Assessment of Fire Hazard Potential within a Hot Cell

Presented by

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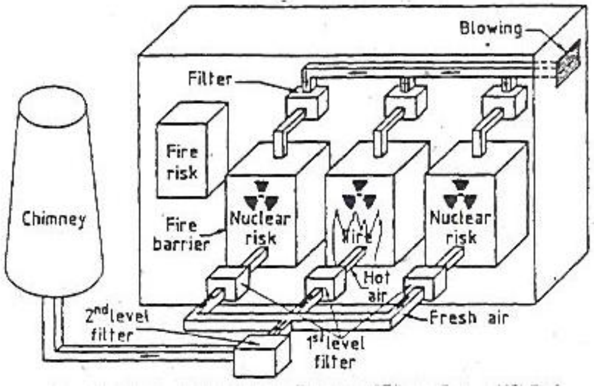
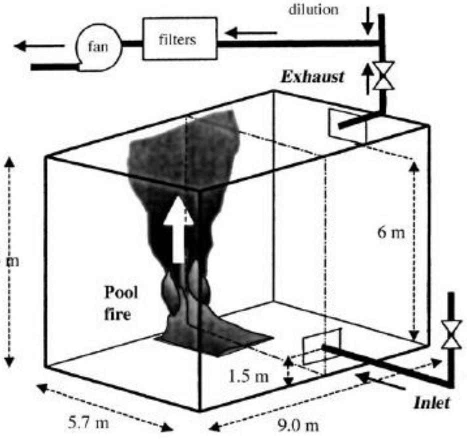
1. Introduction

- Forced ventilated enclosures are common in the nuclear industry.
- Recognizing the safety implications of fire within such enclosures, it is essential that accidental fires are wholly precluded by careful design and operation.



Hot cell/glove boxes

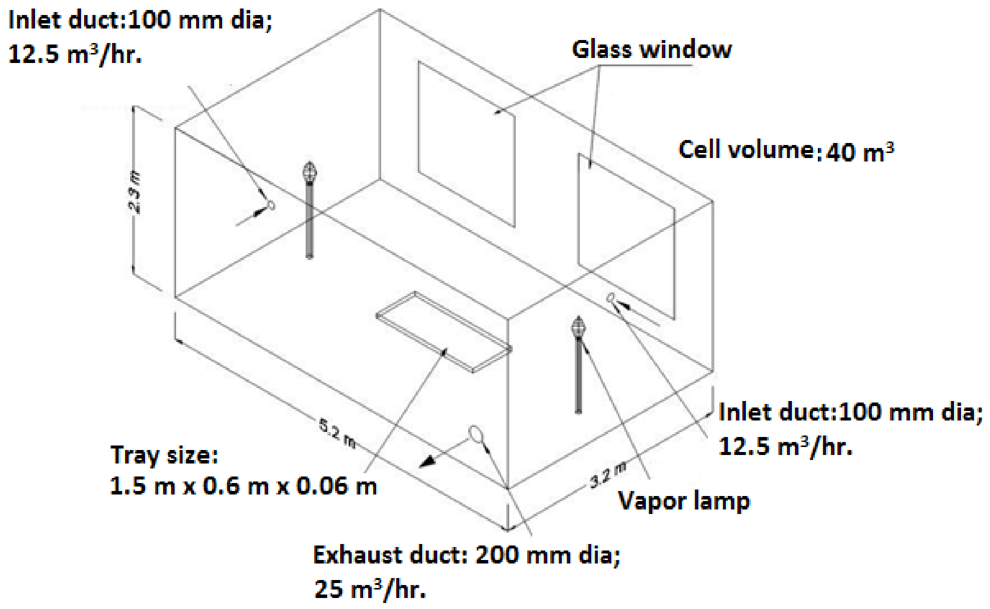
- The present study is aimed at investigating fire safety within in a typical hot cell containing a sodium cleaning system.
- Irradiated fuel subassemblies are cleaned using ethyl alcohol.
- Accidental spill of ethyl alcohol could possibly lead to an enclosure fire scenario.



Reprocessing facility

2. Postulated Fire Scenario

- A scenario is envisaged wherein about 25 L of 99.9% pure ethyl alcohol spills on the leak collection tray (t = 0 s).
- The initial condition within the cell: 95% N_2 and 5% O_2 (inert atmosphere).
- The nitrogen purging system goes out of service at time ‘t’ = 0 s.
- Ambient air leaks into the cell at a specified rate.
- Sodium vapor lamps are ‘ON’, acting as possible ignition source.

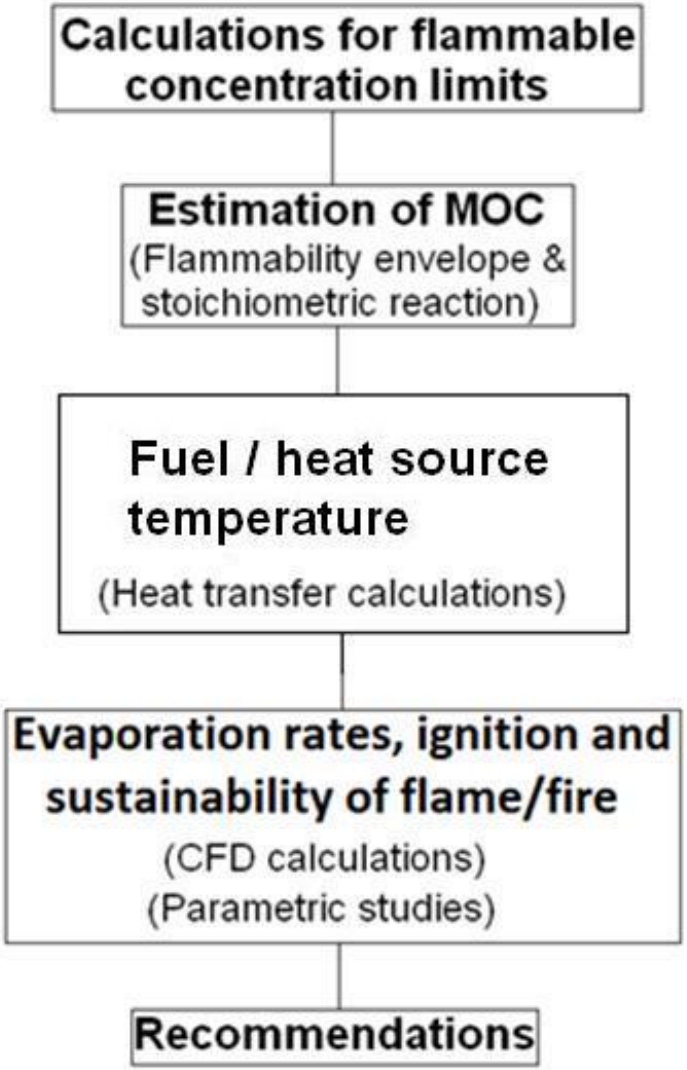


A schematic of the hot cell

Objective

Assess the fire hazard potential due to inadvertent leakage, evaporation and possible ignition of ethyl alcohol vapor in the absence of nitrogen inerting.

3. Calculation Methodology and Tools Used



- The present investigations are carried out using appropriate mathematical models developed in-house at SRI.

- Both lumped parameter as well as CFD calculation techniques are applied.

(a) Flammability Limits

For ethyl alcohol (flash point temperature of 13°C)

LFL ~ 3.3 %; UFL ~ 19.2 % (% vol.)

Quantity of vapor required to form flammable mixture within the hot cell (~ 40 m^3) is calculated as follows:

$$V_e = \left[\left(\frac{V_{cell}}{22.4\times10^{-3}}\right)\times\left(\frac{T_\infty}{T}\right)\times\left(\frac{P}{P_\infty}\right)\right]\times\left(\frac{LFL\ or\ UFL}{100}\right)\times\left(\frac{MW_e}{\rho_e}\right)$$

Minimum and maximum quantity of ethanol needed to attain LFL and UFL conditions: ~ **3.09 L and ~17.81 L** respectively.

Therefore, if 25 L of ethanol completely vaporizes and mixes uniformly within the boxed-up cell, then conditions will be outside flammability limits (~ 27 % by volume).

(b) Estimation of Minimum Oxygen Concentration (MOC)

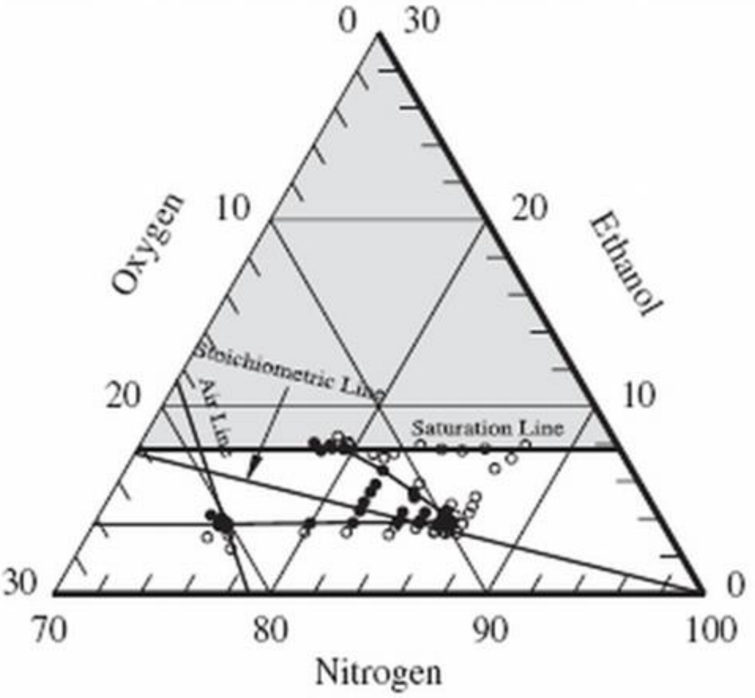
"MOC is the limiting oxygen concentration below which premixed burning can be prevented"

- It is the oxygen concentration corresponding to the stoichiometric reaction of the lean limit fuel i.e., LFL.

- Can also be obtained from the flammability diagram.

- It is evident from the flammability diagram that MOC for ethanol vapor is around 9.9%.

- It is the lowest oxygen concentration in the entire flammability zone .



Flammability envelop for ethanol at 25°C and 1 Atm.

(c) Lumped Parameter Model

The conservation equations for various constituent species i.e., fuel vapor, oxygen and nitrogen within the hot cell can be written as follows:

$$\frac{dY_F}{dt} = \frac{\dot{Q}_{in} \times \xi}{V_{cell}}\left(Y_{F,in} - Y_F\right) + \frac{\dot{Q}_F}{V_{cell}}$$

$$\frac{dY_{O_2}}{dt} = \frac{\dot{Q}_{in} \times \xi}{V_{cell}}\left(Y_{O_2,in} - Y_{O_2}\right)$$

Analytical solution

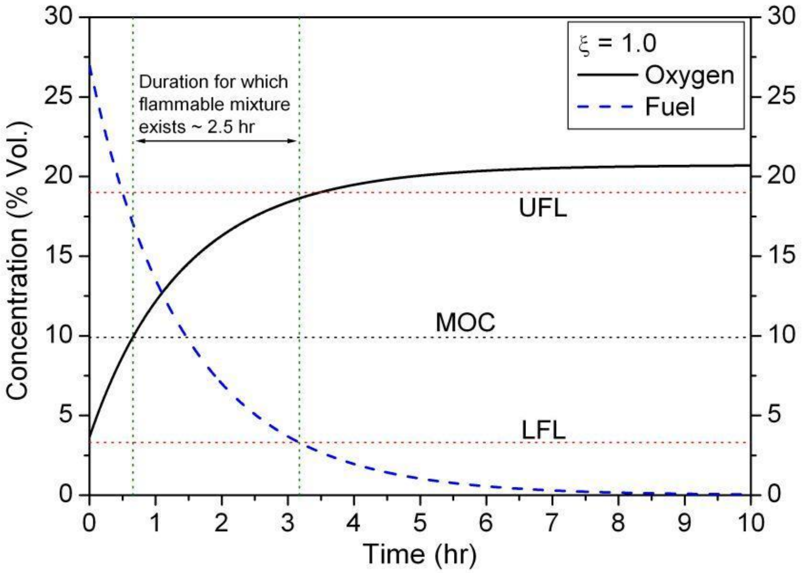
$$Y_F = \left[Y_{F,in} + \frac{\dot{Q}_F}{\dot{Q}_{in} \times \xi}\right] \times \left(1 - e^{-\left(\frac{\dot{Q}_{in} \times \xi}{V_{cell}}\right)t}\right) + Y_{F,o} \times e^{-\left(\frac{\dot{Q}_{in} \times \xi}{V_{cell}}\right)t}$$

$$Y_{O_2} = Y_{O_2,in} \times \left(1 - e^{-\left(\frac{\dot{Q}_{in} \times \xi}{V_{cell}}\right)t}\right) + Y_{O_2,o} \times e^{-\left(\frac{\dot{Q}_{in} \times \xi}{V_{cell}}\right)t}$$

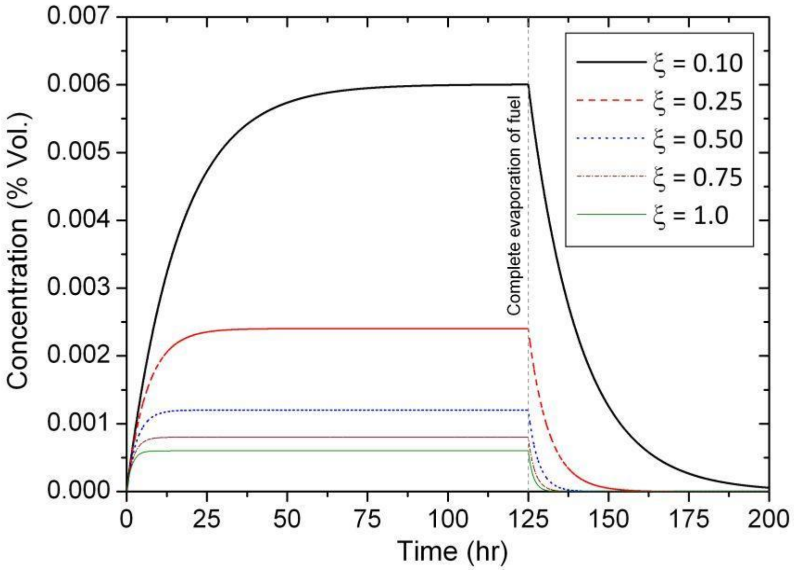
$$Y_{N_2} = 1.0 - (Y_{O_2} + Y_F)$$

The variation of average mass fraction of all species can thus be obtained as a function of time.

Lumped Parameter Model



Instantaneous mixing



Gradual mixing

Complete evaporation, instantaneous mixing

In this case, the spilled fuel is assumed to completely evaporate and mix with the inert cell atmosphere at time t=0 s.

Gradual evaporation and mixing

It is assumed that ethanol begins to evaporate at time t=0 s. Therefore, no vapor is present in the cell initially.

The composition of ambient air entering the cell is taken as 79% N_2 and 21% O_2 in both cases.

(d) CFD Simulations (Evaporation rate)

- The evaporation rate is estimated using an in-house CFD model.

- The average evaporation rate is calculated as follows:

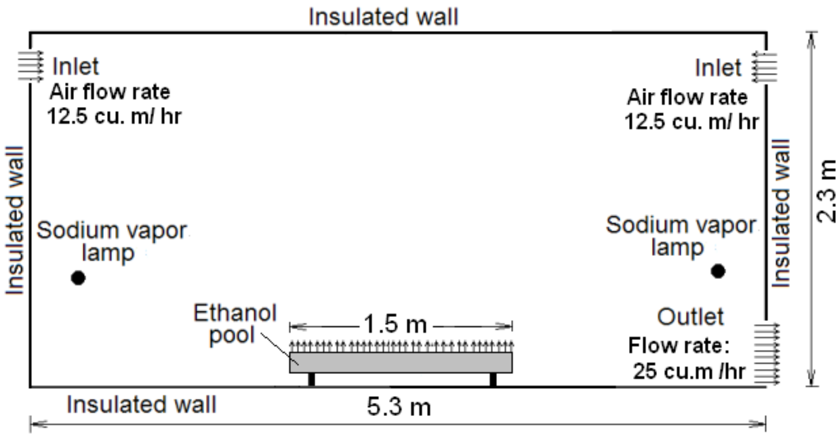
$$\overline{\dot{m}''_F} = \frac{1}{L}\int_0^L \dot{m}''_x dx \qquad \text{kg/m}^2\text{-s}$$

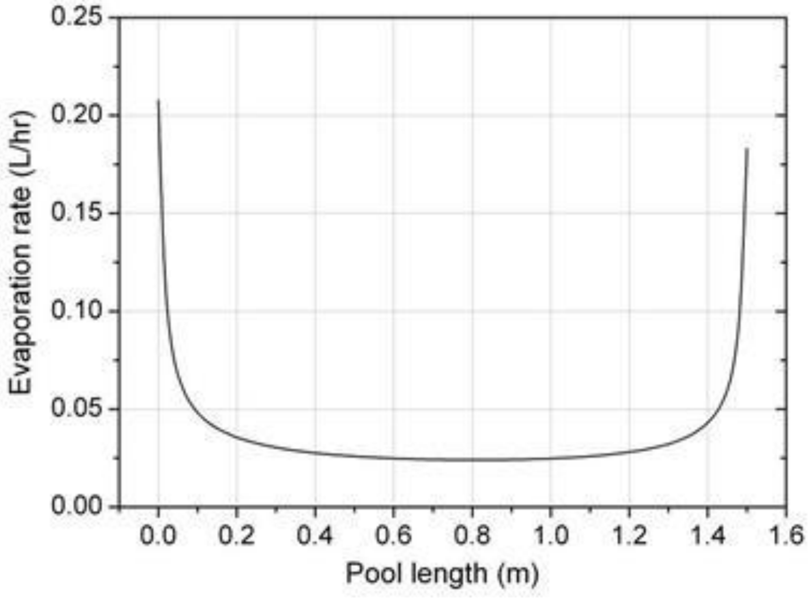
On volumetric basis we can write

$$\dot{Q}_F = \frac{\overline{\dot{m}''_F} \times L \times W}{\rho_e} \qquad \text{m}^3\text{/s}$$

Average evaporation rate ~ 0.035 L/hr.

For the lumped parameter calculations presented earlier, evaporation rate is conservatively taken as 0.20 L/hr.





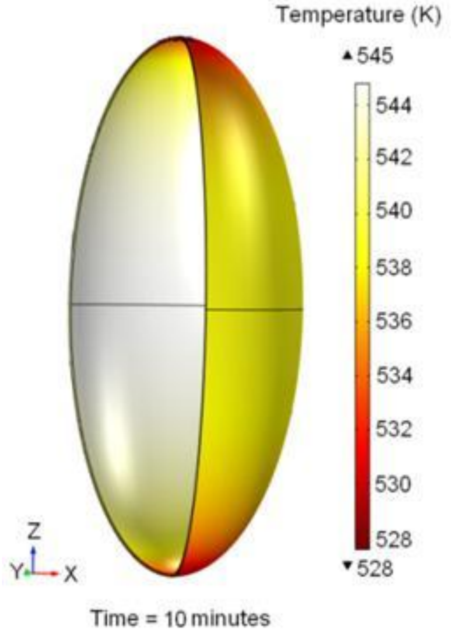
Evaporation rate along pool length (Bulk liquid temperature = 30 °C)

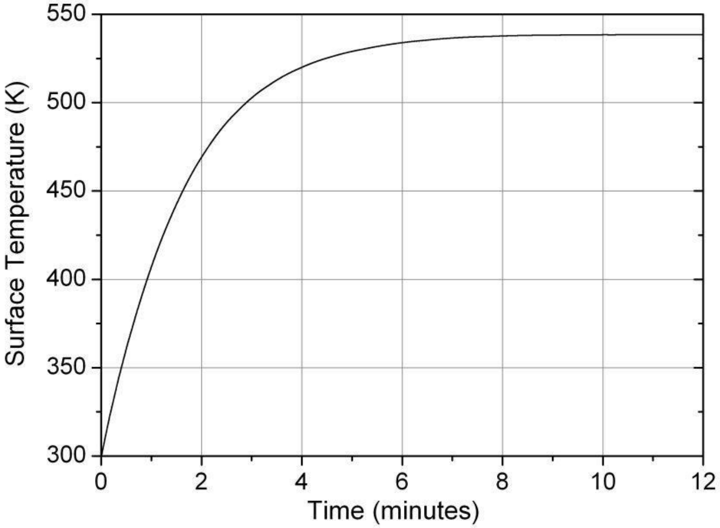
CFD Simulations (Source temperature)

At this point, we seek answer to the following questions:

- How does the composition of fuel-air mixture vary near the sodium vapor lamp (heat source)?
- Will the mixture be within flammability limits, and if so, can the hot surface of lamp bulb cause ignition?

- The maximum outer surface temperature of the lamp quartz glass is estimated by solving the transient energy equation, subject to appropriate boundary conditions.





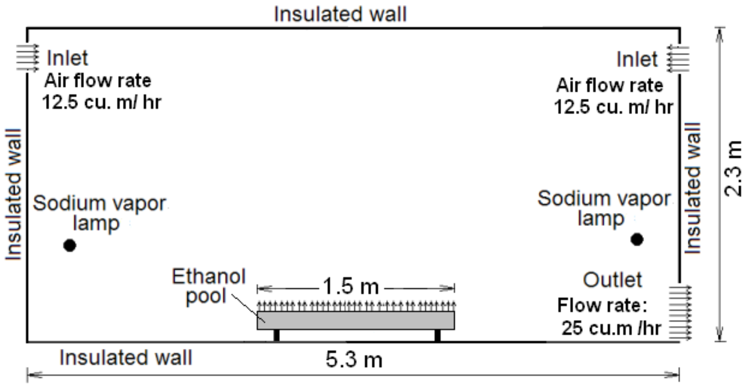
Bulb surface temperature

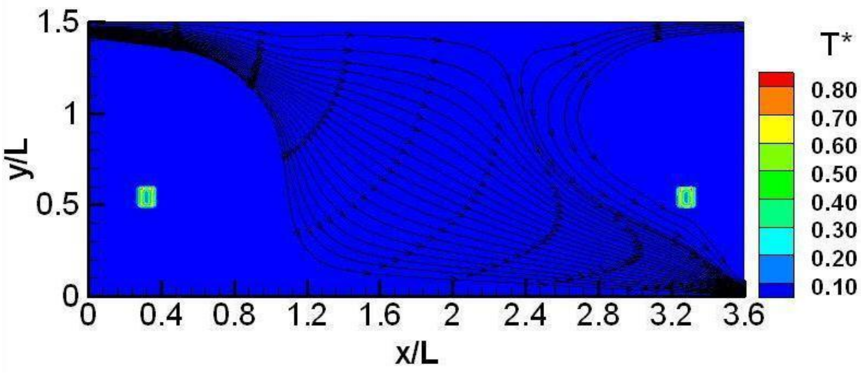
CFD Simulations (flow field and ignition)

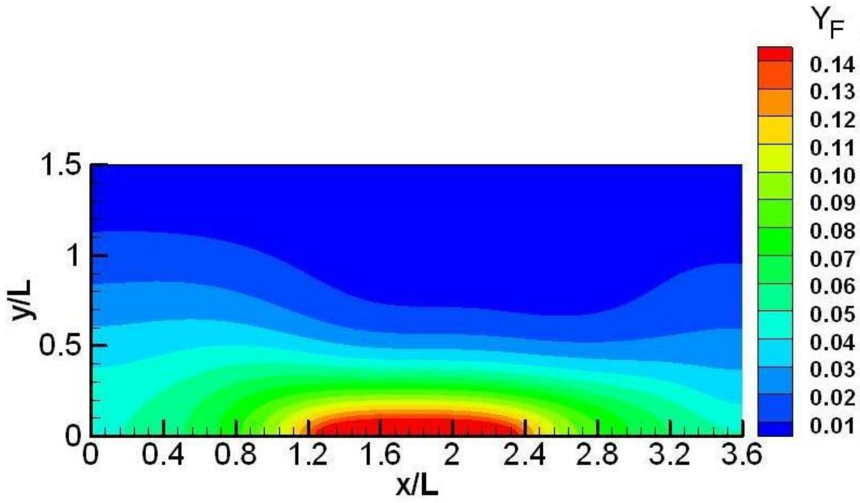
- The fuel vapors generated from the pool surface are transported by the forced convective flow as well as by diffusion.

- Heat source at 275°C continuously attempts to ignite the mixture.

- If the mixture reaches flammability limit near the source, ignition and subsequent burning will occur.







4. Summary and Recommendations

- For instantaneous mixing case, the duration for which flammable mixture exists is around 2.5 hrs.
- If partial mixing is assumed, the duration will increase.
- For the case of gradual evaporation of ethanol, the mixture remains well below the LFL. (More realistic case)
- Prevailing air flow pattern has two effects: (a) mixing, (b) cooling of source. (Both are beneficial)
- The effect of perfect mixing is to lower the average concentration of fuel vapor.

- Maintain O_2 concentration well within 9.9 % vol./vol., (MOC) by inerting with N_2.
- Sodium vapor lamps are unlikely to act as ignition source.
- Auto ignition of ethyl alcohol vapour (365°C) is also ruled out.
- Although flammable mixture is not formed near the lamp bulb, as a safety measure put off the lamps.
- The flammability diagram of should be employed for developing a strategy to avoid fire.

Thank You