AIR MOVEMENT & VENTILATION CONTROL WITHIN BUILDINGS

12th AIVC Conference, Ottawa, Canada
24-27 September, 1991

PAPER 7

Airflow Driven Contaminants. Transport through Buildings.
ANNEX 20 Subtask 2.5.

J.C. Phaff, W.F. de Gids

TNO Building and Construction Research. Department of Indoor Environment, Building Physics and Systems.
PB 29, NL 2600 AA Delft, Netherland.

Synopsis

Air is the main transport medium for contaminants in buildings. Minimizing source strengths has first priority, second is to control air flow rates, supply and exhaust, and directions between zones in buildings.
Computer simulation models for ventilation and pollutant spread in buildings have been proven to give useful predictions. Large measurement campaigns for optimizing ventilation and pollutant problems are complex and expensive. They are often jammed by too many vague parameters influencing the result. The computer models are an alternative and form a supplement to measurements. New ventilation systems or control strategies can be tested to some extent with the models. Measurements for checks and determination of source and sink coefficients for different materials are needed to tune the simulation models.

List of symbols

α	=HCHO emission rate at zero concentration	$\mu g/s/m^2$
β	=reduction coefficient	$\mu g/s/m^2/ppb$
λ	=filter efficiency	-
ρ	=the density of air	kg/m^3
τ	=time constant	s
A	=the deposition surface	m^2
C_{in}	=concentration in the supply air	kg/kg
C_n	=concentration in zone or room	kg/kg
i	=index for individual incoming flows	
j	=index for different surfaces per zone	
k	=reactivity of contaminant	kg/s
k_r	=Radon soil source strength constant	
N_{ach}	=air change rate of the building	h^{-1}
N_{achv}	=air change rate of the subfloor void	h^{-1}
p_{in}	=vapour pressure in the room	Pa
p_{out}	=outside vapour pressure	Pa
p_{sat}	=saturation pressure at inside temperature	Pa
p_{win}	=saturation pressure at cold window	Pa
q_f	=flow rate through the floor	m^3/s
q_{in}	=mass flow rate supplied	kg/s
q_{out}	=mass flow rate extracted	kg/s
RP	=the BRE Radon Parameter	-
ser	=HCHO emission rate	$\mu g/m^2/s$
S_n	=source of pollutant	kg/s
t	=time	s
V	=volume of the zone or room	m^3
Vd	=deposition velocity	m/s
X_{sat}	=moisture content of saturated air	kg/kg

1. Introduction.

IAQ

During the last years indoor air quality (IAQ) has become a very important issue, mostly health related. Reasons for this might be :

* increasing awareness that indoor air pollution affects health,
* a high proportion of time is spent indoors,
* growing capability to measure and simulate pollutant concentrations in and around buildings,
* change in (synthetic)building materials,
* decreasing ventilation rates to save energy.

A description of the term, acceptable IAQ, is : The air should be sufficiently free from biological, physical and chemical contaminants to ensure that there is a negligible risk to the health and safety of occupants.
To improve IAQ, source strengths have to be minimized and an optimization is needed for : supply and exhaust flow rates, flow directions between zones, sink strengths and filter efficiencies.
To sketch the steak for supply optimization, it is nice to keep in mind that less than 3% of the normal ventilation flow rate in buildings (about 0.007 m^3/s per person) is inhaled (about 0.0002 m^3/s), the other 97% is used to dilute pollutants, like odour and CO_2 .

It is expected that analysis of indoor air quality will become more and more important as a part of the design process of healthy indoor air environments and control strategies. Analysis both by measurements and computer simulation.

Process

The main process is the generation of pollutants and dilution by ventilation. Ventilation plays a double role, it dilutes but also spreads the contaminants over the building. Transport by air, entrainment, is the most important mechanism for a pollutant to be spread over a building. This means that controlling the flow directions in a building one can control the spread of pollutants. In many cases however ventilation is not the only loss term. Filtering, deposition to surfaces, chemical reactions and radioactive decays can be more important.
In most investigations pollutant levels are presented. Less attention is paid tot the spread of contaminants within a building, ventilation flow rates and directions.
Single room ventilation efficiency does have an influence on the concentration levels, but in general it is thought that flows from room to room have a larger range of impact on the concentration picture of a building. In this last case, calculations can be done with the assumption of total mixing per room. In the case of local sources with a local exhaust(hood) the source strength must be reduced with the removal efficiency to get a reasonable simulation. An other way would be the use of extra zones around the local source to simulate the removal effectiveness, or to use computer fluid dynamics (CFD).
Flow through large openings has been considered as blind spot. Now a few mechanisms are available that can be used in simulation models (Feustel, 1989). The effect of the large opening flow on the ventilation efficiency end hence the transport of contaminants from zone to zone is yet another vague factor.

Pollutants

The number of pollutants that plays a role, is increasing, partly because of the development of sensitive measurement techniques, simulation techniques and results of research that show the importance to health.
Because of the many pollutants and the many combinations pollutants-materials that serve as an absorber, it will never be possible to create a complete data base with source and sink terms and their relations with other conditions. However it is thought that classes of sources and sinks may be defined that allow for useful handling of measurement results and simulations.
Most investigated pollutants are: H_2O, CO_2 , CO, NO_x , SO_2 , O_3 , HCHO, VOC's, cigarette smoke, Radon , dust, fibres, Pb, micro biological contaminants and odours .

Zone

In measurements and simulation models the term 'zone' is used. A zone can be a small volume element of a room for which concentration, flow rates and other state variables are described. A zone can also be just one room, a set of rooms, or a complete floor or set of floors in a building. Here the word building is used but applications can be any enclosure like cars, planes, cupboards, housing of apparatus.
The choice of the spatial zone dimensions can be given by the limitations during measurements and the capabilities of the simulation model. On the other hand the choice can be based on knowledge about the distribution of concentrations in the building. If an area, which can consist of one ore more rooms, is supposed to have an uniform concentration and ventilation, it can form one zone. If significant spatial variations of concentration occur in a zone it must be split up to give a proper simulation. For measurements this means that in this zone a single sampling point will not be sufficient to depict the whole zone.

Losses

Several mechanisms change the level of a pollutant during the transport from outside to inside, as well as inside from one room to another. These losses may give a greater reduction of the pollutant level than ventilation only. Some mechanisms and coefficients can be found in literature on deposition to surfaces and radioactive decay, nothing has been found on filtering or the penetration efficiency in cracks.
Air cleaning devices and filters can have a predominant effect for instance in clean rooms and operation theatres.

Occupants, exposure

Occupants play a key role. They can influence ventilation and some sources. If the pollutant can impose a health hazard the occupant is important because he is exposed to the (indoor) air.
Therefore a simulation tool must take into account in which room occupants stay, indoor or outdoor, and how long, to calculate average exposures.
For all health related problems the presentation of human exposure is preferable over the concentration histories in the different zones.
Occupants may have a direct influence on pollutant levels, for instance CO_2, therefore scheduled occupants in the different rooms are needed.

It is thought that calculation of the exposure for different groups of occupants for a building with

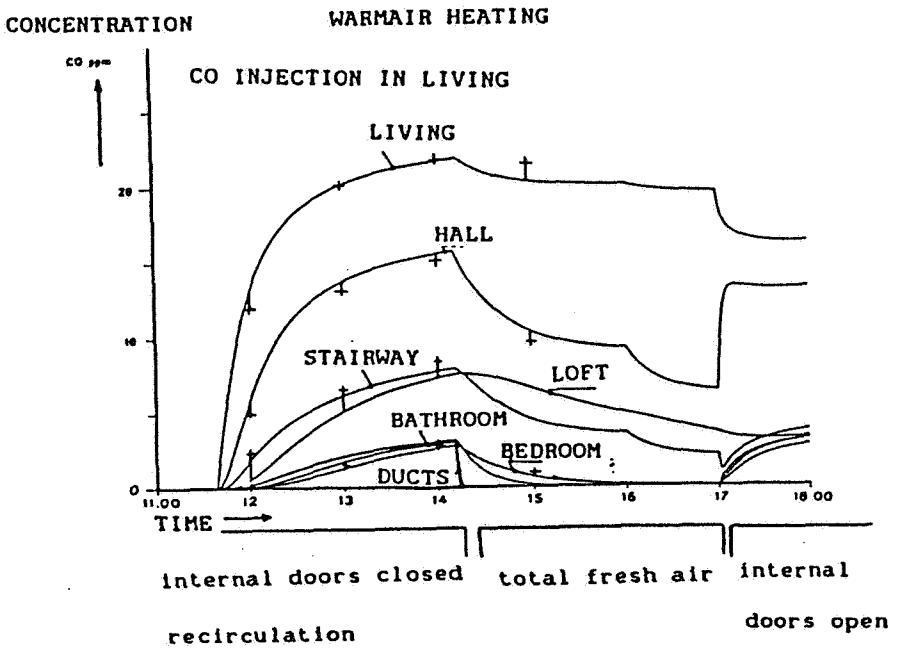

Figure 1. Comparison of model results and measured result for a non absorbing gas.

computer simulation models can be a very efficient way to interpret the IAQ. In this way comparisons with other buildings or variations in same the building are possible.
The exposure can be normalised by demanded limits from standards, and then summed for different chemical substances. Care must be taken for threshold values and non linear steps in the standards like 24 hour limits and 8 hour limits or percentile values.
There are a few cases in which health aspects are not of primary importance, for instance :

* condensation with the risk of building damage,
* pollutants that influence the quality of products in industry,
* dust in clean rooms

In those cases it is not useful to present the exposure of occupants, although it might be possible to present an estimated rate of product failure in stead of concentration histories.

2. Review.

A lot of information can be found on indoor pollutant levels (MCMurry, 1985) (ASHRAE 1989) . Most papers already give a review on existing pollutant levels for the most important pollutants. A lack of information exist on measured losses and sink terms especially in cracks. Some more information is available on sources and source strength of pollutants. Computer models exist which take into account pollutant transport by airflow, based on a mass conservation principle (Axley, 1988 a,b). Some models describe the reduction of a single pollutant under several conditions, for formaldehyde (Grot, 1985) and (Godfish, 1988).
As long as source strengths and ventilation flow rates are properly simulated, excellent agreement between measurements and simulations is found in the case of non absorbed gasses. Some results of air and pollutant transport models are given in figure 1 (Gids 1988) and 2 (Axley, 1988 a).

Spread of contaminants in a single zone has been studied for instance by (Vandaele, 1989). Measurements were performed on 50 points in an attic room of about 38 m^3 with an air tightness of N_{50} =8 . With closed windows and an air change rate of 0.3 +/- 0.1(std) per hour a line source resulted in a ratio between maximum and minimum of the 50 spatial concentrations of 1.2 . A point source gave a spatial concentration ratio of 1.5 . With a window open the air change rate has been 0.75 +/- 0.5(std) per hour. Spatial ratios of the concentration for the line source were 1.2 to 1.3 and for the point source 1.5 to 1.7 .
These single zone concentration ratio's are thought to be much smaller than room-to-room concentration ratio's.
A possibility to include odour in pollutant transport models has been introduced by Fanger (Fanger, 1987).

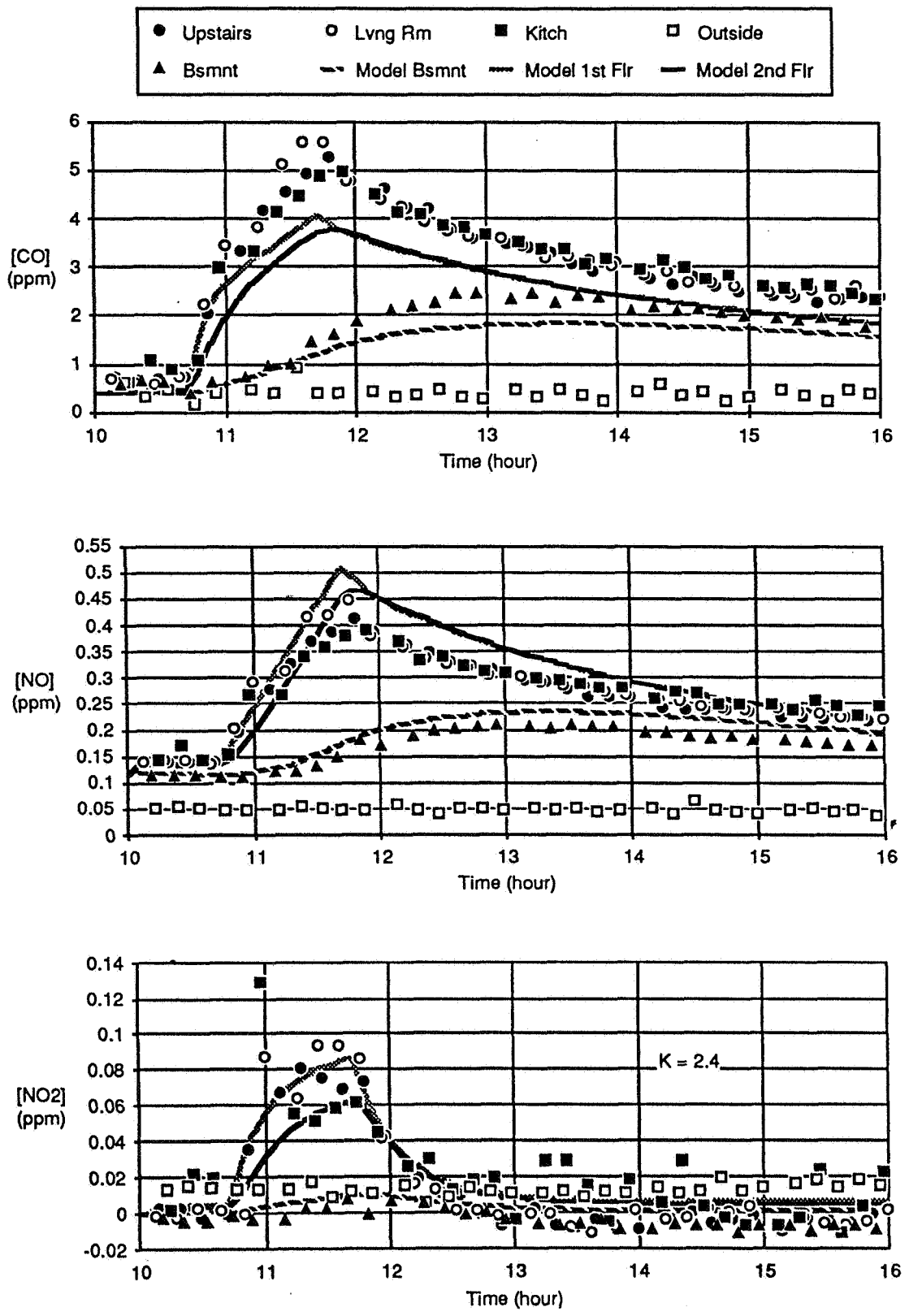

Figure 2. Comparison of a model predicted and measured response for several gasses as pollutants

3. Mechanisms.

3.1 General

The mechanisms can be subdivided into : source-, sink-, dilution-, transport-, exposure- mechanisms.

Assumed is a mass conservation for each zone, while the air is well mixed within the zone, the equation which describes the mass balance can be given (Feustel, 1989);

$$\frac{d(\rho V C_n)}{dt} = \sum_{i=1}(q_{ini}(1-\lambda_i)C_{ini}) - (q_{out} + k)C_n + S_n \quad ...(1)$$

The unit of equation (1) is (kg[contaminant]/s). The summation is for all the incoming flows i.
in which:
With the ventilation time constant :

$$\tau = (\rho V)/q_{in} \qquad (s^{-1}) \qquad ...(2)$$

and with :

$$dt/\tau = (1-e^{-\Delta t/\tau}) \qquad (\Delta t << \tau) \qquad ...(3)$$

This leads to the form that can be used directly in numerical pollutant transport models in which t and t+1 are two successive timesteps:

$$C_{n|t+1} = C_{n|t} + (1-e^{-\Delta t/\tau}) / q_{in} * \left[\sum_{i=1}((1-\lambda_i)C_{ini} * q_{ini})/q_{in} - (q_{out} + k)C_n + S_n\right] \quad ...(4)$$

Equation (4) can be used if the air density remains constant and if the incoming flow is not zero. The substitution of (3) avoids overshoot of the concentration for timesteps as big as the ventilation timeconstant of the zone, but some accuracy is lost. Small zones, like a duct section with large flows, can have very small timeconstants and would otherwise have led to unpractical small time steps in the case of a linear equation.

Filter efficiencies (4) for dust can be found for filter units but unfortunately not for cracks.

The reactivity term k in (4) can be expressed as a deposition velocity to a surface:

$$k = \rho \sum_{j=1}(V_d * A)_j \quad (kg/s) \qquad ...(5)$$

This means that the amount of pollutant in the volume $V_d * A$ disappears per unit of time into the surface A . For low concentrations, say in the 1 ppm range, saturation of the surface doesn't occur. The process has not been found to end in time. Cleaning, renovations or repainting is likely to occur before a saturation would be noticeable.

In experiments the deposition can be determined as a decay rate :

$$1/\tau_{con} = V_d * (A/V) \qquad (s^{-1}) \qquad ...(6)$$

The experimental concentration decay in a closed room without ventilation and deposition only is :

$$\frac{C_t}{C_0} = e^{-t/\tau_{con}} \qquad ...(7)$$

Source terms S_n in (4) are often given as mass flows per time unit and need only scaling into the proper units.

3.2 Air paths

The air from outside passes on its way to inside either a mechanical ventilation system or the building fabric in which losses of a pollutant take place.
In the room some mixing followed by the transport from one room to another room will occur, via a mechanical ventilation system or via cracks, openings around the doors, grids and/or through the construction of the internal walls.
During the transport of air by a mechanical system there can be losses in terms of uncontrolled deposition and/or filtering in the purpose provided filtersection.
The air will leave the building by exfiltration through the building envelope and/or by the mechanical extract system. During this transport a certain amount of the pollutant will be left behind and hence give a decrease of the emission.
The air flow over large openings is mainly not one directional. Due to local turbulence, flow in both directions i.e. inward and outward flow is possible and can occur simultaneously in one opening. In the case of large openings the chance to have total mixing in the room decreases. The flow in the opening and the ventilation efficiency to the bulk air of the room determine the transport of pollutant in both directions via the large opening. Therefore the contaminant transport due to this flow mechanism is not quite well known. In simulation models two estimates are necessary:

case 1. The concentration in a zone has to be kept low by means of large opening ventilation,
case 2. A zone has to be protected against polluted air infiltrating via a large opening.
In the first case the best average air flow exchange over the large opening is needed. In case 2 a higher estimated large opening flow is necessary in order to be sure that the protection pressure hierarchy will be sufficient to keep the contaminant out.
In clean rooms laboratories and hospitals large openings are a thread to the pressure hierarchy. This is an important application of ventilation-pollutant transport models.

3.3 Source mechanisms

As source mechanisms for contaminants can be mentioned: emission or release of mass, evaporation, desorption, resuspension, growth of micro-organisms, radio activity.

Examples of emission or release of mass are for instance: human CO_2 production, combustion products from a furnace, heaters, formaldehyde from particle board and plywood. Grot (Grot 1985) has performed many measurements of the surface emission rate of formaldehyde from wood materials and found in many cases a good agreement with the equation:

$$ser=\alpha - \beta C \qquad ...(8)$$

A useful value has been the surface emission rate at a concentration of 120 $\mu g/m^3$ or 100 ppb and the cutoff concentration where the emission rate becomes 0, defined as:

$$cutoff=\alpha/\beta \qquad ...(9)$$

Correction terms for on α and β for temperature and relative humidity have been determined by (Matthews , 1986).
Degradation of resins increases at increasing temperature and relative humidity, resulting in a higher formaldehyde generation on the average of about 23% per K temperature increase and 5.5% per %RH increase.

Examples of evaporation are: Watervapour in homes, solvents, VOC's from paint, carpet and furniture materials.
Several controlled test chambers have been constructed in Europe to determine the source strength of several furniture materials. These test chambers are based on guide lines of the EC COST working group (Project 613, WG8).

Desorption and resuspension can occur for instance with odours absorbed by furniture materials, gas molecules that are physically bound to the surface and dust particles larger than 1 μm, due to mechanical vibrations or high local air velocities. Vacuum cleaning and walking can temporarily increase the amount of aerosol dust.

Growth of micro-organisms like fungi, house dust mites and allergens from domestic animals are harder to be modelled as besides growth conditions, elapsed time is important. The different stadia of the life cycle of the organisms have different production rates of allergens or fungus spores. Most of these sources are related to moisture, and especially the moisture in the boundary layer near the surface. There is a feeling that instead of measuring and simulating these kinds of sources in buildings in order to show the current status and relations, it would be better to focus on solutions directly: To build buildings that will not be moist, not to use building materials that are a breeding ground, to use beds that can be periodically electrically heated or frozen to kill mites.

Radiation from Radon is commonly investigated (Dijkum, 1986) (Collé, 1980). Geological composition of the soil has a large influence on the Radon generation levels. Uranium rich soil is known to result in higher Rn levels, both directly from the soil and from building materials which originate from such soil. ^{222} Radon has a half life time of about 3.8 days and its daughters to ^{210} Pb all shorter than that. As this half life time is generally much longer than the ventilation time constant of a building, the main loss term is ventilation. This may not be true for spaces with stale air like closed wells, where high concentrations can build up (Meyer, 1983).
Soil generated Rn cannot be looked at separate from its mechanism to infiltrate in a building.
By diffusion Rn enters cracks in the bedrock. Moved by ground water levels, wind pressures on the field around the building, in the soil under the building and in the subfloor void Rn infiltrates in the building. Large local variations and variations in time have been observed. Some of the pressures are related to the shape of the building and the ventilation parameters of the building. Therefore the building and its ventilation parameters have an influence on the amount of Rn that is transported. This can be studied effectively with multizone ventilation- pollutant transport models. BRE has derived a simplified way to handle this process and calls it the Radon Parameter (Hartless, 1990).
For positive pressures between soil gas and subfloor void the equation is:

$$RP=(q_f * \Delta P_f / N_{ach} * N_{achv}) \qquad ...(10)$$

and the radon concentration in the building :

$$Rn_i = Rn_o + k_r * RP \qquad ...(11)$$

The constant k_r includes many different, unpredictable factors such as soil type and Radon generation. The Radon Parameter can be seen as a sense for a buildings sensitivity for Radon infiltration if it would be placed on a Radon generating soil.

Other Radon sources are building materials, domestic and ground water, natural gas and industrial aerosol dust. Attached to aerosol dust or directly, and subsequent respiration it can be deposited on the lung tissue. This leads to an increased tumour risk.
The effect of radioactivity from outdoor air infiltrated in dwellings on the dose has been investigated by (Roed, 1990).

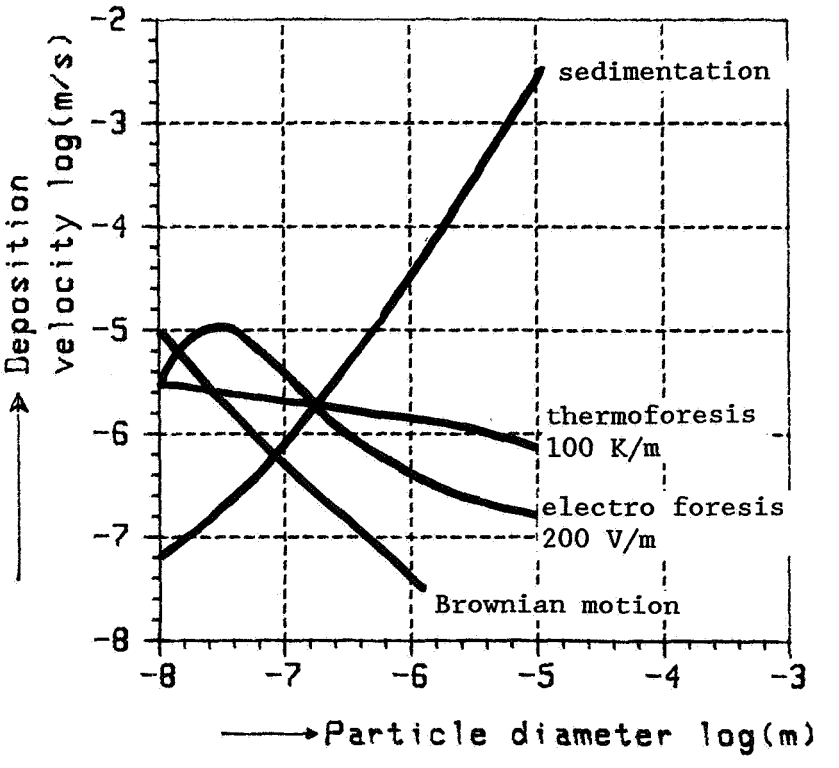

Figure 3. Deposition velocity of particles

3.4 Sink mechanisms

The most important sink mechanisms are: deposition (absorption and adsorption) sedimentation, plate out, filtering, condensation, chemical reaction, radio active decay.

The deposition process has two steps (Lanting, 1991). First there is a pollutant mass transport through the undisturbed boundary layer to the surface. The second step implies chemical or physical interaction with the surface. For gasses the second step is the limiting factor and for particles the first step. With full absorption on the surface the theoretical deposition velocity for gasses should be 1E-5 m/s in stale air, with natural convection and laminar flow along the surface 7E-4 m/s and in turbulent air 1.8E-3 m/s. The real deposition velocity will be lower if not all molecules interact with the surface and can be higher if the surface is rough (for instance carpet) and if the humidity is high for water soluble gasses. Temperature has minor influence on the process.
More processes play a role at the deposition of particles on a surface.
Small particles (cigarette smoke) bind irreversibly to a surface.
The processes that move particles to a wall are:

* Brownian motion (particles <0.5 μm show a gas like diffusion that is bigger than the sedimentation velocity in stale air),
* Thermoforesis (particles >0.05 μm move through a temperature gradient to a 1K colder surface 10 times faster than if the surface is 1K warmer),
* Electroforesis (Computer and TV screens),
* Sedimentation (Stokes, dominant for particles >1 μm).

The particle size is the most important parameter. The effect of the different mechanisms is shown in figure 3.

A summary for the deposition velocity in m/s of gasses is:

Situation	SO_2	NO_2	O_3	HCHO	VOC
Rooms with much absorbing material	6E-4	3E-4	9E-4	1E-4	2E-5
Rooms with little absorbing material	1E-4	3E-5	4E-4	5E-5	2E-6

For turbulent conditions the values are typically 3 times higher.

Data for filter efficiency for particulate matter can be directly applied in pollutant transport models provided that the particle size is known. The effect of aircleaners on other pollutants is not generally known. Some air cleaners for domestic use have been found to have no effect at all on dust concentrations while ionization filters have been found that produce high concentrations of O_3 . Performance of several air-cleaners has been reported by (Daisey, 1988). Most air-cleaners have a lower flow rate than those indicated by the manufacturers. Removal efficiencies for NO_2 and VOC's have been found in the range of 0% to 40% for the various cleaners.

Condensation occurs if for instance a surface is below the dewpoint of the water vapour in the zone. The condensation heat produced, heats up the surface. A detailed simulation is possible only with combined heat flow-ventilation models. Condensation rates can be up to 1E-4 kg/s/m² in bathrooms during a shower.

Chemical reactions in air are for instance SO_2 with H_2O. Most reactions play a negligible role as the concentrations of both contaminants are relatively small.

Radio active decay for Radon can be a significant loss term in spaces with full mixing and a very low air change rate (N_{ach} < 0.01) but also when a relatively high concentration of the heavy Rn formes a stagnant, stratified layer on the floor. Radon is 9 times heavier than air.

3.5 Exposure

If the concentrations in the zones are simulated in time with a computer model, and if those concentrations are good estimates for the concentration inhaled by the occupants, then it is a relative easy step to calculate the exposure to air pollutants.
In fact it is a way of presenting the vast amounts of results from multizone concentration histories into a few daily, weekly or for instance annually averaged exposures for a defined set of occupants.
Exposure does not deal with the problem of health risks, dose-effect relations. It is only meant here as a sense for a better IAQ in a building.
In literature the term exposure is also used for intake of contaminants via food and skin (EPA, 1989). The here mentioned 'exposure to air pollutants' does not deal with that.

If the occupant does not influence the sources and sinks and ventilation then with a record of the concentrations from a single simulation run, the exposure for many occupant patterns (in which room they stay) can be calculated without recalculating the concentrations.
If the occupant does influence the parameters, for instance with CO_2 as a gas, then the complete concentration simulation run has to be repeated for every occupant schedule.
In most cases the ventilation flow rates will not be driven by the contaminant levels in buildings as the concentrations will be low enough to neglect their influence on the air density and thus on the buoyancy or stackeffect pressures. This means that with a fixed record of ventilation flow rates many concentration histories can be produced.
An exception might be H_2O vapour as a contaminant, which does have a small influence on stack effect. The effect of water vapour 0.001kg/kg dry air is about the same as the effect of 0.17 K temperature difference.
Air flows within one room can be influenced by concentration differences but in most cases heat that is co-generated (cooking) or air movements by the generation activities (vacuum cleaning) have a larger influence on air movements than concentration only.

4. Standard contaminant levels.

Many standards exist for acceptable levels of indoor contaminants. Overviews can be found in (ASHRAE 1989) and (Canadian EHD, 1987). Values differ between countries. A selection is made here. Contaminant levels should be as low as possible. Within pollutant transport models these values can be used to normalise predicted levels, and to signal if threshold values are exceeded.

Source	short term		long term	
	µg/m³	ppm	µg/m³	ppm
moisture			<80% RH at surfaces	
formaldehyde	120	0.1	60	
CO	1E4	9		
CO_2		10,000		1000 (comfort)
SO_2			80	0.03
O_3	240	0.12		
dust			40	
NO_x			100	0.055
Pb			0.5 to 1.5	
VOC's			component dependent typical several 10.000 µg/m³ unless carcinogen	
radiation			25mrem/y 28nSv/h	

A ranking of agens for health risk assessment has been performed by (Lanting, 1990 a) based on:

* MAC values and WHO guidelines or odour
* existence of sources
* emission/exposure profile in time
* concentration levels of exposure.

Sources with the highest priority for which exposure or measures to be taken, are known are: Combustion appliances, tobacco smoke, formaldehyde from particle board.

Sources with high priority and insufficient knowledge about exposure and measures to be taken, are:

* pesticides, wood conservation, additives to textile
* aldehydes and carbon acids in wood, floor covering, textile or in combination with odour
* phthalate-esters in plastics, paints and glues
* isocyanates in paint, insulation foam, glues
* water based paints and cleaning products with glycol-ethers, -esters, alcohols, conservatives, fungicides
* floor covering vinyl linoleum and textile with suspect carcinogenic compounds, softeners or in combination with odour.
* cleaning and maintenance products with suspect carcinogenic compounds or in combination with odour.
* mercury from broken thermometers and barometers.
* terpenes in floor and furniture wax, cosmetics, wood products, paint.

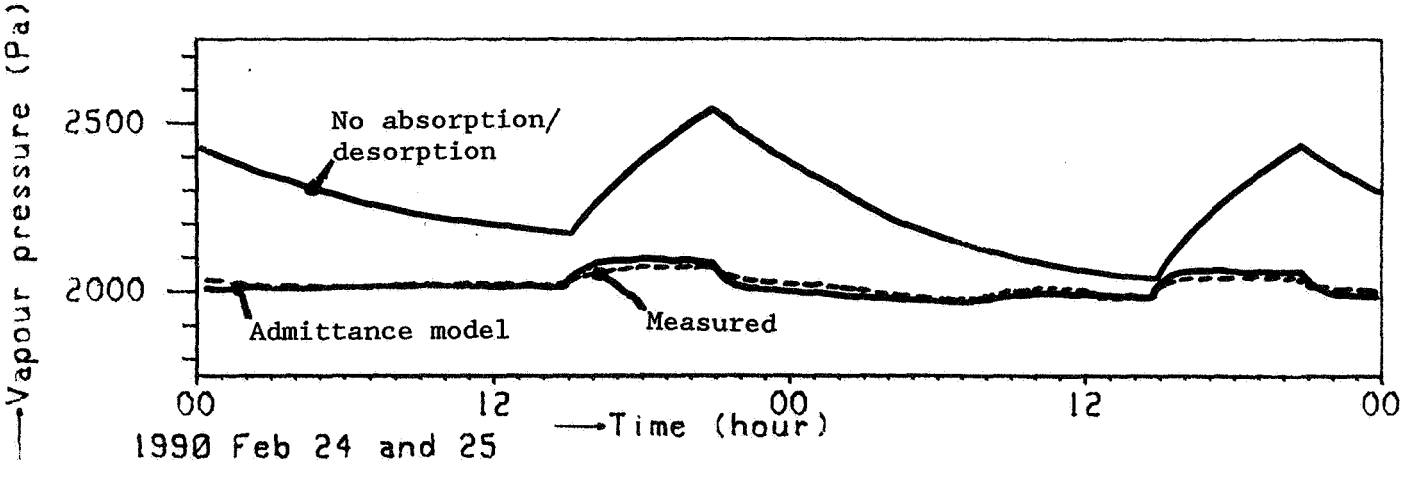

Figure 4. Moisture admittance model of Jones, BRE

5. Contaminants from indoor

moisture, formaldehyde, CO, CO_2 , O_3 , dust, NO_x , VOC's, radiation.

Moisture generation rates in homes generally are about 7 to 14 kg/day. Moisture is of importance as one of the growth conditions of microorganisms. It is thought that ANNEX 24 will yield specialized models to predict moisture transport through building components, like for instance the Danish model Match.
A promising simplified dynamic model, called moisture admittance model, has been produced by BRE (Jones, 1990).
Its coefficients have been experimentally fitted with results from 2 experimental rooms and need work to be generally applicable in buildings and with non uniform surface temperatures. The equation looks like:

$$\frac{d(p_{in})}{dt} = \{N_{ach}(p_{in} - p_{out}) - 2.5p_{in} + (1.4 \text{ to } 1.8)p_{sat} - 0.3p_{win}\}/3600 + S_n * p_{sat} / X_{sat} \quad ...(12)$$

The coefficients are valid for the specific test chamber. In figures 4 a comparison of the model with measurements at a changing vapour input is shown.

A recent overview of existing concentrations of formaldehyde in European countries has been given by (COST , 1990). The outdoor background concentration is about 1 $\mu g/m^3$ with peaks up to 100 $\mu g/m^3$ due to traffic.
Formaldehyde from building materials has been shown to be a non constant source (Grot, 1985) (Godfish, 1988). Moisture, temperature and the Formaldehyde concentration itself influence the generation process. Source strengths of particle board and plywood have been found in the range of 0.003 to 0.5 $\mu g/m^2/s$ at a formaldehyde concentration of 0.1 ppm. Cutoff concentrations, where the emission becomes 0, have been found to be in the range of 0.2 to 0.4 ppm (240 to 480 $\mu g/m^3$) with some medium density fibre boards up to 1.8 ppm (1800 $\mu g/m^3$). An excellent agreement between the measured formaldehyde concentrations and a mass balance indoor air quality model has been obtained.
Other sources of formaldehyde are UF-insulation foams, tobacco smoke, combustion gasses from gas appliances, traffic, industry (production of resins). Formaldehyde source strengths of 0.4 to 4 $\mu g/kJ$ were measured by (Traynor, 1985) at unvented heaters.

Carbon monoxide is produced by incomplete combustion, cooking, traffic.
The number of fatal CO poisonings per year in Holland normalised for a 1000.000 population:

0.4	kitchen unvented geysers
0.14	geysers with a flue
0.29	central and decentral heaters
0	cookers and other appliances

In 17 % of kitchens (Brunekreef, 1981) CO concentrations were measured above 50 ppm after using the unvented geyser for 15 minutes . CO source strengths of 13 to 165 $\mu g/kJ$ have been found for unvented gas heaters under poor ventilation conditions by (Traynor, 1985).

The current trend is to use closed gas-appliances, with a fan for supply and exhaust gas and separate flues. The amount of supply air for gas burning is usually negligible, 1 to 3% of the ventilation flow rate of the house. Closed appliances have a better efficiency due to the lower, controlled excess supply air flow rate.
Malfunctioning natural gas exhaust flues in airtight houses with mechanical extract ventilation are a known problem (Steel, 1982).
Unintended transport from parking garages to buildings has been reported by (Hodgson, 1989) and can impose a CO and VOC source. CO levels of 10 ppm have been measured in the building above the garage.

CO_2 is produced by combustion. The human CO_2 production is about 5.6E-6 m^3/s, mainly dependent on the skin area(Dubois area) and the metabolic rate.

NOx is also produced by combustion from gas appliances and traffic. Traynor (Traynor 1985) measured source strengths for unvented gas heaters to be from 10 to 20 $\mu g/kJ$ both for NO and NO_2 .
Average indoor levels of more than 200 $\mu g/m^3$ (0.1 ppm) with 1-minute peaks of 4000 $\mu g/m^3$ (2 ppm) have been found in homes with unvented gas appliances (COST 1989 NO_2). Negative health effects are reported at concentrations as low as 200 $\mu g/m^3$. The trend is to use cooking ranges with special low NO_2 burners.

VOC's have been shown to be originating form solvents in liquid-process copiers in an office building at rates of 2 kg solvent/day total for 26 copiers (Hodgson, 1989). Other sources of VOC's are finishing, furniture materials. An unexpected source might be the evaporating benzene from gasoline from cars in parking garages attached to a building.

To determine material source strengths a series of european test cells has been made within COST 613 TG 8. It is expected that many results will soon be available from this. In principle these test rooms allow for determination of sink rates as well. Two floor covering carpet tiles with PVC back emitted 4600 $\mu g/m^2/h$ total VOC on the first day and 2700 on the 7th day, the second tile 1160 and 370 $\mu g/m^2/h$ (Wal, 1991).

Ozone is generated by photochemical processes like in laser printers. Measurements in a test chamber with some adsorption on walls showed source strengths of 10 $\mu g/s$ or about 100 μg per copy without any

filter on the printer. Filter efficiencies have been reported from 70 to 99% .
Some air cleaners for domestic use with an ionisation filter section produce up to 1 $\mu g/s$ O_3 .

6. Contaminants from outdoor.

In most cases outdoor levels will be used as an input to pollutant transport models.
Outdoor levels are mainly influenced by industry, traffic and agriculture. Below are given some figures from various guide lines just to give some idea.

Sources	target average annual levels $\mu g/m^3$
SO_2	30
Dust	30
NO_x	25
Ozone	120
lead	0.5

Measured levels can have very large peaks if measured in the vicinity of the source. For NO_2 levels in the range of 100 $\mu g/m^3$(year) have been reported in urban area's with hourly values up to 1000 $\mu g/m^3$ due to traffic. Some simplified and limited calculation models exist for levels as a function of traffic intensity (Jansen, 1987).

7. Control Strategies.

An overview of strategies has been given by (Levin, 1992).

7.1 Indoor sources.

The general strategy is to minimize source strengths. As ventilation in cold climates or cold periods increases energy consumption, the preference is to keep the ventilation rates close to minimum rates (IEA ANNEX 9, 1987) (Trepte, 1989).
During warm periods ventilation may be higher, due to open windows, and pollution levels may be non important with respect of the cold period.
At outdoor temperatures higher than acceptable, cooling by air conditioning will lead to the same preferable minimum ventilation as in cold periods.
To increase the effect of ventilation, air flow rates must be at the proper locations and controlled in time. This means local exhaust near sources and local supply near occupants, displacement ventilation.
Increased ventilation during cooking is common. But the local exhaust above the cooker is usually not very effective compared with a fume cupboard. Local exhaust near showers in bathrooms, WC , on printers and copiers is rarely seen. In Industry too local exhaust is often not applied because of (supposed) draw backs to the accessability of processes.
Demand controlled ventilation (IEA ANNEX 18) is the (near) future to optimize IAQ versus the used ventilation flow rates.
In many cases the control of flow directions prevents contaminated air to reach occupants or to enter into sensitive areas. Unfortunately in most buildings the natural flow direction spreads the contaminant through the building, like Radon from the crawlspace and vehicle exhaust gasses from the basement parking garage.
Evaporation of gasoline from cars in the garage is effectively reduced by the Californian canisters, a carbon filter in the car. This is an environmental measure but it also reduces benzene exposure from parkings into buildings.
A special case of flow direction control is the operation theatre in hospitals and clean rooms. Large openings (doors) and temperature differences can spoil the desired pressure hierarchy. Large bypass flows through grilles besides such doorways can minimize the disturbance, and maintain sufficient air velocity in the open door way to avoid a two-way flow.

7.2 Outdoor sources.

If outdoor sources have a constant too high level, filters or cleaners must be used to get an acceptable IAQ. Some contaminants can be removed very efficiently or disappear already in the HVAC or humidifier like SO_2.
Care must be taken at the position of the air inlets, not on the side of busy traffic or the exhaust on the roof.
If outdoor concentrations fluctuate and the duration of peaks are shorter than the building ventilation time constant then a time control of the amount of outdoor air may be possible. A good example for this is the control of ventilation in vehicles in dense traffic. The problem here is that the ventilation time constant in vehicles is usually in the range of some 100 s and a quick response of the sensor and control is needed. The reduction of the concentration level in the intake air can be large as outside levels in traffic usually fluctuate with a ratio of 1:100. Switching off the outdoor air supply

increases indoor source effects. An optimum has to be found, a perfect field of application for 'intelligent' controllers. An example in a simulated bus of 48m³ with measured outside NO_x concentrations as input, is given in figure 5. To account for some internal pollutant generation 34 µg/s is added as source. Two runs have been made : one with fixed ventilation flow rate 0.5 m³/s, the second with the same integral flowrate but switched on and off (30% on, with 3 times the nominal flow rate) if the outside concentration is lower than inside (no sensor-control delay).
Average outside concentration is 688 µg/m³, inside 748 at constant ventilation and 283 at controlled ventilation. The effect is dependent on the amount of internal pollutant load, which is about 10% of the outside pollutant load in figure 5.

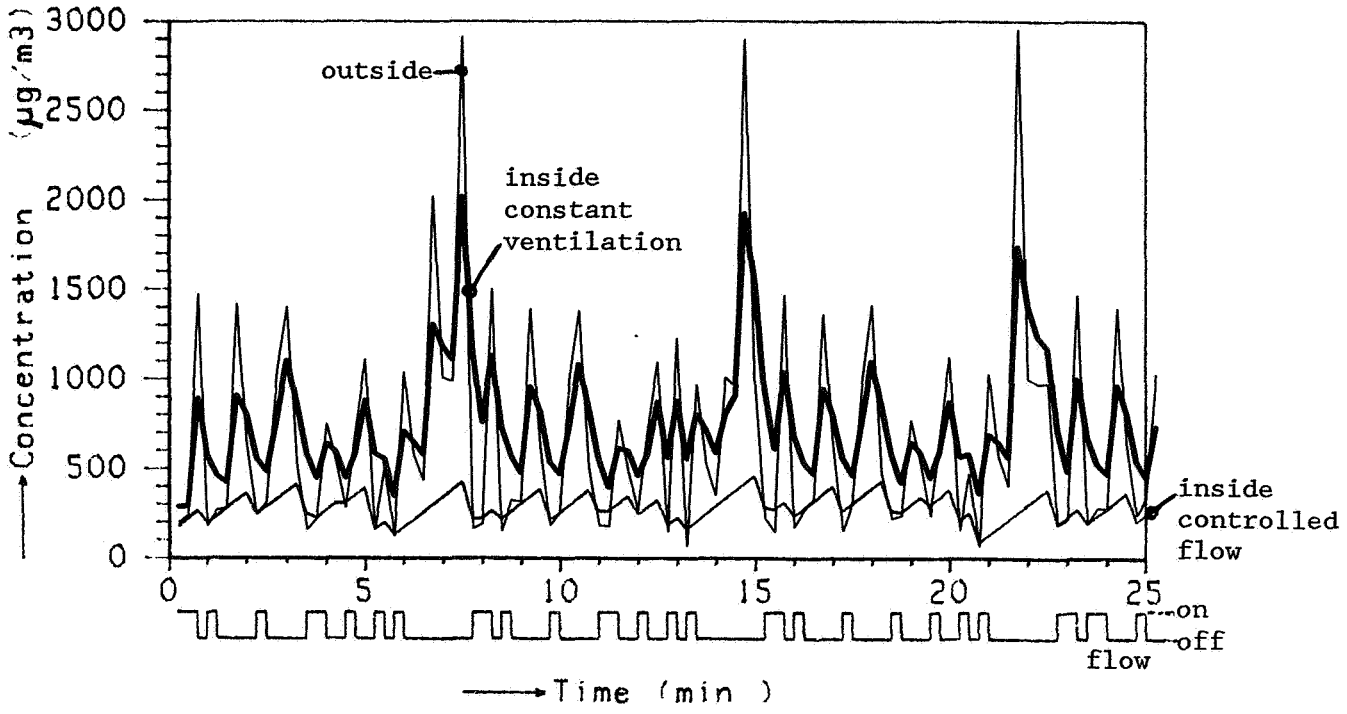

Figure 5. Simulated NO_x concentrations in a bus, constant and controlled ventilation.

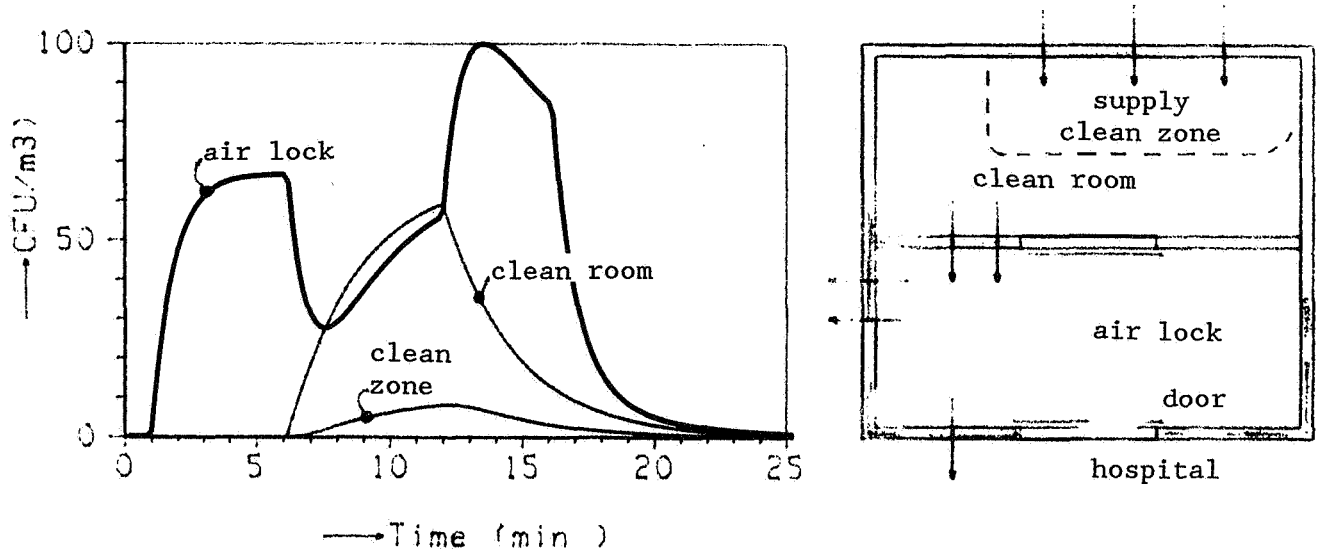

Figure 6. CFU concentration in an isolation chamber and floor plan.

7. Examples

7.1 NL Archives and museums

In museums and archives IAQ is not health related but meant to prevent deterioration of paper and cultural inheritage. SO_2 , NO_2 and O_3 have been measured in 6 buildings by (Lanting, 1990 b). A significant part of the outdoor pollution is introduced via the HVAC system, from which the recirculation ratio has been varied. SO_2 is absorbed by the humidifier of the HVAC system. Low levels of the contaminants indoors have been explained by the rapid absorption by the large quantities of archival material. Outside the working hours 100% recirculation has been advised.

7.2 Hospitals

Pollutant transport models can be used for prediction of the number of dust particles that contains germs that could cause infection. This is called CFU, Colony Forming Units, expressed in CFU/m³ . In this example the source strength of a person is 20 CFU/s . Levels of CFU's are simulated in a protected room and its air lock to the corridor, when a person enters from the air lock into the protected room. The limit is 10 CFU/m³ in the clean zone in the protected room. Figure 6 shows the concentrations.

At minute 1 a person enters the air lock, at 6 the protected room is entered and the door is open for 10 seconds. At 12 the person returns to the air lock, which is left at minute 16. No CFU generation is taken into account for a patient staying in the protected room .

7.3 NL Leidschendam

Airborne moisture transport has been investigated by (Oldengarm , 1990) (Elkhuizen, 1990). In a dwelling three moisture generation types have been considered:

* cooking
* shower
* laundry drying

Moisture storage and release from walls and furniture could be seen as simultaneous measurements of different tracers were used. In figure 7 the moisture content from 12:00 to 14:00 is below that of a non absorbed tracer, indicating absorption of moisture. After 14:00 moisture is released from the surface and the moisture content is higher than the equally scaled non absorbed tracer gas.

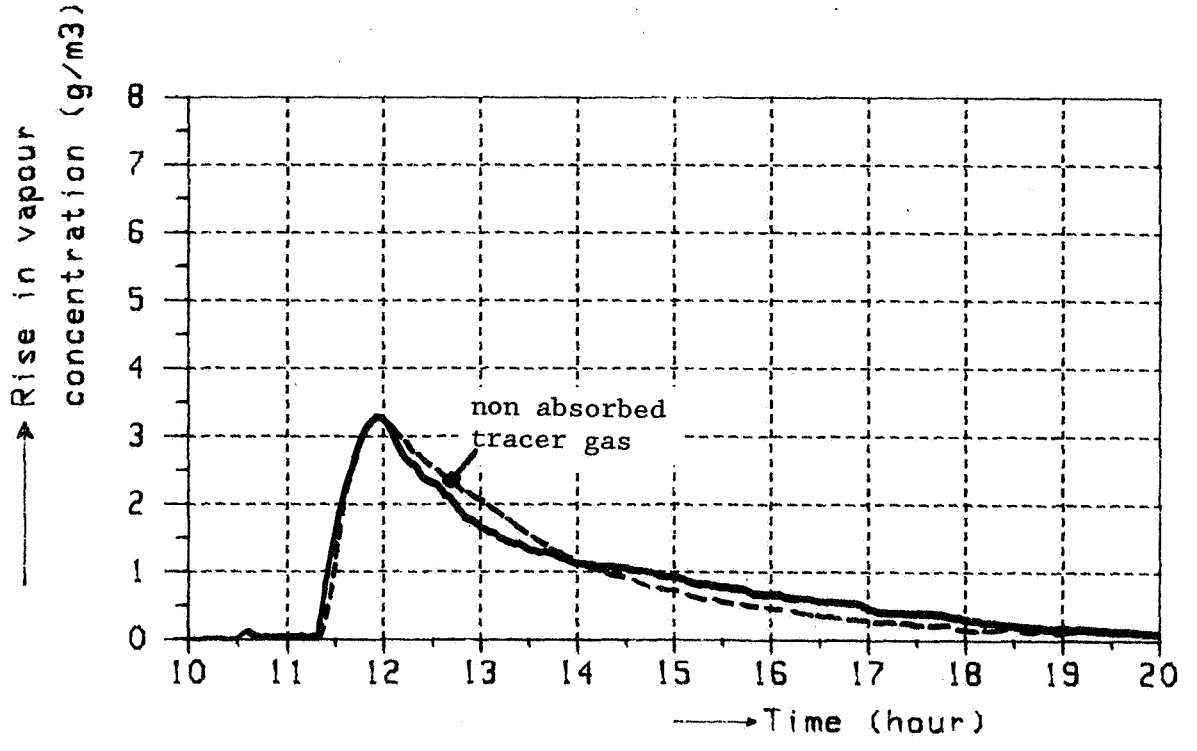

Figure 7. Vapour concentration in a house after a 30 minute moisture input, compared to a similar scaled non absorbed tracer.

7.4. NL Almere Schools

Schools have a high demanded ventilation rate, N_{ach} >2.5 h^{-1} , which is generally not met with natural ventilation, because windows are not sufficiently opened. As a result CO_2 concentrations over 3400 ppm were measured in a period with switched off mechanical ventilation (Knoll, 1984).
Perceived odour, based on questionnaires, however did not differ much for the period the system has been on, with less than 1200 ppm CO_2 . Conclusion is that occupants in schools are not capable of controlling their windows in order to get an acceptable IAQ.

7.5. NL Lelystad.

The aim of the Lelystad project has been to compare houses with warm air heating and recirculation of air with houses with warm water heating and no recirculation of air. Recirculation of air from living room to bedrooms has not been allowed by the Dutch standard NEN 1087. It is said that in houses with warm air heating and recirculation there are more problems with allergic reactions and respiratory diseases. No investigation exists that proves this. The thought is that the forced air movement in the heating system and high velocities at the grilles keep the dust moving. This has been proven to be not true, grille velocities are too low to resuspend dust.
The air tightness of both houses meets the demanded value in the Dutch standard (NEN 2686), with N_{50} =1.3 (air heating) and 3.1 (water heating) per hour.
Three tracer gasses have been injected in the living rooms under various conditions. Figure 1 warm air heating and figure 8 warm water heating.

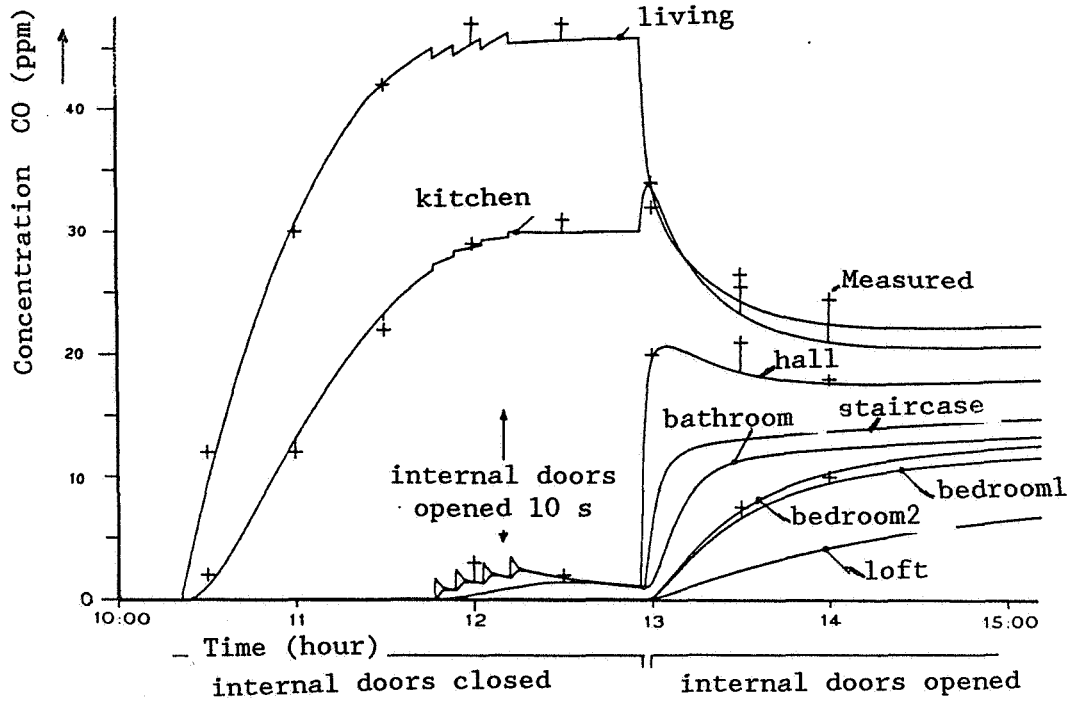

Figure 8. Measured and simulated concentrations. Warm water heating.

The gasses were :

gas	target concentration in the living room.	
Carbon monoxide	25	ppm
Nitrous dioxide	0.2	ppm
Paraffine oil aerosol and cigarette smoke	1000	µg/m³

Carbon monoxide is not absorbed and served as a tracer to see the spread of air and dilution from living room to the other rooms.
NO_2 is absorbed by building materials and is used to show the effect of absorption.
Paraffine oil smoke has been used to simulate cigarette smoke. The oil drops show a plate out effect and are adsorbed when the air hits a surface or filter. Spread of cigarette smoke is considered to be one of the important draw backs of recirculation.
In figure 9 and 10 the ratios between the concentrations of the different gasses are drawn by

normalising them to the same value in the living room.
The deposition velocity to the floor area for NO_2 are about 0.5mm/s.

Ratio of NO_2 and smoke to CO in the livingroom. Internal doors closed.

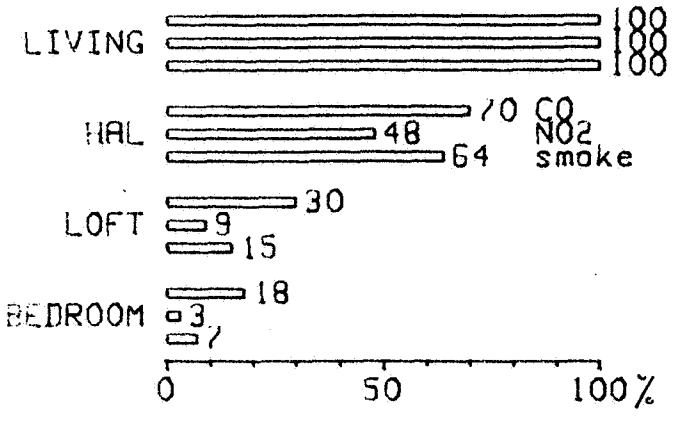

Figure 9. Warm air heating

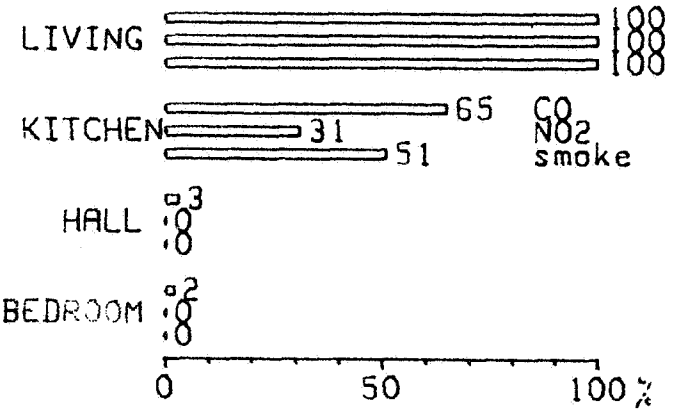

Figure 10. Warm water heating.

A second set of measurements has been held (Kornaat, 1990). Thereby Al_2O_3(97%) and TiO_2(2%) dust particles of 2 tot 14 μm (90%) have been injected into all rooms. The decay has been monitored with Tyndallometers which have their peak sensitivity between 2 to 5 μm. The theoretical velocity at which these particles will fall to the ground is about 2 mm/s.
Dust concentrations have been simulated for different conditions, as shown for the living room in Figure 11.

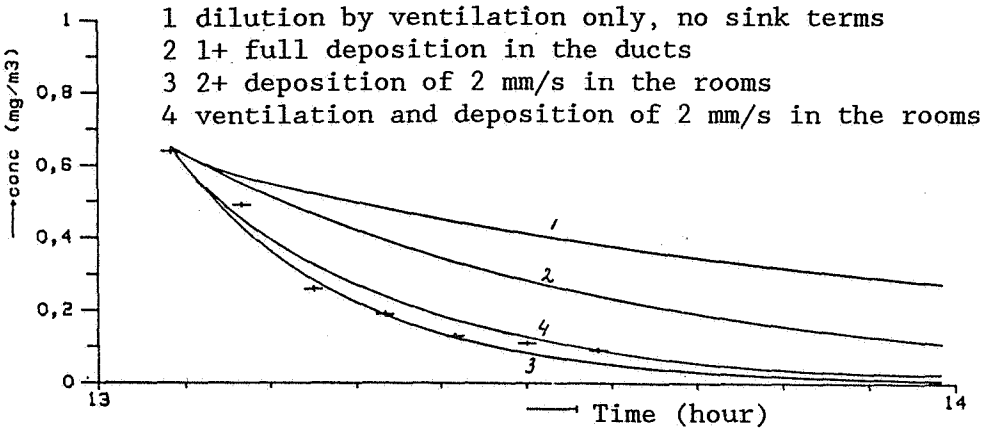

Figure 11. Measured and simulated decay of dust.

For the combination of "ventilation and full deposition in the ducts and a certain deposition velocity in the rooms" the influence of the deposition velocity in the simulations has been investigated. The deposition velocity has been set to: 1,2 and 4 mm/s, see figure 12.

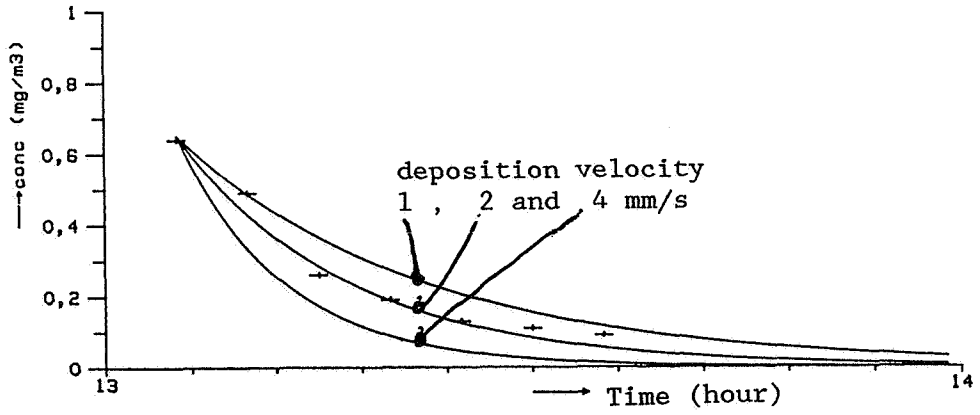

Figure 12. Measured and simulated decay of dust, varied deposition.

8. References

ASHRAE. 1989. Ventilation for Acceptable Indoor Quality. ASHRAE standard 62-1989. Atlanta, GA, USA.

Axley, J, 1988 a. Indoor air quality modelling. U.S. department of Commerce, NBS. Washington, USA. July 1988

Axley, J. 1988 b. Progress toward a general analytical method for predicting indoor air pollution in buildings. Indoor air quality modelling. Phase 3 report NBSIR 88-3814. NIST, Gaithersburg, MD, USA.

Brunekreef, B. and others 1982. Indoor carbon monoxide pollution in the Netherlands. Environment International, 8 (1982), 193-196.

Canadian Environmental Health Directorate, 1987. Exposure Guidelines for Residential Indoor Air Quality. Ottawa, Canada.

Collé, R. and McNall, P. E., Jr 1980. Radon in Buildings. NBS Special Publication 581. Washington, D.C. USA.

COST, 1989, NO_2 . Indoor pollution by NO_2 in European countries. COST project 613 Report 3. EC, Luxembourg.

COST, 1990. Indoor Air Pollution by Formaldehyde in European Countries. COST project 613, Report 7. EC, Luxembourg.

Daisey, J.M. and others, 1988. Efficiencies of portable air cleaners for removal of nitrogen dioxide and volatile organic compounds: Final report. LBL, Berkeley, USA.

Dijkum, P.H. Van, and others, 1986. Straling in het Leefmilieu. (report in Dutch. Radiation in the environment). Utrecht, NL: PEO

Elkhuizen. P.A. and others, 1990. Measurements of air borne moisture transport in a single family dwelling at Leidschendam. IBBC-TNO, B90-128. Delft, NL.

EPA, 1989 . Exposure Factors Handbook. EPA 600.8-89.043. Washington, D.C. USA.

Fanger, P.O., 1987. Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. Energy and Buildings, 12(1988) 1-6.

Feustel, H. 1990. Fundamentals of the multizone air flow model- COMIS. AIVC, Technote 29. Warwick, UK.

Gids, W.F. de and others 1988. Recirculation of air in dwellings. 9th AIVC Conference, paper 17. AIVC, Warwick, UK.

Godfish, 1988. Residential Formaldehyde Control by Mechanical Ventilation. Muncie, Indiana, USA: Applied Industrial Hygiene, Vol3, No. 3, March 1988.

Grot, R.A. and others, 1985. Validation of models for predicting formaldehyde concentrations in residences due to pressed wood products. U.S Department of Commerce, NBS. Washington, D.C. USA.

Hartless, R.P. 1990. BREVENT - a Ventilation Model. Building Research Establishment. UK.

Hodgson, A.T, and others 1989. Source strengths and sources of volatile organic compounds in a new office building. Air and Waste Managenment Association. 82 meeting. Paper 89-80.7. June 1989, Anaheim, CA, USA.

IEA ANNEX 9, 1987. Minimum Ventilation Rates. Uhldingen, Germany :Stephanus Druck.

IEA ANNEX 14, 1990. Condensation and Energy. Volume 2 . Guidelines & Practice. Leuven (B): ACCO.

IEA ANNEX 18, 1990. Demand Controlled Ventilating System. State of the Art Review. Stockholm, Sweden: Swedish Council for Building Research.

Jones,R. , 1990. Modelling water vapour pressure conditions in an enclosed space. BRE, CIB conference, Rotterdam, NL

Knoll, B. , 1984. Energiezuinige scholen in Almere. (report in Dutch. Energy efficient schools in Almere). IMG-Rapport C553, TNO, Delft, NL

Kornaat, W. 1990. Invloed van luchtverwarming op stofconcentraties in de binnenlucht. (report in Dutch. Influence of air heating on particle concentrations in the indoor air.) MT-TNO, R 89/298. Delft, NL

Lanting, R. , 1990 a. Selectie van chemische agentia in het binnenmilieu t.b.v kwantitatieve risicoschatting (report in Dutch. Selection of chemical agens in the indoor environment for quantitative risk estimation.) Gabimil: Deelprojekt1. MT-TNO, Delft NL.

Lanting, R.W. 1990 b . Air pollution in archives and museums, its pathways and control. MT-TNO, P90/015. Delft, NL

Lanting, R. , 1991 . Depositie snelheden van gassen en deeltjes in het binnenmilieu. (report in Dutch. Deposition velocities of gasses and particles in the indoor environment). TNO-Bouw, Delft, NL.

Levin, H, 1992. Critical building design factors for indoor air quality and climate: current status and predicted trends. Indoor Air,Vol 1, No 1, March 1991, Copenhagen, Denmark.

MCMurry, P.H. and others, 1985. Air and aerosol infiltration in homes. ASHRAE transactions, part 1, 1985

Meyer, B. 1983. Indoor Air Quality. Massachusetts, USA: Addison-Wesley.

Oldengarm, J. and others, 1990. Field experiments on airborne moisture transport. Paper I-22. CIB, Rotterdam, NL

Jansen, J. and others, 1987. Onderzoek naar de invloed van files op de emissie van NO_x , NO_2 en CO en de luchtkwaliteit op en rond de weg.(report in Dutch. Influence of traffic jams on the emission of ... on and near the road) R87/235 MT-TNO, Delft, NL

Roed, J. and A.J.H. Goddard, 1990. Ingress of radioactive material into dwellings. Seminar on Methods and Codes for Assessing Offsite Consequences of Nuclear Incidents. CEC, Athens, Greece. May 7-11, 1990.

Steel, F. 1982. Airtight Houses and Carbon Monoxide Poisoning. Canadian Building Digest. Ottawa Canada.

Traynor, G.W and others, 1985.Indoor air pollution due to emissions from unvented gas-fired space heaters. Air Pollution Control Association Volume 35 No.3 . USA.

Trepte, L and F. Haberda, 1989. Minimum ventilation rates and measures for controlling indoor air quality. AIVC, Technote 26. Warwick, UK.

Vandaele, L. 1989. Air change rate and pollutant distribution in an attic space. Results of summer time measurements. First draft. BBRI Brussels, Belgium.

Wal, J.F. van der, 1991. Onderzoek naar de emissie van vluchtige organische verbindingen uit materialen. (report in Dutch. Investigation of the emission of VOC's from materials). TNO-Bouw, Delft, NL.