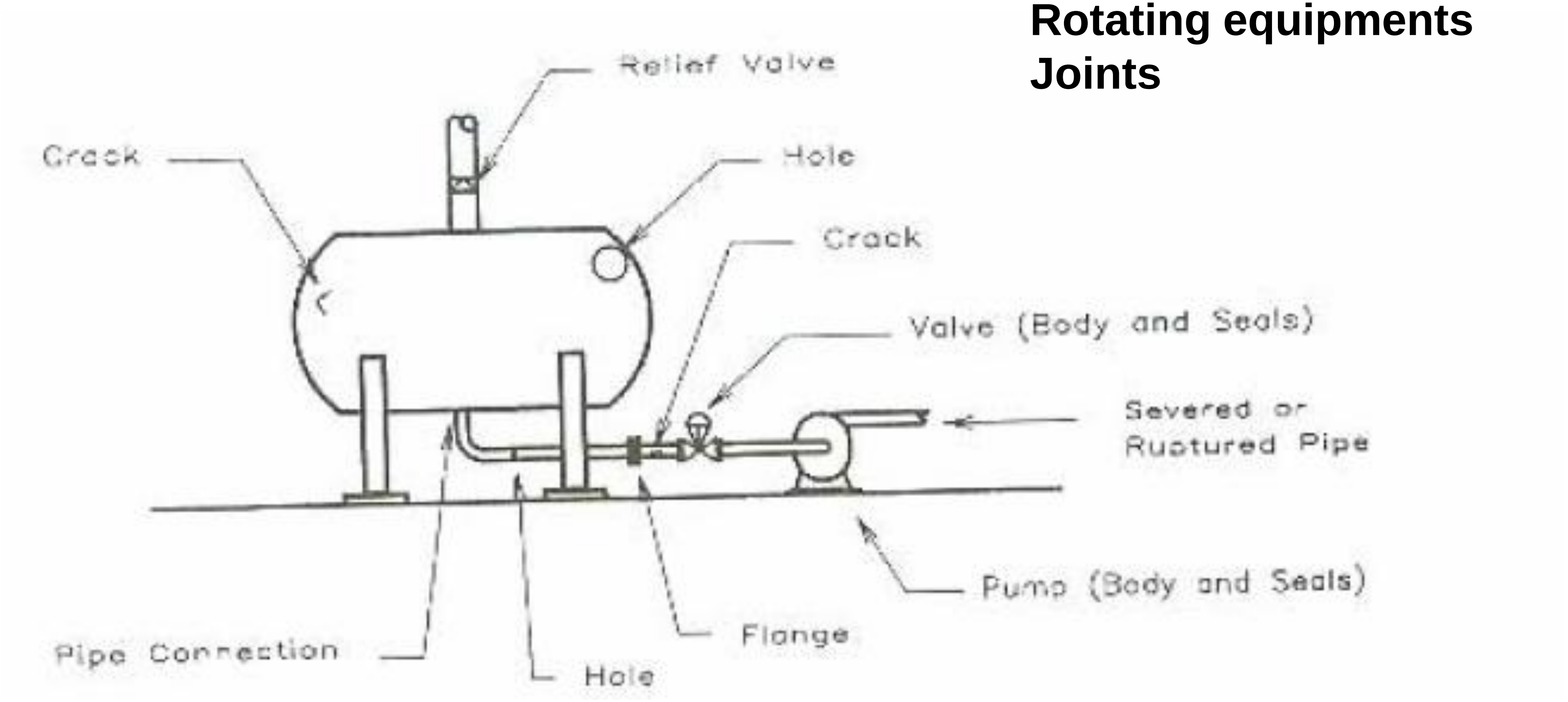
Source Models, Liquids

Source of release

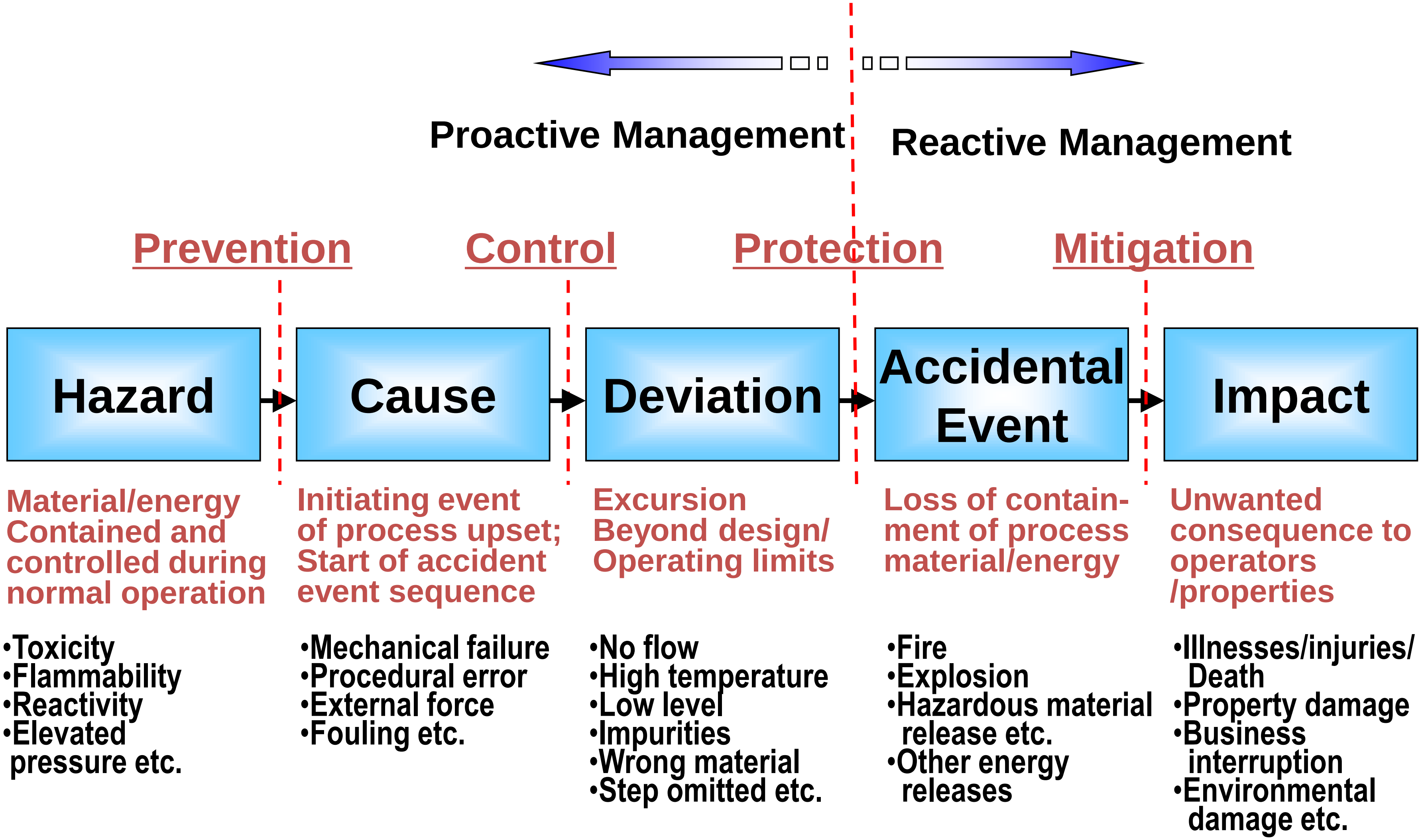
Tanks
Pipelines
Rotating equipments
Joints



Source Models: Purpose I

- Most incidents
  - spills of reactive, flammable, and toxic materials.
    - ☜ Pipe ruptures, holes/cracks in tanks, flanges

Accidental Flow



Proactive Management

Reactive Management

Prevention

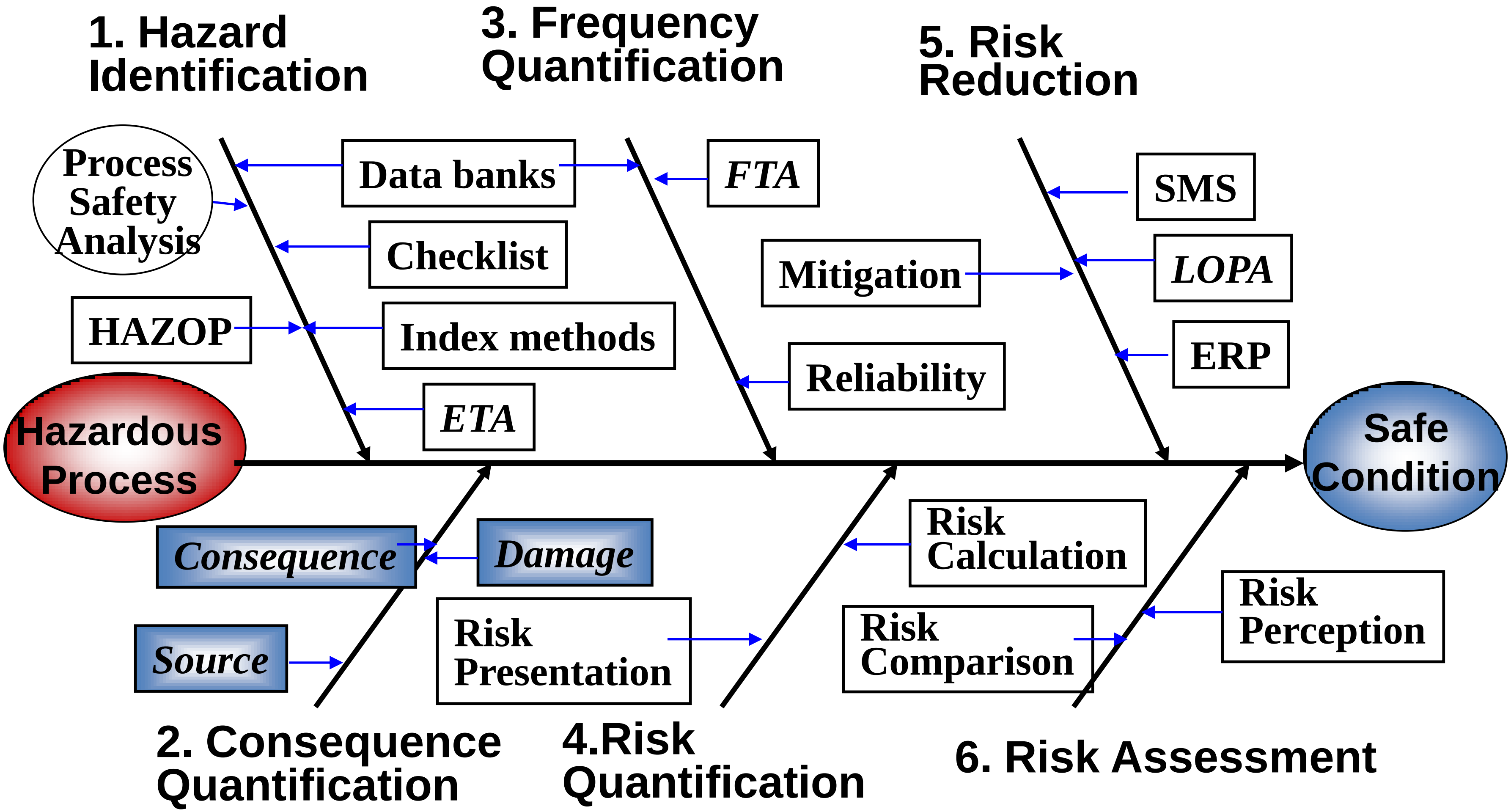
Control

Protection

Mitigation

Hazard	Cause	Deviation	Accidental Event	Impact
Material/energy Contained and controlled during normal operation	Initiating event of process upset; Start of accident event sequence	Excursion Beyond design/ Operating limits	Loss of containment of process material/energy	Unwanted consequence to operators /properties
•Toxicity •Flammability •Reactivity •Elevated pressure etc.	•Mechanical failure •Procedural error •External force •Fouling etc.	•No flow •High temperature •Low level •Impurities •Wrong material •Step omitted etc.	•Fire •Explosion •Hazardous material release etc. •Other energy releases	•Illnesses/injuries/ Death •Property damage •Business interruption •Environmental damage etc.

Risk Analysis Methodology



1. Hazard Identification

3. Frequency Quantification

5. Risk Reduction

Process Safety Analysis

Data banks

FTA

SMS

Checklist

Mitigation

LOPA

HAZOP

Index methods

ERP

Reliability

ETA

Hazardous Process

Safe Condition

Consequence

Damage

Risk Calculation

Risk Perception

Source

Risk Presentation

Risk Comparison

2. Consequence Quantification

4.Risk Quantification

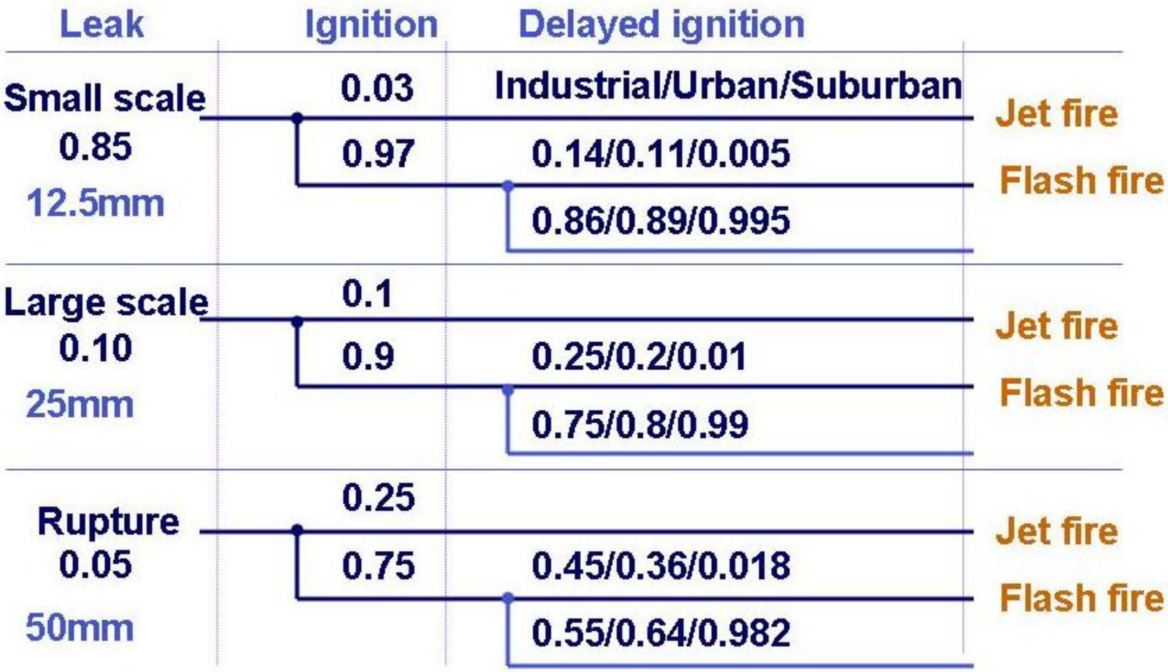
6. Risk Assessment

Source Models: Purpose II

- Source models estimate
  - rates of discharge, amounts released, state of discharge
- Sources of flashing, misting, evaporating, or boiling liquids followed by dispersions
- Releases of gases, liquids, aerosols

Source Models: Purpose III

- Effect model estimate
  - consequences of incidents: injuries, deaths, structural damages, environment.



Jet fire

Pool fire

Source Models Treated

- Liquids from holes: pipes, tanks
- Liquid flow through pipes
- Gases from holes: pipes, tanks
- Gas flow through pipes
- Flashing liquids
- Liquid evaporation (already considered)
- Liquid boiling

Flow of Liquids through Holes

Mechanical energy balance for a fluid:

$$\int \frac{dP}{\rho} + \frac{\Delta \bar{u}^2}{2\alpha g_c} + \frac{g}{g_c}\Delta z + F = -\frac{W_s}{m}$$

Energy: VΔP, KE, PE, friction, shaft work

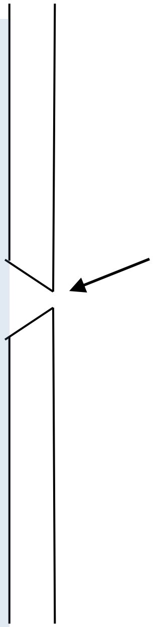
Process fluid

$P = P_g$

$u_1 \sim 0$, velocity

$\Delta z \sim 0$, elevation

$W_s = 0$



leak

Surroundings

$P = 1$ atm

$u_2 = \bar{u}$

A = leak area

Energy balance for leaking to atmosphere

$$\frac{\Delta P}{\rho} + F + \frac{\bar{u}^2}{2\alpha g_c} = C_1^2\left(\frac{\Delta P}{\rho}\right) + \frac{\bar{u}^2}{2\alpha g_c} = 0$$

Velocity profile factor, *α*, 0.5 (laminar) to 1 (turbulent)

Friction term, *F*, approx by discharge coefficient, P. 113, eqn 4-3, C$_1$, from exp

Ave discharge velocity: $\bar{u} = C_0\sqrt{\dfrac{2g_cP_g}{\rho}}$, $C_0 = C_1\sqrt{\alpha}$

Mass flow rate from area A:

$$Q_m = \rho\bar{u}A \quad = \quad A\,C_0\sqrt{2g_c\rho P_g}$$

Discharge Coefficient

- **C_0 depends on the Reynolds number (a) and hole diameter (C_1).**
- **Use known values of C_0,**
  - **0.61 for sharp orifices and for large *Re* (exit velocity independent of hole size)**
  - **Well-rounded nozzle 1**
  - **Short pipe attached to vessels 0.81**
  - **If unknown, use 1.0 to maximize the estimated flow for process safety applications.**

Tank Discharge: Energy Balance

Energy balance for hole *h_L* below liquid level:

$$\left(\frac{\Delta P}{\rho}+\frac{g}{g_c}\Delta z+F\right)+\frac{\bar{u}^2}{2\alpha\, g_c} = C_1^2\left(\frac{\Delta P}{\rho}+\frac{g}{g_c}\Delta z\right)+\frac{\bar{u}^2}{2\alpha\, g_c}=0$$

Average discharge velocity:

$$\bar{u}=C_o\sqrt{2\left(\frac{g_c P_g}{\rho}+g h_L\right)}$$

Mass flow rate from hole of area *A*:

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

Tank Discharge: Liquid Height

Mass of liquid above the leak with cross section area, *A_t*:

$$m = \rho A_t h_L$$

Rate of mass decrease in the tank: $\dfrac{dm}{dt} = \rho A_t \dfrac{dh_L}{dt} = -Q_m$

Solve for and integrate $\dfrac{dh_L}{dt}$ **to obtain** $h_L(t)$

$$h_L = h_L^o - \frac{C_o A}{A_t}\sqrt{\frac{2 g_c P_g}{\rho} + 2 g h_L^o}\, t + \frac{g}{2}\left(\frac{C_o A}{A_t} t\right)^2$$

Set *h_L* = 0 and solve for *t_e*, time to empty to level of leak.

Tank Discharge: Leak Time, $Q_m(t)$

Time to leak at *P_g*: $t_e = \frac{1}{C_o g}\left(\frac{A_t}{A}\right)\left[\sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^o\right)} - \sqrt{\frac{2 g_c P_g}{\rho}}\right]$

Time to leak at *$P_g = 0$*: $t_e = \frac{1}{C_o g}\left(\frac{A_t}{A}\right)\sqrt{2 g h_L^o}$

Substitute *$h_L(t)$* into original *Q_m* to obtain *$Q_m(t)$*, mass discharge rate at any time:

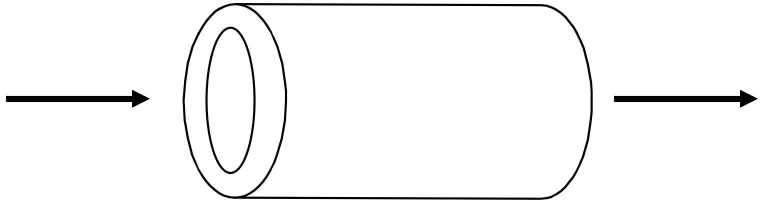
$$Q_m = \rho \bar{u} A = \rho A C_o \sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^o\right)} - \frac{\rho g C_o^2 A^2}{A_t} t$$

Initial height, h_L^o

Liquid Discharge from a Tank

- Calculation Equation Summary
  - Amount of material discharged to leak level
  - Time required for this material to leak
  - Maximum mass flow rate through the leak at $t = 0$
  - Average discharge velocity and mass flow rate at any time

Liquids in Pipes: Energy Balance



P_1, u_1, Z_1 → → P_2, u_2, Z_2

Mechanical energy balance, constant density:

$$\frac{\Delta P}{\rho} + \frac{\Delta \bar{u}^2}{2\alpha\, g_c} + \frac{g}{g_c}\Delta z + F = -\frac{W_s}{m}$$

Energy: V∆P, KE, PE, friction, shaft work

The KE term can often be neglected.

Liquids in Pipes: Friction

Friction term is sum of all friction elements:

$$F = \left(\sum_i K_{f\,i} \right) \frac{\bar{u}^2}{2g_c}$$

K_{f_i} **is excess head loss for element *i* in piping system**

for flow in pipe of length *L*, inside diameter, *d*:

$$K_f = \frac{4fL}{d}$$

Fanning friction factor, *f*, is function of *Re* and ε , p.122, eqn 4-32 (Colebrook eqn)

Fanning Friction Factor

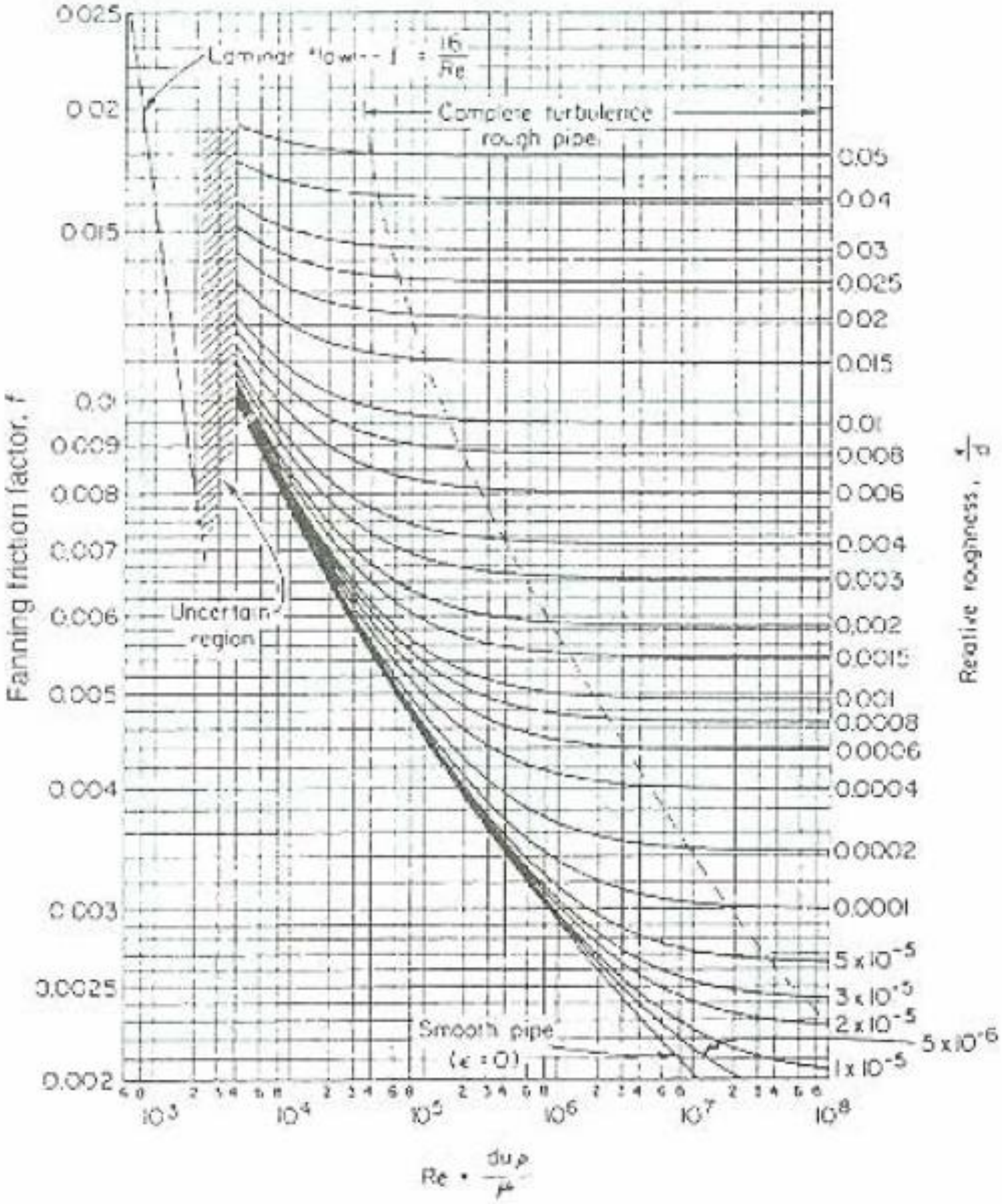
- ***f(Re)*** **shown in Fig. 4-7, p. 123. Various regimes**
- **Laminar flow, *f* = 16/*Re***
- **Turbulent flow, *Colebrook Equation***

$$\frac{1}{\sqrt{f}} = -4\log\left(\frac{1}{3.7}\frac{\varepsilon}{d} + \frac{1.255}{R_e\sqrt{f}}\right)$$

ε **is roughness factor;** ε / d **is relative roughness**

For large *Re*, *f* is independent of *Re*: $\frac{1}{\sqrt{f}} = 4\log\left(3.7\frac{d}{\varepsilon}\right)$

For smooth pipe, ε ***~ 0:*** $\frac{1}{\sqrt{f}} = 4\log\frac{R_e\sqrt{f}}{1.255}$



0.025
0.02
0.015
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.0025
0.002
Fanning friction factor, f
Laminar flow — $f = \frac{16}{Re}$
Complete turbulence rough pipe
Uncertain region
Smooth pipe ($\epsilon = 0$)
0.05
0.04
0.03
0.025
0.02
0.015
0.01
0.008
0.006
0.004
0.003
0.002
0.0015
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
5×10^{-5}
3×10^{-5}
2×10^{-5}
5×10^{-6}
1×10^{-5}
Relative roughness, $\frac{\epsilon}{d}$
10^3
10^4
10^5
10^6
10^7
10^8
$Re = \frac{du\rho}{\mu}$

2-K Method for Flow Friction

Equivalent pipe length method for all piping fittings:

$$L_{eq,total} = L_{st\ pipe} + \sum_i L_{eq,i}$$

2-K uses actual lengths and 2 parameters: K_1, K_∞

$$K_f = \frac{4fL}{d}$$ **, pipe lengths**

$$K_f = \frac{K_1}{\mathrm{Re}} + K_\infty \left(1 + \frac{1}{ID_{in}} \right)$$ **, elbows, tees, valves**

$$K_f = \frac{K_1}{\mathrm{Re}} + K_\infty$$ **, pipe entrances, exits**

Depending on the *Re* regimes, may be simplified.

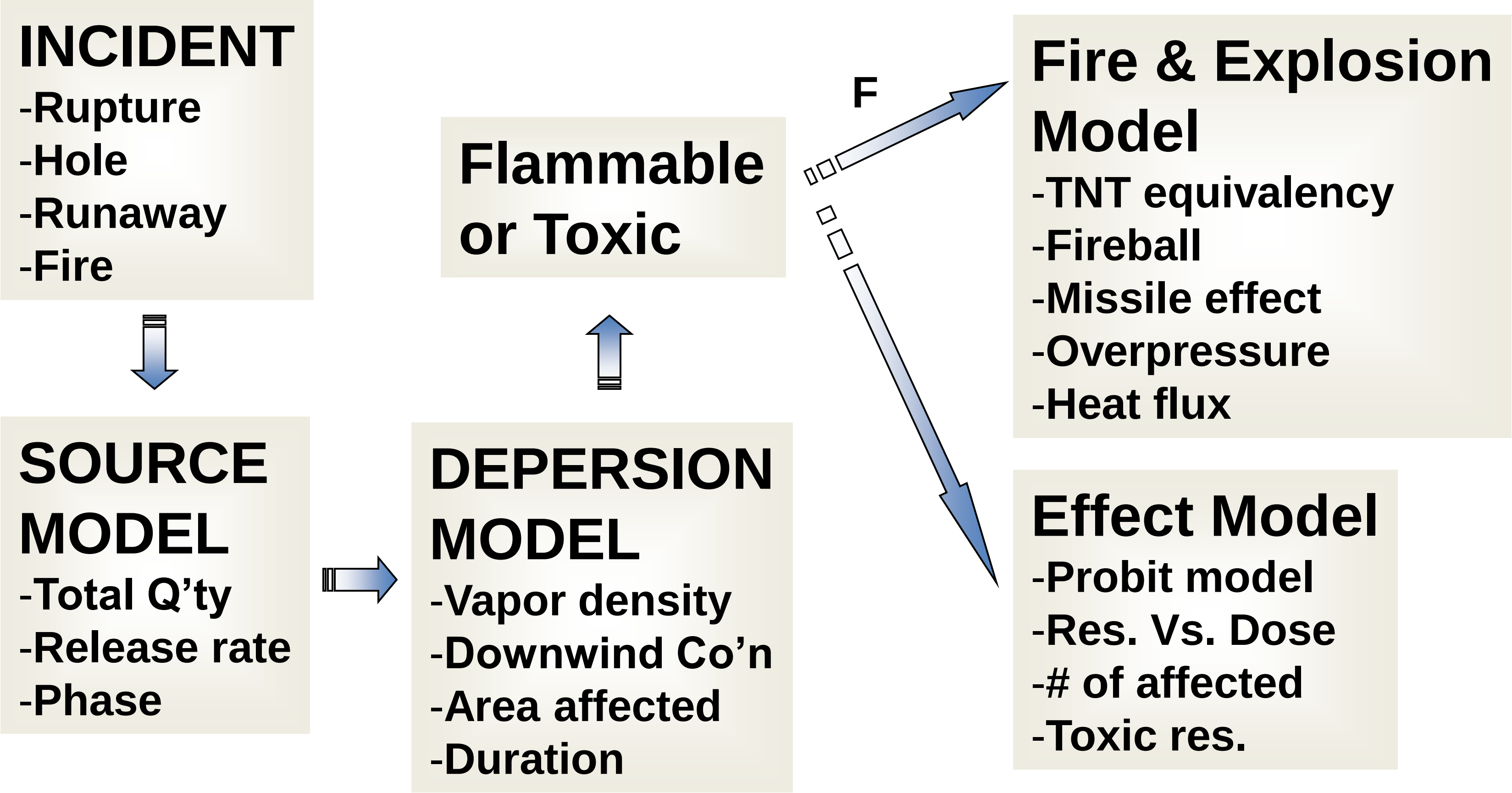
Pipe: Estimate Mass Flow Rate

Summary

1. **Obtain system info between *start* and *end* points: fittings, fluid properties, pressures, elevations, velocity**
2. **State energy balance for *start* and *end*; Drop KE term?**
3. **Include loss terms for *F*. Depending on flow regime, estimate or guess $\bar{u}$ at *end*.**
4. **Estimate *Re* and corresponding *f* and *F***
5. **Substitute values into energy balance and calculate $\bar{u}$**
6. **If $\bar{u}$ not ~ guessed value, return to Step 3 until converged**
7. **Calculate mass flow rate, source term: $\rho \bar{u} A = Q_m$**
8. **Test the effect of approximations on $\bar{u}$ and Q_m**

Source Models, Gases

Consequence Analysis



INCIDENT
- Rupture
- Hole
- Runaway
- Fire

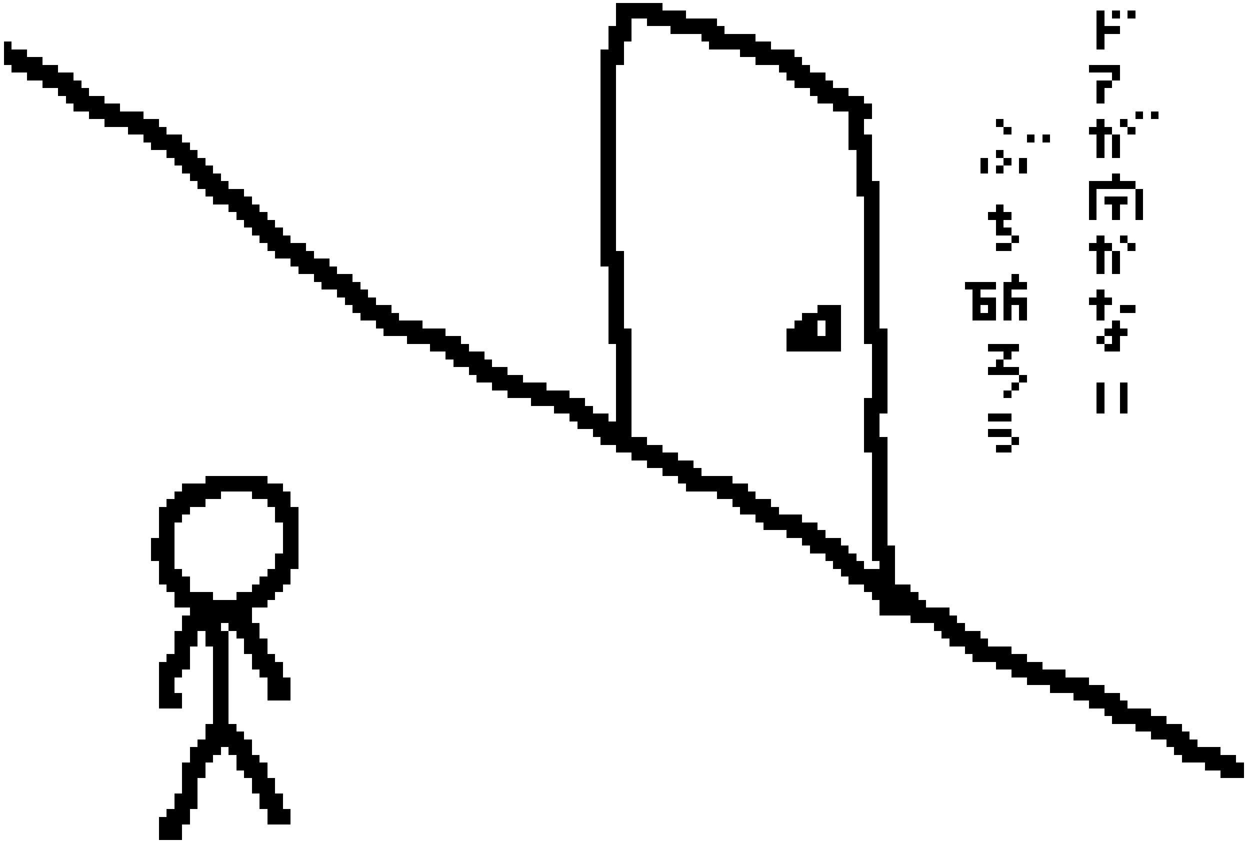
SOURCE MODEL
- Total Q’ty
- Release rate
- Phase

DEPERSION MODEL
- Vapor density
- Downwind Co’n
- Area affected
- Duration

Flammable or Toxic

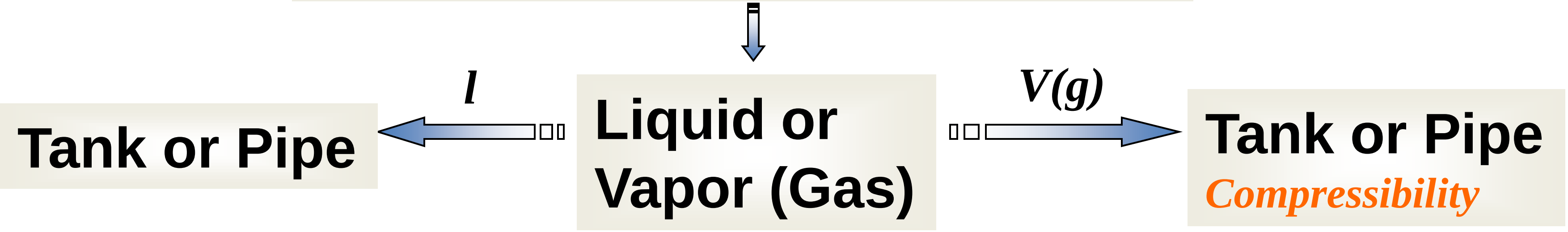
Fire & Explosion Model
- TNT equivalency
- Fireball
- Missile effect
- Overpressure
- Heat flux

Effect Model
- Probit model
- Res. Vs. Dose
- # of affected
- Toxic res.


ドアが開かない
ぶち破ろう

Release Rate Model

$$\int \frac{dP}{\rho} + \frac{\Delta \bar{u}^2}{2\alpha g_c} + \frac{g}{g_c}\Delta z + F = -\frac{W_s}{m}$$



Tank or Pipe

l

Liquid or Vapor (Gas)

V(g)

Tank or Pipe

Compressibility

Tank, General $$Q_m = A C_0 \sqrt{2 g_c \rho P_g}$$

$$\int \frac{dP}{\rho} = \frac{\Delta P}{\rho}$$

Tank, Head $$Q_m = \rho A C_o \sqrt{2\left(\frac{g_c P_g}{\rho} + g h_L^o\right)} - \frac{\rho g C_o^2 A^2}{A_t} t$$

Pipe **F =** $func(L, d, \varepsilon, \mathrm{Re})$

Mechanical energy

Flow of Gases through Holes

- Large changes in pressure and density, unlike liquids

$$\int \frac{dP}{\rho} \neq \frac{\Delta P}{\rho}$$

- Throttle expansion through cracks
  - with large frictional losses and lower velocities, *not treated here*
- Free expansion with isentropic behavior approximated
  - important for safety analysis
- Assume small potential energy changes,
- No shaft work, $W_s = 0$

$$\Delta z \sim 0$$

Mechanical Energy Balance

$$\int \frac{dP}{\rho} + \frac{\Delta \bar{u}^2}{2\alpha g_c} + \frac{g}{g_c}\Delta z + F = -\frac{W_s}{m}$$

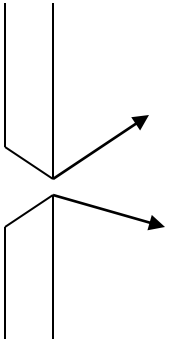
Process

$P \;\; = P_o$

$u_1 \sim 0$

$\Delta z \sim 0$

$W_s = 0$



Surroundings (choked)

$P_{ext} < P_{choked}$

Gas at throat (choked)

u_2 = sonic velocity

$P_{throat} = P_{choked}$

Free expansion: $$\int \frac{dP}{\rho} + \frac{\bar{u}^2}{2\alpha g_c} + F = 0$$

Isentropic Expansion

Incorporate friction term:

$$\int \frac{dP}{\rho} + F = C_1^2 \left(\int \frac{dP}{\rho} \right)$$

$$C_1^2 \int_{P_o}^{P} \frac{dP}{\rho} + \frac{\bar{u}^2}{2\alpha g_c} = 0$$

Ideal gas, isentropic expansion: $\frac{P}{\rho^\gamma}$ **= a,** $\gamma = C_p / C_v$

Integrate and solve for $\bar{u}$ **Mass flow rate:**

$$Q_m = C_o A P_o \sqrt{\frac{2 g_c M}{R_g T_o} \frac{\gamma}{\gamma - 1} \left[\left(\frac{P}{P_o} \right)^{2/\gamma} - \left(\frac{P}{P_o} \right)^{(\gamma+1)/\gamma} \right]}$$

Heat Capacity Ratio Values

Real gas: $$C_P - C_V = \left[P + \left(\frac{\partial E}{\partial V} \right)_T \right] \left(\frac{\partial V}{\partial T} \right)_P$$

Perfect gas: E(T), PV = RT $\longrightarrow$ $\boldsymbol{C_P - C_V = R}$

Atoms: C_V = (3/2)R

$$\gamma = \frac{C_P}{C_V} = \frac{(3/2)R + R}{(3/2)R} = \frac{5}{3} = 1.67$$

Molecules: C_V = 3R, nonlinear; (5/2)R, linear

Diatomic/triatomic

(normal T)

$$\frac{C_P}{C_V} = \frac{3R + R}{3R} = \frac{4}{3} = 1.33, \text{nonlinear}$$

$$\frac{(5/2)\mathrm{R} + \mathrm{R}}{(5/2)\mathrm{R}} = \frac{7}{5} = 1.40, \text{linear}$$

Choked Pressure

For safety assessments: need maximum flow rate

Differentiate Q_m by P/P_o and set to zero:

$$\frac{P_{choked}}{P_o} = \left(\frac{2}{\gamma + 1} \right)^{\gamma/(\gamma+1)}$$ **($P_{ext} < P_{choked}$) , function of** γ

Choked pressure: maximum downstream pressure resulting in the maximum flow. Sonic u at throat.

Q_m independent of downstream conditions

$$Q_{m,choked} = C_o A P_o \sqrt{\frac{\gamma g_c M}{R_g T_o} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)}}$$

Discharge Coefficient, C_o

- For non-choked flows: for sharp-edge holes, $R_e > 30{,}000$, use $C_o = 0.61$
- Choked flows: C_o increases as P decreases. Therefore:
- For choked flows, use $C_o = 1$
- For C_o not known, use $C_o = 1$

Flow of Gases through Pipes

- Isothermal and adiabatic models predict similar results for most real cases
- The adiabatic model predicts larger values and is preferred for process safety estimations.
- Mach number, $Ma = \bar{u} / a$
- Speed of sound (ideal gas),

$$a = \sqrt{\gamma g_c R_g T / M}$$

Adiabatic Gas Flow Model

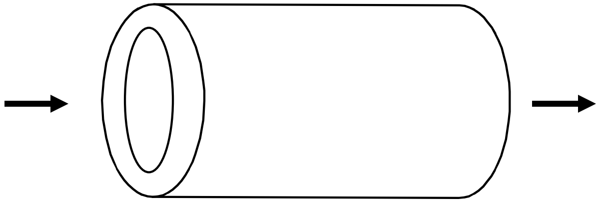
- **Gas expansion → decrease in pressure, increase in velocity, KE increases**
- **Temperature: tends to increase due to KE increase; tends to decrease due to friction**
- **Adiabatic choked flow: most important and most usual case for safety estimations**

Adiabatic Choked Flow, Pipe

External, $P < P_{choked}$

$\Delta z \sim 0$; $W_s = 0$

$$\Delta Q = 0$$



P_1, T_1, u_1, Ma_1 → **$P_{choked}, T_2, a, Ma_2 = 1$**

Mass flux

$$G = \frac{\dot{m}}{A} = Y_g \sqrt{\frac{2 g_c \rho_1 (P_1 - P_2)}{\sum K_{f_i}}}$$

Gas expansion factor

$$Y_g = Ma_1 \sqrt{\frac{\gamma \sum K_{f_i}}{2} \left(\frac{P_1}{P_1 - P_2} \right)}$$

Calculation Procedure

- **Use correlations for Y_g and sonic pressure drop ratio, $(P_1-P_2)/P_1$, Tab. 4-4, p. 143 or Figs 4-13, 4-14**

1. **Obtain gas and pipe system information, ΔP,**
2. **Assume fully developed turbulent flow; find f** $\sum K_{f_i}$
3. **Find $(P_1-P_2)/P_1$, Fig 4-13; check if sonic, $P_{ext} < P_2$; calculate P_2**
4. **Determine Y_g from correlation**
5. **Calculate mass flow rate,** $AG = \rho \bar{u} A$
6. **Check flow assumption from value of Re**

Flashing Liquids

- Liquids held at T above boil point, $T_{b;}$ P > 1 atm.
- Sudden release to lower pressure can be explosive.
- Model assumes adiabatic behavior
- Excess energy provides heat of vaporization to reduce T to T_b (model assumes no heat dissipated.)

Source Model for Liquid Vaporized

Excess energy of liquid (pure): $Q = m_L C_p (T_o - T_b)$

***T_o*: liquid temp before release**

Mass of vaporized liquid: $m_V = \dfrac{Q}{\Delta H_V} = \dfrac{m_L C_p (T_o - T_b)}{\Delta H_V}$

Fraction vaporized:

$$f_V = \frac{m_V}{m_L} = \frac{C_p (T_o - T_b)}{\Delta H_V}$$

Source Model for Boiling Liquids

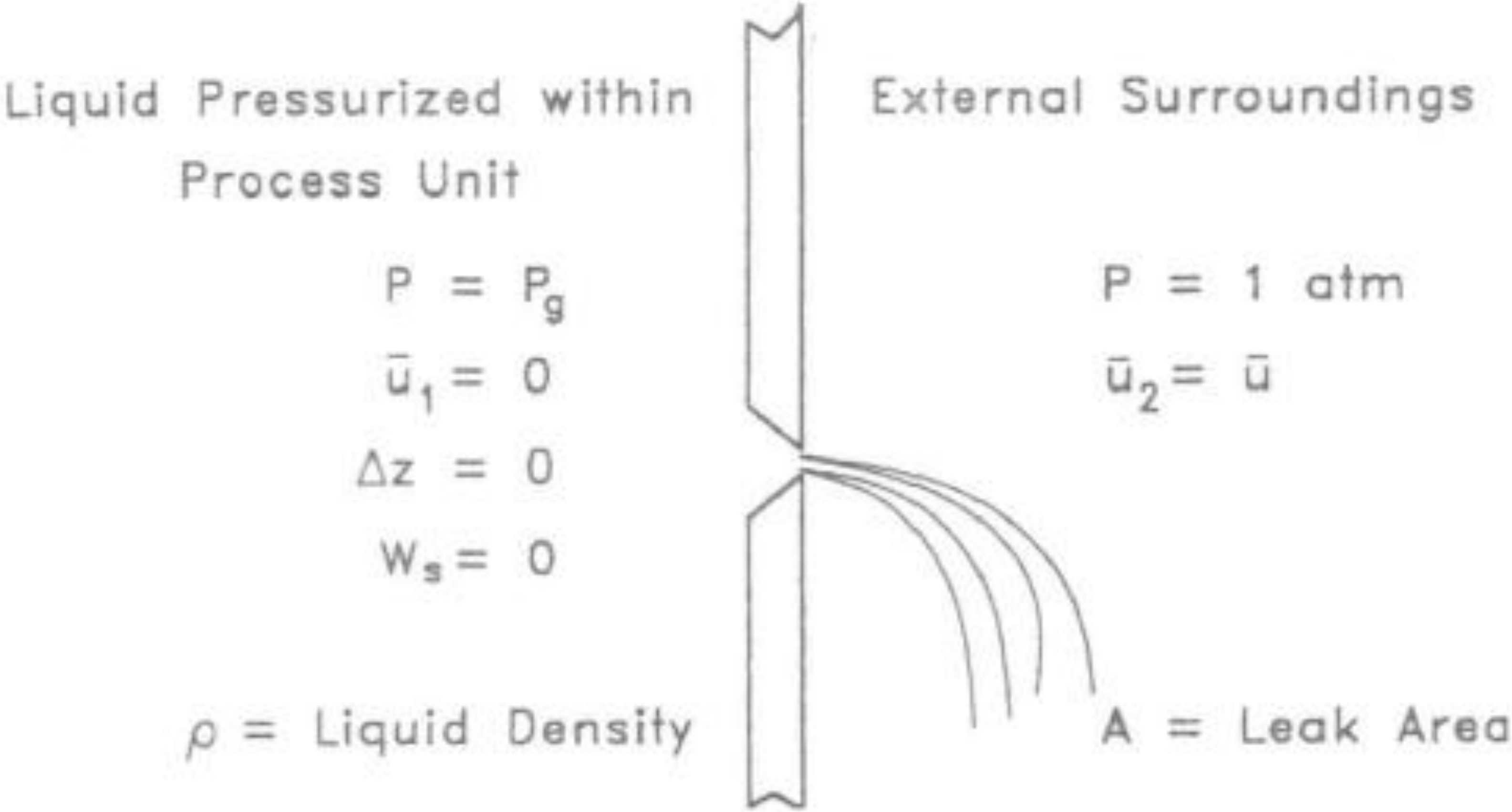
- **Boiling rate determined by heat transfer from surroundings: ground, air, radiation**
- **Initial stage: heat flux, q_g, from ground based on thermal conductivity, k_s, and diffusivity, a_s, of soil; temp of soil, T_g, time after spill, t:**

$$q_g = \frac{k_s(T_g - T)}{\sqrt{\pi \alpha_s t}}$$

- **Rate of boiling:**

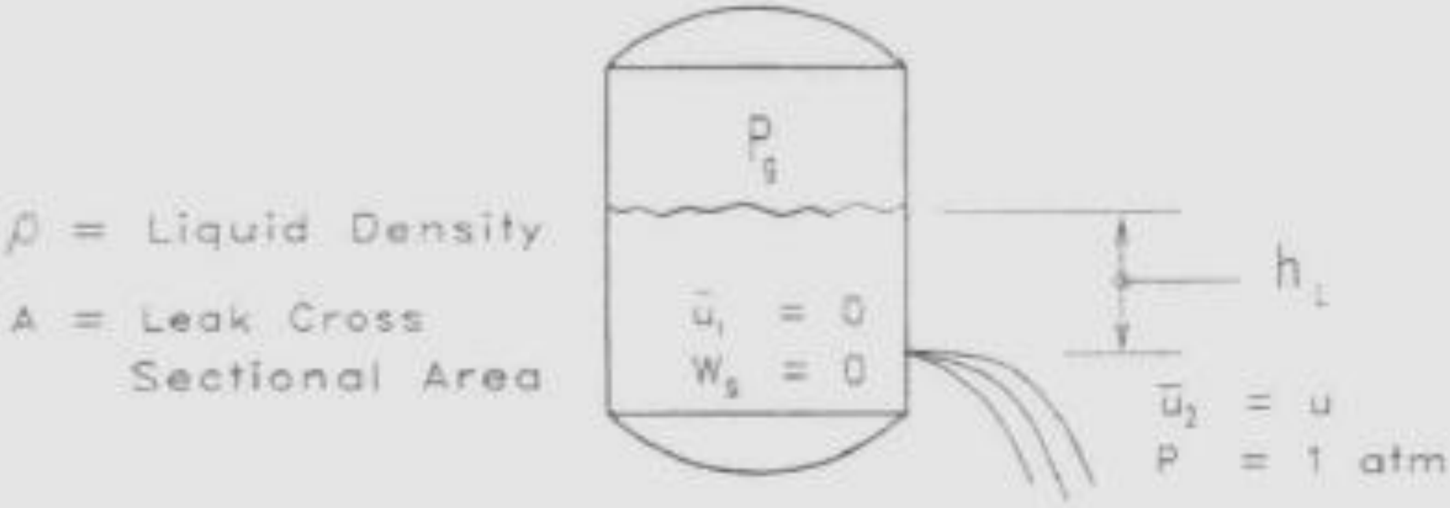
$$Q_m = \frac{q_g A}{\Delta H_V}$$

A, area of pool



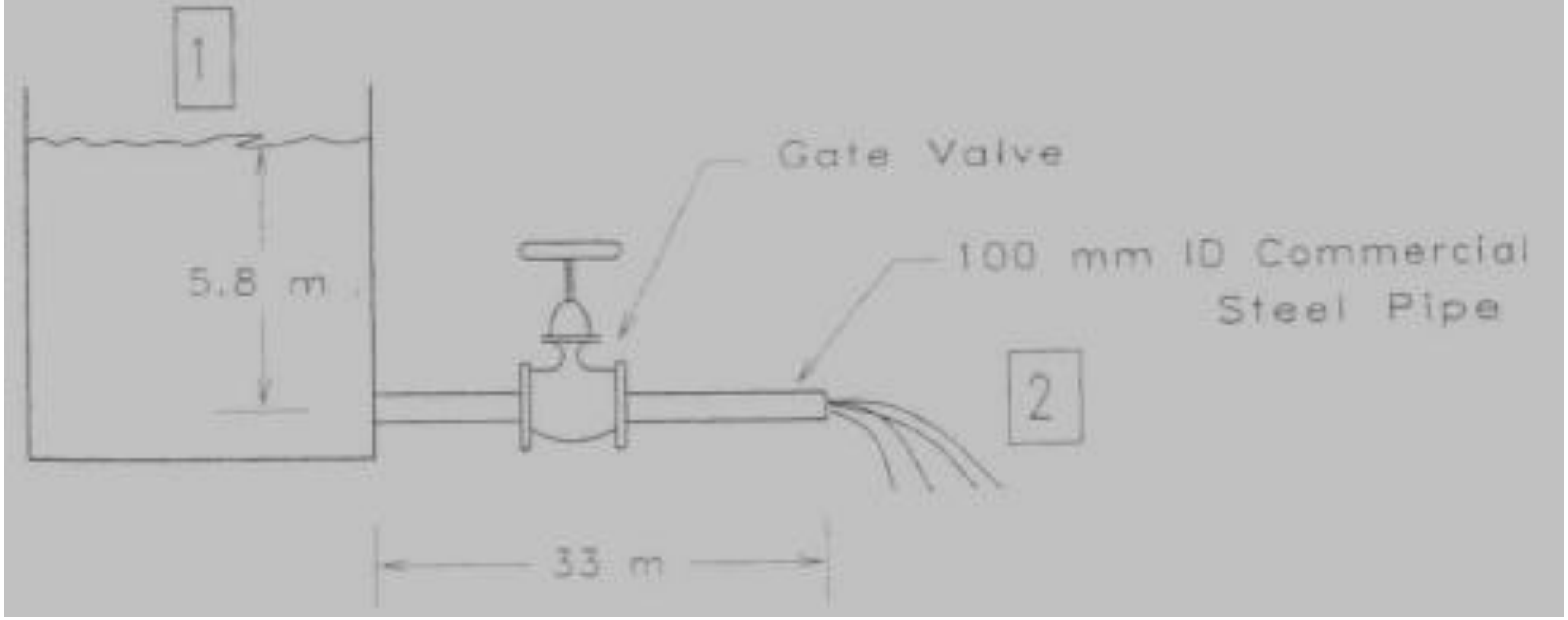
$$\boxed{Q_m = AC_o\sqrt{2\rho g_c P_g}}$$

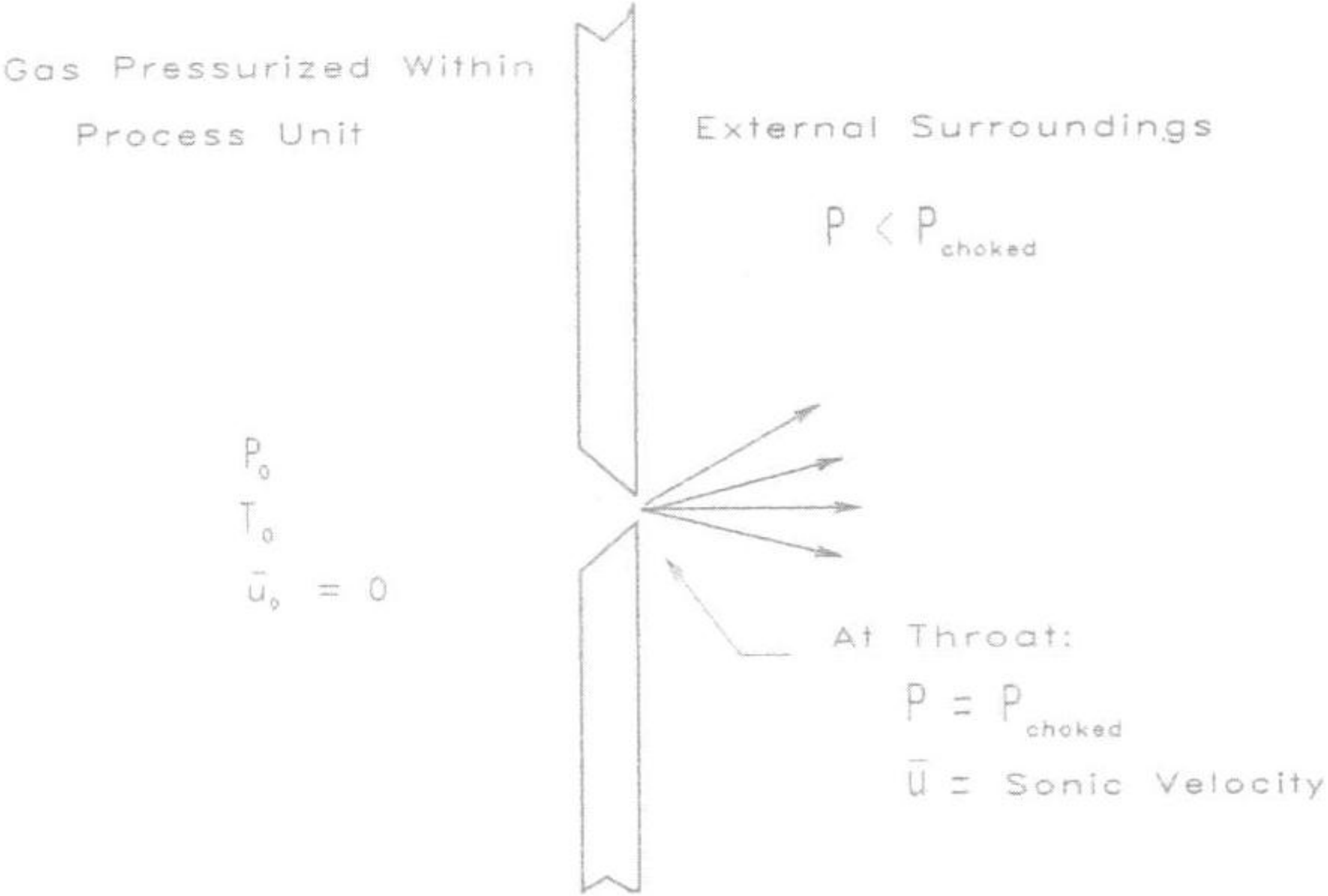
Process Vessel



$$Q_m = \rho A C_o \sqrt{2\left[\frac{g_c P_g}{\rho} + g h_L\right]}$$

$$\frac{g}{g_c}\Delta z + F = 0.$$




Gas Pressurized Within
Process Unit
External Surroundings
$P < P_{choked}$
P_0
T_0
$\bar{u}_0 = 0$
At Throat:
$P = P_{choked}$
$\bar{u}$ = Sonic Velocity