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The Protection Ability of the Building Shell Against Sudden Outdoor Air Contamination

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A sudden contamination of the outdoor air by some toxic gas can have several causes. To find out the protection afforded by sheltering indoors was the primary goal of the investigation. The object of the computational approach was a single family house with two floors. Three different models were utilized to calculate the infiltration air flows, the contaminant transport inside the building and the temperature decay of the building. The variation in the weather parameters was treated using the two-dimensional distribution of the outdoor air temperature and wind speed and a statistical approach. The results show the cumulative distribution functions of the relative doses inside the building for different tightness levels and exposure times.

NOMENCLATURE

C	concentration (cu)
C_i	concentration in zone i (cu)
D	dose (cu h)
D^*	relative dose (%)
$\langle D \rangle$	mean dose (cu h)
$\langle D^* \rangle$	relative mean dose (%)
D_i	dose in zone i (cu h)
D_{out}	dose outdoors (cu h)
$f(w, T)$	frequency function of the two dimensional temperature speed distribution (%)
$f(\langle D^*(t) \rangle$	frequency function of the relative mean dose (%)
$F(\langle D^*(t) \rangle)$	cumulative frequency function of the relative mean dose (%)
K	flow coefficient (kg h^{-1} Pa^n)
n	flow exponent (−)
n_{50}	air change rate at 50 Pa (l/h)
N	number of zones in the building (−)
p_{ij}	frequency, two dimensional (−)
p_k	frequency, one dimensional (−)
Δp	pressure difference (Pa)
P	probability (%)
q_m	mass flow rate (kg s^{-1})
t	time, exposure time (h)
t'	dummy variable of integration (h)
t_a	advance time (h)
T	air temperature (°C)
w	wind speed (m s^{-1})
α	risk (%)
cu	contaminant unit

INTRODUCTION

A SUDDEN contamination of the outdoor air is possible for several reasons: An accident during the transportation of liquid agents, a sudden emission from an industrial plant or a disaster in a nuclear power plant. These are some examples of phenomena with drastic consequences but quite a small probability. The emissions from traffic can also occur suddenly during the rush hour, Fig. 1 [1] and appear every day with a probability of one hundred per cent. The simplest and fastest way for people to shelter in such a situation is to go inside a building. The building shell does not, however, give a perfect protection. The contaminated outdoor air penetrates the building through cracks, openings and the ventilation network. The concentrations and consequently the doses begin to grow inside, although not as fast as outdoors. What is the reduction in the dose compared to outdoors? What action should the inhabitants take to minimize the dose? Finding an answer to these questions was the main goal of this investigation. The consequences of such events to the indoor air concentration and dose levels have been studied [2–4], yet not many publications dealing with this subject are available. The authorities responsible for the regulations regarding the air tightness of buildings and sheltering strategy for emergency situations should in particular have some quantitative knowledge to support their decisions.

In this investigation a computational approach to the

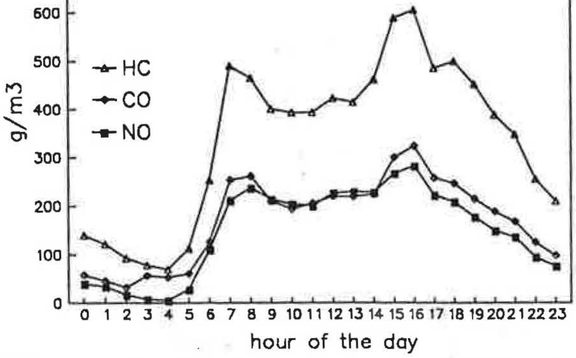

Fig. 1. Measured concentrations in the outdoor air caused by the traffic [1].

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problem has been chosen. To make measurements would have been the other possible way. It would, however, be a very laborious and expensive way, and if the influence of the building tightness and the weather statistics were also to be investigated, the amount of work would be enormous. Computing tools to calculate the infiltration and exfiltration air flows have been available already for some time [5] and development of the codes continues [6]. In the present application the transport of contaminants inside the building is an additional phenomenon to be mastered. The air flows through doorways and other large openings inside the building tend to be bidirectional and a sufficient algorithm for this purpose combined with the multi-zone calculation must also be available. Moreover, if e.g. the influence of the heating cutoff is to be investigated, a thermal model of the building is needed.

Sudden outdoor air contamination is usually caused by both particles and gases. For example, the emissions from traffic contain many gases but also a great amount of different kinds of particles. The Chernobyl accident produced radioactive particles but the greater part of the radioactive iodine was in gaseous form [7]. The behaviour of gases and particles during penetration into the building is quite different and must be taken into consideration. A gas usually goes through the construction as such without any absorption or similar processes taking place. The particles are partly filtered in the construction in a way which is not known for the present. Anyhow, the size distribution of the particles, the tightness of the building and the details of the construction influence the particle penetration.

In this paper the protection ability of a single family house is reported. A sudden gaseous contamination of the outdoor air is the starting point for the computational investigation. The people have sheltered inside the building. All the outer doors and windows are closed. The ventilation is cut off and the ductwork plugged up.

THE BUILDING

Construction

The object of the computational examination is a single family house with two floors and a ridge roof, Fig. 2. This type of building is quite common in Finland and the other Nordic countries. Very often it is a pure wooden construction, but can be brick faced as well. The materials are not of great importance to the infiltration calculation. The thermal behaviour of the building does, however, depend on the materials used in the construction. The building is not a real existing one. It only represents a common type of house and its leakage characteristics can for calculation purposes be fixed on certain levels, no matter what materials and working methods are used in practice. The first floor has five rooms: a living room, kitchen, bedroom, bathroom and hall. The second floor consists of five rooms too: three bedrooms, a hall and a WC. The floors are connected by stairs of a very open type. The total floor area of the living space is 140 m^2 and the corresponding volume is 315 m^3.

Airtightness

The location and distribution of the leakage sites and the total airtightness of a building are somewhat individual, building-specific properties. Some knowledge of these properties does exist [8–11], however, the differences between various buildings can be remarkable. Potential leakage sites are all joints between walls, ceilings, floors, windows and doors. The infiltration can take place through porous material layers as well. Further, all passages of pipes, ducts and wires through the building shell can form routes for the air. To describe the total tightness of the building shell, the air change rate at 50 Pa, often referred to as the n_{50} value, was utilized. The envelope leakage area was changed, keeping the leakage distribution constant, to achieve different tightness levels. Values between 1.0 l/h and 15.0 l/h for the n_{50} value were used, which should, according to measurements [10–13], cover most of the building stock in Finland and other countries with a similar climate.

Ventilation system

In an emergency situation when people are sheltering indoors, one of the most urgent tasks is to cut off the ventilation and plug the ducts. This is assumed to happen, and for this reason the effect of the ventilation ducts has not been treated separately in the calculations and the object building contains no description of a ventilation system. However, if plugging is omitted, the ventilation ducts form an additional flow path which is connected parallel with the other flow routes of the building envelope. This means that the n_{50} value of the envelope and of the ductwork can be added to form the air change rate at 50 Pa of the whole system. A mechanical exhaust system for a single family house designed in the conventional Finnish manner raises the n_{50} value of the building of about 1 l/h. The corresponding figures for a natural ventilation system and a system with mechanical exhaust and supply are of the order of 1.6 l/h and 2 l/h, respectively.

Environment

The environment of the building has a strong influence on the indoor conditions when contaminated outdoor air penetrates the building. The topography of the area, vegetation, other buildings and man-made constructions mainly affect the process in two ways: first, by guiding the flow of the outdoor air and in some cases creating an unhomogeneous concentration distribution in the area and second, by affecting the wind induced pressure on the outer surfaces of the building shell, and as a consequence the air flows through the envelope. In the calculations of the infiltration air flows, measured wind pressure coefficients of a real building in a real environment were used [14].

COMPUTING TOOLS AND PROCEDURE

Air flows

To calculate the infiltration, exfiltration and internal air flows of the object building, a multizone infiltration and ventilation simulation program MOVECOMP [15] was used. On the basis of the input data the program forms a flow network with pressure nodes and flow paths. The mass balances of the nodes and the characteristics of the flow paths make up a system of unlinear algebraical equations. MOVECOMP solves this system of equations

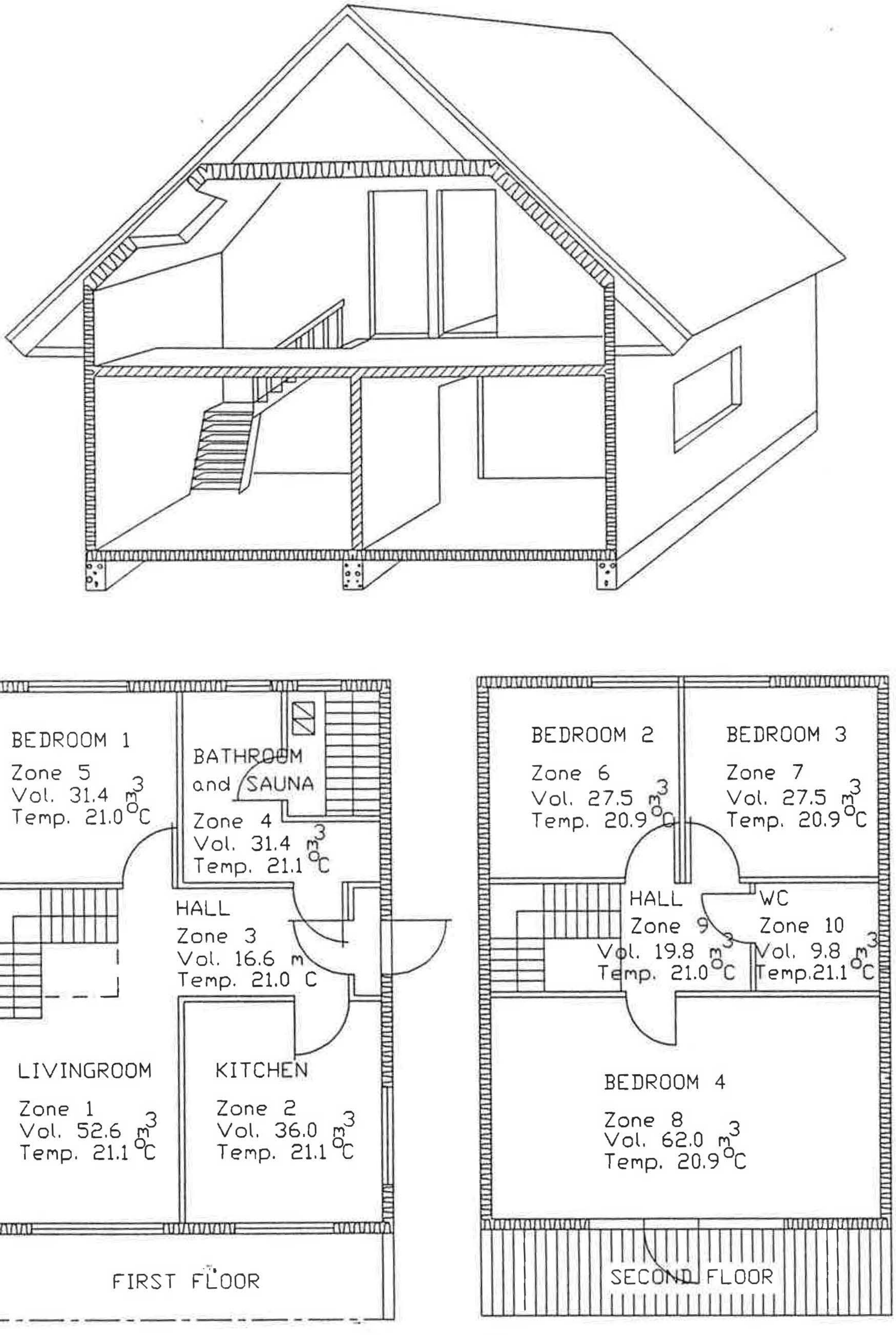

Fig. 2. The building.

using the Newton-Raphson algorithm improved with ideas from non-linear optimization. As an output the mass flow rates through the flow paths and the pressures of the nodes are given. The physical phenomenon relating to the air flow through the building shell is well known and with a properly working code the reliability of the results mainly depends on the input data. The user should be able to estimate the flow coefficients, the parameters related to the flow paths and other input data well enough to get trustworthy results. Thus, the question of reliability is directed at the user of the program rather than at the program itself.

Contaminant transport

The concentrations and doses versus time in the rooms of the single family house caused by contaminated outdoor air infiltration were calculated using a computing tool MULTIC [16] developed especially for this purpose. The calculation is based on the multi-zone theory where the mixing of the contaminant in each zone is assumed to be complete and instantaneous, which leads to a uniform concentration inside each zone. The circulating air flows through large openings between adjacent zones are calculated using a simple analytical procedure [17]. The input data are the temperatures, volumes, exhaust flow rates and initial concentrations of the zones and the net flow rates between the zones. The exhaust flow rates and the net flow rates are produced by MOVECOMP, the other data is given by the user. The output data contains the time evolution of the concentrations and the doses in each zone. The movement of air inside a building is an extremely complicated process. For this reason a program like MULTIC has to contain several quite rough assumptions to be able to treat this subject at all. One assumption is the uniformity of the concentrations, others are included in the procedure for calculating the circulating air flows between the zones. The doubt about the reliability of the results is justified. Some validation has been done [18, 19] and it shows that the success varies from case to case. Generally the results are, however, satisfactory and the performance of the program can be considered sufficient for this investigation.

Thermal dynamics

To be able to predict the thermal behaviour of the building, and especially the changes in the indoor air temperature when the heating is cut off, a simple thermal model TDYN [20] was used. The model is a control volume heat balance model consisting of fifteen thermal capacities. The mathematical solution is achieved using the finite difference scheme. The derivatives of the temperatures are weighted according to the Crank-Nicolson method. The parameters of the model were identified using temperatures measured in a building according to

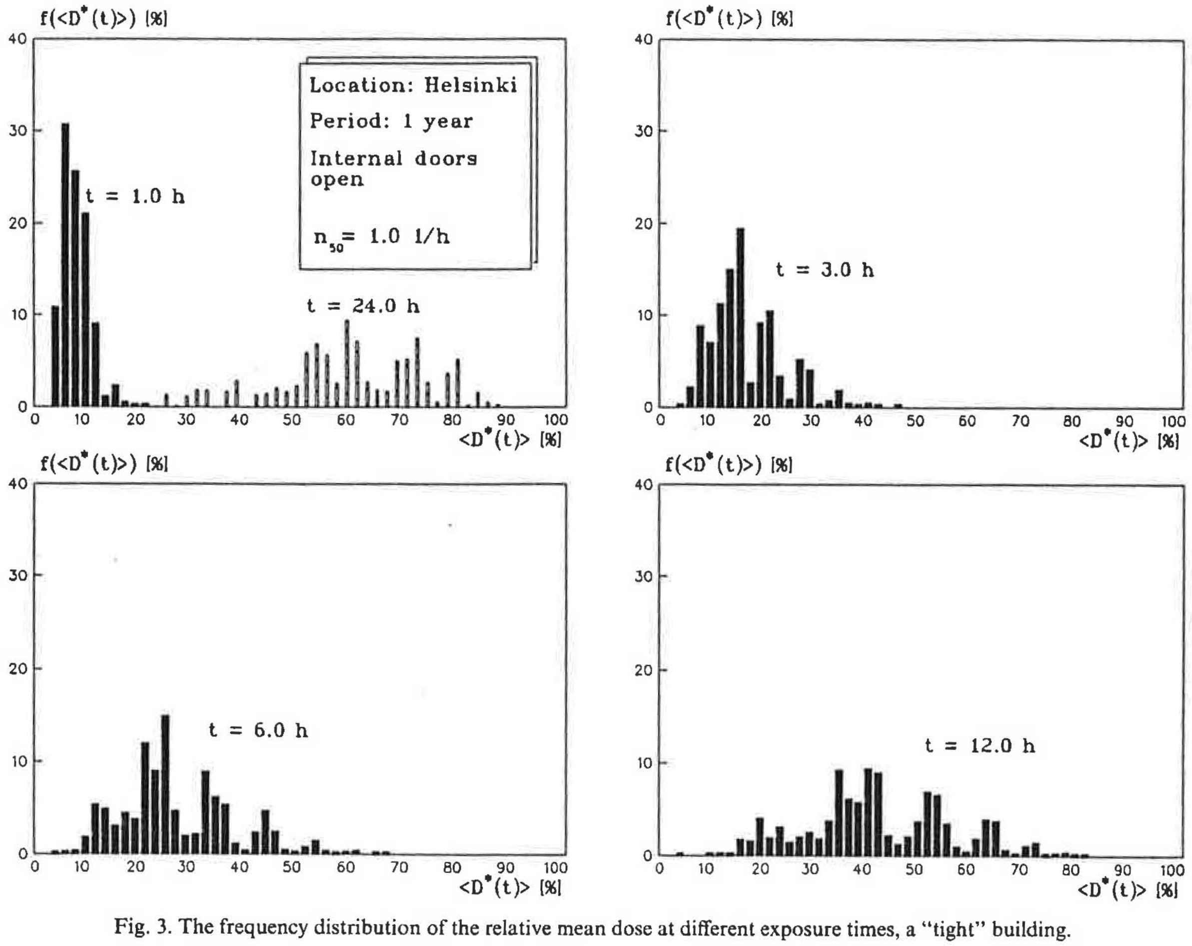

Fig. 3. The frequency distribution of the relative mean dose at different exposure times, a "tight" building.

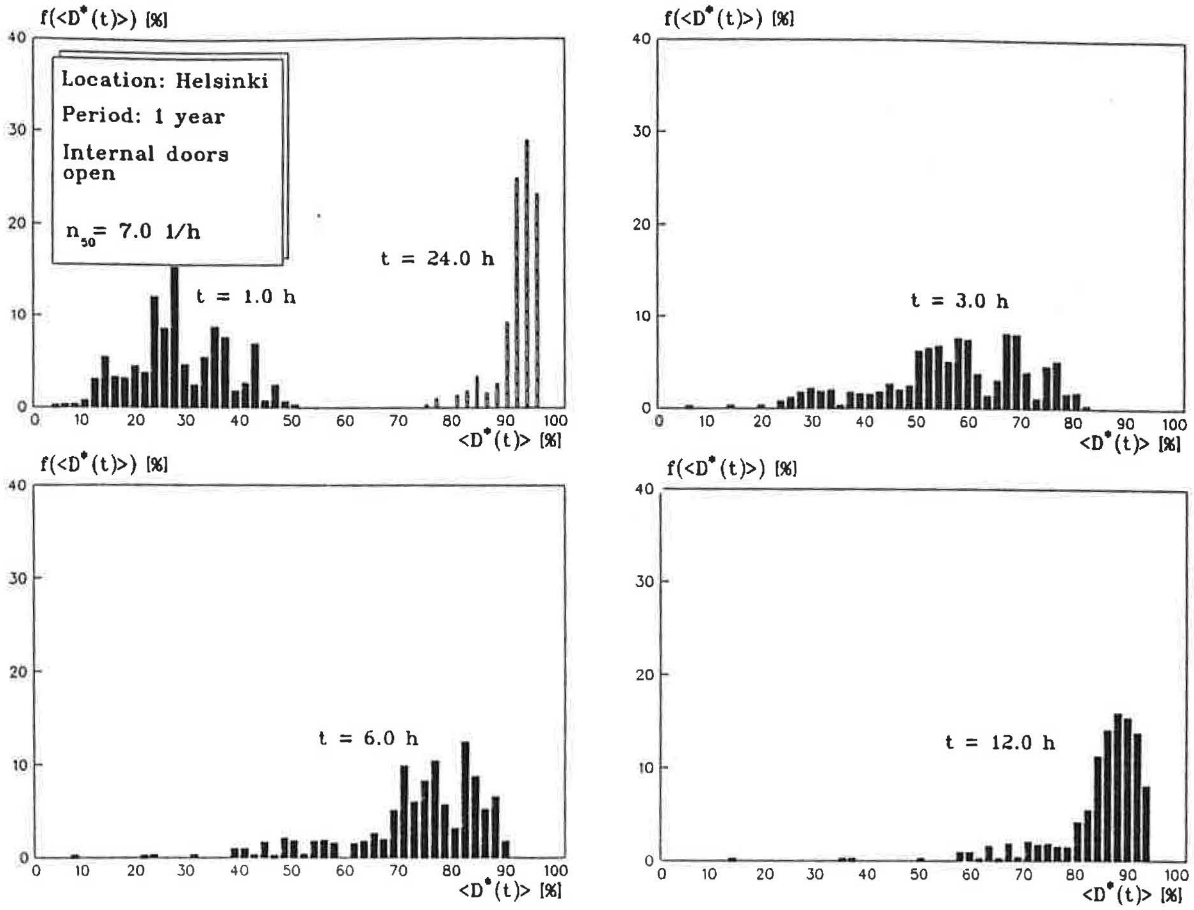

Fig. 4. The frequency distribution of the relative mean dose at different exposure times, a "normal" building.

Fig. 2. The model predicts the indoor air temperatures satisfactorily and is consequently suitable for the calculation of the temperature decay.

INPUT DATA

Pressure coefficients

The pressure coefficients used as input data for MOVECOMP were values measured in situ [14]. The building used for the measurements was very similar but not identical to the building presented in Fig. 2. Therefore the pressure coefficients do not exactly correspond to the shape in Fig. 2. The possible difference is, however, not essential, because this building represents the whole stock of single family houses which, on the other hand, has widely varying properties. For each facade and slope of the roof only one pressure coefficient was used, which represented the mean value for the surface in question.

Leakage paths

Because the purpose was not to examine a real, existing building, but rather a theoretical object representing a group of buildings, the leakage sites could be chosen using experience gained from real buildings. According to this principle 80% of the envelope leakage area was distributed proportional to the length of the joints. Furthermore, 10% of the total leakage area was placed in the kitchen floor because of the water, drain and hydronic heating pipe passages and another 10% of the total area was in the ceiling of the second floor because of the ventilation duct passages. All the material layers were assumed to be airtight. As a consequence 48% of the envelope leakage area was located on the first floor and 52% on the second floor. Inside the building all the walls and the ceiling of the first floor were assumed to be airtight and the only leakage sites were the doorways and the opening for the stairs. In all, 55 leakage paths in the building shell and 9 paths inside the building were used.

Flow exponent

In MOVECOMP the connection between the mass flow rate q_m flowing through the flow path and the pressure difference Δp on both sides of the path is presented using the power-law equation

$$q_m = K \Delta p^n, \tag{1}$$

where K is the flow coefficient at reference conditions (101,300 Pa, 20°C) and n is the flow exponent. The flow coefficient is related to the size of the opening and the flow exponent is dependent on the type of flow. For a laminar flow $n = 1.0$ and for a fully turbulent flow $n = 0.5$. In real buildings the flow paths through the building shell are combinations of different parts and the type of flow varies from part to part. Consequently an effective value for the flow exponent between 0.5 and 1.0 has to be chosen. For crack flow the flow exponent value $n = 0.65$ and for large openings $n = 0.50$ were chosen [8, 21–23] to be used in the calculations.

Flow coefficients and airtightness

Four different airtightness levels for the building envelope were used in the calculations. For a very tight building a value $n_{50} = 1.0$ l/h was chosen. Values $n_{50} = 3.0$ l/h and 7.0 l/h represented a "normal" building and the value $n_{50} = 15.0$ l/h was used for a very leaky building. The flow coefficients for each level were adjusted using MOVECOMP for a computational pressurization in the following way. All the internal doors were opened to achieve an even pressure distribution. The wind speed was put at 0.0 m/s and the temperature difference between inside and outside at 0.0°C to eliminate irrelevant driving forces. Two fixed exhaust flows corresponding to the tightness level in question were defined, one from the first floor and one from the second floor. The flow coefficients of the outer leaks representing the flow paths of the envelope were then adjusted with a scale factor to give a computed under pressure of 50 Pa inside the building. The distribution of the flow coefficients remaind unchanged and was the same for every tightness level.

The flow coefficients of the inner doors are not very critical from the viewpoint of the net air flows as long as the doors are open because the flows are determined by the much larger flow resistance of the building shell. When the doors are closed, the situation may change. Now the flow resistances of the doors are of the same magnitude as the resistances of the leaks of the envelope and the influence on the flows is remarkable. The flow coefficients for the closed doors were estimated using information based on measured pressure drops in crack flow [24]. Three different door constructions were used: height 2.0 m, width 0.8 m, with a straight through crack, dimension in the direction of flow 50 mm, only the gap thickness was varied. A "leaky door" had a gap thickness of 3.5 mm and the flow coefficient 47.9 kg h^{-1} $Pa^{-0.67}$. A "normal door" had a gap thickness of 1.8 mm and the flow coefficient 12.7 kg h^{-1} $Pa^{-0.85}$. A "tight door" had a gap thickness of 0.49 mm and the flow coefficient 0.187 kg h^{-1} $Pa^{-0.95}$.

Zones

For the contaminant concentration calculation the building has to be divided into zones which are each assumed to have a uniform concentration. The choice of zones affects the computed results to some extent [18, 19]. The most straightforward solution is to put each room in one zone. This was the procedure in this context and together ten zones, five downstairs and five upstairs, were selected, Fig. 2. The first and the second floor are

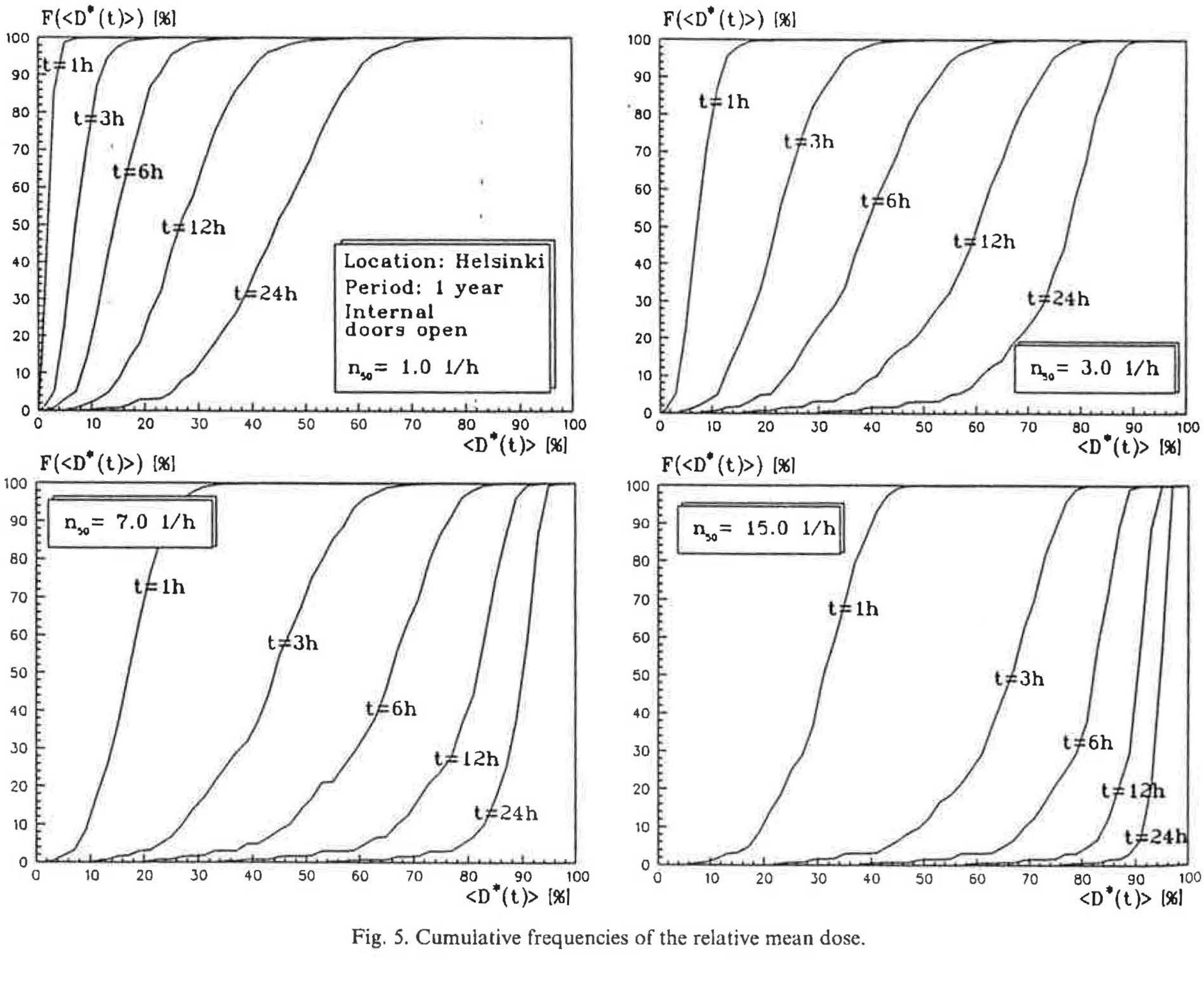

Fig. 5. Cumulative frequencies of the relative mean dose.

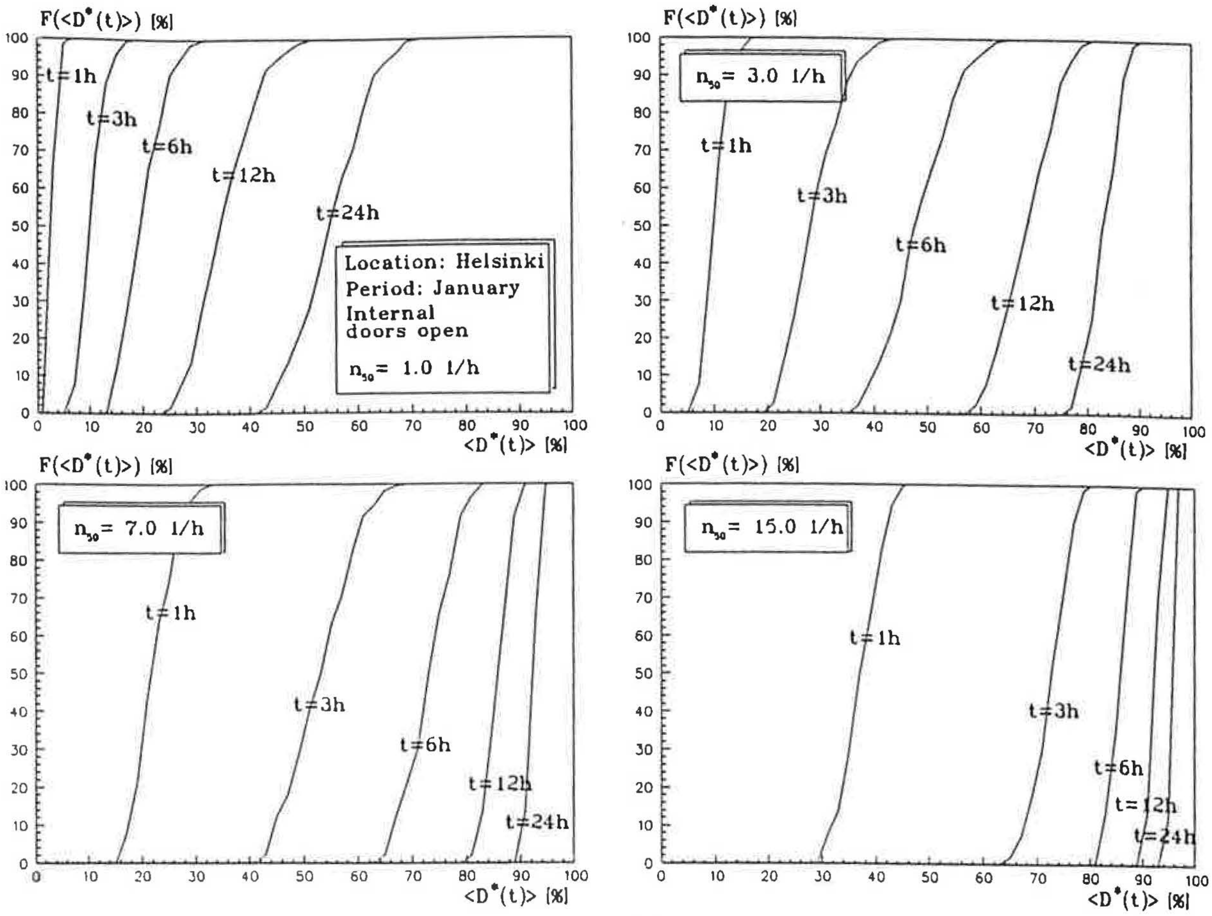

Fig. 6. Cumulative frequencies of the relative mean dose.

connected through zones 1 and 9, which are the living room and the upstairs hall. In between is a stair of a very open construction which, from a theoretical point of view, could be described as a rectangular opening in a horizontal plane. Here the air flows are vertical, from up to down and vice versa. Some work concerning vertical flows has been done [25–27], however, no simple algorithm for calculating vertical air flows between floors is available at the moment. For this reason the transport of contaminants between zones 1 and 9 was treated in the same way as the transport between horizontally adjacent zones. This procedure does not meet the real conditions but the error due to this approach is within acceptable limits in this application, where the air flows in any specific, existing building are not striven for.

Indoor temperatures

The temperatures of the indoor air in different zones have a remarkable effect on the contaminant transport between adjacent zones. Here the temperatures were simply chosen according to the experience gained from measurements in similar situations [18, 19]. As long as the doors are open, temperature differences from 0.1°C to 0.3°C are typical in dwellings where the heating or cooling load is not very unevenly distributed. The temperature differences between adjacent zones were chosen as 0.1°C while the mean indoor temperature was about 21°C, Fig. 2. This assures a moderate transport of the contaminants and eliminates stagnant areas in the system. When the doors are closed, considerably larger temperature differences can occur. This, however, no longer affects the contaminant transport because the flows become unidirectional.

Weather

The most important weather parameters affecting the pressure distribution and the infiltration and exfiltration flows of a building are the outdoor air temperature and the wind speed and direction. The mean two-dimensional frequency distributions of the temperature and the speed values measured during the years 1961–1980 [28] were used as input data for the calculations. The weather stations and thus also the locations of the object of the computational examination were Helsinki 60°19′N, 24°58′E and Oulu 64°56′N, 25°22′E. The yearly mean temperature in Helsinki during the observation period was 4.4°C and in Oulu 1.9°C. The mean value for the wind speed was 3.9 m/s in Helsinki and 4.0 m/s in Oulu.

The meteorological data never describes the local conditions near the building in the best possible way. For this reason the measured wind data was reduced with a coefficient of 0.5, which takes into account the difference of the terrain and the height between the weather station and the building [29, 30]. For the outdoor temperatures no criteria for corrections were available. The correlation between wind speed and direction was also available. The effect of the direction was, however, tested only in some cases because of the much more complicated and laborious calculation procedure and the fact that the orientation of the object building of the type used here does not greatly affect the primary results.

RESULTS

Concepts

As already mentioned earlier, a sudden gaseous contamination of the outdoor air was the starting point for the calculations. To be more precise, the outdoor air concentration increases from 0 to 100 cu (contaminant units) at the moment $t = 0$ and remains at that value. This is of course a very theoretical starting point and does not correspond to the real physical phenomenon [4], where the outdoor concentration usually varies considerably as a function of time. The air capacity of the building does, however, even out the influence of the variations and the indoor concentrations correspond to the mean concentration outside.

The relevant quantity from the health point of view is, however, not the concentration but the dose, which is the integral of concentration over time. In this context the dose in zone i at the moment t is defined as the linear dose according to the equation

$$D_i(t) = \int_0^t C_i(t')\,dt', \tag{2}$$

where the integration begins at the time of the step change in the outdoor concentration and t' is a dummy variable of integration. Further, a mean dose, to describe the effect of the contaminant in the whole building with N zones, is needed

$$\langle D(t)\rangle = \frac{1}{N}\sum_{i=1}^{N} D_i(t). \tag{3}$$

This is the dose the occupant would get if he could move around the building from zone to zone extremely fast and spend infinitely short time periods in each zone. This is in practice not possible. The mean dose is an estimate of the dose an occupant gets as he moves around in the building. The concentrations and the dose inside the building are dependent on the concentration level outside. The inside dose can, however, be proportioned to the outside dose by dividing the former by the latter according to the equation

$$D_i^*(t) = \frac{D_i(t)}{D_{out}(t)}, \tag{4}$$

which gives the relative dose at moment t and in zone i. The mean dose for the whole building can be proportioned to the outside dose as well

$$\langle D^*(t)\rangle = \frac{\langle D(t)\rangle}{D_{out}(t)}, \tag{5}$$

to give the relative mean dose at moment t. The relative mean dose describes, in a way, the ability of a building to protect the occupants against sudden outdoor air contamination when the location of the building and consequently the weather is specified.

Statistical approach

The two-dimensional frequency distribution of the temperature and wind speed for one year was the basis for the statistical approach:

$$f(w,T) = \begin{cases} p_{ij} & \text{when } w = w_i \quad (i = 1,2,\ldots) \\ & \text{and } T = T_j \quad (j = 1,2,\ldots), \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where w is the wind speed, T is the outdoor air temperature and p_{ij} is the frequency of the pair of values in question. The temperatures varied from $-32°C$ to $+30°C$ with class intervals of 2.0°C and the wind speed varied from 0 m/s to 14 m/s with class intervals of 2.0 m/s. From a physical point of view this distribution is a continuous one, but presenting it as pairs of mean values based on measurements in practice makes it discrete. Calculation of the air flows, concentrations and doses corresponding to each speed-temperature combination presented by equation (6) produces new one-dimensional dose distributions

$$f(D(t)) = \begin{cases} p_k & \text{when } D(t) = D_k(t) \quad (k = 1,2,\ldots) \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where D represents any type of dose, absolute, relative or mean, t is the exposure time and p_k is the sum of the frequencies of those cases which give a dose value inside the limits of the class in question. Some examples of the frequency distribution of the relative mean dose at different exposure times and for difference tightness levels are presented in Figs 3 and 4. Here the weather data is from Helsinki and contains long term mean values for one year. The class intervals for the relative mean dose in the figures are 2% and the class midpoints are 1%, 3%, . . . , 99%.

The cumulative frequency function of the dose is mathematically described by the equation

$$F(D_n(t)) = \sum_{k=1}^{n} f(D_k(t)). \tag{8}$$

The cumulative frequency function can be considered as the probability or the relative time when the dose $D(t)$ will not be more than the value $D_n(t)$ if a sudden contamination occurs, i.e.

$$P(D(t) \leqslant D_n(t)) = F(D_n(t)). \tag{9}$$

As a consequence, the risk of the dose exceeding some threshold value $D_n(t)$ during an exposure time t is

$$\alpha(D_n(t)) = 1 - F(D_n(t)). \tag{10}$$

Basic results

The basic results contain cumulative frequencies of the relative mean dose calculated using three different weather periods for two different locations, Helsinki and Oulu. All the inner doors were wide open. The indoor temperatures of the zones were according to Fig. 2. The four different airtightness levels mentioned earlier and

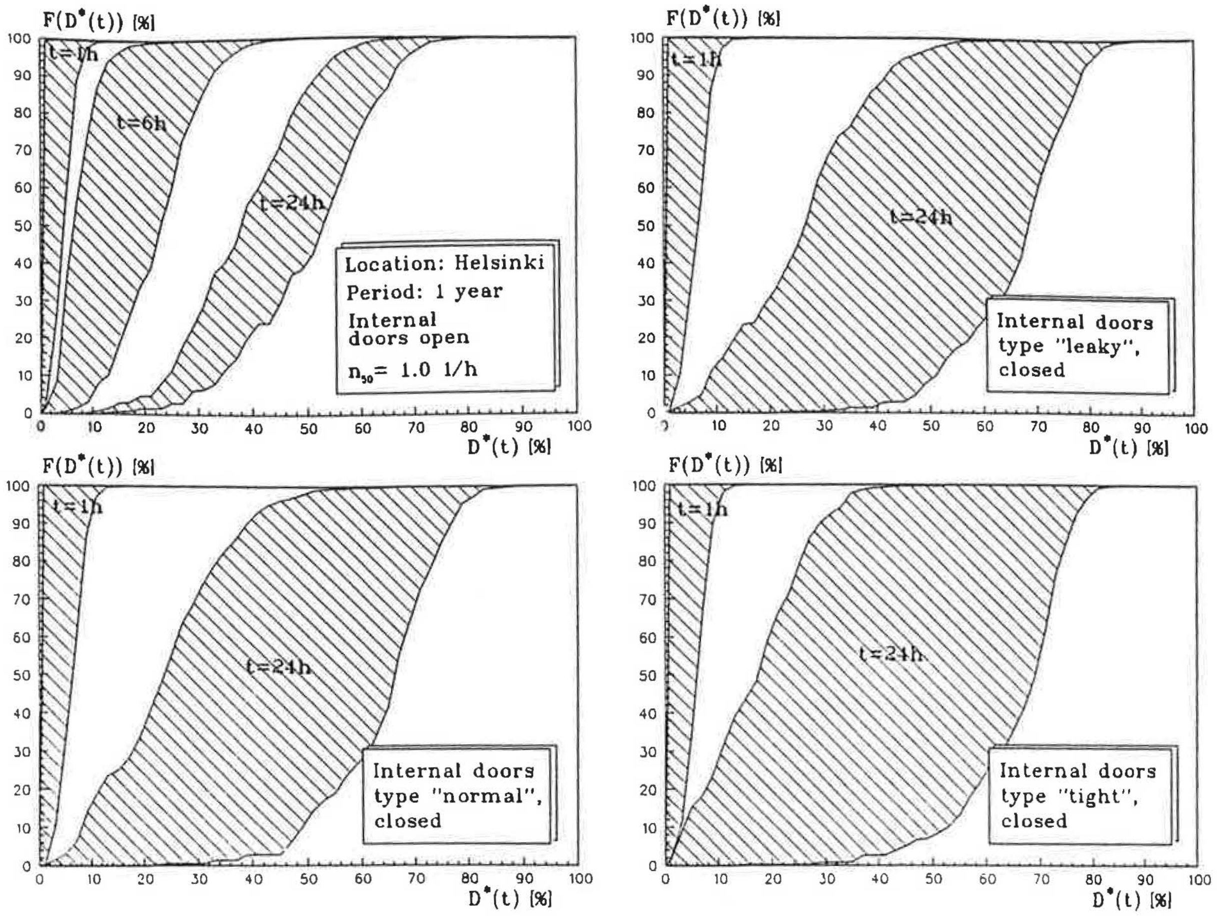

Fig. 7. Ranges covering all cumulative frequencies in different zones in a "tight" building.

five different exposure times t = 1 h, 3 h, 6 h, 12 h and 24 h were used. Two examples of cumulative frequencies corresponding to different weather periods are shown in Figs. 5 and 6. The basic results show that the most significant factors affecting the cumulative frequencies are the tightness level of the building, the exposure time and the weather period. The influence of the tightness level is very obvious. With decreasing airtightness, the cumulative frequency lines move to the right, which means a higher risk of exceeding some specified value of the relative dose. The increasing exposure time has a similar effect. A more thorough presentation of all computed results is given in reference [20].

Special attention should be paid to the influence and meaning of the weather period. The results concerning the one year period can be interpreted as mean probabilities for the whole year. The contamination of the outdoor air can, in this case, happen at any time during the year. If, however, the contamination occurs during the winter, the temperature difference between indoors and outdoors is large and, as a consequence, the doses inside grow higher than average. In fact, the probabilities presented vary with the season. The computed values for January weather data thus represent minimum values for the cumulative frequency function, but maximum values for the risk. The weather data used in the calculations is average data from a twenty year period. For this reason the weather for an individual, real year or month can lead to slightly different values from those based on the average data.

Influence of the internal doors

Even though the building is assumed to be surrounded with air having a uniform concentration, the concentration and dose values inside the building grow at a different speed in different zones. This phenomenon arises mainly from two factors. First, the temperature difference between inside and outside drives the usually colder outdoor air through the walls and the floor into the first floor and back again through the walls and the roof from the second floor. Second, the wind makes the outdoor air penetrate through the walls from the windward side of the building. When the doors between adjacent zones are open, a usually quite effective transport of the contaminant from zone to zone occurs. This is due to air flows circulating through the doorways created by the temperature differences between the zones. The concentrations in the zones do not differ remarkably. When the doors are closed, there are no circulating air flows and the transport of the contaminant occurs through the cracks around the door. In this case much larger variation is expected between the concentration values in different zones.

The influence of the inner doors is presented in Figs.

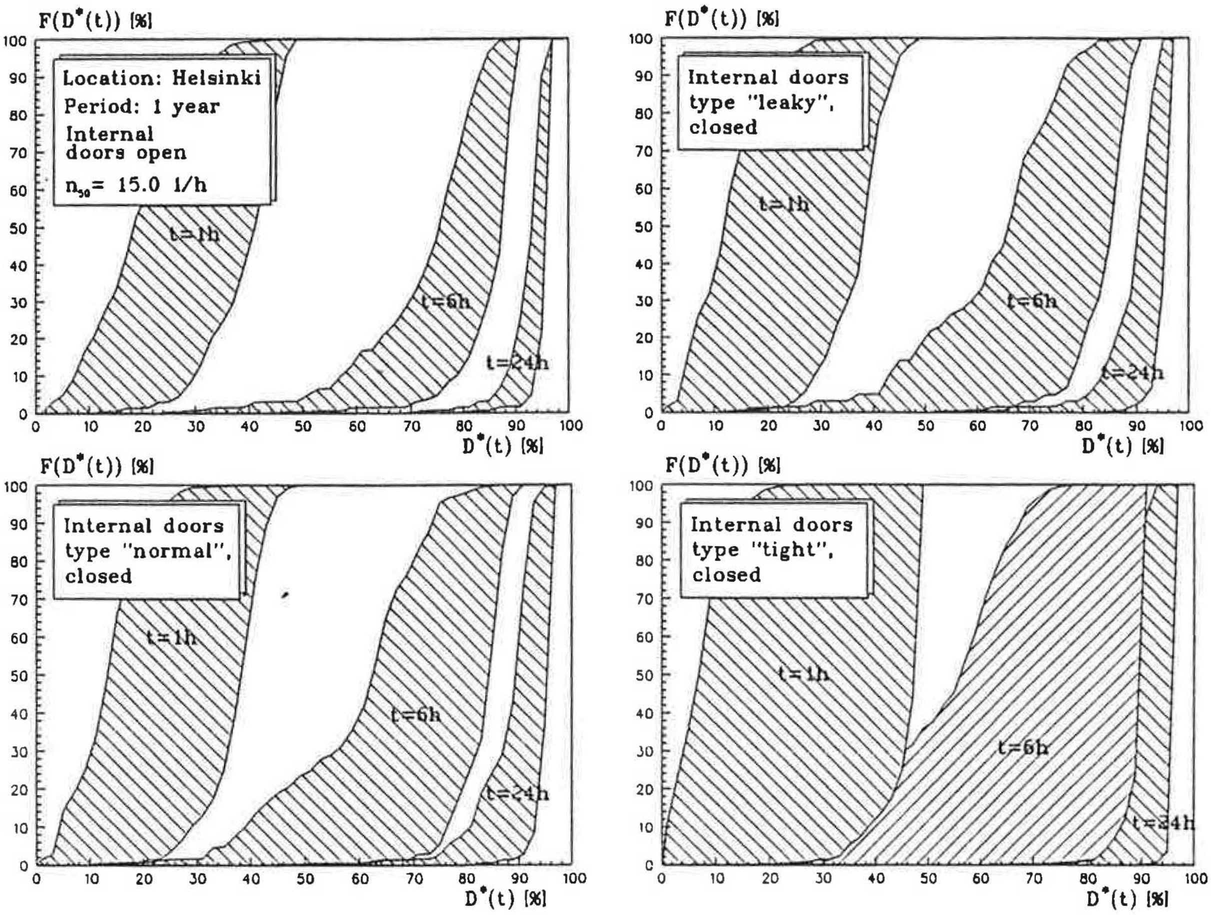

Fig. 8. Ranges covering all cumulative frequencies in different zones in a "very leaky" building.

7 and 8, which show the ranges between the minimum and maximum cumulative frequencies of the relative doses. The maximum values, on the right edge of the range, are from the zone where the highest concentrations and doses occur. The minimum values are from the zone having the lowest dose values in the building. The input data of the calculations corresponds to the "basic results" with the exception that the status and the type of the doors has now been varied and that only one location and period is under consideration.

Figure 7 presents the results for a very tight building. In a tight building the concentrations grow slowly and do not usually reach the outdoor values during the 24 hour exposure time. The ranges between the minimum and maximum lines are not very wide in the case of open doors because of the strong mixing. Closing the doors does not in practice affect the position of the ranges because in a tight building the status and type of the doors has only a small influence on the air flows through the envelope. The extreme values at longer exposure times do, however, draw away from each other and the ranges grow, the wider the tighter the doors are. The cases with "leaky" and "normal" doors are almost identical. The "tight" doors seem to decrease the air flows slightly, which moves the whole range to the left towards the smaller values.

What happens if the building envelope becomes more leaky? The consequence can be seen in Fig. 8. The contaminant penetrates the building faster and the dose ranges bounded by the lowest and highest frequencies move to the right towards the larger values. The range for short exposure times is wider than for long exposure times because the concentrations grow fast in the beginning and much slower later on. In a leaky building closing the doors clearly decreases the air flows through the building shell and the dose ranges move to the left towards the smaller values.

The conclusions from the viewpoint of sheltering are: If a good guess of the zones with smaller concentrations and doses can be made, the inner doors should be closed. In a tight building the greatest benefit is derived from this during a long exposure time, while in a leaky building the advantage is gained when the exposure time is relatively short. However, if such knowledge does not exist, the doors should be kept open to allow mixing between zones and to avoid the risk of exposure to the largest concentrations.

Influence of the occupant location

Considerable differences in the dose values between zones have been established. To avoid large doses, knowl-

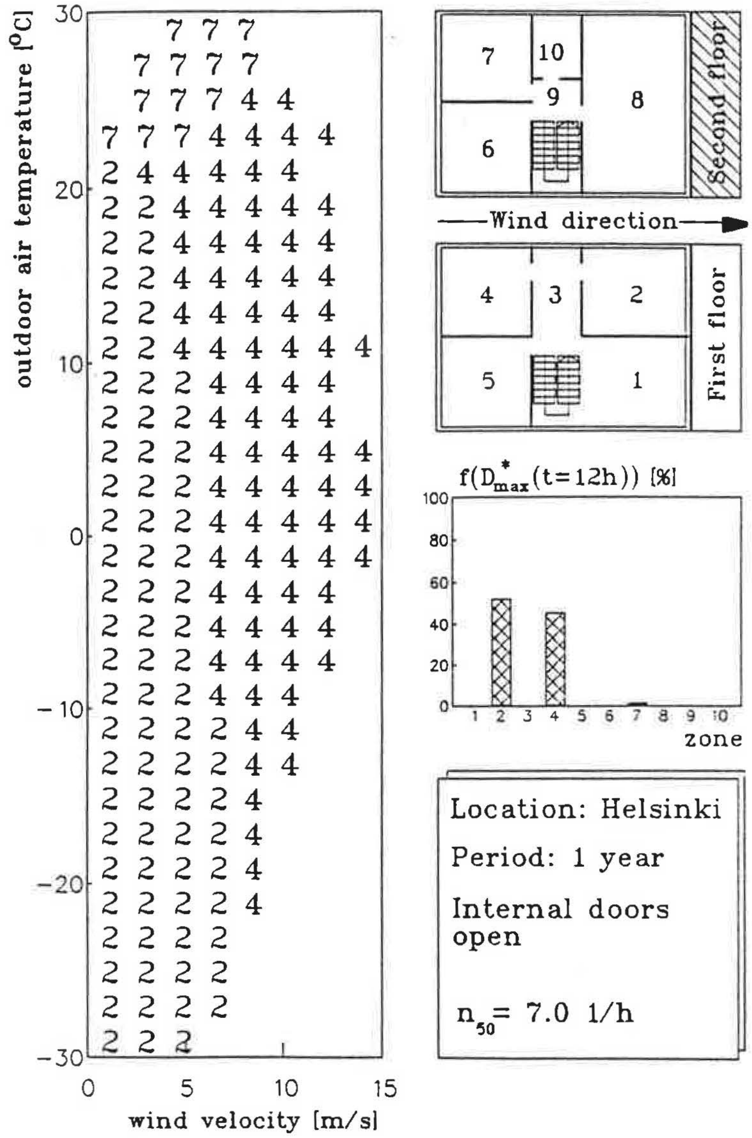

Fig. 9. The location in the building and frequency of the maximum dose values after a 12 hour exposure time.

edge of the zones with the lowest and highest concentrations would be useful for occupants sheltering indoors. In this context the most important parameters affecting the location of the maximum and minimum concentrations are the outdoor air temperature, the wind velocity and direction, and the status of the internal doors. The tightness of the building is of minor importance as long as the leakage distribution is kept unchanged. In Figs. 9 and 10 examples of the computed results are shown as the numbers of the zones with the maximum or minimum dose after a 12 hour exposure time. The numbers of the zones are placed in a coordinate system where the corresponding outdoor air temperature and wind speed can be read from the coordinate axis. The frequency of the location of the maximum or minimum is presented as well.

In all, the results are much as expected. The temperature difference between indoors and outdoors is the major driving force when the wind speed has low values. The lower the outdoor temperature is, the more air penetrates the building shell to the first floor. Depending on the doors, the maximum values occur in zones 2 or 3. If the outdoor temperature is higher than inside, which happens quite seldom at this location, the maximum values correspondingly occur on the second floor in zones 7 or 10. With higher wind speed values the maximum is on the windward side of the building, usually in the first floor.

The minimum dose values usually occur on the second floor and the leeward side of the building. Depending on the wind direction and the doors, the smallest values are in zones 6 or 8, in very few cases in zone 10 or on the first floor in zone 5.

From the viewpoint of sheltering, the following rules can be given: If the outdoor temperature is lower than indoors, go to the second floor. If the outdoor temperature is higher than indoors, stay on the first floor. If, additionally, the wind direction is known, close all the doors and go to the leeward side of the building.

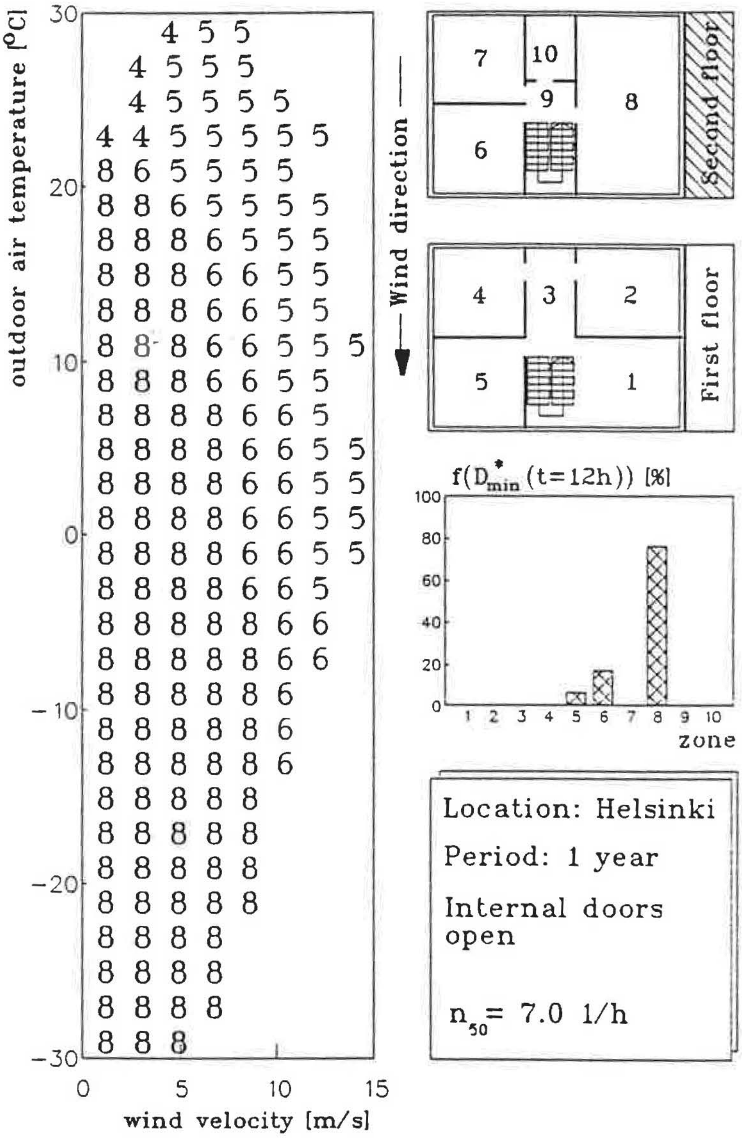

Fig. 10. The location in the building and frequency of the minimum dose values after a 12 hour exposure time.

Influence of the indoor temperatures

The indoor temperatures influence the transport of contaminants in two ways. First, when the inner doors are open, the temperature differences between adjacent zones generate the circulating flows from zone to zone. However, it is difficult to make any universal conclusions considering this phenomenon because the air temperatures in the zones depend on so many factors. Second, the temperature difference between indoors and outdoors affects the infiltration air flows. The smaller is the difference, the smaller are the flows through the envelope. With respect to sheltering, this second phenomenon is more relevant and offers potential for reducing the penetration of contaminant.

When the outdoor temperature is lower than the indoor and the heating is cut off, a decay of the indoor temperature follows, leading to reduced infiltration. If the heating is cut off at the beginning of the contaminant exposure, the decay of the temperature is not fast enough to have any significant influence on the doses. If, however, warning of air contamination is received in advance, the heating can be cut off in advance and some benefit gained. The longer is the time between the heating cutoff and the beginning of the exposure, called the advance time, the slower is the rise in the inside concentrations and the doses. When the heating is not cut off, the indoor temperature and the infiltration air flow remain constant during the calculation. When the advance time $t_a = 0$ h, the heating is cut off at the beginning of the exposure and both the temperature and the air flow decrease with time. When the advance time is 6 h or 12 h, the temperature and consequently the air flow are already a little lower at the beginning of the exposure. The influence on the concentration and dose is quite small. An example of the statistical approach with the heating cut off is given in Fig. 11. The benefit gained through the cutoff in a tight building decreases with time. This is due to the small infiltration flows and slowly

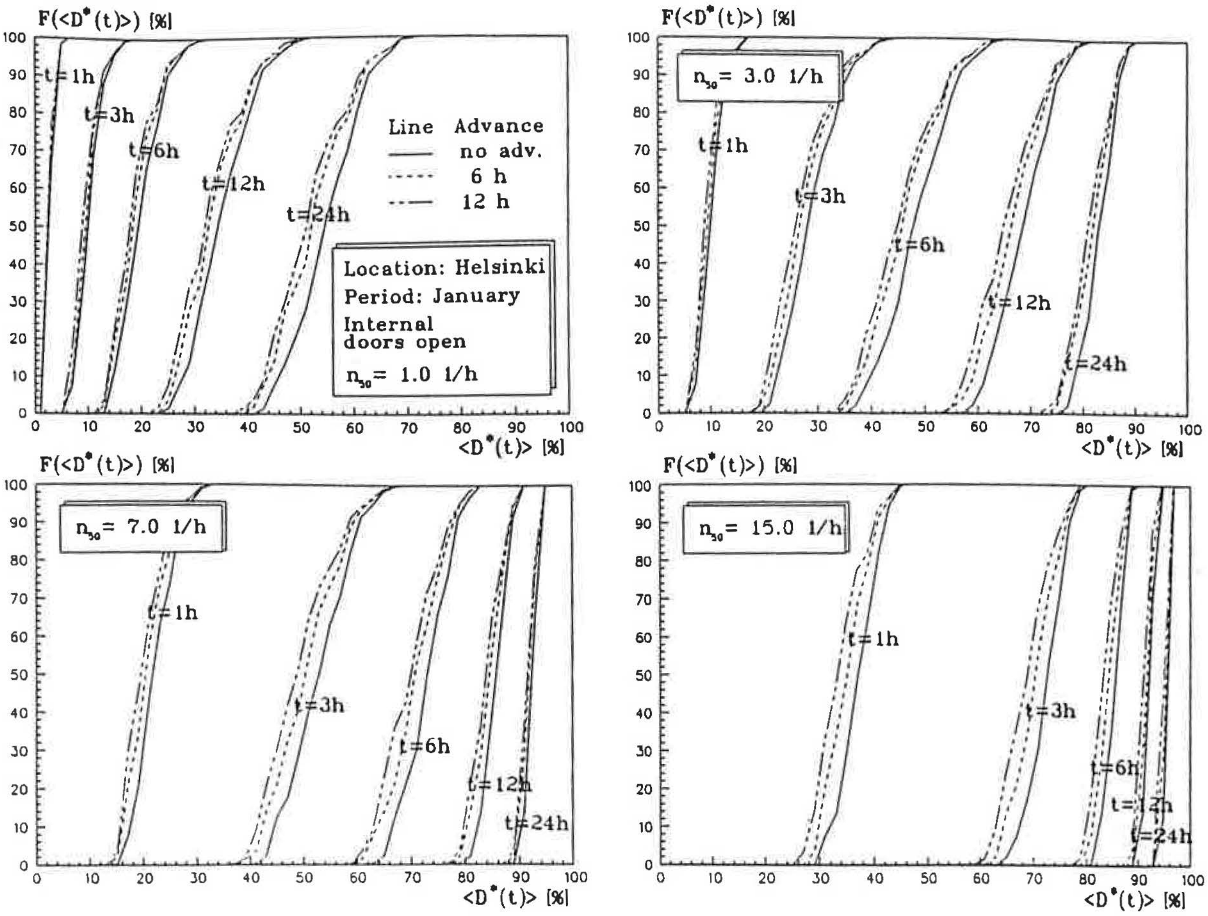

Fig. 11. Cumulative frequencies of the relative mean dose with different advance times for the heating cutoff.

growing concentrations, which do not reach the outdoor concentration during 24 hours. In a leaky building the concentrations reach the outdoor level in a few hours and the largest differences in the doses appear in the beginning of the exposure.

From the viewpoint of sheltering, not very much is gained by cutting off the heating. However, in threatening situations all possible measures must be taken to decrease the dose. When the circumstances are favorable for this procedure, which is a low enough outdoor temperature and a long enough advance time, the heating and all other temperature sources in the building should be cut off as fast as possible.

Other measures can also be considered to increase the temperature decay before and during the exposure. Airing the building before the exposure is one possibility. Increasing the thermal conductance of the building shell by e.g. opening the inner window frames is another possibility. However, a risk is inherent in both. In the former the right timing is crucial. In the latter the tightness of the building might suffer and some additional sealing could be necessary.

DISCUSSION

In theoretical calculations using models, several factors always exist which cause uncertainty in the results. In the following some of these factors and their consequences are discussed: The weather parameters used as input data come from a meteorological station. These parameters are not identical with the ones near a building because each building is surrounded by a microclimate of its own. Naturally some kind of relationship exists between the meteorological and the local parameters. As far as the wind speed is concerned, this relationship was roughly described using the factor 0.5.

The air flows through the building envelope are computed using a stationary wind pressure. In reality, however, the wind pressure is fluctuating. This phenomenon has been investigated both theoretically and empirically [21, 31, 32]. It is not possible to give any universal quantitative result. A common opinion seems to be that the fluctuations increase the infiltration and exfiltration air flows to some extent. As a consequence the calculated doses are slightly underestimated.

The value of the flow exponent describing the flow through the cracks in the building shell has an influence on the computed results. The flow coefficients of the leakage paths were determined by the flow exponent and the n_{50} value in a situation where the pressure difference between indoors and outdoors was 50 Pa. The pressure differences during the computation were, however, much smaller, of the order of 0–20 Pa. Such a procedure leads to a variation in the air flows depending on the flow exponent chosen. For example, with a typical pressure difference of 5 Pa, the air flow through a flow path with a value for the flow exponent $n = 0.60$ is 26% larger than in the case $n = 0.70$. Consequently, such an effect causes some uncertainty in the air flows, the concentrations and the doses and needs to be examined further.

The sudden step change in the outdoor concentration is, of course, only hypothetical. The real concentration in such situations varies considerably with time [4]. On the other hand, the air capacity of the building evens out the fastest fluctuations, and the concentrations and doses inside correspond to the mean value outdoors. Slower changes in the outdoor concentration level are, however, always possible and cannot be taken into account in calculations of such a universal nature as those presented here.

Because the outdoor concentration fluctuates in a real situation, the biological response to the concentration peaks is probably much higher than indicated by the outdoor dose [4]. As a consequence the denominator in equations 4 and 5 defining the relative dose is an underestimation and further, all the relative dose values are slightly overestimated. The magnitude of the overestimation depends on the toxic gas and the volume of the fluctuations.

As has already been mentioned, the purpose was to investigate single family houses as a group of buildings, not any specific building. Bearing this in mind, despite all the aspects mentioned, the results can be considered to be of the correct magnitude and they should be useful for the authorities in making decisions and taking action on sheltering in single family houses.

CONCLUSIONS

The most important property of a building, and one that vitally affects the contaminant penetration, is the tightness of the building shell. In a leaky building, depending on the exposure time, the doses are from two to fifteen times as much as in a tight building.

Closing the inner doors leads to higher doses in some parts of the building and lower doses in other parts, as the dispersion of the concentrations increases. By closing the inner doors and choosing the location in a proper way inside the building, the occupant can decrease the dose by an additional 50% compared with the mean value. Cutting off the heating has no significant influence on the doses.

From the viewpoint of sheltering in a single family house with two floors, the following rules can be given: Close all doors and windows. Cut off the ventilation and seal the ducts. If the outdoor temperature is lower than indoors, go to the second floor. If the outdoor temperature is higher than indoors, stay on the first floor. If, additionally, the wind direction is known, close all the inner doors and go to the leeward side of the building. If the outdoor air temperature is very low, cut off the heating and all other temperature sources in the building.

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