Mitigation of radiation dose through deposition to indoor surfaces

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Introduction

When an accident occurs that involves releases to the atmosphere of toxic materials the first action of the civil defence authorities is to urge people to go indoors and close the windows and doors. A review of measurements of Indoor/Outdoor concentration of airborne pollutants (e.g. Alzona et al. (1979)) reveals that most substances of outdoor origin have a lower concentration in indoor air, but a more detailed knowledge of the magnitude and mechanism of this reduction is disireable.

Since inhalation dose is directly proportional to air concentration (for a given particle size) the dose reduction factor, DRF, can be defined theoretically as the ratio between the indoor pollutant concentration, C_i, and the outdoor pollutant concentration, C_o, integrated from the start of the cloud passage, t_o, to infinity. Considering the house to be a single box with an air exchange with an infinite outdoor volume a simple differential equation can be derived by equating the change in indoor concentration per unit time with the difference between the production (ingression from the outside) and loss of particles (indoor deposition). This equation can be solved analytically. The solution this equation shows that the time integrated DRF equals the equilibrium ratio for constant outdoor pollutant concentration:

$$DRF = \frac{\int_{t_0}^{\infty} C_i(t)dt}{\int_{t_0}^{\infty} C_o(t)dt} = f\,\frac{\lambda_r}{\lambda_r + \lambda_d}$$

where f is the fraction of particles in outdoor air penetrating the building envelope, λ_r is the air exchange rate and λ_d is the deposition constant. This is a general result for all shapes of passing clouds, as emphasized by Roed et al. (1991), when it is assumed that λ_r and λ_d are constant. The air exchange rate, λ_r, may change if the weather conditions change, but in all circumstances the value used in modeling will be an average value, which again will give an average value for the dose reduction factor. The deposition constant, λ_d, will vary with the particle size, but for each size class and type of pollutant the expression will be valid. Some authors , e.g. Engelmann (1992), have given a more optimistic expression for the DRF by including a term describing ventilation of the house right after the passage of an rectangular cloud and thus reducing or removing the contribution to dose from the 'tail' after passage, but this factor has been found to be to unrealistic to be included in the model.

Experimental

The indoor deposition is the least well known parameter determining the indoor inhalation dose. Very little information exists on the depostion of particles larger than 0.5 μm in houses. In order to improve our understanding of the mechanisms governing the indoor-outdoor air activity ratio Imperial College and Risø National Laboratory have developed a particle tracer technique, where silica particles are labelled with dysprosium and used as tracers for indoor depostion experiments. The idea is to disperse the particles in a real house and measure the decrease in tracer concentration by taking consecutive air filter samples. During the experiment, the air-exchange rate is measured and the deposition constant, λ_d was then to be found by subtracting the air exchange rate, λ_r, from the decay constant, λ_t. The air-exchange rate was measured by releasing SF_6 gas into the test room and monitoring the decrease in concentration by gas chromatography. The absolute decrease with time of both the tracer gas and the particle concentration is proportional to the concentration and the decay will thus follow an exponential curve if the experimental conditions are constant during the test. Both these decay constants are found by linear regression. For all the four houses studied the deposition velocity, v_d, has been calculated using the geometric surface, S, to volume, V, ratio. That is, no contribution from the surface of furniture, etc. has been included in the surface area of the furnished rooms. Such measurements would be difficult to make in an objective and reproducible way.

Results and discussion

Results and a detailed description of the individual experiments in the four houses have been given by Roed et al. (1991), Byrne (1995) and Lange (1995). Despite the differences between the test conditions in the various houses, the results are in good agreement, with increasing deposition velocity for increasing particle size and degree of furnishing. Table 1 shows the average results for furnished and unfurnished rooms. As tests only

were made with furniture in the room during the Jersie experiment there is actually only 'unfurnished' results from three houses. In all experiments, the deposition velocity was highest under the furnished conditions. In Table 1 the deposition can also be seen to increase with particle size as predicted by deposition theory for supra-micron particles, but the actual deposition velocities exceeds those predicted by the theories that only includes gravitational settling by a factor of 2 to 5. When the results were compared with the measurements of indoor deposition presented in Roed & Cannell (1987): Table 2 good agreement was observed. For Be-7 which is associated with particles in the size range of 0.5 to 1.0 μm, Lange (1994), an average deposition velocity of ~~0.71 x 10^{-4} ms^{-1}s was found. The indium particles had a AMAD of 0.5 to 0.7 μm, which is close to that of Be-~~ 7, and the deposition velocity has been found to be 0.61×10^{-4} ms^{-1} for unfurnished rooms and 0.82×10^{-4} ms^{-1} for a furnished room on average. Roed and Cannell found a v_d of 3.1 to 3.9×10^{-4} ms^{-1} for Ce-144. This corresponds to the v_d of 4 or 5.5 μm particles in Table 1 and this would be reasonable size for cerium as it belongs to refractory group of release products as described in Rulik et al. (1987).

Size [μm]	GSD [ ]	Avg. v_d Unfurnished [$10^{-4}ms^{-1}$]	Avg. v_d Furnished [$10^{-4}ms^{-1}$]
0.5	1.60	0.61±0.08(2)	0.82±0.08(6)
2	1.48	1.13±0.16(5)	1.36±0.50(5)
3	1.20	1.33±0.37(2)	2.25(1)
4	1.07	2.42±0.17(5)	3.11±0.6(5)
5.5	1.18	3.03±0.04(2)	3.24(1)

Table 1 Measurements of indoor Deposition Velocities in four houses. The first two columns show size and geometric standard deviation, GSD, of the test aerosol. The last two columns gives the average deposition to all surfaces measured in three different test houses. The numbers in the parentheses give the number of tests for each condition.

A data set was selected where the correlation coefficients were better than 0.95 for the tracer aerosol decay curves. Twelve results from unfurnished houses and fifteen results from furnished houses were chosen. Experiments where small mixing fans were operated during the test have been included in these data sets. A power regression and a linear regression have been made for the data, expressing the deposition velocity as a function of the particle size. Average deposition velocity was chosen rather than the deposition constant in order to take the different surface to volume ratios of the test rooms into account. The correlation coefficient is given in the parentheses:

$$v_d = 1.23(d_p)^{0.65} \; (r = 0.96)$$

where v_d is the average deposition velocity to all surfaces and d_p is the particle diameter. In both the unfurnished and the furnished rooms the power regression had the best correlation coefficient, i.e. 0.96 compared to 0.90 and 0.95. They found that the deposition velocity increased linearly with the particle size in the particle size range investigated. Since the formulae presented in equations (2.3) to (2.5) are purely empirical, it must be emphasised that they are not valid outside the particle size range investigated, i.e. 0.5 to 5.5 μm.

Present models of the effect of sheltering during releases of radioactive materials to the atmosphere consist of a single factor giving a common dose reduction factor, DRF, for all nuclides. A value of 0.5 is currently used in probabilistic accident consequence assessment codes, Brown (1989) (except noble gases for which DRF = 1.0, i.e. no reduction in inhalation due to indoor residence). In order to provide a more realistic model that takes into account properties of the released material the empirical formula for indoor deposition is used together with equation (2.2) to calculate dose reduction factors, DRFs. equation (2.6) shows the derived formula:

$$DRF = \frac{\lambda_r(U_{wind}, \Delta T)}{S/V * 1.23(d_p)^{0.65} + \lambda_r(U_{wind}, \Delta T)}$$

where the deposition constant, λ_d, is found by multiplying the average deposition velocity with an average S/V ratio for the buildings in question. In the review by Engelmann (1992) surface to volume ratios were summarised for a number of different buildings: 1.74 m^{-1} for apartment buildings/houses, 1.3 m^{-1} for office buildings and 0.66 m^{-1} for industrial buildings. These values do not include contributions from furniture and equipment in the room. The average S/V of the test rooms was 1.69 m^{-1} and a value of 1.7 m^{-1} has been used in the model calculations shown in Figure 1.

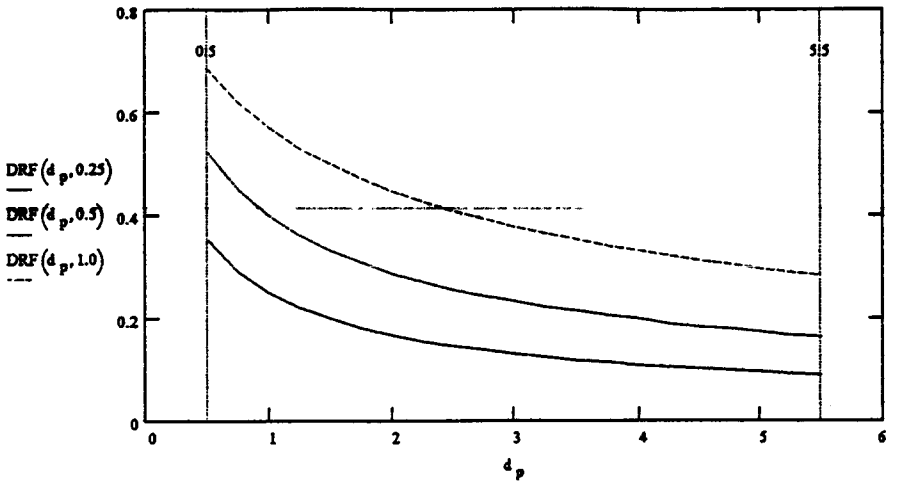

Figure 1 DRF's as function of particle size and air-exchange rate. The number after 'd_p' in the left margin of the figure is the air-exchange rate for that line style. A surface to volume ratio of 1.7 m^{-1} have been used corresponding to a medium sized living room. The vertical lines indicate the valid particle size range, i.e. 0.5 to 5.5 mm.

The air-exchange rate can be expressed as a function of the weather conditions, outdoor temperature and wind speed. The temperature difference over the building envelope can be expressed as the difference between the outdoor temperature and the indoor temperature, typically about 21 °C. The air-exchange rate was determined as a function of these parameters for a typical Danish houses by Kvisgaard et al. (1988). Engelmann (1992) quoted several references and used an equation similar to equation (2.3) for calculation of air-exchange rates for houses in the USA from data on wind speeds and temperature difference. In the Figure the DRF is plotted as a function of particle size for three different values of the air-exchange rate. An assumed surface to volume ratio of 1.7 m^{-1} was used in these calculations. It can be seen that the DRF decreases significantly with particle size. The three values for the air-exchange rate used (0.25, 0.5 and 1.0 h^{-1}) represents a low, medium and high value and the DRF varies between 0.1 and 0.7 or factor of seven depending on the particle size for these air-exchange rates. These relatively large variations in DRF clearly justifies a more detailed model for the DRF.

References

Alzona, J.; Cohen, B.L.; Rudolph, H.; Jow, H.N. and J.O. Frohliger, Indoor-outdoor relationships for airborne particulate matter of outdoor origin, Atmospheric Environment, Vol. 13, pp. 55-60, 1979.

Brown, J., Sheltering in the event of an accident. Atom 389, pp. 17-19, 1989.

Byrne, M. An experimental study of the deposition of aerosol on indoor surfaces, Ph.D. dissertation, Imperial College, London, 1995.

Engelmann, R.J. Sheltering effectiveness against plutonium provided by buildings. Atmospheric Environment. Vol. 26A, No. 11, pp. 2037-2044, 1992.

Jost, D.T.; Gäggeler, H.W.; Baltensperger, U.; Zinder, B. and P. Haller, Chernobyl fallout in size-fractionated aerosol, Nature, Vol. 324, pp. 22-23, 1986.

Lange, C., Indoor deposition and The protective effect of houses against airborne pollution, Risø-R-780(EN), 1995.

Roed, J. & R.J. Cannell. Relationship between Indoor and Outdoor aerosol concentration following the Chernobyl accident. Radiation Protection Dosimetry, Vol. 21, No. 1/3, pp. 107-110, 1987.

Roed, J.; Goddard,A.J.H.; MacCurtain,J.; Byrne, M. & C. Lange. Reduction of Dose from Radioactive Matter ingressed in Buildings. Cadarache, 1991.

Rulik, P.; Bucina, I. and I. Malatova, Aerosol Particle Size Distribution in Dependence on the Type of Radionuclide after the Chernobyl Accident end in the NPP effluents, Proceedings of the XVth Regional Congress of IRPA on the Radioecology of Natural and Artificial Radionuclides. Sweden, FS-89-48T, 1013-4506, 1989.

Tschiersch, J. and B. Georgi, Chernobyl Fallout Size Distribution in Urban Areas, J. of Aerosol Science, Vol. 18, No. 6, pp. 689-692, 1987.