CE 400 / CE 500

Process Safety Management

Lecture 10 Source Models

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How Big is the Leak?

- Once we have identified scenarios where we might have a Loss of Containment (LOC) we need to obtain a credible estimate of how big that leak may be
- It is important to note that these calculations are not meant to give exact amounts of what might be released in a given incident because the conditions during the incident will vary (tank levels, temperatures, etc)
- What we want are conservative estimates that will give the largest REALISTIC amount

Flow of Liquid Through a Hole in a Pressurized Vessel

$$Q_m = AC_0\sqrt{2\rho g_c P_g}$$

- Derived from a mechanical energy balance
- Q_m is mass flow rate of discharge
- A is area of hole
- P_g is internal pressure relative to atmosphere
- ρ is liquid density
- g_c is gravitational constant = 32.17 $\frac{ft \cdot lb_m}{lb_f \cdot s^2}$

$$= g_c = \frac{1\, {kg\, m}/{s^2}}{N} = \frac{1\, {kg\, m^2}/{s^2}}{J}$$

- C_0 is discharge coefficient

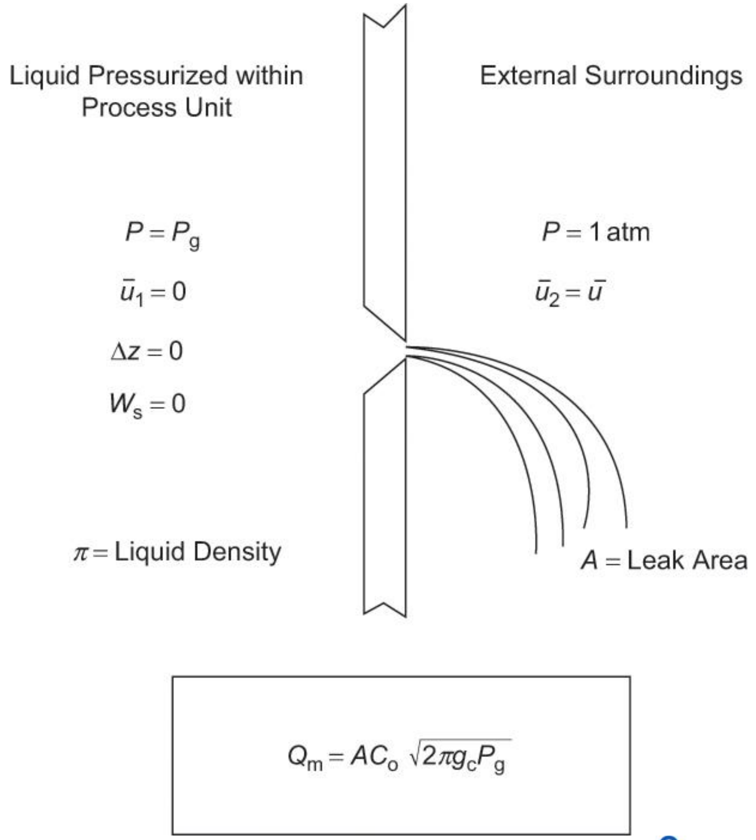


Figure 4-4 Liquid escaping through a hole in a process unit. The energy of the liquid resulting from its pressure in the vessel is converted to kinetic energy, with some frictional flow losses in the hole.

Discharge Coefficient

- The discharge coefficient, C_0, is a complex function of Reynolds number and the diameter of the hole
- Sharped Edge Orifice and Reynolds # > 30,000:

  C_0 is roughly 0.61
- Well rounded nozzle:

  C_0 is roughly 1
- Short section of pipe attached to vessel (length to diameter ratio > 3):

  C_0 is roughly 0.81
- **When in doubt, be conservative and use $C_0 = 1$**
  - You will estimate a larger flow…we don't want to underestimate the hazard

Example

- A drop in pressure is observed in a pipeline transporting benzene
- Pressure immediately returns to 100 psig
- 90 minutes later a ¼" hole is found and the transfer is shutdown to repair the leak
- Specific gravity of benzene is 0.8794
- Area of orifice is $A = \frac{\pi D^2}{4} = \frac{\pi\left(0.25\ in * \frac{ft}{12\ in}\right)^2}{4} = 3.41 * \ 10^{-4}\ ft^2$
- Density of benzene = $0.8794\ * 62.4\ {}^{lb_m}/_{ft^3} = 54.9\ {}^{lb_m}/_{ft^3}$
- Use equation on previous slide with a discharge coefficient of 0.61 assumed for orifice type leak

Example

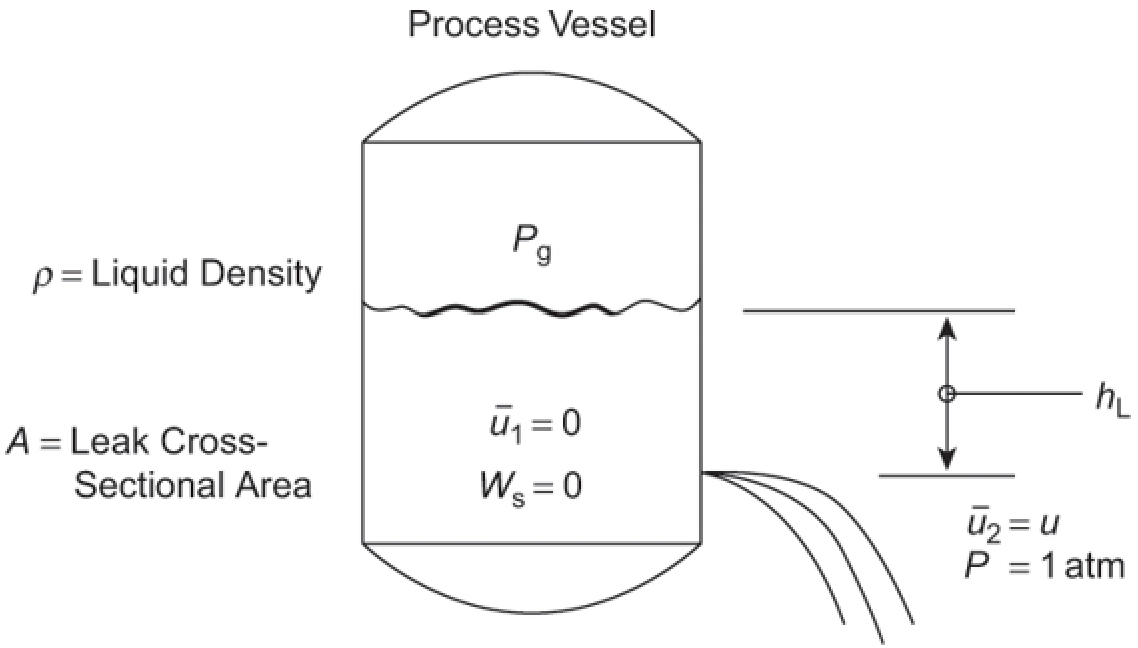
- $Q_m = AC_0\sqrt{2\rho g_c P_g} = 3.41 * 10^{-4}\, ft^2 * 0.61 * \sqrt{2 * 54.9\, {}^{lb_m}/_{ft^3}\, 32.17\, \frac{ft\, lb_m}{lb_f\, s^2}\, 100\, \frac{lb_f}{in^2} * 144\, \frac{in^2}{ft^2}}$
- Q_m =1.48 ${}^{lb_m}/_s$
- The total quantity spilled is 1.48 ${}^{lb_m}/_s * 90\,\text{min} * 60\; {}^{s}/_{min} = 7990\, lb_m$

- Now in this case if we assume that the pipeline was located over soil, the rate is not as important as the total quantity because it is absorbed into the soil relatively quickly
- We would be more concerned with the environmental leak than with acute exposure
- Another way to check would be to look at the amount that actually made it to its expected destination versus how much should have transferred in that time
  - Depending on their relative magnitude the leak amount may be within the noise of your measurements

Flow of Liquid through a Hole in a Tank

$$Q_m = \rho A C_0 \sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L\right)}$$

- h_L is the height of the liquid above the hole



Time to Drain down to the Hole in a Tank

$$t_e = \frac{1}{C_0 g}\left(\frac{A_t}{A}\right)\left[\sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^0\right)} - \sqrt{\frac{2 g_c P_g}{\rho}}\right]$$

- h_L^0 is the height of the liquid above the hole at time 0
- A_t is the cross-sectional area of the tank

Example

- A cylindrical tank 20 ft high and 8 ft in diameter is storing benzene
- Tank is padded with nitrogen at a pressure of 1 atm gauge
- Liquid level is 17 ft
- A 1 in puncture occurs at a height of 5 ft

a) Estimate the gallons of benzene spilled

b) The time required for it to leak out

c) The maximum flow rate

Area of tank $$A_t = \frac{\pi D^2}{4} = \frac{\pi (8\,ft)^2}{4} = 50.2\,ft^2$$

Area of Leak $$A = \frac{\pi D^2}{4} = \frac{\pi \left(\frac{1}{12}\,ft\right)^2}{4} = 5.45 * 10^{-3}\,ft^2$$

Gauge Pressure $$P_g = 1\,atm * 14.7\,\frac{lb_f}{in^2} * \frac{144\,in^2}{ft^2} = 2.12 * 10^3\,\frac{lb_f}{ft^2}$$

Example

a) Estimate the gallons of benzene spilled

Simply the volume of liquid above the leak

$$V = A_t \, * \, h_L^0 = 50.2\,ft^2 \, * \, (17\,ft \, - 5\,ft) \, * \, \frac{7.48\,gallons}{ft^3} = 4506\,gallons$$

Example

b) The time required for it to leak out

$$t_e = \frac{1}{C_0 g}\left(\frac{A_t}{A}\right)\left[\sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^0\right)} - \sqrt{\frac{2 g_c P_g}{\rho}}\right]$$

$$t_e = \frac{1}{0.61 * 32.17\,\frac{ft}{s^2}}\left(\frac{50.2\,ft^2}{5.45 * 10^{-3}\,ft^2}\right)\left[\sqrt{2\left(\frac{32.17\,\frac{ft\,lb_m}{lb_f s^2} * 2.12 * 10^3\,\frac{lb_f}{ft^2}}{54.9\,{}^{lb_m}\!/_{ft^3}} + 32.17\,\frac{ft}{s^2} * 12\,ft\right)} - \sqrt{\frac{2 * 32.17\,\frac{ft\,lb_m}{lb_f s^2} * 2.12 * 10^3\,\frac{lb_f}{ft^2}}{54.9\,{}^{lb_m}\!/_{ft^3}}}\right]$$

$$t_e = 56.4\,minutes$$

Example

c) The maximum flow rate – occurs at time zero

$$Q_m = \rho A C_0 \sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^0\right)}$$

$$Q_m = 54.9\ {}^{lb_m}\!/_{ft^3} * 5.45 * 10^{-3}\ ft^2 * 0.61 \sqrt{2\left(\frac{32.17\ \frac{ft\ lb_m}{lb_f s^2} * 2.12 * 10^3\ \frac{lb_f}{ft^2}}{54.9\ {}^{lb_m}\!/_{ft^3}} + 32.17\ \frac{ft}{s^2} * 12\ ft\right)}$$

$$Q_m = 10.4\ \frac{lb_m}{s}$$

Choked Flow of Gases or Vapors through Holes

- This leads to the maximum flow possible
- Flow is independent of downstream P
- $(Q_m)_{choked} = C_0 A P_0 \sqrt{\frac{\gamma g_c M}{R T_0}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$
- $\gamma = {}^{C_p}/{}_{C_v}$, the ratio of the heat capacities
- M is the molecular weight of the escaping gas
- R is the gas constant

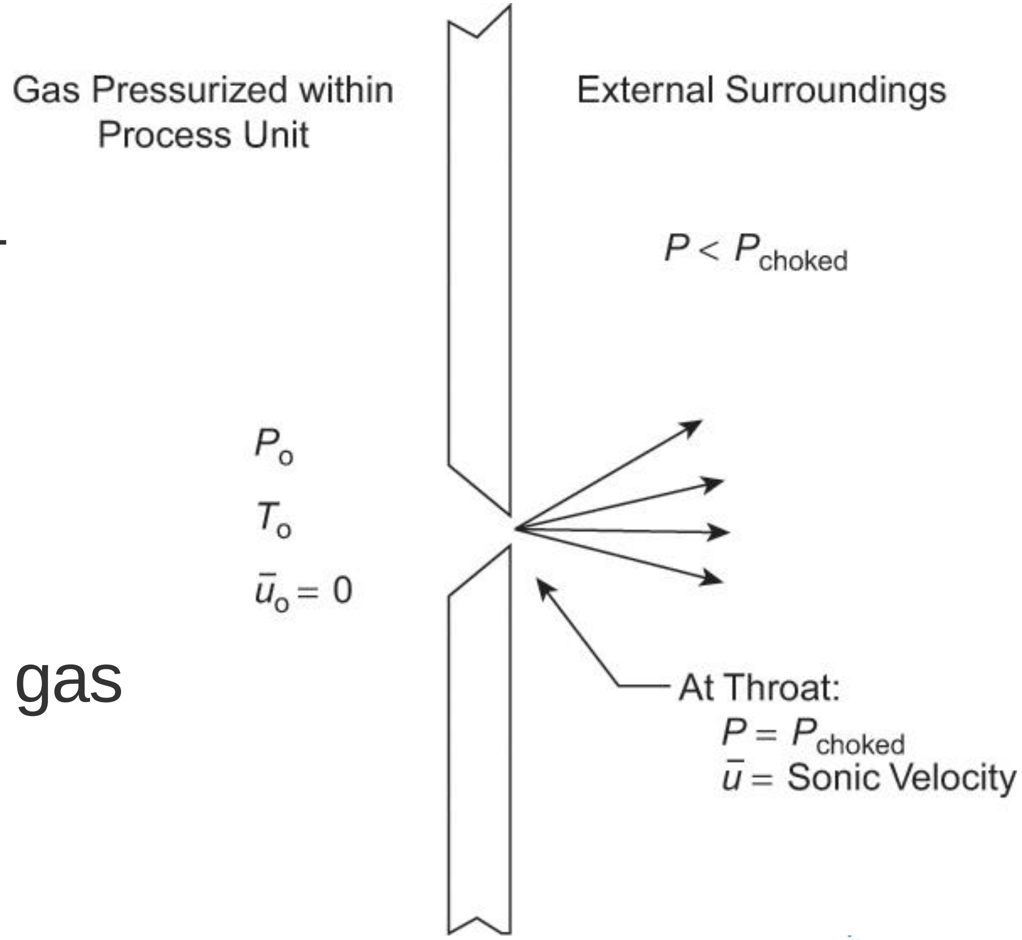


Figure 4-10 Choked flow of gas through a hole. The gas velocity is sonic at the throat. The mass flow rate is independent of the downstream pressure.

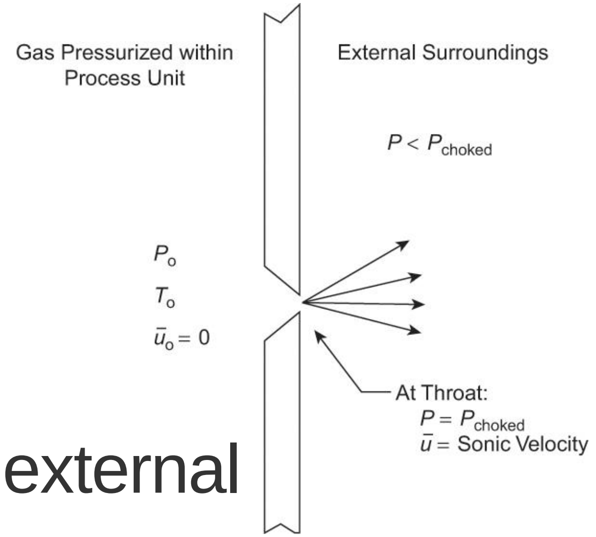
Source Models

Table 4-3 Heat Capacity Ratios γ for Selected Gases[a]

Gas	Chemical formula or symbol	Approximate molecular weight (M)	Heat capacity ratio $\gamma = C_p/C_v$
Acetylene	C_2H_2	26.0	1.30
Air	–	29.0	1.40
Ammonia	NH_3	17.0	1.32
Argon	Ar	39.9	1.67
Butane	C_4H_{10}	58.1	1.11
Carbon dioxide	CO_2	44.0	1.30
Carbon monoxide	CO	28.0	1.40
Chlorine	Cl_2	70.9	1.33
Ethane	C_2H_6	30.0	1.22
Ethylene	C_2H_4	28.0	1.22
Helium	He	4.0	1.66
Hydrogen	H_2	2.0	1.41
Hydrogen chloride	HCl	36.5	1.41
Hydrogen sulfide	H_2S	34.1	1.30
Methane	CH_4	16.0	1.32
Methyl chloride	CH_3Cl	50.5	1.20
Natural gas	–	19.5	1.27
Nitric oxide	NO	30.0	1.40
Nitrogen	N_2	28.0	1.41
Nitrous oxide	N_2O	44.0	1.31
Oxygen	O_2	32.0	1.40
Propane	C_3H_8	44.1	1.15
Propene (propylene)	C_3H_6	42.1	1.14
Sulfur dioxide	SO_2	64.1	1.26

[a]Crane Co., *Flow of Fluids Through Valves, Fittings, and Pipes*, Technical Paper 410 (New York: Crane Co., 2009), *www.flowoffluids.com.*

Checking for Choked Flow



$$\frac{P_{choked}}{P_0} = \left(\frac{2}{\gamma + 1}\right)^{\gamma/(\gamma-1)}$$

- Calculate the choked pressure in the throat, P_{choked}. If the external pressure is less than P_{choked} then we do have choked flow
  - The velocity of the fluid in the throat is the velocity of sound
  - Velocity and mass flow rate cannot be increased by reducing the downstream pressure
  - P_0 is the internal pressure in the vessel
- This is known as Choked, Critical, or Sonic Flow

Example

A vessel containing helium stored at 350 psig and 75 F forms a hole of diameter 0.07 in. Determine the initial mass flow of this leak

Ratio of Heat Capacities $\gamma = 1.66$

Area of Leak: $A = \frac{\pi D^2}{4} = \frac{\pi\left(\frac{0.07}{12}ft\right)^2}{4} = 2.67 * 10^{-5}\ ft^2$

Initial Absolute Pressure: $P_0 = 350\frac{lb_f}{in^2} + 14.7\ \frac{lb_f}{in^2} = 364.7\ \frac{lb_f}{in^2}$

Calculate Choked Pressure: $\frac{P_{choked}}{P_0} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)} = \left(\frac{2}{1.66+1}\right)^{1.66/(1.66-1)} = 0.488$

$$P_{choked} = P_0 * 0.488 = 364.7 * 0.488 = 178\ \frac{lb_f}{in^2}$$

Because the external pressure (atmospheric, $14.7\ \frac{lb_f}{in^2}$) is less than the choked pressure we do have choked flow

Assume a discharge coefficient of $C_0 = 1$

Example

$$(Q_m)_{choked} = C_0 A P_0 \sqrt{\frac{\gamma g_c M}{R T_0}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$$

- $\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)} = \left(\frac{2}{1.66+1}\right)^{(1.66+1)/(1.66-1)} = 0.317$

$$(Q_m)_{choked} = 1 * 2.67 * 10^{-5}\, ft^2 * 364.7\, \frac{lb_f}{in^2} * \frac{144\, in^2}{ft^2} \sqrt{\frac{1.66 * 32.17 \frac{ft\, lb_m}{lb_f s^2} * 4.0 \frac{lb_m}{lb\text{-}mol}}{1545 \frac{ft\, lb_f}{lb\text{-}mol\, ^\circ R} * 535\, ^\circ R} * 0.317} = 0.0127\, \frac{lb_m}{s}$$

Source Models

Table 4-6 Guidelines for Selection of Process Incidents

Incident characteristic	Guideline
Realistic release incidents[a]	
Process pipes	Rupture of the largest diameter process pipe as follows: For diameters smaller than 2 in, assume a full bore rupture. For diameters 2–4 in, assume rupture equal to that of a 2-inch-diameter pipe. For diameters greater than 4 in, assume rupture area equal to 20% of the pipe cross-sectional area.
Hoses	Assume full bore rupture.
Pressure relief devices relieving directly to the atmosphere	Use calculated total release rate at set pressure. Refer to pressure relief calculation. All material released is assumed to be airborne.
Vessels	Assume a rupture based on the largest diameter process pipe attached to the vessel. Use the pipe criteria.
Other	Incidents can be established based on the plant's experience, or the incidents can be developed from the outcome of a review o derived from hazard analysis studies.

Source Models

Worst-case incidents[b]	
Quantity	Assume release of the largest quantity of substance handled on-site in a single process vessel at any time. To estimate the release rate, assume the entire quantity is released within 10 min.
Wind speed / stability	Assume F stability, 1.5 m/s wind speed, unless meteorological data indicate otherwise.
Ambient temperature / humidity	Assume the highest daily maximum temperature and averag[e] humidity.
Height of release	Assume that the release occurs at ground level.
Topography	Assume urban or rural topography, as appropriate.
Temperature of release substance	Consider liquids to be released at the highest daily maximu[m] temperature, based on data for the previous three years, or process temperature, whichever is higher. Assume that gase[s] liquefied by refrigeration at atmospheric pressure are relea[sed] at their boiling points.

Dow's Chemical Exposure Index Guide (New York: American Institute of Chemical Engineers, 1994).
US EPA, RMP Offsite Consequence Analysis Guidance (Washington, DC: US Environmental Protection Agency.