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Variation of Indoor Shelter Effectiveness Caused by Air Leakage Variability of Houses in Canada and the USA

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ABSTRACT

For a group of houses exposed to the same weather conditions during a toxic gas release air exchange rates vary considerably due to differences in construction. The variability in these leakage characteristics is examined using a data base of fan pressurization leakage tests on 214 Canadian and 210 USA houses. The 10th and 90th percentiles of effective leakage area varied by factors of 2 to 5 for both Canadian and USA houses. For idential weather conditions, the average air exchange time constant of Canadian houses would be about three times longer than USA houses. These results indicate that the protection afforded by sheltering indoors will be highly variable within a neighborhood of houses exposed to the toxic release, and with different types of housing. Effective emergency planning must take this variability into account.

In the past, evacuation has been the standard response to protect the public from exposure hazards caused by toxic a gas release. Because evacuation was the only alternative considered, emergency planning consisted of providing methods for warning people, and advising them on the best evacuation route. However, in densely populated areas a call for evacuation has a significant chance of simply stranding people outdoors in a traffic jam where they will be exposed to the full effects of a toxic gas cloud. Even when traffic moves smoothly people tend to travel by familiar routes, and may spend part of their evacuation time driving directly through the toxic cloud. If the emergency is long enough for the news to spread, people away from their homes may increase traffic problems by attempting to return home. All these human factors must be included to make reasonable estimates of evacuation times.

In densely populated areas, the difficulty of managing an effective evacuation makes indoor sheltering a viable alternative. Because more than 90% of the population is indoors at any time, advising shelter is an easy course of action. It leaves people in familiar surroundings, close to supplies of food and water, and with access to radio and television announcements.

If toxic gas is released for only a short time, indoor sheltering is always the best choice. The difficulty is to define what we mean by a "short time duration". A very tight house with doors and windows closed may provide several hours of effective shelter. In contrast, an older leaky house may provide the same degree of shelter for only a few minutes.

In deciding on the merits of shelter versus evacuation we must be aware that there is a strong psychological bias to counselling action as opposed to inaction. If advise evacuation, and people die trapped in traffic, or travel into instead of away from the dangerous cloud, we view this as misfortune. However, if we advise people to shelter indoors, and some deaths occur because their leaky buildings are unable to protect them, there is a sense of personal responsibility for advising people to stay put. We need to be clear on what our social and legal responsibilities are, and how planners will respond to the pressures to be reactionary and advise evacuation as an easier moral alternative than sheltering.

This study will examine the natural variability of air leakage rates into houses exposed to the same weather conditions. The objective will be to provide quantitative information to aid planners in specifying the longest duration of release for which indoor sheltering will be an effective means of protection.

Predicting Toxic Gas Effects

In order to compare toxic gas exposures for people who remain outdoors, evacuate, or shelter indoors, a computational model of the chain of events from the moment of gas release to its final effect on people must be constructed. This is a formidable task which requires us to:

- Predict the release rate variation with time.
- Predict the outdoor average concentration caused by atmospheric dispersion between the source and the building.
- Predict the outdoor concentration fluctuation intensity, the frequency spectrum of these fluctuations, and the probability of observing periods of zero concentration.
- Predict the rate of air leakage into the building, and the efficiency of mixing of toxic gas infiltration with the indoor air volume.
- Predict the indoor average concentration, fluctuation intensity, and frequency spectrum.
- Predict the adverse response of people located outdoors and indoors exposed to these time varying concentrations.

To make matters more difficult it is not enough to determine how a person with average susceptibility sheltered in an average house under average weather conditions will respond to a release of average duration. At the very least we must deal with a "realistic worst case", in which a susceptible person in a leaky house is exposed to a long duration release. The difficulty we face with this approach is that what may be "realistic" to one person may be unrealistic to another. Our ideal should be to estimate the range of each of the variables so that we can assign a probability to a particular "realistic" worst case.

Predictive models should not be more complicated than the natural variability of the processes they are trying to desribe. Engineers and meteorologists waste a great deal of effort on improving the model components that they understand best, such as the rate of release, when other links in the chain of events, such as the biological response, have a high degree of uncertainty and variability. In making predictions for indoor toxic gas exposure we should focus our efforts on strengthening the weakest links in the chain of our predictions, and not in perfecting what we are able to do best. This paper will attempt to strengthen one of those links, the estimation of variability in air infiltration rates.

Measuring Building Leakage

Fan pressurization is the standard method used to measure building air leakage characteristics. A variable speed fan is mounted in an open door or window and used to determine flow rate at several different indoor-outdoor pressure differences. The air leakage sites on the building envelope are forced to infiltrate (with the fan exhausting) and exfiltrate (with the fan blowing in), and an average leakage is determined. This measured leakage characteristic is then used to estimate natural infiltration, where, as shown in Figure 1 some of the leakage sites have in-flow, and others have out-flow.

For a fan pressurization test, we measure the total leakage area A_L of a building. If all the leaks behave like short orifices, the Bernoulli equation tells us that the flow rate Q, m^3/s is

$$Q = A_L \left(\frac{2}{\rho}\right)^{0.5} (\Delta P)^{0.5} \tag{1}$$

where ρ, kg/m^3 is the air density, and ΔP, Pascals (N/m^2) is the indoor-outdoor pressure difference. In reality the leakage sites on a building do not behave like orifices, and the flow rate follows a power law

$$Q = C(\Delta P)^n \tag{2}$$

where C is the leakage coefficient and n is an exponent that varies between $n = 0.5$ for orifice flow and $n = 1.0$ for laminar flow in long narrow cracks. For most houses, $n = 0.65 \pm 0.1$, see Sherman, Wilson and Kiel (1984), and this value will be used for examples in this study. If the exponent n is not equal to 0.5, the apparent leakage area A_L will depend on the pressure at which the fan pressurization test is carried out. This is easy to see if we combine (1) and (2) to write

$$A_L = C\left(\frac{\rho}{2}\right)^{0.5} (\Delta P_{ref})^{n-0.5} \tag{3}$$

To measure the leakage characteristic of a building, a fan is used at several pressures to measure Q and ΔP. These values of Q and ΔP are then used to find C and n by a curve fit, and the effective leakage area A_L is calculated from (3) at a reference pressure of $\Delta P_{ref} = 4$ Pascals, typical of actual wind-induced infiltration pressures, see Sherman and Grimsrud (1980).

Air infiltration is induced by wind pressure, and by "stack effect" pressure caused by the difference between indoor and outdoor air density. These two effects combine in a complex non-linear way to induce the total air leakage rate. Using the Alberta Infiltration Model, AIM-1, developed by Wilson and Walker (1988), it can be shown that the stack effect is negligible (causing less than a 20% error) if the indoor-outdoor temperature difference, ΔT, is small enough to satisfy the equation

$$\Delta T < 4\ U^2 \tag{4}$$

with ΔT in °C and U, the local windspeed at roof height, in m/s. In most cases $U > 2$m/s (4.5 MPH), so $\Delta T < 16$ C (28.8F) allows us to ignore stack effect. For the comparisons here, we will consider only the wind-induced infiltration.

This infiltration depends not only on the leakage area, but also on the fraction of leakage in the walls, ceiling and floor, which will see different wind pressures. In AIM-1, the complex flow paths are accounted for by a wind factor f_w and a local wind shelter coefficient S_w in the infiltration flow rate

$$Q_w = C\ f_w S_w\ (\frac{\rho U^2}{2})^n \tag{5}$$

where Q_w is the wind-induced air infiltration rate. These coefficients are an extension of the original orifice flow model of Sherman and Grimsrud (1980). Values of f_w and S_w are developed in Wilson and Walker (1988) for various types of house construction, leakage distribution and shelter by local obstructions. Typically $f_w = 0.25$ and $S_w = 0.5$.

House Leakage Data Base

A data base of house leakage measurements from several different investigators was collected in 1983 by our research group at the University of Alberta. The locations of the 214 Canadian houses and 210 USA houses are shown in Table 1. The leakage areas of this group of houses was analysed by Kiel, Wilson and Sherman (1985) who explained the high variability in leakage areas through differences in age and type of construction. A group of 91 Canadian houses with special energy efficient tight construction were not included in the present study because they do not represent typical existing housing stock.

The most important factor that influences leakage area is whether a house has an air-vapor barrier in the walls and ceiling. As a rough estimate, houses built in cold climates after 1960 usually have a vapor barrier, while older houses do not. With this in mind, the present study divided the houses in the data base into two groups, pre-1961 and post 1961 year of construction. In a toxic gas release the houses receiving a high exposure are likely to fall within a radius of a few kilometers from the point of release. In this limited neighborhood most houses should have a fairly narrow age range, hopefully in one of these two categories.

The expected range of leakage areas was analyzed by assuming a log-normal probability distribution for the variability of leakage area. This log-normal distribution, shown in Figure 2, has several desirable features. For the case of high variability it predicts only positive leakage areas, unlike a normal (Gaussian) distribution which can give the unrealistic prediction of negative leakage area. When the variability is small relative to the mean, the log-normal distribution is identical to a normal probability distribution, see Atchison and Brown (1957).

Table 1

Data Base of Fan Pressurization Leakage Tests

USA		CANADA	
Location	Number	Location	Number
Oroville, California	56	Ottawa, Ontario	67
Davis, California	32	Saskatoon, Saskatchewan	136
San Francisco, California	16	Edmonton, Alberta	11
Rochester, New York	50		
Eugene, Oregon	24		
Waterbury, Vermont	25		
Atlanta, Georgia	7		
TOTAL	210	TOTAL	214

The leakage area, normalized with the above-grade occupied floor area is shown in Figure 3, with bars indicating the range of values expected to contain 80% of individual leakage areas for a log-normal probability distribution. The numbers listed above and below the bars are the limits defining these 10th and 90th percentile limits. The results have a large variability, and clearly show the differences between houses built to local building codes in the highly variable USA climate, compared to Canadian houses constructed to meet a national building code in a relatively uniform cold climate.
For the limited sample of USA houses, it is difficult to determine whether the high variability is caused by the wide variation in local construction standards, or by large differences in climate, which would tend to encourage leaky houses in temperate regions.

To assess the effects of leakage area variability on the effectiveness of indoor shelter we must estimate the variability in air exchange rate in terms of a mixing time constant for toxic gas infiltration.

Building Leakage Time Constant

Assuming that infiltration, which carries the outdoor toxic gas concentration, mixes completely with the indoor air volume V, m^3, inside the building, the time constant τ_B, seconds, of the building is

$$\tau_B = \frac{V}{Q} = \frac{3600}{ACH} \qquad (6)$$

where ACH is the air exchange rate expressed in air changes per hour. Using (3) in (5) and then in (6)

$$\tau_B = \frac{V}{f_w S_w A_L U^{2n}} \left(\frac{2\Delta P_{ref}}{\rho} \right)^{n-0.5} \qquad (7)$$

The reference pressure ΔP_{ref}, windspeed U and the density ρ are all constants for a group of houses exposed to the same weather conditions. For the moment, we will assume that the wind factor f_w and shelter coefficient S_w are the same for all houses in the exposed area. In addition, it is reasonable to assume that all buildings have rooms with about the same ceiling height, so that the ratio of internal volume V to above grade occupied floor area A_F is a constant. Under these conditions we find that, for a fixed wind speed during exposure,

$$\tau_B \propto \frac{1}{\left[\frac{\text{Leakage Area}}{\text{Floor Area}} \right]} \qquad (8)$$

and, for changing windspeed on a particular building, assuming $n = 0.65$

$$\tau_B \propto \frac{1}{(\text{Windspeed})^{1.3}} \tag{9}$$

In all the comparisons which follow, we assume arbitrarily that the average Canadian house built between 1961-83 has a fixed air exchange rate of 0.6 ACH, which is a time constant $\tau_B = 100$ minutes. Because this average house has a normalized leakage area of $A_L/A_F = 2.21$ cm^2/m^2 of floor area, the leakage time constants for other buildings could be calculated using (8), and are shown in Figure 4. By using fan pressurization leakage areas we make the implicit assumption that the houses would have all doors, windows and fireplace flues closed, and all ventilation fans shut off during the toxic gas sheltering period.

If, for the sake of argument, we were to define a short duration release as one which lasted less than one building leakage time constant, this "short duration" would change more than a factor of five depending upon whether the leakiest 10th percentile building or the tightest 90th percentile building was used as our standard. It is also interesting to note in Figure 4 that the leakiest Canadian houses have time constants three times longer than the leakiest American houses, indicating that indoor sheltering in a Canadian house would be a viable alternative for releases that lasted three times longer than in the USA.

Sensitivity to Location of Building Leaks

Fan pressurization tests determine only the total leakage area of a building envelope, and not where the leakage sites are located. To test the sensitivity of air exchange rate to the location of leakage sites, three different leakage distributions were considered. These leakage distributions are shown in Figure 5, and represent the extremes of all the leaks in the walls, equal distribution between walls and ceiling/floor leaks, and all leaks in the floor and ceiling. For these three cases the Alberta Infiltration Model AIM-1 was used to calculate the wind factors f_w for three different construction types:slab-on-grade, concrete basement, and ventilated crawl space.

Figure 6 shows the variation in relative building leakage time constant for these three leakage distributions. Slab-on-grade and full concrete basement constructions produce the same leakage conditions with floor level leaks concentrated in a crack around the edge of the building. For this reason, only two bars are shown on the graph and "basement" also represents the "slab-on-grade" construction. The results in Figure 6 are reassuring, because they show that radically different leakage area distributions between walls, floor and ceiling change the building time constant by only about 20% for a given total leakage area A_L. Similar results were found by Wilson and Kiel (1985) who also examined the effect of building shape using a simpler orifice flow infiltration model of Sherman and Grimsrud (1980).

The one exception in Figure 6 is a house with a leaky floor over a crawl space. For this situation the air exchange rate is only about half (and the time constant approximately double) the basement or slab-on-grade construction. However, houses with ventilated crawl spaces tend to have much larger total leakage area than the basement or slab-on-grade construction. The results in Figure 6 show that a house with a crawl space can have 90% more leakage area than a house with a full basement, and still maintain the same air exchange rate. In other words, the tendency of houses with crawl spaces to have higher leakage area is offset by a lower potential for wind pressure to cause air exchange.

Variability in Indoor Concentration

Arbitrarily setting the air exchange rate at 0.6 air changes per hour for an average 1961-83 Canadian house produces a reference building time constant of 100 minutes shown in Figure 4. Under the same weather conditions the average 1961-83 USA house will have a leakage time constant of 41 minutes, and a 10% to 90% range of 23 minutes to 103 minutes.

This factor of four variability in building time constant has a significant effect on indoor concentration. Figure 7 shows the indoor concentration time profiles that result from a steady outdoor concentration of 200 ppm with a release duration of 120 minutes. At the end of two hours the leaky USA house will see a concentration of 199 ppm while the tight house will see only 138 ppm. In addition, Figure 8 shows that although people who remain indoors see a smaller peak concentration than those who remain outdoors, people indoors after the plume has passed will continue to be exposed to high concentrations while those outdoors are in clear air. The question that is, "Is it better to shelter indoors and see a lower concentration peak but be exposed for a longer time?"

Effects on People: Toxic Load

To deal with the combined effect of concentration and exposure time a linear time-integrated dose has been used successfully in predicting cumulate effects such as heavy metal and radiation poisoning. However, for most toxic gases the effects of concentration and exposure time are non-linear, so that doubling the concentration for the same exposure time causes more than twice as great an adverse effect. The simplest non-linear dose is the toxic load L

$$L = \int_o^t C^p \, dt \tag{10}$$

where C is the instantaneous concentration, whose ensemble mean and turbulent fluctuation intensity may both be functions of time. The exponent, p, varies between 1.1 and 3.5 for most industrial gases, see ten Berge (1986).

Incorporating these non-linear effects is essential when estimating the benefit of indoor shelter. To see this, consider a toxic gas with a linear dose-response relationship, $p = 1.0$. For this linear response it can be shown that concentration fluctuations have no effect on the dose. Even more remarkable, we can show that the indoor dose and outdoor dose for the profiles in Figures 7a,b,c are exactly the same, (400 ppm-hours) regardless of how leaky the building is! However, linear dose does not give a correct picture of the complex biological response to a toxic gas exposure.

In contrast, when the toxic load exponent p in (10) is greater than 1.0, concentration fluctuations have a strong effect, and sheltering indoors produces a significantly lower toxic load L. However, making predictions becomes much more difficult because we must estimate the mean concentration, its fluctuation intensity, and the frequency spectrum of these fluctuations. At present, there are no operational atmospheric dispersion models capable of this difficult task, and estimates for these effects must await their development.

Conclusions and Recommendations

The present study of variability of building air leakage rates has addressed the natural variability of only one of the six components that must be predicted in order to estimate the adverse effects of short term exposures to toxic gas releases. From the limited data base of fan pressurization tests in houses in the USA and Canada, the following general conclusions can be drawn:

- The natural variability of construction causes modern houses in both Canada and the USA to vary in leakiness by about a factor of two above and below the mean value.
- Indoor shelter is a more attractive option in Canada than in the USA. For both old and new houses the leaky 90th percentile Canadian houses have an air exchange rate three times smaller (i.e. a time constant three times longer) than 90th percentile USA houses exposed to the same weather conditions.
- Indoor shelter protection increases considerably at low wind speeds. For example, if the average USA house has a leakage time constant of 41 minutes at some reference wind speed, (9) predicts that the time constant will increase to 100 minutes if the wind speed decreases by a factor of two.
- The relative distribution of leakage sites between walls, floor and ceiling is not an important factor in determining building time constant.

Dispersion models which attempt to predict indoor concentrations should include the strong wind speed dependence of building leakage time constant, and should also attempt to account for the large variation in air exchange rate between houses in the same neighborhood exposed to the same weather conditions.

The next important task is to quantify the highly non-linear nature of biological response for varying levels of physical activity. At present, this subject does not have the strong foundation of a broad data base of experiments in animal toxicology.

Acknowledgements

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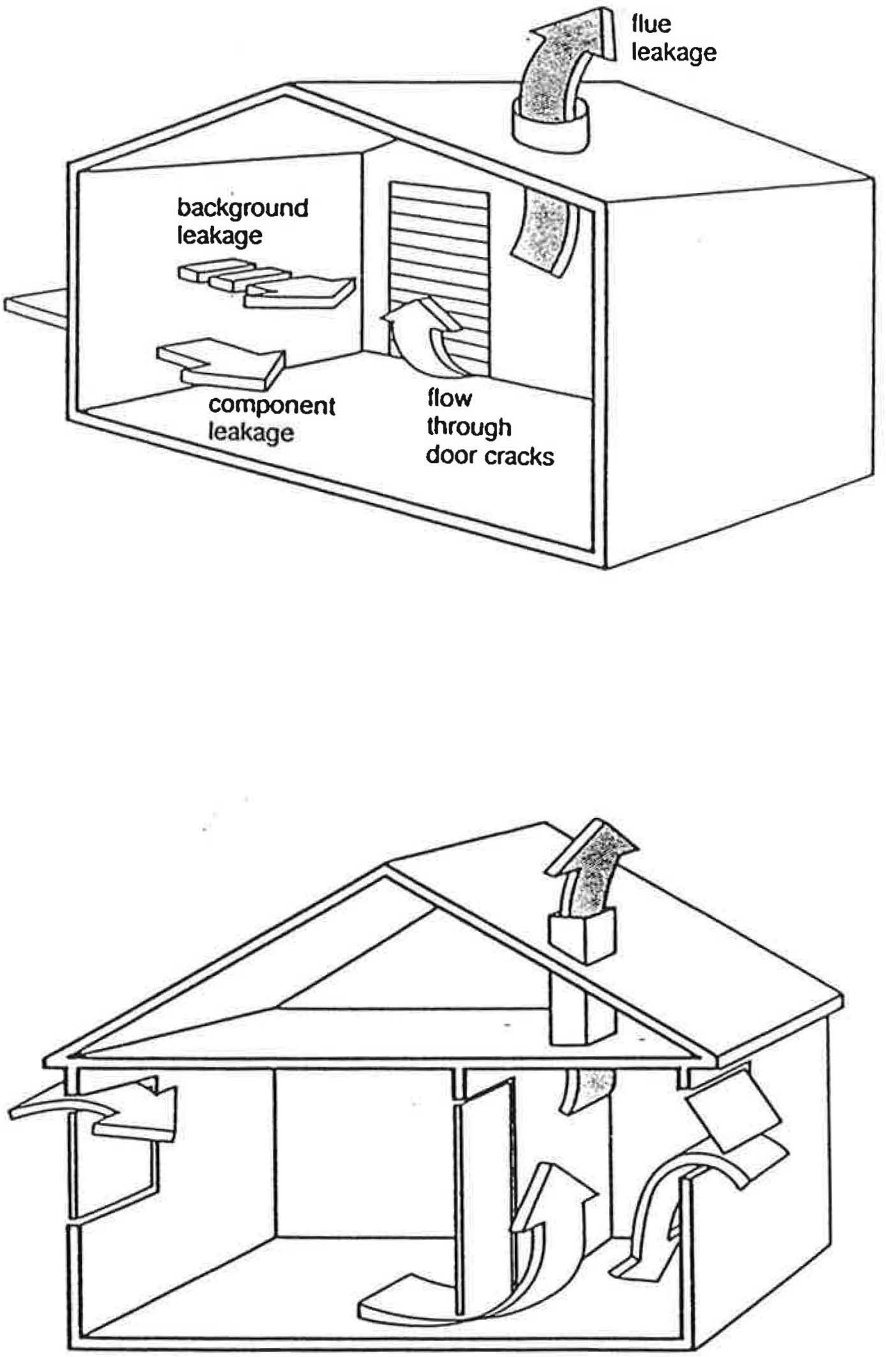

Figure 1 Air Infiltration in a Two Zone Building (from A.I.V.C. (1986)).

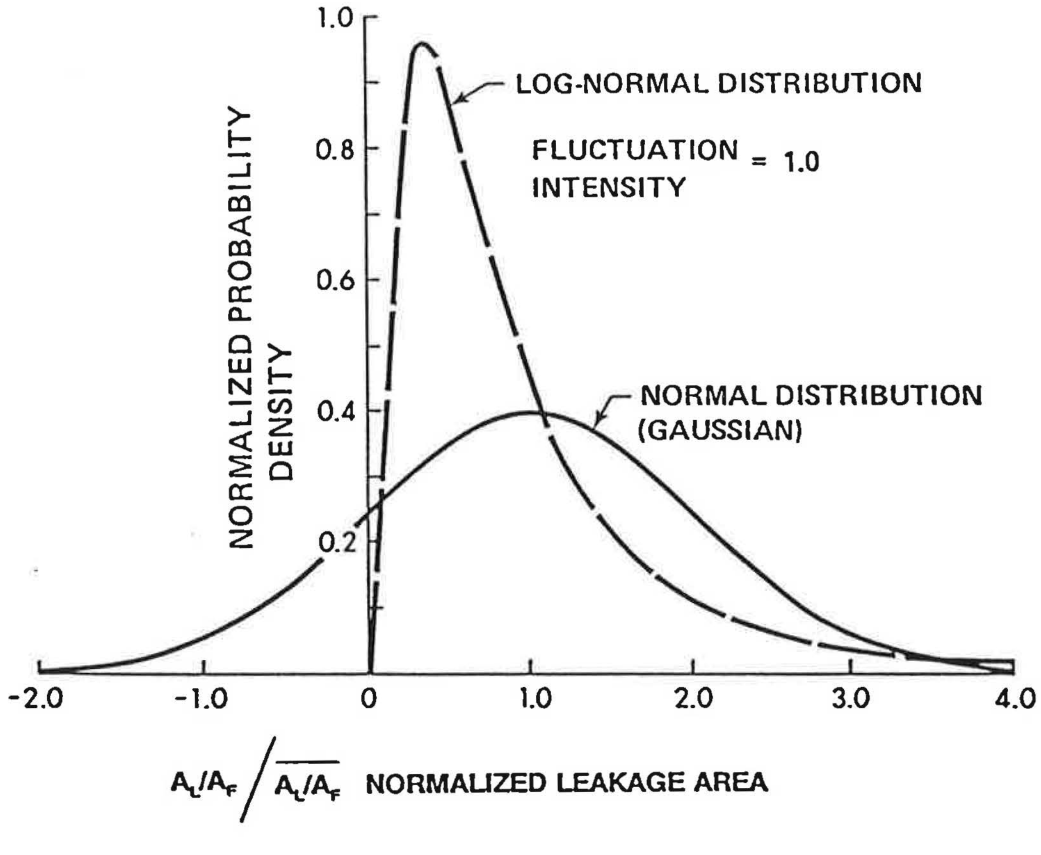

Figure 2 Comparison of Lognormal and Normal Probability Distributions

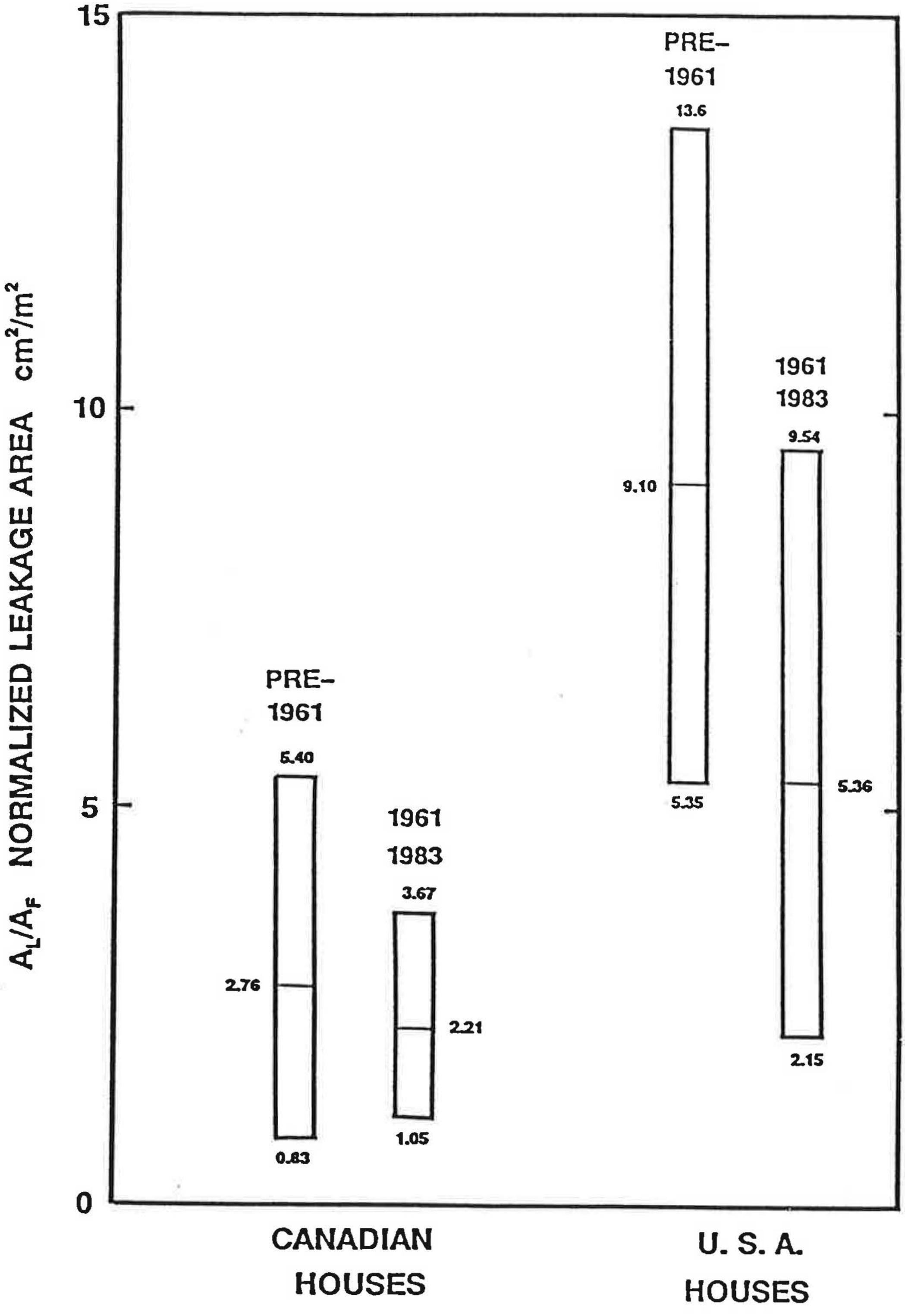

Figure 3 Leakage Area at ΔP_{ref} = 4 Pascals Measured by Fan Pressurization in 305 Canadian and 210 U.S.A. Houses (bars show 10% to 90% range about mean).

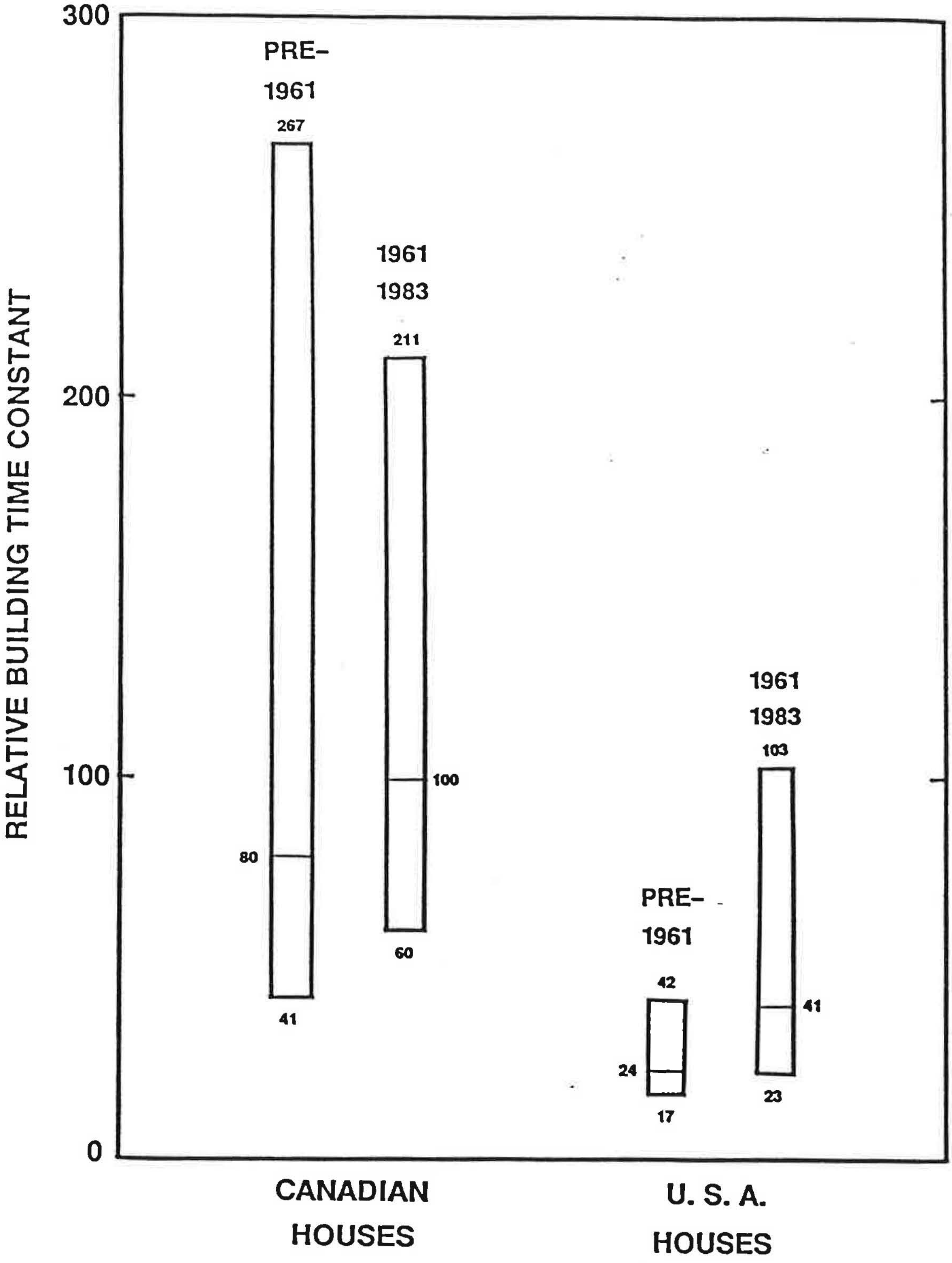

Figure 4 Relative Building Infiltration Time Constants (assuming 1961-83 average Canadian house at 100 minutes, bars show 10% to 90% range).

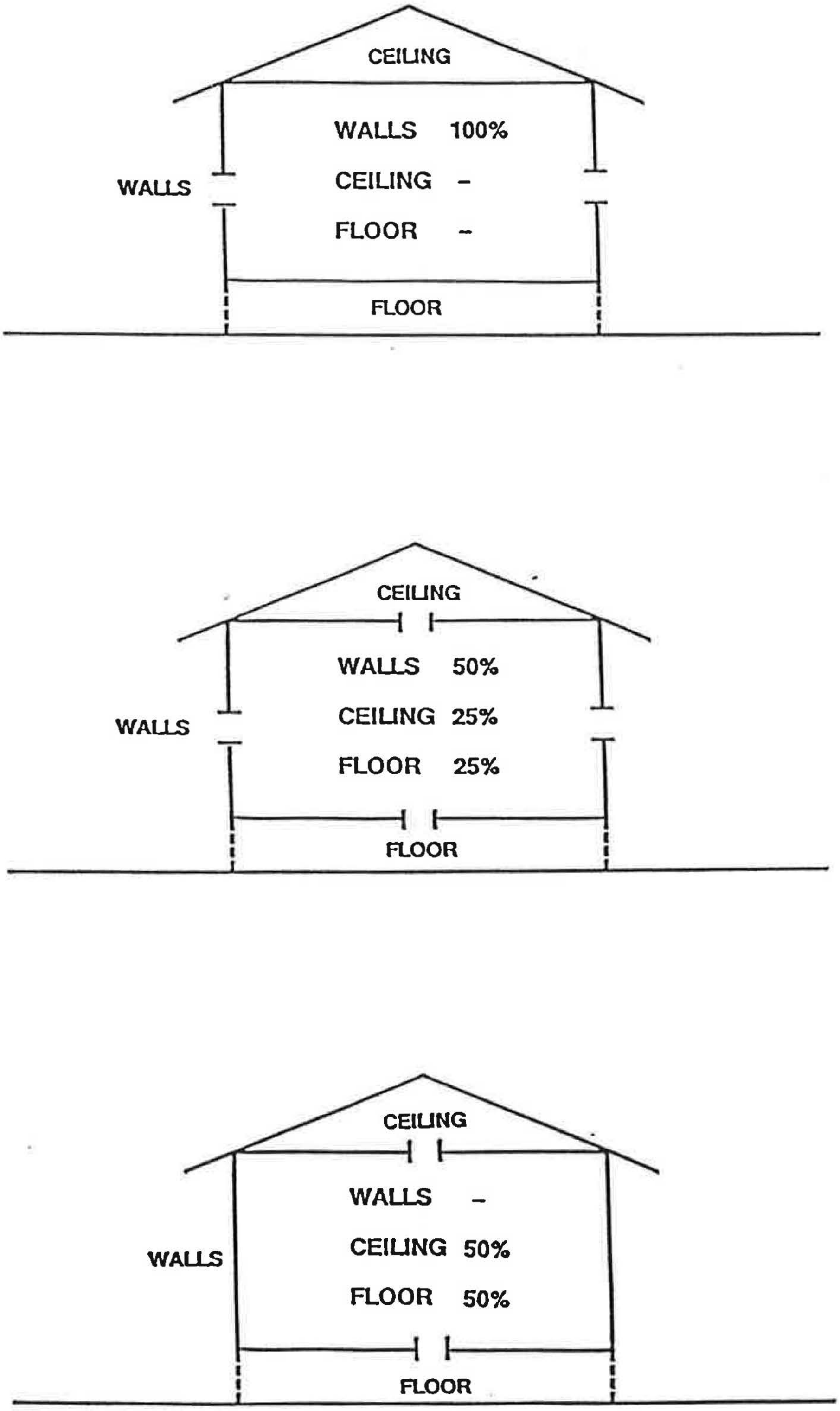

Figure 5 Building Leakage Area Distributions for Sensitivity Tests.

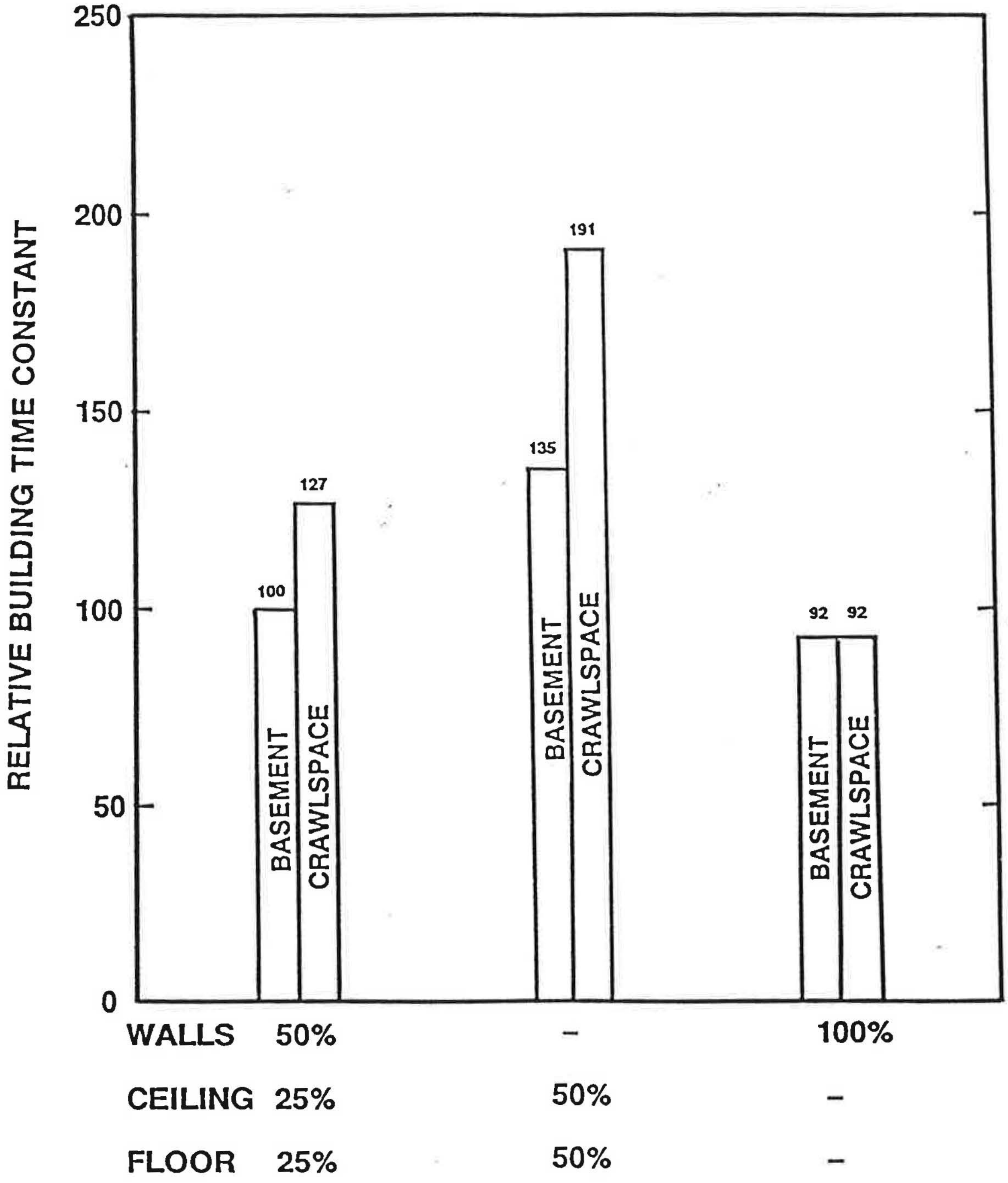

Figure 6 Sensitivity of Wind-Induced Building Infiltration Time Constant to Leakage Area Distribution (reference house with basement, 50% in Walls, 25% in Ceiling, 25% in Floors fixed at 100 minutes, n = 0.65).

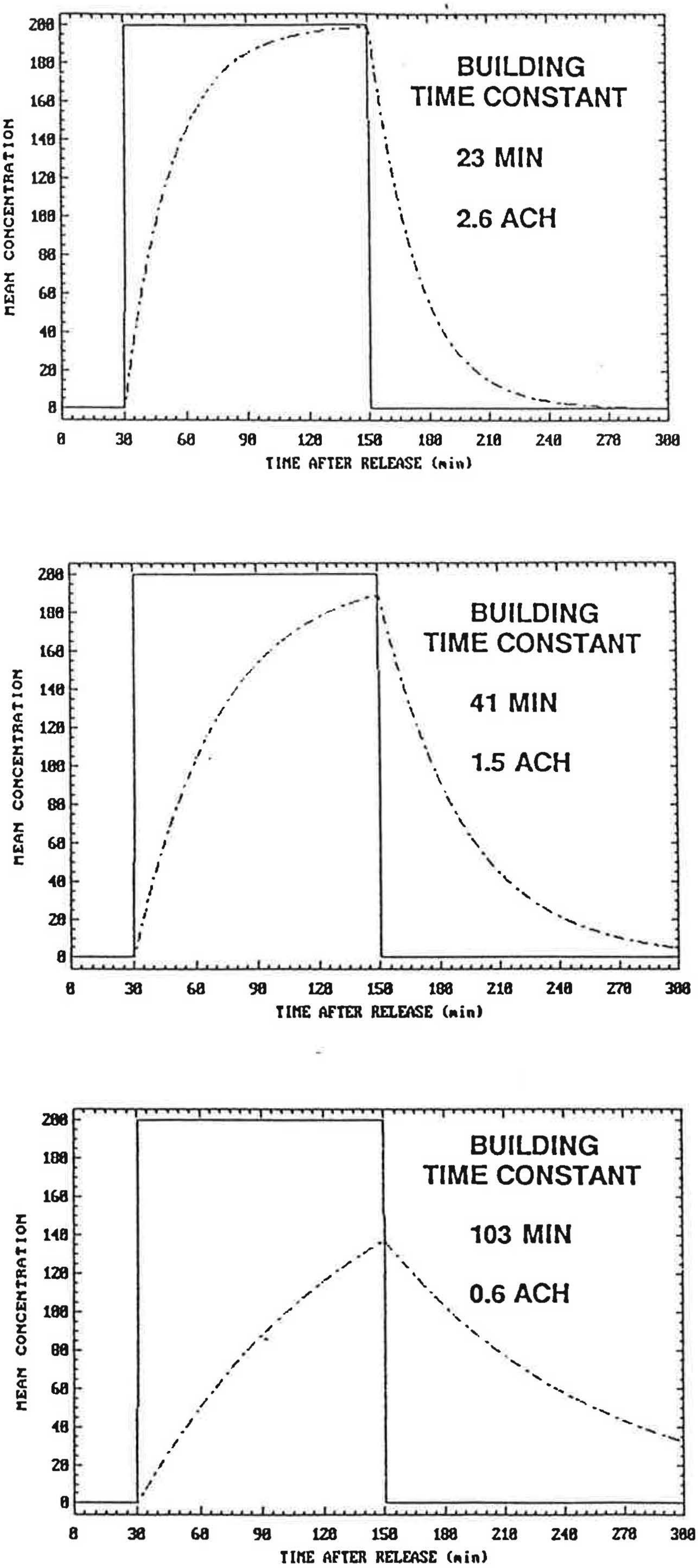

Figure 7 Outdoor and Indoor Mean Concentrations for 10%, Mean, 90% Leakage Area range of U.S.A. Houses.