Materials and Properties IV
Outgassing

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CERN Accelerator School (CAS) on Vacuum for Particle Accelerators
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Outline

- Gas source and main features.
- Order of magnitude.
- Outgassing of water vapour from metals
- Outgassing of water vapour from polymers
- Outgassing of H_2 from metals

Outline

Preamble: outgassing rate versus pumping speed

The total outgassing rate Q and the effective pumping speed S define the pressure in a vacuum system:

$$\boxed{P = \frac{Q}{S} + P_0}$$

P_0: ultimate pressure of the pumping system.

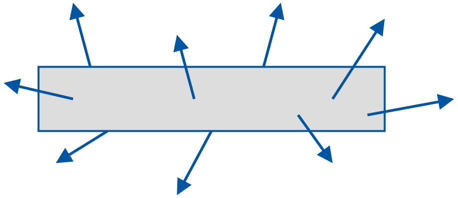
In general, *in particle accelerators*, the effective S varies between 1 to 1000 $l.s^{-1}$) while Q **can extend over more than 10 orders of magnitude** (≈$10^{-5} \rightarrow 10^{-15}$ mbar $l.s^{-1}.cm^{-2}$).

The **right choice of materials and treatments** is compulsory in the design of vacuum systems (especially those for accelerators).

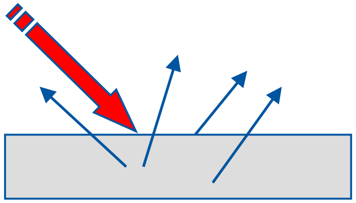
In this respect the **measurement of outgassing rate is an essential activity** for an ultra-high vacuum expert.

Reminder: Terminology

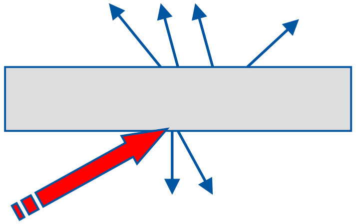
- Outgassing is the spontaneous evolution of gas from solid or liquid.



- Degassing is the deliberate removal of gas from a solid or a liquid.

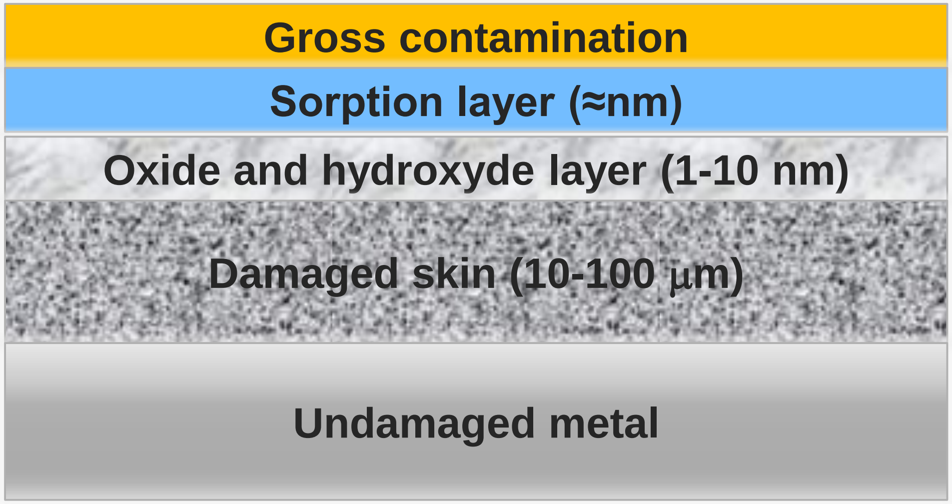


- Desorption is the release of adsorbed chemical species from the surface of a solid or liquid.



Gas sources

Contamination onto surfaces is a source of gas.
After production, the **surface** of vacuum components is **always contaminated**.
They must be **thoroughly cleaned** before installation.



oils, dirt, …→ **Gross contamination**

C_xH_y, H_2O, Cl, …→ **Sorption layer (≈nm)**

Me_xO_y, → **Oxide and hydroxyde layer (1-10 nm)**

excess dislocation, voids → **Damaged skin (10-100 μm)**

Undamaged metal

Solvent or detergent cleaning

See Mauro Taborelli presentation on Monday 22nd

Outgassing: main features

Gas molecules dissolved in the bulk of **materials** are also a source of gas.

They diffuse towards the surfaces and are then released.

Polymers dissolve a **significant quantity** of molecules, **in particular H_2O**.

Metals can dissolve only **limited quantities** of small atoms that, at room temperature, are immobile in the lattice, except for hydrogen.

In one day, H atoms travel in average **4 μm in austenitic stainless steels**, while O atoms travel the same distance in 1000 years.

Therefore, amongst the dissolved elements in the bulk of metals, **only H_2 is released at room temperature**.

For comparison, in one day, **H_2O molecules move along about 20 μm** in **PEEK**, a high-performance polymer.

Outgassing rates: orders of magnitude

Neoprene (10 h pumping):

$q_{H2O} \approx 10^{-5}$ mbar l s^{-1} cm^{-2}

$q_{H2O} \approx 10^{14}$ molecules s^{-1} cm^{-2}

Unbaked stainless steel (10 h pumping):

$q_{H2O}=3\times10^{-10}$ mbar l s^{-1} cm^{-2}

$q_{H2O}=7\times10^{9}$ molecules s^{-1} cm^{-2}

Baked stainless steel (150º C x 24 h):

$q_{H2}=3\times10^{-12}$ mbar l s^{-1} cm^{-2}

$q_{H2}=7\times10^{7}$ molecules s^{-1} cm^{-2}

Baked OFS Copper (200º C x 24 h):

$q_{H2}=3\times10^{-14}$ mbar l s^{-1} cm^{-2}

$q_{H2}=7\times10^{5}$ molecules s^{-1} cm^{-2}

Instruments equipped with hot filaments are an **important source of gas**.

'Indicative' value for CERN instruments after standard degassing procedure:

Bayard-Alpert gauges (W filaments)

$Q \approx 10^{-9}$ mbar ℓ s^{-1}

$Q \approx 3\times10^{10}$ molecules s^{-1}

Residual gas analyzer (W filaments)

$Q \approx 10^{-8}$ mbar ℓ s^{-1}

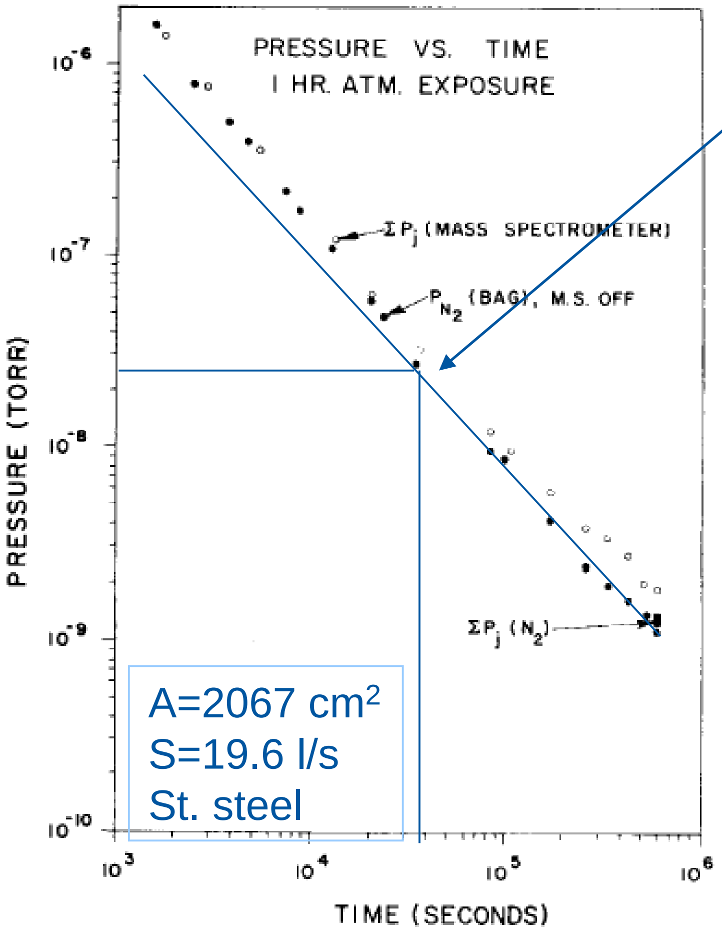
$Q \approx 3\times10^{11}$ molecules s^{-1}

Equivalent **in quantity** to ≈ 1 m^2 of stainless steel.

Outgassing of water vapour from unbaked metallic alloys

Outgassing of water vapour

D. Edwards Jr. Journal of Vacuum Science and Tech.,14(1977)606 and 14(1977)1030



A=2067 cm^2
S=19.6 l/s
St. steel

q(10h) = 2 x10^{-10} Torr l s^{-1} cm^{-2}

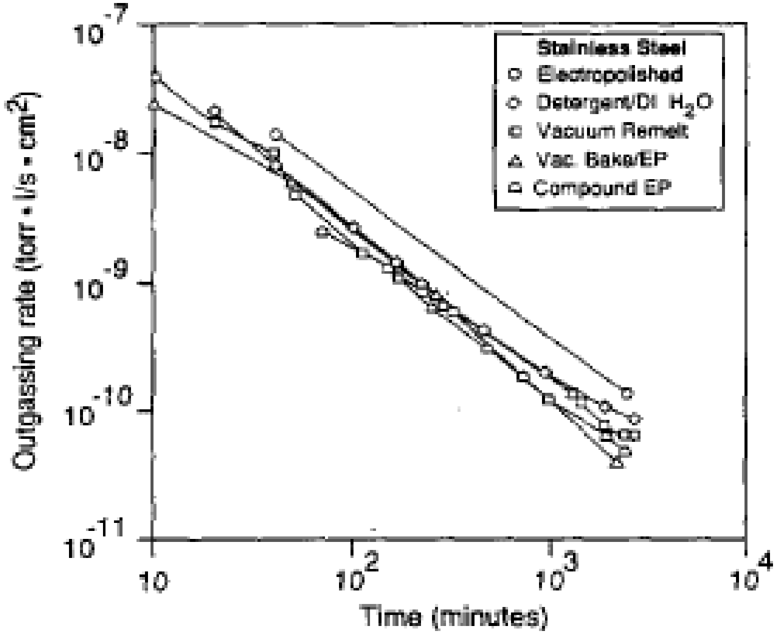
$$q_{H_2O} \approx \frac{3\times 10^{-9}}{t[h]}\left[\frac{mbar\ l}{s\ cm^2}\right]$$

Experimental values valid **for all metals used for vacuum chamber** manufacturing

The outgassing rate of an unbaked material **depends on pumping time**, it is not an intrinsic value!

Outgassing of water vapour

H.F. Dylla, D. M. Manos, P.H. LaMarche
Jr. J. Vac. Sci. and Tech. A, 11(1993)2623



$$q_{H_2O} \approx \frac{3 \times 10^{-9}}{t[h]} \left[\frac{mbar\ l}{s\ cm^2} \right]$$

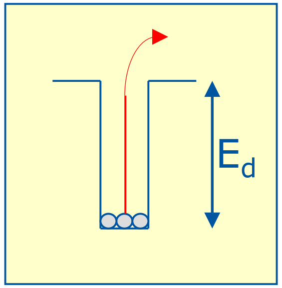
The most effective way to accelerate the release of water vapour is *in-situ* bakeout at least at 120°C for 12 hours.

Water vapour outgassing rate of austenitic stainless steel that underwent four different surface treatments.

The source of H_2O is recharged after each venting to air.

Interpretation: single desorption energy

Mean stay time at room temperature



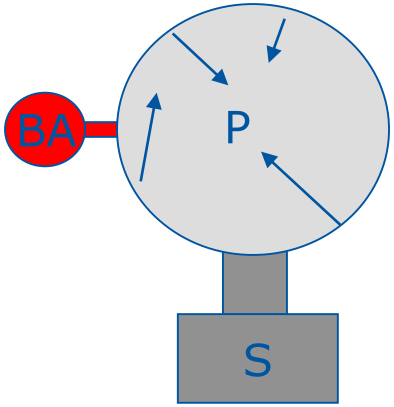
The mean stay time (sojourn time) is given by the Frenckel law:

$$\tau_d = \tau_o e^{\frac{E_d}{k_B T}}$$

where the value of τ_o is usually assumed to be about 10^{-13} s ($\approx h/K_B T$).

Interpretation: single desorption energy

Pressure decrease

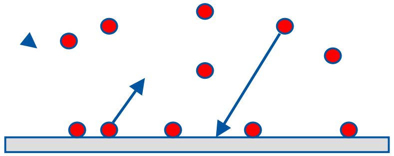


variation of the quantity of gas in the gas phase

$$\begin{cases} V\dfrac{dP}{dt} = -SP + \dfrac{N_s\Theta}{\tau_d} \\ \dfrac{d\Theta}{dt} = -\dfrac{\Theta}{\tau_d} \end{cases}$$

quantity of gas leaving the surface

quantity of gas removed by the pump



Θ= fraction of sites occupied
The total number of sites N_s is assumed to be ≈10^{15} cm^{-2} → $4x10^{-5}$ mbar l $s^{-1}cm^{-2}$

$$P(t) \cong \frac{N_s}{S \cdot \tau_d} e^{-\frac{t}{\tau_d}} \quad \text{for} \quad t > \tau_d$$

The solution is plotted for:

V=10 ℓ, S=10 ℓ /s, N_s=2245x4x10^{-5} mbar ℓ

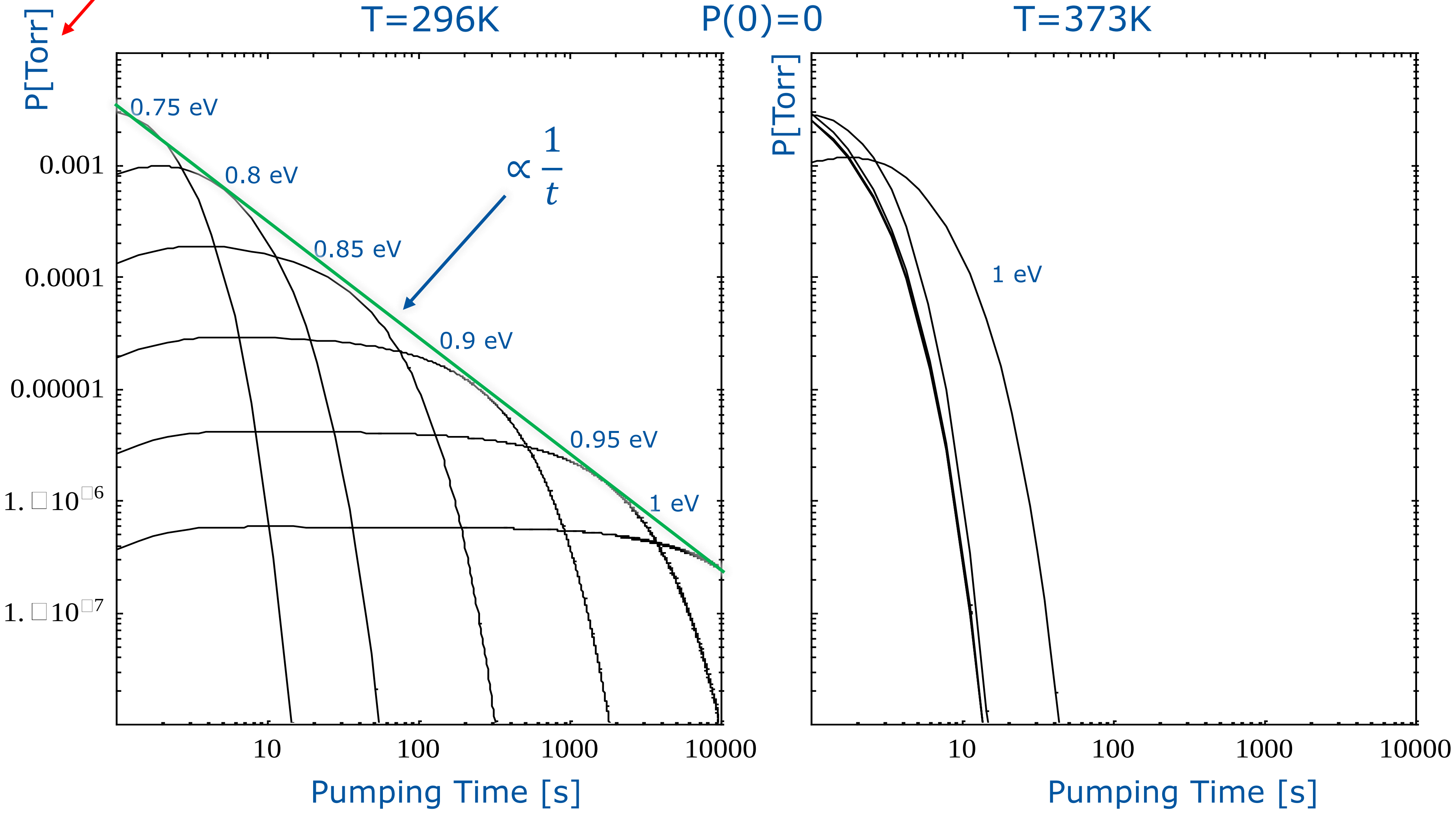
and different energies

Interpretation: single desorption energy

1Torr =1.33 mbar

Pressure decrease for different adsorption energies and two values of T

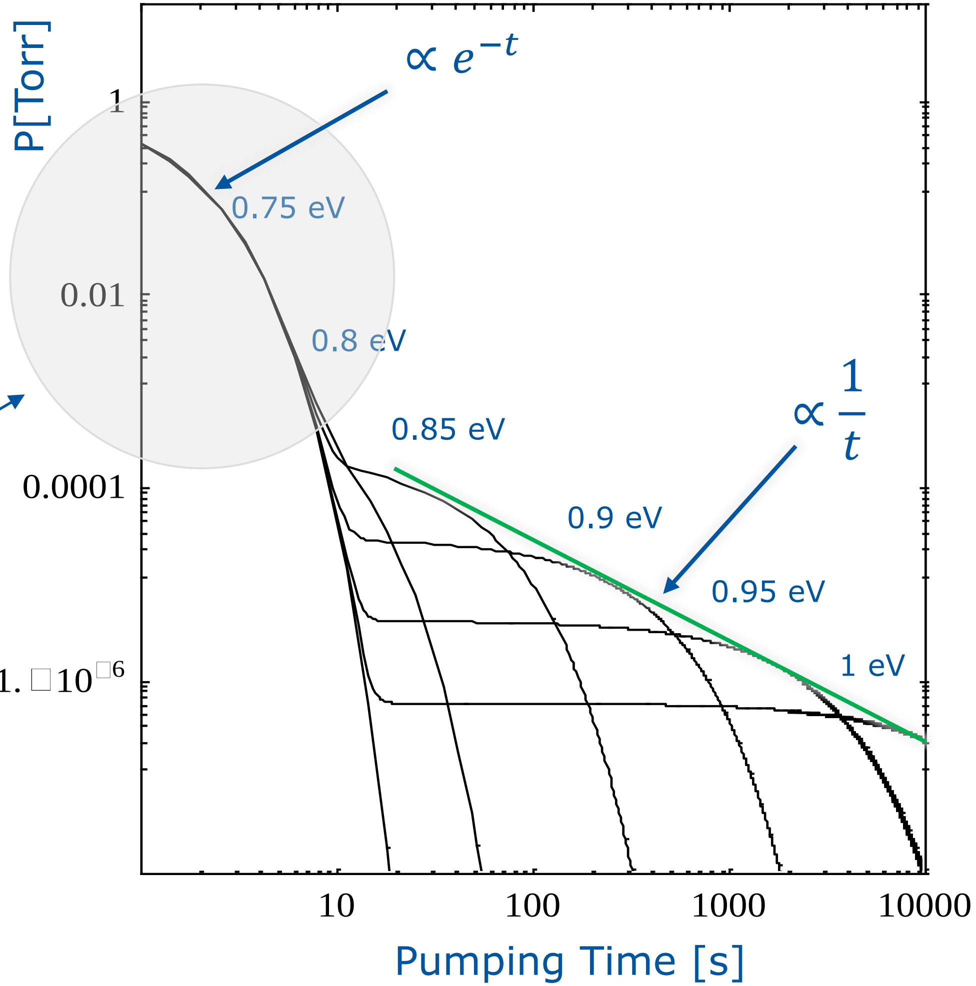
T=296K P(0)=0 T=373K



Interpretation: single desorption energy

Pressure decrease for different adsorption energies

$T=296K$
$P_o=1$ Torr



Effect of the molecules already in the gas phase at t=0

Water vapour outgassing from polymers

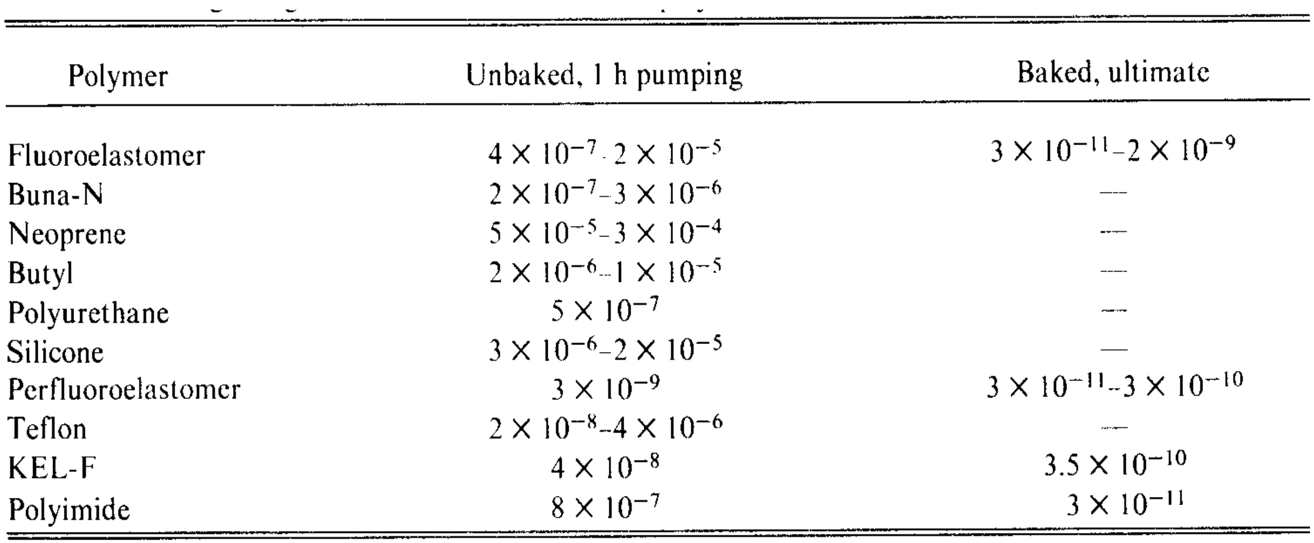
Outgassing of polymers

Polymers, in particular in their amorphous structures, can **dissolve huge quantities of gas, in particular water vapour**.

The **water vapour solubility is very high**; for example for common materials like Viton, PEEK, and Vespel (Kapton) the content of water in equilibrium with 50%-humidity air at 20°C is **0.21, 0.2, and 1 wt. %,** respectively.

The huge quantity of dissolved gas and the **relatively high mobility** through the polymeric chains result in **much higher outgassing rates** than the ones of metals. This is particularly marked for **water vapour**.

R. N. Peacock, J. Vac. Sci. Technol., 17(1), p.330, 1980



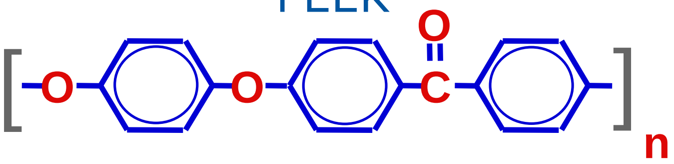
Polymer	Unbaked, 1 h pumping	Baked, ultimate
Fluoroelastomer	4×10^{-7}-2×10^{-5}	3×10^{-11}–2×10^{-9}
Buna-N	2×10^{-7}–3×10^{-6}	—
Neoprene	5×10^{-5}–3×10^{-4}	—
Butyl	2×10^{-6}–1×10^{-5}	—
Polyurethane	5×10^{-7}	—
Silicone	3×10^{-6}–2×10^{-5}	—
Perfluoroelastomer	3×10^{-9}	3×10^{-11}–3×10^{-10}
Teflon	2×10^{-8}–4×10^{-6}	—
KEL-F	4×10^{-8}	3.5×10^{-10}
Polyimide	8×10^{-7}	3×10^{-11}

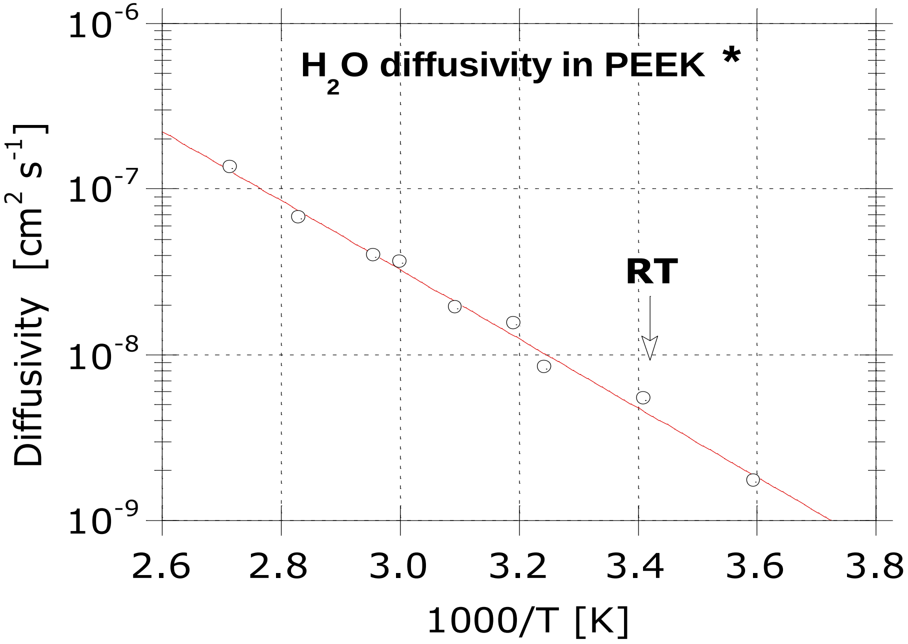
The maximum bakeout temperature depends on the type of polymer; it is limited to about 200 °C for Viton®.

Outgassing of polymers

Example:

PEEK





Water solubility:

0.1 to 0.5 wt.% (4.4 to 22×10^{19} molecules/cm^3)

10 to 50 times larger than the H total content in as produced austenitic stainless steel

Water diffusivity at RT:

5×10^{-9} cm^2 s^{-1}

2000 times larger than that reported for H in austenitic stainless steel.

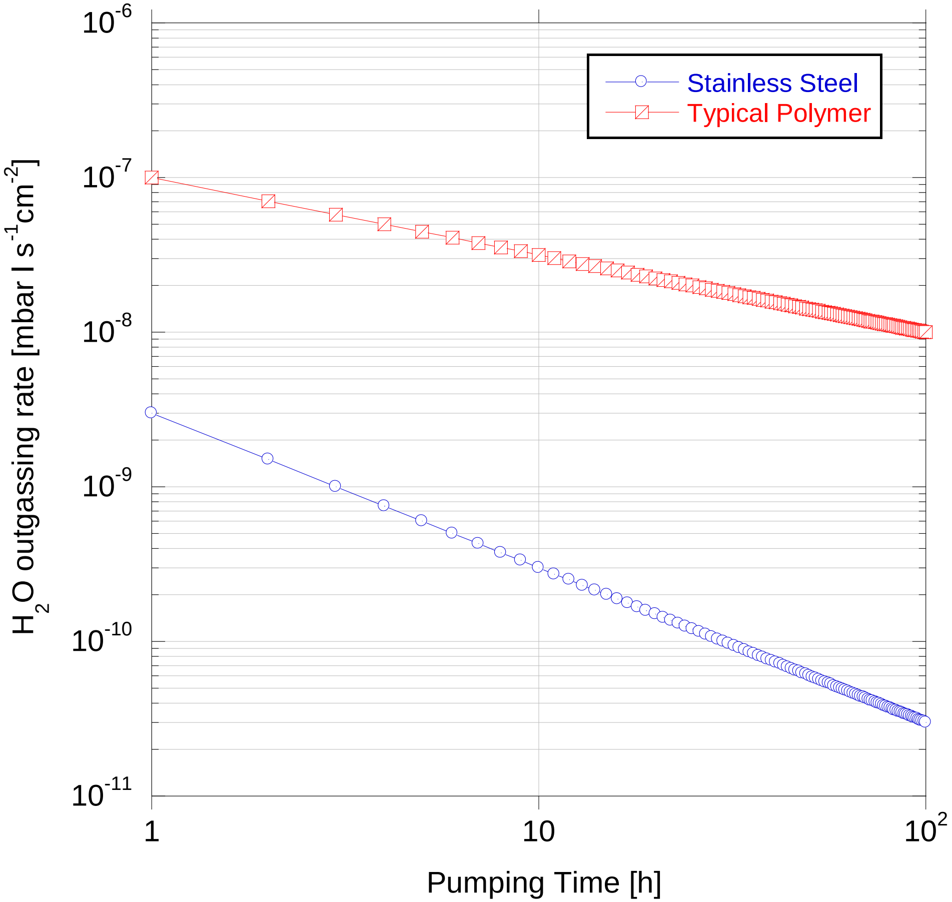
[*] After G.Mensitieri et al., J.Appl.Polym.Sci., **37**, 381, (1989)

Outgassing of polymers

The outgassing rates of **thick slab of polymers** decrease with the inverse of the square root of the pumping time t:

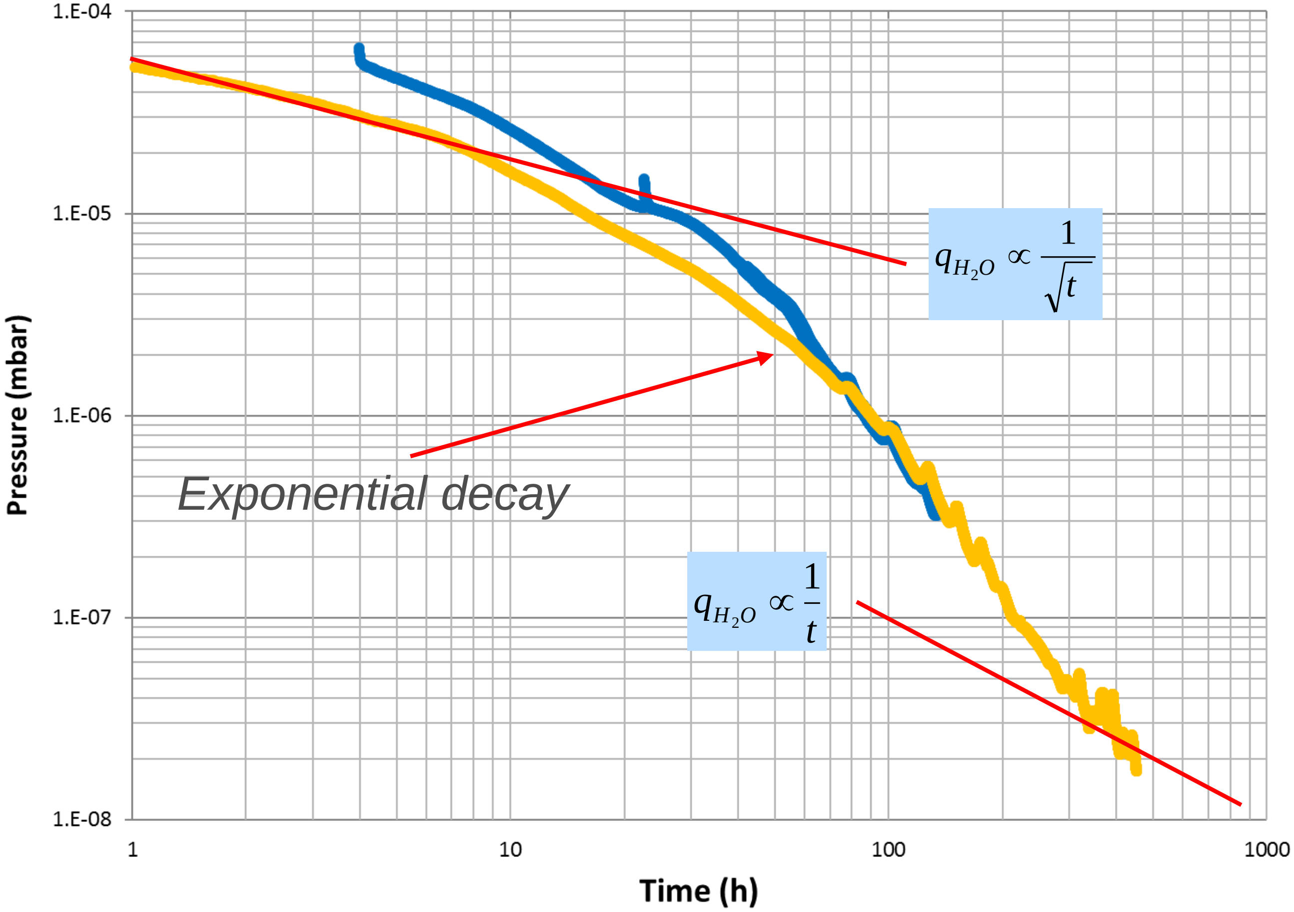
$$\boxed{q_{H_2O} \propto \frac{1}{\sqrt{t}}}$$

The decrease of water vapour outgassing rate is much slower in polymer than in metals.



Outgassing of polymers

Case study: Outgassing of Axon wires, 0.2-mm-thick Kapton insulation



Courtesy of Jose Antonio Ferreira Somoza

Outgassing of polymers

- Another important limitation of polymers used as seals is **the high gas permeability.**

- Gas penetrates into the material and diffuses towards the vacuum system. The permeation flow may **limit the ultimate water vapour pressure** in vacuum systems and **affect the sensitivity of helium leak-detection**.

- The **permeation flow of atmospheric water vapour** through a Viton O-ring, 5 mm cross section diameter, 6 cm torus diameter is **≈ 10^{-7} Torr l s^{-1}**. The **stationary condition** (ultimate permeation) will be attained **after about two months**.

Outgassing of H_2 from metals used in vacuum systems for particle accelerators.

Outgassing of hydrogen

For metallic alloys, as soon as water vapour outgassing is strongly reduced, by either long pumping or bakeout, **H_2 outgassing rate becomes the highest one**.

This gas is dissolved in metals as single H atoms. Its **diffusion is relatively fast** and, after **recombination on the surface**, it can be released as molecular hydrogen.

Most of the **H atoms are dissolved in liquid metals**, during the production process.

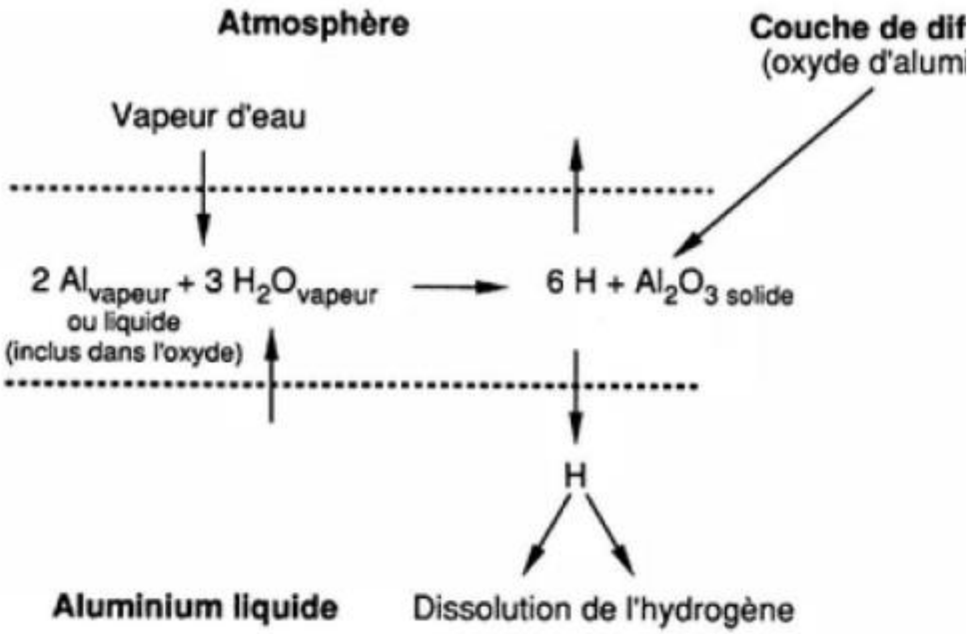
H atom mobility and solubility in the liquid state are higher than in the solid state.

Typical sources of H are:

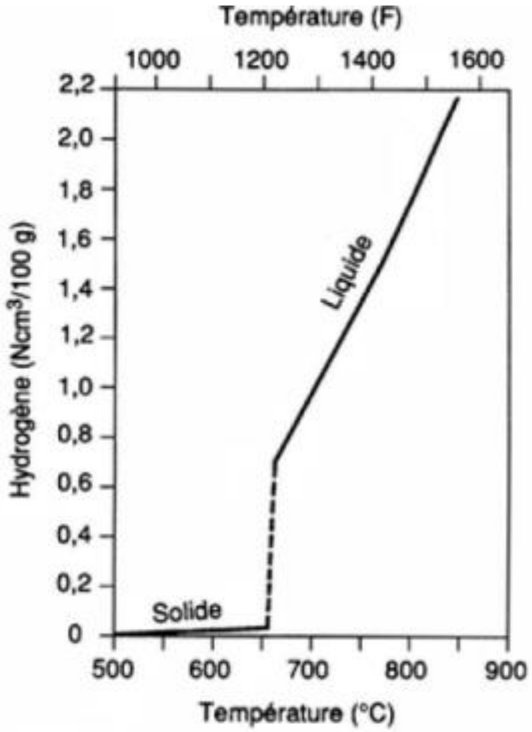
- metals ores;
- tools needed for fusion;
- refractory materials of furnaces;
- combustion and treatment gas;
- *water vapour and fluids used for quenching (for example the hyper-quench of austenitic stainless steels is carried out from 1100°C in water, air, or oil).*

Outgassing of hydrogen

Example of a process of H_2 dissolution in liquid Al



If the solidification is fast, **the gas is trapped in the solid** far form the equilibrium



1 Ncm^3 correspond à 1 cm^3 de gaz mesuré dans les conditions normales de température (°C) et de pression (10^5 Pa).

Typical H_2 contents are about **1 wt. ppm** for copper, aluminum, and austenitic stainless steel

Outgassing of hydrogen

As for water vapour, hydrogen-outgassing rate is **reduced by heating**.

The high temperatures **increase the H atoms mobility** and, as a result, accelerate the depletion of the residual hydrogen content.

However, there is a **crucial difference between water vapour and hydrogen**.

Each time the vacuum system is exposed to air, water molecules re-adsorb on the surface, while **hydrogen is not recharged** in the bulk of the metal.

For most of the materials used for the manufacturing of vacuum chambers, the H **solubility is very low** in the solid state.

For example, to recharge **1 wt. ppm** of hydrogen at room temperature in stainless steel, the material has to be in equilibrium with the gas at **7 bar**. The hydrogen pressure in air is roughly 10^{-4} mbar, which gives a maximum recharging of about 2.10^{-4} wt. ppm.

Outgassing of hydrogen: effect of bakeout

For **copper and aluminium alloys**, a few bakeout at 150-200°C for 24 hours are sufficient to reduce the hydrogen-outgassing rate to less than 10^{-13} mbar l s^{-1} cm^{-2}.

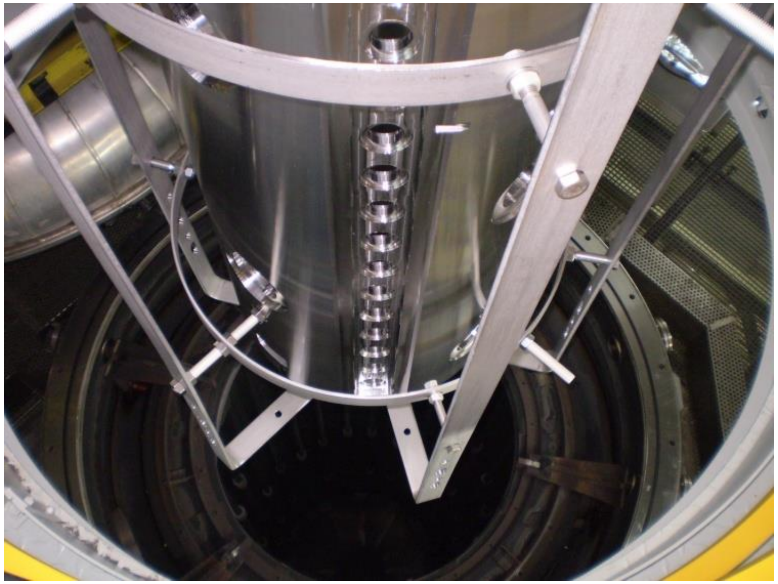
For **austenitic stainless steel**, higher temperatures are needed to have a similar effect for a few-mm-thick vacuum chambers. Repeated bakeout at temperature higher than 200°C may have a significant influence.

Materials	**Bakeout T[°C] x 24 h**	**q [mbar l s^{-1} cm^{-2}]**
Austenitic st. steel	150	$3\ 10^{-12}$
Austenitic st. steel	200	$2\ 10^{-12}$
Austenitic st. steel	300	$5\ 10^{-13}$
Copper Silver added (OFS)	150	$3\ 10^{-12}$
Copper Silver added (OFS)	200	$\approx 10^{-14}$
Beryllium after brazing	150	$< 10^{-14}$
Al alloys	150	$< 10^{-13}$

Outgassing of hydrogen: effect of vacuum firing

For austenitic stainless steels, a radical effect is obtained by heating in a vacuum furnace to temperatures up to about 1000°C.

Such a treatment is called ‘**vacuum firing**’. At CERN, it is carried out at **950°C for 2 h**.



The **CERN’s large furnace**: useful height and diameter: 6 m and 1 m, respectively. Maximum charge weight: 1000 Kg. Ultimate pressure: about 10^{-7} mbar; pressure at the end of the 950°Cx2h treatments: 10^{-5}mbar.

Outgassing of hydrogen: effect of vacuum firing

- ***T* < 500°C**

  H atom diffusion in austenite is too slow

- ***500°C (600°C)< T < 900°C*** (depending on the steel grade)

  carbide and carbo-nitride precipitation

  residual δ-ferrite transformation into σ- phase (very brittle)

- ***T > 1050°C***

  Solution annealing, abnormal grain growth, recrystallisation, excessive nitrogen loss

Outgassing of hydrogen: effect of vacuum firing

Thermal treatment	Outgassing rate [mbar l s^{-1} cm^{-2}]	Comment
200°C x 24 h	2×10^{-12}	
300°C x 24 h (*)	5×10^{-13}	1.5 mm thick
Vacuum firing(*)	**≈ 5×10^{-15}**	950°C x 2 h $P_{H2}=2 \times 10^{-5}$ mbar 1.5-mm-thick slabs

(*) J-P Bojon, N. Hilleret, B. Versolatto

H_2 outgassing value for vacuum-fired beam pipes assumed for **design of vacuum systems** in the ISR era : **2×10^{-13}** mbar l s^{-1} cm^{-2}.

Outgassing of hydrogen: effect of vacuum firing

Modification of mechanical and metallurgical properties after vacuum firing

Hardness HB (ISO 6506)

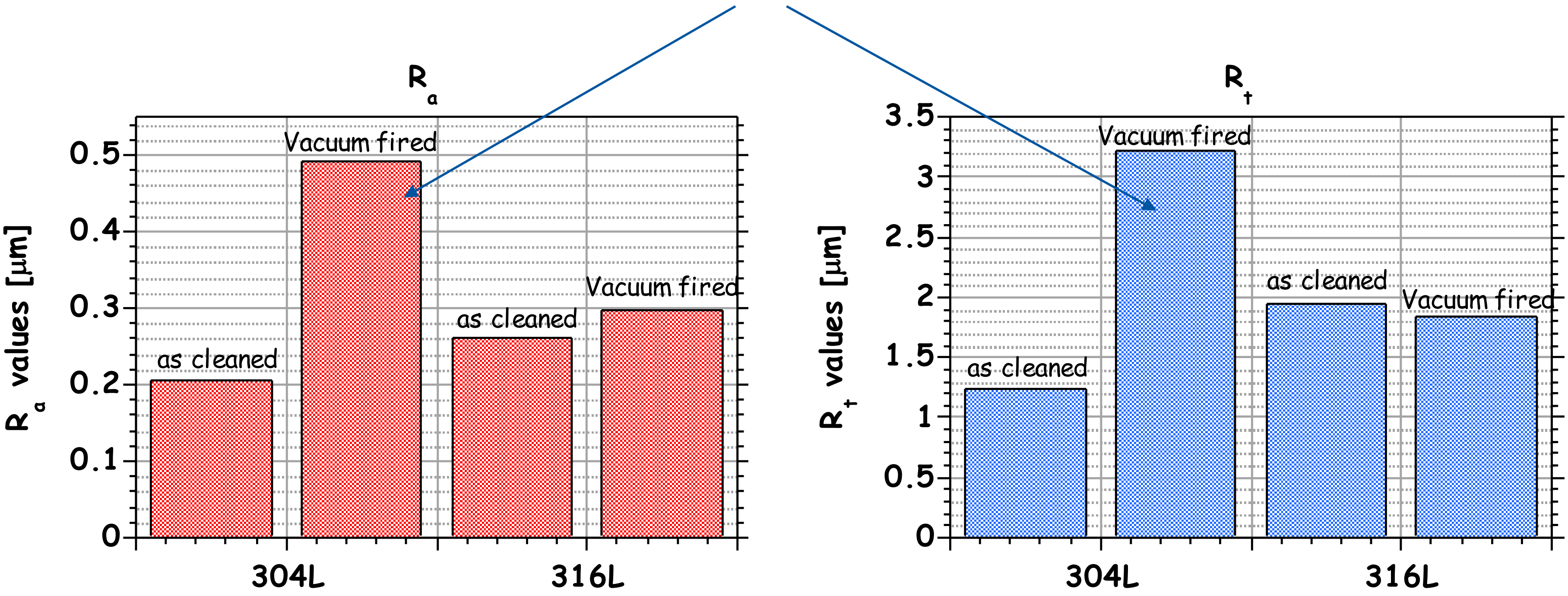
	As received	Fired 950° C
304L (UHV use)	150	128
316LN	155	151

No additional precipitates have been detected after vacuum firing at 950° C

No significant variation of ”rupture strength” and “stretch at break”: less than 5%

Outgassing of hydrogen: effect of vacuum firing

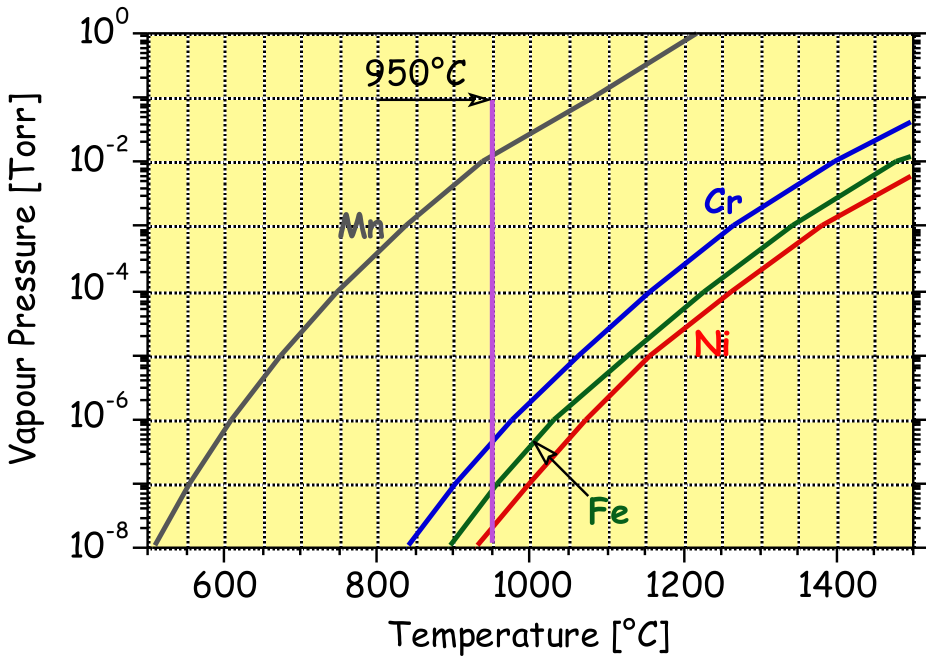
Modification of the surface roughness induced by vacuum firing


recrystallization

Outgassing of hydrogen: effect of vacuum firing

Sublimation of metallic elements during vacuum firing

Vapor pressure of the pure elements



Diffusion coefficients at 950°C in austenite:

[R.K. Wild, Corrosion Science, 14(1974)575]
[A.F. Smith, R. Hales, Metals Science Journal, 9(1975)181]

$D_{Cr} = 7 \times 10^{-15}$ cm^2 s^{-1}

$D_{Mn} = 6 \times 10^{-15}$ cm^2 s^{-1}

$D_{Fe} = 2 \times 10^{-15}$ cm^2 s^{-1}

$D_{Ni} = 5 \times 10^{-16}$ cm^2 s^{-1}

- **After vacuum firing** the oxide layer is **strongly enriched with Fe**: Cr/Fe= 0.33 for 316L and 0.22 for 304L (0.75 for cleaned); oxide thickness as for cleaned.
- Cr2p$^{2/3}$ and O1s lines indicate the presence of **less hydroxides** than on cleaned samples (Cr_2O_3 and Fe_2O_3)

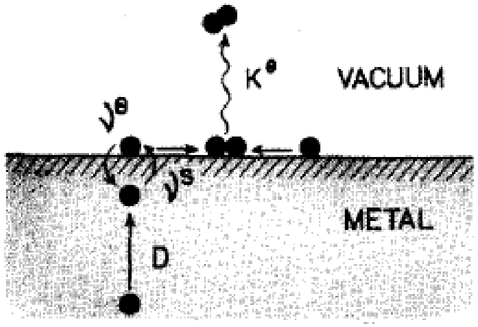
J. Gavillet and M. Taborelli, unpublished results

Outgassing of hydrogen: effect of vacuum firing

BN surface segregation

- At temperature higher than 700°C, boron segregates to the surface and, in N added stainless steels (316LN), can form h-BN. Heating temperatures higher than 1150°C are needed to dissolve the h-BN layer.
- BN does not form for B concentration lower than 9 ppm.
- When the concentration is equal or larger than 9 ppm BN forms only when B is free to move, namely not blocked in BN precipitates already existing in the steel bulk.
- The BN layer strongly reduces the surface wettability and may produce peel-off of thin film coatings.
- The BN layer can be effectively removed by electropolishing.

Theory of hydrogen outgassing: two models

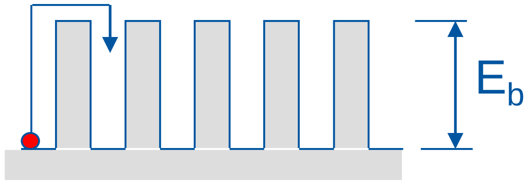


Two limiting mechanisms are considered:

1. diffusion limited outgassing→ $q(t) \propto -\frac{\partial c}{\partial x}$
2. recombination limited outgassing→ $q(t) \propto (c_w)^2$

Theory of hydrogen outgassing: diffusion

Diffusion, in most of the cases of interest, is described by the **Fick's equations**:



$$D(T) = D_0 \cdot e^{-\frac{E_b}{k_B T}}$$

$$-D\frac{\partial c(x,t)}{\partial x} = \Gamma(x,t)$$

$$D\frac{\partial^2 c(x,t)}{\partial x^2} = \frac{\partial c(x,t)}{\partial t}$$

where c(x,t) is the concentration in the solid and Γ is the flow of molecules per cm^2

In the limit of this model, the outgassing rate is equal to a half of the flux of atoms arriving at the surface by diffusion (2 H atoms = 1 H_2 molecule):

$$\boxed{q(t) = -\frac{1}{2}D\frac{\partial c(x,t)}{\partial x}\bigg|_{x=SURF.}}$$

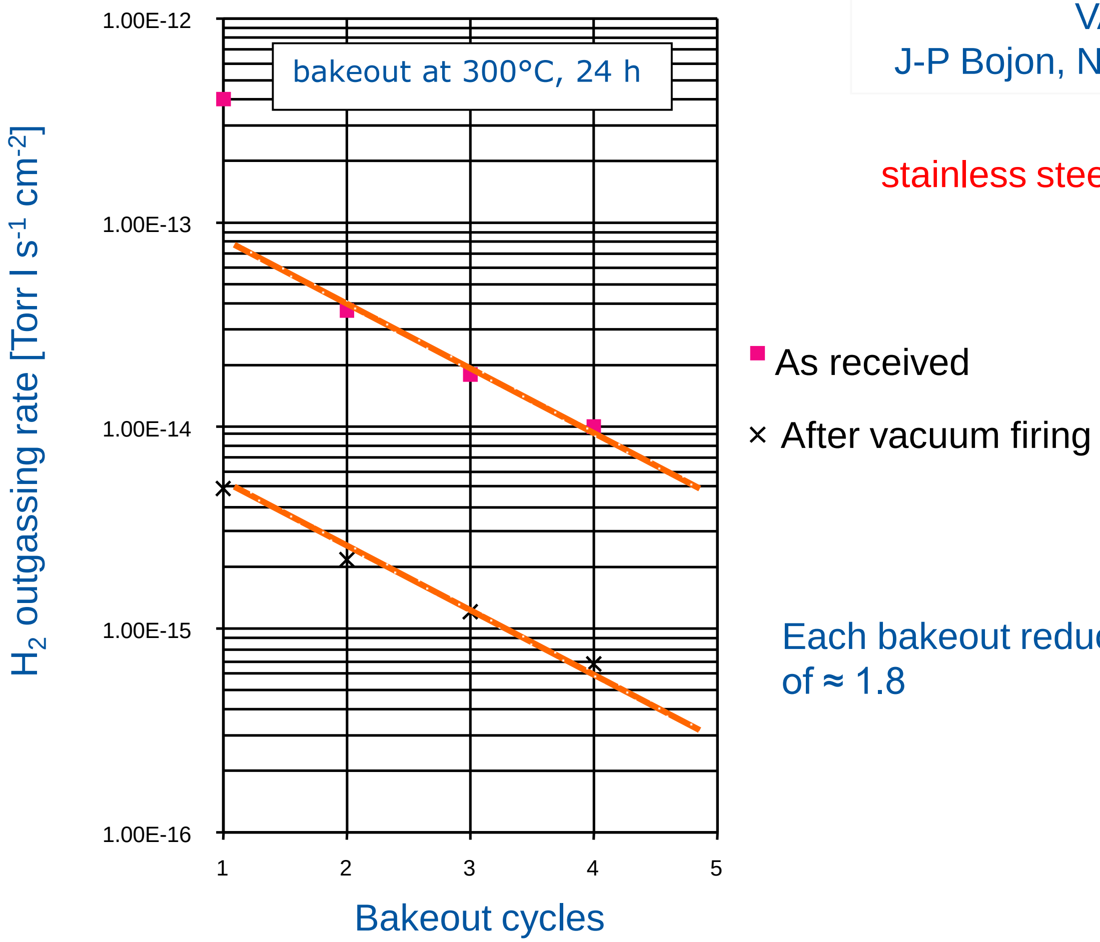
Theory of outgassing: diffusion of dissolved gas

Diffusion model of H_2 outgassing: slab approximation

Case study 1:

316 LN Stainless steel: CERN AT-VAC int. note
J-P Bojon, N. Hilleret, B. Versolatto

stainless steel sheets 1.5-mm thick



Each bakeout reduces the outgassing rate by a factor of ≈ 1.8

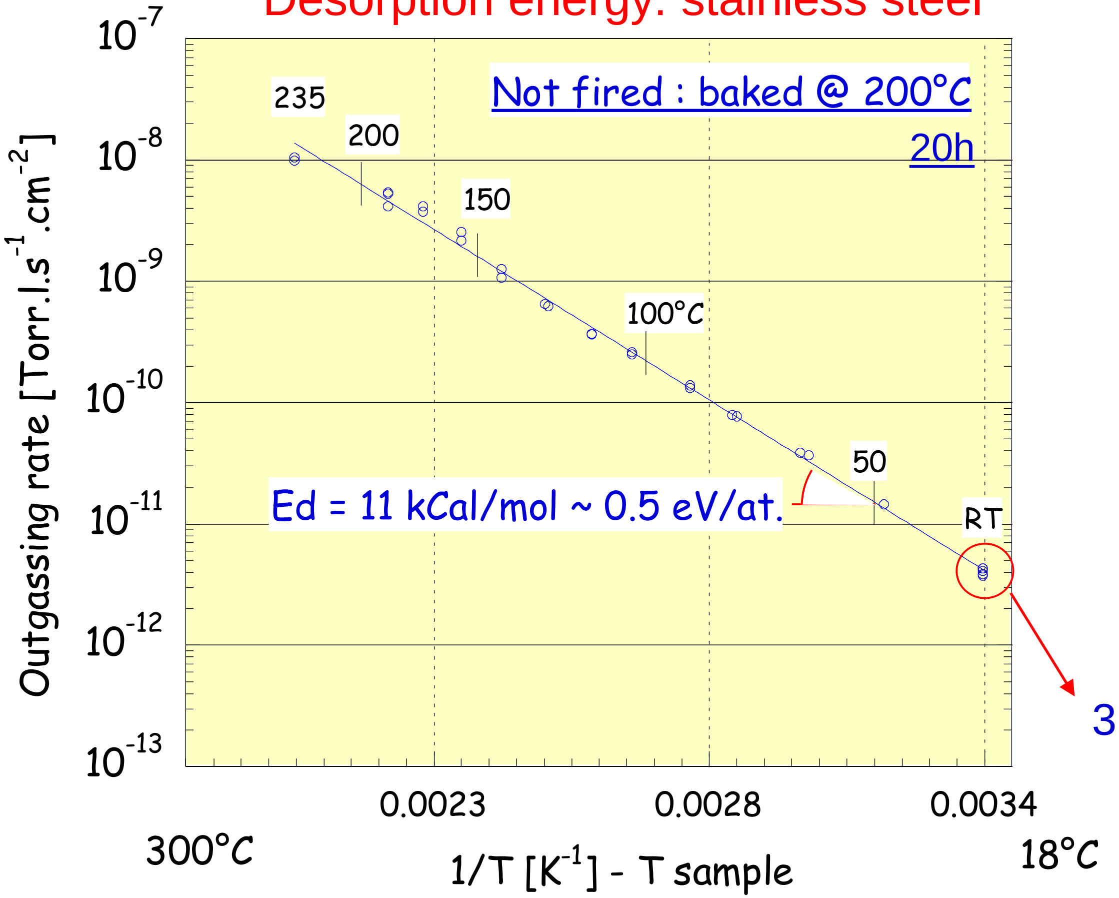
Theory of outgassing: diffusion of dissolved gas

Diffusion model of H_2 outgassing: slab approximation

Case of study 2:

Stainless steel: CERN unpublished results (Géraldine Chuste)

Desorption energy: stainless steel



3. 10^{-12} Torr.l.s^{-1}.cm^{-2}

Vacuum pipe dimensions

Length	200 cm
Diameter	3.4 cm
Thickness	2 mm

Literature:

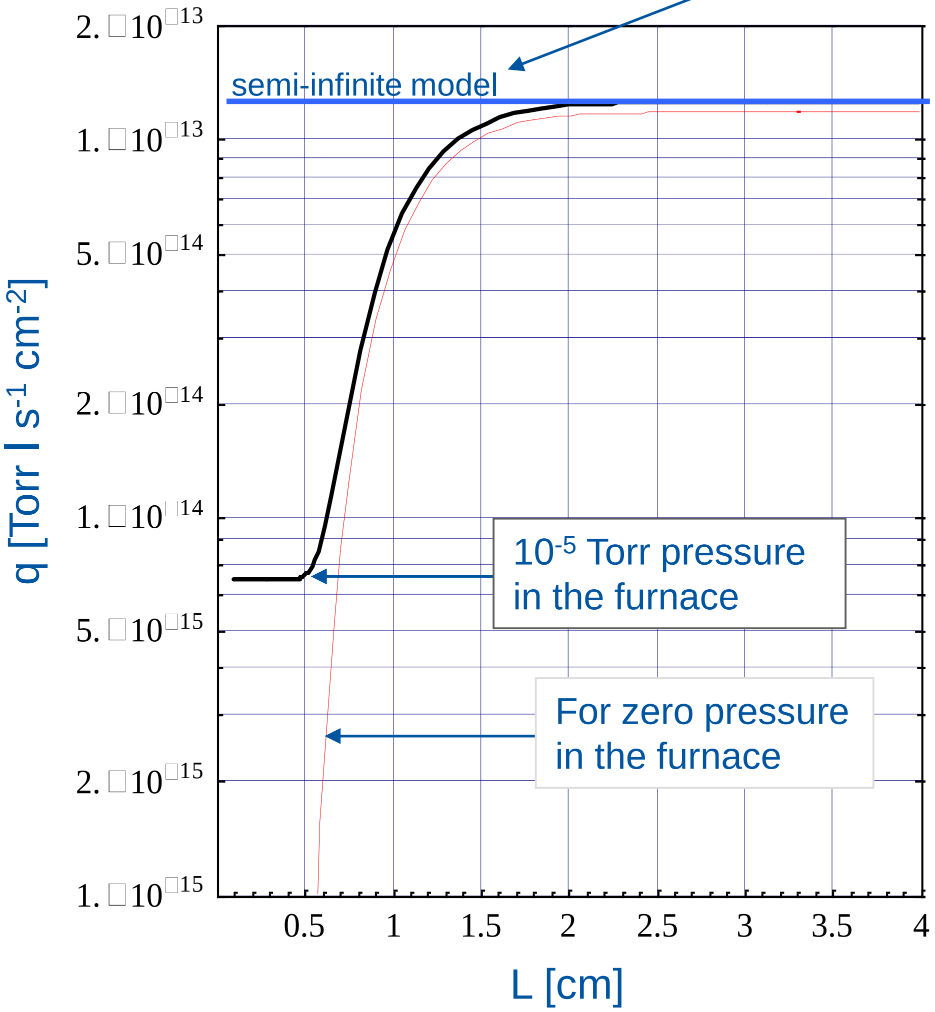
0.5 eV/ at. ≈ diffusion energy of hydrogen in austenitic stainless steel

OK!

Theory of outgassing: diffusion of dissolved gas

Case of study 3:

$$\frac{D(T)\cdot c_0}{\sqrt{\pi\cdot\left(D(T_f)t_f + D(T_{bo})t_{bo}\right)}}$$



10^{-5} Torr pressure in the furnace

For zero pressure in the furnace

Vacuum firing

Parameters	Symbol	Values
Temperature of the firing treatment	T_f	950°C
Duration of the firing treatment	t_f	2 hours
In situ bakeout temperature	T_{bo}	150°C
Duration of the in situ bakeout	t_{bo}	24 hours
Initial content of residual hydrogen	c_o	1 ppm wt (≈50 ppm at.)
Hydrogen equilibrium concentration on slab surfaces during firing	c_w	0.06 ppm wt. Equivalent to P_{H2}=1.3x10^{-5} mbar

Theory of outgassing: diffusion of dissolved gas

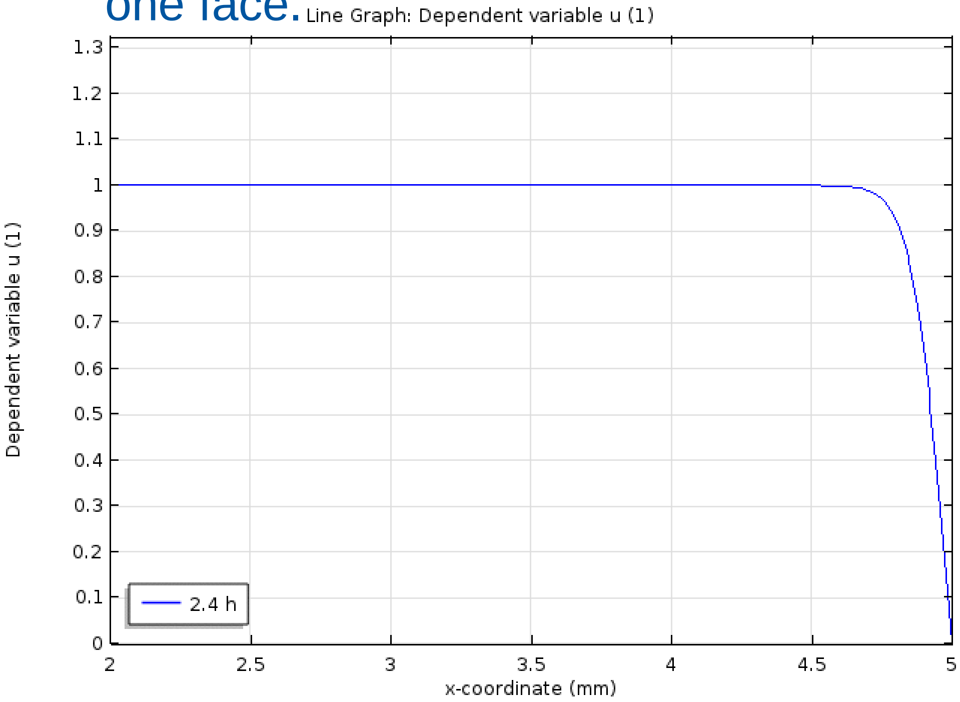
Case of study 4:

Water in polymers

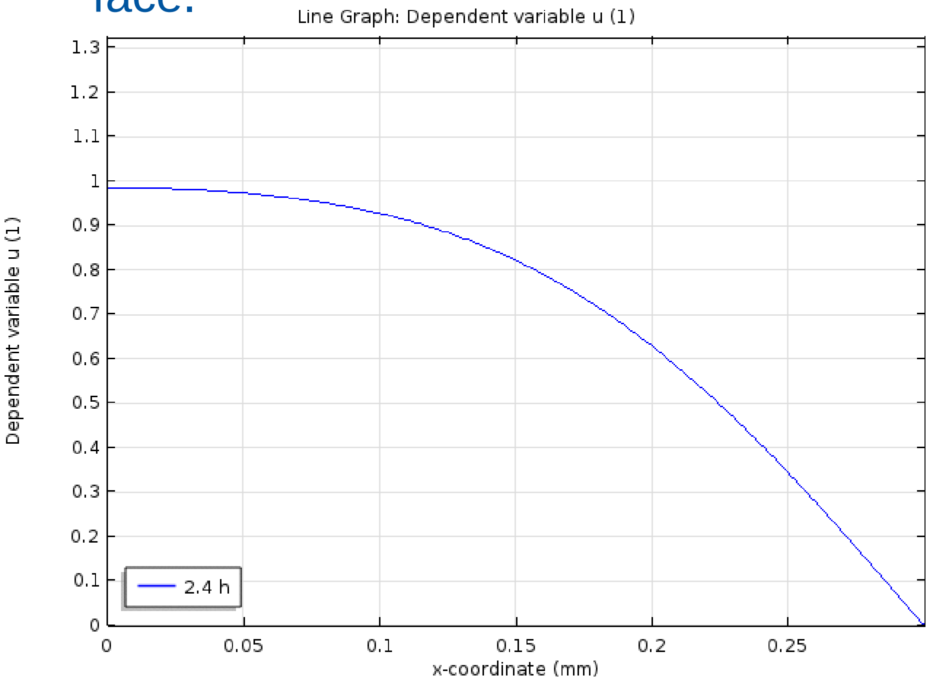
Chosen value for diffusivity of water molecules in polyimide:

$$D_{H_2O} \cong 10^{-9}\ \frac{cm^2}{s}$$

Thick Kapton slab; impermeable in one face.



Thin Kapton slab; impermeable in one face.



Outgassing databases: be attentive!

Ti 6Al 4V ?

Google: ‘outgassing vacuum materials’

Princeton Plasma Physics Lab

http://ncsx.pppl.gov/NCSX_Engineering/Materials/VacuumMaterials/Outgassing_Data.pdf

Fermi National Accelerator Laboratory

http://lss.fnal.gov/archive/tm/TM-1615.pdf

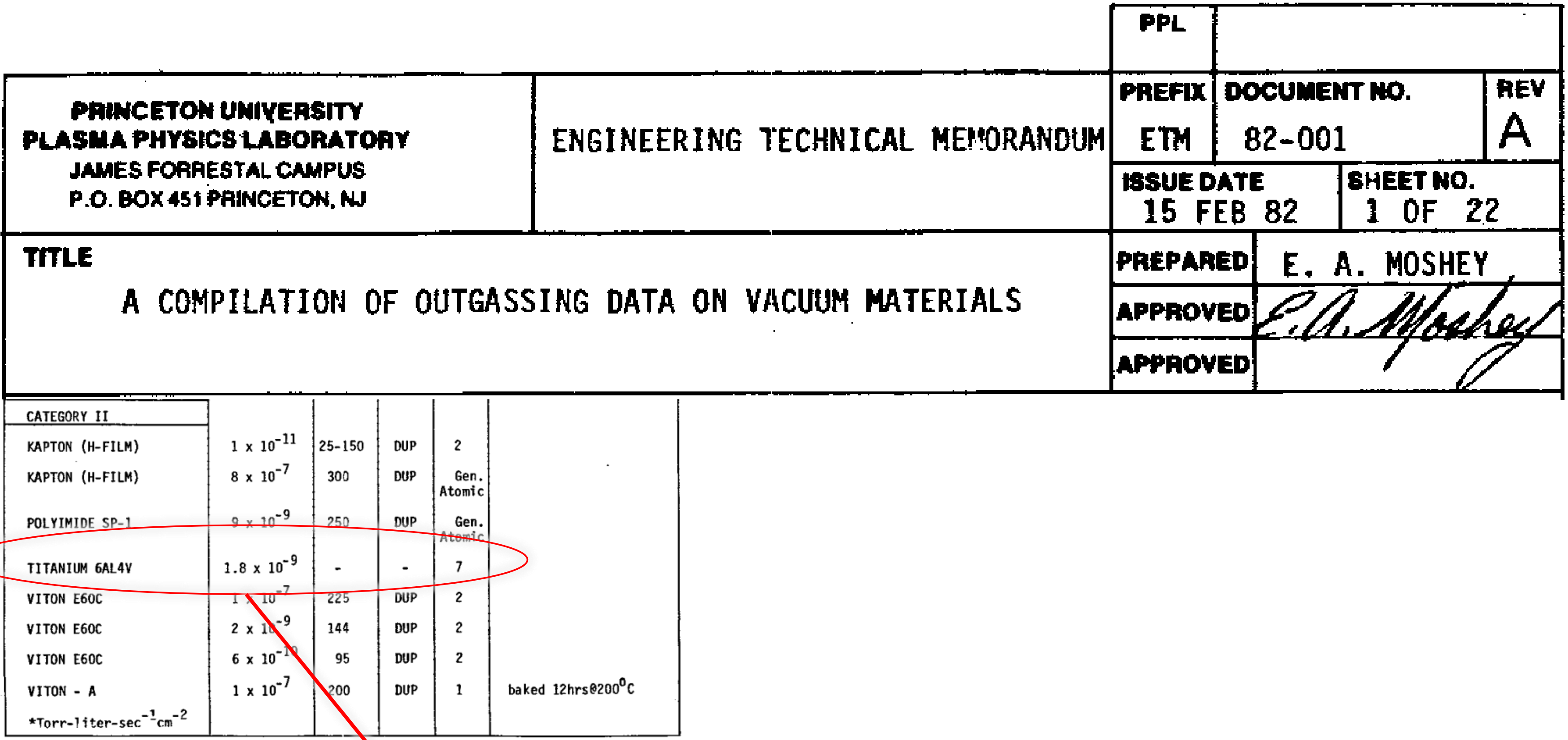
http://home.fnal.gov/~mlwong/outgas_rev.htm#ss

NASA

https://outgassing.nasa.gov/

Vacom

https://www.vacom.de/en/downloads/white-papers?download=3024:outgassing-rates-of-aluminum-compared-to-stainless-steel



PPL	

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ENGINEERING TECHNICAL MEMORANDUM

PREFIX	ETM
DOCUMENT NO.	82-001
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PREPARED	E. A. MOSHEY
APPROVED	E.A. Moshey
APPROVED	

TITLE

A COMPILATION OF OUTGASSING DATA ON VACUUM MATERIALS

CATEGORY II					
KAPTON (H-FILM)	1×10^{-11}	25-150	DUP	2	
KAPTON (H-FILM)	8×10^{-7}	300	DUP	Gen. Atomic	
POLYIMIDE SP-1	9×10^{-9}	250	DUP	Gen. Atomic	
TITANIUM 6AL4V	1.8×10^{-9}	-	-	7	
VITON E60C	1×10^{-7}	225	DUP	2	
VITON E60C	2×10^{-9}	144	DUP	2	
VITON E60C	6×10^{-10}	95	DUP	2	
VITON - A	1×10^{-7}	200	DUP	1	baked 12hrs@200°C
*Torr-liter-sec^{-1}cm^{-2}					

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Space environment and vacuum properties of spacecraft materials

T J Patrick, *University College London, Mullard Space Science Laboratory, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK*

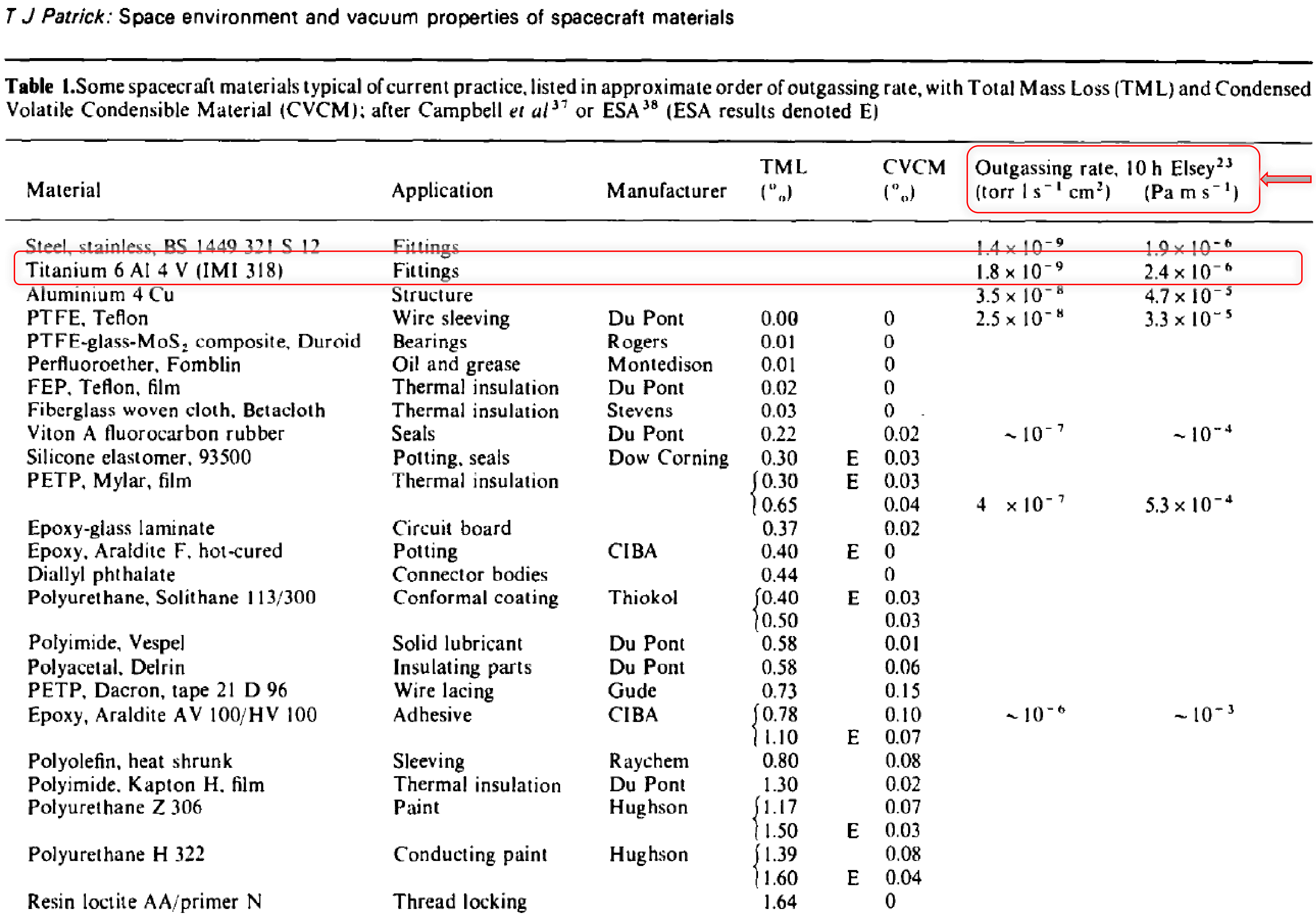

Table 1. Some spacecraft materials typical of current practice, listed in approximate order of outgassing rate, with Total Mass Loss (TML) and Condensed Volatile Condensible Material (CVCM); after Campbell *et al*[37] or ESA[38] (ESA results denoted E)

Material	Application	Manufacturer	TML (%)		CVCM (%)	Outgassing rate, 10 h Elsey[23] (torr l s^{-1} cm^{-2})	(Pa m s^{-1})
Steel, stainless, BS 1449 321 S 12	Fittings					1.4×10^{-9}	1.9×10^{-6}
Titanium 6 Al 4 V (IMI 318)	Fittings					1.8×10^{-9}	2.4×10^{-6}
Aluminium 4 Cu	Structure					3.5×10^{-8}	4.7×10^{-5}
PTFE, Teflon	Wire sleeving	Du Pont	0.00		0	2.5×10^{-8}	3.3×10^{-5}
PTFE-glass-MoS_2 composite, Duroid	Bearings	Rogers	0.01		0		
Perfluoroether, Fomblin	Oil and grease	Montedison	0.01		0		
FEP, Teflon, film	Thermal insulation	Du Pont	0.02		0		
Fiberglass woven cloth, Betacloth	Thermal insulation	Stevens	0.03		0		
Viton A fluorocarbon rubber	Seals	Du Pont	0.22		0.02	$\sim 10^{-7}$	$\sim 10^{-4}$
Silicone elastomer, 93500	Potting, seals	Dow Corning	0.30	E	0.03		
PETP, Mylar, film	Thermal insulation		0.30	E	0.03		
			0.65		0.04	4×10^{-7}	5.3×10^{-4}
Epoxy-glass laminate	Circuit board		0.37		0.02		
Epoxy, Araldite F, hot-cured	Potting	CIBA	0.40	E	0		
Diallyl phthalate	Connector bodies		0.44		0		
Polyurethane, Solithane 113/300	Conformal coating	Thiokol	0.40	E	0.03		
			0.50		0.03		
Polyimide, Vespel	Solid lubricant	Du Pont	0.58		0.01		
Polyacetal, Delrin	Insulating parts	Du Pont	0.58		0.06		
PETP, Dacron, tape 21 D 96	Wire lacing	Gude	0.73		0.15		
Epoxy, Araldite AV 100/HV 100	Adhesive	CIBA	0.78		0.10	$\sim 10^{-6}$	$\sim 10^{-3}$
			1.10	E	0.07		
Polyolefin, heat shrunk	Sleeving	Raychem	0.80		0.08		
Polyimide, Kapton H, film	Thermal insulation	Du Pont	1.30		0.02		
Polyurethane Z 306	Paint	Hughson	1.17		0.07		
			1.50	E	0.03		
Polyurethane H 322	Conducting paint	Hughson	1.39		0.08		
			1.60	E	0.04		
Resin loctite AA/primer N	Thread locking		1.64		0		

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Outgassing of vacuum materials—II

R J Elsey, *The Rutherford Laboratory, Chilton, England*

A paper in our Education Series: The Theory and Practice of Vacuum Science and Technology in Schools and Colleges.

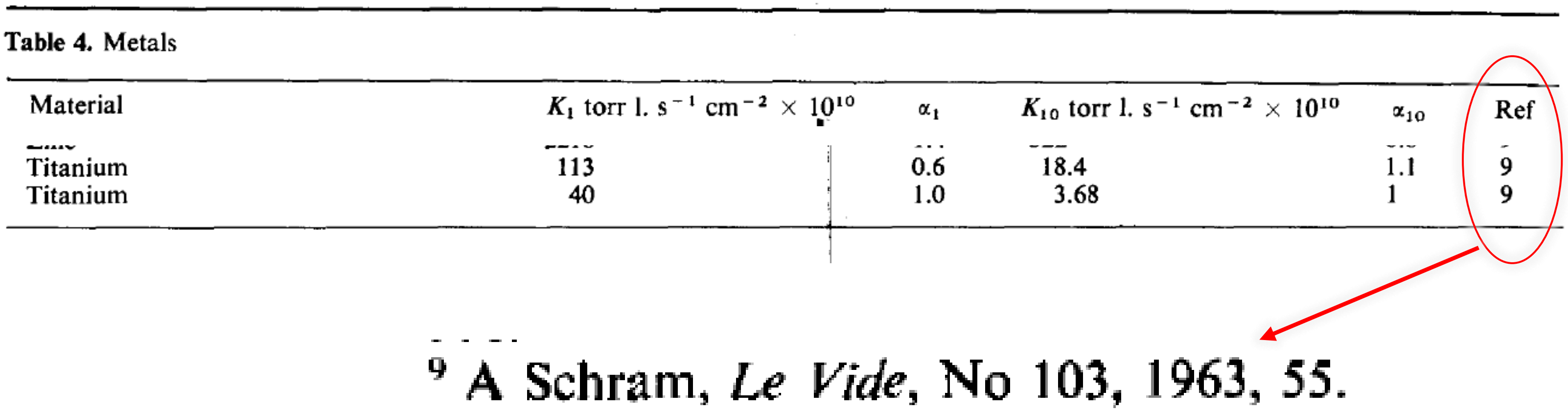
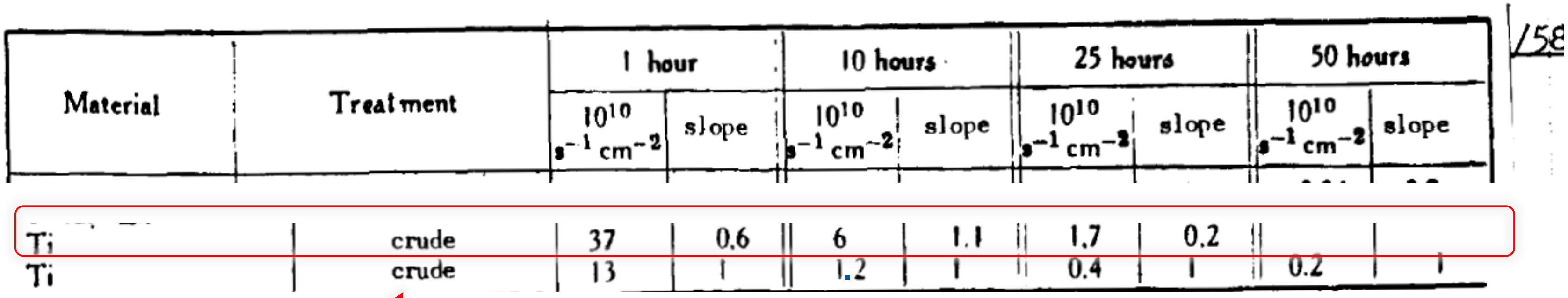


Table 4. Metals

Material	K_1 torr l. s^{-1} cm^{-2} × 10^{10}	α_1	K_{10} torr l. s^{-1} cm^{-2} × 10^{10}	α_{10}	Ref
Titanium	113	0.6	18.4	1.1	9
Titanium	40	1.0	3.68	1	9

[9] A Schram, *Le Vide*, No 103, 1963, 55.



/58

Material	Treatment	1 hour		10 hours		25 hours		50 hours	
		10^{10} s^{-1} cm^{-2}	slope	10^{10} s^{-1} cm^{-2}	slope	10^{10} s^{-1} cm^{-2}	slope	10^{10} s^{-1} cm^{-2}	slope
Ti	crude	37	0.6	6	1.1	1.7	0.2		
Ti	crude	13	1	1.2	1	0.4	1	0.2	1

?

1963	1975	1981	1982
A Schram, Le Vide	R J Elsey, Vacuum	T J Patrick, Vacuum	Princeton data base
Ti, crude, 2 values	Ti, ~~crude~~, 2 values	~~Ti~~ **Ti6Al4V**, ~~crude~~, ~~2~~ **1** values	~~Ti~~ **Ti6Al4V**, ~~crude~~, ~~2~~ **1** values

Conclusions

Outgassing rates depends on **materials and treatments**.

For **unbaked metals**, **water vapour is the leading outgassed** molecule. Its outgassing rate is **inversely proportional to the pumping time**. It is not strongly dependent on treatment and grade. Venting to air cancel the effect of previous gas release,

Multi-energy adsorption models explain the pressure decrease.

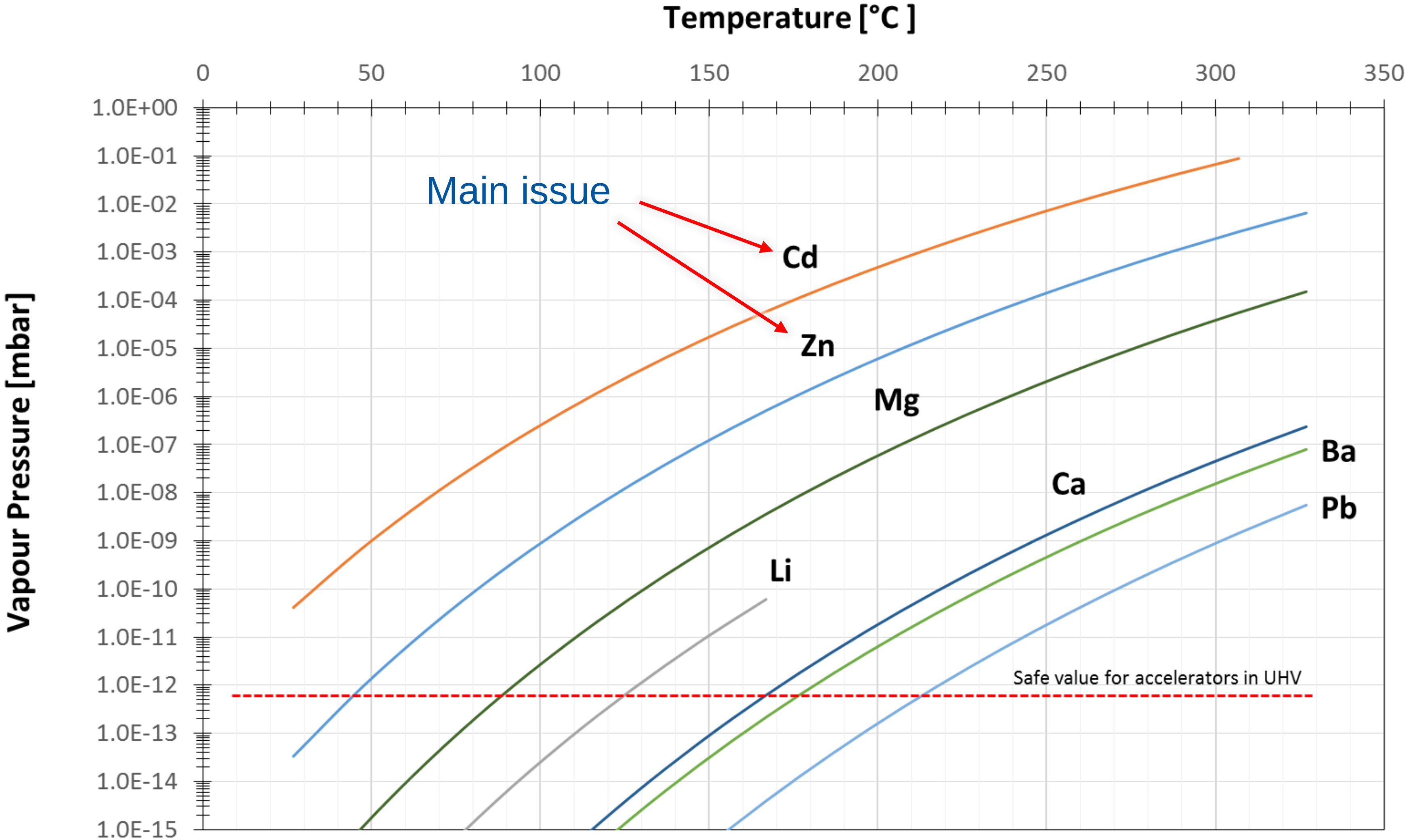
For **baked metals**, the outgassing process is **dominated by hydrogen**. It depends on the nature of the material and, **strongly, on the applied thermal treatment**. **Venting to air does not recharge hydrogen** into solid metal used for vacuum chambers.

Diffusion theory explains the measured data and is predictive for hydrogen content and wall thicknesses generally used for particle accelerators.

Organic materials absorb and release much more gas than metals; their gas release rate is higher and lasts longer than metallic alloys. **Avoid any polymer** (if you can)!

Thanks for your attention

Vapour pressure of pure metals



https://www.iap.tuwien.ac.at/www/surface/vapor_pressure

Reminder: Units of gas quantity

- The quantity of gas can be presented in number of molecules (N) or in pressure-volume (PV) units.
- The two values are related by the ideal gas equation of state:

$$P \cdot V = N \cdot k_B \cdot T \rightarrow N = \frac{P \cdot V}{k_B \cdot T}$$

- The pressure-volume units are transformed to number of molecules when divided by $k_B T$.
- The same number of molecules is expressed by different pressure-volume values at different temperatures. In general, the pressure-volume quantities are quoted at room temperature: 296 K.

$$k_B = 1.38 \cdot 10^{-23} \left[\frac{N \cdot m}{K} = \frac{Pa \cdot m^3}{K} \right]$$

$$k_B = 1.38 \cdot 10^{-23} \left[\frac{Pa \cdot m^3}{K} \right] = 1.04 \cdot 10^{-22} \left[\frac{Torr \cdot \ell}{K} \right] = 1.38 \cdot 10^{-22} \left[\frac{mbar \cdot \ell}{K} \right]$$

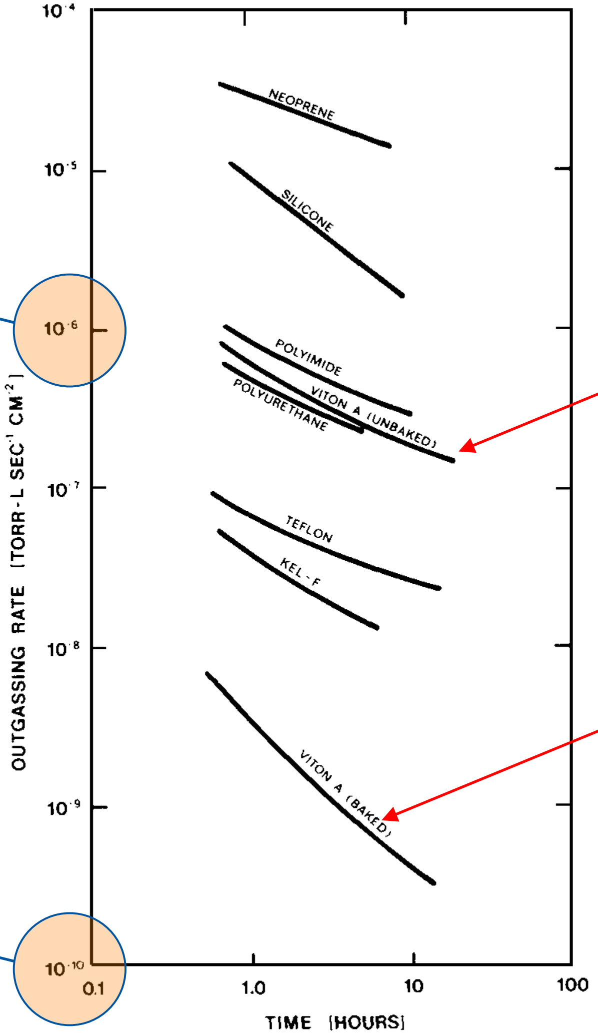
$$\text{for } T = T_{RT} = 296 \text{ K}$$

$$\frac{1}{k_B T_{RT}} = 2.45 \cdot 10^{20} \left[Pa \cdot m^3 \right]^{-1} = 3.3 \cdot 10^{19} \left[Torr \cdot \ell \right]^{-1} = 2.5 \cdot 10^{19} \left[mbar \cdot \ell \right]^{-1}$$

Outgassing of polymers

Outgassing rate of water vapour for polymers

R. N. Peacock, J. Vac. Sci. Technol., 17(1), p.330, 1980



10^{-6}

10^{-10}

unbaked Viton

baked Viton