PUBLIC PROTECTIVE ACTIONS

**EFFECTIVENESS OF SHELTERING
IN
BUILDINGS AND VEHICLES
FOR
PLUTONIUM**

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SUMMARY

Publications on indoor concentrations of pollutants and on natural ventilation of buildings are reviewed for data relevant to sheltering against inhalation of particles and gases from accidental releases. Equations for the reduction of dose and for interior concentration are presented. The dose reduction depends upon the integrity of construction of the shelter, indoor-outdoor temperature difference, wind speed, deposition velocity of the contaminant, and duration of the plume. A "virtual air exchange rate" is defined that incorporates the natural air exchange rate, deposition velocity, and the shelter's interior area and volume. General solutions for residences are then graphed for application to particles and gases.

The specific coefficients appropriate to plutonium particles are deduced from the literature review, and representative DRFs are calculated for residences and office buildings. Calculated DRFs are very low for buildings of good construction, and especially for plumes of short time duration. For a well-constructed house, the DRF for a cloud of plutonium particles of 30 minutes duration is generally less than 0.05. The low values make sheltering a highly competitive choice among protective actions against particles whose primary pathway of exposure is inhalation. However, the magnitude of these estimates of exposure are quite sensitive to assumptions about mixing and deposition inside the shelter, and further research is needed to verify them.

The very limited information on sheltering offered by automobiles indicates that a moving car offers no protection unless the contaminant has a high deposition rate inside the car. There is a suggestion that a stationary car offers significant protection for short times, but more data are needed.

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INTRODUCTION

Background

The purpose of this paper is to collect and present current knowledge relevant to the protection offered by sheltering against exposure to plutonium particles released to the atmosphere during accidents.

The protection offered by sheltering against airborne chemicals and radioactivity can be substantial. For particulate clouds of long duration, such as outdoor air pollution, pollen, and soil particles, concentrations inside buildings are generally found to be 10-50% of the outdoor concentrations. For clouds of short duration about the shelter, e.g., 15 minutes or less, the total exposure through inhalation in a shelter may easily be as low as one-twentieth of that outside. These lower values are primarily a result of the length of time it takes to change inside air with outdoor air, and deposition of the contaminant during and after entry to the shelter.

For those many contaminants for which effects are linear with the airborne concentration, it is convenient to define a Dose Reduction Factor (DRF). In the past, the DRF has been defined as the ratio of the radiological dose that may be incurred within the shelter to that in the outdoors. As such, it includes the dose through shine from plumes aloft and from material deposited on the surface.

For this paper, which is concerned only with the inhalation pathway, the DRF is the ratio of the time-integrated concentration inside the shelter to that outdoors. It is important to note that the range over which effects are linear with concentration may be limited for many contaminants. Examples are when concentrations produce effects that are irreversible, or when concentrations are below effects threshold levels.

Brenk and De Witt (1987) reviewed existing literature and compiled their estimates of inhalation dose reduction factors for different chemical and physical forms of radionuclides, and for buildings and vehicles with and without air conditioning and filtering systems operating. These ranged from 0.004 in a clean room to one in poorly filtered manufacturing facilities, for a plume lasting 6 h. They did not give their estimates for brief plumes. Since there do not appear to be new or original data in the paper, their estimates for 6 h are not reproduced here.

Brown (1988) presented a brief and concise review of Dose Reduction Factors for radiological incidents, concluding that "sheltering could significantly reduce the doses from inhalation and material in the cloud received by individuals under the plume". In his paper he apparently equates the DRF for inhalation to the ratio of indoor and outdoor concentrations (I/O ratio) observed by others, which is true only for plumes of longer duration.

Past work on sheltering against radioactivity has primarily dealt with the complex problem of shielding (absorption) against gamma radiation, such as is provided by walls, earth and other dense materials (e.g., le Grand et al. 1986). Even after interior concentrations approach equilibrium with the outdoor concentration, the shelter will still provide some shielding against radiation emanating from the outdoors. These circumstances and the associated "protective factors" against gamma radiation do not apply to plutonium particles with its low energy radiation.

Aldrich and Ericson (1978) reported on a shelter model for deposition and airborne concentration of emissions from a reactor accident, including a literature review, equations, and graphed results. Birenzve (1983) used a less complex model and discussed the effects of filtration and deposition, and how they might be modified. (The DRF is the inverse of the Protection Factor, a term generally used in radiation protection to treat shielding against radiation.)

Anno and Dore (1978) calculated both the whole body radiation exposure protection and the inhalation dose reduction offered by sheltering from reactor accidents (including noble gases, iodines, and other gamma emitters). Their report contains extensive equations, graphed results for reactor accident plumes of 0.5, 1.0 and 3.0 h duration, and discussion. Kocher (1980) made similar calculations for the Three-Mile Island Accident, and calculated a dose reduction to 0.072 and 0.44 of that outdoors from radioiodine for two interior deposition rates, assuming air exchange rates of 0.5-1.5 h⁻¹. Both results are quite sensitive to their assumptions about the deposition of iodine.

Sheltering Against Inhalation of Plutonium

The primary exposure pathway for plutonium is through inhalation, with subsequent internal deposition and transport to other organs. The deposition depends upon breathing rate, particle size and particle mass, with the larger of the remaining particles having the greater probability of being deposited at each of the successive stages of the respiratory system. The Task Group on Lung Dynamics (1966; ICRP 1979) defined three compartments for use in deposition: 1) the nasopharynx beginning with the anterior nares and extending down to the level of the larynx or epiglottis, 2) the trachea-bronchial tree down to and including the

terminal bronchioles, and 3) the pulmonary compartment, consisting of the respiratory bronchioles, alveolar ducts, atria, alveoli and alveolar sacs.

"Inspirable" particles are all those capable of entering via nose or mouth. The "thoracic mass fraction" are those capable of penetrating past the larynx and are less than 25 micrometers. "Respirable" particles are those capable of penetrating past the terminal bronchioles into the pulmonary region, and are less than 10 micrometers.

In this paper, information is presented relevant to sheltering in buildings and vehicles from inspirable outdoor particles. Particles with an aerodynamic diameter larger than 10 micrometers are either not inspired, are deposited exterior to the pulmonary region, or are exhaled (Hatch and Gross 1964; Lippman 1977; International Commission on Radiological Protection 1979). Because the greatest health implications are associated with respirable particles, the primary concern is with particles less than 10 micrometers aerodynamic diameter, although particles which are deposited above the pulmonary region may also have health implications.

The "aerodynamic diameter" of a particle is defined as the diameter of a sphere of unit density having the same fall velocity as the particle. The fall velocity of a small particle in air varies with its density, the square of its diameter, and its shape. A convenient way of comparing aerodynamic diameters for spheres is to compare the products of the squared diameter and density. Plutonium oxide has a density of 10. Thus, plutonium particles less than 3.16 micrometers physical diameter are respirable, as are particles of unit density less than 10 micrometers physical diameter. If the contaminant is attached to a host particle, such as plutonium might be attached to a soil particle, their combined aerodynamic diameter is the controlling parameter for determining the deposition in the respiratory tract.

CALCULATIONS OF DOSE UNDER SHELTERING CONDITIONS

The time integrals of the airborne concentrations, for each particle size that is being inhaled, are used in the calculation of the inhalation dose. The method is described in Elder et al. (1982). However, such detailed dose calculation is unnecessary for the purposes of this paper. It will be sufficient to calculate the ratio of the exposures inside and outside the shelter for the same time interval. This ratio is the Dose Reduction Factor, DRF.

$$DRF = \int (I/O) dt \quad (1)$$

where^a (I/O) is the ratio of the concentrations indoors and outdoors, which is a function of time and particle size.

When preparing a safety analysis for an hypothetical accidental release of plutonium at the DOE Pantex plant, Dewart et al. (1982) reasoned that a 2 micrometer aerodynamic equivalent diameter could be used to conservatively represent the respirable range for organ dose calculations. This conclusion was based on empirical size distribution data from the Roller Coaster field studies of detonations involving plutonium. Dewart deduced from these data that 5 micrometers was the probable activity median aerodynamic diameter (AMAD) of the 20% of the plutonium that was of respirable size. However, 5 micrometers would give a comparatively low pulmonary deposition, which is where the plutonium has greater health implications. Therefore, she selected 2.0 micrometer AMAD for use in the ICRP Task Group Lung Model. If size distribution data are available for a specific accident, they should be considered instead.

If the outdoor concentration is relatively constant, the inhalation Dose Reduction Factor (DRF) is the same as the equilibrium ratio of the indoor/outdoor concentrations (I/O) for a particular size particle. Therefore, if I/O ratios for 2 micrometer particles were available for the cloud duration of concern, we could use that ratio as a conservative approximation to the DRF for all respirable particles from a plutonium accident.

$$DRF_{Pu} = (I/O)_2 \quad (2)$$

Parameters Determining Dose Reduction Factor

The airborne concentration within a shelter relative to that outside depends primarily upon the rate at which air is exchanged with the outdoors, removal of the contaminant as it passes between the shelter and outdoors, and deposition rate of the contaminant within the shelter (Birenzvice 1983; Chester 1988; Cristy and Chester 1981; Sherman 1987). In theory, it also depends upon any resuspension of material once deposited in the shelter; however this will contribute only a small fraction to the interior airborne concentration during cloud passage, and can be ignored for the purposes of this paper.

The "air change rate" or "exchange rate" is the volumetric flow rate of air into and out of the shelter (the "infiltration rate")

a. A list of symbols is provided at the end of this paper.

divided by the volume of the shelter. The exchange rate depends upon the shelter's volume, the tightness of fit of doors and windows, the existence of vertical routes such as chimneys, flues and elevator shafts, whether heating, cooling and ventilation systems are operating, indoor-outdoor temperature difference, wind speed, the orientation of the building to the wind, and sheltering of the structure by surrounding trees and buildings. Formulas relating exchange rates to winds, temperature difference, and the area of cracks in the shelter walls and entrances can be found in ASHRAE (1989) and Sherman (1987).

The amount of the contaminant filtered out as it enters the building, and the amount subsequently deposited within the building, depend upon the area and nature of the shelter's interior surface, the tightness of fit of doors and windows, the size (if particulate), reactivity (if gaseous), and the velocity and turbulence of the air flow within the shelter.

General equations that define the indoor concentration from external and internal sources are found throughout the literature (e.g., Wadden and Sheff 1983). The following development is provided for persons new to the topic. The physical relationship of the shelter and processes are illustrated in Figure 1. The equations describing the outdoor and indoor concentrations for a tracer as a function of time, t , are

$$R V = Q \quad (3)$$

$$dC_i/dt = R (C_o - C_i) \quad (4)$$

where R is the air change rate, C_i is inside air concentration, assumed well mixed, C_o is the concentration outside the shelter, assumed constant, V is the volume of the shelter, and Q is the infiltration or volumetric flow rate through the shelter. For the purpose of sheltering calculations, the abrupt arrival of an outdoor plume of sufficient duration may be regarded as a sudden change from a concentration of zero to the average concentration of the plume. The inside concentration responding to this is

$$C_i = C_o \{1 - e^{-RT}\} \quad (5)$$

The inside exposure is the time integral of the inside air concentration

$$\text{EXPOSURE } I = C_o \{ T - (1/R) + (e^{-RT})/R \} \quad (6)$$

and the outdoor exposure is the time integral of the outdoor air concentration

$$\text{EXPOSURE } O = C_o T \quad (7)$$

Fig 1. Illustration of the relationships between a shelter's wall, the shelter, the infiltrating airflow, Q , the amount of contaminant entering the wall structure, QC_0 , the fraction that manages to escape capture in the wall during ingress, f , the concentration of the contaminant inside the shelter, C_i , and the rate of contaminant deposition inside the shelter, v_dAC_i .

The ratio of the inside and outdoor exposures is the DRF

$$\text{DRF} = C_o \{ T - (1/R) + (e^{-RT})/R \} / C_o T \quad (8a)$$

$$= 1 - (1/RT) + (e^{-RT})/RT \quad (8b)$$

where T is measured from the time of the cloud arrival and does not exceed the length of time that the cloud envelopes the shelter. As time becomes large, the DRF approaches 1.0.

These equations also apply for the loss of a contaminant or tracer from inside the shelter to the outside. They can thus be used to determine exchange rates by use of a tracer, and can also be used to determine the shelter's volume if air containing a tracer is pumped into the shelter at a known rate. One might also be able to estimate the volume by releasing and mixing a known amount of tracer in the shelter and extrapolating its concentration back to zero time, although this apparently has not been attempted.

Deposition Within the Shelter

The deposition of the contaminant within the shelter further reduces the inhalation exposure, and thus contributes to a lower DRF (better protection). Meteorologists have defined an empirical "deposition velocity". The deposition flux to the surface is the product of the deposition velocity and the airborne concentration:

$$\text{Deposition flux} = v_d C \quad (9)$$

where v_d is the deposition velocity (dimensions of LT^{-1}), and C is the airborne concentration at a reference height above the surface (dimensions of quantity L^{-3}).

This deposition velocity depends upon the nature of the surface as well as of the contaminant. Strong determinants are size for particles and reactivity with the surface for gases. Clearly, the physical, chemical and biological nature of the surface should also have an effect. A summary of observed and theoretical deposition velocities was made by Sehmel (1984).

The potential significance of interior deposition can be demonstrated by comparing the air exchange rate with $(v_d A/V)$, where A is the interior area and V is the volume. For an unfurnished room 4 m x 4 m x 2.4 m, and a deposition velocity to walls, ceiling and floors of 0.013 cm s^{-1} , such as might apply to 2 micrometer particles, yields $(v_d A/V) = 0.86 \text{ h}^{-1}$. This value is larger than the air exchange rate for shelters of good construction.

Deposition Removal During Ingress

One expects that the larger particles will be more effectively removed within the walls during ingress. Probably this will depend upon various physical parameters of the particles and the "cracks" in the walls. Although it is possible that deposition during ingress is a function of the air exchange rate, intuitively, such an effect should be small compared to the influence of particle size and the size of the cracks themselves. Measurements by Roed and Cannell (1987) support this view.

There is little evidence as to what size a particle must be for significant removal during ingress. Cristy and Chester (1981) reported that there was no evidence of such ingress removal of 2 micrometer diameter spores used in their experiments. As particle size and deposition velocities are increased, at some point the fraction penetrating into the shelter should decrease.

Dockery and Spengler (1981) deduced from their studies of I/O relationships on sulfates and particles that only about 70% of respirable particles penetrate indoors. However, this conclusion follows an introductory assumption that deposition inside the building can be neglected for small particles. This incorrect assumption probably affects other conclusions of the paper as well. A similar error was made by Aldrich and Ericson (1978) when they assumed that the I/O ratio was determined by deposition during ingress.

Observed Indoor/Outdoor Concentrations

Air quality studies have been made of the relation between indoor and outdoor concentrations of gaseous and particulate pollutants. Certain of these Indoor/Outdoor ratios (I/O) can be regarded as applying to continuous plumes of long duration, as is the approximate nature of most urban and natural emissions. If certain conditions are met, then the I/O ratios for a pollutant will be the same as the DRF for an accident. These conditions are that the temporal, physical and chemical characteristics of the plumes be the same, and that there are no significant radioactive decay or sources within the shelter.

The DRF will be smaller than the equilibrium I/O ratio (that is, offer better protection) for plumes that envelope the shelter for shorter times. Thus, I/O ratios represent the maximum DRF (minimum protection) available from that shelter for contaminants having the same physical and chemical characteristics as these analogues.

Thompson et al. (1973) measured indoor and outdoor concentrations of the mass of airborne particles (as sampled on filters) for 11 California buildings in the summer and the fall. Because these were buildings in normal use with their various cooling systems operating, the indoor/outdoor ratios (I/O) of particles are only indicative of the minimum protection offered against particles. The ratios were strongly affected by the activities that generate and re-entrain particles within the buildings, the velocity of the air movement, and the removal by air filters and precipitators (Table 1). The ratios are subject to unquantifiable bias by large particles that do not present a health threat through inhalation.

Table 1. The I/O ratios for particulate mass, observed by Thompson et al. (1973), for some of the buildings with refrigeration air conditioning.

Building Type	Filtration Type	Air Changes (h^{-1})	I/O Ratio
Private home	Electrostatic	unk	0.07
Hospital	High efficiency	4	0.08
Convalesc. home	Spun glass	7	0.14
Hospital	High efficiency	unk	0.25
Sr. High School	Spun glass	4	0.36
Shopping Mall	Oiled wire	4	0.44
Dept. Store	Spun glass	4	0.48
Elem. School	Spun glass	4	0.49
Jr. High School	Spun glass	4	0.82

Higher I/O values, near or greater than one, were measured for buildings without filtration and for those with evaporative coolers. These numbers are interesting, but essentially useless to this paper because the conditions (with normal activity, e.g., opening of doors, and operation of air conditioning) are so different from what should be occurring during sheltering.

Raunemaa et al. (1989) measured I/O for aerosols in occupied office buildings, houses and apartments in urban and suburban areas of Helsinki. Exchange rates were not measured. The I/O ratios of the averaged concentrations for lead were 0.44 and 0.28 in summer and winter respectively in the urban buildings. Ratios for other elements were larger, and often greater than one as a result of indoor sources. Assuming that more outside ventilation air is used in the summer than in the winter because of the respective airconditioning and heating loads, the value of 0.28 may be the closer as to what would be I/O during sheltering conditions.

Andersen (1972) measured the I/O ratios for sulphur dioxide and total suspended particles in an unoccupied room with no internal sources and the doors and windows closed over the period of 7 months. The I/O ratios averaged about 0.51 for sulphur dioxide and 0.69 for particles. Offerman et al. (1982) measured I/O ratios in a two week period in January-February in Rochester, New York, in two "relatively tight" houses. The ratios for sulfur and lead were those in the "fine" particles (Table 2). The average air exchange rates were 0.38 and 0.42 h^{-1} in the two houses, and they ranged from 0.21-0.61 h^{-1} .

Table 2. Indoor/Outdoor ratios observed by Offerman et al. (1982) in two houses.

Contaminant	House 1 R = 0.38 h^{-1}	House 2 R = 0.42 h^{-1}
Sulfur particles	0.39	0.59
Lead particles	0.32	0.47
SO ₂	0.25	0.33
Ozone	0.75	0.66

Alzona et al. (1979) found that the average equilibrium ratio of indoor/outdoor (I/O) mass concentrations for natural airborne particles (outdoor origin) ranged from 0.10-0.42 in several closed buildings, homes, and two automobiles. In all cases, windows and doors were closed and there was no forced circulation (or filtering). That the indoor concentrations were lower than outdoors was attributed to deposition during and after entry. The authors concluded that particle size was a strong factor, with the smaller, submicrometer diameter particles (lead and bromine) having the higher average (I/O) ratio (0.42).

This conclusion is further supported by the observations that, when a window was "cracked open", the indoor and outdoor concentrations of lead and bromine were the same, whereas the indoor concentrations of the presumably larger calcium, iron, and zinc were smaller than the outdoor concentrations. Particle size was not actually measured, but a reference was quoted that reported typical size ranges associated with the elements being measured. Because these are not monodisperse (single-sized) particles, a few large particles could have drastically affected the ratios.

A followup study used the same techniques to determine I/O ratios for a variety of buildings and rooms, many in use, including university offices, public schools, a store, rooms and attics in

homes, and university laboratories, ranging from 8-90 years old. Cohen and Cohen (1979) reported average (I/O) ratios of 0.38 for lead, 0.36 for bromine, 0.14 for calcium, and 0.22 for iron. The latter two were believed to be the larger particles. Again, exchange rates and particle sizes were not measured, and there were occasional, unexplained, large deviations.

Christensen and Mustonen (1987) reported (I/O) ratios of ^7Be of 0.23-0.45 in four different Finnish flats built in 1968-72, and 0.40-0.47 in four experiments on one Norwegian wooden house built in 1954.^a The authors report they believe the exchange rate in the Finnish flats to be about 0.2 h^{-1} as per building codes, but it was not measured.

Roed and Cannell (1987) measured airborne concentrations of several radioisotopes from the Chernobyl accident, and found the concentrations to be between 10 and 50% of those outdoors. The house was described as a "typical Danish house with a natural air exchange rate of 0.4 h^{-1} ." The reduction was ascribed to deposition in the house.

Yocum et al. (1971) measured I/O ratios for several pollutants and for total suspended particles in occupied public buildings, office buildings, and two homes in Hartford. The ratios show the effects of seasons and human activity that one might expect. Although the winter night-time ratios (Table 3) are affected by the heating plant, they probably minimize indoor sources such as cooking and tobacco smoking, and minimize the opening of windows and doors.

Table 3. Indoor/Outdoor ratios for total suspended particles in occupied buildings during the winter (Yocum et al. 1971).

Building	Day	Night
Library	0.16	0.26
City Hall	0.27	0.30
Office Building	0.31	0.48
Office Building	0.33	0.33
Home	0.43	0.41
Home	0.51	0.39

a. ^7Be is a cosmogenic nuclide created primarily in the high atmosphere, where it becomes attached to natural aerosols (Engelmann and Perkins 1970).

These I/O ratios should apply to other buildings of similar construction and air exchange rates. From these many I/O ratios for particles, it can be concluded that the maximum DRF for particles in closed buildings with the air cycling and filtering off is probably less than 0.1 for large but inspirable particles, and 0.4 for gases and very small particles.

Dose Reduction for a Depositing Tracer

The equations for a depositing tracer can be obtained by multiplying C_o by a coefficient, f , to represent the fraction that escapes deposition in the wall during ingress, and adding a (negative) removal term of $(-v_d A C_i)$ to account for dry deposition after the tracer is inside the shelter

$$V \frac{dC_i}{dt} = fQC_o - C_i b \quad (10)$$

$$DRF = (fRV/b) \{ 1 - (V/bT) + (V/bT) e^{-bT/V} \} \quad (11a)$$

$$= (fR/R^*) \{ 1 - (1/R^*T) + (1/R^*T) e^{-R^*T} \} \quad (11b)$$

$$C_i/C_o = (fR/R^*) \{ 1 - e^{-R^*T} \} \quad (12)$$

where

$$b = (Q + v_d A) \quad (13)$$

$$Q = RV \quad (14)$$

$$R^* = (R + v_d A/V) = b/V \quad (15)$$

Use of the virtual exchange rate, R^* , facilitates calculation, presentation, and understanding of the contribution of deposition to the DRF. (The use of the term "virtual exchange rate" is believed to be original with this paper.)

If the structure has a sufficient amount of filtered outside air forcibly introduced to the building to create a positive pressure inside, there will be little "natural infiltration". Then Q will be the rate at which outside air is brought inside, and fQC_o will be the rate at which contamination is brought inside, where $(1 - f)$ is the filter's efficiency for removing the contaminant.

As T becomes very large, the DRF approaches (fR/R^*) , which intuitively must be the equilibrium (I/O) ratio for plumes of long duration. Therefore, for those pollutants and released materials with the same depositional characteristics,

$$DRF = (I/O)_{eq} \{ 1 - (1/R^*T) + (1/R^*T) e^{-R^*T} \} \quad (16)$$

DRF and C_i/C_o for various (I/O) and R^*T are given in Table 4 and illustrated in Figure 2.

Table 4. Dose Reduction Factors and ratios of inside/outdoor concentrations for depositing materials. The DRF for a nondepositing material is the case where $fR/R^* = 1.0$ and $R^* = R$.

fR/R^*	R^*T	DRF	C_i/C_o
1.0	0.1	0.048	0.095
	0.2	0.094	0.181
	0.4	0.176	0.33
	0.6	0.248	0.451
	0.8	0.312	0.551
	1.0	0.368	0.632
	1.6	0.501	0.798
	2.0	0.568	0.864
	3.0	0.683	0.950
	4.0	0.755	0.982
	5.0	0.801	0.993
	6.0	0.834	0.998
	10.0	0.900	1.000
0.75	0.1	0.036	0.071
	0.2	0.070	0.136
	0.4	0.132	0.247
	0.6	0.186	0.338
	0.8	0.234	0.413
	1.0	0.276	0.474
	1.6	0.376	0.599
	2.0	0.426	0.648
	3.0	0.512	0.713
	4.0	0.566	0.736
	5.0	0.601	0.745
	6.0	0.625	0.748
	10.0	0.675	0.750
0.5	0.1	0.024	0.047
	0.2	0.047	0.090
	0.4	0.088	0.165
	0.6	0.124	0.276
	0.8	0.156	0.275
	1.0	0.184	0.316
	2.0	0.284	0.432
	3.0	0.342	0.475
	4.0	0.378	0.491
	5.0	0.405	0.497
	6.0	0.417	0.499
	10.0	0.450	0.500

0.4	0.2	0.038	0.073
	0.4	0.070	0.132
	0.6	0.099	0.180
	0.8	0.125	0.220
	1.0	0.147	0.253
	2.0	0.227	0.346
	3.0	0.273	0.380
	4.0	0.302	0.393
	5.0	0.321	0.397
	6.0	0.333	0.399
	10.0	0.360	0.400
0.3	0.2	0.228	0.054
	0.4	0.053	0.099
	0.6	0.074	0.135
	0.8	0.093	0.165
	1.0	0.110	0.190
	2.0	0.170	0.259
	3.0	0.205	0.285
	4.0	0.226	0.295
	5.0	0.240	0.298
	6.0	0.250	0.299
	10.0	0.270	0.300
0.2	0.2	0.019	0.036
	0.4	0.035	0.066
	0.6	0.050	0.090
	0.8	0.062	0.110
	1.0	0.074	0.126
	2.0	0.114	0.173
	3.0	0.137	0.190
	4.0	0.151	0.196
	5.0	0.160	0.199
	6.0	0.167	0.2
	10.0	0.180	0.2
0.1	0.1	0.0048	0.0095
	0.2	0.0094	0.0181
	0.4	0.0176	0.033
	0.6	0.0248	0.0451
	0.8	0.0312	0.0551
	1.0	0.0368	0.0632
	1.6	0.0501	0.0798
	2.0	0.0568	0.0864
	3.0	0.0683	0.0950
	4.0	0.0755	0.0982
	5.0	0.0801	0.0993
	6.0	0.0834	0.0998
	10.0	0.0900	0.100

Fig. 2. The Dose Reduction Factor (DRF) as a function of the air exchange rate, R , time, T , fraction of the contaminant that penetrates the shelter's structure, f , and the virtual air exchange rate, R^* . At large values of $R \cdot T$, the DRF approaches the equilibrium ratio of indoor and outdoor concentrations, I/O .

For shelters with a recirculating air system and inline filter, an additional removal term should be added to the DRF equation

$$V \frac{dC_i}{dt} = fQC_o - C_i[Q + v_d A + (1 - f_r)Q_r] \quad (17)$$

where Q_r is the recirculation flow rate through the filter, and f_r is the fraction that penetrates the recirculation filter.

If we redefine b as

$$b = [Q + v_d A + (1 - f_r)Q_r] \quad (18)$$

the formulas for DRF and C_i will continue to be the same as before:

$$DRF = (fRV/b) \{1 - (V/bT) + (V/bT) e^{-bT/V}\} \quad (11a)$$

$$C_i/C_o = (fRV/b) \{1 - e^{-bT/V}\} \quad (12)$$

As before, if b is large, the DRF is small, and approaches fRV/b over time. Clearly, a high flow rate through an efficient filter can overwhelm any ingress of the plume and make C_i and the DRF very small.

Indoor Mixing Efficiency

It is necessary to discuss the effect of internal mixing. Scientists investigating indoor contamination use an "effective air exchange rate" (Constance 1970; Drivas 1972; Repace 1987; Wadden and Sheff 1983) which is equivalent to mb/V , where m is a "mixing efficiency factor" that reflects the homogeneity of mixing indoors. In this paper, it is assumed that the indoor air is well mixed, that is, $m = 1$.

It is not clear how the mixing factor can be measured or can be determined without affecting the dry deposition. It may be practical but mathematically awkward to treat the problem as a shelter having many compartments. Perhaps, the mixing might be estimated during natural ventilation by observing spatial differences in the rates of change of concentration, and be experimentally measured (as a function of Q) during forced ventilation with nondepositing tracers from the equation

$$dC_i/dt = (mQ/V) C_i \quad (19)$$

Another experimental approach would be to measure the natural buildup of concentration over time, and then measure the concentration when it has been averaged by abrupt mixing throughout the shelter.

Although it is assumed for this paper that $m = 1$, one must recognize that sheltering air concentrations will be affected by "short circuits" of air flow between the infiltration points and the outdoors (especially when strong winds exist or forced air circulation is operating), that interior concentrations will be higher initially near cracks such as may surround windows and doors, that "dead" air spaces are likely to exist within complicated structures and furnished rooms, and that furnishings will affect air flows. These considerations have implications not only for the interpretation of experimental results, but also for optimizing the placement of persons within shelters.

Little quantitative information has been found on the spatial variation of concentrations under sheltering conditions. Under low air flow rates, spatial deviations from the mean can be substantial. Most measurements of exchange rates have been made with some mixing deliberately introduced. One can obtain from the literature an impression that the interior air concentration is reasonably uniform and satisfies Equation (12) when central air fans are operated in a recirculation mode. Therefore, unless one positions himself near a door or window, takes refuge in an interior room or closet with the doors shut, or otherwise avoids the free air of the room, the DRFs presented in this paper should apply.

Exposure Following Cloud Passage

Once the cloud has passed, the concentration inside the shelter decreases exponentially with time, and continues to contribute exposure to occupants until they exit or the shelter is aired. Recall that the exposures inside and outside the shelter are

$$\text{EXPOSURE I} = C_o \{ T - (1/R) + (e^{-RT})/R \} \quad (6)$$

$$\text{EXPOSURE O} = C_o T \quad (7)$$

The inside concentration during the cloud's presence is

$$C_i = C_o \{ 1 - e^{-RT_e} \} \quad (20)$$

The inside concentration decays exponentially following cloud passage, and is

$$C_i = C_o \{ 1 - e^{-RT_e} \} \{ e^{-RT_2} \} \quad (21)$$

The integral of this concentration is the inside exposure for the post-passage time period from T_e to T_2

$$\text{EXPOSURE II} = C_o \{ 1 - e^{-R^*T_e} \} (1/R^*) \{ 1 - e^{-R^*T_2} \} \quad (22)$$

where T_e is the length of time that the cloud envelopes the shelter. T_2 begins at T_e and is the amount of time following cloud departure. The DRF is then the sum of the two integrated concentrations divided by the integrated outdoor concentration

$$DRF = \{EXPOSURE I + EXPOSURE II\} / EXPOSURE O \quad (23)$$

To avoid this additional exposure there is required assurance that the cloud has substantially passed and a recognition of this by the occupants, or notification. The cloud may not have a well-defined end, and there may be pockets or puffs of the cloud delayed in their passage for a short time by buildings and vegetation. The concentration that has built up in the shelter relative to that lingering outdoors will be less for those shelters with the lower exchange rates and higher internal deposition, and, if they exist, with internal recirculation filters. However, in the absence of filtering, deposition, and significant radioactive decay, the exposures inside and outside will eventually integrate to the same values if the occupants do not exit and the air exchange rate remains constant (i.e., they do not air out the shelter).

Measured Dose Reduction Factors for Radioiodine

Megaw (1962) released radioiodine upwind of a "hut" and measured concentrations outside and inside the building. The ventilation rate of the building was also measured using a tracer gas in advance of each radioiodine experiment. For the two experiments with air exchanges of 1.8 and 2.0 h^{-1} , the respective time integrals of the concentrations (exposures) inside the hut were 0.22 and 0.17 of that outside (Table 5).

Because Megaw did not provide the time length of the releases of the radioiodine, the only way we can test Equation (11) against the data from those experiments is to assume a value for T . The use in Equation (11b) of $v_d = 0.005 \text{ cm s}^{-1}$, $A = 708 \text{ ft}^2$, and $V = 1080 \text{ ft}^3$ (which give $v_d A / V = 0.387 \text{ h}^{-1}$), and a release time of 15-20 min, provides good agreement between the exchange rate and DRF data for most of Megaw's tests. This good agreement requires that the deposition velocity inside the building be quite small. In other words, the equation fits the data when R is not much larger than R .

If we use Megaw's values of deposition velocity for those cases where Megaw reports a large deposition velocity inside the building, the equation predicts a much lower DRF than he measured. Although the samplers inside the building were run for an additional two hours after the plume had departed, this probably is not enough to account for the discrepancy. It is likely that the

deposition velocity to the wooden building walls was significantly less than that to his copper sampling surfaces. Metals are a highly effective deposition surface for iodine^a.

Megaw also ran experiments using Aitken nuclei generated by igniting paraffin-soaked sand upwind of the hut. Equation (11) gives the same DRF value as observed by Megaw for Aitken nuclei (Table 5) when one uses: the building dimensions and air exchange rate given in his paper; $v_d = 10^{-3} \text{ cm s}^{-1}$ (which is reasonable for very small particles); an assumed $(I/O)_{eq}$ ratio of 0.95; and the graphed data from his Figure 2 for the apparent release time of 0.5 h. The small deposition velocity has the effect of implicitly assuming that R^* is only slightly larger than R . There are insufficient data in Megaw's paper to permit definitive application of the equation to the other experiments on Aitken nuclei and radioiodine. The close agreement for this one case is undoubtedly fortuitous, but it does suggest that Equation (11) provides reasonable predictions.

Anno and Dore (1978) apparently combined the 12 Dose Reduction Factors observed by Megaw for both tracers, including the two tests with windows open, and attributed the average of 0.51 as primarily due to filtering by the structure during ingress (pages 12 and 52 of their paper). They used a subsequent radioiodine deposition velocity inside the shelter of 0.025 cm s^{-1} , which is within the $0-0.24 \text{ cm s}^{-1}$ range of those observed by Megaw on copper discs in these experiments with radioiodine. This deposition velocity is 1/20th of those typically measured outdoors (Sehmel 1984).

The magnitude of these deposition velocities can be compared to those calculated by Leaderer et al. (1981, 1984). These investigators used cigarette smoke as a contaminant in experiments in a controlled chamber with recirculating air. From the assumption that the difference in decay rates between nondepositing carbon monoxide and total suspended particulates was due to deposition of the particulates, they calculated a deposition velocity of 0.007 cm s^{-1} . Ninety-eight percent of the particles had sizes of 0.05-1.0 micrometer, with a volume median diameter of 0.225 micrometer. The paper suggests (but does not state) that they made this calculation using only the floor area rather than the total internal area. If the entire internal area had been used, the calculated deposition velocity would have been proportionately smaller. They stated that the high air recirculation used in the experiments probably facilitated the deposition.

a. Soldat, J. Private communication to Rudolf Engelmann. Battelle Northwest, Richland, WA 99352 (1990).

Table 5. Dose Reduction Factors measured by Megaw (1962) for radioiodine and Aitken nuclei.

R (h ⁻¹)	DRF
Radioiodine tests	
1.8	0.22
2.0	0.17
2.4	0.65
4.3	0.44
5.5	0.26
Radioiodine tests with windows open	
5.3	0.72
8.0	0.69
Aitken nuclei tests	
0.8	0.59
2.1	0.34
2.4	0.58
2.5	0.70
2.5	0.78

AIR EXCHANGE RATES

Experimental Determination of Exchange Rates

For those structures for which the exchange rate is uncertain and critical to decisions on sheltering, such as might be the case for schools, hospitals, school buses, prisons, etc., the exchange rate can be determined with a tracer experiment. A passive, nondepositing tracer, such as carbon dioxide, halocarbon, helium or sulfur hexafluoride is released in the structure, and its concentration is measured as a function of time. A depositing tracer of the same character as the contaminant of interest can be used to determine the virtual exchange rate. The data may be plotted on semilogarithmic paper.

$$\ln (C_2/C_1) = R (t_2 - t_1) \quad (24)$$

$$\ln (C_2/C_1) = R^* (t_2 - t_1) \quad (25)$$

Both R and R^* can be measured as the slope of the logarithm of the indoor concentration versus time, in the absence of an outdoor concentration of comparable magnitude.

Air exchange measurements can also be made using a continuous injection of a passive tracer, either at a constant rate or at a rate varied to hold interior concentrations constant. Nazaroff et al. (1983) note that the complexity of instrumentation controlling the release rate of the tracer can offset advantages.

Sherman (1987) presents a model developed at Lawrence Berkeley Laboratory for determining infiltration from climate indicators and fan pressurization of buildings. The leakage rate of buildings can be determined by measuring the air flow rate when the fan is pressurizing buildings to different pressures. The leakage rate can then be used to estimate infiltration (air exchange rates in the absence of the fan). Sherman states that it is clear that when short-term or highly specific estimates of infiltration are required, the approach used in his paper (of using pressurization data, average climate, and correction factors for height, shielding and size of individual leaks) is not advisable.

The measurements of exchange rates can be interpolated and perhaps extrapolated with caution and uncertainty to other environmental conditions by considering that the exchange rate is believed to vary as the wind speed, the square root of the vertical distance between inlets and outlets of the building, and some power of the indoor-outdoor temperature difference. Relationships for these dependencies are found in American Society of Heating, Refrigerating and Air-Conditioning Engineers (1989) and Sherman (1987). These relationships are not independent of one another, and so cannot be simply added together.

Seemingly good relations with wind speed in several separate studies could fail when all data are combined. Note that the effect of the wind may be influenced by the shape and size of the building, shielding by other buildings or trees, and the wind direction with respect to the building. The reported wind in one study may not be comparable to that in another because of significant differences in the representativeness of the wind measurements. Wind speed can vary significantly with height above ground, and it also varies over distance. A wind measured at an airport may be different from the actual wind at the building, not only because the height of measurement is different, but because the atmospheric flow field may be quite different at the airport. For these reasons, some uncertainty exists in the choice of a wind speed to use when retrieving air exchange rates from published formulas or figures.

A difference of one mile per hour wind speed has about the same effect as a difference of $3-6.4^{\circ}\text{F}$ (Bahnfleth et al. 1957; Las-

chober and Healy 1964). Wind speed has a strong influence on the exchange rate, more than doubling the exchange rate for a doubling of the wind speed above about 6 mph. However, note that the outside concentration of a contaminant from a localized source will vary inversely as the wind speed at the source point, and thus nearly compensate for the increased exchange rate in the total exposure.

Working with single closed rooms within occupied houses, Howard (1966) did not find a correlation between exchange rate and temperature difference, even when the chimney in the living room was open. He attributed this to whatever effect there was from the small (with few exceptions, not over 10 °F) temperature differences being overridden by wind-induced suction. Whether the chimney was open or not had a marked effect.

The dependency on the square root of the temperature difference was demonstrated for one house in Ottawa by Tamura and Wilson (1964). Their data for two houses also indicate a linear dependence on the wind speed at 25 ft above ground, but the range of speeds in the data is small. The dependency on the wind speed was demonstrated for two research houses by Bahnfleth et al. (1957) and for split-level residences by Laschober and Healy (1964). However, the air exchange appeared to depend linearly on the indoor-outdoor temperature difference (rather than on its square root) for a specified wind speed.

Hunt and Burch (1975) were able to correlate exchange rate for one townhouse as both a linear and a squareroot relationship with temperature. They also found that when wind speed was negligible, sealing leaks had little effect on reducing infiltration, and that the closing of a chimney when changing from gas to electric heat also produced little increase in infiltration. These seemingly anomalous results were obtained with a house built within a large environmental chamber. The authors report that the concentrations of the tracer in the surrounding chamber were too small to affect the results.

Luck and Nelson (1977) measured exchange rates in a one-story house near Minneapolis airport in two heating seasons. The house was unoccupied and had automated forced-air gas heat. With the indoor humidifier off, the exchange rate varied from 0.48-1.57 h⁻¹ over a wide range of wind speeds and temperature differences. Three weeks after the humidifier was turned on, the exchange rate dropped to 0.19-0.36 h⁻¹ for a month, and continued to remain low for at least two more weeks after it was again turned off. They attributed the lower exchange rates to swelling of the building's wood, with a time lag in changing the humidity within the wood. In the discussion following the paper, they noted that resilient weather stripping might reduce the differences with humidity.

Persily (1985) measured the leakage of a house in New Jersey over the period of a year through fan pressurization, and concluded that a 25% variation in leakage was due to changes in the moisture content of the building materials, with about two weeks delay time behind the outdoor humidity.

Differences in the construction and environment of two houses caused noticeable differences in the exchange rates (Bahnfleth et al. 1957). One house was a 2-story brick house with full basement surrounded by houses and trees, the other was a single-story frame structure with basement located on an open site. The winter infiltration rate for a given temperature difference and wind velocity was higher than that for summer, apparently as a result of the combined effect of the chimney and bare trees. The effect of the heating plant chimney was pronounced, and from that Bahnfleth et al. deduced that a two-story house would have a greater potential for air flow than would a one-story house. Tamura and Wilson (1964) also discussed the strong effect of chimneys and flues. (Note that this chimney effect probably is not present in electrically heated homes, but should exist with gas-fired hot water heaters.) Bahnfleth et al. (1957) concluded that "An allowance of one-third air change per hour for all sources of air leakage for the entire volume may be considered average for a well constructed residence at average conditions of wind and temperature difference."

An attic exhaust fan had a dramatic effect on infiltration for a test bungalow (discussion by Coblenz et al. following the paper by Bahnfleth et al. 1957). Attic fans should not be overlooked when making emergency response plans. Attics may have good air exchange with the house through access trap doors, whole-house fan louvers, required gaps in the insulation around recessed lights and chimneys, and vents installed to vent stale air from cathedral ceilings. Attic fans are generally controlled by thermostats in the attic.

Measured Exchange Rates - Residences with Normal Activities

Numerous experiments have been conducted to determine air exchange rates for buildings. Typical exchange rates vary from 0.07 to 4.0 h⁻¹, but these rates depend upon the size and structural "tightness" of the buildings, and the intentional (designed) air intake through ventilation systems. Strong winds, indoor-outdoor temperature differences, and structural channels such as chimneys, stairwells and elevator shafts increase the exchange rates. Newer buildings and buildings in colder environments with their heavier insulation, vapor barriers and weather stripping tend to have the lower exchange rates. The exchange rate can be reduced further by shutting down all ventilation systems, closing doors and windows, and sealing door and window frames. Matthews et al. (1990) found that taping ductwork in crawlspaces significantly reduced the entrainment of outside air.

Some investigators (Coblentz and Achenbach 1963) calculate the exchange rate for the entire house as the sum of the products of the measured exchange rates in individual rooms and their corresponding percentage of the total house volume. Although they do not so state, this may lead to an overestimation of the actual exchange rate for the house (because the loss from one room into an adjacent room is not a loss to the outdoors).

Dick and Thomas (1951) reported, in their publication on the ventilation of occupied houses in the UK, that their earlier work on heated but unoccupied houses showed an average exchange rate of 2 h^{-1} with the average wind speed of 8.5 mph. They did not report indoor-outdoor temperature differences, but one can presume that in the UK the differences must have been 20-35 °F. They noted that when they blocked ventilators beside the front door and sealed the worst gaps in badly fitting windows, the average exchange rate reduced to 1.5 h^{-1} . The coefficients in their fitted linear equation suggest a minimum exchange rate of 0.87 h^{-1} , which they attributed to the effects of flues and heating.

Handley and Barton (1973) surveyed the literature for exchange rates in American single family residences during normal family activities and with normal ventilation air provided from the outside. From this they suggested using a range of $0.5\text{-}1.5 \text{ h}^{-1}$. (It is believed that all the data they used are also considered in this paper.)

Nazaroff et al. (1983) reported on the exchange rates for seven relatively air-tight occupied homes in Rochester, NY in winter, with heating systems on and occupants affecting ventilation (opening of doors and windows, exhaust fans). The exchange rates, averaged over one or two weeks, were $0.27\text{-}0.47 \text{ h}^{-1}$. They also measured the exchange rate in an eighth house in mid-March, without the same weatherization features, and with the occupants similarly affecting the ventilation. The average over a week, during which winds varied from a few to near 30 mph, was 1.16 h^{-1} .

Traynor et al. (1989) reported the exchange rates for nine occupied California houses in January through March. The houses had a wide variety of heating, cooking, vent fans, age and construction. The exchange rates varied from 0.35 to 1.36 h^{-1} .

Sherman and Wilson (1986) measured the exchange rate for a one-room, single-story research "house" the size of a two-car garage in Alberta. With a simulated forced-air furnace and fan operating to maintain inside temperature, the monthly-averaged exchange rate varied from 0.17 h^{-1} in July to 0.39 h^{-1} in December.

The exchange rates reported above are not applicable to pre-planned sheltering where doors and windows should not be opened, where outside ventilation air should not be provided, and where appliances, kitchen and bathroom exhaust fans, heating and air conditioning should be turned off. They could perhaps be used to estimate the DRF for sheltered persons not properly informed or not following instructions.

Measured Exchange Rates - Buildings, Quasi-Sheltering Conditions

Elkins and Wensman (1971) measured the air exchange rates for two identical houses of "modern tight construction" in Ohio over a 10-month period. The daily rates varied from 0.24-0.83 h⁻¹ for the gas-heated house, and 0.13-0.42 h⁻¹ for the all-electric house. The rates also varied over short periods. Some of the variation was due to the normal activities of the occupying families including door openings, and some due to changes in wind including of wind direction. Elkins and Wensman thought that the effects of temperature difference were small, particularly in the single-storied house with electric heat and its chimney blocked. The exchange measurements made at night (when the family might be sleeping) are given in the Table 6. The temperature differences in the table are the differences between the reported outdoor temperatures and 70°F.

Table 6. Exchange rates in two houses when the family was probably asleep (Elkins and Wensman 1971).

Time	R	W	Temp Difference
	(h ⁻¹)	(mph)	(°F)
Gas Heated House			
0037	0.62	6.9	34
0127	0.54	6.8	40
0232	0.83	12.2	65
0500	0.50	8.2	66
Electric House			
0053	0.31	5.6	36
0100	0.33	10.0	42
0400	0.33	9.0	42
0136	0.41	6.2	46

Jordan et al. (1963) investigated the infiltration in two research houses in Minnesota under "static conditions", that is, with no opening of doors and windows or use of appliances or fans. The houses were heated with baseboard electric heaters. From their data the authors concluded that "it is evident that with houses as well constructed and tightly weatherstripped as these, and under conditions of no occupancy, the actual air changes per hour ranged well under 1/2 and can safely be taken as 1/3 under almost all conditions of wind velocity and temperature difference encountered. However, the actual infiltration increased greatly when clothes dryer, shower or range fan was in operation..."

Much of the published data on exchange rates are for occupied buildings with heating or air conditioning systems operating. Apartment house and office building ventilation systems are intentionally designed to bring in outside air. For calculation of sheltering, it is more appropriate to use exchange rates for buildings with those systems shut down, if such are arranged in advance of an emergency as part of the response plan.

Shair and Heitner (1974) remarked that "it is especially important to note that increasing the recirculation rate of air significantly increased the infiltration rate (in their experiments on two rooms in a Caltech campus building). No other observation of such effect has been found in the literature. Shair and Heitner thought that it resulted from a change in pressure differential between the inside and outside of the building, but one can also envisage a system that does not entirely close off makeup air when the recirculation fans are operating.

The magnitude of the effect of operating forced-air heating and air conditioning (HAC) is of interest because it helps improve estimates of the sheltering ability of residences when the HAC is deliberately turned off. Matthews et al. (1990) investigated the influence of HAC on air exchange rates in 39 occupied houses in eastern Tennessee. The air exchange rate increased on average of $0.33 \pm 0.37 \text{ h}^{-1}$ with HAC operation. The proportionate increase with HAC was greater with the "tighter" houses, more than doubling the exchange for houses with an exchange rate of $< 0.5 \text{ h}^{-1}$, but increasing to 1.4 times as much for "leakier" houses. Application of this increase with HAC to the Traynor et al. (1989) houses in California would decrease the range of exchange rates to $0.17\text{--}1.0 \text{ h}^{-1}$ when HAC was off. This range would still contain the effects of exhaust fans and other activities of normal living.

Traynor et al. (1988) measured air exchange rates on a research house in April in Oregon. Fireplaces were sealed, and combinations of electric and space heaters were used for heating. With windows deliberately opened 1 cm, the exchange was 0.43 h^{-1} , with

windows closed and "house tightening" the exchange was 0.07 h^{-1} , and with additional insulation the exchange was 0.05 h^{-1} . These were average values over approximately week-long periods.

Laschober and Healy (1964) measured the exchange rate for two split-level residences in winter with gas and electric heat. These houses had only 2-inch batt insulation and were modified to some extent for the study. One of these, the "Hydronic Research House" is a contemporary (in 1964) split-level with single pane windows and no storm sash, and gas-boiler heat. There was minimal insulation (only 1-inch batt in the walls and 2-inch blanket in the cathedral ceiling). With doors and windows closed and heating systems operating, the exchange rates varied from 0.20 to as much as 1.79 h^{-1} in the somewhat better-insulated house, and from 0.32 to as much as 2.67 h^{-1} in the less-insulated "Hydronic Research House".

The situations in Table 7 were selected as approximating sheltering conditions. They neither have people opening and closing doors and windows, nor have active systems designed to exhaust air or bring in outside air. They do include houses with chimneys and flues and other "natural" structural channels that may exist. Data where temperature differences exist are included, as these might exist for some time after HAC were shut down. The data in Table 7 and similar data from these references were combined to produce Figures 3 and 4. It was relatively easy to draw smooth isopleths to within a factor of 2 of most of the data in Figure 3. The shape of the isopleths in Figure 3 was then applied to the drawing of isopleths for the few data available for Figure 4.

The data supporting Figure 4 are entirely from Laschober and Healy (1964) for their "Hydronic Research House". One cannot be confident that this house is fully representative of older houses of poor insulation. In contrast, one can have some confidence that Figure 3 represents more recent houses of good insulation under sheltering conditions. Caution should be used in application of these Figures outside North America. Substantial differences may exist in building design, materials, and climates.

There appears to be a minimum exchange of 0.1 h^{-1} for tight houses and 0.3 h^{-1} for leaky houses, and there is a suggestion of changes in the coefficients of linearity above 10 mph and/or 50°F temperature difference. Note that the exchange rate appears to vary as the first or somewhat greater power of temperature, rather than as $1/2$. Figures 3 and 4 apply only to residences with doors and windows kept closed, and intake and exhaust fans off.

Table 7. Measured residential air exchange rates selected for conditions approximating those of sheltering.

Description of house	Temp. Diff. (°F)	Wind (mi h ⁻¹)	R (h ⁻¹)
<u>Bahnfleth et al. (1957):</u>			
Home data extrapolated to zero values of wind and temperature difference	0	0	0.12
<u>Tamura et al. (1964):</u>			
Two occupied houses, furnace off, furnace blower on			
House No. 1	0	0	0.04
summer	2-6	1-8	0.06-0.17
winter-spring	16-36	0-12	0.12 - 0.28
winter	32	7.7	0.24
House No. 2	0	0	0.06
summer	0-3	0.5-8	0.06-0.23
winter-spring	30	5.9	0.50
winter-spring (furnace on/off)	45	10.2	0.63
<u>Jordan, Erickson and Leonard (1963):</u>			
Electrically heated homes			
kitchen and bath fans off	25-38	12-18	0.12-0.20
	27-43	3-10	0.14-0.23
<u>Elkins and Wensman (1971):</u>			
Tightly constructed home			
nighttime, occupied			
Electric heat	36-42	5.6-10.0	0.31-0.41
Gas heat	34-65	6.9-12.2	0.5-0.83
<u>Laschober and Healy (1964),</u>			
"Residence No.4", split-level,			
Electric heat on	38	7.8	0.20
	26	19	1.60
Gas heat on	17	6	0.30
	62	17	1.79
<u>Laschober and Healy (1964),</u>			
"Hydronic House" Boiler heat	1	2.5	0.32
	3.4	4.3	0.51
	57.3	14.4	2.43
	70	14.2	2.67

Fig. 3. Exchange rate for closed homes of modern construction and good insulation, with furnace and fans off. The number of air exchanges per hour are presented as a function of the indoor-outdoor temperature difference and the wind speed.

Fig. 4. Exchange rate for closed homes of older construction and poor insulation with furnace and fans off. The number of air exchanges per hour are presented as a function of the indoor-outdoor temperature difference and the wind speed.

Measured Exchange Rates - Office Buildings

We might assume that apartment houses and office buildings would have comparable or lower exchange rates than houses under the same constraints regarding fans and open doors. The I/O data from Yocum et al. (1971) support this assumption. However, there are only limited data for office buildings with air systems off.

A study of one nine-story office building in Washington DC showed an exchange rate of 0.36 h^{-1} when the makeup vents were closed (Kelnhofer et al. 1976). The wind speed was not given. The elevator shaft vents which could not be closed, and toilet exhausts, and probably other significant openings existed. This building was being retrofitted for energy conservation, and may not be representative. On the other hand, the substantial vents that existed challenge the assumption that office buildings would be more effective shelters than residences. Of course, a direct flow from lower entrances up the elevator shaft might bypass the interior rooms, especially if the office doors were closed for sheltering. Use of $R = 0.36 \text{ h}^{-1}$ and $v_d A/V = 0.66 \text{ h}^{-1}$ yields an fR/R^* of 0.35, which is comparable to the (I/O) reported by Yocum et al. (1971) of office buildings.

Grot and Persily (1986) measured infiltration of eight Federal office buildings, seven of them built after energy guidelines for construction were in effect. (The authors stated that "these buildings tend to perform better than most existing federal office buildings".) The infiltration was measured while the buildings were unoccupied and with outside air intake dampers closed, but with ventilation fans running^a.

The exchange rates for most of the buildings showed a dependence upon both temperature difference and wind speed, but it does not appear that the eight buildings can be regarded as from the same data set. The building averages, with "extreme winds excluded", ranged from 0.20 to 0.70 h^{-1} , and the average of these averages was 0.41 h^{-1} . There are no physical differences reported in the paper that would seem to account for the differences in average exchange rates. The investigators cannot be sure to what extent elevator vents and various exhaust systems might have operated during the unoccupied hours of the measurements despite the building systems being set to recirculate^b.

a. Ventilation fans were required to mix the tracer through the buildings.

b. Persily, A. Private communication to Rudolf Engelmann. National Institute of Standards and Technology, Gaithersburg, MD. 1990.

Persily and Grot (1985) also noted that the exchange rates provide a measure of the tightness of the building shell and of any leakage in the heating, ventilating and air conditioning (HVAC) system, and that ventilation systems are often designed to pressurize a building, which will lead to more air leakage than that induced by weather alone. For these eight buildings, then, one can assume that the exchange rates during sheltering (with all ventilation systems off) would be somewhat less than these measurements.

Measured Exchange Rates - Vehicles

Peterson and Sabersky (1975) measured the air exchange rate of a moving "stock Chevrolet" using CO as a tracer. With the air conditioning set at a maximum, the exchange rate appeared to be linear with speed, from 0.3 min^{-1} at rest to about 0.65 min^{-1} at 60 mph. A single measurement of 0.4 min^{-1} was made with the car stationary and the air conditioner off. However, at the maximum air conditioner setting, and at all times that the engine is running, a small fan drew outside air into the car. The authors did not discuss the seeming discrepancy between the 0.3 and 0.4 min^{-1} values for the stationary car. It is also uncertain whether the effect of the fan is additive to the effects of the car speed at all speeds, i.e., whether the exchange rate at 60 mph would have been 0.35 min^{-1} if the small fan had not been operating.

They also measured the decrease of ozone inside the car with the engine and therefore all air conditioning and ventilation fans off. The rate of decrease (virtual exchange rate) was 1.2 min^{-1} . They attributed this rapid decrease entirely to decay of the ozone on the interior surfaces. It appears that they did not measure the exchange rate for a nonreactive, nondepositing tracer with the engine off.

They noted that values of $v_d = 0.17 \text{ ft min}^{-1}$ (0.086 cm s^{-1}), $A/V = 7.0 \text{ ft}^{-1}$, and $R = 36 \text{ h}^{-1}$ at 50 mph would give the observed I/O ozone ratio of $1/3$. These values correspond to $R^* = 108 \text{ h}^{-1}$, which will bring the inside concentration to near equilibrium in only 3-4 minutes; indeed, an equilibration time of 200 s for ozone in the moving car was observed by Petersen and Sabersky. In contrast to ozone, the concentrations in the moving car of CO, NO and NO_x , supposedly nondepositing, were about equal to the outside concentrations.

This deposition rate (rather, decomposition rate) for ozone is within the range of those measured by Sabersky et al. (1973) on various surfaces within a test chamber. These ranged from $0.001 \text{ ft min}^{-1}$ on plate glass to $0.214 \text{ ft min}^{-1}$ on cotton, neoprene and wool.

One virtual exchange rate of 0.088 min^{-1} for 2 micrometer aerodynamic diameter particles has been measured for a closed, stationary automobile with HAC and fans off^a. As of March, 1990, the time of the writing of this paper, the actual exchange rate had not yet been measured, nor had measurements been made for a moving vehicle. The research was continuing. This lower value of R^* with particles, although for a more recent vintage and different car, supports the idea that the large decrease in ozone observed by Peterson and Sabersky was primarily due to reactions with surfaces.

Although recent automobiles may be more tightly constructed, it may tentatively be concluded that a moving stock automobile with an operating fan offers essentially no protection against inhalation of contaminants, unless those contaminants rapidly deposit on interior surfaces. It may be that a stationary automobile without an operating fan offers substantial protection against all airborne contaminants, but there are little or no data as yet to confirm or contradict this possibility.

APPLICATION TO ACCIDENTS RELEASING PLUTONIUM PARTICLES

Dose Reduction Factors for Plutonium

This paper develops a generic approach to calculating the DRFs from sheltering against inhalation of all contaminants. Experiments using particles of the same characteristics as plutonium particles from hypothesized accidents have not been conducted, so it would seem rather bold to predict DRFs straight-away for sheltering. Nevertheless, in this section values of v_d , f , A/V , and R specific to plutonium are estimated for use in Equations (11) and (12). It seems reasonable that a set of equations and coefficients, that are compatible with diverse data on I/O ratios, exchange rates, depositions, and DRFs for various other contaminants, can be applied with some modest confidence to plutonium in the absence of direct experimentation. This section presents best estimates of the values for plutonium based on present information.

When preparing a safety analysis for an hypothetical accidental release of plutonium, Dewart et al. (1982) reasoned that a 2 micrometer aerodynamic equivalent diameter could be used to conservatively represent the respirable range of plutonium for organ dose calculations. A deposition velocity of $v_d = 0.013 \text{ cm s}^{-1}$ is used for 2 micrometer aerodynamic particles

a. Engelmann, R. J.; Pendergrass, W. Unpublished data. Atmospheric and Turbulence Diffusion Division, National Oceanic and Atmospheric Administration, PO Box 2456, 456 South Illinois Avenue, Oak Ridge, TN 37831. 1990.

based on Sehmel (1984) for low turbulence. Lacking information to the contrary, this value is assumed to apply to all buildings regardless of their interior surfaces and furnishings.

A value of $f = 1$ is assumed for gases and particles less than 2 micrometers, based only on the observations of Cristy and Chester (1981) on spores, and the success in reproducing Megaw's (1962) results with Aitken nuclei.

For residences and apartment buildings, it is assumed that $A/V = 0.53 \text{ ft}^{-1}$, which corresponds to an unfurnished room $8 \times 13 \times 16$. It is assumed, without any measurements whatever, that office buildings are somewhat more austere and have fewer walls and higher ceilings, and that industrial buildings such as factories and warehouses are even more austere and have even fewer walls and higher ceilings. Accordingly, $A/V = 0.4$ is used for office buildings, and 0.2 for industrial buildings. These assumptions lead to:

$$\begin{aligned} v_d A/V &= 0.81 \text{ h}^{-1} \text{ residences and apartment buildings} \\ &= 0.66 \text{ h}^{-1} \text{ for office buildings} \\ &= 0.31 \text{ h}^{-1} \text{ for industrial buildings} \end{aligned}$$

Theoretically, these values should represent the relative effectiveness of deposition within the different types of buildings. The ratio $0.81/0.66 = 1.32$ is not very different from the 1.67 Mueller et al. (1973) ratio of bedroom/office ozone decomposition rates. Mueller et al. estimated A/V as 0.99 ft^{-1} for one furnished bedroom and 0.86 ft^{-1} for one furnished office, the ratio of which is only 1.15. These area estimates were made by assuming that each accessory could be evaluated as a rectangular parallelepiped.

In their calculations, Aldrich and Ericson (1978) used 0.3 h^{-1} for the indoor fractional deposition rate of a 2 micrometer diameter particle, presumed to be the mass median diameter for a core melt reactor plume. We use a range of $0.31\text{--}0.8 \text{ h}^{-1}$, the value depending upon the building, for a 2 micrometer aerodynamic diameter particle, presumed to represent plutonium from an accident.

The exchange rates from Figures 3 and 4 are used for both homes and apartment buildings. An exchange rate of 0.36 h^{-1} is used as the best estimate for office buildings under all conditions except for high wind speeds. The value of R for industrial buildings, such as auto repair shops, factories and warehouses, is truly a matter for guesswork, and may be expected to vary widely. The value probably depends upon the extent to which the building is normally heated and/or airconditioned, since the builder and owner would take corresponding measures to conserve energy. Therefore, values from Figure 4 are used for industrial buildings.

The above values were used to calculate example DRFs for residences, office buildings and industrial buildings for Table 8.

Table 8. Predicted Dose Reduction Factors (DRF) for sheltering in different types of buildings during plutonium accidents. The virtual exchange rate R^* is the sum of the air exchange rate R and the fractional rate of deposition inside the shelter, $v_d A/V$. The DRF approaches fR/R^* as time becomes large.

Temp (°F)	Wind (mi h ⁻¹)	R (h ⁻¹)	R [*] (h ⁻¹)	Time (min)	DRF	fR/R [*]
Residences of Good Construction ($v_d A/V = 0.81 \text{ h}^{-1}$):						
5	1	0.1	0.91	15	0.012	0.110
				30	0.022	
				45	0.030	
				60	0.038	
20	5	0.21	1.02	15	0.024	0.206
				30	0.045	
				45	0.062	
				60	0.077	
50	15	0.71	1.52	15	0.078	0.467
				30	0.134	
				45	0.188	
				60	0.227	
"Leaky" Residences ($v_d A/V = 0.81 \text{ h}^{-1}$):						
5	1	0.35	1.16	15	0.040	0.302
				30	0.073	
				45	0.100	
				60	0.123	
20	5	0.7	1.51	15	0.077	0.464
				30	0.138	
				45	0.186	
				60	0.224	
50	15	2.3	3.11	15	0.225	0.740
				30	0.364	
				45	0.453	
				60	0.512	

Table 8 continued.

Temp (°F)	Wind (mi h ⁻¹)	R	R* (min)	Time	DRF	fR/R*
Office Buildings (v _d A/V = 0.66 h ⁻¹):						
all	all	0.36	1.02	15	0.041	0.353
				30	0.076	
				45	0.106	
				60	0.132	
Industrial Buildings (v _d A/V) = 0.31 h ⁻¹):						
5	1	0.35	0.66	15	0.041	0.530
				30	0.079	
				45	0.112	
				60	0.142	
20	5	0.7	1.01	15	0.081	0.693
				30	0.149	
				45	0.207	
				60	0.257	
50	15	2.3	2.61	15	0.234	0.881
				30	0.389	
				45	0.495	
				60	0.568	

The cloud duration times selected for the table are probably as great or greater than the length of an accidental release of plutonium. In any case, the DRF theoretically will not exceed the values of fR/R^* in the final column. The reader can use deposition velocities appropriate for other particle sizes or contaminants, and other exchange rates when known, to calculate DRFs for other situations.

Sheltering and Evacuation as Protective Actions

Lindell et al. (1985) have provided a discussion of the criteria for choosing between sheltering and evacuation for reactor accidents that release gases and particles. The criteria should also apply to accidents with releases of plutonium particles or toxic chemicals, after the dramatic differences in the form of the radiation and the time available for action are taken into account. The authors provide an extensive bibliography on evacua-

tion and public perception, but little on sheltering. The criteria posed by Lindell et al. include:

- o Evacuation, typically, would eliminate rather than attenuate the level of exposure. However, exposure could occur during evacuation.
- o Expedient respiratory protection (respirators, wet cloths, etc.) would significantly increase the effectiveness of either sheltering or evacuation (but not for noble gases).
- o An individual's response to an emergency is a result of his or her perception of the hazard and available protective actions. This is affected by personal beliefs, and the perception of the official sources' expertise and trustworthiness.
- o There is a potential for serious traffic problems when population densities are high. Elevated levels of evacuation risk could occur during severe weather hazards.
- o Radiation exposures could produce behavioral and psychosomatic consequences in some persons.
- o The economic costs of evacuation would be much higher than those of sheltering for all economic sectors.
- o The relative effectiveness of sheltering and evacuation (for reactor plumes) have demonstrated the relevance of the magnitude of the release, length of delay prior to initiation of protective action, dose reduction offered by structures, and speed of evacuation.
- o To choose between sheltering and evacuation on a case-by-case (building-building) basis, one would need to have data on the dose reduction factor for each (of the buildings).

These criteria provided by Lindell et al. are compatible with knowledge of physics, radiation, meteorology, and research done on air exchange rates and dose reduction offered by buildings.

In addition to the above criteria, when choosing between sheltering and evacuation, consideration must be given to whether the released material poses acute and/or chronic effects, whether the effects are linear with total exposure, whether a threshold may exist, and whether a brief exposure to high concentration may be the most serious threat. If effects are linear with total exposure, the time integral of the concentration is determining.

If a threshold for acute effects exists, or if exposure to high concentrations are the most serious threat, sheltering can be highly effective since it greatly reduces the peak exposure. It may be the most conservative choice since it will eliminate the risk of an exposure during an evacuation.

Koch and Tadmor (1988) compared evacuation vs sheltering strategies for nuclear power plant accidents. They noted that sheltering in regular buildings as well as in designated shelters is

highly effective in reducing early fatalities and other deterministic effects, mainly due to the existence of a dose threshold. They concluded that, for severe nuclear power plant accidents, sheltering was found to be preferable in most cases over evacuation as the main immediate protective measure, unless evacuation can be carried out before the radioactive cloud reaches the populated area.

Koch and Tadmor also compared the effectiveness of sheltering vs evacuation for reducing late fatalities at two sites, and found that sheltering in regular buildings with expedient respiratory protection is preferable to evacuation at the site where there was a great traffic load. At the other site evacuation may be preferred, if it can be completed before arrival of the cloud, thus making it possible to avoid low radiation doses. Their comparisons assumed the building exchange rates of Aldrich, which, according to the data presented above, are too high for sheltering. The use of lower exchange rates would make sheltering all the more attractive for both sites.

Sheltering in buildings or vehicles with a high air exchange rate will not be greatly effective against exposure from a sustained cloud, especially if the shelter is not ventilated after the cloud passage. On the other hand, if the cloud duration about the shelter is short compared to the time needed for an air exchange, and if the building is ventilated after cloud passage, sheltering will be quite effective.

With the more capable computers available today, it seems feasible to enter detailed data on sheltering protective factors, even down to individual buildings, and to program the finer (detailed) aspects of deciding between sheltering and evacuation, an expert system if you will.

CONCLUSIONS

Results

The calculated DRFs for plutonium in Table 8 are very low for tight buildings, and especially for plumes of short time duration. These low values make sheltering a highly competitive choice among protective actions for accidents releasing radionuclides whose primary pathway is inhalation. Sheltering is even more favored when one considers the uncertainties associated with evacuation, such as of the time remaining before the plume arrival, and of the plume location vis-à-vis evacuation direction. It is easy to conceive of situations where it would be less risky to first shelter against the airborne plume, and later evacuate as needed to protect against subsequent resuspension and exposure to deposited radioactive material.

In view of the sensitivity of the DRF to the rate of interior deposition of a contaminant, the DRFs calculated with deposition velocities appropriate to the outdoors should be regarded as best current estimates only. Research is required to clarify and quantify this aspect of sheltering.

Some Concerns with Regard to Deposition

There are some suggestions in the data that challenge the application of outdoor deposition velocities to the interior of a shelter.

It must be noted that the parameter $v_d A/V$ has strong influence on the DRF and the equilibrium I/O ratio. Ignoring for the moment the uncertainty in calculating A/V for a furnished room, a wide range of deposition velocities has been observed in the outdoors over various surfaces and under various atmospheric conditions. It may be argued that one simply doesn't know the deposition inside the shelter unless it is measured specifically for that contaminant, that shelter, and under the air circulation conditions of the sheltering.

For example, I/O ratios of 0.5 for sulphur dioxide can only be attained with a deposition velocity on the order of 0.005 cm s^{-1} , which is much less than the $0.5\text{--}5 \text{ cm s}^{-1}$ typical of sulphur dioxide in the outdoors (Sehmel 1984). Megaw's (1962) data on radioiodine can be fitted with a deposition velocity of 0.005 cm s^{-1} , which is also significantly less than those found outdoors. The I/O ratios of about 0.6 for total mass of suspended particles also require a low deposition velocity, but these data are more difficult to extrapolate because of the wide size distribution in the total mass, and the fact that deposition velocities depend on particle size.

On the other hand, the single measurement of $R^* = 1.9 \text{ h}^{-1}$ for the stationary automobile suggests that the outdoors deposition velocity of 0.013 cm s^{-1} for 2 micrometer diameter particles is appropriate for the interior of an automobile, and that one can use deposition velocities measured in the outdoors in sheltering calculations.

Sehmel (1973) predicted significant differences in deposition to floors, walls and ceilings, with the difference being very dependent upon particle size, and on turbulence and air velocity as represented by u^* . Following Sehmel, for low turbulence, the deposition of 2 micrometer particles on the ceiling is predicted to be orders of magnitude smaller than that on walls and floor. If one has thereby overestimated the ratio A/V , that error would be offset by an associated underestimation of v_d in the fitting of R^* and I/O to empirical data. In effect, the product $v_d A/V$ presently can be regarded as a single empirical parameter for which the data are very inadequate.

The interior deposition velocity may be quite dependent upon the movement of air within the shelter, and on the length of time since the contaminant has entered the shelter. It will be very difficult to measure the deposition inside buildings without providing some mixing to assure representativeness of air concentration measurements. Yet, that small mixing may also affect the deposition velocity. This matter of deposition within shelters is clearly a high priority research area.

Regardless of concerns over uncertainty in the deposition velocity, the I/O ratios must represent the maximum DRF that a shelter would afford. *It must be emphasized that the impulse to use a maximum or "conservative" rather than a "best estimate" value for the DRF works counter to making the optimum choice between protective actions.*

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APPENDIX A

List of Symbols

A	is the area of the interior, including furnishings
b	is $(Q + v_d A)$, or
b	is $(Q + v_d A + f_r Q_r)$ when a filter is operating
C	is concentration. When in association with v_d , airborne concentration at a reference height
C_i	is the inside air concentration
C_1	is the inside concentration at time t_1
C_2	is the inside concentration at time t_2
C_o	is the concentration outside the shelter
f	is the fraction of the tracer that passes through the walls into the shelter
f_r	is the filter efficiency for the tracer and $(1 - f_r)$ is the fraction that passes through the filter
(I/O)	is the ratio of the indoor and outdoor concentrations
$(I/O)_2$	is the I/O ratio for 2 micrometer aerodynamic diameter particles
$(I/O)_{eq}$	is the equilibrium value of I/O
m	is the mixing factor
Q	is the infiltration or volumetric flow rate through the shelter
Q_r	is the recirculation flow rate through the filter
R	is the air change rate
T_e	is the time that the cloud envelops the shelter
T_2	is the time post cloud passage at which the shelter is exited or aired.
V	is the volume of the shelter
v_d	is the deposition velocity