An evaluation of the air quality in research laboratory facilities and the effect to the related outdoor environment

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SUMMARY
The planning and designing of research laboratory facilities is confronted with the imperative task of assuring healthy indoor ambiance and protection of the outside environment. The complexity of the mission is amplified by the needs of offering the comfort for occupants and optimum conditions for research, under cost and energy efficiency constraints and calls of using environmental friendly materials and solutions. The indoor air quality in laboratories using chemicals is maintained by moving high volumes of conditioned air through the laboratory space that is eventually discharged to the outside. Minimizing the ventilation flow rates, while maintaining healthy indoor conditions, is an essential objective. The paper makes available information intending to: (1) find an association between minimum ventilation rates and permissible air quality levels and (2) evaluate the effect of emissions from laboratory ventilation on the outside environment. In the studied case of a typical chemistry research laboratory facility, it is shown that remarkable dilution levels could be achieved by combining the air extracted from all laboratories into a single exhaust stream under certain safety provisions.

KEYWORDS
Laboratory ventilation, Air changes, Permissible exposure limits, Odor, Dilution.

INTRODUCTION
Air quality and energy consumption are confrontational criteria during the design as well as during the entire existence of the building. Research based on calculation of concentration of contaminants resulted from accidental spills (Sandru and Xing, 2005) and sampling the air to determine the concentration (Sharp, 2007) has proved the fact that there are substantial resources for reducing the ventilation rates in laboratory spaces. Minimizing the energy cost for ventilation could be achieved by transferring energy between the air exhausted and supplied to the laboratories and by reducing the air flow rates. One of the most debated safety issues today is how far the air flow could be diminished without compromising the indoor air quality. A direct related issue is how polluted is the discharge of the laboratory ventilation system into the surroundings. Production laboratories or pilot plants are not the subject of this study. Research and teaching laboratories are considered. These facilities are more likely to be placed in populated areas where the presence of the air exhaust stacks is regarded with anxiety as signs of health threat.

METHODS
Laboratory ventilation rate and the indoor air quality.
It is a practice in laboratory ventilation design that a minimum rate should be provided for assuring a protective working environment. If the rate of air flow in is not determined by the heat rejected inside the space or by the needs from the exhaust of containment equipment, the
design flow should be the minimum recommended air exchange rate, usually expressed as air changes per hour (ACH).

The minimum ACH is a practical value recommended by regulations and publications but not imposed by codes. No scientific methodology is known for supporting the recommended values used by design. They are rather practical values that have been generated during the existence of mechanical ventilation and may have been well established during times of low-priced energy. They seem to offer a comfortable sense of protection, but more than ever, today the numbers are under intense challenge by the energy saving demands.

The ACH is not the best criterion to evaluate the dilution of a contaminant in the air. At the same rate of chemical release on identical laboratory floor areas and different room heights, the same ACH lead to different dilution levels. Room height information is necessary to be added for correction. This factual error could be eliminated by using the criterion of flow rate per unit of floor area ($m^3/sm^2$). However, for the reference to the existing terminology and to the values applied in practice, ACH term is used in the present paper.

Minimum ventilation rates should be regarded and evaluated in the light of the safety limits for air quality. These limits are defined as occupational exposure limits OEL, known as TLV (Threshold Limit Value) or PEL (Permissible Exposure Limits) and represent the maximum airborne concentration of a hazardous substance in the air to which occupants can be safely exposed day after day. The more demanding of the two limits is used to express the OEL.

In addition, the minimum air exchange should refer to the odor level. The odor is one of the most important factors triggering complaints about the indoor air quality. It is possible that this factor had substantial contribution to establishing the current ACH levels. Odor Threshold Limits have been measured and published with inconsistency in values, proving that the perception levels are very subjective.

![Figure 1. Comparison of Occupational Exposure Limits and Odor Threshold Values.](image-url)
Figure 1 illustrates a comparison of Occupational Exposure Limits and Odor Threshold Limits for a variety of chemicals used in laboratory practice. It could be noticed that in general the odor threshold limits are below the occupational exposure limits; therefore the presence of the chemical in the air is sensed at safe concentrations. However, the odor itself is not the appropriate indication of hazard: in the case of Benzene the odor perception comes after the concentration is already hazardous. Other dangerous chemicals present the same feature. Others are merely odorless; the carbon monoxide is a classical example.

**Evaluation of air exchange required to maintain safe and odorless indoor environment.**
To find a correlation between the air flow required to sustain minimum quality levels, the evaporation of chemicals in laboratory space under specific conditions has been analyzed. The method developed by Sandru and Xing (2005) has been applied to the liquids shown above to calculate the rates of air exchange ACH needed to reach Occupational Exposure Limits and Odor Threshold Limit. Anhydrous Ammonia was separately evaluated based on vaporization of binary mixtures. The volumetric concentration (ppm) was calculated as:

$$C_v = \frac{\dot{m}_v}{Q} \times 10^6$$  

(1)

Where $\dot{Q} (m^3/s)$ is the air flow rate and $\dot{m}_v$ is the convective mass flow rate from evaporation (kg/s). $\dot{m}_v$ was determined by equation:

$$\dot{m}_v = h_mA_v(\rho_{v,s} - \rho_{v,\infty})$$  

(2)

where $A_v (m^2)$ is the area of mass transfer, $\rho_{v,s} (kg/m^3)$ the vapor density at liquid-air interface and $\rho_{v,\infty}$ the vapor density in the free stream of air. $h_m (m/s)$, the average mass transfer coefficient was calculated using the heat and mass transfer analogy [3]

The number of air changes is calculated as:

$$ACH = 10^6 \frac{\dot{V}_v}{V_L \ OEL_{ppm}}$$  

(3)

where $\dot{V}_v = \dot{m}_v / \rho_{v,s}$ is the evaporated flow rate (m$^3$/s) and $V_L$ is the laboratory volume.

**The effect of the laboratory ventilation exhaust to the outside environment.**
The method could be accurately used for analyzing the level of concentration of chemicals in the air at the point they are exhausted into the atmosphere. Research and teaching laboratories are known of handling large varieties of small-laboratory scale quantities under a high diversity in time. The codes and protocols throughout the world impose handling the chemicals inside containment equipment such as fume hoods (fume cupboards). It is not possible to evaluate how many of the same type of experiments take place simultaneously in a laboratory building; therefore conclusions could only be convincing if extreme usage is assumed. This approach is taken in the following analysis.
Two cases are studied:
(1) The individual discharge from a heavy loaded fume hood. The containment is accomplished by moving high flow rates through the opening of a fume hood. As a result, a great level of dilution is achieved.

(2) The combined exhaust from all hoods in a building with a significant number of users performing simultaneously the same procedure. The concentration of the combined flow in this case is:

\[ C_{\text{mix}} = \frac{\sum V_i}{\sum Q_i} \times 10^6 \text{ (ppm)} \]  

The additional atmospheric dilution after the air is discharged at the stack has not been approached for minimizing the number of variables. The discussion is based on concentration achieved by methods applicable inside the facility.

RESULTS AND DISCUSSIONS
Indoor air
A case of inattention of an open recipient misplaced in the laboratory space has been considered. The evaporation from a 0.04 m² open tray in a ventilated room of an area of 33 m² or 100 m³ volume was calculated and used to determine the minimum air (ACH) that would be needed for providing a “safe” and odorless environment. The comparative results, shown in Figure 2 vary dramatically from non-realistically high to extremely low air changes.

![Figure 2. Air changes per hour required for not exceeding the OEL and Odor Threshold Limit](image)

One conclusion is obvious: an open vessel containing harmful liquids exposed in the laboratory space is hazardous. High and costly air changes of 15 or more do not eliminate the
threat of breathing odorous air at dangerous concentrations. A perfect homogenization of vapor and air could not be reached; the room ventilation could not offer protection in the immediate vicinity of the source. Containing the chemicals is a vital procedure. However, for most of the analyzed substances, a rate of 4 air changes keeps the dilution below the exposure limits. Boosting the air flow to 10 or 15 ACH does not bring additional benefit in any regard.

Figure 2 also reveals that, with one noticeable exception, minimum air changes based on Odor Threshold Values substantially exceed those resulting from Occupational Exposures Limits. This could explain high air changes used in facilities where odorous vapors are released. A typical example is the animal holding rooms where the rodents used for research are held in cages vented into the space. 10 to 20 air changes per hour have been used without achieving an odorless environment. Ammonia, as one of the gases released, needs a high dilution to stay below the Odor Threshold Limit. The lesson learned in this case led to engineering solutions of containing the animals in ventilated cages connected to the laboratory exhaust ductwork. The rooms are ventilated at 6 air changes per hour or less. The result: odorless environment and significant energy saving.

**Concentration at the fume hood discharge to the outdoor**

The analysis considered the following extreme condition: 3 trays of 0.04 m$^2$ each were exposed to evaporation in a typical fume hood of 1800 mm wide and 0.76 m$^2$ access opening area, operating at a face velocity of 0.5 m/s. The concentrations at the fume hood outlet are presented in Figure 3 in comparison with the occupational exposure limits, OEL.

Although a substantial dilution is reached and most of the evaporation products are discharged at safe concentration levels, the hazardous substances still remain far above the occupational exposure limits. It is noticeable that one fume hood exhaust may discharge hazardous mixtures into the environment. Achieving a better dilution prior to release into the atmosphere is always a goal of the design process with regard to safety.

![Figure 3. Concentration of product evaporation in the fume hood discharge. Comparison with Occupational Exposure Limits.](image-url)
The essential effect of combining the air exhausted from laboratories.
The results shown in Figure 4 illustrate the capability of releasing highly diluted mixture into the ambiance by combining the laboratory exhaust air flow into a single system.

The following case study of an extreme loading of the fume hood system in a research laboratory building has been analyzed: a chemistry research building of 120 modular spaces of 33.3 m² each of a total net area of 4000 m². A density of one hood per module was considered. Simultaneous, similar experiments using the same substance have been considered in two scenarios of 10% and 50% of all hoods. In each hood an open tray of 0.04 m² is exposed to evaporate at the rate calculated as described above.

Figure 4 shows the results in comparison with the Occupational Exposures Limits. In the atypical case of simultaneous presence of one open tray of the same liquid in 60 out of 120 hoods, the concentration in the combined exhaust only three chemicals discharged at concentrations above the Occupational Exposure Limits. In a more close to reality situation of 12 hoods in simultaneous identical operation, only one substance is released in the environment at unsafe concentration; that is the Formaldehyde at 5.2 ppm relative to the safe level of 2 ppm. At this level, the atmospheric dilution will instantaneously bring concentration to safety even before the vertical plume starts to descend.

Closing the sash of the hood at all times, except for accessing operations, greatly reduce the energy cost. The flow of the fume hood at closed sash is approximately 1/3 of the flow used in the case study, leading to substantial energy saving. The concentrations in the analysis above would be 3 times higher in the extreme situation of all sashes closed, but still at comfortable levels to provide a healthy outdoor environment after the atmospheric dilution.

Figure 4. The effect of combining the discharge from fume hoods. Concentration at stack in comparison with Occupational Exposure Limits.
Combining the exhaust flow from various laboratories is not a new practice. It is accepted by the US codes with the condition that the system is designed to operate without interruptions in any circumstances. This is practically achieved by a central fan system of \((n+1)\) redundancy and supplying emergency power to all fans. The fire codes restrict combining the exhaust to zones of fire separations but allow combining the systems from all zones at the roof level or in fire protected enclosures. For fire protection reasons, the codes do not allow fire dampers in a combined exhaust system or turning off the exhaust during the fire or smoke. Exceptions from this practice, when the effluents from processes should not be combined, are perchloric acid and radioisotope hoods. The protection of the environment from highly hazardous separate emissions is assured by retaining the hazard through scrubbing and filtering before discharging.

Compatibility of chemicals released in the combined exhaust system has been addressed in the past and continues to concern some uninformed participants. Extremely low concentrations, far below the explosion limits, achieved in a research fume hood and further enhanced in the combined exhaust cannot spark a chemical reaction in the ductwork system where no concentrated source of energy such as heat, high pressure or radiation exists. Such conditions could not be developed and should not be a concern in a diluted exhaust system of a research or teaching laboratory facility.

**CONCLUSIONS**

Designing the laboratory ventilation systems for accidental spills of chemicals is not realistic. This would result in enormous flow rates and gigantic air systems. In addition, such provision would still not provide safety conditions for occupants; the ventilation of the room could not offer protection in the immediate vicinity of the source.

The analysis discloses the fact that low air changes per hour of 4 could be a realistic design base, providing safe and odorless environment if the containment provisions and laboratory protocols are strictly implemented.

The paper reveals the extremely beneficial effect of combining the air exhausted from laboratories in reducing the energy consumption and diluting to safety the effluents from building exhaust into the outdoor environment. The stacks on research and teaching facilities deserve to be reconsidered as means of maintaining a healthy environment rather than health threatening ghosts.

**REFERENCES**


