Environmental disasters and bio-terrorist attacks? Can buildings protect us against airborne pollutants?

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INTRODUCTION

HVAC systems are meant to give people safe, healthy, comfortable and productive conditions to live or work in. It is a well-known fact that the HVAC engineering sector is not always successful in this task and sometimes fails in it altogether. The notorious 'Sick Building Syndrome' (SBS) is most common in buildings with extensive HVAC systems. Insufficient ventilation, poor maintenance and a complex system design are the main risk factors. Another problem that we could add to this little list is that of 'short circuiting', which occurs when the air intake is incorrectly located with regard to the exhaust air outlet.

Besides these intrinsic pitfalls of HVAC systems, there are some external dangers. What must be done if the quality of outdoor air falls short of public health standards? What if dirty air, smog, smoke, soot particles etc. make the air unfit for human consumption? What if the outdoor air has been contaminated by an environmental accident? What if vandals or terrorists have deliberately polluted or contaminated the surrounding air or the ventilation air by chemical, biological and radiological (CBR) agents ?

AIR - A VITAL COMMODITY

Air is a vital commodity which must meet the highest quality standards. The ventilation of spaces which people occupy is thus essential to the hygiene and health of the indoor environment. The Dutch dictionary (Van Dale 2000) defines ventilation as '*the supply of fresh air to, and the removal of stale air from, a space'*. In the hazards mentioned above, the supply of fresh air is the main problem but not the only one. The ventilation system could be responsible for spreading airborne contaminants - ranging from harmless to dangerous or even deadly - through an entire building.

Is it possible to monitor the air quality? Could the HVAC system be made capable of purifying the ventilation air? Must the system always be deactivated? What would that imply for the indoor air quality and for the functioning of the organization in the building? Can HVAC systems offer protection or do they actually increase the dangers? Are there differences between various HVAC systems in these respects?

VDI GUIDELINES

The *Verein Deutscher Ingenieure* has published guidelines for the function of air handling systems in periods of air pollution (VDI 1993). The guidelines distinguish general principles, smog situations, radioactive emissions and other contaminants. The general (and more or less obvious) principles are:

- Switch off the ventilation. Given an infiltration rate of 0.3 h^{-1}, but ignoring adsorption and desorption[1] in the interior, it will take 13 hours for the level of pollution to reach that of the outdoor air. At an infiltration rate of 0.1 h^{-1} it will take no less than 39 hours. See figure 1.
- Clean the ventilation air by means of filters, air washers, absorption, catalytic oxidation etc.
- Adjust the operation schedule of the ventilation to peaks and minima in the air pollution, e.g. by restricting working hours, intermittent operation etc.

INFILTRATION

Minimizing infiltration of outside air offers essentially a good possibility to keep CBR agents as much as possible outside the building, but the effect strongly depends upon the air tightness of the façade, and the pressure difference outside and inside the façade.

At wind-force > 6 Beaufort and wind direction perpendicular to the façade, the infiltration rate can be estimated at app. 0,5 h^{-1} for very tight buildings and much higher for normal buildings. Figure 1 shows the course of the CBR concentration inside and outside the building at various infiltration rates under these conditions, adsorption and desorption being ignored.

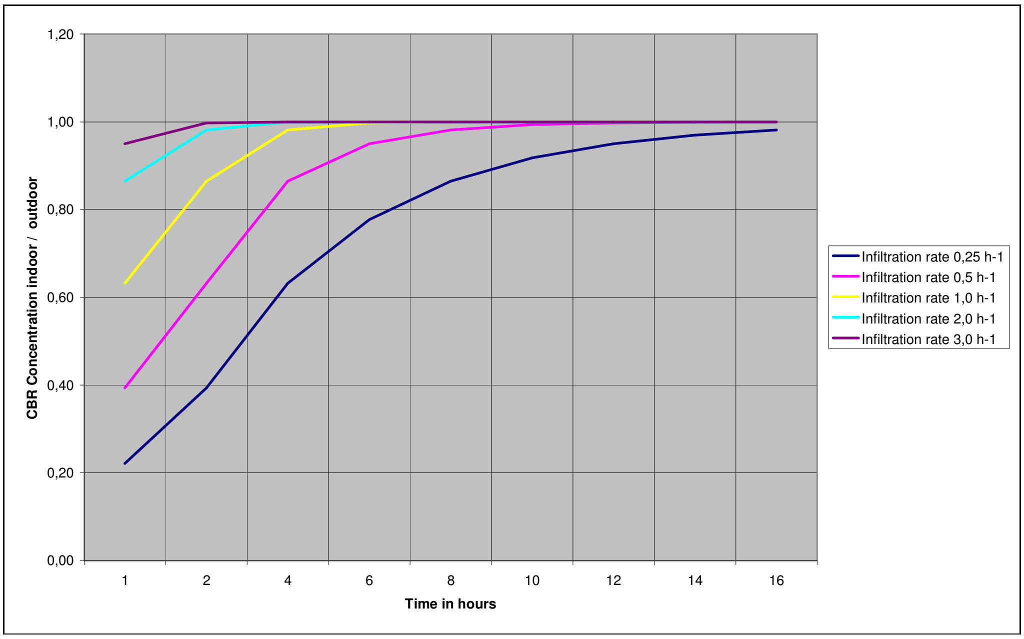

Figure 1 – Course of the CBR concentrations indoor /outdoor as a function of time and infiltration rate

BUILDING PRESSURIZATION

In principle building pressurization could be applied as a security tool (Persily 2004), but in practice this is only feasible at low wind speeds and very good air tightness of the building or at wind directions about parallel to the façade when there is a negative outside pressure. This is explained in figure 2 and text below.

At a wind-force of 5…6 Beaufort perpendicular to the façade the pressure difference outside / inside the façade can easily vary from 50 Pa to 100 Pa for buildings in suburban areas and flat unobstructed areas exposed to wind respectively. It goes beyond saying that building pressurization will be impossible in these cases.

Buildings that are potential bio-terrorist targets or vulnerable for environmental disasters should preferably be positioned with the head façade to the predominant wind direction.

ADSORPTION AND DESORPTION IN THE INTERIOR

If the building ventilation is disabled in response to an emergency, contaminants can nonetheless enter the interior from the outside by infiltration. Several values for the rate at which this takes place are mentioned in VDI 3816 (see before), but these values do not take into account absorption, adsorption and desorption in the interior. The effect of these phenomena is not negligible, however, as is apparent from much research (Indoor Air 99, sessions Q4 - Indoor/Outdoor Comparison). The interior can absorb gaseous substances and adsorb particulates, so that the concentration of pollutants in the interior environment is generally less than that in the outdoor air. The reverse is true when the external contamination level declines, e.g. at night, and the interior releases substances by desorption. This same, familiar phenomenon by which smoke, kitchen or lavatory smells may cling to someone's clothing and be released again when the wearer enters a clean space. The literature generally refers to this as the 'sink and source' effect. It is amplified by a high 'fleece factor', which is the total surface area of all textile materials in an interior, e.g. carpeting, curtains and furniture, divided by the interior volume (units m^{-1}; Skov 1990). Extensive ongoing research is being conducted into these effects, both physically and using CFD models.

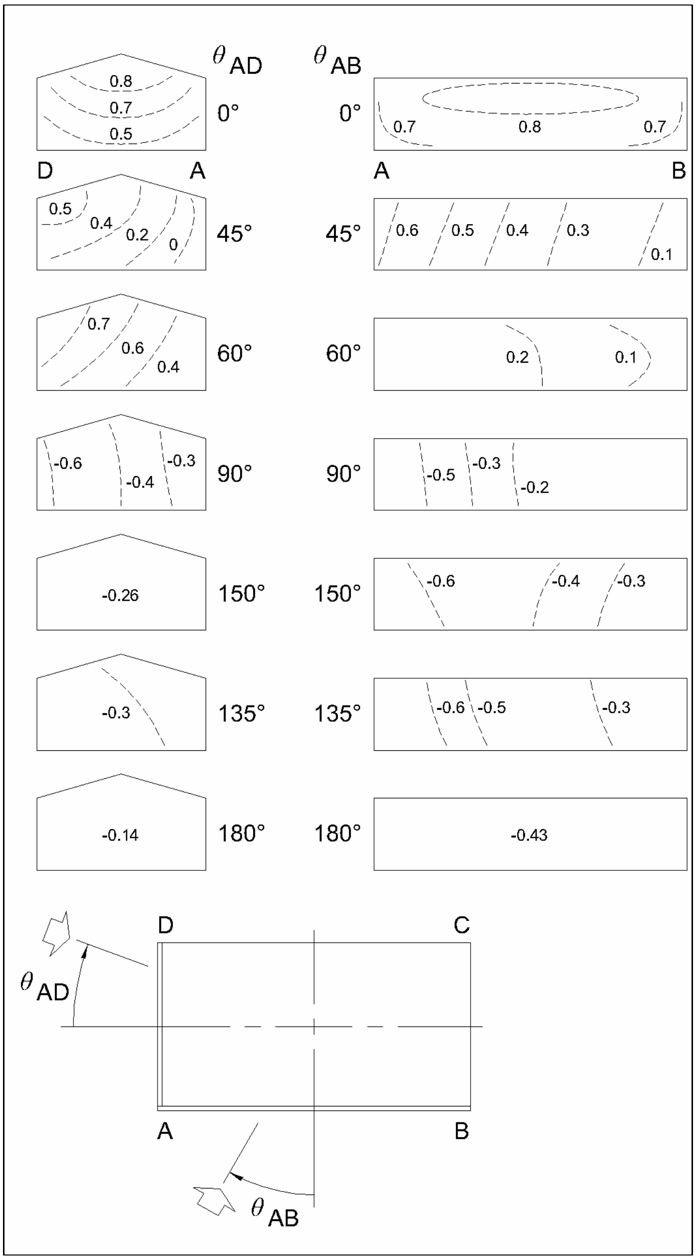

Figure 2 –Wind pressure coefficients

This figure, extracted from the ASHRAE Fundamentals Handbook, but also published in other publications (Allard, Francis 1998), shows the rough pressure coefficients at various wind directions.

The pressure coefficient Pc is the number by which the dynamic wind pressure has to be corrected to calculate the thrust on an obstacle.

The thrust is calculated by the formula:

$$p_s = C_{p*}p_d$$

where

p_s = thrust in Pa

C_p = pressure coëfficiënt

p_d = dynamic wind pressure in Pa

The dynamic wind pressure is calculated by the Bernoulli formula:

$$p_d = \rho * v^2/2$$

where

ρ = ambient outdoor air density in kg/m^3

v = approach wind speed in m/s

The figure shows the head- and the longitudinal facade at various wind directions.

The dotted lines are the isobars, areas with equal wind pressure coefficients.

The figure shows that at wind directions $\theta_{AD} = 0^0$ and $\theta_{AD} = 90^0$ the longitudinal facades are at negative pressure.

SHORT CIRCUITING

Short circuiting occurs when the intake air is contaminated by gases and used air exhausted from the building. Airborne pollutants can theoretically be spread through the whole building by this means. It is a familiar phenomenon to workers who smell frying onions, or whatever happens to be cooking in the canteen kitchen, whenever the wind blows in a certain direction. This happens because the wind blows air extracted from the kitchen towards the ventilation air intake, thus spreading the odour (usually in a very dilute form) through the entire building.

The situation is much more serious when air contaminated with legionella bacteria, e.g. from a cooling tower, finds its way into a building. Similarly, a notorious hazard for hospitals is the distribution of airborne pathogens due to a short circuit between the exhaust air and the ventilation air inlets. Several such instances are known to have occurred in the Netherlands. From the point of view of ventilation engineering, this brings us close to the topic of bio-terrorism hazards.

Excluding any possibility of short circuiting is a significant task for HVAC engineers, although it may sometimes be a far from easy one. Figure 3 illustrates a short-circuit proof air intake and exhaust design. Regardless of the wind direction, clean outside air is always drawn in from the windward side of the building and dirty air is carried off with the wind on the lee side.

A solution of this kind must be incorporated into the design of the building at an early stage. The HVAC designer should thus be involved at the outline stage of the development planning process, and for this purpose must already have a good picture of a suitable HVAC system, including the size and position of the associated equipment rooms. It goes without saying that the architect also has an important say in these ‘*core decisions’* in the design process. So set him a challenge: to make something that not only functions efficiently but also looks good!

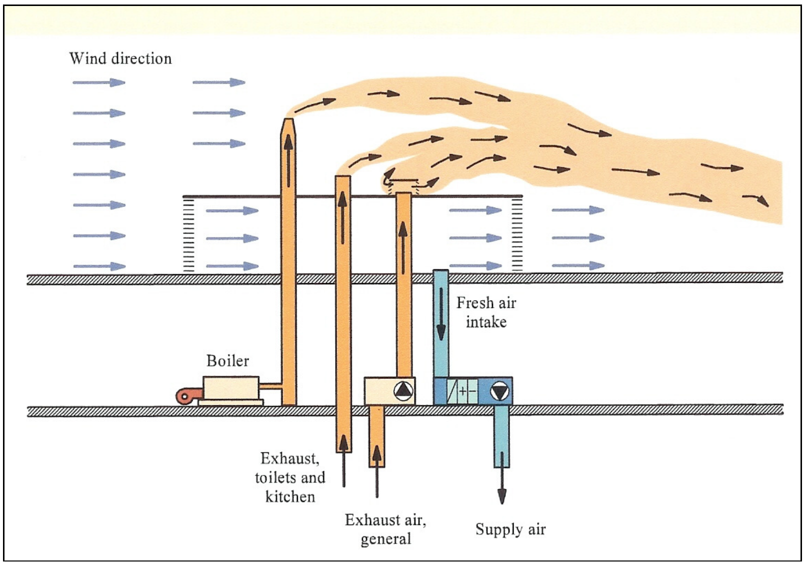

Figure 3 Short-circuit proof air intake

A SAFE AIR INTAKE

It is not the intention of this article to explore all the ins and outs of air induction; for that, see the literature. A substantial reference review was published by the AIVC[2] (Limb 1995).

Deliberate pollution of the intake air due to vandalism, terrorism or any other motives must be prevented. Some people might regard a home-made smoke bomb in the fresh air intake as just a practical joke, but a teargas cartridge would be a much nastier piece of work. Life-threatening terrorism enters the picture if someone were to introduce potentially fatal pathogenic organisms into the air intake. After 9-11 reports of this nature came from the United States, about an alleged terrorist plot to contaminate the air conditioning system of the Capitol.

The intake grille for ventilation air must therefore be positioned so that it is inconspicuous and/or inaccessible from outside the building. Intake grilles at ground level are highly undesirable, not only because of the risk of malicious interference but also because there is often more pollution of the induced air by exhaust fumes, pollen or other pollutants. An air intake below ground level, e.g. via a cellar light-well as is occasionally used for basement air conditioning plant, is absolutely unsuitable because of its tendency to form accumulations of moisture and dirt which are breeding grounds for moulds and bacteria.

The photograph of the rear of the Municipal museum in The Hague shows an example of a discreet and pretty inaccessible air intake position. A new HVAC system was installed some years ago as part of a major renovation project, with the main air handling plant situated in the basement. The air intake placing is visible in the photograph, but can you spot it?[3]

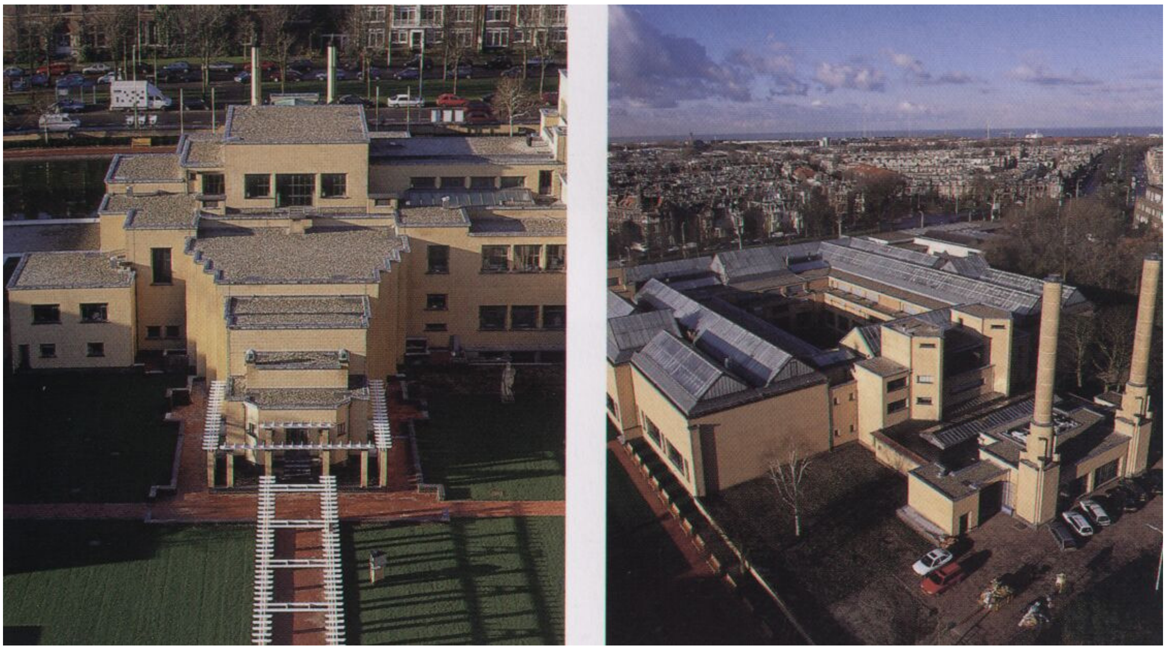

Figure 4 -Municipal museum, The Hague. Left front entrance. Right rear.

AIR DAMPERS

Connections to the air treatment plant for the intake of outdoor air and the exhaust of used air must always be equipped with motor-operated air dampers. These dampers must have effective sealing so that they are indeed airtight when closed, and they must be closed in the event of an imminent environmental disaster or bio-terrorist attack.

An interesting question is where the signal for closing the air damper must originate from. The advantage of an unpleasant smell is that it quickly warns people something is wrong. The same applies to acrid pollutants like chlorine, ammonia etc. The human nose could be the basis for an authorized person or agency to issue the “close dampers” command. Obviously, any open windows would have to be closed at the same time.

Unfortunately, people cannot perceive certain lethal gases such as carbon monoxide or pathological organisms such as legionella bacteria and anthrax spores. Sensors for these potential contaminants are however either already available or under developments. Mass spectrographic has proved successful in detecting soot particles, radioactive isotopes, bacteria and spores. *'Off-the-shelf bacteria detectors are clearly just a matter of time.'* (Marijnissen 2001, Schrauwers 2001).

Regional and municipal disaster plans should include the issuing of alerts at various danger levels, and building managers must know how to respond to them.

How long the air quality will remain acceptable in a building which is sealed off from the outside air will depend largely on its density of occupation, the impermeability of the outside walls and the recirculation capability of the air conditioning plant.

AIR RECIRCULATION

Intake grilles for outdoor air are generally dimensioned in accordance with the required ventilation volume, normally approx. 2 to 3 air changes per hour calculated over the effective floor area. In 'all air' systems, the complete space cooling is provided by air, for which purpose the ventilation rate is raised considerably. A familiar example of this is the VAV (Variable Air Volume) system, in which a large proportion of the air is recirculated. When external conditions permit, this system saves energy by operating with 100% outdoor air. This has two implications:

- The intake for outdoor air must be 2 or 3 times as large as that needed for ventilation only, so increasing the risk of short-circuiting.
- The recirculated air originates from within the building itself, and is thus vulnerable to contamination from a source inside the building.

Research has demonstrated that systems that use recirculation are more prone to Sick Building Syndrome, since tobacco smoke and volatile organic compounds originating from the interior are circulated with the ventilation air. The proceedings of the Healthy Buildings and Indoor Air conferences[4] have produced numerous examples of this happening. These systems have therefore become less popular in North-West Europe since the mid 1980s, and they are now rarely used in office buildings in the Netherlands. In the United States, however, their popularity is as high as ever.

The fact that recirculating systems can be contaminated from a source within the building makes them extra vulnerable to bio-terrorism. The terrorist might be an inconspicuous employee who performs his sinister business in the privacy his own office.

THE INDOOR ENVIRONMENT WITH CLOSED AIR DAMPERS

Non-recirculating systems – see figure 6

Air conditioning systems which operate with 100% fresh air and which lack a recirculation capability must be deactivated in the event of an emergency. The quality of interior air deteriorates quickly under these conditions because all bio-emissions have to be contained within the net usable volume of the interior.

If the ventilation air also serves as a medium for interior heating and cooling, the HVAC system is entirely incapacitated as a result. This is equally true of induction systems, which rely on the airflow for delivering heat and cooling. On the other hand, HVAC systems which include fan-coils, cooling convectors and cooled/heated ceiling systems are capable of maintaining interior thermal conditions without ventilation.

Systems with recirculation – See figure 6

In principle, an air conditioning system with a recirculation capability can continue operating during an emergency, as long as the external air dampers remain closed. The gross volume of the interior space connected to the ventilation system (including ceiling cavities, machine rooms etc.) is available for containing bio-emissions, so the quality of the indoor air will not deteriorate as quickly as with a non-recirculating system.

All HVAC systems with recirculation, including VAV and induction systems, may remain in operation and are capable of maintaining interior thermal conditions without ventilation.

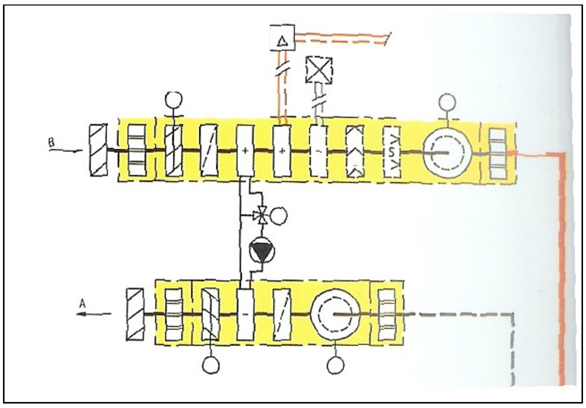

Figure 5 – Non-recirculating HVAC system

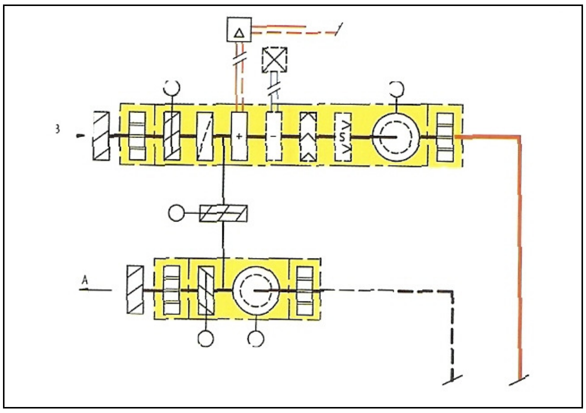

Figure 6 – Recirculating HVAC system

DETERIORATION OF INTERIOR AIR QUALITY

The concentration of CO_2 in the interior air can be used as an indicative parameter for air quality. As an initial assumption, it seems reasonable to take this concentration as 800 ppm at the start of the emergency.

The CO_2 concentration can be calculated as a function of time by the following formula:

$C_i(t) = C_e + (C_o - C_e)\, e^{-n.t} + P/(n \times V) \times [\, 1 - e^{-n.t}\,]$ (in ppm) (Recknagel 2000)

where:

$C_i(t)$ = CO_2 concentration in the interior at time (t) in ppm
C_e = CO_2 concentration in the external air
C_o = CO_2 concentration in the interior at time (0)
P = CO_2 production rate in the interior cm^3/h
n = infiltration rate h^{-1}
V = effective interior volume in m^3
t = time in hours.

Figure 7 shows examples of changing interior CO_2 concentration as a function of time. In all the variants shown, C_e is taken as 350 ppm and C_o as 800 ppm. The effective interior volume V is assumed to be 27 m^3 for non-recirculating systems, calculated for an office of 10 m^2 floor area with a free height below the ceiling of 2.7 m. For systems with air recirculation, an average occupation density of 1 person per 15 m^2 and a height including ceiling cavity of 3 m are assumed, giving V = 45 m^3.

The CO_2 production is taken as 20 l/h = 0.02 x 10^6 $cm^{3/h}$ per person. The infiltration rate is taken as 0,1 or 0.2 h^{-1} respectively, which are very low figures.

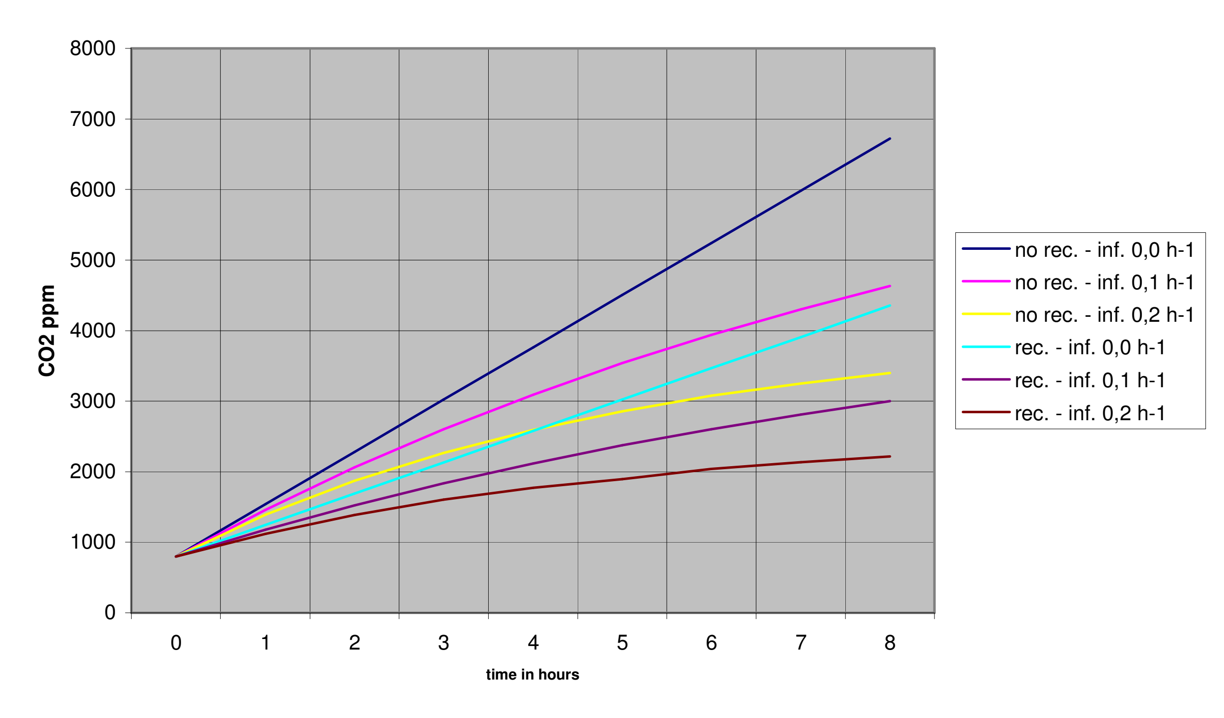

Figure 7 - development of CO_2 concentration in the interior without ventilation

DISCUSSION

The Dutch ARBO (occupational health and safety) Policy Rules qualify good interior air conditions as a CO_2 concentration less than 1,000 ppm; an upper boundary value of 1,200 ppm is given. In the case of incidental deviations from the intended use, resulting in greater contamination levels e.g. during temporarily increased staffing periods, the CO_2 concentration may not exceed a maximum of 1,500 pm.

These are comfort limits which relate to the appreciation of the olfactory quality of the air by persons who enter from fresh air conditions and are thus not adapted to the interior air quality (Pettenkofer 1877). This is a reasonable assumption for public buildings and other offices with a busy traffic of ambulant, non-adapted persons.

The sensory awareness of certain odours diminishes after a while due to habituation (usually referred to as adaptation, in the present context). This effect is strongest for human odours, and also occurs to some extent for a moderately smoky atmosphere. While people are deprived of fresh air due to an emergency, there is no objection to the CO_2 concentration rising considerably higher. Indeed, it is unlikely that the smell-adapted occupants would even notice it.

Reference may be made in this connection to research on air quality in aircraft interiors, where CO_2 concentrations ranging from 1,500 to 2,000 ppm are the rule rather than the exception. One study reports nonetheless only a small minority (about 4%) of subjects grading the air quality as poor (Pierce 1999, Nagda 1991).

The MAC value[5] for CO_2 in the air is 5,000 ppm. This is the maximum concentration which one can breathe for 8 hours per day without endangering ones health. This limit would only be exceeded in the above analysis with no air recirculation and an infiltration rate of 0 (no rec. – inf. 0,0 $^{h-1}$).

AIR FILTERS

Air filters play a crucial part in HVAC systems for both hygienic and technical reasons. Besides protecting people from particulates in the outdoor air, they protect the system from internal contamination which can in turn endanger the air quality of the interior.

The finer the suspended particles, the more difficult it is to catch them in an air filter. The most widely used filters nowadays have an efficiency of 80 - 85 % for a particle size of 1 micron, while 90 - 95 % is the best achievable for comfort applications[6]. This is illustrated in Figure 2.

Bacteria have a particle size ranging from 0.3 to 30 microns; as can be seen from the graph, submicron particles are only partially retained in even the optimum filter efficiency (A). Viruses are smaller than 0.05 micron, so can pass through these filters unimpeded. In any case, it may be wondered how these micro-organisms would behave if they were captured by an air filter. Rampant growth on a nutritious, well-oxygenated substrate of dust and moisture such as is present in an air filter, would seem to be a foregone conclusion and has moreover been noted in several studies.

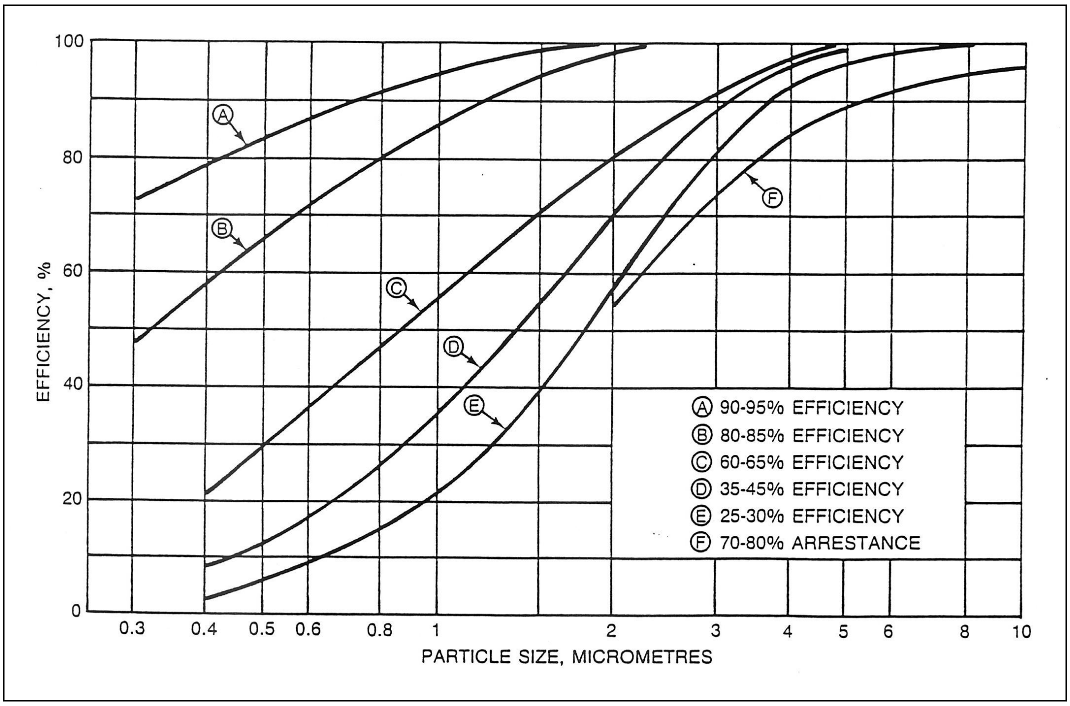

Figure 8- Typical efficiency of air filters in relation to particle size according to ASHRAE.

ELECTROSTATIC AIR CLEANERS

One type of air filter which has an efficiency of practically 100% for particles of approx. 0.3 micron and larger is the electrostatic filter. It has an ionization section in which the suspended particles are given an electrical charge, and a collector section in which they are caused to precipitate by an electrostatic force. The collector section is periodically washed with water containing a detergent. Larger systems are generally fitted with an automatic washing device.

Electrostatic air cleaners are, as stated, capable of capturing very small particles, including not only microbiological entities but tobacco smoke, pollens, fly ash, soot etc. The high-voltage field also results in the production of ozone, which oxidizes odorous substances and kills bacteria and viruses. Their capability of precipitating very fine particles, which in the event of an external air pollution could be contaminated or saturated with hazardous substances, makes electronic filters attractive in situations where a high standard of air quality is required.

An ideal filter combination would consist of an electrostatic filter followed by a serially connected air washer, which will neutralize any remaining ozone, absorb odorous substances, cool the air and dry or humidify it as appropriate. In an emergency, the exceptionally efficient purification of the air makes it possible to use 100% recirculation for a very lengthy period without endangering the indoor air quality (Bronsema 1996 and 1997).

The operation of this filter/washer combination may be compared to the effect of a thundery shower after a hot, smoggy day. The oxygen-rich cold water not only purifies the air but produces an invigorating, fresh atmosphere.

Air filters of this class could in principle offer excellent protection in the event of an environmental emergency or a bio-terrorist attack. They can also make a contribution to energy conservation and to the improvement of indoor air quality in combination with all kinds of air conditioning and ventilation systems. They are available commercially in many different models. Only their high price (10 to 16 times that of conventional air filters), their long payback time and their "high tech" character (which frightens off both installation engineers and users) have so far stood in the way of their widespread use for comfort applications in Europe (Bronsema 1996).

In the United States, where domestic air heating systems are common, they are a common household appliance. The users wash the filter once a week in the dishwashing machine and thus assure themselves of clean air in the home.

NATURAL AND HYBRID VENTILATION?

The above considerations apply principally to mechanically ventilated commercial buildings. Residential buildings are usually ventilated naturally in Western Europe, although there is a rising interest in natural and hybrid ventilation systems in commercial buildings as well.

In natural and hybrid ventilation systems, the outside air is delivered directly from outside through trickle ventilators and/or windows. This makes it more difficult to contaminate the air deliberately from a central point. See figure 9.

Hybrid ventilation systems for commercial buildings are presently extensively under development in the Netherlands. Interior cooling can be achieved in combination with such systems by integrating systems such as cooling convectors, cooled floors and slab activation. (cooling and/or heating of the building mass).

When natural air intake is used, the concentration of particulates is generally less in the interior than outside the building, which automatically provides a measure of safety (see before). Particles which enter the building tend, as mentioned, to attach themselves to the walls, floors, ceilings and furnishings of the interior, and thus remain suspended in the air for a shorter period. The extent to which this happens depends, however, on the adsorbent characteristics of these surfaces and on air currents caused by human activities, computer cooling fans etc.

One thing is certain. In the event of an imminent terror attack or environmental emergency, people in buildings with hybrid and natural ventilation systems can protect themselves to some extent by closing the windows and trickle ventilators.

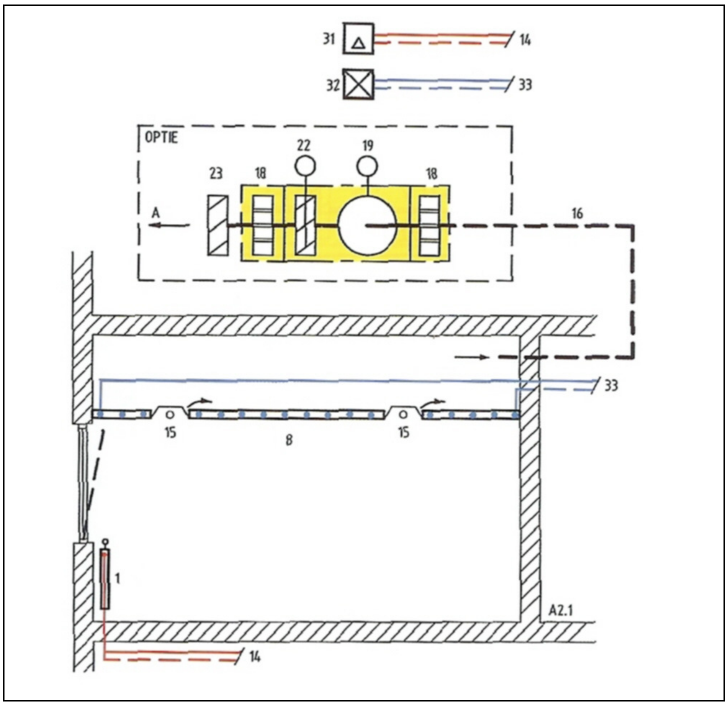

Figure 9 – Hybrid natural / mechanical ventilation

CONCLUSIONS

HVAC systems can be a risk factor in the event of environmental emergencies, of which the bio-terrorist attack can perhaps be regarded as an extreme form. On the other hand, if well designed, these systems are capable of providing protection.

In the event of an environmental emergency, the HVAC system can operate in recirculation mode for a considerable period without endangering the health of the occupants. Systems should preferably be provided with a recirculation option, even if designed for normal operation with 100% outdoor air.

The signal to "close outdoor air dampers and open return dampers" must come from someone high in the decision hierarchy. Abuse of this authority, e.g. to conserve energy, must be prevented.

Buildings in potentially vulnerable locations and buildings of considerable public importance (including emergency centres) must be provided with the best possible air cleaning facilities, such as the combination of an electrostatic filter with an air washer as described above.

Building managers must be familiar with the actions to be taken in the event of an emergency. These actions can be summed up as follows:

- Close all windows and wall grilles.
- For air handling systems using 100% outdoor air:
  "stop ventilation fans and close external air valves".
- For air handling systems with a recirculation option:
  "close outdoor air dampers and change to 100% recirculation".

Detailed scenarios should be prepared for every building, and their use must be coordinated on the basis of an emergency plan. Scenarios of this kind prove valuable in any environmental disaster.

EPILOGUE

'There is no reason at all change the construction or use of buildings in the Netherlands to take account of potential bio-terrorism. The risk of attack, e.g. using a crop sprayer, is very low. On the other

hand, there are other, greater dangers to health which merit greater attention. Firstly, there is the risk of chemical accidents in the vicinity of chemical plant or of transportation routes for hazardous chemicals. The same rules apply to a bio-terrorist attack as to a chemical accident. The basic scenario is: when the siren sounds, go indoors, close the windows and doors and listen to the radio or TV. Special instruments have been developed to provide additional protection, including warning systems for deaf occupants, radio-graphically and centrally de-activatable ventilation systems in blocks of flats, and special shelter scenarios. For the last, sheltering on the lee side of a building with internal doors closed offers additional protection. The concentration of substances is much lower there, and it takes longer for substances to penetrate...'

This statement originates from the head of the Environmental Medicine section of the Rotterdam Public Health Department. (Woudenburg 2001).

It was curiosity, not sensationalism, that prompted me to write this article. That curiosity has been satisfied for the moment, but I do wonder whether the relation between municipal/regional emergency plans and those for individual buildings has been considered, and if so what form it takes. Shouldn't buildings intended to serve as crisis centres in emergency situations be required to meet special standards?

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NOTES

[1] In *absorption,* the substance soaks into the mass of a material; in *adsorption*, it adheres only to the surface. *Desorption* is the reverse of these processes. Adsorption and desorption in the interior are non-trivial factors which will make the actual times longer than those stated.

[2] Air Infiltration and Ventilation Centre - www.AIVC.org

[3] Recent connection to the Hague District Heating system made the boiler chimneys redundant. They were provided with stainless steel liners and are now used for fresh air intake.(Consultant B. Bronsema). Berlage, famous Dutch architect, would undoubtedly have been pleased with this solution. So was the architect responsible for refurbishing the museum, Job Roos, who won the Berlage Prize in 1998.

[4] '*Healthy Buildings*' are the official conferences of ISIAQ (International Society of Indoor Quality and Climate, www.isiaq.org). *'Indoor Air'* conferences are organized by ISIAS, the International Society of Indoor Air Sciences, a scientific association. ISIAQ is more practice-oriented than ISIAS.

[5] Maximum Allowable Concentration

[6] A 'comfort' application means a HVAC system for human comfort rather than for industrial purposes, computerrooms etc.