A Slippery Slope

The Importance of Draining in Process Safety

October 2021

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Problem Description

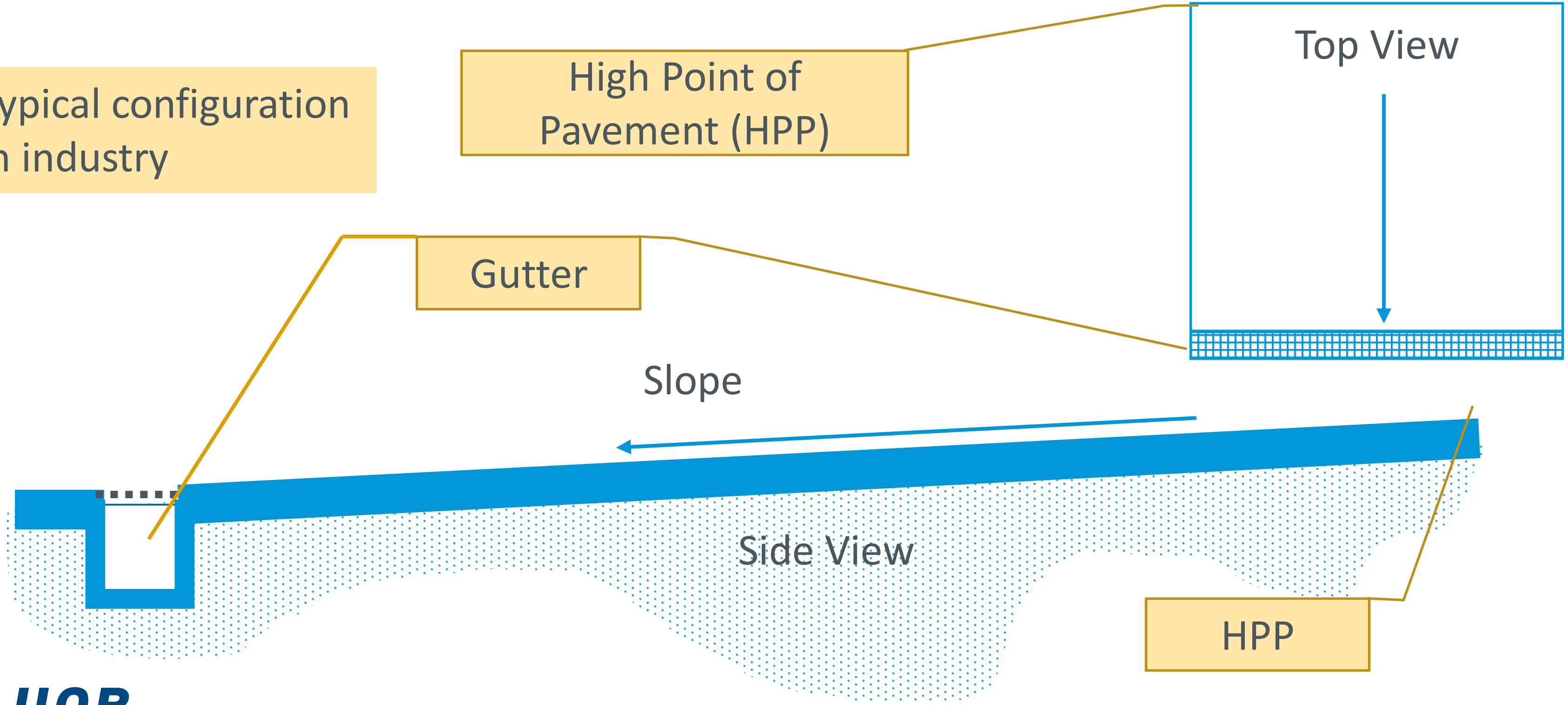
- Brownfield projects in existing (congested) areas
- Current models (i.e., PHAST/SAFETI-NL) provide conservative results
  - Standard burning rate
  - No adjustment for sloped areas or thin layer liquid spills
  - No contingency for fuel removal
- Spill fire dynamics are fundamentally different than stagnant pool fires

Model

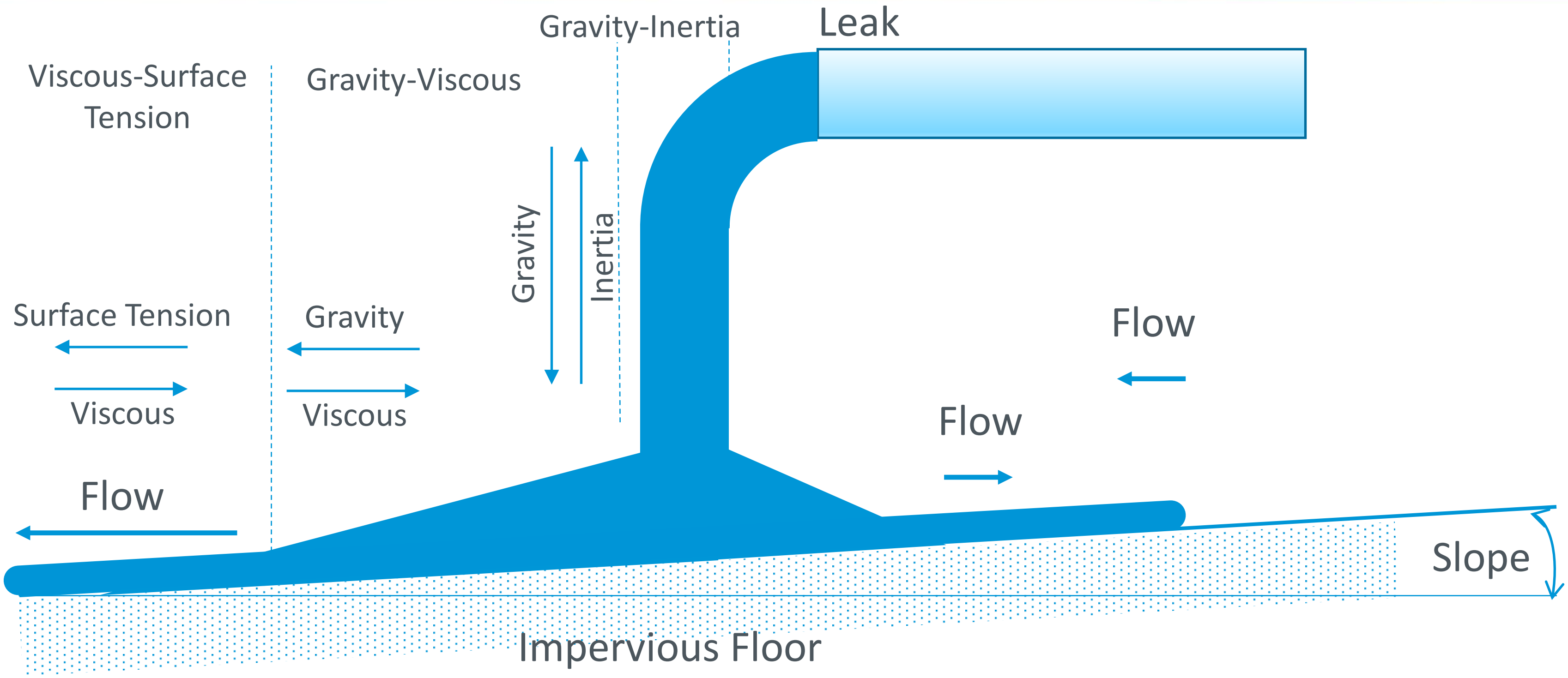
- Spill of liquid fuel on sloped concrete floor
  - Initial Gravity-Inertia Regime
  - Gravity-Viscous Regime
  - Viscous-Surface Tension Regime
- Assumed gutter for spill removal with sufficient capacity to remove the collected liquid
- Ignition of flammable vapour leads to spill fire on sloped floor

Impervious Floor

Typical configuration in industry



Spill Dynamics



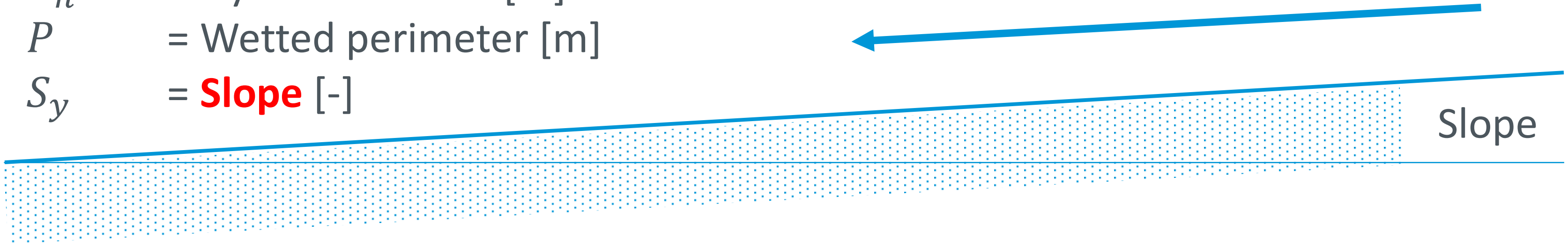
Liquid Velocity Downhill

- Manning Equation

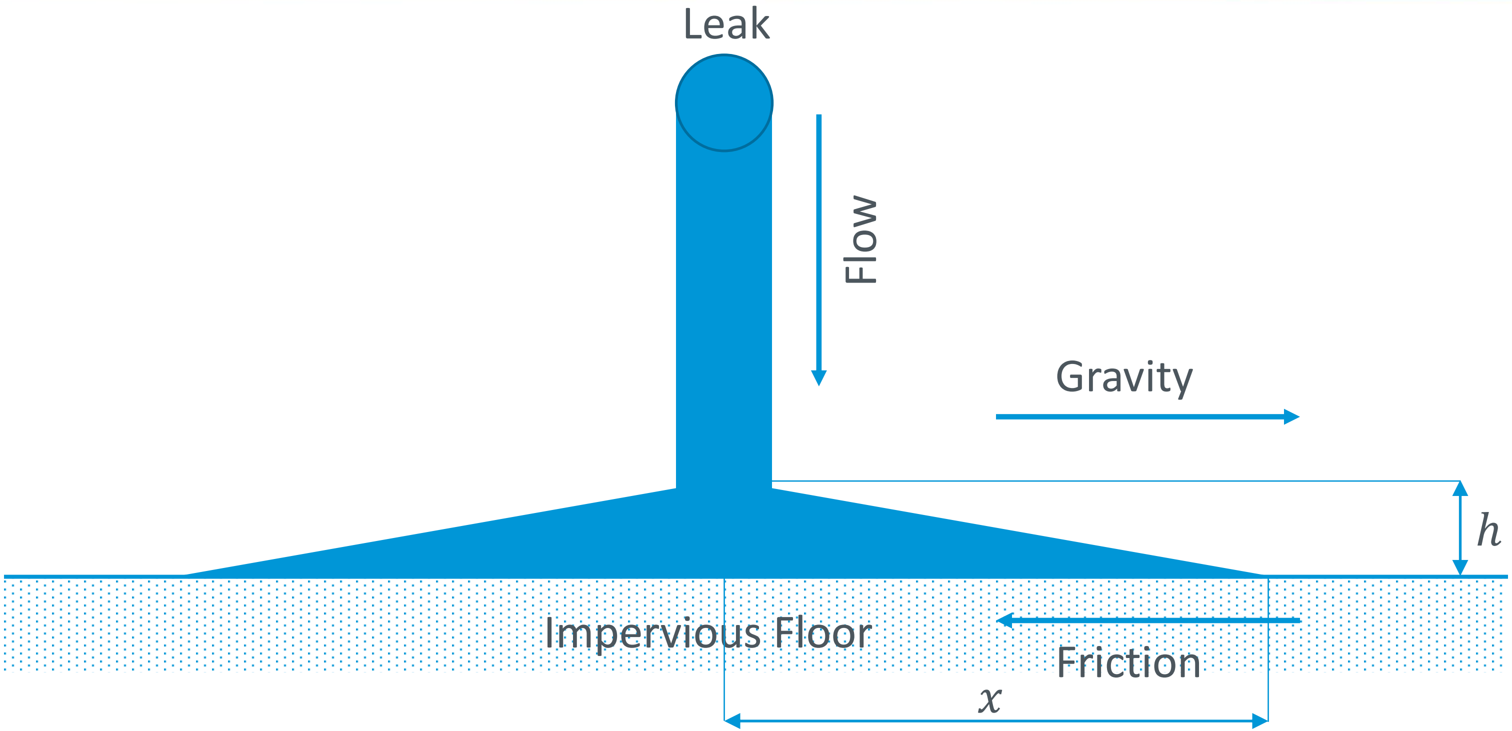
$$Q = v_y A = \frac{k}{n} A \, R_h^{2/3} \, S_y^{1/2} \qquad R_h = \frac{A}{P}$$

Q	= Flow rate [m³/s]
v_y	= Velocity down slope [m/s]
A	= Cross sectional flow area [m²]
k	= Unit factor k =1
n	= Manning's roughness coefficient [s/m$^{1/3}$]
R_h	= Hydraulic radius [m]
P	= Wetted perimeter [m]
S_y	= **Slope** [-]

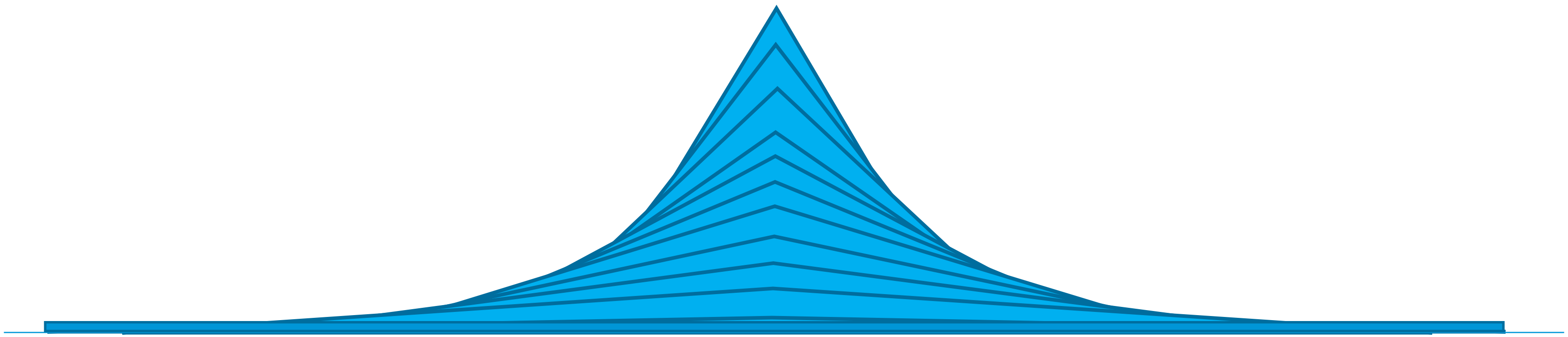
$$v_y = \frac{k}{n} R_h^{2/3} \, \mathbf{S_y^{1/2}}$$



Spill Cross Flow



Cross Sectional Movement



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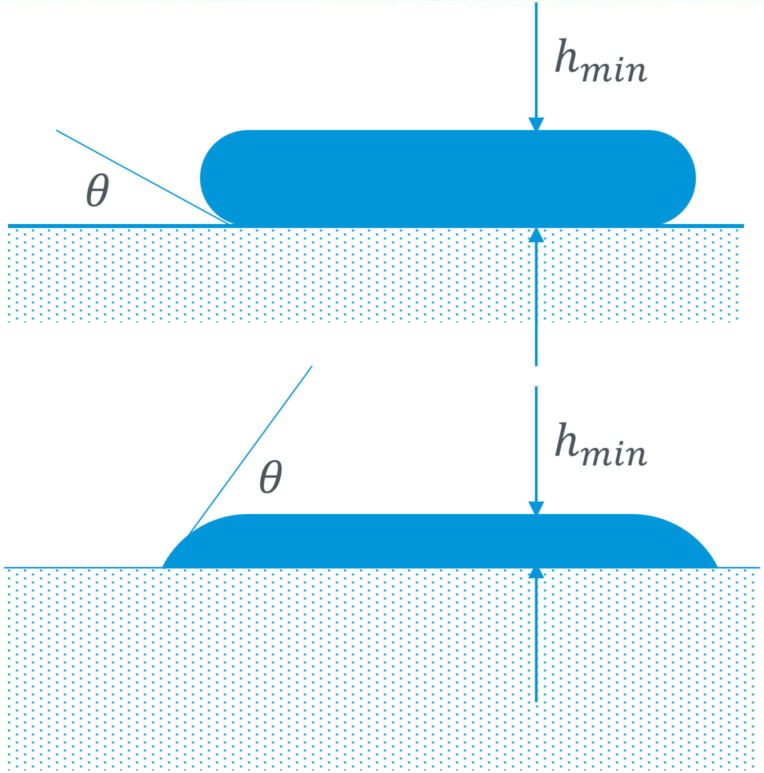
Liquid Layer Thickness

$$h_{min} = \sqrt{\left(\frac{2\sigma\left(1 - cos(\theta)\right)}{\rho g}\right)}$$

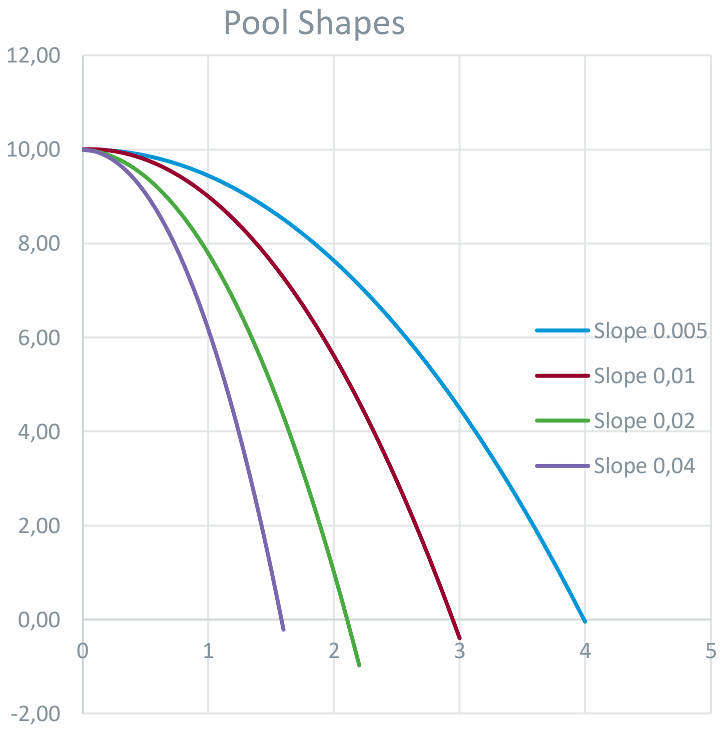
h_{min} = Minimum Layer Thickness [m]
σ = Surface Tension [N/m]
θ = Contact Angle [°]
ρ = Density of the Liquid [kg/m³]
g = Gravitational Acceleration [m/s²]

Contact Angle depends on substance and substrate



Pool Shapes (Top View)

- Water
- Concrete
- Q = 400 lpm
- y_{target} = 10 m



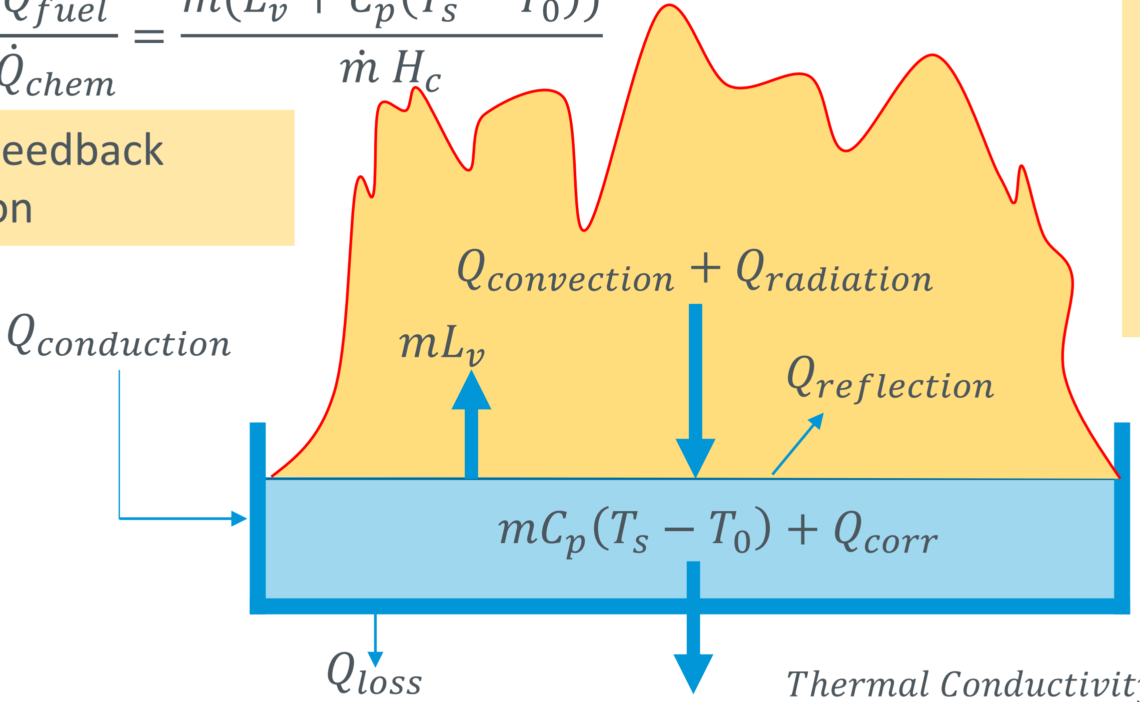
Result Liquid Flow (Q=185 lpm, Water, Concrete, y_{target} = 10 m)

Slope [Sy]	Time [s]	X_{target} [m]	Pool Size [m^2]	Pool Volume [m^3]
0.005	55.6	2.31	39.4	$172x10^{-3}$
0.010	51.6	2.10	35.2	$160x10^{-3}$
0.020	47.8	1.87	31.4	$148x10^{-3}$
0.040	44.4	1.66	28.1	$137x10^{-3}$

Heat Balance Stagnant Pool Fire

$$\chi_s = \frac{\dot{Q}_{fuel}}{\dot{Q}_{chem}} = \frac{\dot{m}(L_v + C_p(T_s - T_0))}{\dot{m}\,H_c}$$

Heat Feedback Fraction



Time to stable combustion is due to heating the liquid pool to NBP, typically 5 – 10 minutes

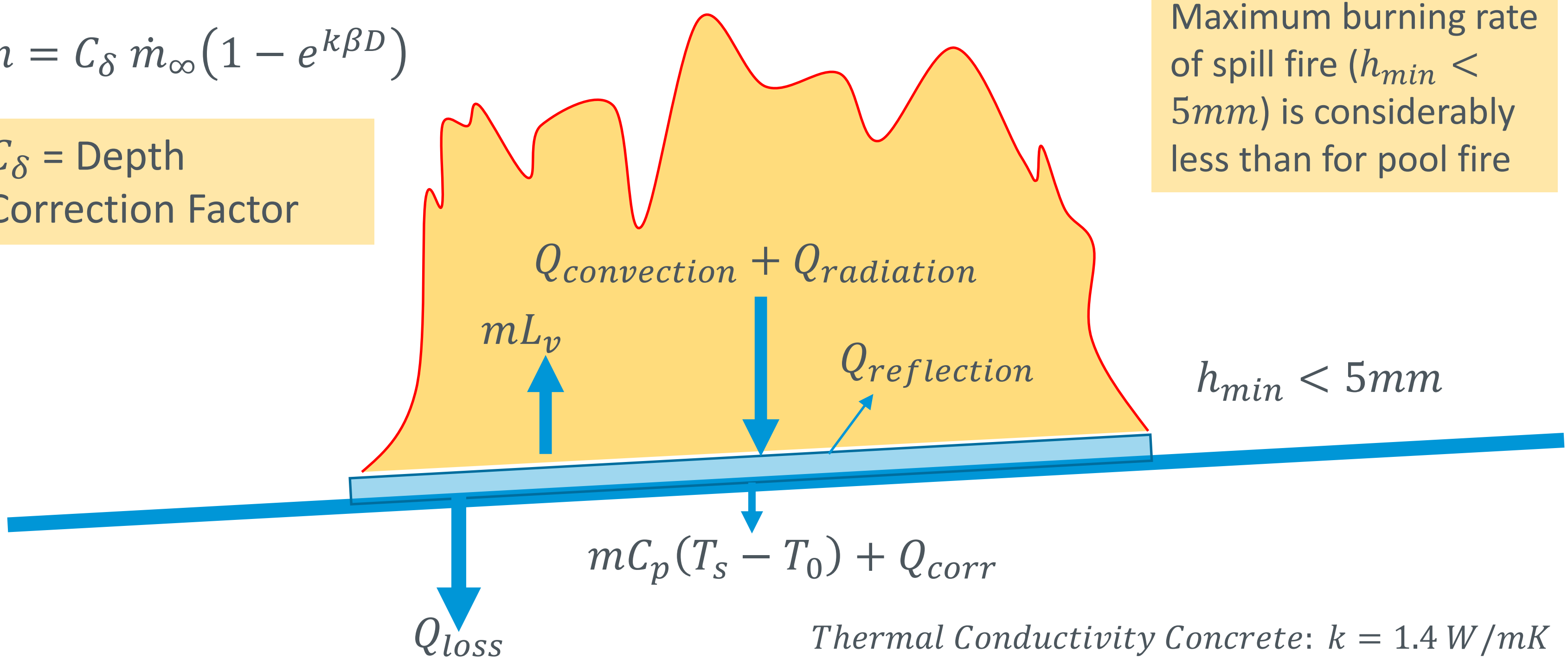
$Thermal\ Conductivity\ Liquid:\ k = 0.11\ W/mK$

Heat Balance Spill Fire

$$\dot{m} = C_\delta \, \dot{m}_\infty \left(1 - e^{k\beta D}\right)$$

C_δ = Depth Correction Factor

Maximum burning rate of spill fire ($h_{min} < 5mm$) is considerably less than for pool fire



$Thermal\ Conductivity\ Concrete:\ k = 1.4\ W/mK$

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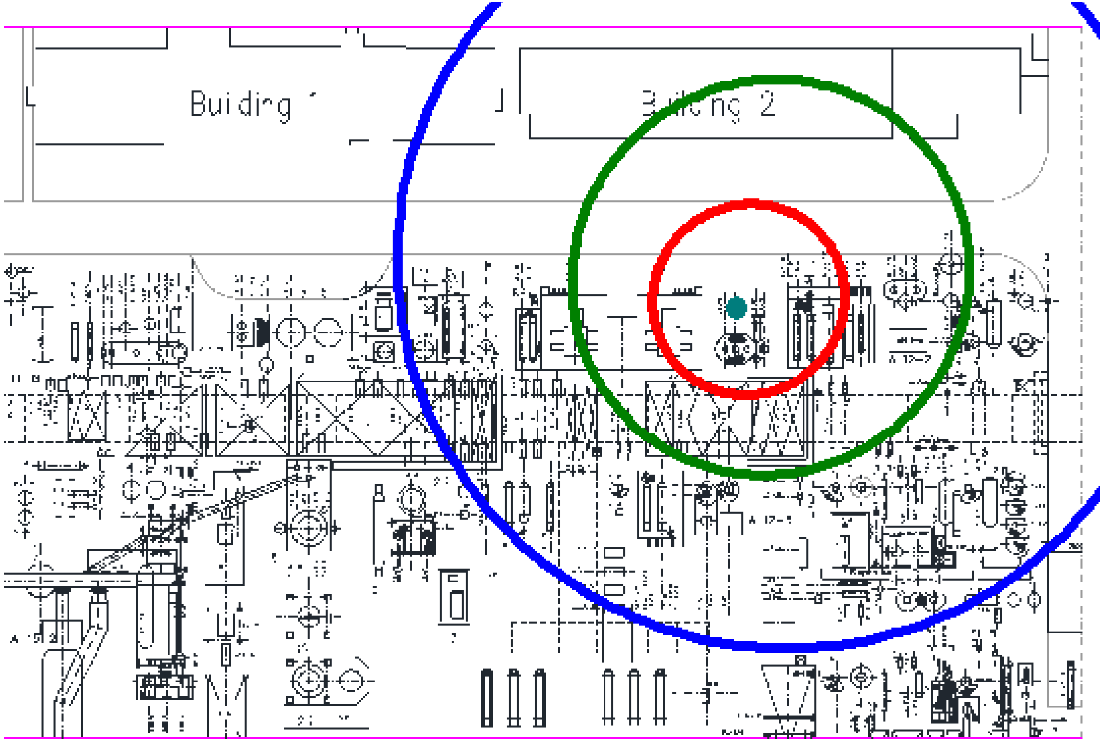
Pool Fire vs. Spill Fire

- Burning rate of stagnant (deep) pool fires are significantly higher than spill fires (Literature provides for the spill fire values of 0.2 – 0.8 times the pool fire standard mass burning rate)
- The spill depth is an important parameter which determines the mass burning rate
- Substrate (i.e., Concrete) acts as a heat sink for radiative energy
- Not all fuel is consumed by the fire. Part is removed through the drain system
- Absorbed heat from the fire is discharged with the liquid

Heat Radiation Contours

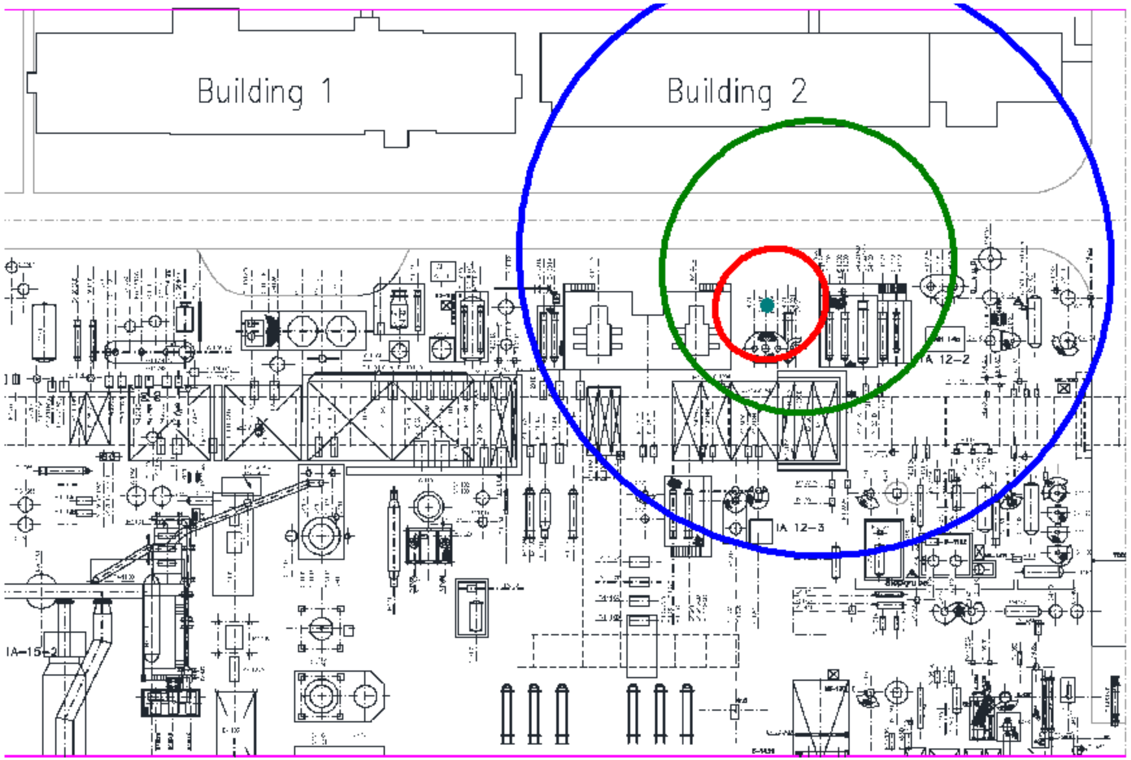
- Leakage 2.12 kg/s N-Heptane
- Late pool fire radii

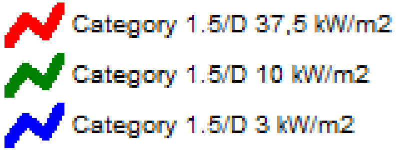


Category 1.5/D 37,5 kW/m2
Category 1.5/D 10 kW/m2
Category 1.5/D 3 kW/m2

Heat Radiation Contours

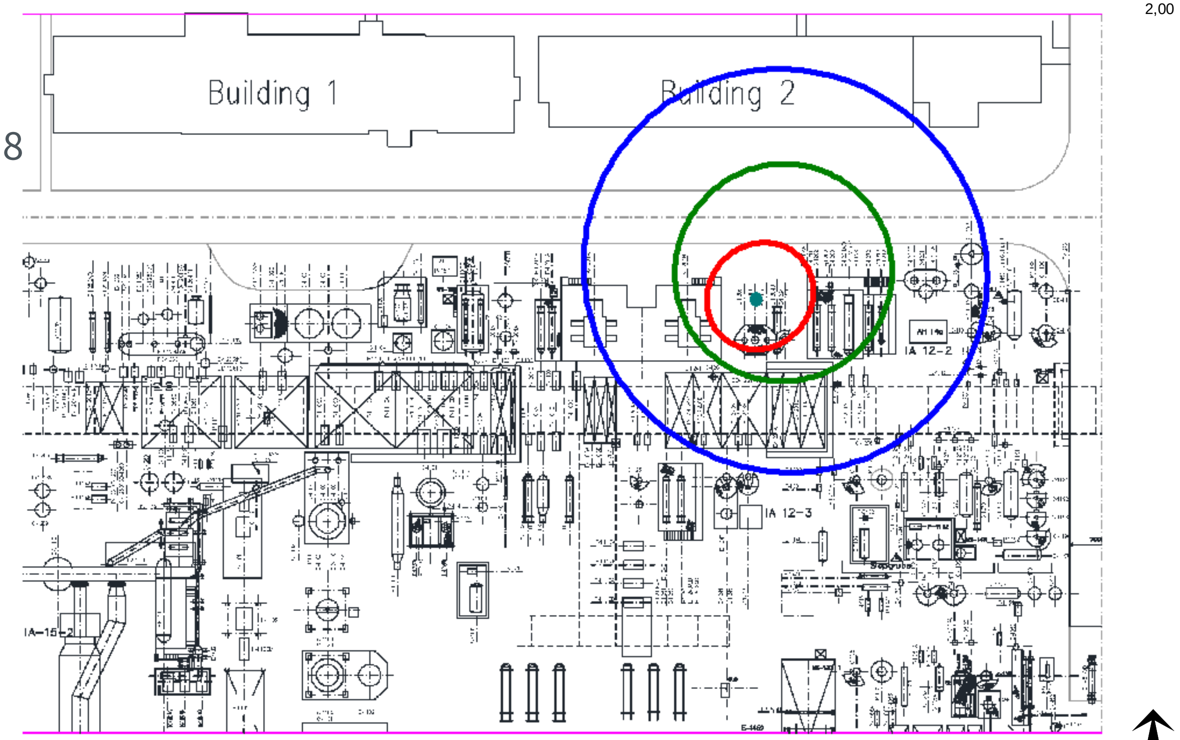
- Leakage 2.12 kg/s N-Heptane
- Pool size = 31 m^2 (Sy=0.005)
- Standard Burning Rate N-Heptane ($m=0.044\ kg/s.m^2$)

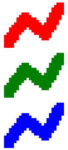




Heat Radiation Contours

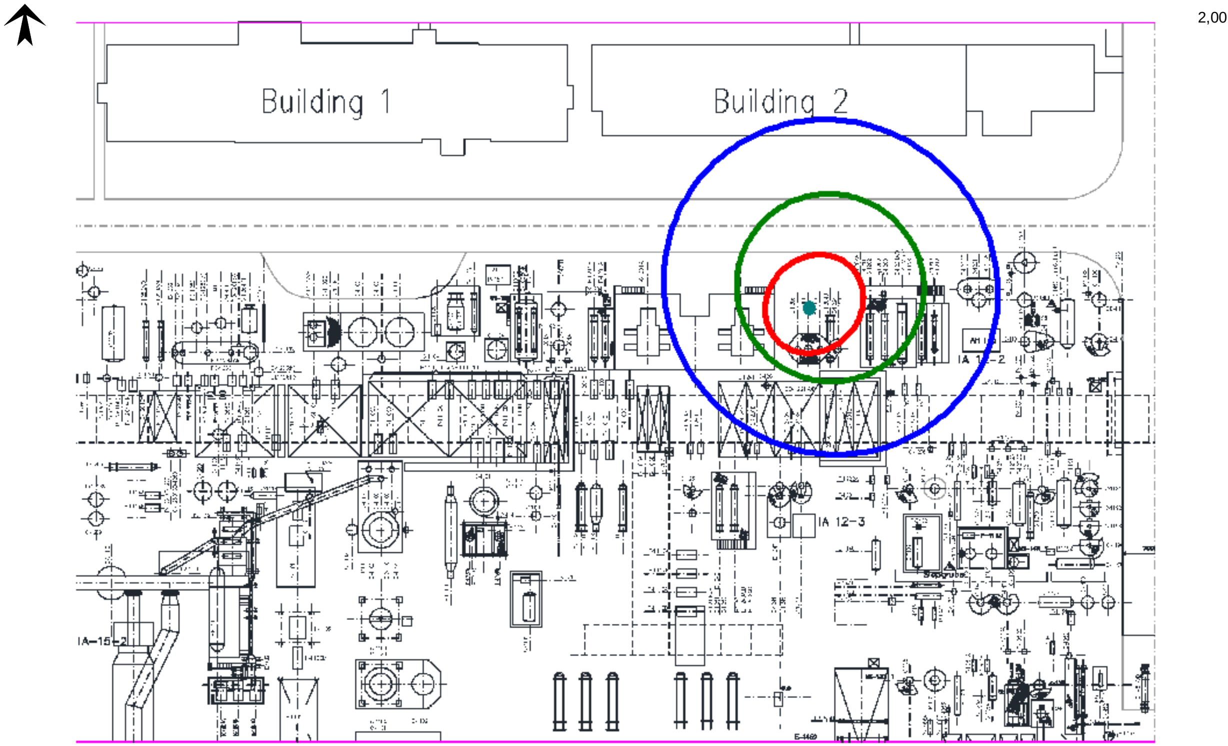
- Leakage 2.12 kg/s N-Heptane
- Pool size = 31 m^2 (Sy=0.005)
- Depth Correction Coefficient = 0.8





Heat Radiation Contours

- Leakage 2.12 kg/s N-Heptane
- Pool size = 24 m² (Sy=0.04)
- Depth Correction Coefficient = 0.5



Category 1.5/D 37,5 kW/m2
Category 1.5/D 10 kW/m2
Category 1.5/D 3 kW/m2

Conclusion

- Minimum liquid height depends on Surface Tension of the spilled liquid and Substrate properties
- Increased slope will reduce the area of a liquid spill
- Decreased area of the spill will reduce the consequence of area depending events like pool fire and pool evaporation
- Burning rate of spill fires (with low liquid height h<5mm) is considerably less than standard burning rate for pool fires
- Increased slope removes more unburned fuel
- Sloped floor provides passive protection (**i.e., always there, never fails**)

Literature

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Thank You

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