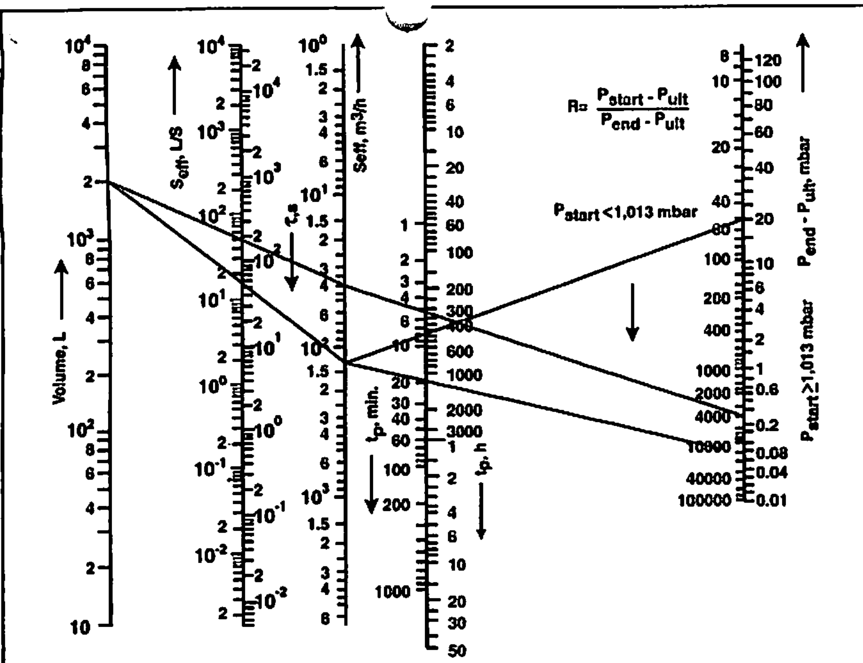

FIGURE 1. NOMOGRAM

This nomogram has five columns with multiple labels, (Symbols and units are in nomenclature table). Identification:

1. Volume (V_L) to be evacuated
2. S_{eff} prevailing at the container
3. Time constant, τ
4. Pumpdown time, t_p
5. p_{start} is the pressure at $t_p = 0$. p_{end} is the required pressure at the end of pumping. p_{ult} is the ultimate pressure of the pump.

The examples will show how to connect the lines. The layout of the nomogram takes the pressure dependence of the pumping speed into consideration.

Example 1: Evacuate a container $V_L = 2{,}000$ using a rotary-plunger pump. $P_{start} = 1{,}013$ and $S_{eff} = 60\ m^3/h$. What is t_p to reach $p_{end} = 0.1$?

1. Draw a straight line from the 2,000 L point in column 1 through the 60 m³/h point in column 2. The extended line intersects column 3 at τ = 120 s (approximately)
2. According to the manufacturer, $p_{ult} = 0.03$. Calculate $p_{end} - p_{ult} = 0.1 - 0.03 = 0.07$. Draw a straight line from τ = 120 on column 3 to the 0.07 point on the right side of column 5. The intersection with column 4 is 18 min. Conservatively round up to 20 min

Example 2: Change to end pressure to 10^{-2} mbar. This is lower than p_{ult} of the plunger pump. The solution is to put a Roots pump in series. Refer to the plunger pump as the backing pump. For the Roots pump: $S_{eff} = 200\ m^3/h$, $p_{ult} = 4 \times 10^{-3}$, and $p_{start} = 20$.

Pumping is a two-step process. Use the backing pump from 1,103 mbar to 20 mbar. Then switch on the Roots pump to completion at 0.01 mbar.

1. The line from 2,000 L in column 1 through 167 L/s in column 2 intersects column 3 and then the connection from there to 20 on the right side of column 5, cuts $t_p = 7.5$ min at column 4.
2. Calculate r: $r = (20 - 0.004)/(0.01 - 0.004) = 3{,}300$
3. For the Roots pump, the line from 2,000 L in column 1, through 56 L/s in column 2 intersects column 3 at τ = 40. Connect this point by straight line to $r = 3{,}300$ in column 5, left side. The line crosses column 4 at 5.3 min.
4. Add the times: 7.5 + 5.3 = 12.8 and then round up to 15 min

FIGURE 1. Follow the detailed instructions to estimate the pump downtime of a container in the rough and medium vacuum ranges [2]

CRITERIA FOR SIZING CONNECTING LINES [6]

Vacuum pump	Assumed velocity, ft/s
Steam jet	
System pressure, torr	
0.5 – 5	300
5 – 25	250
25 – 150	200
150 – 760	150
Liquid ring pump	
Single stage*	100
Two stage	150
Rotary piston	
Single stage	50
Two stage	25
Rotary vane: **	
Single stage	200
Two stage	400
Rotary blowers	
Atmospheric discharge	50
Discharging to backing pump	100

* Assumes the pump features dual inlet connections and uses an inlet manifold

** Based on rough-vacuum process pumps. Use 25 ft/s for high-vacuum pumps

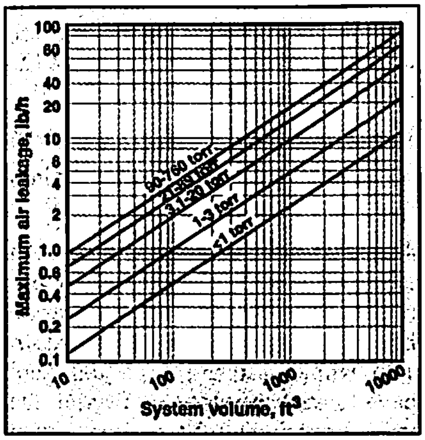

FIGURE 2. Chart to estimate maximum air leakage into a commercally tight system [3]

ing capacity and vacuum level requirements. These are usually low-vacuum systems that typically operate around 600 – 680 torr.

In all vacuum systems, particularly high vacuum, economics dictate that the acfm handled must be minimized. This means that air leakage must be strictly controlled. Also contemplate purging inerts and removing condensables, with appropriate chillers, as close to the vacuum user as practicable.

Pressure drop

Even in a vacuum, the flow of gas requires a pressure drop; there just isn't much to work with. Allowable pressure drop for piping systems is on the order of magnitude of 10% of the absolute pressure. This means that, for example, a 10-torr vacuum system can tolerate only 1 torr of line pressure drop.

As depth of vacuum increases, the actual displacement rate of gas flow increases linearly, allowable pipeline pressure drop is proportionally less, and vacuum line sizes increase. If the system piping and equipment do not have an adequately-low pressure drop, then no matter how big the vacuum-generating device is, it can never achieve the desired level of vacuum (Figure 4).

Flow characteristics vary with the absolute pressure. While the Reynolds Number is important in calculations, it is the Knudsen Number (*Kn = mean free path / vessel diameter*) that defines the flow. Deep vacuum is properly defined as the region of molecular flow, $Kn > 0.5$. Individual molecular interactions are small relative to gas molecule-vessel wall interactions. Vacuum level is typically under 7.5×10^{-4} torr.

Equation (2) is used to calculate flow.

$$F_a = 1{,}983 d^3 / L \quad (2)$$

In Knudsen Number ranges 0.01 to 0.5, the flow is in a transitional region. This is the higher end of the deep vacuum range (approximately 7.5×10^{-5} to 7.5×10^{-1} torr). Helpful graphs (Figure 5) confirm the boundaries of the range. It is extremely hard to calculate flow. Hiring a consultant is recommended.

Many processes are in the viscous-flow regime, $Kn < 0.01$. This is in a range >0.75 torr, and, as with pressurized flow, there are three regimes: laminar, turbulent and transition.

Reynolds Numbers provide boundaries of the regimes (Equation 3), Laminar Flow is at $Re < 2{,}300$; turbulent flow is at $Re > 4{,}000$ and transition lies between 2,300 and 4,000. Figure 6 condenses this.