Summary

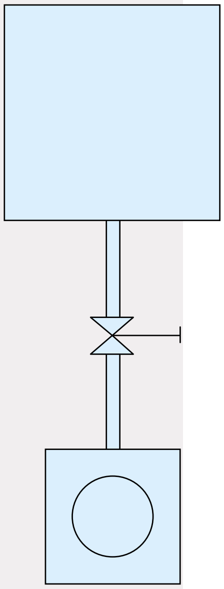
VACUUM TECHNOLOGY

Pumping systems

Elements of vacuum techniques

In the pages that follow, we have assembled a number of useful elements for determining the circuits placed into operation under high-vacuum conditions. We make no claim herein to present an exhaustive examination. The technical departments of Alcatel Vacuum Technologies can be contacted for advisory assistance with respect to unfamiliar pumping conditions.

A vacuum system comprises:



A tank to be emptied

- Volume
- Surface area
- Type of materials
- Product contents

Pipes

(Diameter
Length
Materials
Accessories)

- Surface area
- Conductance
- Type of material

One (or several) vacuum pumps

- Flow
- Ultimate Vacuum
- Compression ratio
- Backstreaming
- Selectivity

Goal

Obtain, on the basis of a known initial pressure, a final pressure within a specified time frame.

Pipes (including taps, elbows, etc.) reduce the efficiency of the vacuum pumps connected to the pipe network.
The conductance measurement is used to characterize these pipes.

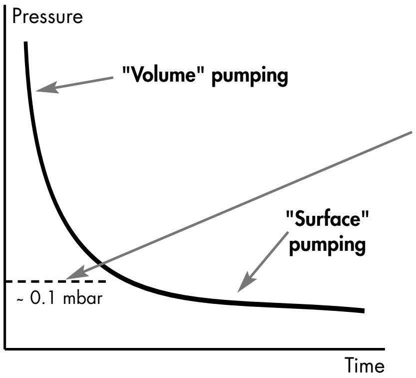
The various phases of a vacuum pumping

"Volume" pumping

The vacuum pump extracts from the target tank all gas molecules contained within the volume confined by the tank walls.

"Surface" pumping

The vacuum pump extracts molecules emanating from desorption of the walls or the contents within the tank (the vacuum pump is still said to balance the degassing process). This second phase may, for example, correspond to a liquid evaporation.

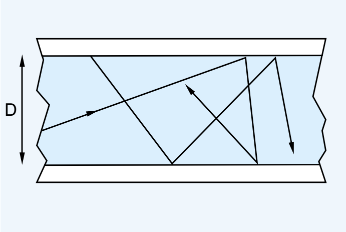


In general, this point of inflection in the flow state appears at pressure levels of less than 0.1 mbar. It may also appear at higher pressure levels (e.g. evaporation of solvents).
The calculation methods employed differ according to whether the pumping is positioned in one or the other of the two phases.

Different flow states within a cylindrical pipe of diameter D, with a gas pressure P

Re = Reynold's Number, λ = Mean free path

Molecular flow

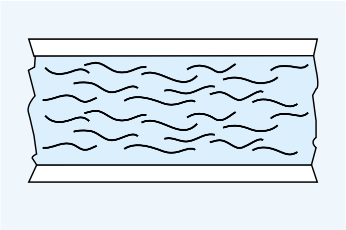


For air:
$P \times D > 2 \times 10^{-2}$ mbar.cm

$\lambda = \frac{D}{3}$

Each gas behaves as if it was alone.

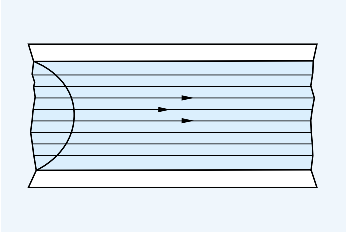
Transitional flow



$1200 < Re < 3000$

This flow state is neglected in vacuum techniques.

Laminar flow



Parabolic distribution of speeds.

2 criteria:

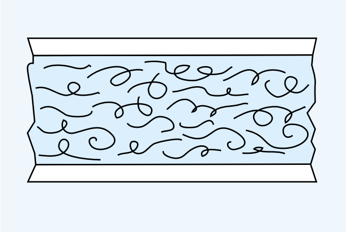
a/ $\lambda = \frac{D}{100}$

b/ $Re < 1200$

For air:
$P \times D > 0.7$ mbar.cm^{-1}

$\frac{Q}{D} < 150$ mbar. l.s^{-1}.cm^{-1}

Turbulent flow



$Re > 3000$
Rather uncommon in vacuum techniques.

Encountered in the transient state and at high pressure (near atmospheric pressure)

$\frac{Q}{D} > 400$ mbar. l.s^{-1}.cm^{-1}

Conductances calculation

Definition

P_1 P_2

Circulating gaseous flow = Q (mbar $l.s^{-1}$)

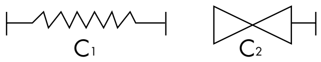
$P_1 > P_2$

By definition

$$C = \text{Conductance } (l.s^{-1}) = \frac{Q}{P_1 - P_2}$$

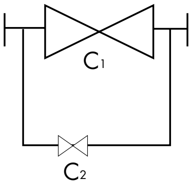
Conductance association

In series



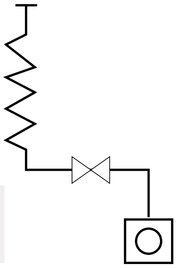
$$\frac{1}{C_R} = \frac{1}{C_1} + \frac{1}{C_2}$$

In parallel



$$C_R = C_1 + C_2$$

Impact on vacuum pump flow rates



$$\frac{1}{S_e} = \frac{1}{C} + \frac{1}{S}$$

The volumic flow rate of vacuum pumps is reduced by the conductance of the pipes.

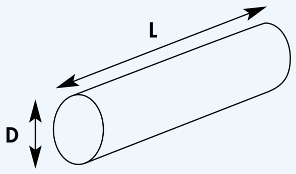
Effective pumping speed: . . . . S_e

Pipe with overall conductance: C

Vacuum pump with volume pumping speed: . . . . S

Notes

The formulae provided below are valid for straight cylindrical pipes with a circular cross-section.



Laminar flow state

General formula

$$C = \frac{\pi \times D^4}{128\ n \times L} \times \overline{P}$$

with n = viscosity of the gas.

The conductance varies with the average pressure $\overline{P}$.

Example: for air at 20°C.

$$C = 137 \times \frac{D^4}{L} \times \overline{P}$$ with: C in $l.s^{-1}$

λ in cm

D in cm

$\overline{P}$ in mbar

Conductances calculation

Molecular flow state

General formula:

$$C = \frac{1}{6}\sqrt{\frac{2\pi \times RT}{M}} \times \frac{D^3}{L}$$

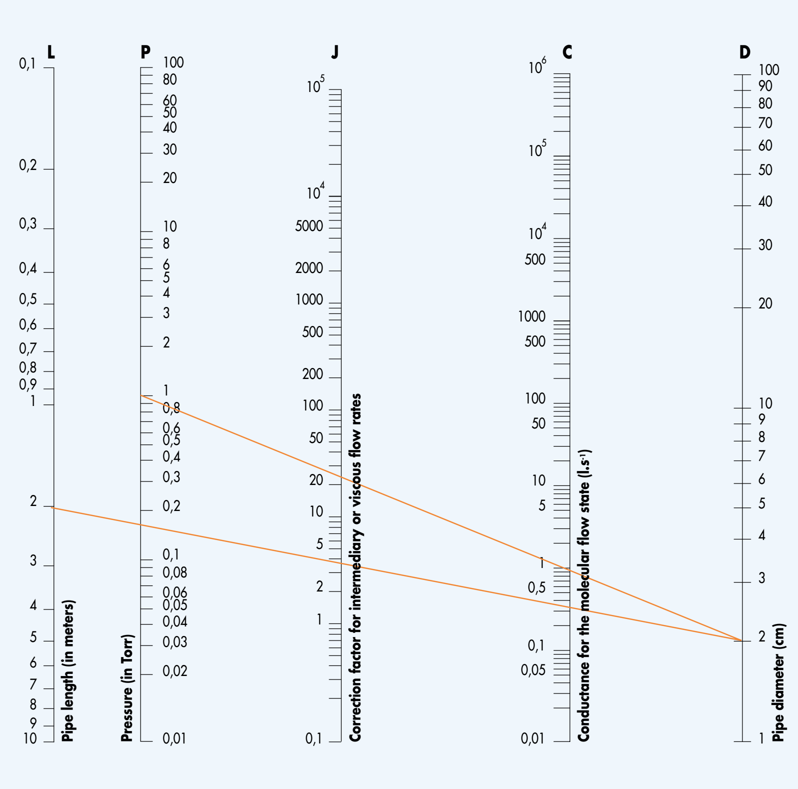
with
R = Molar Gas Constant
M = Molar mass (kg)
T = Temperature (Kelvin)

For air at 20°C, $C = 12.1 \times \frac{D^3}{L}$

In the molecular flow state, conductance remains an independent variable.

The previous formula is only valid for sufficiently long pipe sections (L/D > 20). For shorter pipes, a correction factor J, read off of the adjacent diagram, is to be introduced. For gasses other than air, a correction factor (see table below) is also used.

Gaz	H_2	He	H_2O	Ar	Co	Hg
α	3.78	2.67	1.26	0.85	0.81	0.38



Pipe conductance determination

The point-aligned chart laid out above enables determining the conductance of a given pipe section, regardless of the flow state (molecular or viscous). On the basis of the pipe length and diameter, the C-scale intercept provides the conductance value in the case of the molecular flowstate ($12.1 \times \frac{D^3}{L}$).

The actual conductance is equal to the product of C x J, where J is the correction coefficient that takes into account the flow state through the pipe network.
The coefficient J is obtained at the intersection with the average pressure scale.
On the basis of the conductance C of the pipes and the flow rate S of the pump used, the calculation of effective flow rate S_1 through the installation can be carried out by applying the following formula:

$$\frac{1}{S_1} = \frac{1}{S} + \frac{1}{C}$$

Example:

Let's determine the conductance of a pipe with a diameter of 20 mm, a length of 2 m and an average pressure of 1 torr.

The line connecting the point D = 2 cm with the point L = 2 m cuts the C-scale line at point 1, at a value equal to 0.5 $l.s^{-1}$.
The line connecting the point D = 2 cm with the point P = 1 torr cuts the J-scale line at point 2, at a value equal to 30.

The conductance value is therefore equal to:
0.5 x 30 = 15 $l.s^{-1}$

Pumpdown Time calculation

The calculation of pumpdown time with a vacuum pump operating at a constant volumic flow rate and with a threshold pressure considerably lower than the target pressure is as follows:

$$t = 2.3 \frac{V}{S} \log \frac{P_0}{P_f}$$

(Homogeneous units)

P_0 = initial pressure

P_f = final pressure

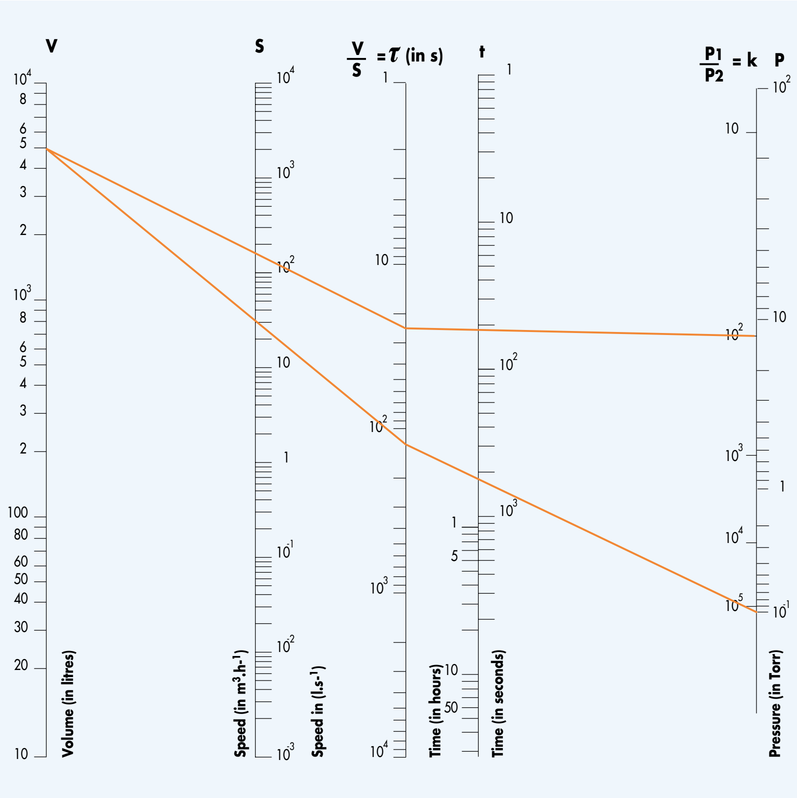
t = transition time from P_0 to P_f

V = tank volume

S = pump flow rate

It is recommended to use the specific pressure-drop curves for each pump model (see the chapter entitled "Rotary Vane Pumps"), which take account of the ultimate pressure and the flow rate variation with respect to inlet pressure.

Point-aligned chart for determining the pumping time as a function of the final target pressure, while incorporating the reduction in pumping speed of the primary pumps operating at low pressure.



> **Note**
>
> We recommend connecting the Alcatel slide vane rotary vane pumps using pipes with a diameter equal to that of the suction orifice. If their length is less than 3 m, the pumping time between atmosphere unit 0,1 mbar is slightly increased (less than 20 %).

Units

Pressure

The legally-accepted unit of pressure measurement is the Pascal (1 N/m^2), as well as its multiples and decimals, whereas the common unit are the millibar (a multiple of the Pascal) and the torr.
1 torr (mm Hg) = 133 Pa
1 mbar = 100 Pa = 1 hPa

Example:

mbar
↓
1 torr → 1.333 millibar

Pressure unit conversion table

	Pa	bar	kg/cm²	Atmosph.	g/cm²	Torr*	m bar	inch.Hg	psi
1 Pa	1	10^{-5}	1.02×10^{-5}	0.9869×10^{-5}	1.02×10^{-2}	0.75×10^{-2}	10^{-2}	0.2953×10^{-3}	0.1451×10^{-3}
1 bar	10^{5}	1	1.02	0.9869	1020	750	1000	29.53	14.51
1kg/cm²	0.980×10^{5}	0.980	1	0.968	1000	735	980	28.96	14.22
1 Atmosph.	1.013×10^{5}	1.013	1.033	1	1033	760	1013	29.95	14.70
1 g/cm²	98	0.098×10^{2}	10^{-3}	0.968×10^{-3}	1	0.735	0.98	0.02896	0.1422
Torr*	133.3	0.1333×10^{-2}	1.36×10^{-3}	1.36	1	1.333	0.03937	0.01934	
1 mbar	100	01.10^{-2}	1.02×10^{-3}	0.9869×10^{-3}	1.02	0.750	1	0.02953	0.01451
1 inch Hg	3386	3.386×10^{-2}	0.03453	0.03345	34.53	25.4	33.86	1	0.4910
1 psi	6890	6.89×10^{-2}	0.0703	0.008	70.3	51.75	68.947	2.041	1

*1 Torr = 1 mm Hg.

Pumping Speed

This measurement quantity is the most commonly used for characterising a vacuum pump. The legally-accepted unit of measurement is the m^3/sec or its decimal, the dm^3/sec (litre/sec).

	m³/s	l/s	m³/h	l/mn	CFM
m³/s	1	10^{3}	3600	6.10^{4}	2.12×10^{3}
l/s	10^{-3}	1	3.6	60	2.12
m³/h	2.78×10^{-4}	2.78×10^{-4}	1	16.7	5.89×10^{-1}
l/mn	1.67×10^{-5}	1.67×10^{-1}	6.10^{-2}	1	3.53×10^{-2}
CFM(1)	4.72×10^{-4}	0.471195	1.699	28.32	1

(1) American unit = cubic feet per minute

Gaseous flow rate

The legally-accepted unit of measurement is the $Pa.m^3.s^{-1}$.
It must not be overlooked however that the gaseous flow rate is an alternative expression of the mass flow rate.

Equivalent	atm cm³/s	Pa.m³/s	mbar l/s	Torr l/s	Lusec	SCCM
atm cm³/s	1	0.1	1	0.76	760	60
Pa m³/s	10	1	10	7.5	7500	600
mbar l/s	1	0.1	1	0.76	760	60
Torr l/s	1.3	0.13	1.3	1	1000	78.7
Lusec	1.3×10^{-3}	1.3×10^{-4}	1.3×10^{-3}	10^{-3}	1	7.87×10^{-2}
SCCM (1)	1.66×10^{-2}	1.66×10^{-3}	1.66×10^{-2}	1.27×10^{-2}	12;7	1

Application example: 1 $Pa.m^3.s^{-1}$ = 10 $mbar.l.s^{-1}$
(same scale-reading system as for the "Pressure" table)

Physical characteristics

Miscellaneous physical constants

Avogadro's number:
6.02252×10^{23} molecules/mole

Normal volume of a perfect gas:
22.414 litres/g.mole (0°C - 1013 mbar)

Molar gas constants

$R = 0.08205$ liter.atm.g^{-1}mole^{-1} K^{-1}
$= 8.314 \times 10^{-7}$ erg.g^{-1}mole^{-1} K^{-1}
$= 8.314$ Joules.g^{-1}mole^{-1} K^{-1}
$= 1.987$ cal.g^{-1}mole^{-1} K^{-1}
$= 10.73$ psia.cu ft.lb^{-1}mole^{-1} R^{-1}

Boltzmann's constant:
$k = 1.38 \times 10^{-23}$ J.K^{-1}

Stefan's constant:
$\sigma = 5.672 \times 10^{-4}$ W.m^{-2}.K^{-1}

Physical characteristics of various gases and vapours

TYPE		Molecular properties			Normal boiling point (subjected to 1013 Pa)	
		Molar Mass	Kinetic diameter	Sutherland's constant	Temperature	Density
		M (kg mol.$^{-1}$)	$\sigma_{(T)}$ (m)	T_s (K)	T_e (K)	ρ (kg m^{-3})
Hydrogen	H_2	2.014×10^{-3}	2.62×10^{-10}	70.6	20.37	7.081×10^{-1}
Helium	He_4	4.000×10^{-3}	2.19×10^{-10}	80	4.23	1.253×10^{-2}
Ammonia	NH_3	$17.018 \times .10^{-3}$		472	239.73	6.812×10^{-10}
Water	H_2O	18.001×10^{-3}	4.68×10^{-10}	659	373.15	9.583×10^{-2}
Nitrogen	N_2	27.993×10^{-3}	3.76×10^{-10}	102	77.34	8.080×10^{-2}
Air	$\overline{M} = \sqrt{\Sigma \vartheta_1 M_1}$	29.088×10^{-3}	3.68×10^{-10}	119.5	81.65	9.950×10^{-2}
Oxygen	O_2	31.973×10^{-3}	3.56×10^{-10}	125	90.19	1.140×10^{-3}
Argon	Ar	39.911×10^{-3}	3.67×10^{-10}	142	87.29	1.402×10^{-3}
Freon 12	$CC1_2F_2$	120.823×10^{-3}			242.6	
Sulphur hexafluoride	SF_6	145.944×10^{-3}				1.540×10^{-3}

$T_2 = 273.15$ K
$T_\theta = T_0 + 0°C$
$T_{20} = 293.15$ K

$$\sigma_{(T)} = \sigma_{(293)} \left(1 + \frac{T_s}{29}\right) / \left(1 + \frac{T_s}{T}\right)$$

$$P_{\upsilon(\theta)} = P_{\upsilon(20)} \frac{T_{20}}{T_\theta}$$

TYPE		Gaseous state				
		Unit density	Dynamic viscosity	Critical constants		
		pu (20) (kg m^3Pa^{-1})	η (20) (Pa s)	T_c (K)	P_c (MPa)	P_c (kg.m^{-3})
Hydrogen	H_2	8.264×10^{-7}	0.880×10^{-5}	33.20	1.2970	3.102×10^{-1}
Helium	He_4	1.641×10^{-6}	1.950×10^{-5}	5.20	0.2290	6.930×10^{-1}
Ammonia	NH_3	6.982×10^{-6}	0.986×10^{-5}	405.55	11.2980	2.350×10^{-2}
Water	H_2O	7.388×10^{-6}	1.006×10^{-5}	647.15	22.0900	3.125×10^{-2}
Nitrogen	N_2	1.148×10^{-5}	1.761×10^{-5}	126.00	3.3934	3.110×10^{-2}
Air	$\overline{M} = \sqrt{\Sigma \vartheta_1 M_1}$	1.810×10^{-5}	1.810×10^{-5}	132.45	3.7693	3.500×10^{-2}
Oxygen	O_2	1.312×10^{-5}	1.977×10^{-5}	154.31	5.0372	4.299×10^{-2}
Argon	Ar	1.638×10^{-5}	2.199×10^{-5}	150.69	4.8632	5.308×10^{-2}
Freon 12	$CC1_2F_2$	4.957×10^{-5}	1.212×10^{-5}			
Sulphur hexafluoride	SF_6	5.988×10^{-5}	1.450×10^{-5}	318.70	2.7602	7.300×10^{-2}

$$\eta_{(\theta)} = \eta_{(20)} \sqrt{\frac{T_\theta}{T_{20}} \left(1 + \frac{T_s}{T_{20}}\right) / \left(1 + \frac{T_s}{T_\theta}\right)}$$

Conversions

Length

The legal unit is the meter, its multiples and sub-multiples.

1 angstrom (Å) =
1.10^{-10} m = 1.10^{-4} micron = 1.10^{-8} cm

1 inch (U.S.) =
2.54 x 10^{-2} m = 2.54 cm

1 foot (U.S.) =
0.3048 m = 30.48 cm

1 yard (U.S.) = 0.9144 m

1 mile (nautical) =
1.8533 x 10^{3} m = 1.8533 km

1 mile (U.S.) =
1.6095 x 10^{3} m = 1.6095 km

Dynamic viscosity

1 kp s/m^2	= 9.8067 Pa s
1 kp h/m^2	= 3.5304 x 10^{4} Pa s
1 Poise = 1 cg/cm s	= 1.0000 x 10^{-1} Pa s
1 lb/ff hr	= 4.1338 x 10^{-4} Pa s
1 kg/ff hr	= 9.1134 x 10^{-4} Pa s
1 lb/ff s	= 1.4882 Pa s

Kinetic viscosity

1 stoke = 1 cm^2/s	= 1.0000 x 10^{-4} m^2/s
1 dm^3/hr in	= 1.0936 x 10^{-5} m^2/s
1 ff^2/hr	= 2.5806 x 10^{-5} m^2/s
1 ff^2/s	= 9.2903 x 10^{-2} m^2/s

Specific calorific capacity

1 kcal/kg°C	= 4.1868 x 10^{3} J/kg K	= 4.1868 x kJ/kg K
1 cal/g °C	= 4.1868 x 10^{3} J/kg K	= 4.1868 x kJ/kg K
1 Btu/lB °F	= 4.1868 x 10^{3} J/kg K	= 4.1868 x kJ/kg K
1 Chu/lb °C	= 4.1868 x 10^{3} J/kg K	= 4.1868 x kJ/kg K

(1) American unit = cubic feet per minute

Thermal conductivity

1 kcal/m h °C	= 1.1630 W/m K
1 cal/cm s °C	= 4.1868 x 10^{2} W/m K
1 Btu/ft^2 hr (°F/in)	= 1.4423 x 10^{1} W/m K
1 Btu/ft^2 (°F/ft)	= 1.7307 x 10^{3} W/m K

Mass

1 grain	= 6.4800 x 10^{-5} kg
1 lb	= 4.5359 x 10^{-1} kg
1 ton (short) = 20 cwt. sh.	= 9.0719 x 10^{-2} kg
1 ton (long) = 20 cwt. l.	= 1.0161 x 10^{-3} kg

Mass-flow rate

1 lb/hr	= 1.2600 x 10^{-5} kg	= 4.5360 x 10^{-1} kg/h
1 ton/day (short)	= 1.0500 x 10^{-2} kg/s	= 3.7800 x 10 kg/h
1 ton/day (long)	= 1.1760 x 10^{-2} kg/s	= 4.2336 x 10 kg/h
1 ton/hr (short)	= 2.5200 x 10^{-1} kg/s	= 9.0720 x 10^{-2} kg/h
1 ton/hr (long)	= 2.8224 x 10^{-1} kg/s	= 1.0161 x 10^{-3} kg/h

Temperature

∂ °C	= (∂ + 273.15) K	= ∂ °C
∂ °F	= 5/9 (∂ - 32) + 273.15 K	= 5/9 (∂ °F - 32) °C
1 °R	= 5/9 K	= 4/9 °R - 273.15 °C

Volume

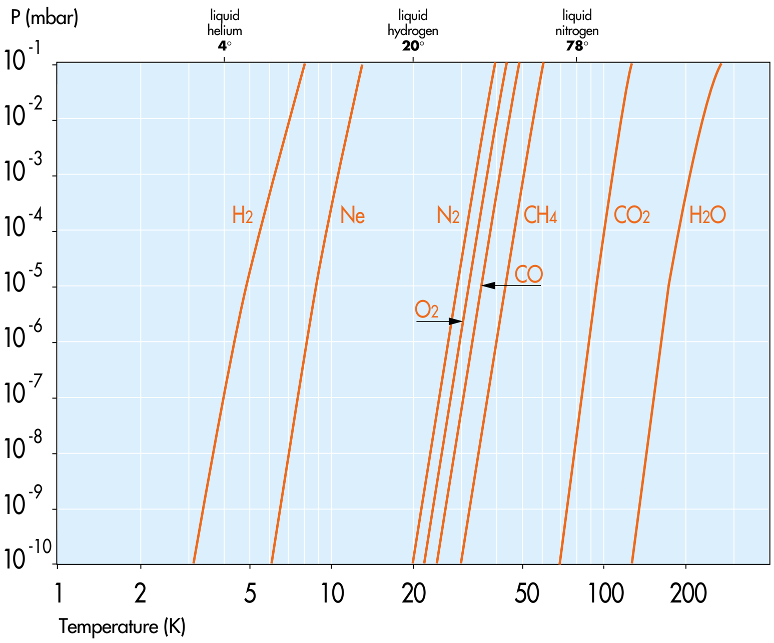
1 in^3	= 1.6387 x 10^{-5} m^3
1 ft^3	= 2.8317 x 10^{-2} m^3
1 yd^3	= 7.6455 x 10^{-1} m^3
1 US gal	= 3.7853 x 10^{-3} m^3
1 UK gal	= 4.5460 x 10^{-3} m^3
1 US bushel (dry)	= 3.5239 x 10^{-2} m^3
1 UK bushel (dry)	= 3.6369 x 10^{-2} m^3
1 barrel (petroleum US)	= 1.5898 x 10^{-1} m^3
1 register ton =100 ft^3	= 2.8317 m^3

Specific volume

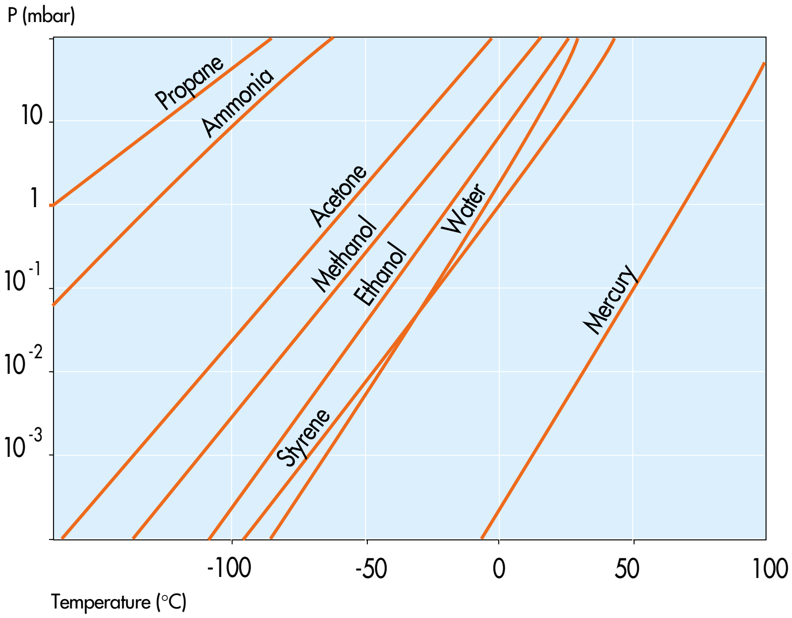
1 ft^3/kg	= 2.8317 x 10^{-2} m^3/kg
1 ft^3/lb	= 6.2428 x 10^{-2} m^3/s

Saturated vapor pressure of common gases at low temperatures

Normal boiling point



Saturated vapor pressure (mbar)



Saturated vapor pressure (mbar)