VACUUM SYSTEM DESIGN AND MAINTENANCE

SESSION VI
APPLICATION OF VACUUM SYSTEM DESIGN: SCOPING A PROJECT AND PRACTICAL CONSIDERATIONS

14TH JUNE 2018

EDWARDS

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OVERVIEW

With a foundation gained in vacuum physics, materials, pumps, gauges and associated equipment we naturally seek to apply this to the development of a new system or perhaps optimisation of a current system. This can be very challenging as there are many issues and factors which must be considered and addressed; each with a different ‘weighting’ dependent upon the individual project’s objectives and specifications.

In this session we will discuss design considerations and system modelling techniques which range from simple manual calculations to highly complex computerised software.

Examples from a range of vacuum applications sectors will be used for illustration culminating in a class exercise

CONTENTS

VI – Vacuum system design – practice project

- What the system for? What Specification?
- Initial consideration on vacuum system layout
- Modelling
- Conclusions (type of pumps, pumping speed of each)

1. **General Considerations (~1.5 hours)**

- Conceptual design
- Safety – safety manual(s), exhaust pressure restrictions, transients, ‘Trace’ elements, ATEX etc.
- Modelling – first principles and software. Other modelling FEA, stress etc.
- System Examples

2. **Practical - work groups (~45 mins)**

3. **Short presentations – discussion (~45 mins)**

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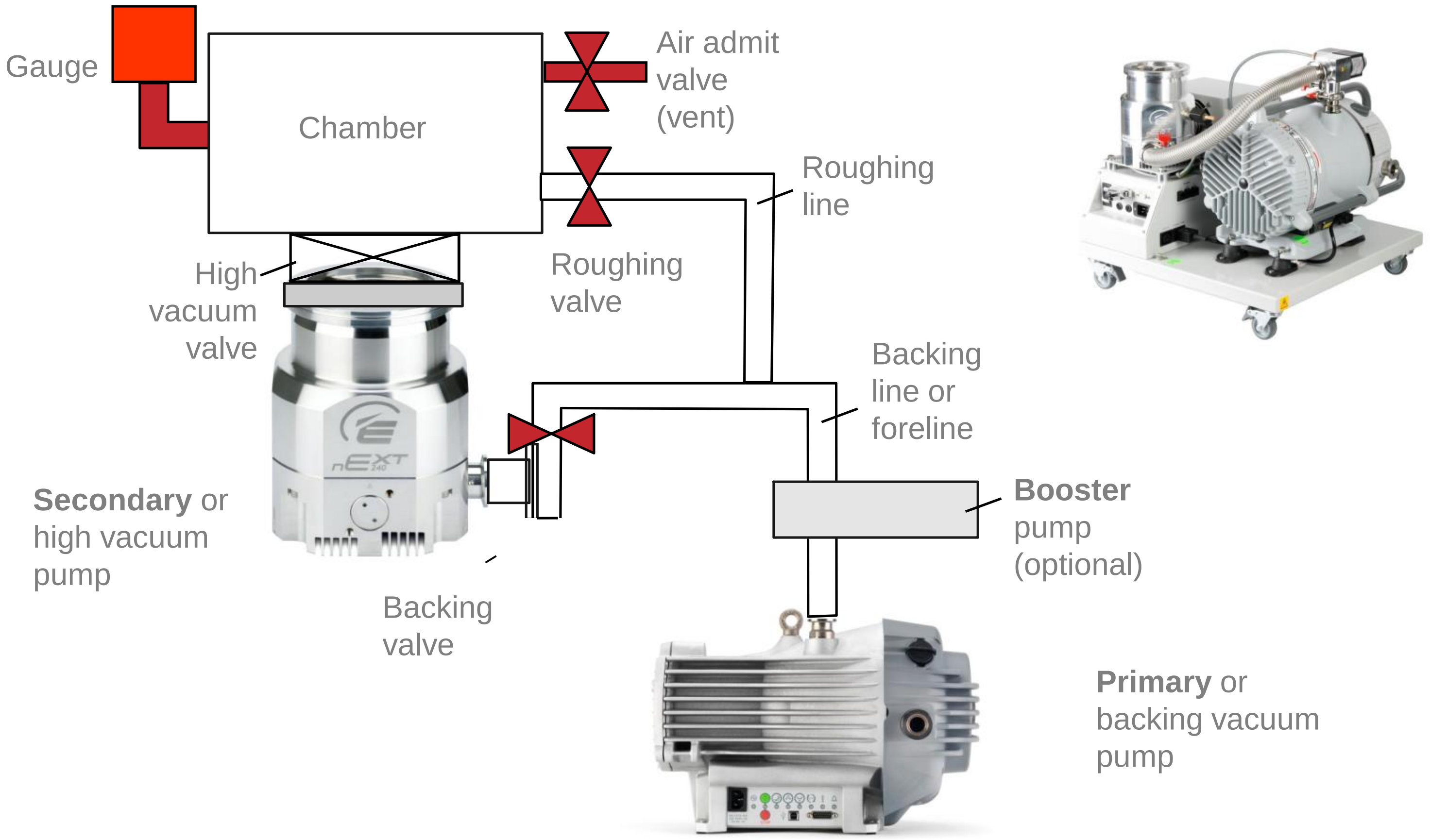
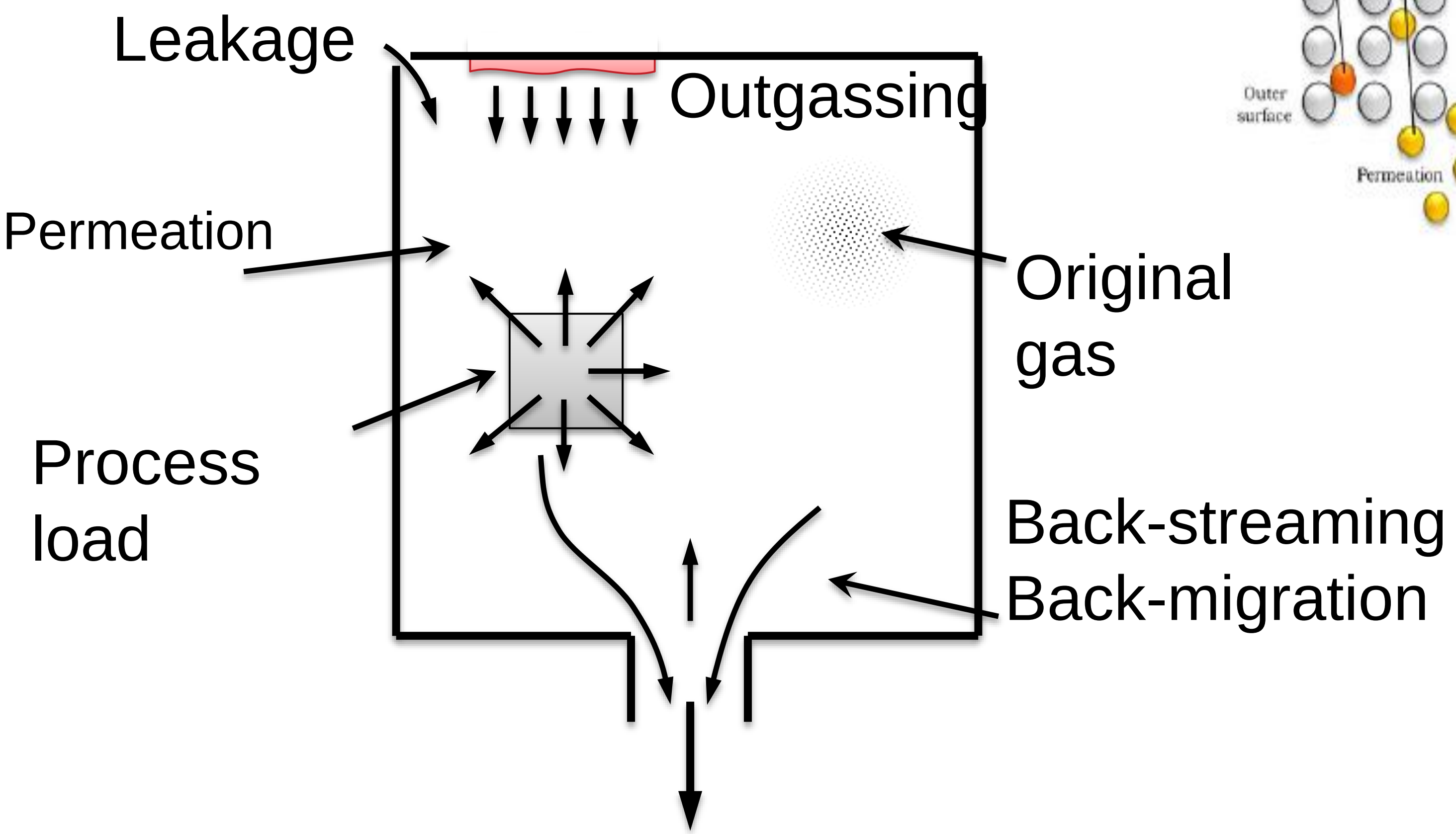
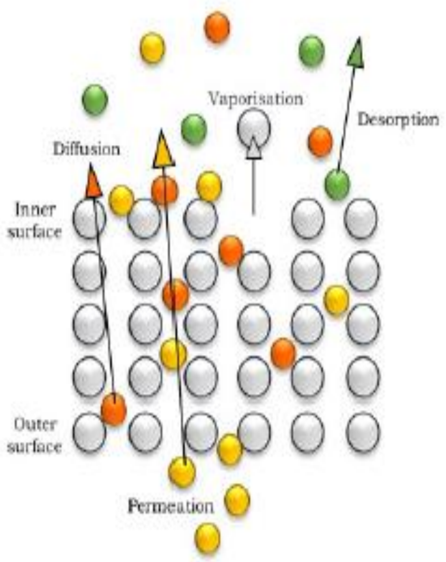
SYSTEM TERMINOLOGY



SOURCES OF GAS IN VACUUM





Process Gas Load is the gas added to the chamber from its process application: if present it is normally the dominant load;

Other sources are seen as 'contamination'

Leakage is external gas entering the system through fabrication or sealing defects

Back-streaming/back-migration is the movement of contaminants from the pump and fore-line into the chamber

Outgassing is the gradual release of gas from chamber walls and surfaces (includes surface material vapourisation)

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PUMPED CHAMBERS - SOURCES OF ‘FREE’ GAS

Many sources of gas and vapour molecules including:

- initial venting (gas onto surfaces and in volume)
- leaks (porosity and construction defects)
- pump inefficiencies (back-streaming, back-migration, Compression Ratio)
- process effects (usually temperature related)
- materials’ vapour pressure
- permeation
- outgassing
- trapped volumes

THE PUMP-DOWN 'RATE EQUATION'

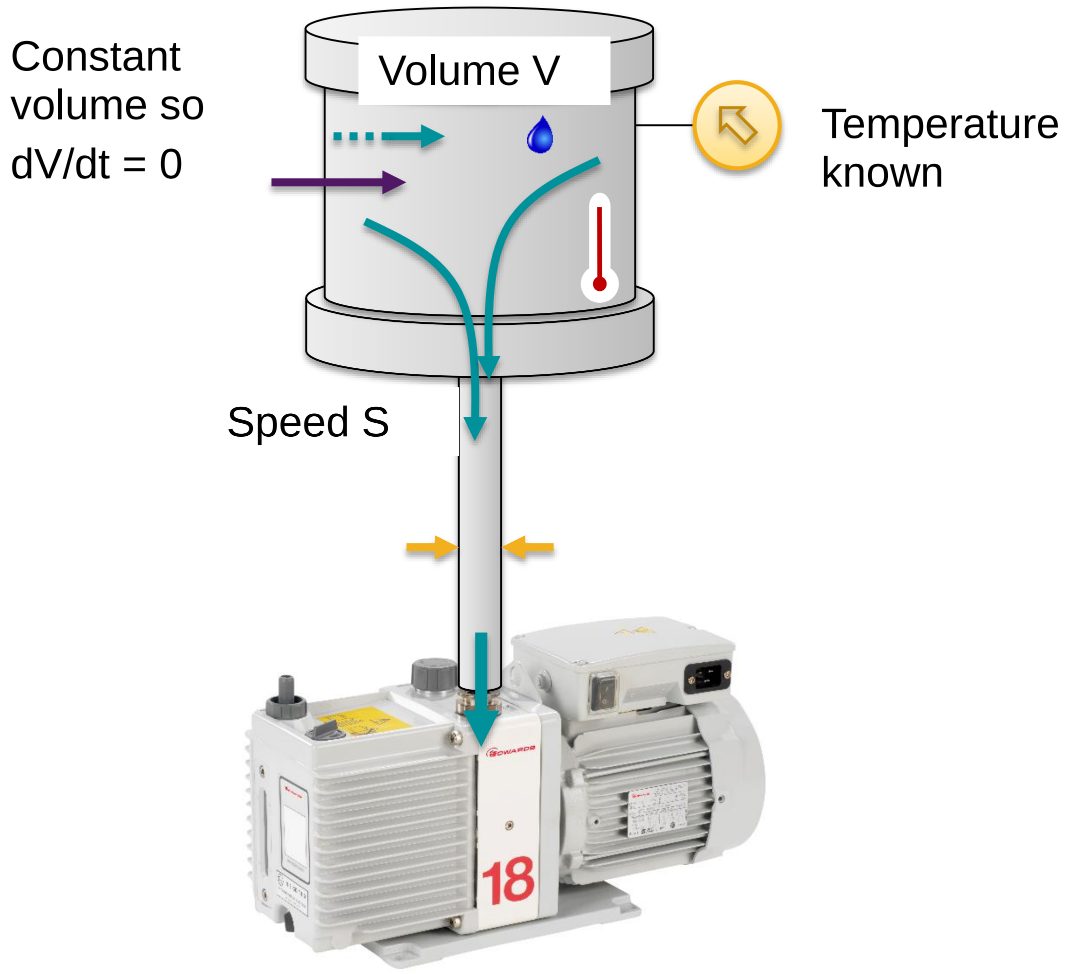
Conserving throughput

$$\frac{d(PV)}{dt} = -V\frac{dP}{dt} = PS$$

$$-V\frac{dP}{dt} = P \cdot S$$

$$\int \frac{dP}{P} = \frac{-S}{V}\int dt$$

This solves as: $P = P_1 e^{-\frac{S}{V}t}$



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PUMPDOWN TIMES

If we have a chamber pumped by a constant speed pump, the time to go from pressure P_1 to P_2

$$t = \frac{V}{S} ln\left(\frac{P_1}{P_2}\right)$$

$$t = 2.3\frac{V}{S}\log_{10}\left(\frac{P_1}{P_2}\right)$$

Rearranging for S

$$S = 2.3\frac{V}{t}\log_{10}\left(\frac{P_1}{P_2}\right)$$

System time constant τ = V/S this is an exponential fall where in time t = t pressure reduces by x 1/e

This is also applicable when a stable equilibrium is perturbed by a an increased gas load – e.g. a gas burst, reference leak, process valve open etc.

Equilibrium restored in 3 or 4 x τ

PUMP-DOWN TIMES: EXAMPLE

What would be the pump-down time of chamber of 1 m^3 from 1,000 mbar to 10 mbar using a dry pump of 50 m^3/h (assuming constant speed in this pressure range)

$t = 1/50 \times \ln(1000/10)$

$= 0.09$ hours ~ 6 mins

LIMITS TO FINAL PRESSURE

- Previous equation predicts the pump will achieve an ultimate pressure of $\boldsymbol{P_f}$ = 0 and will approach $\boldsymbol{P_f}$ at a steady rate
- Real systems: pump speed **S** varies with pressure as does pipework conductance also sources of gas act to replenish the free gas in volume **V** at a rate **Q**
- Assuming ***Q*** is constant, the equation for flow rate becomes:

$$SP = -V\,(dP/dt) + Q$$

LIMITS TO FINAL PRESSURE

After rearranging and integrating with respect to time then time to pump to pressure P_f from P_o

$$t = \frac{V}{S} \ln \left(\frac{P_o - Q/S}{P_f - Q/S} \right)$$

A steady contribution of gas Q into the vacuum chamber throughout the pump-down changes the ultimate pressure to $P_f = Q/S$ from unrealistic $P_f = 0$

PUMPDOWN TO LOW PRESSURE

Consider a 300 l chamber pumped from 10^{-3} mbar to 10^{-6} mbar by a 3,000 l/s turbomolecular pump

$$t = 2.3\frac{300}{3000}\log_{10}\left(\frac{10^{-3}}{10^{-6}}\right) = 0.69\ s$$

In reality it takes much, much longer!

- **OUTGASSING!**

The effect of the volume here is negligible

- < 1 s for 3 decades

Instead we simply work out when the outgassing has fallen to a level we can pump at 10^{-6} mbar

PUMPDOWN TO LOW PRESSURE

- To calculate outgassing we need an area and a rate:
  - Assume a 3 m^2 area
  - Outgassing rate of $2 \cdot 10^{-7}$ mbar.l/s/cm^2 at 1 hour, decreasing with $1/t$
    - t_{rate} = 1 hour, n = 1
- Throughput balance:

$$P \cdot S = A.\frac{q}{\left(\frac{t}{t_{rate}}\right)^n}$$

$t = 3 \cdot \frac{10^4 \cdot 2 \cdot 10^{-7}}{10^{-6} \cdot 3000}$ = 2 hours

- The time taken to get to 10^{-3} mbar is small compared to this time

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PUMPDOWN TIMES

- These formulae are a simple rough estimate
- They ignore
  - Pipework
    - We can handle this by calculating the net speed from a conductance calculation
    - Pipework volume can be significant
  - Most pumps do not have constant speed across all pressures
    - We can handle this by slicing the speed curve into roughly constant sections
  - Outgassing/leaks
    - A constant leak is easy to manage, outgassing is much harder
- It's all too hard for a hand calculation!
  - PumpCalc uses more complex and more accurate methods!

OUTGASSING

Surface outgassing at time can be determined from

$$Q_t = \frac{A \cdot Q_{1hour}}{t^n}$$

Not valid for t ~ 0

We need to know the value of n and after what time the system was under vacuum when the outgassing was measured (usually after 1 or 10 hours)

For most planar metallic surfaces *n* is ~ 1

This gives the very useful *1/t* rule that the outgassing rate will halve for every doubling of the time interval

For porous/permeable surfaces e.g. rubber, ceramic etc. *n* ~ 0.5 and outgassing reduces more slowly

Surfaces with porous surface layers e.g. rusty mild steel, n is > 1

Over a limited time period, the outgassing flow rate can be fitted to [3]:

$$\dot{Q} = \sum \frac{a_{1h} \cdot A}{(\frac{t}{1h})^{\alpha}}$$

where A is a geometrical surface term, a_{1h} is the outgassing rate after 1 hour, α is the decay constant and the sum is over all contributions from all surfaces. Values of the decay constant range from around 0.2 to 1.2 and give an indication of the type of material and outgassing mechanism.

- $\alpha \approx 1$ - desorption from surfaces
- $\alpha \approx 1$ - metals, glasses and ceramics over a wide range (1s >100h)
- $0.4 < \alpha < 0.8$ - polymers
- $\alpha \approx 0.5$ - diffusion controlled outgassing from the bulk

OUTGASSING

Appl. Sci. Converg. Technol. 26(5): 95-109 (2017)
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Review Paper

A Review of Outgassing and Methods for its Reduction

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Abstract There are several contributions to the gas load of a system of which often the most important is outgassing. Adsorption occurs via two main processes, physisorption and chemisorption, and can be described using five (or six) classifying isotherms. Outgassing is the result of desorption of previously adsorbed molecules, bulk diffusion, permeation and vapourisation. Looking at the desorption rate, pumping speed and readsorption on surfaces, the net outgassing of the system can be calculated. There is significant variation in measured outgassing rates between different materials but also between published rates for the same materials, in part due to the number of different methods used to measure outgassing. This article aims to review the outgassing process, outgassing rates, measurement methods and techniques that can be used to reduce the outgassing of a system.

Keywords: Outgassing, Materials, Surfaces, Cleanliness, Particle-free

Material	Treatment	Average of literature values for outgassing rate Torr·l·s^{-1}·cm^{-2}	Standard deviation of literature values for outgassing rate Torr·l·s^{-1}·cm^{-2}
Aluminium	Fresh	$2.22x10^{-7}$	$5.28x10^{-7}$
	Degassed (24 hr)	$8.70x10^{-8}$	N/A
	Baked (15 hr @ 250°C)	$3.99x10^{-13}$	$1.70x10^{-15}$
	Baked (20 hr @ 100°C)	$3.86x10^{-14}$	$1.59x10^{-15}$
Duraluminium		$1.49x10^{-7}$	$3.00x10^{-8}$
Iron		$2.02x10^{-7}$	$2.79x10^{-7}$
Brass	Cast	$1.10x10^{-6}$	$1.42x10^{-7}$
	Waveguide	$3.50x10^{-7}$	$7.06x10^{-8}$
Copper	Fresh	$1.76x10^{-8}$	$1.18x10^{-6}$
Copper	Mechanically polished	$2.21x10^{-8}$	$8.99x10^{-10}$
OHCF Copper	Fresh	$1.76x10^{-8}$	$3.10x10^{-9}$
OHCF Copper	Mechanically polished	$2.21x10^{-9}$	$8.99x10^{-10}$
Gold	Wire, fresh	$8.49x10^{-8}$	$1.03x10^{-7}$
Mild steel	Fresh	$4.66x10^{-7}$	$6.45x10^{-8}$
	Slightly rusty	$1.47x10^{-6}$	$1.95x10^{-6}$
	Chromium plated, polished	$9.98x10^{-9}$	N/A
	Aluminium spray coated	$5.99x10^{-8}$	$1.06x10^{-10}$
Steel	Chromium plated, fresh	$5.06x10^{-9}$	$2.98x10^{-9}$
	Chromium plated, polished	$9.08x10^{-9}$	$1.17x10^{-9}$
	Nickel plated, fresh	$3.86x10^{-9}$	$6.17x10^{-10}$
	Nickel plated	$1.33x10^{-7}$	$2.45x10^{-7}$
	Descaled	$2.69x10^{-7}$	$5.43x10^{-8}$
Molybdenum		$3.06x10^{-7}$	$3.61x10^{-7}$
Stainless steel		$2.21x10^{-7}$	$1.99x10^{-7}$
	Fresh	$1.45x10^{-8}$	$4.085x10^{-9}$
	Sanded	$8.27x10^{-9}$	$3.39x10^{-11}$
	Electropolished	$7.00x10^{-9}$	$9.30x10^{-9}$
	Mechanically polished	$4.24x10^{-9}$	$6.02x10^{-9}$
	Baked (30 hr @ 250°C)	$3.00x10^{-12}$	$4.33x10^{-16}$
Zinc		$1.93x10^{-7}$	$3.96x10^{-8}$
Titanium		$7.61x10^{-9}$	$5.14x10^{-9}$
Pyrex	Fresh	$7.42x10^{-9}$	$6.27x10^{-11}$
Neoprene		$3.00x10^{-5}$	$4.33x10^{-9}$
Polystyrene		$2.00x10^{-5}$	N/A
Plexiglas		$2.02x10^{-6}$	$1.19x10^{-6}$
Viton A	Fresh	$8.50x10^{-7}$	$4.68x10^{-7}$
	Baked	$8.00x10^{-9}$	N/A
PVC	24 hr @ 95% RH	$2.37x10^{-6}$	$2.50x10^{-6}$
Teflon/PTFE		$1.06x10^{-6}$	$1.88x10^{-6}$

Table 4: Averages and standard deviations of collected literature values for outgassing rates of various common vacuum materials after different treatments [36, 71, 72, 73, 74, 75, 76, 77, 78, 79], N/A for standard deviation indicates that only a single literature value was found for a particular material

OUTGASSING RATES

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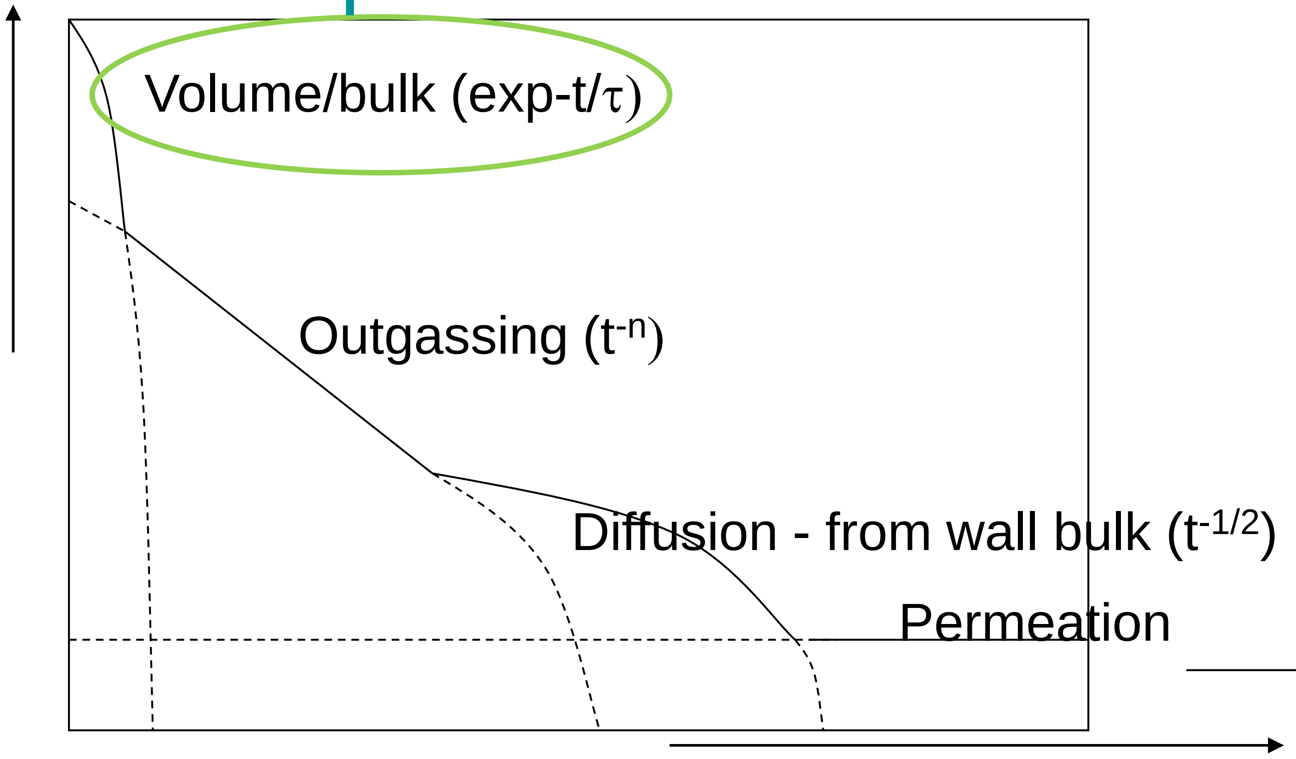
NET OUTGASSING – PUMP DOWN

$$P_{ult} = P_0 \exp(-St/V) + \frac{Q_{outgas}}{S_{eff}} + \frac{Q_{diffusion}}{S_{eff}} + \frac{Q_{permeation}}{S_{eff}}$$

Here S and T assumed constant



Leaks: load depends on leak size

Pressure (Torr)	Major Gas Load
Atmosphere	Air (N_2, O_2, H_2O, Ar, CO_2)
10^{-3}	Water vapour(75% - 95%)
10^{-6}	H_2O, CO
10^{-9}	CO, H_2
10^{-10}	CO, H_2
10^{-11}	H_2

In synchrotrons etc. also have stimulated emission from surfaces

SAFETY

- exhaust pressure restrictions
- transients
- ‘trace’ elements
- ATEX etc.
- reactions
- local procedures
- scenario and fault analysis

ATEX: an introduction

SAFETY

There are 28 language versions of the 2016 Issue E Safety Manual (P400-40-100).

https://www.edwardsvacuum.com/uploadedFiles/Content/Pages/About_Us/Edwards_Vacuum_Safety_Booklet.pdf

OVERVIEW OF MODELLING TOOLS

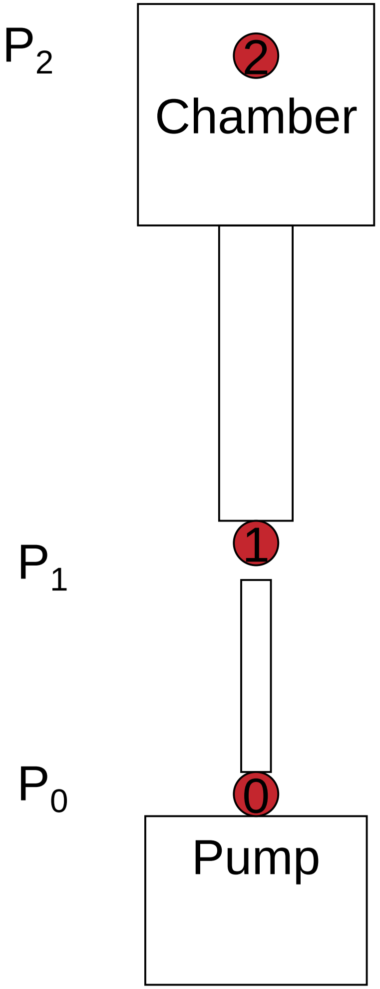
There are various modelling tools that have been created by Edwards

- Vacuum System Modelling
  - PumpCalc
  - TransCalc
- Mechanism Modelling
  - Pump Modeller
  - HSM Toolkit
  - Scroll Pump Modeller
- Thermal Modelling
  - Thermal Toolkit
  - Booster Thermal
- Here's a quick look at some of them

PUMPCALC & TRANSCALC

- Edwards' in-house vacuum system modelling software
  - PumpCalc
    - "Simple" Systems
    - Easy Interface
    - Gives rapid solutions to most systems
  - TransCalc
    - Network-based solution for complex systems
    - Very versatile
      - From UHV to mass spectrometers to steel degassing
    - Requires more expertise to run

PUMPCALC AND TRANSIENT MODELS - TRANSCALC



Calculate speeds and conductances based on pressures in 0,1 and 2 i.e. S_o, $C_{0,1}$, $C_{1,2}$.

Conserve throughput

$$\dot{P}_0 = \frac{1}{V_0}\left(C_{0,1}\cdot\left(P_1 - P_0\right) - P_0\cdot S_0\right)$$

$$\dot{P}_1 = \frac{1}{V_1}\left(C_{0,1}\cdot\left(P_0 - P_1\right) + C_{1,2}\cdot\left(P_2 - P_1\right)\right)$$

$$\dot{P}_2 = \frac{1}{V_2}\left(Q_{Outgas} + C_{1,2}\cdot\left(P_1 - P_2\right)\right)$$

$$\underline{\dot{P}} = \underline{\underline{A}}\cdot\underline{P} + \underline{B}$$

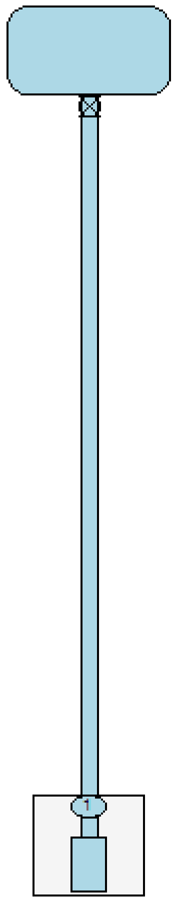
Time step must be small enough that S, C are approximately constant

PUMPCALC

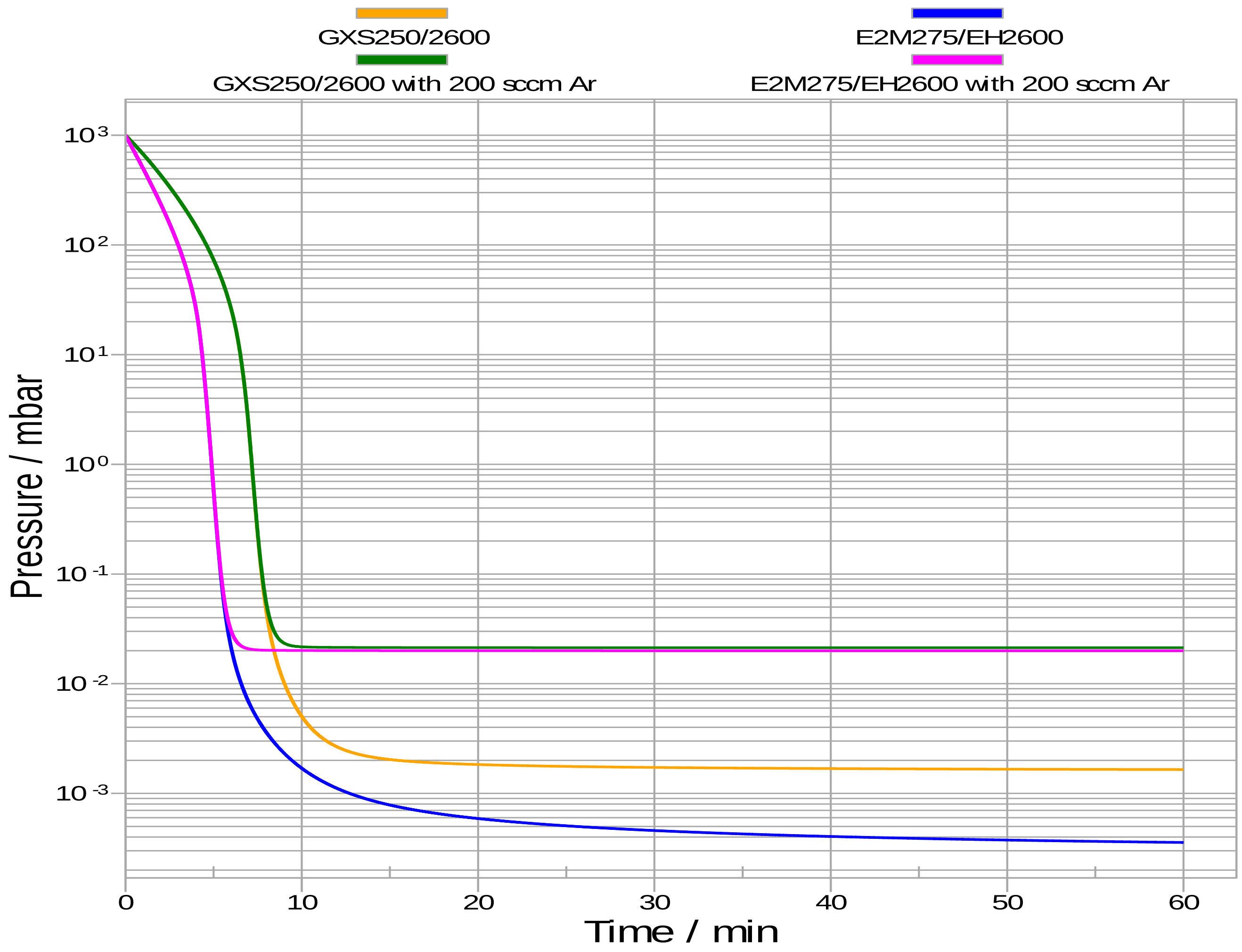
- Solutions for “Simple Systems”
  - A chamber
  - A foreline
  - A pump set

- More complex systems can be modelled if symmetry can be used to simplify them

- Uses transient modelling to capture the dynamics of chamber pumpdowns

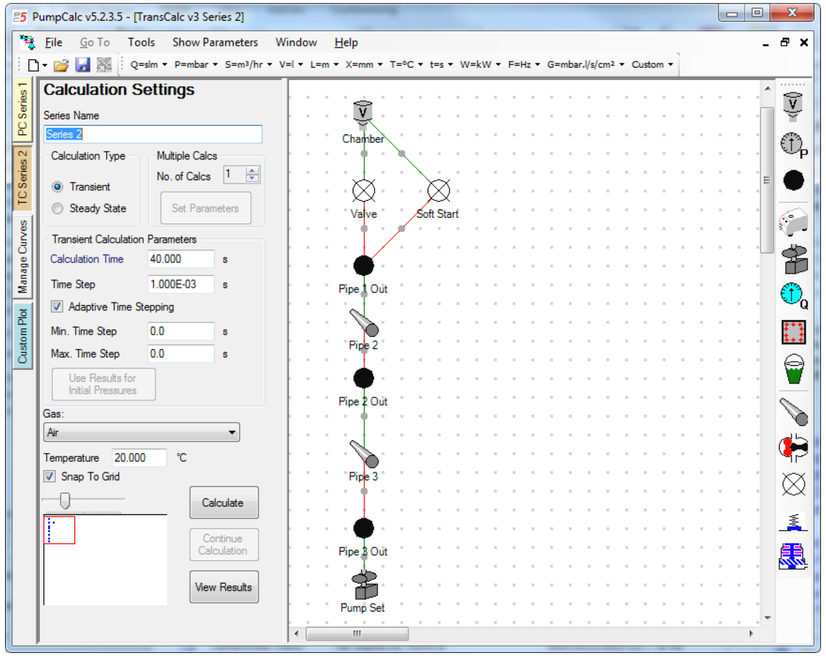


PUMPCALC EXAMPLE : 4000 LITRE CHAMBER PUMP DOWN



VACUUM SYSTEM MODELLING TOOLS: TRANSCALC

- Transient, network-based vacuum system solution software
- Allows Edwards to design complex systems with multiple chambers, pumps and time-dependent control
- Allows more parameterisation and in-depth analysis
- Dynamic modelling of pumps and boosters
- Very wide range of applications



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EXAMPLE #1 SPECIFICATIONS AND REQUIREMENTS

Objective: Determine steady state conditions for distributed system as below

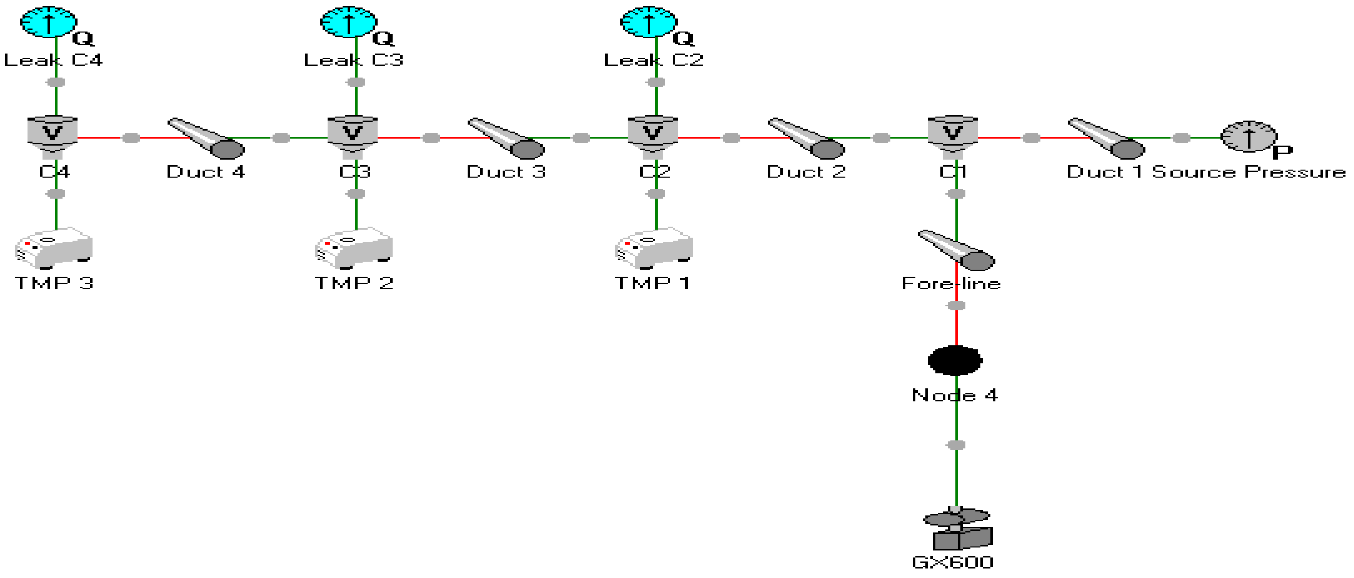
Variables:

Source pressure (SP): 0.01 mbar to 15 mbar

Connecting ‘ducts’: 5 to 20 mm diameter x 120 mm length (in each case ducts 1 to 4 are common)

Gases: N_2, Ar and Xe

N.B for Xenon: SP = 1 mbar and ducts = 5 to 10 mm diameter x 120mm length



EXAMPLE #1 - SYSTEM PARAMETERS

Chamber Volume ~ 2m^3

Surface area: ~16m^2

Stainless Steel-chamber: assume 316L with fluoro-elastomer seals

Assume stated out-gassing =7e-9 mbarl/s/cm^2 is at t = 1 hour and n = 1

Vent with N_2

No process gases, clean application

No bake-out

Stated leak-tightness = 5e-9 mbarl/s

There are internal fixtures: account for this by using an Area Factor (AF) = 1.5
AF = 1 is an empty chamber

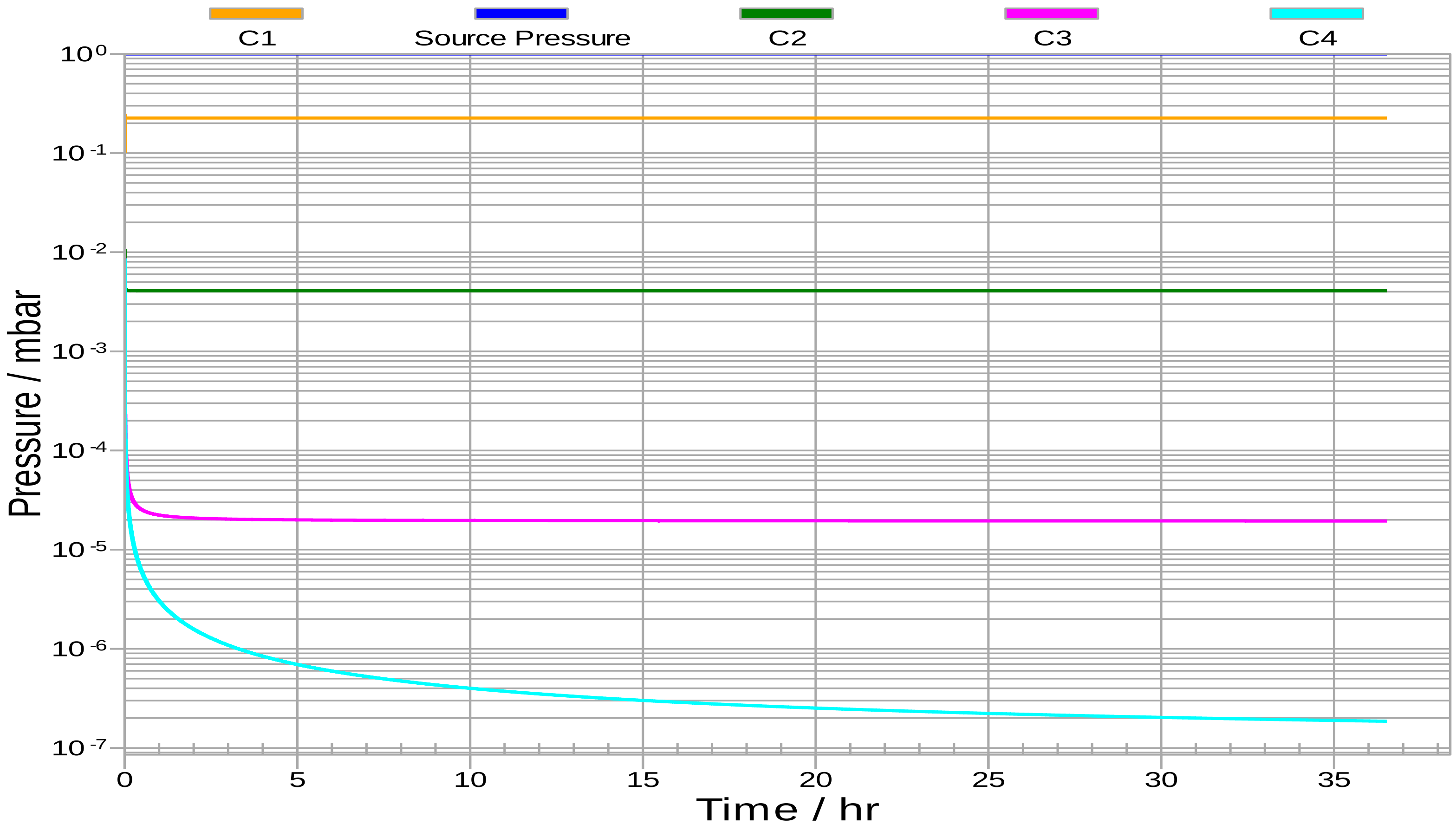
Pump-Ports: 2 X DN250-CF

Dry Pumps (low vibration would be fine)

Pump-down target is from atmosphere to 5e-6 mbar to 1e-7 mbar in 1 to 2 hours

#1 RESULTS – TYPICAL PUMP-DOWN

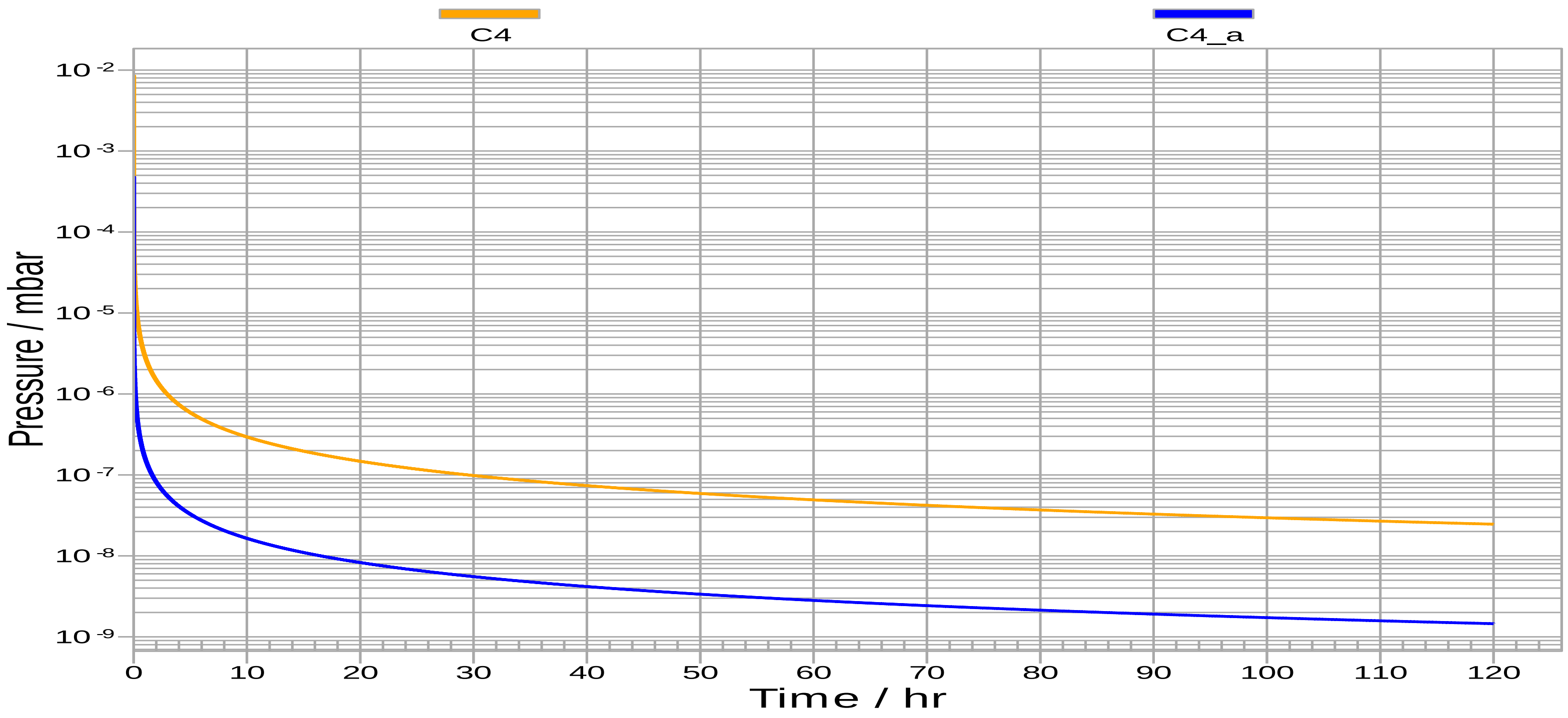
Example is for Nitrogen with SP = 1 mbar and duct diameter = 20 mm



#1 EFFECT OF OUTGASSING -

Graph below shows the case of Nitrogen SP = 15 mbar, 5mm diameter Ducts and different chamber outgassing rates@1.8e-7 mbarl/s/cm^2 (C4 – typical of stainless steel) and 1e-8 mbar l/s/cm^2 (C4_a typical of a highly polished/cleaned system)

Hence for the lower gas flows (small ducts and lower SP values) outgassing has a major impact



SYSTEM DESIGN – MANY THINGS TO CONSIDER: INCLUDING…

- Ultimate pressure required
- Target pump-down time
- Allowable pump start-up and stop times
- Dimensions, geometry and lay-out of whole vacuum system - conductance restrictions
- Chamber connections available – inlet and outlet
- Gas/vapour species to be pumped and residual gases at a given vacuum level
- Pump mechanism efficiency for specified gases/vapours (e.g. compression ratio)
- Process load (throughput) - match pump speed to desired operating pressure
- Vapour handling capacity (e.g. gas ballast/purge facilities)
- Purge flows needed for pump operation (e.g. shaft-seals) and process regimes (e.g. to prevent condensation)
- Ambient environment temperature
- Bake-out protocols, temperature and cycles
- Heat loads (conduction, convection and radiative) and cooling available (e.g. fan, ambient, water, specific coolant)
- Exhaust piping geometry/configuration (will determine pump backing/exhaust pressures)
- Exhaust connection (e.g. individual exhaust lines, exhaust to atmosphere or common/coupled exhaust lines) – possibility of ‘cross-interference’

INCLUDING…

- Pump-orientation required (e.g. inverted, close-coupled)
- Materials of construction (compatibility with pumped materials etc.)
- Leak-tightness
- Cleanliness (e.g. oil back-streaming) and specific characteristics required (e.g. no halogens for NEG)
- Oil carry over: (e.g. oil-loss and return/replenishing in OSRV pumps)
- ‘Regeneration’ requirement (e.g. for Cryogenic pumps)
- Allowable noise – volume and frequencies
- Power/voltage/frequency available
- Maximum distance of power/communication cables
- Compliance with all safety requirements and practices (e.g. specific national/local, ATEX, CE, IP, UL, CSA etc.)
- Required pumping of hazardous materials (e.g. corrosives, flammables, toxics, oxidisers, asphyxiants etc.) ‘Process gas loads’
- Pumping dusts – pump compatibility (e.g. build-up in ‘clearance’ mechanisms) and safety (dust explosion risk)
- Compatibility with Electrical fields and Electrostatic Pulse environment compatibility
- Compatibility with local Magnetic fields
- Radiation duty and load: dose rate and radiation type/Quality Factor (neutrons, protons, gamma, alpha, beta etc.)
- Vibration resistance (and earth-quake resistance) requirements

- Maximum allowable stray magnetic field from pump
- Maximum allowable vibrations from pump
- Pump-orientation required (e.g. inverted, close-coupled)

- Inlet protection and configuration (e.g. traps, filters, inlet screen etc.)
- Outlet accessories (e.g. silencers, traps, filters etc.)

- On board or remote electronics
- Communication protocols

- Size and Accessibility – can the pump fit and be easily monitored and accessed for service?
- Service: required interval (e.g. to comply with scheduled facility down-times) and regime (e.g. in-house/in-situ service required or can the pump be sent to a service centre?)
- **Price – capital cost, recurrent costs (e.g. utilities, oil disposal etc.) and service costs.**
- **Expected life-time**

GROUP EXERCISE

Consider a vacuum system (Small, Medium or Large) which you have designed/used, are now designing and/or are planning

What ‘approach’ will you take? – Wet/Dry, Service interval, safety, interlocks

What factors are most important?

What utilities are available?

What are the constraints. Technical and commercial (capital cost, service interval, accessibility, local requirements, expertise level, experience, preference etc.)

How will you define the vacuum components needed?

Having attended this week’s training what if anything would you change or will you change in the design?

GROUP EXERCISE - GUIDE

Equipment required	Pumps, gauges, valves, flanges, windows, chamber, entire systems? etc
Volume of system	m3/litre/cubic feet etc
Geometry	Cylinder, box etc Is a P&ID and/or sketch of the system available
Internal Surface Area	m2/ft2 etc
Materials of constuction	Stainless, aluminium, glass etc
Outgassing rates	Torrl/s/cm2, mbar.l/s/m2 etc. if known
Area Factor	1 is default
Seals used	Flourelastomer, CF etc
Details of internal fixtures	Materials and their surface areas
History of use of system	Previously baked, left in humid atmosphere, vented to N2 etc.
Pump-down targets	Starting pressure and final pressure to be achieved in which time
Fore-line/flanges	Geometry of pipes between primary pump and system., number of bends etc.
Chamber pump connections	Flange sizes, elbows, gate valves used etc.
System leak-rate	mbar.l/s etc.
Gases and vapours to be pumped	What are they? O2, Helium, HF etc
Flow rates of these and desired operating pressure	Flows in sccm, slm, g/hour, Torr.l/s etc and required operating pressure. N.B 'Trace' levels is not enough information
Is there any process reactions/chemistry in the system	If Yes please state the actual reactions and products from them
Pump type preferences	OSRV, dry, TMP, Cryo or IGP etc.
Stated safety aspects	Need to state any aspects of corrosion, flammables, asphyxiants, toxic products and reactions
ATEX or equivalents required?	Internal and/or external zoning required?
Any other information or comments	Requirement for gauges,

VACUUM SYSTEM DESIGN AND MAINTENANCE

SESSION VI
APPLICATION OF VACUUM SYSTEM DESIGN: SCOPING A PROJECT AND PRACTICAL CONSIDERATIONS

14TH JUNE 2018

EDWARDS

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