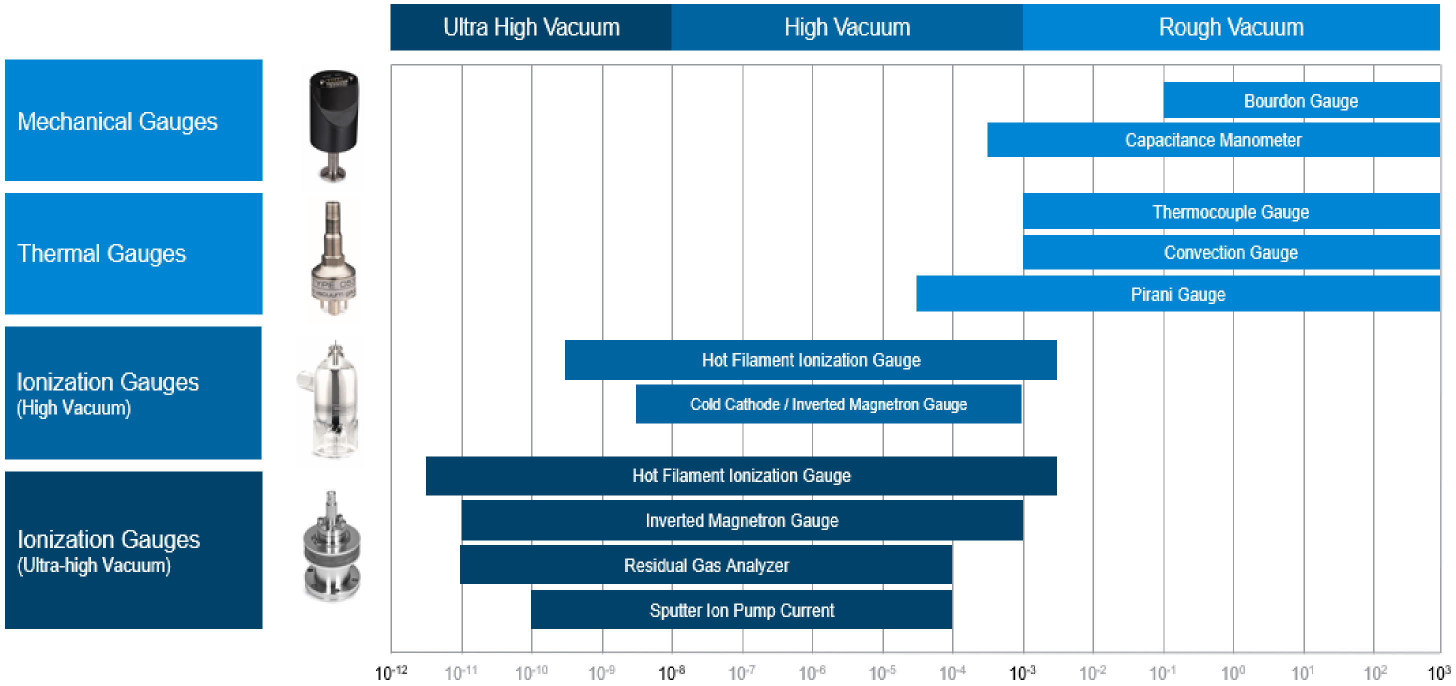
Why Rough, High & Ultra High Vacuum?



Creating Vacuum

requires different technologies in different pressure regimes

Why Rough, High & Ultra High Vacuum?



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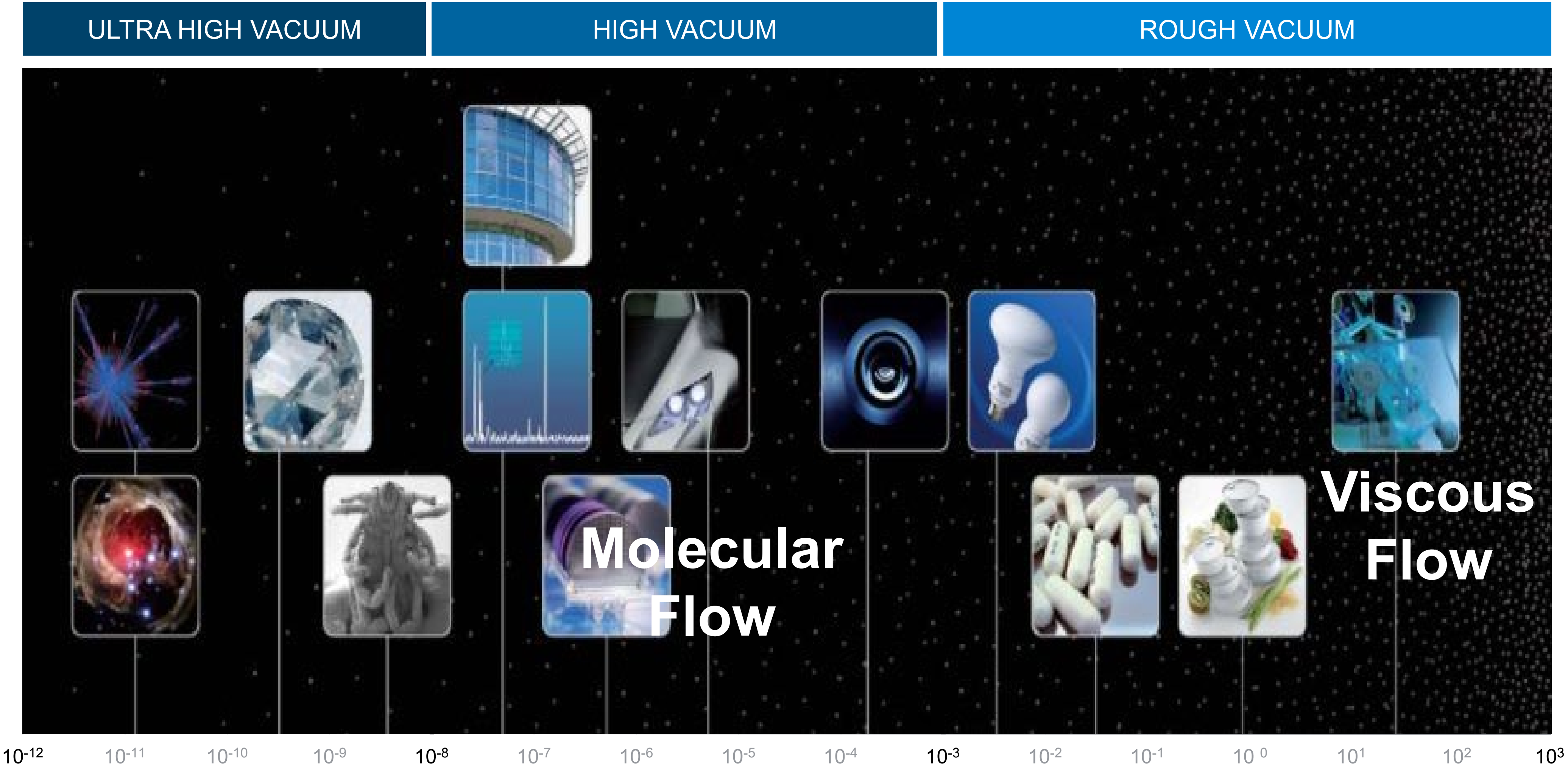
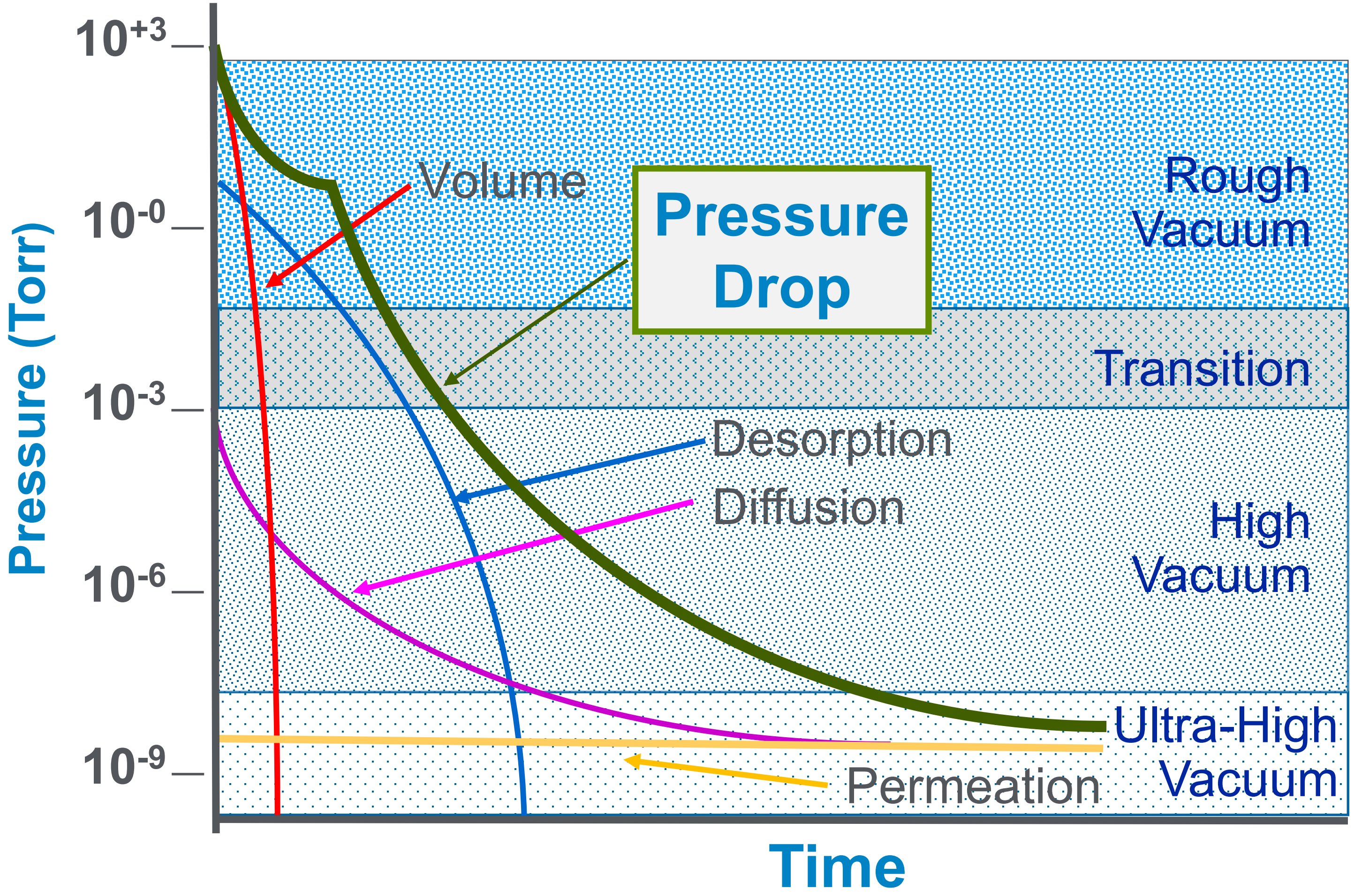
Measuring Vacuum
requires different technologies in different pressure regimes

Rough, High & Ultra High Vacuum



Why Rough, High & Ultra High Vacuum?

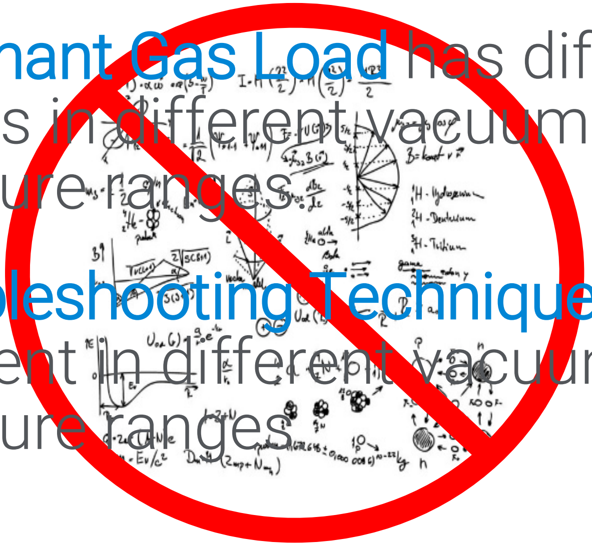


Molecules behave differently at different vacuum pressures:

- Viscous Flow: Atmosphere to 10^{-1} Torr
- Molecular Flow: Below 10^{-3} Torr

Dominant Gas Load has different origins in different vacuum pressure ranges

Troubleshooting Techniques are different in different vacuum pressure ranges



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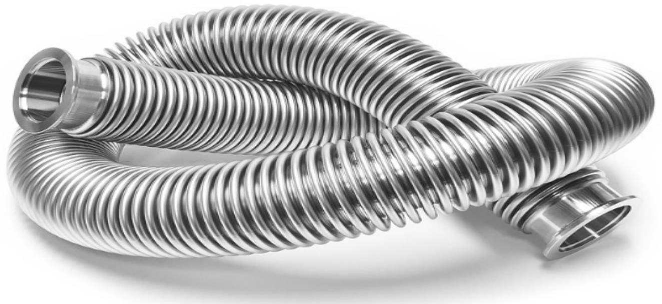
Conductance: Viscous Flow vs Molecular Flow

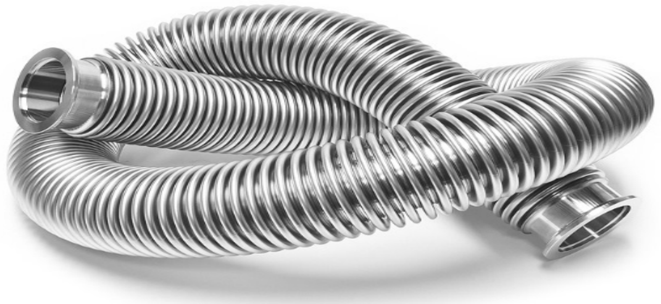
Viscous Flow



$$C = 180\ D^4 \times P/L \quad \text{(l/sec)}$$

D = Diameter of tube in cm
L = Length in cm
P = Pressure in Torr

Molecular Flow



$$C = \frac{12.1\ D^3}{L} \quad \text{(l/sec)}$$

D = Diameter of tube in cm
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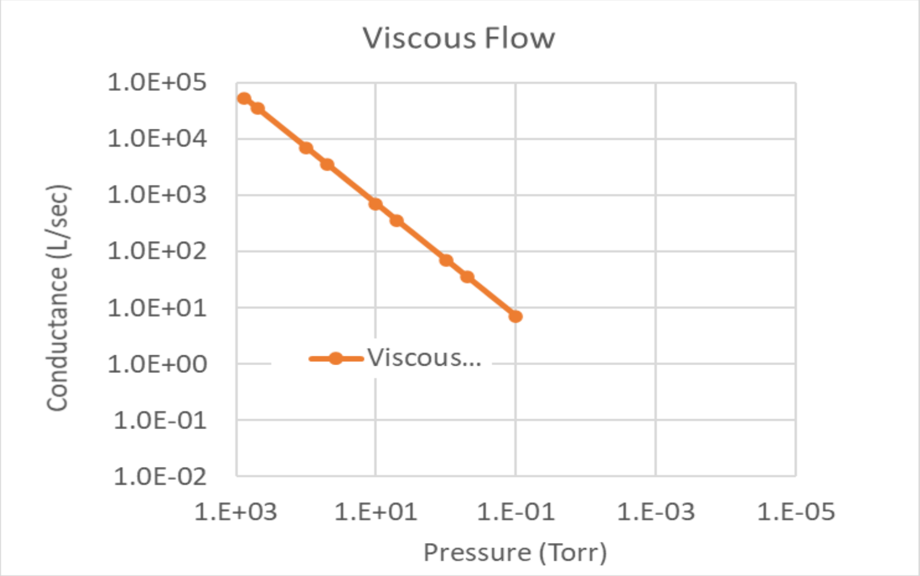
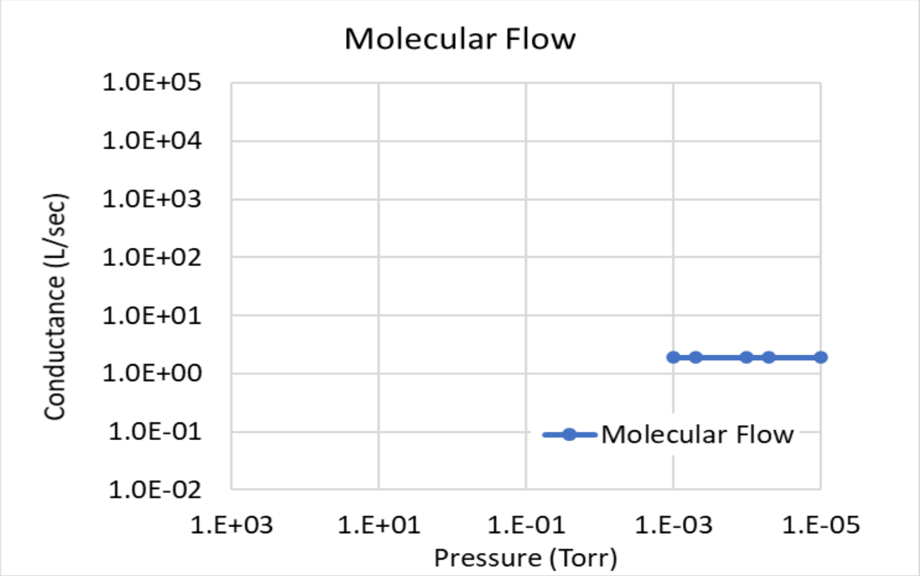
Conductance: Viscous Flow vs Molecular Flow

Viscous Flow



Molecular Flow



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Viscous Flow

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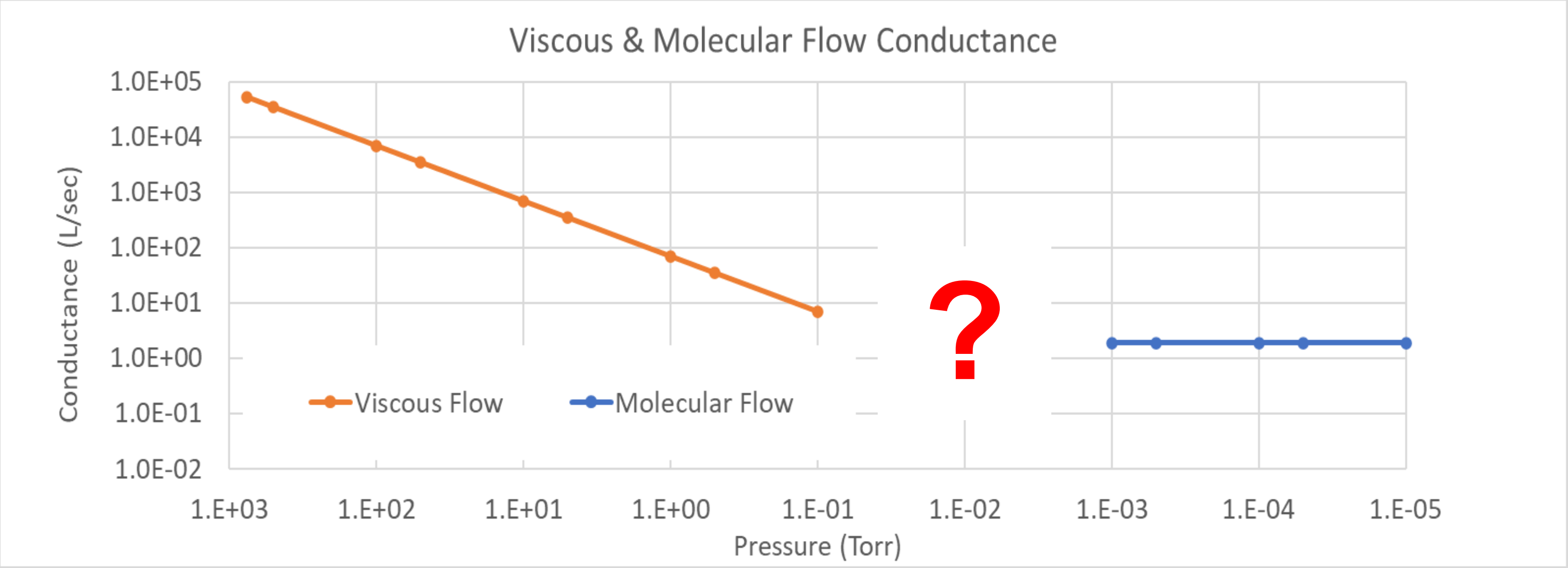
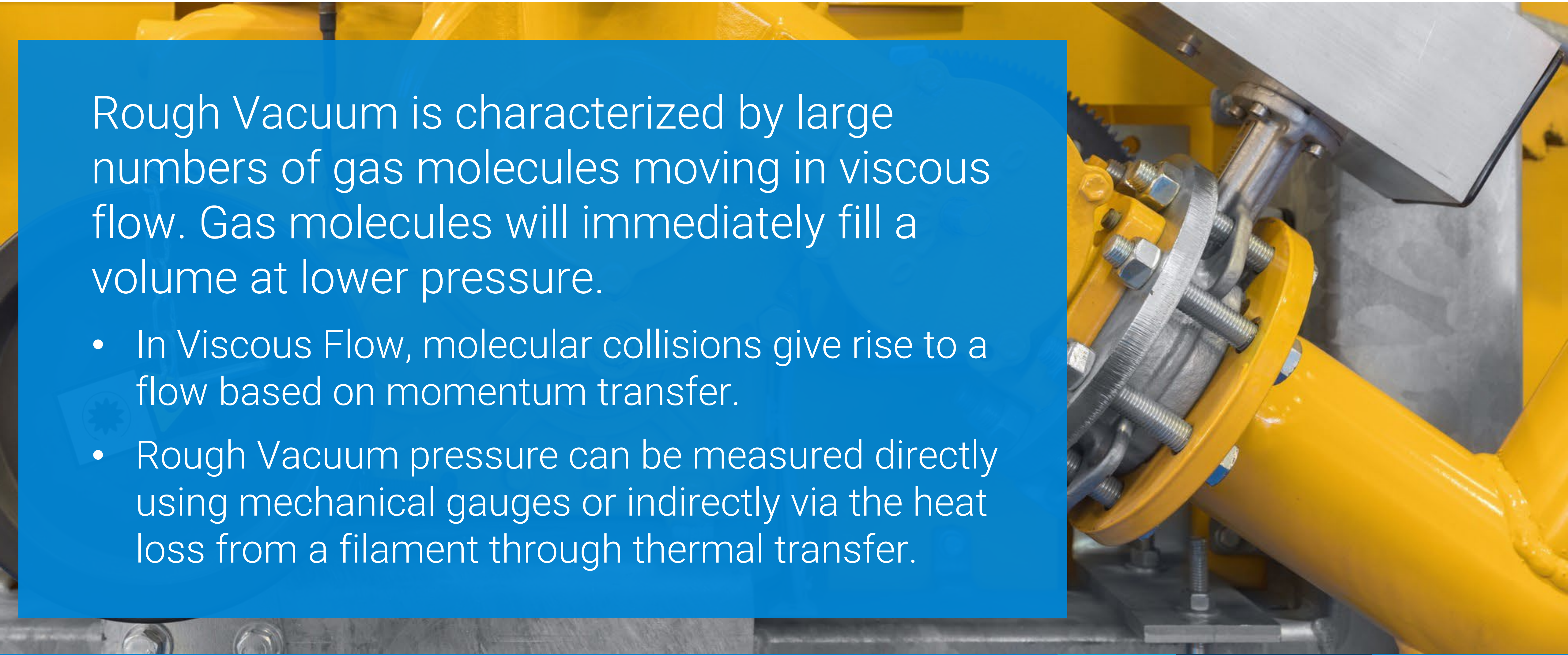


Rough Vacuum: Atmosphere – 10^{-3} Torr

Creating & Measuring Rough Vacuum

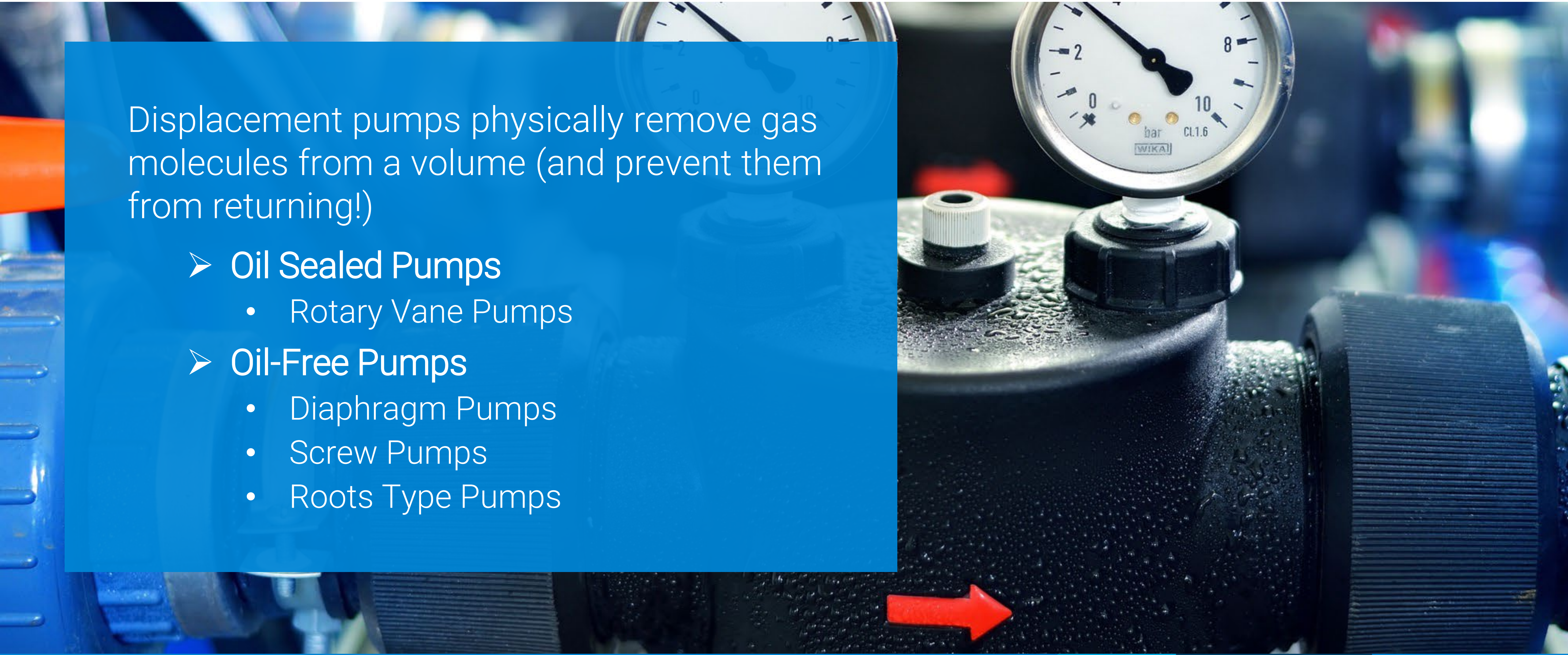
Viscous Flow



Rough Vacuum is characterized by large numbers of gas molecules moving in viscous flow. Gas molecules will immediately fill a volume at lower pressure.

- In Viscous Flow, molecular collisions give rise to a flow based on momentum transfer.
- Rough Vacuum pressure can be measured directly using mechanical gauges or indirectly via the heat loss from a filament through thermal transfer.

Creating Rough Vacuum: Displacement Pumps



Displacement pumps physically remove gas molecules from a volume (and prevent them from returning!)

- **Oil Sealed Pumps**
  - Rotary Vane Pumps
- **Oil-Free Pumps**
  - Diaphragm Pumps
  - Screw Pumps
  - Roots Type Pumps

Rotary Vane Pump

Rotating drum with sliding vanes rotates to create a ‘sweeping’ motion that compresses gas.

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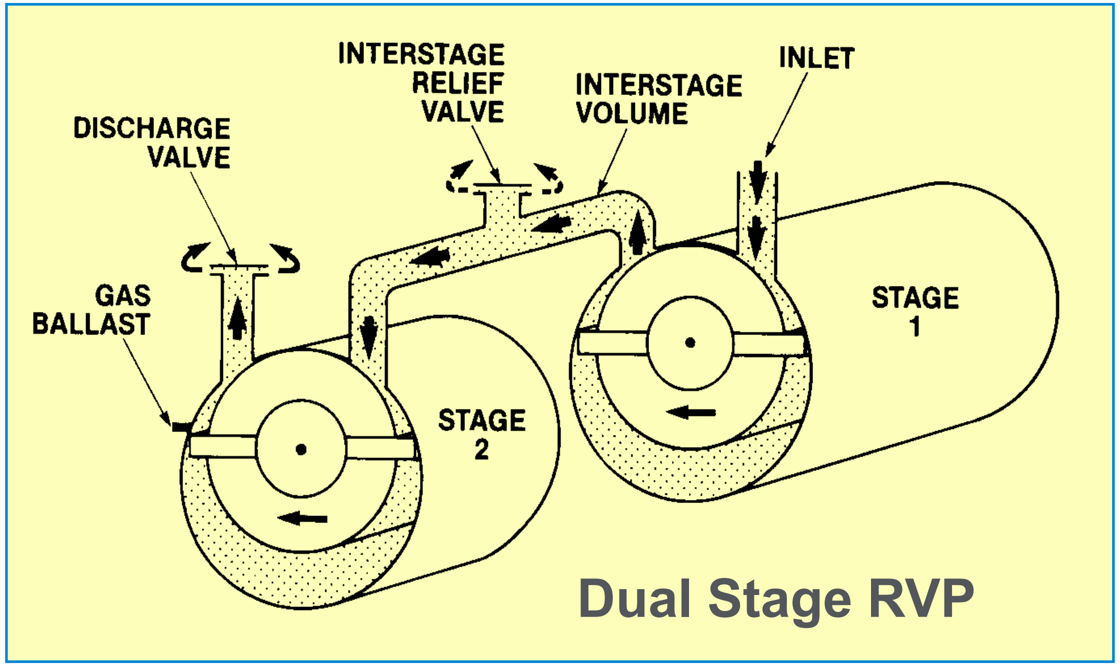
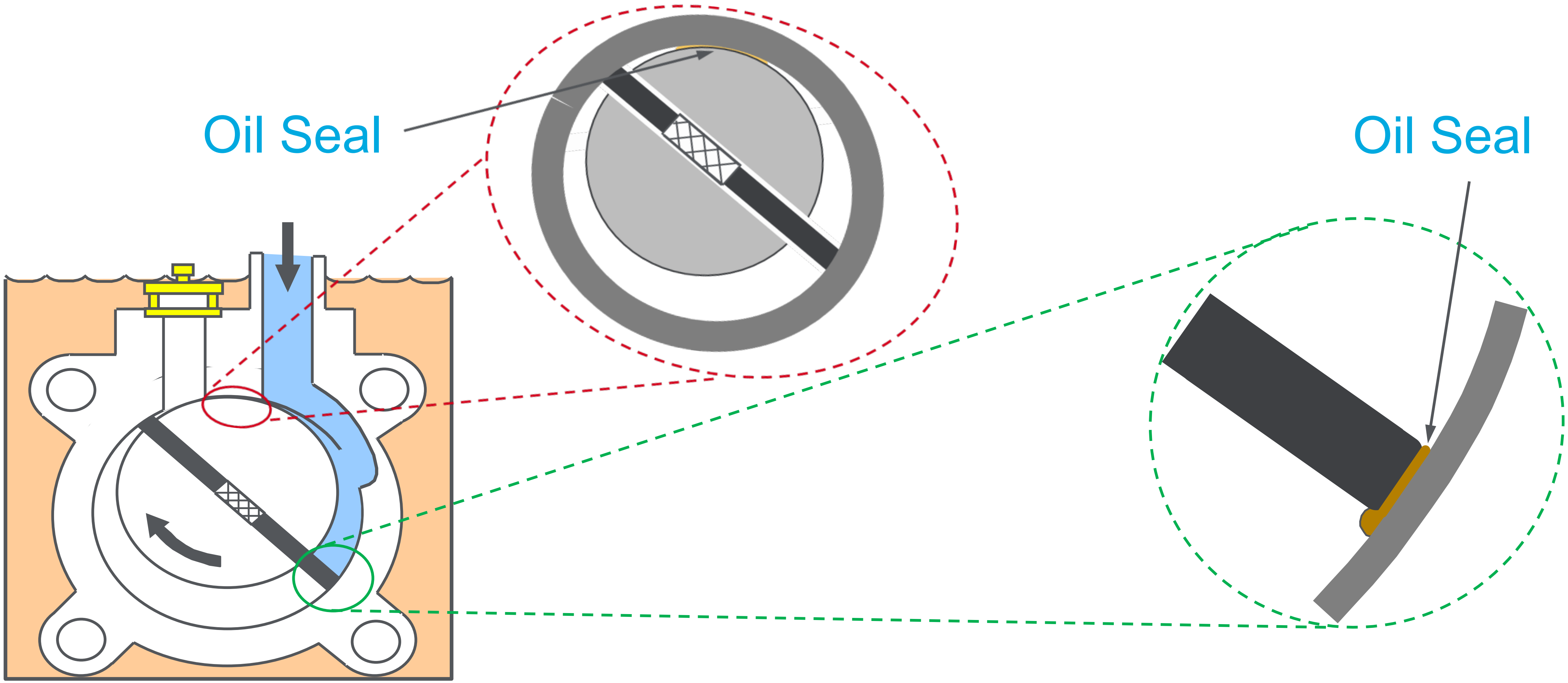


Oil Sealed Rotary Vane Pumps



Rotary Vane Pump

Rotating drum with sliding vanes rotates to create a ‘sweeping’ motion that compresses gas.

Oil forms a thin seal preventing gas from migrating between the high pressure and low pressure sections of the pump

Inverter Technology eliminates 25 m^3/hr threshold (single ϕ power) AND 50/60 Hz performance imbalance.

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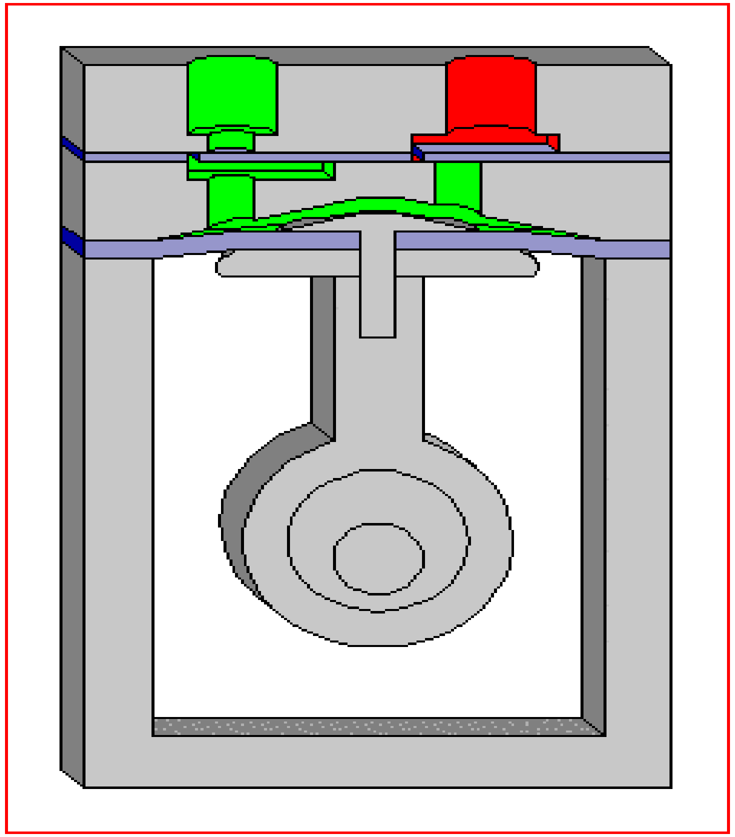
Diaphragm Pump

Crank distorts flexible diaphragm to create increased volume.

Gas in viscous flow travels through the inlet valve to fill the newly created volume.

Further travel of the piston compresses the gas forcing it through the exhaust valve.



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Oil-Free Scroll Pump

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Orbiting scroll creates a low pressure volume inside the pump.

Gas in viscous flow enters the space between the Orbiting and Stationary scroll sets.

As gas is forced towards the center, the volume decreases so the pressure increases.

At the center of the scrolls, an exhaust valve opens to allow the compressed gas to escape.

Oil-Free Scroll Pump

Dual Stage Scroll-Pumps MAY be required when supporting Turbo-pumps on UHV systems.

Inlet isolation valve prevents possible back-flow of tip seal material (on start-up) and eliminates potential to 'shock' turbo during shut-down.

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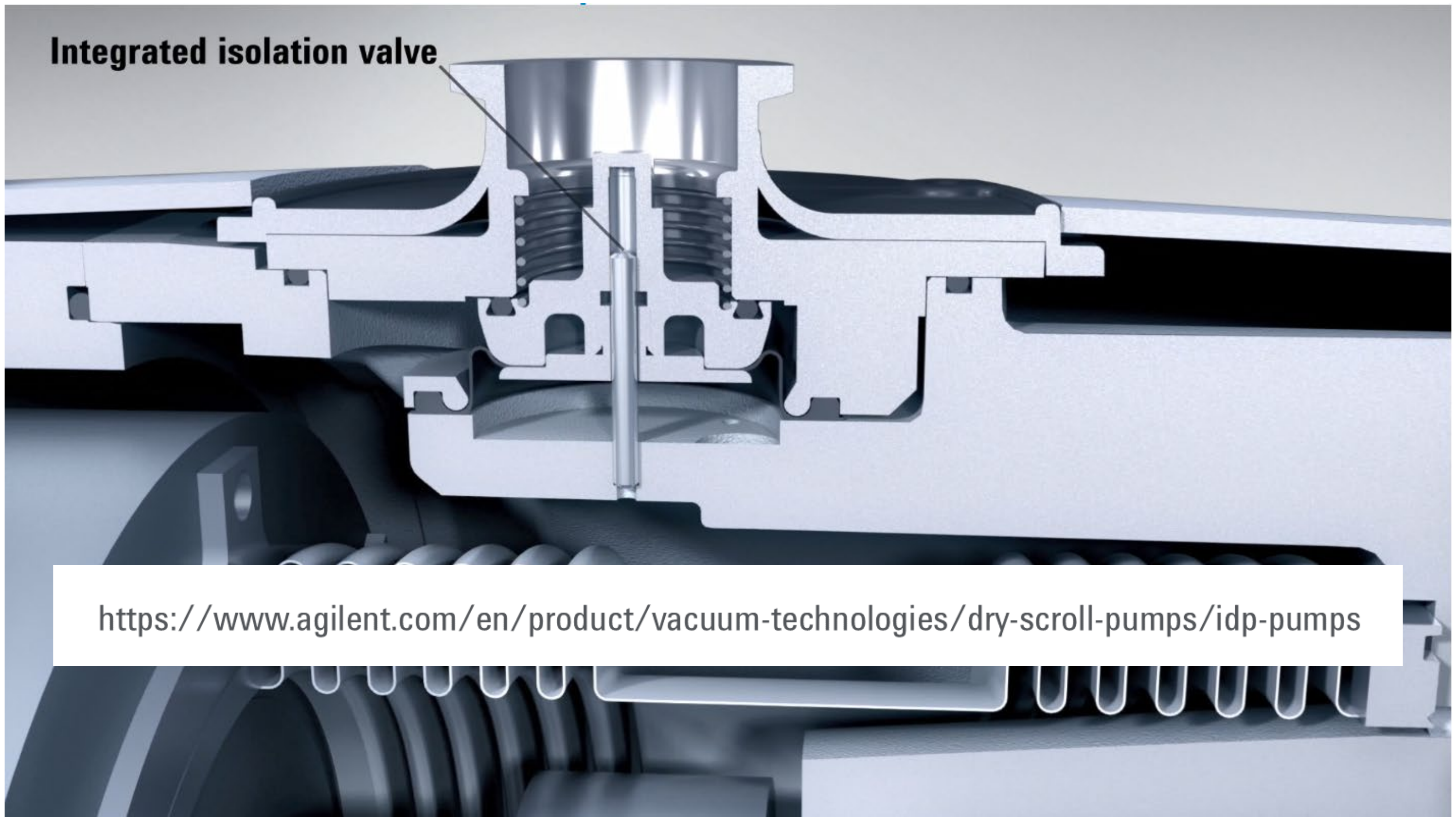
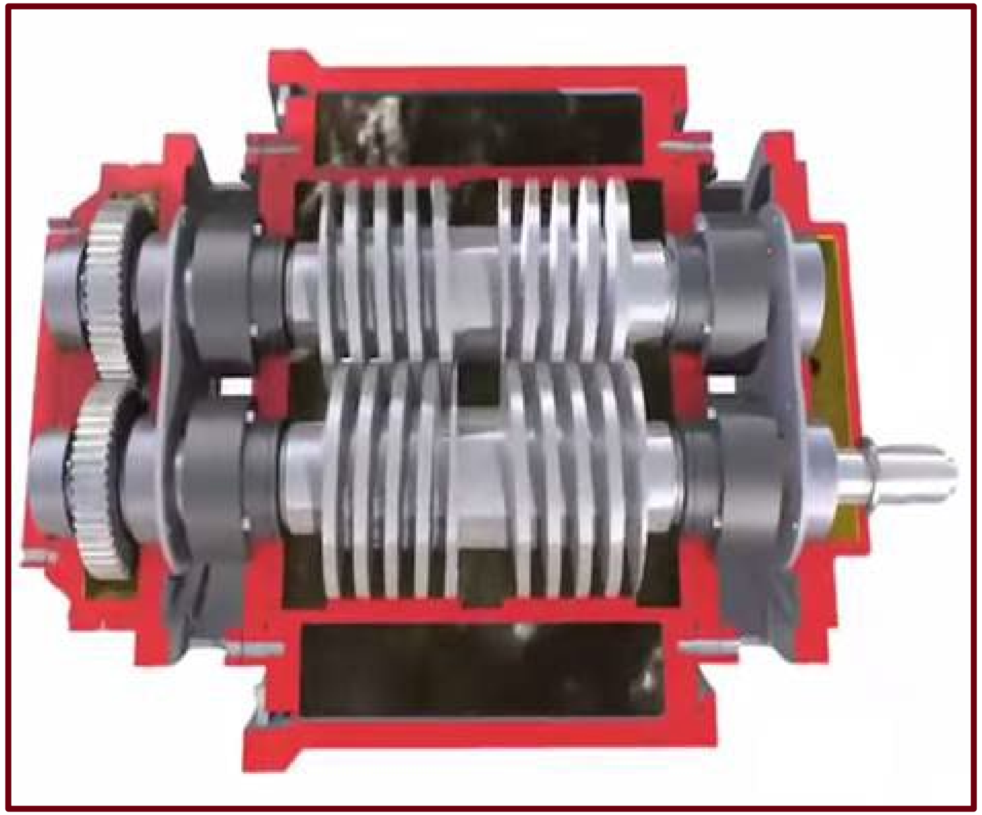


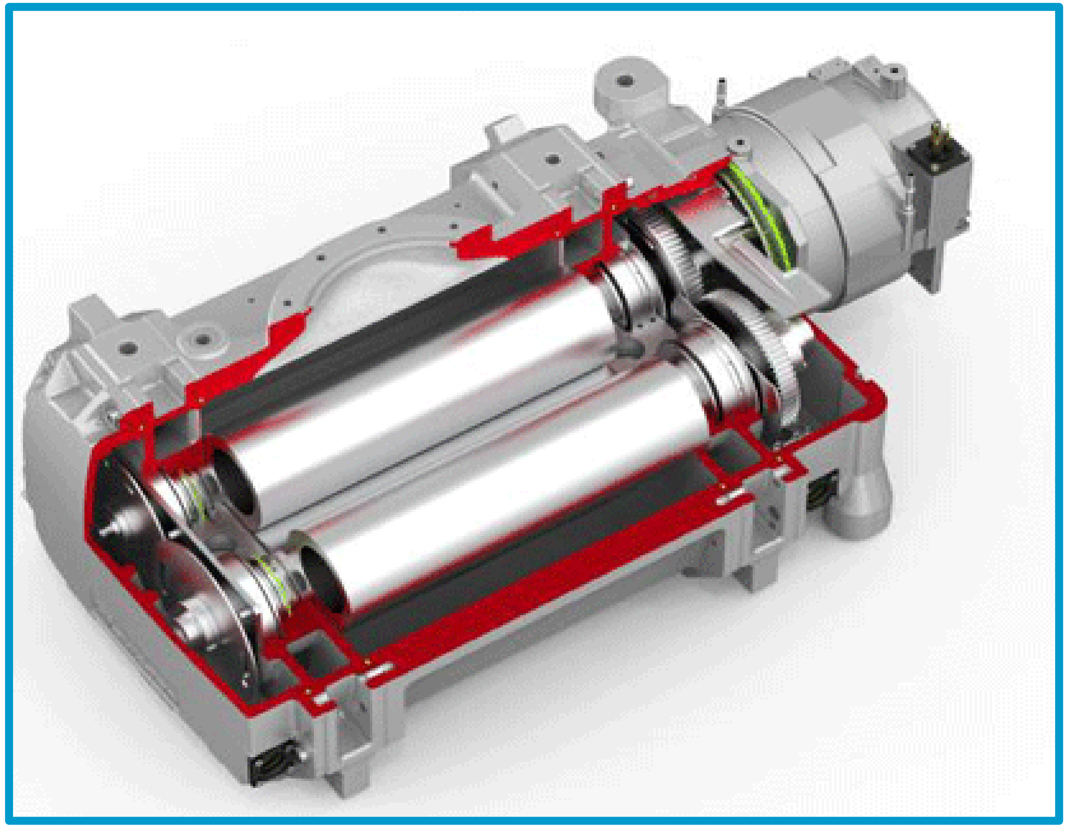
https://www.agilent.com/en/product/vacuum-technologies/dry-scroll-pumps/idp-pumps

Oil-Free Alternatives

Variable Pitch Screw Pump



Roots Pump



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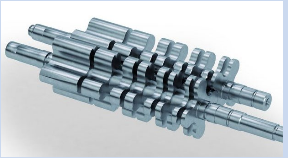
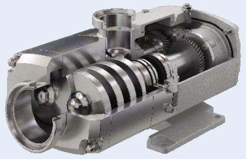
Rough Pump Comparison

Type		Advantages	Disadvantages
	**Diaphragm**	✓ Low initial cost ✓ Relatively quiet	× Low pumping speed × Poor ultimate pressure × Maintenance can be difficult
	**Oil Sealed Rotary Vane** (Single & Dual Stage)	✓ Low ultimate pressure ✓ Low initial cost ✓ Oil Traps Contaminants	× Backstreams oil × Waste oil (hazard) × Synthetic oil $$
	**Multi-Lobe Roots Pump**	✓ Oil-free, particle-free ✓ Performance remains constant ✓ Long maintenance interval	× Maintenance cost is high × Noise × Weight
	**Dry Screw Pump**	✓ Oil-free, particle free ✓ Harsh environment capable	× Cost & Noise × Frequent maintenance × Water cooling typical
	**Dry Scroll** (Single & Dual Stage)	✓ Oil-free ✓ Low ultimate pressure ✓ Hermetic and isolated ✓ Quiet	× Permeable to light gases × Clean applications only × Tip seal replacement

Rough Vacuum: Atmosphere – 10^{-3} Torr

Measuring Rough Vacuum

Measuring Vacuum Pressure

Vacuum gauges are an essential tool for Rough, High and Ultra-high vacuum systems.

Gauge Selection

Different technologies are required for different pressure regimes: Gauges are broadly categorized as Rough, High, or Ultra-high vacuum gauges.

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Accuracy is expensive! Most operators select a vacuum gauge with highest accuracy at the pressure of greatest importance.

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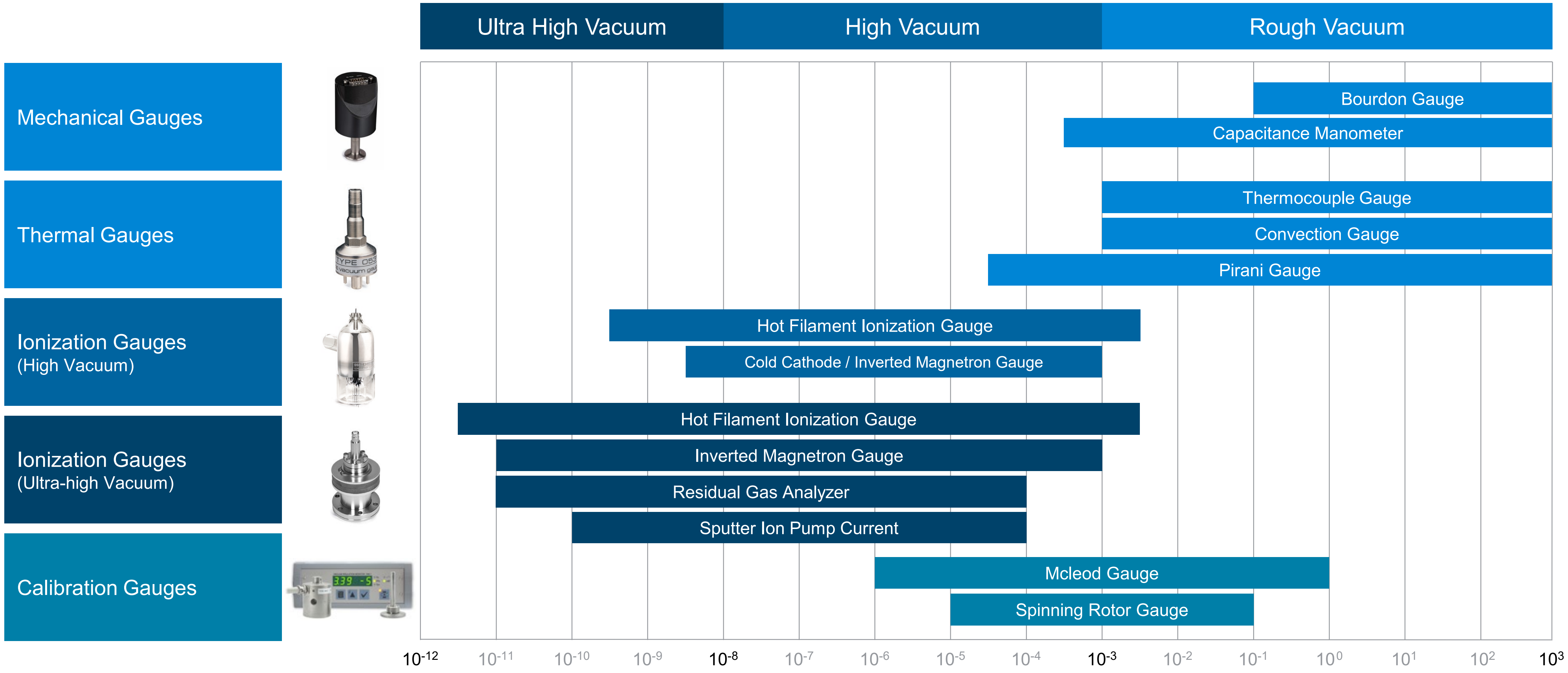
System integration: How will the Gauge interface with my vacuum system

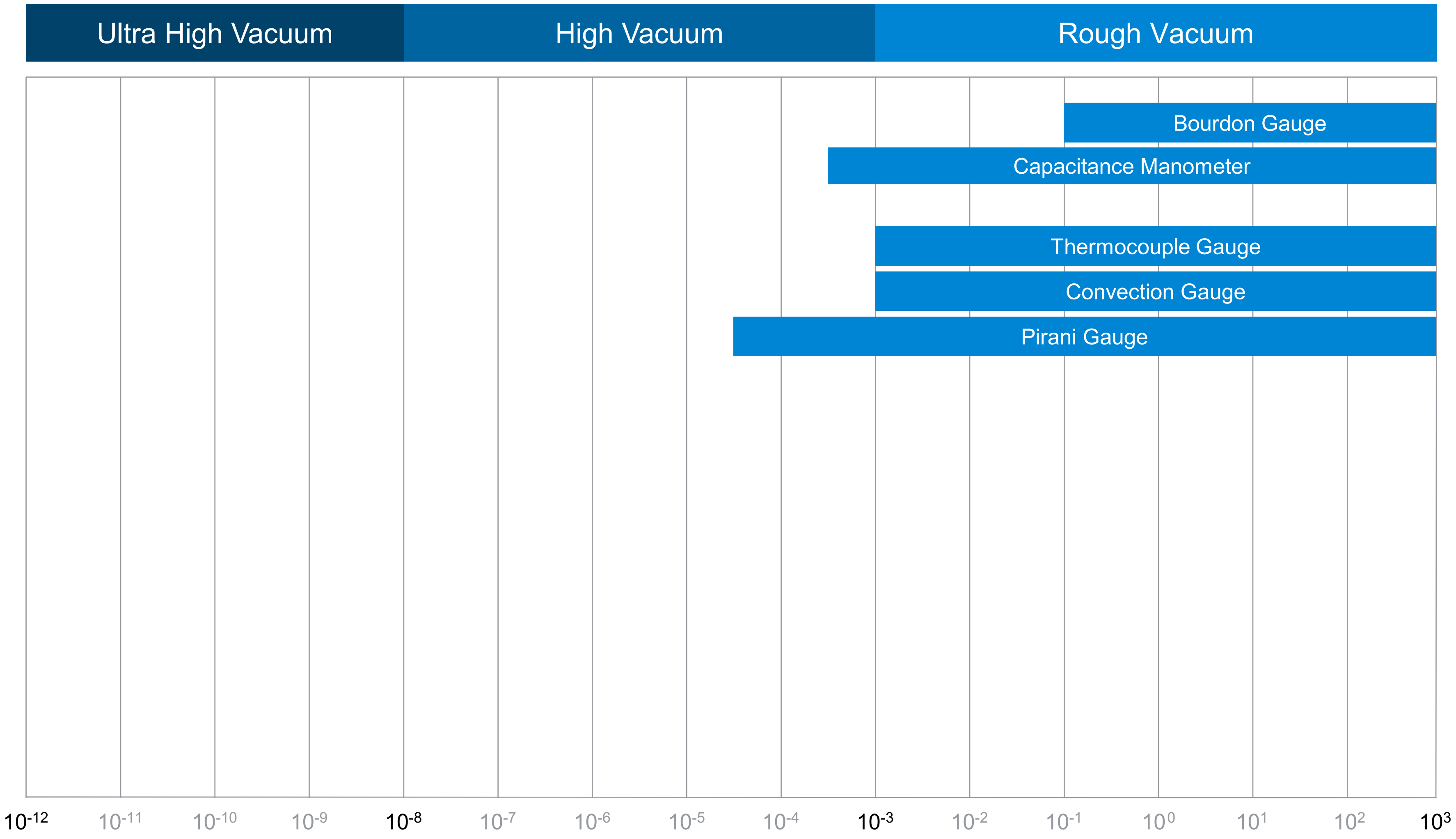
Measuring Vacuum Technologies



Vacuum Measurement Technologies

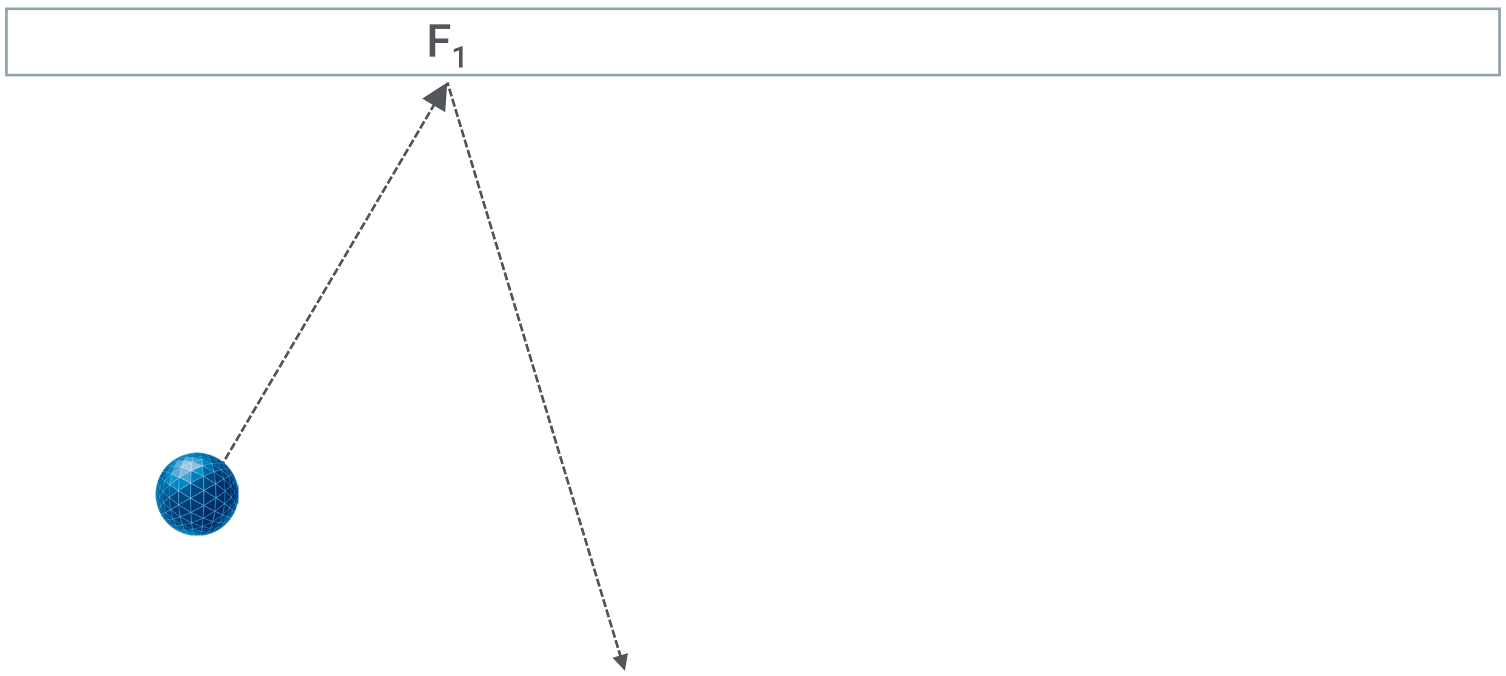
Mechanical Gauges

Thermal Gauges



Mechanical Deflection Principle

Mechanical deflection gauges directly measure the physical impact of gas molecules striking a surface.



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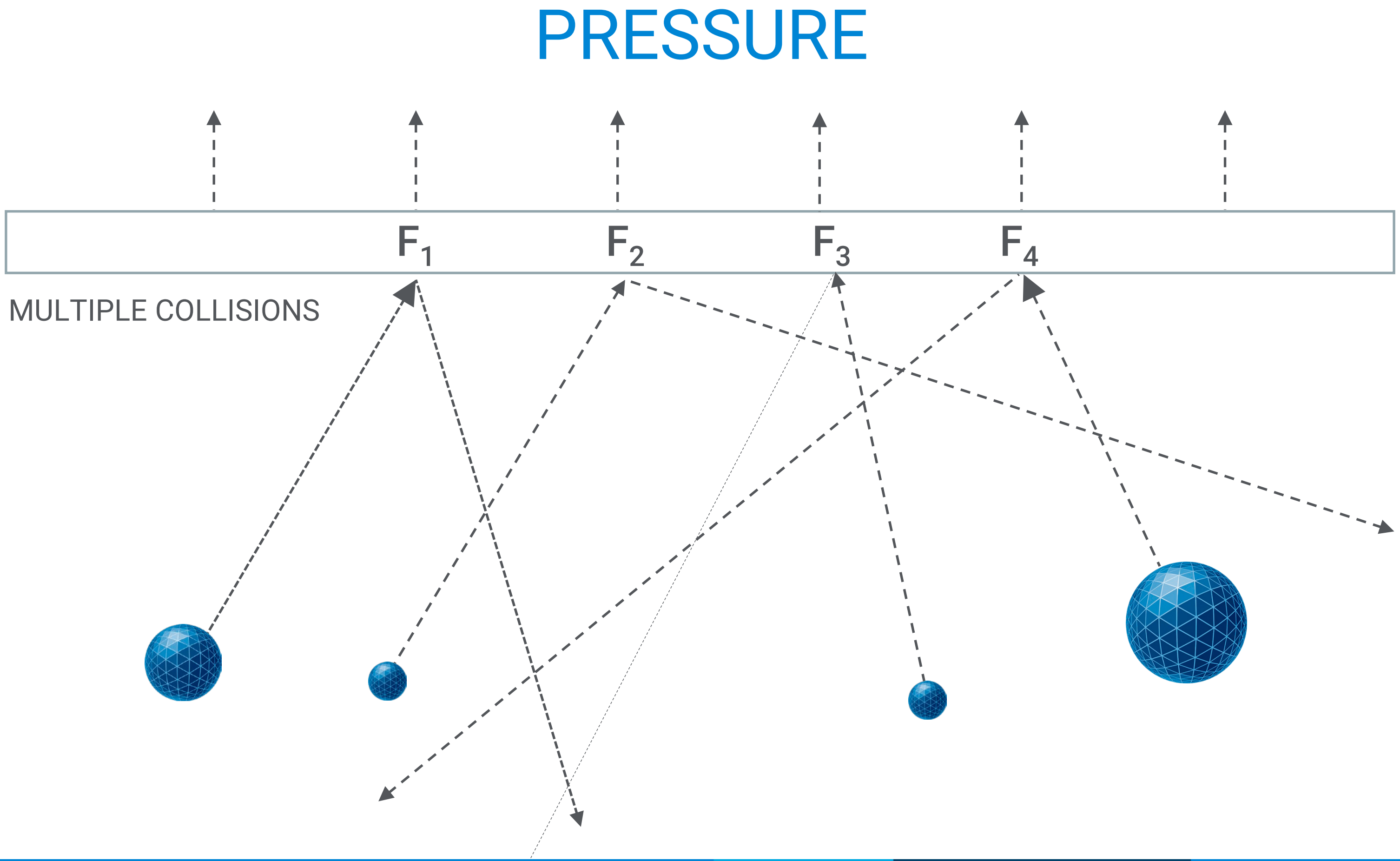


Bourdon Gauge

Elastic Element

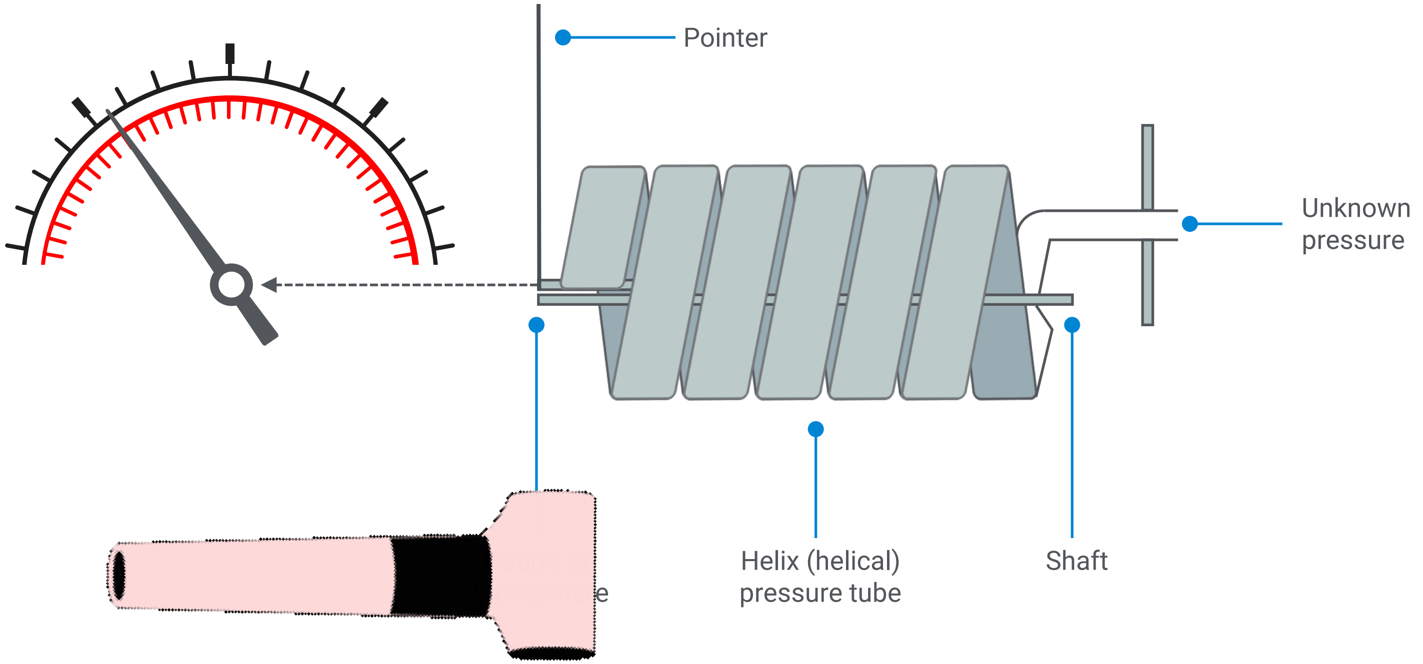
- Rough vacuum gauge good from Atm to ≈ 1 Torr

Near Atmosphere Pressure Validation

- Sometimes added to compensate for thermal gauge reading inaccuracy when using measuring gas species other than air/nitrogen

Bourdon Gauge

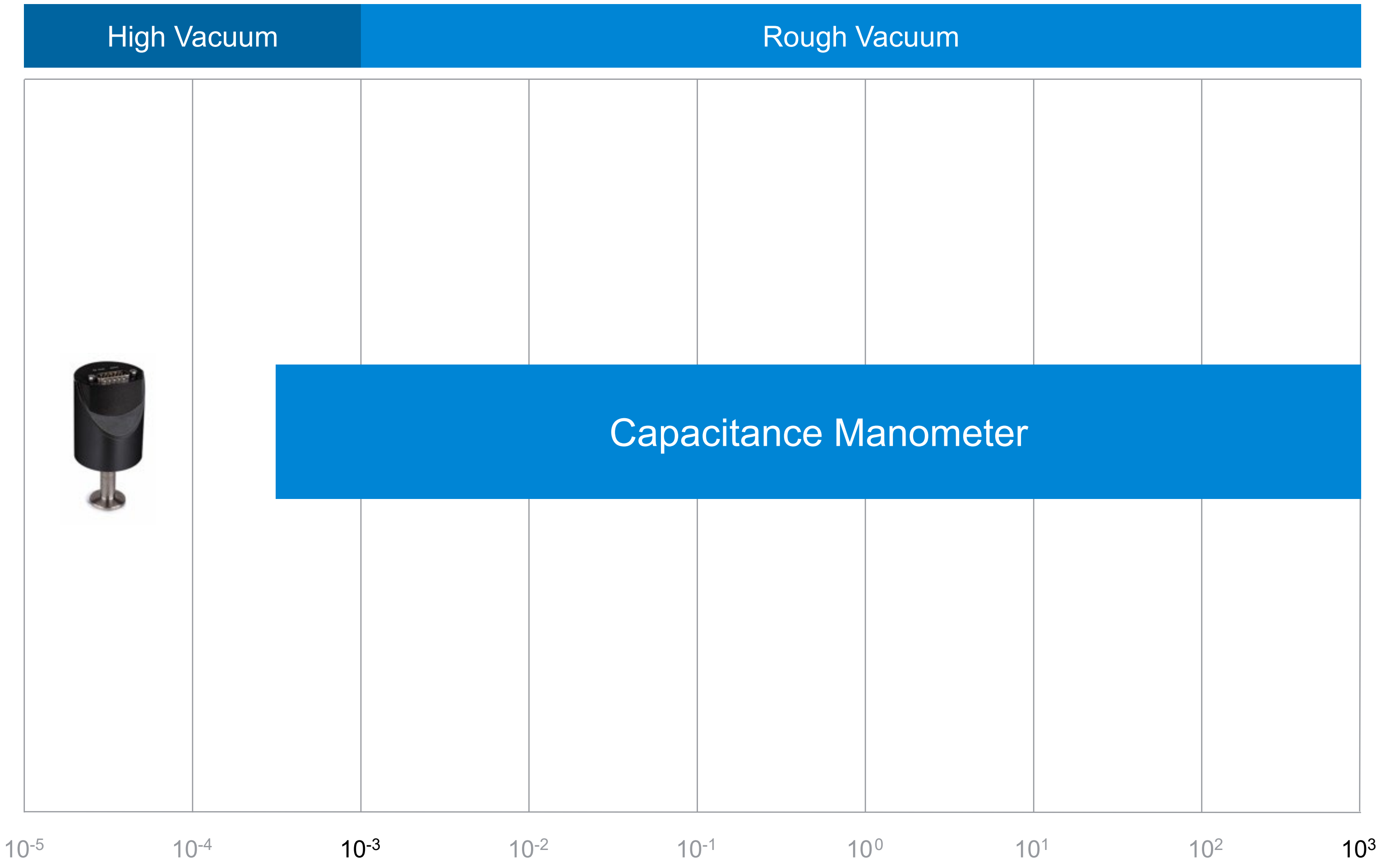
When pressurized, a flattened tube tends to straighten or regain its circular form in cross-section enabling the rotation of the dial tip.



Rough Vacuum: Atmosphere – 10^{-3} Torr

Capacitance Manometer

Seven decades of accurate pressure measurement over a range from atmosphere 10^{+3} to 10^{-4} Torr.



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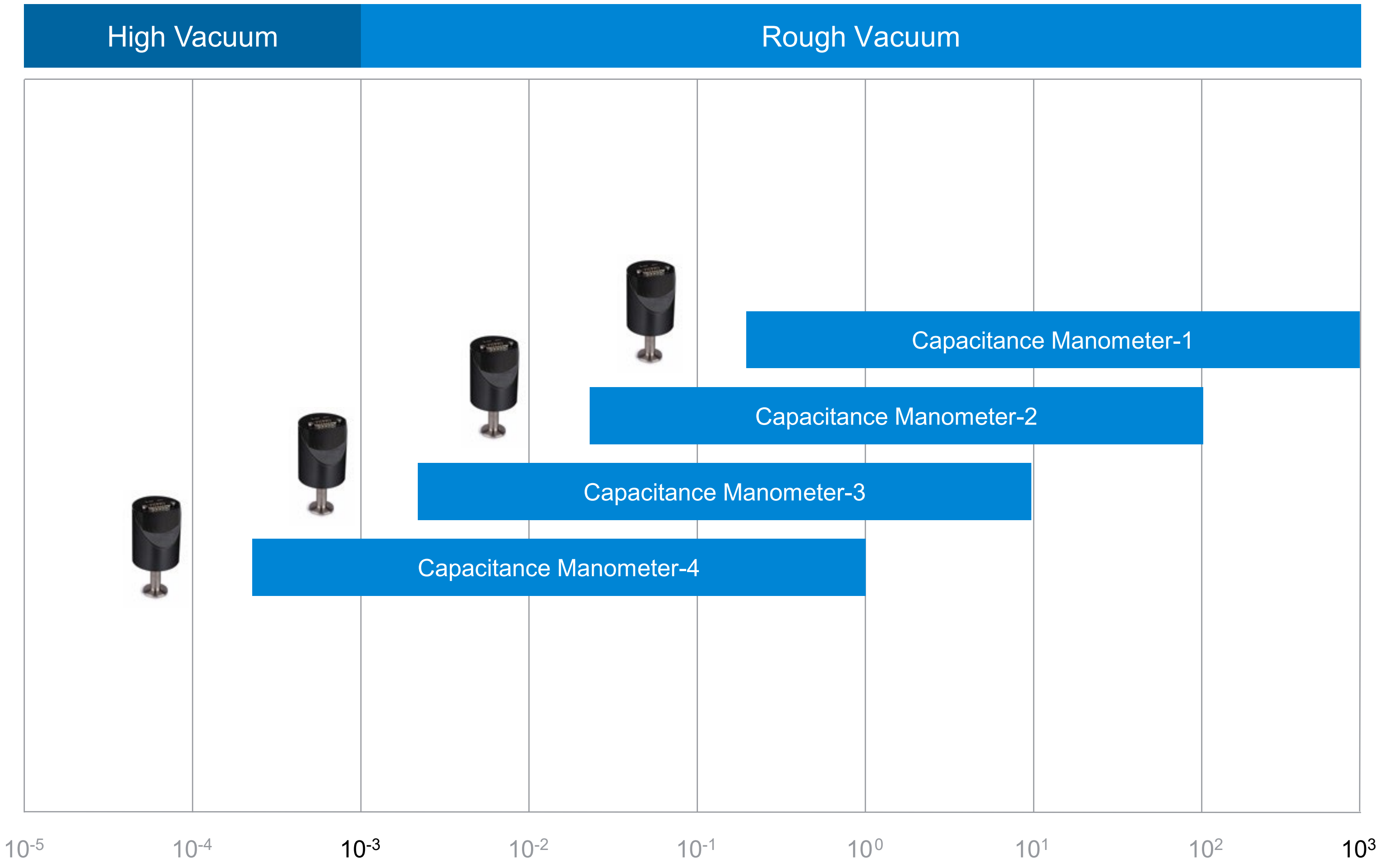
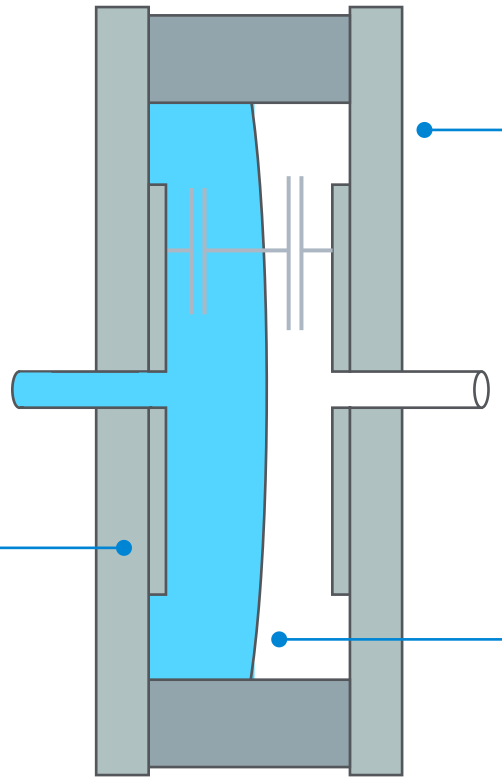


Capacitance Manometer

Diaphragm positioned between chamber pressure and reference pressure* flexes based on differential. Deflection of the diaphragm changes the capacitance of a circuit.

* << gauge minimum pressure



Capacitance Manometer

Accuracy

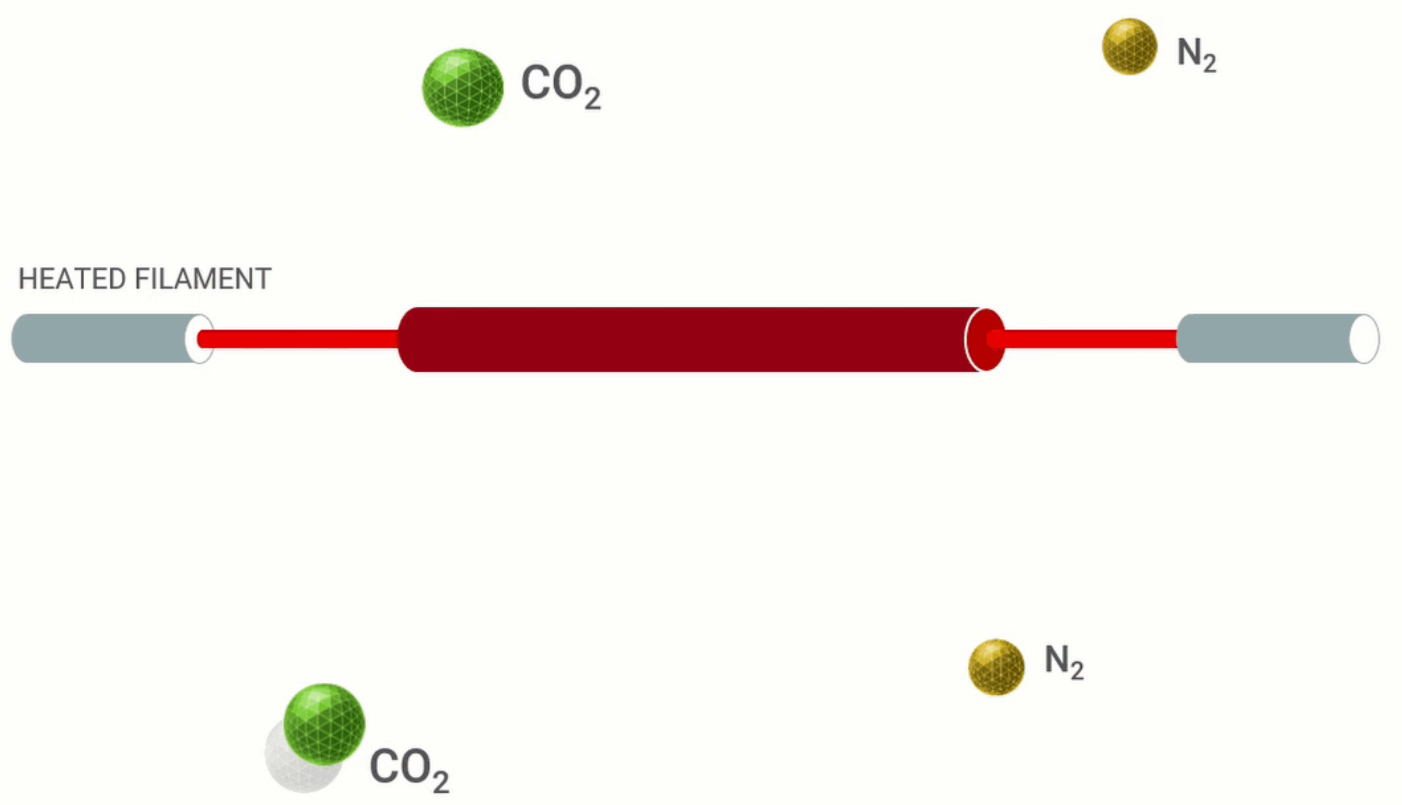
- Extremely accurate, gas independent gauges

Dynamic Range

- Each 'version' of the gauge is effective over about 3.5 decades of pressure

Thermal Transfer Principle

Thermal transfer gauges measure the energy lost to gas molecules from a heated filament in vacuum.



Thermocouple Gauge

Temperature Measured

- Least expensive gauge for reading from about 2 Torr to 1 mTorr
- Slow response when large pressures changes occur

Correction Factor

- Caution when measuring pressure of gases other than air/nitrogen

Convection Gauge

Current Measured

- Measuring current (vs temperature) improves response time

Dynamic Range

- Convection gauge has wider dynamic range (than TC gauge): Atm to 1 mTorr

Pirani Gauge

Voltage Measured

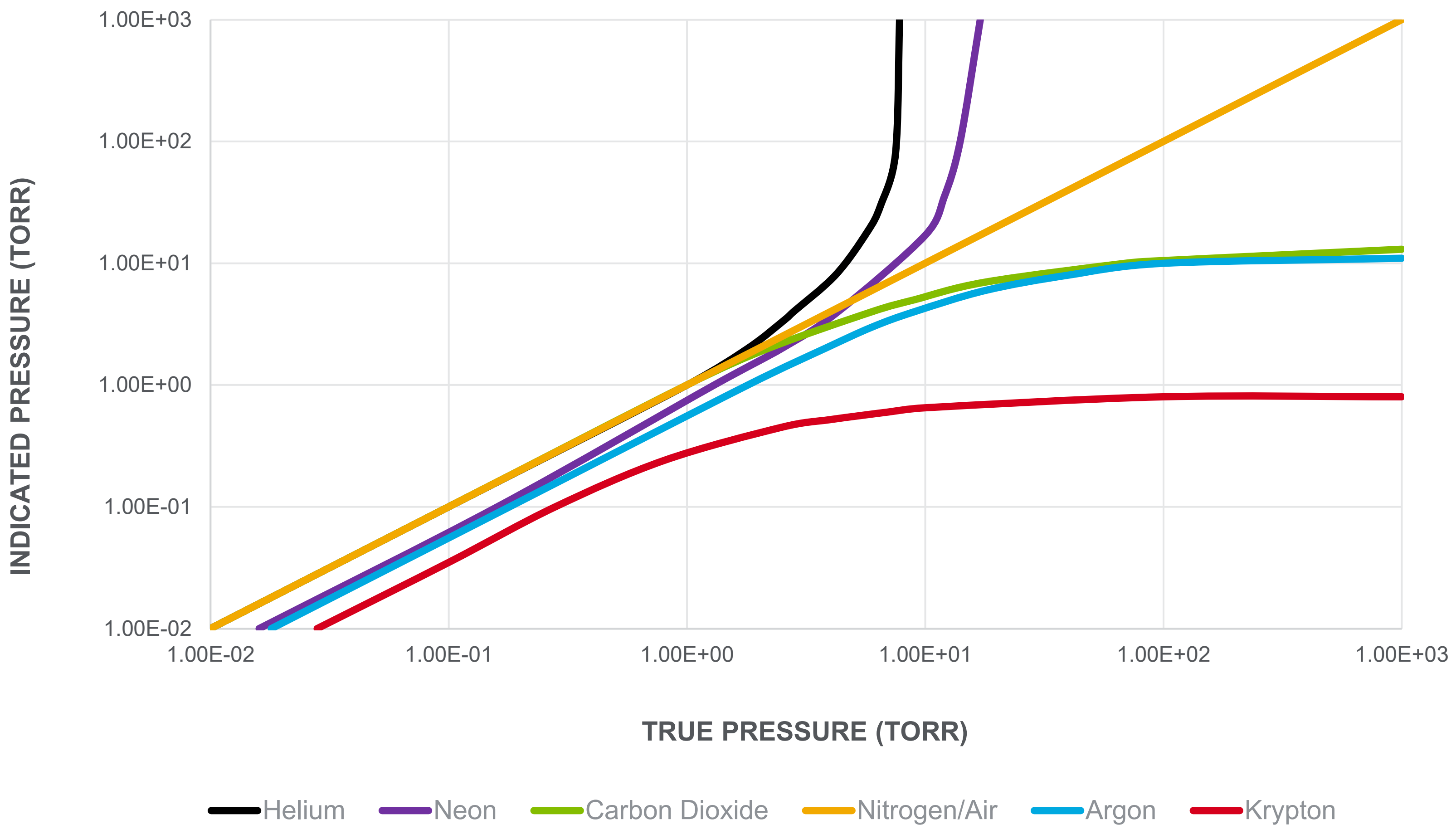
- Thermal transfer gauge (Atm to 5 x 10^{-5} Torr) incorporating Wheatstone Bridge Circuit for improved accuracy, range and response time

Position Independent

- Can be mounted vertically or horizontally

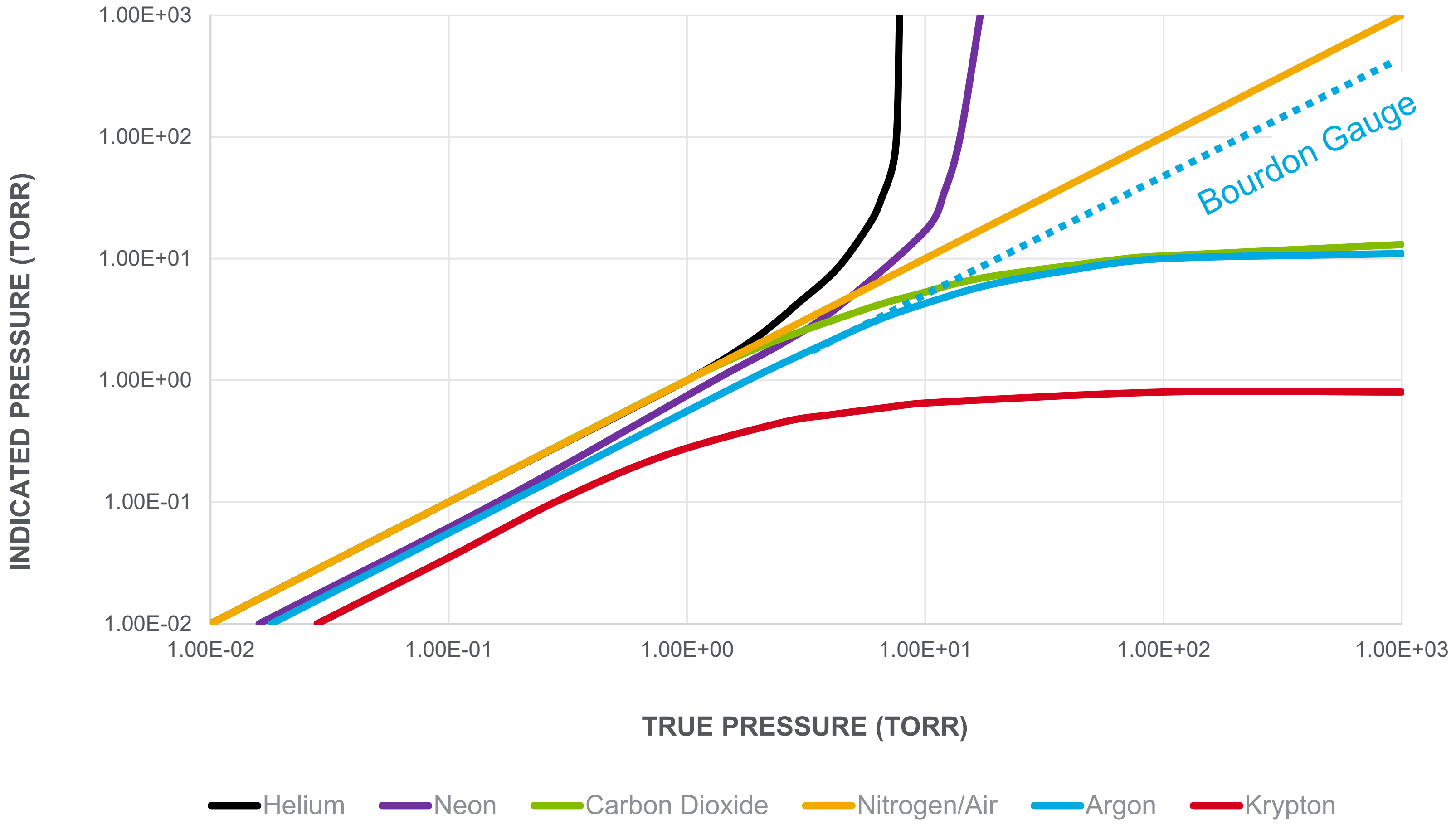
Thermal Gauge Response Varies with Gas Type

Thermal transfer gauges read differently for different gas species; most are calibrated for nitrogen (air).



Thermal Gauge Response Varies with Gas Type

GAS TYPE	CORRECTION FACTOR
Helium	0.80–1.10
Neon	1.40
Carbon Dioxide	0.90
Nitrogen/Air	1.00
Argon	1.59—1.70
Krypton	2.2—2.4

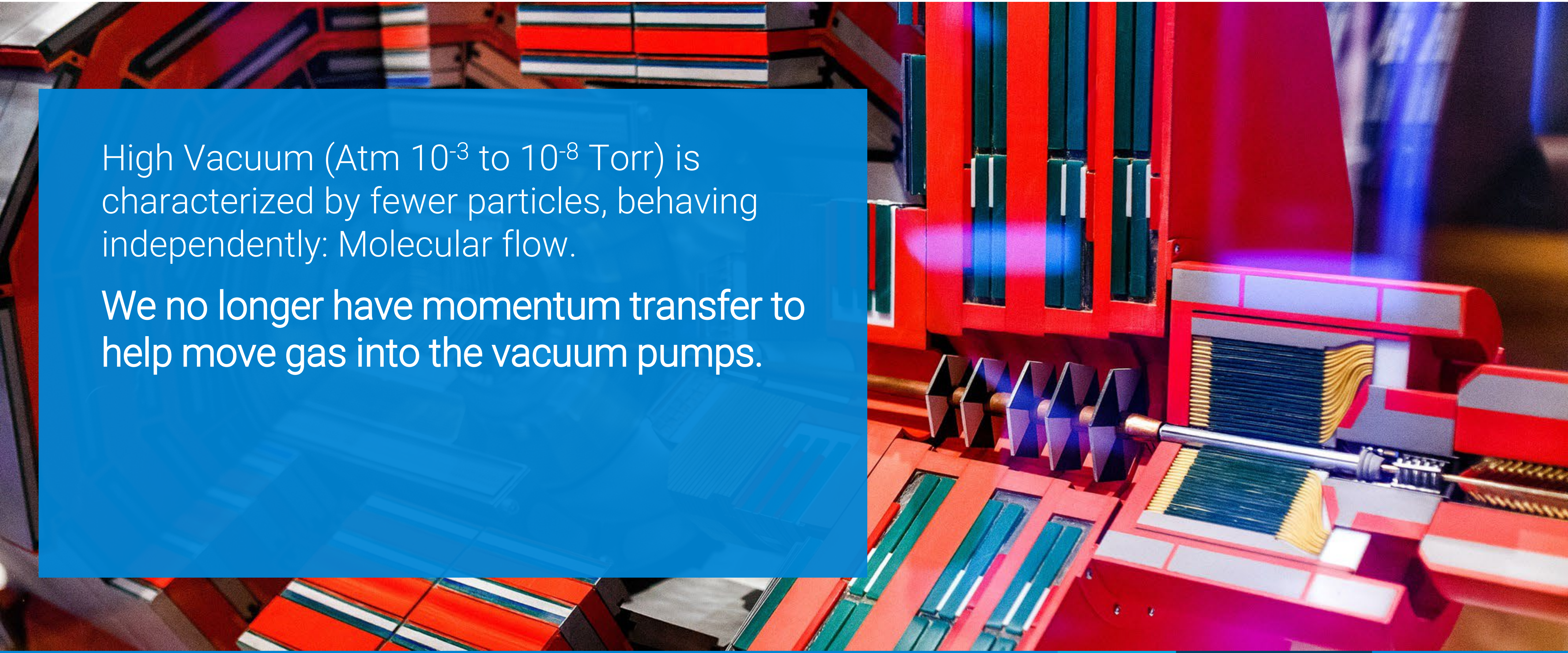


Thermal Gauge Comparison

		Advantages	Disadvantages
	Thermocouple	• Low cost • Rugged • Easily calibrated	• Slow response • Limited accuracy, range • Dependent on gas type
	Convection	• Medium response • Wider range than TC	• Position dependent • Limited accuracy • Dependent on gas type
	Pirani	• Measure to mid 10^{-5} Torr range • Fast response • Position independent	• Dependent on gas type

Creating High Vacuum

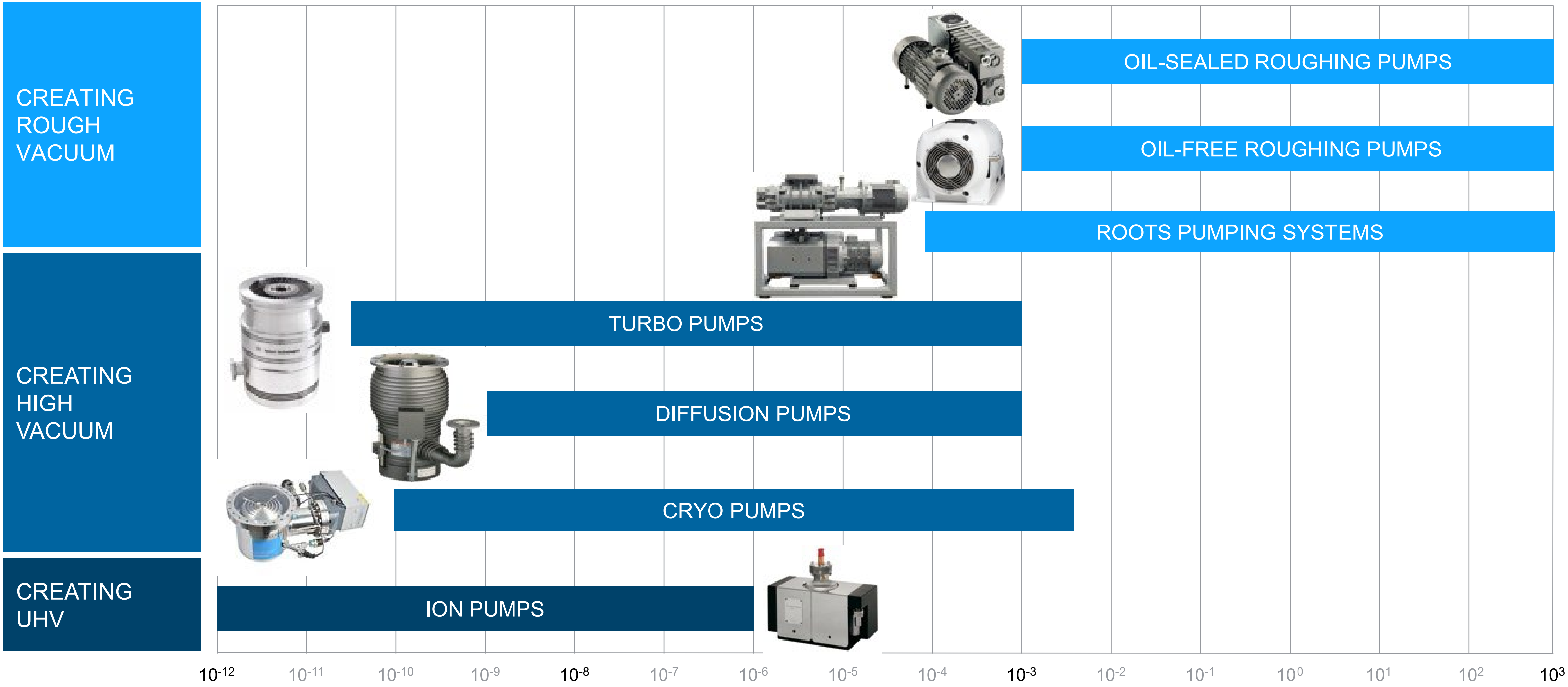
Creating High Vacuum



High Vacuum (Atm 10^{-3} to 10^{-8} Torr) is characterized by fewer particles, behaving independently: Molecular flow.

We no longer have momentum transfer to help move gas into the vacuum pumps.

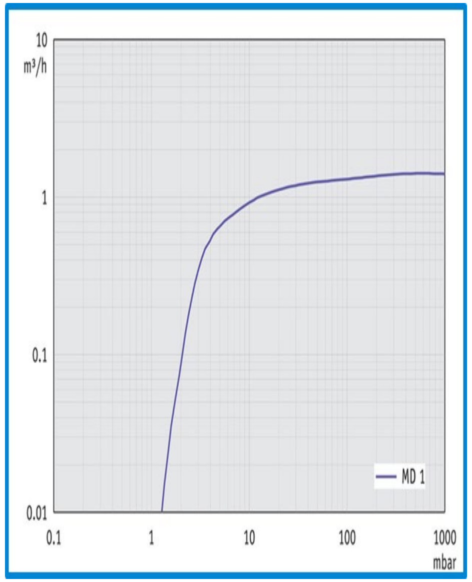
Vacuum Technologies Sorted by Pressure



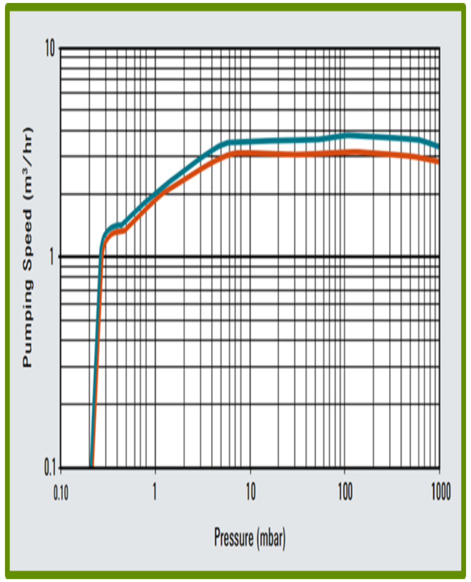
From Viscous Flow to Molecular Flow

The *effective pump speed* of all our rough vacuum pumps falls off drastically below about 10^{-1} Torr

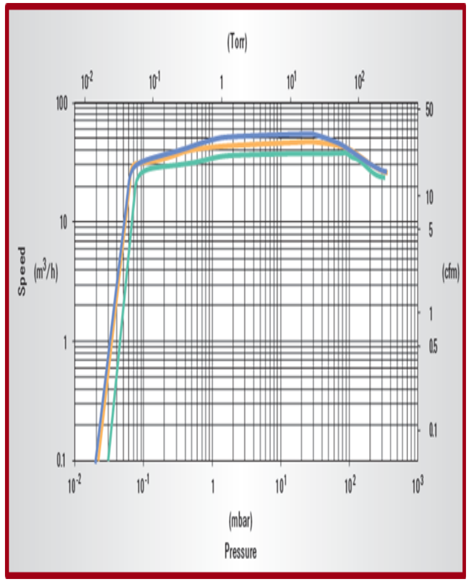
Diaphragm Pump



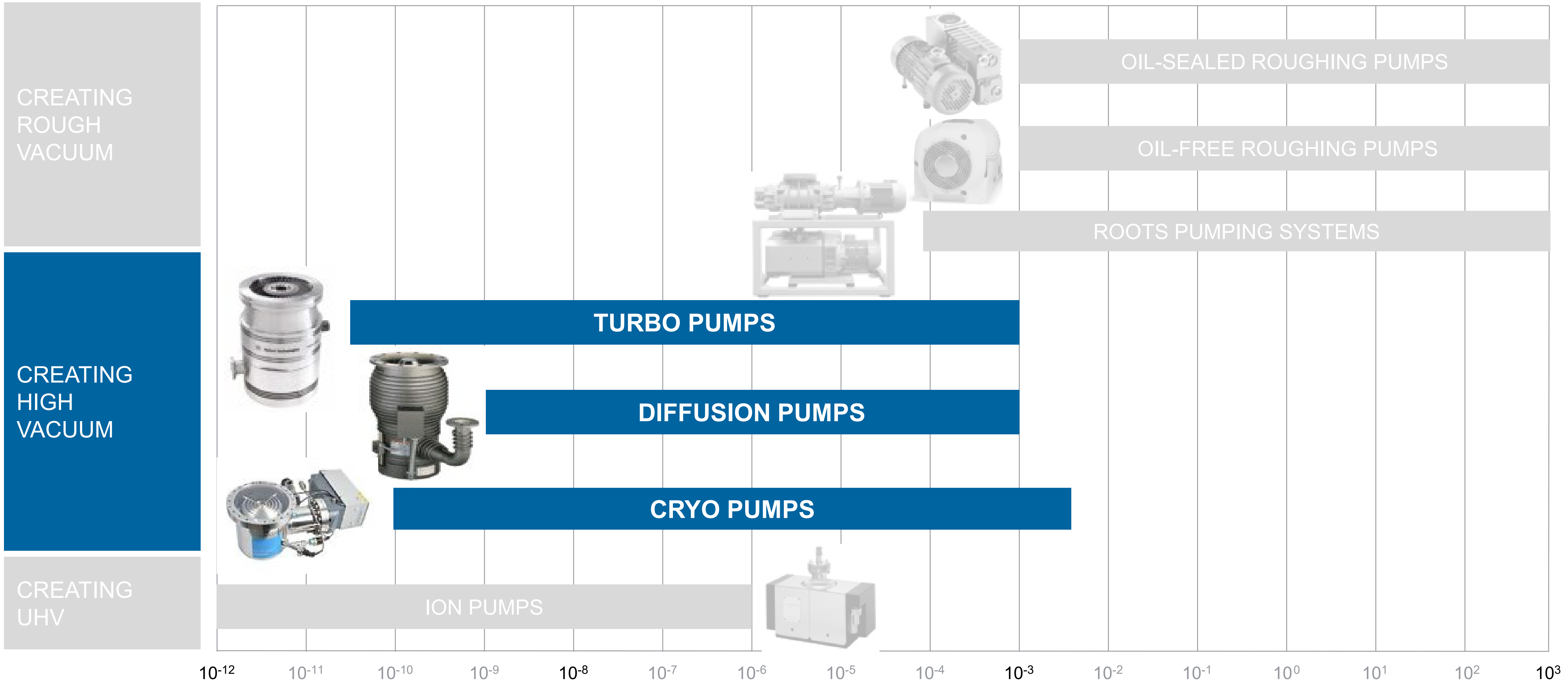
Oil-Free Scroll Pump



Oil-Sealed Rotary Pump



Vacuum Technologies Sorted by Pressure



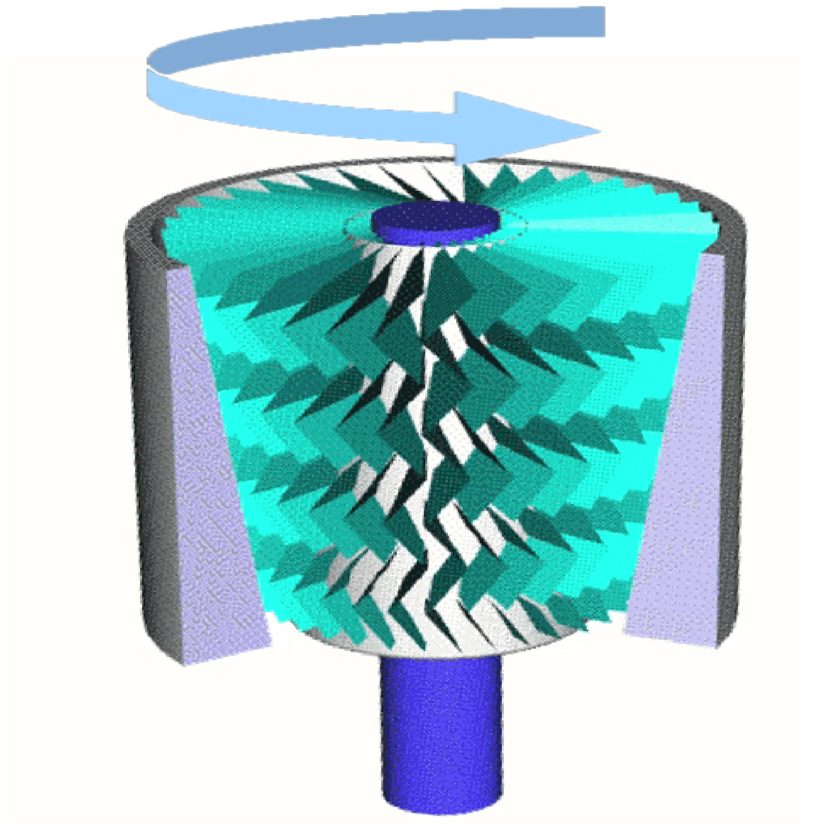
Turbo Pump: Principle of Operation

Axial Compressor

- Gas is compressed through MOMENTUM TRANSFER
- Gas molecules entering the pump inlet are struck by the first rotating Blade and are deflected downward
- Molecule 'reflects' off the first stationary element (Stator) which has the complimentary angle
- Multiple compression stages (Blade/Stator pairs) can compress gas to about 10^{-3} Torr

Turbo pump of this design required ***backing pumps*** capable of maintaining around 10^{-3} Torr at the turbo pump exhaust:

- Dual Stage RVPs
- Dual Stage Scroll Pumps



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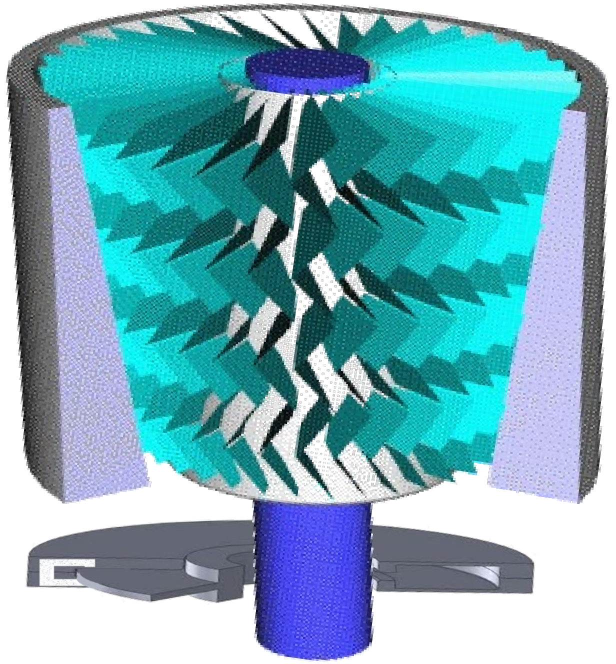
Molecular Drag Stage

- Drag stages compress gas beyond the limits of blades/stators



Molecular Drag Stages

Gaede Drag Stage

- Gas molecules ‘land’ on a surface and spend a finite residence time there
- IF the surface is in motion, molecules leave the surface with a component of momentum in the direction of rotation

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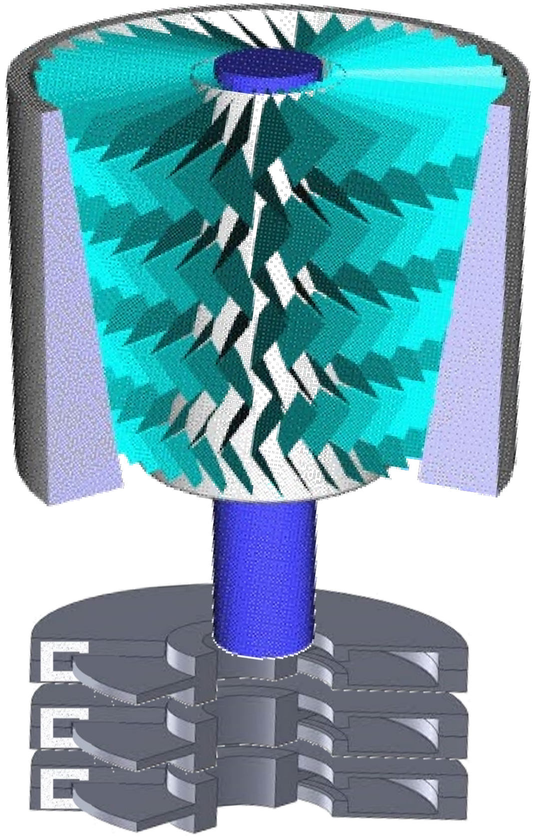
Molecular Drag Stage

- Drag stages compress gas beyond the limits of blades/stators
- Multiple drag stages allow modern turbos to exhaust around 1 - 10 Torr

Molecular Drag pumps require *smaller*, backing pumps with much *‘poorer’* ultimate pressure specifications



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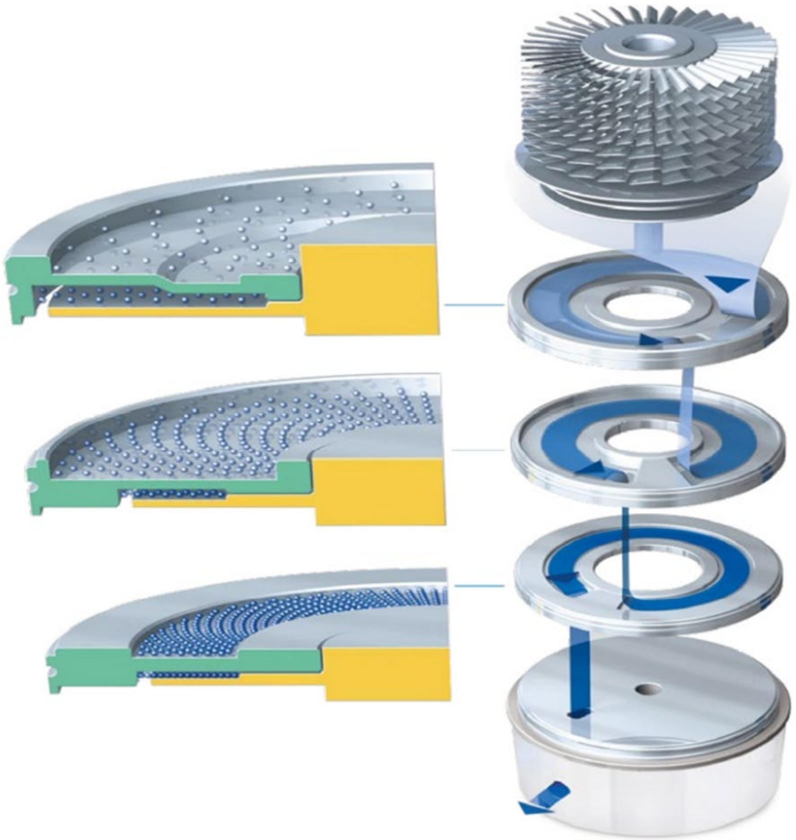
- Gaede, Holweck and Siegbahn Designs

MacroTorr (Gaede)



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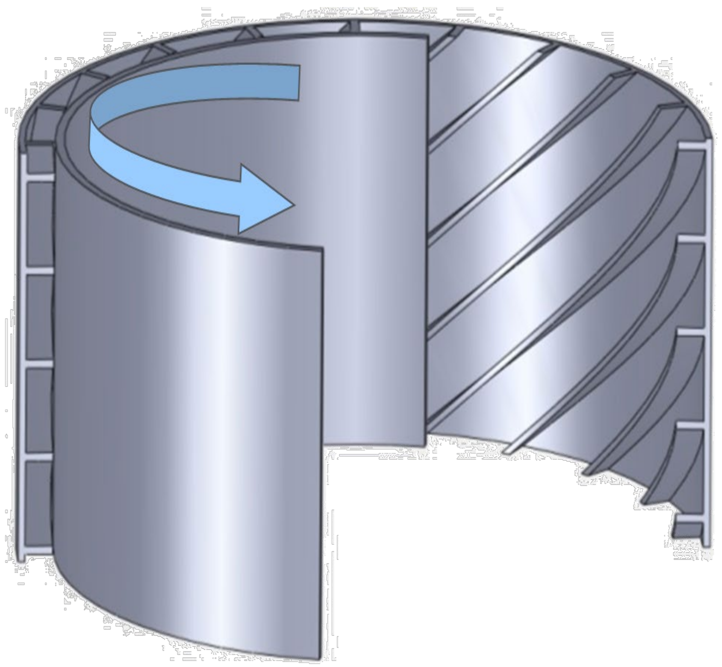
(Holweck)



Turbo Pump: Principle of Operation

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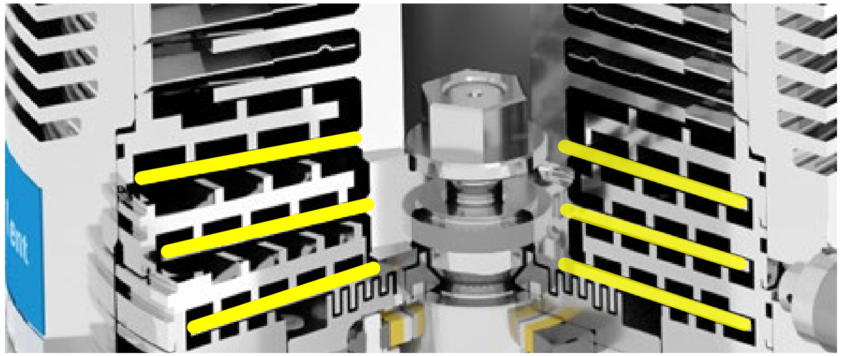
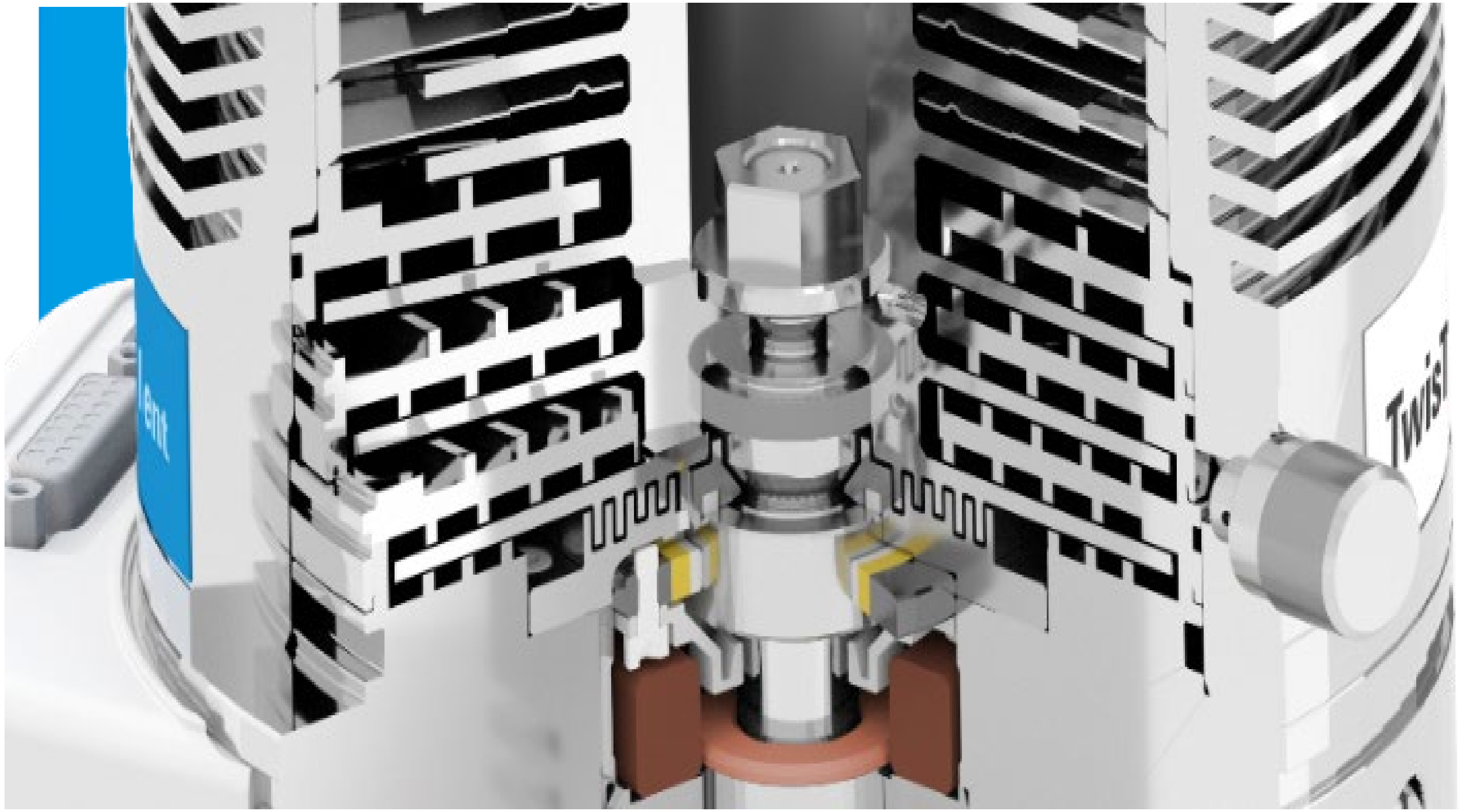
TwisTorr (Siegbahn)



TwisTorr Drag Stage: Principle of Operation

Stators with **planar helical channels** replace the ‘stripper’ of the Gaede design.

SIX individual compression stages provide longest path for light gas molecules for lowest ultimate pressure.

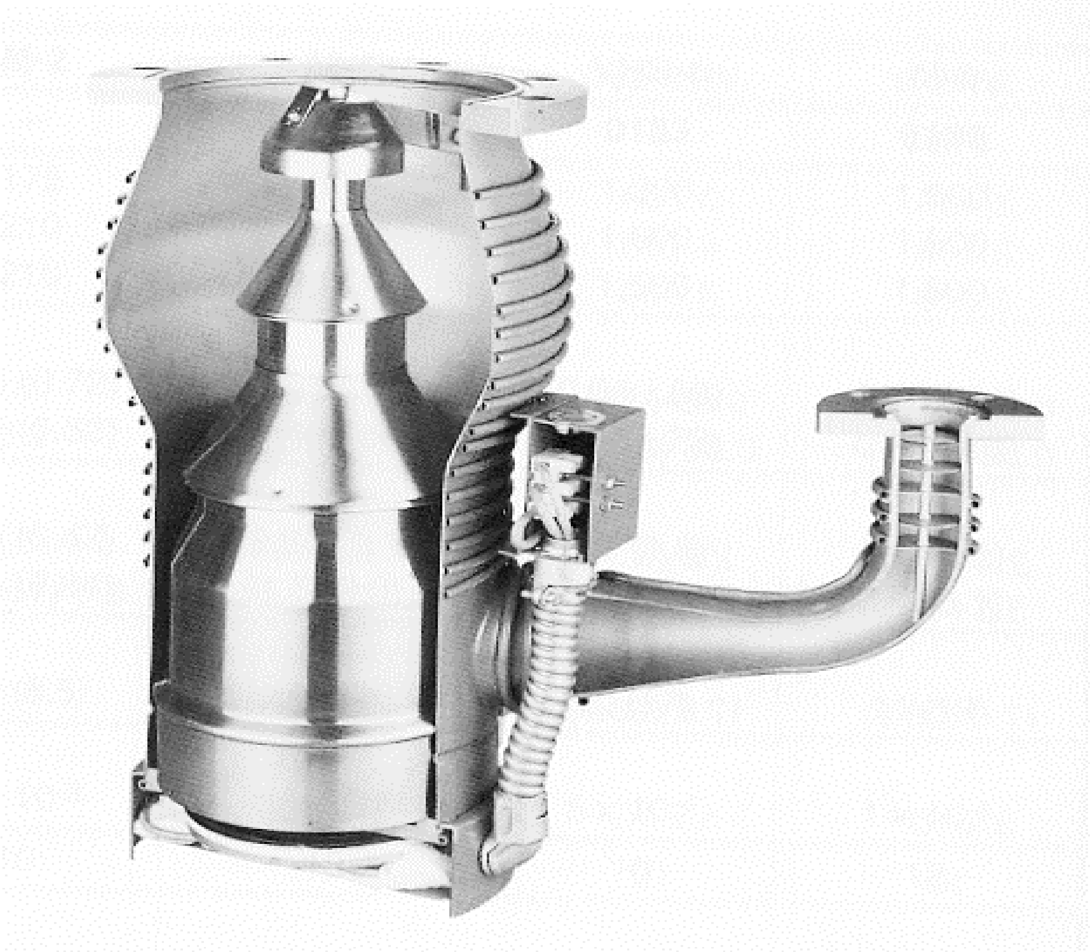


Diffusion (Vapor Jet) Pump

Pump fluid (typically hydrocarbon or silicon based oil) is heated and ejected at high speed from a ‘jet’ forming a conical stream of high velocity particles.

Momentum transfer drives gas molecules outward from the center and down towards the exhaust of the pump.

Multiple jet stages provide a compression effect.



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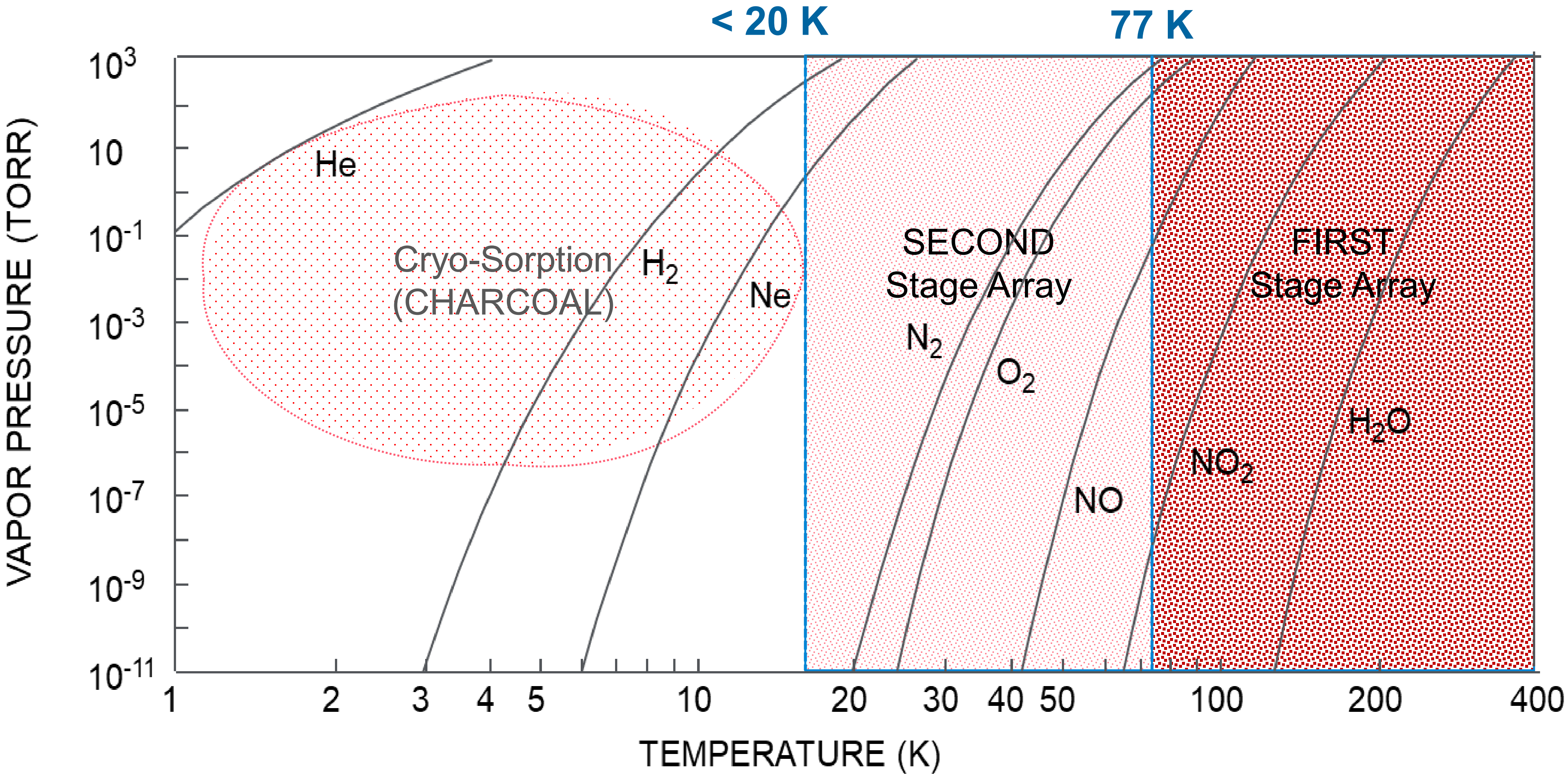
Cryogenic Pump

Cryo-condensation: Gas molecules are cooled below the condensation and are captured or trapped on cryo-arrays.

Highest capacity for pumping water vapor.

Periodic ‘regeneration’ is required when pump becomes saturated (unable to maintain sufficiently low temperature to trap gases).

Vapor Pressure of Some Gases



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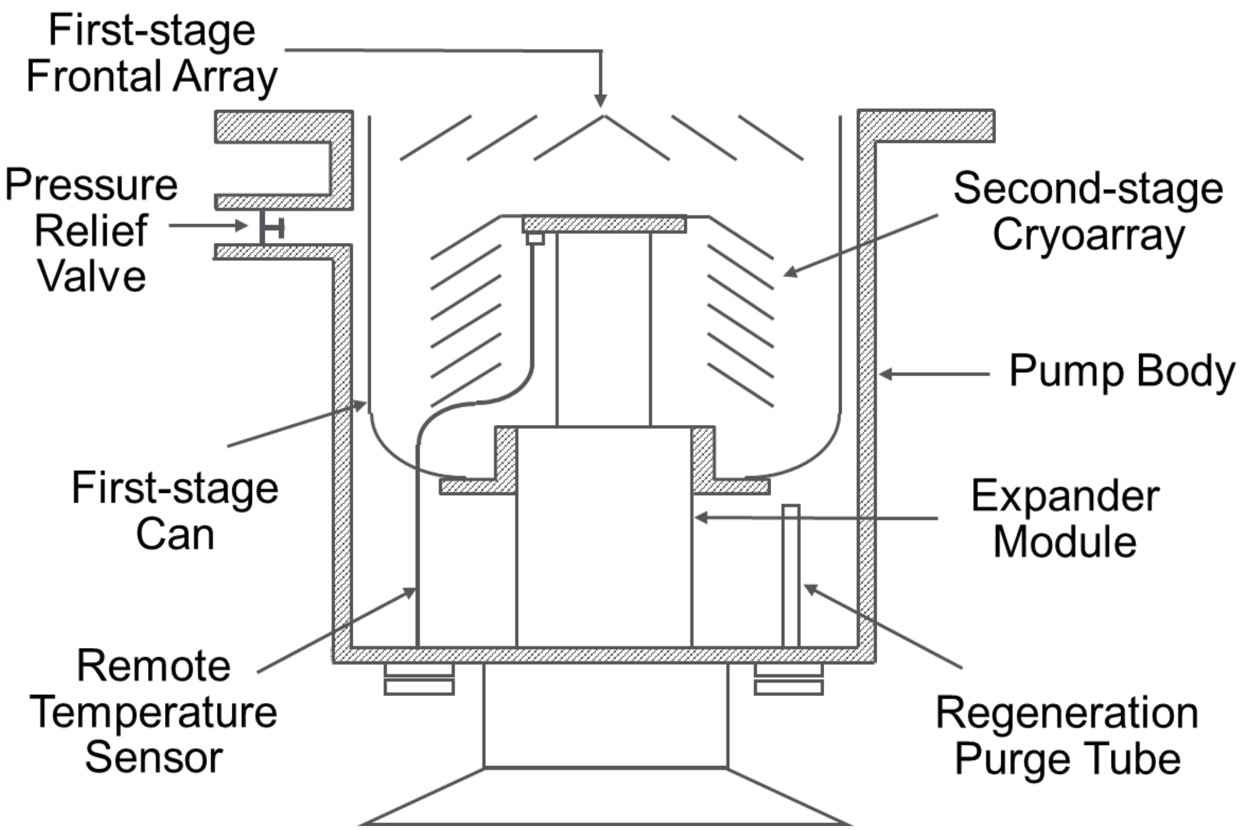
Cryogenic Pump

Pumping Mechanisms:

1st Stage (77 K)
- Condensation (H_2O, NO_2)
- Cryo-Trapping (Ar_2)

2nd Stage (< 20 K)
- Condensation (NO, O_2, N_2, Ar_2)

Charcoal (< 20 K)
- Cryo-Sorption (Ne, H_2, He)



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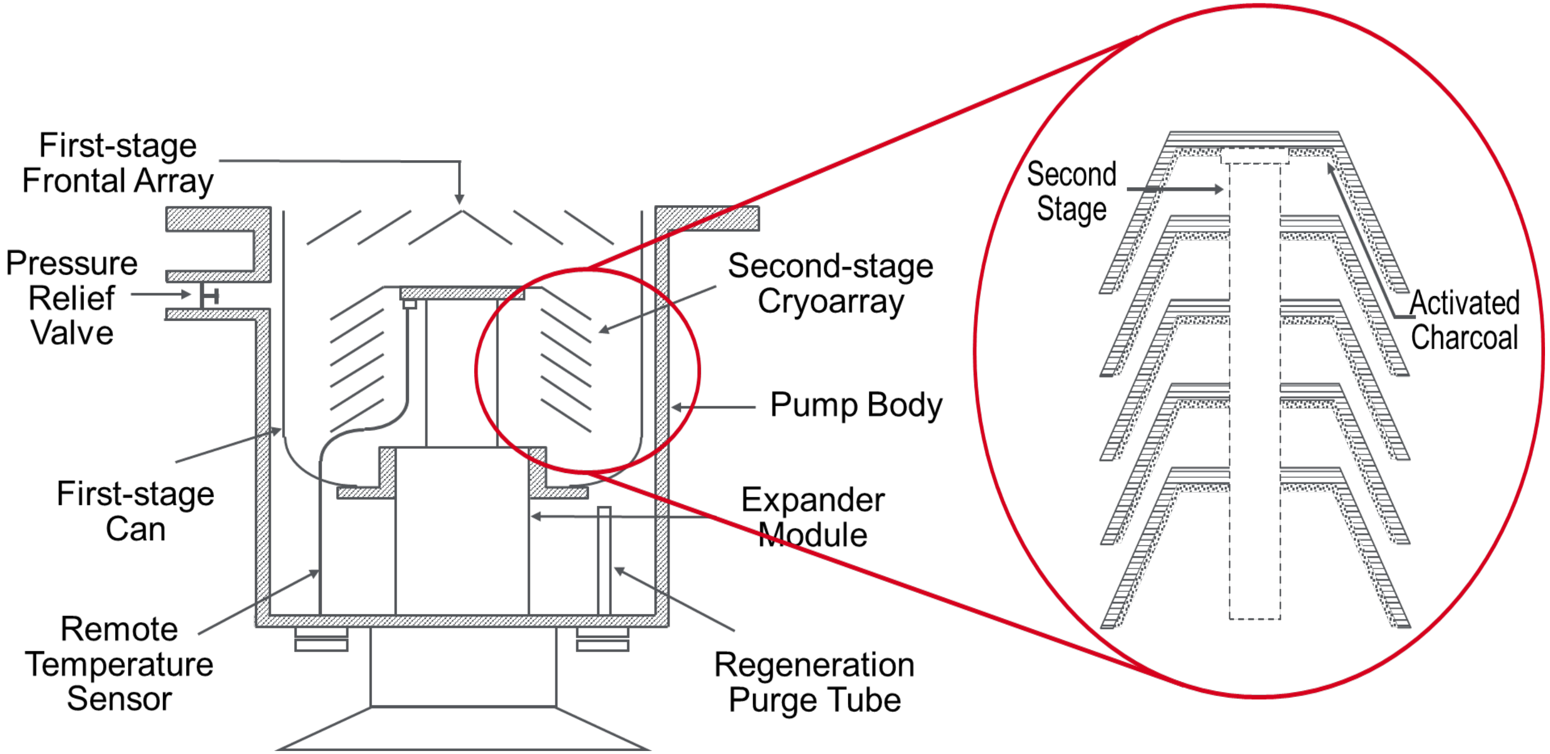
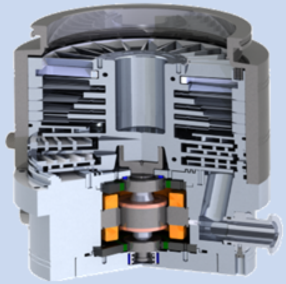
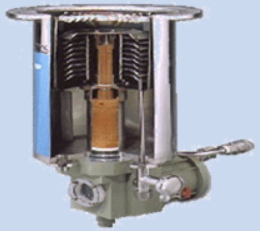
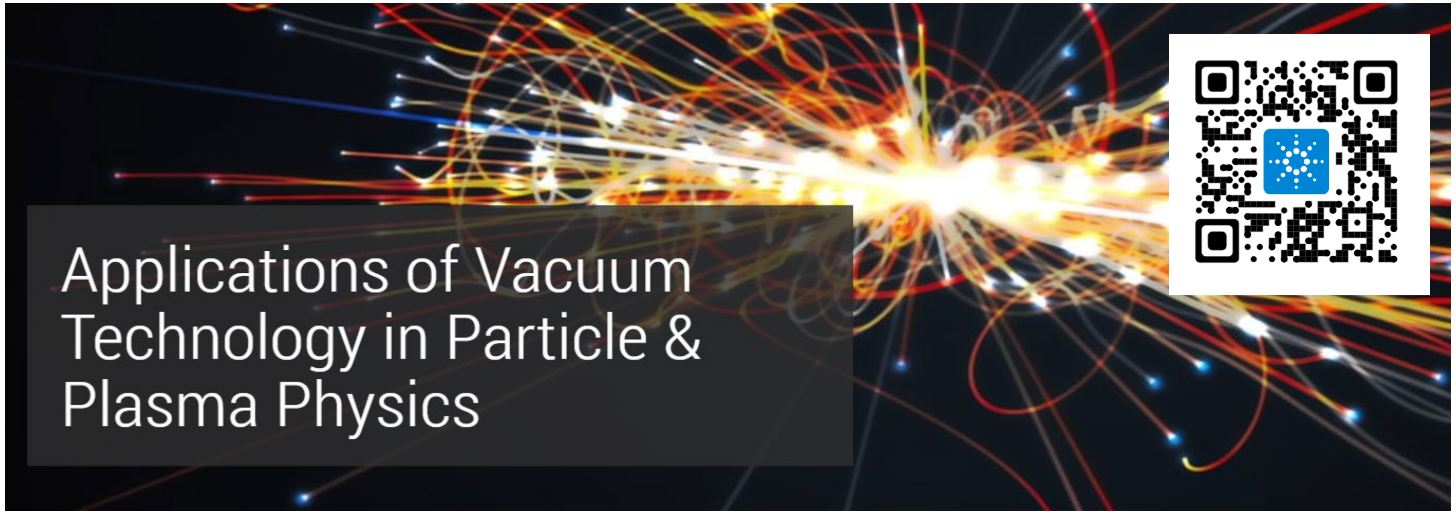


High Vacuum Pump Comparison

Type	Advantages	Disadvantages
	✓ Low Ultimate Pressure ✓ Clean, Continuous Pumping ✓ Smaller Forepump Required	× Mechanical Bearing × Some Vibration
	✓ Low Cost ✓ No Moving Parts ✓ Low Maintenance	× Backstreaming × No Foreline Tolerance × May Require Cold Trap
	✓ High H_2O pumping speed ✓ Mounts Any Orientation ✓ Clean	× Regeneration Required × Affected by Heat × Vibration

Agilent Resources



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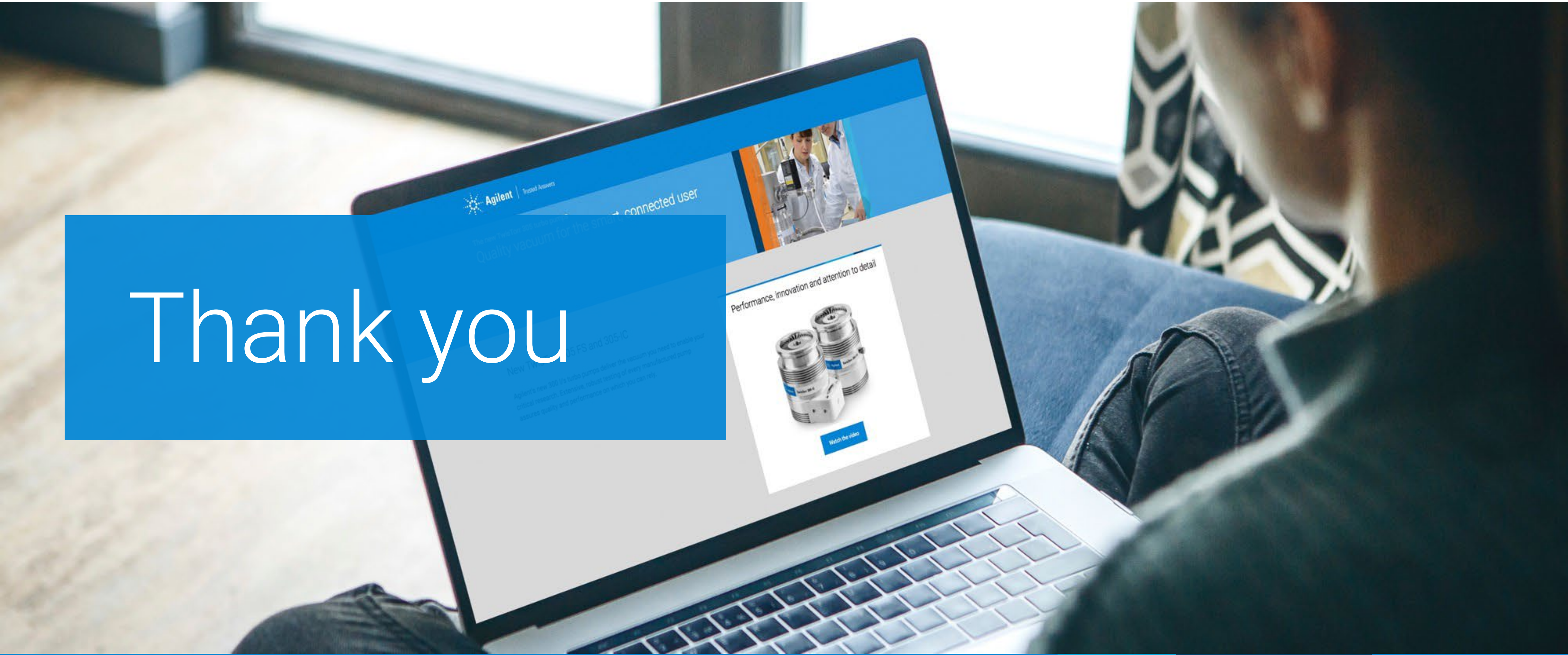
QUESTIONS?



Thank you