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Stay Indoors or Evacuate To Avoid Exposure to Toxic Gas?

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Summary

Evacuation of people from their homes and workplaces is a standard response to the hazards created by the release of toxic gas. However, by staying indoors a person can take advantage of the clean air stored within the house volume, as well as the damping the house provides for sudden changes in outdoor toxic gas concentration. The relation between indoor and outdoor concentration is explored in this study, where it is shown that in most cases the risk of exposure to high concentration levels is substantially reduced by remaining indoors during the entire period of toxic gas release. Ratios of indoor to outdoor concentration are presented for typical rates of air infiltration and outdoor concentration variation.

Deciding to Evacuate

Ordering an evacuation is one of the most important decisions to be made during an emergency in which workers and the public are threatened by high concentrations of toxic gas from an accidental release. While there are certainly good reasons for excluding people from the danger area by diverting vehicle and pedestrian traffic, it is much less clear whether it is a good idea to demand (or even suggest) that people leave the shelter of their workplace or home to flee on foot or by car.

Why ask people to leave their homes? Not only is a house a superb life support system, with food, warmth, telephone, TV and radio, but above all it contains a stored volume of fresh clean air which will often sustain the occupants through a short term toxic gas release episode. Reducing risk by staying indoors is not a new idea. A thorough review of the technical aspects of the advantages of such havens has been published recently by Prugh (1985).

So when, if ever, should we be tempted to leave the shelter of our homes or workplaces to avoid exposure to toxic gas? To answer this question we must know the type of release, it's duration, and the amount of advance warning we have of the emergency. For example, in the case of an explosive or flammable gas that may leak through the sewer system and invade a building, it is usually safer to leave than to stay. Also, when we are far enough from the release, and there is several hours advance warning, it may be practical for people to leave before any danger of exposure during evacuation. Here, the decision of whether to evacuate or stay should be based on common sense and experience, without the need for any study of the technical details of the release.

Unfortunately, in many cases such as a pipeline rupture or well blowout, there will be little or no advance warning of the arrival of the toxic gas cloud. This is the situation we will deal with here, where the toxic gas is hydrogen sulfide mixed with other natural gas vapors.

One important characteristic of hydrogen sulfide is that while it is toxic for short term exposures, there appears to be little cummulative long-term integrated dose effects. For this reason we need only concern ourselves with the short term concentration peaks to which an individual is exposed, without considering the integrated dose. Focusing on the peak concentration considerably simplifies our task in determining the effectiveness of a building in providing shelter during a sour gas release episode.

Infiltration of Outside Air into Buildings

To resist our infamous winters, most Canadian buildings are tightly constructed and exchange indoor and outdoor air relatively slowly. Figure 1 shows a schematic illustration of the infiltration of contaminated air and the opposite (and equal) exfiltration of indoor air from a house.

If, in reality, the contaminated gas entered through a door or a window in a concentrated puff like that shown in the figure, there would be little advantage to remaining indoors to avoid exposure. However, in a typical Canadian building exfiltration occurs up the furnace flue, from ventilation fans, and through holes near the ceiling level, and infiltration occurs over a large number of small leakage sites, such as the cracks around windows and doors, and the gap between the building walls and the basement foundation. These widely distributed infiltration leakage points combined with internal air circulation in the open spaces of the building allow contaminated outside air to mix completely with indoor air to reduce the H_2S concentration.

The amount of air exchange, expressed in internal volume air exchanges per hour, depends upon the combined leakage area of the infiltration sites, and the driving pressures generated by indoor-outdoor temperature difference and by wind speed. Because wind speed and temperature difference have a natural variability due to the weather conditions, the air exchange rate will vary with time as shown in Figure 2. These variations can be predicted by simple infiltration flow equations, using known values of indoor-outdoor temperature difference and local wind speed.

For houses in Alberta the air exchange rate varies from about 0.2 to 1.0 air changes per hour depending on the season of the year and the tightness of house construction. For the purposes of this study we will define a "typical" Alberta house as having an infiltration rate of 0.5 air changes per hour. It should be kept in mind that because the outdoor air infiltrating into the house is completely and immediately mixed with indoor air, an infiltration rate of 0.5 air changes per hour does <u>not</u> imply that <u>all</u> the clean air in the house will be displaced by contaminated air in 2.0 hours.

For the well-mixed interior volume of the house it is more useful to think in terms of an exchange rate "time constant" or "turnover time", which is defined as the reciprocal of the infiltration air change rate. The building time constant τ_B (in hours) is simply

$$\tau_B = \frac{1}{\text{(air changes per hour)}}$$

For a well-mixed indoor volume it is easy to show that 63% of the original indoor air will have been replaced by contaminated outdoor air in 1.0 τ_B hours. After 3.0 τ_B hours 95% of the indoor air will have been replaced. For our typical Alberta house with 0.5 air changes per hour, the time constant is τ_B = 2.0 hours, at which point 63% of the indoor air has been replaced by outdoor air.

Outdoor Concentration Variation and Fluctuations

In order to predict the damping and time lag effects caused by the infiltration turnover time constant it is essential to understand the variations in outdoor concentration that will occur. Figure 3 shows the time varying concentration that will be observed outside a building from a pipeline rupture. The rupture produces an initially high flow rate that gradually decreases as the gas within the closed pipe volume depletes. If we were to repeatedly fill and rupture the pipe in an identical way with the same weather conditions, the highly variable individual concentration-time traces would produce a group (or "ensemble") average concentration, as shown in Figure 3. There are two distinctly different types of time variation in this figure. The first is caused by changes in the rate at which H_2S is being released from the rupture, and the second by the random variability in the process of dilution by atmospheric mixing and dispersion.

Virtually all mathematical models which predict downwind concentrations from atmospheric dispersion are limited to predicting only this ensemble average concentration. Few people who use the information from such model predictions realize that they are seeing the average value shown by the dashed line in Figure 3. Even if the model prediction is perfect, the real concentration variation caused by an individual release has a 50% probability of falling above the average, and an equal probability of falling below. This natural variability is caused by atmospheric turbulence and other random variables, and is the cause of a great deal of suspicion, frustration, and lack of confidence in the results of mathematical modelling.

It is clear from the concentration profile in Figure 3 that the mean value predicted by a mathematical model is hardly adequate to assess the risk of being exposed to high peak concentrations in a single rupture episode. The statistical method needed to predict peak values is the subject of current research, and some results are summarized by Wilson and Simms (1985).

Indoor Damping of Outdoor Mean Concentration

For the moment, let's ignore the natural fluctuations in concentration caused by atmospheric turbulence. With these high frequency fluctuations removed, Figure 4 shows the variation of indoor concentration for two time variations of outdoor ensemble mean concentration. The building infiltration time constant τ_B produces the same time response lag that would be evident in an electrical capacitor or hydraulic surge tank.

For a pipeline rupture the outdoor average concentration can often be approximated as exponential decay. Figure 5 shows the indoor concentration for this outdoor variation. Even for a ventilation rate of 10 air changes/hour (which is 20 times higher than our typical Alberta house) the indoor concentration is never higher than 10% of the maximum outdoor value. For this exponentially decaying outdoor concentration the maximum indoor concentration depends only on the ratio of the air infiltration turnover time τ_B to the outdoor concentration decay time constant τ.

Let's define the "total duration" of a pipe rupture episode as 3τ, at which point about 95% of the gas has been released from the pipe. Then, the table below shows the maximum indoor concentration, neglecting turbulent fluctuations, as a fraction of c_0 the initial maximum outdoor concentration, (see Figure 4).

Episode Duration (3τ)	Max Indoor Concentration as % of Initial Outdoor C_0 for 0.5 air changes per hour
0.12 hrs (7.2 min)	2%
1.2 hrs	13%
12.0 hrs	50%

It is clear from these estimates that for a house with only 0.5 air changes per hour, even a relatively long release episode with a duration of 12 hours still provides a significant reduction in the average concentration to which an individual is exposed indoors.

There is however, a price to pay for this protection. It is easy to see from Figure 5 that although the indoor maximum concentration is much smaller, the building acts as a storage reservoir for contaminated air long after the outside concentration has decreased to zero. In the case of hydrogen sulfide, where we are only interested in the peak concentration, this longer persistence indoors is not an important factor. For other toxic gases where the integrated dose may be important, staying indoors may be a disadvantage.

Concentration Peaks from Turbulent Fluctuation

The advantages of staying indoors are even more apparent when we look at the rapid concentration fluctuations and peak values caused by random variations of turbulent mixing in the atmosphere. These rapid changes are shown in the instantaneous concentration profile of the single release in Figure 3. Figure 6 shows schematically the expected variation of indoor and outdoor concentration fluctuations for an outdoor exposure with a constant mean value such as well blowout, and the same variation for an ensemble mean whose average decreases with time, such as a depleting pipe rupture. The infiltration turnover time constant causes the building to damp out most of the outdoor fluctuations, and prevents indoor concentrations from reaching the peak values seen outdoors.

Outdoor concentration variations contain a wide range of fluctuation frequencies. For our typical Alberta house with 0.5 air changes per hour Wilson and Simms (1985) showed that the random variation in these concentration fluctuations would be reduced by about a factor of five between indoors and outdoors. The implications of this fluctuation damping are apparent in Figure 6, where we see that even when the outdoor average remains constant (and the indoor average approaches it after three turnover time constants), the peak indoor H_2S level will be much less than those experienced outdoors.

The key question is how large are concentration fluctuations in atmospheric dispersion? For a wide range of wind speeds, atmospheric stability and release conditions, both wind tunnel and full scale field measurements indicate that the fluctuation intensity, excluding the periods of zero concentration when the plume is meandering, have a standard deviation that is about equal to the mean value. This is a very high degree of variability in outdoor concentration, and a rough rule-of-thumb is that peak concentrations 300% larger than the mean will be observed about 1% of the time. For example, when the outdoor mean concentration of H_2S is 100 ppm for a one hour period, concentrations of 400 ppm and higher will be observed for about half a minute during that hour.

Because the standard deviation of the indoor concentration is reduced by a factor of 5, the value which will be exceeded indoors 1% of the time is only about 50% larger than the mean indoor air concentration. For example, if the outdoor concentration maintains an average of 100 ppm of H_2S, after 6 hours the indoor mean concentration mean will also be 100 ppm, and its fluctuation due to outdoor variability will cause peaks higher than 150 ppm about 1% of the time. This is considerably less than the 400 ppm peaks that are observed outdoors.

From all these estimates, it is apparent that there is a considerable advantage to remaining indoors to avoid exposure to high peak levels of concentration fluctuations caused by the random variability inherent in atmospheric diffusion.

Emergency Response Planning

The conclusions from this study are clear and unambiguous: It is almost always better to stay indoors than to evacuate. While this conclusion is clear from a technical point of view, it raises some difficult issues that must be addressed: how do we convince people to remain indoors and not run outside at the first whiff of sour gas?

Because the greatest risk to workers and to the public will usually occur in the first hour after an accidental release, there will be little time to respond, and even less to inform the public of impending danger. What must be done is to educate the public to stay indoors during the first critical hour after an accidental release begins.

However, there are political and psychological problems associated with informing people in advance of what to do in the remote possibility of a sour gas exposure. People who are informed of such risks tend to become alarmed and resentful of possibility of exposure. This is particularly true for members of the public whose exposure is involuntary, and whose perception of the degree of risk depends more upon the mortality rate from an individual event than the actual risk of dying. (This is the reason why we fear airline crashes and diseases such as AIDS, while completely ignoring the much greater risks of choking on a bite of steak or falling down stairs and breaking our necks.)

The risk of being killed by a toxic gas release from a pipeline rupture is very small. Figure 6 shows the predictions of a risk model developed by Choukalos (1980) based on the pipe rupture dispersion theories of (Wilson 1979). What is remarkable is that standing outdoors immediately beside a pipeline produces a risk of exposure of about 4 chances in a million of being exposed to a fatal concentration in any one year. This risk is 10 times less than being killed while fishing or skiing, or dying in a home fire.

Even more remarkable is the risk incurred by a person who is indoors when the rupture occurs. For a person indoors, in a house located only 100 meters from the rupture, the annual risk of a fatal exposure is about 1 part in 10 million, equivalent to the chance of being struck by lightning, or being killed by an animal bite or insect sting.

Why are we tempted to order evacuation and so increase a person's risk of fatal exposure by a factor of 10 or even 100? I believe the primary reason for this is that we are reactionary, and believe that it is better to do something than to do nothing. It is time to educate both ourselves and the public the best way to cope with this type of risk may be a passive one. We no longer try to drag injured people from automobile wrecks before the ambulance arrives: it is time to stop dragging people from their homes during a short term toxic gas release episode.

All of which leads us to the final question: how do we get them to stay indoors and miss all the excitement?

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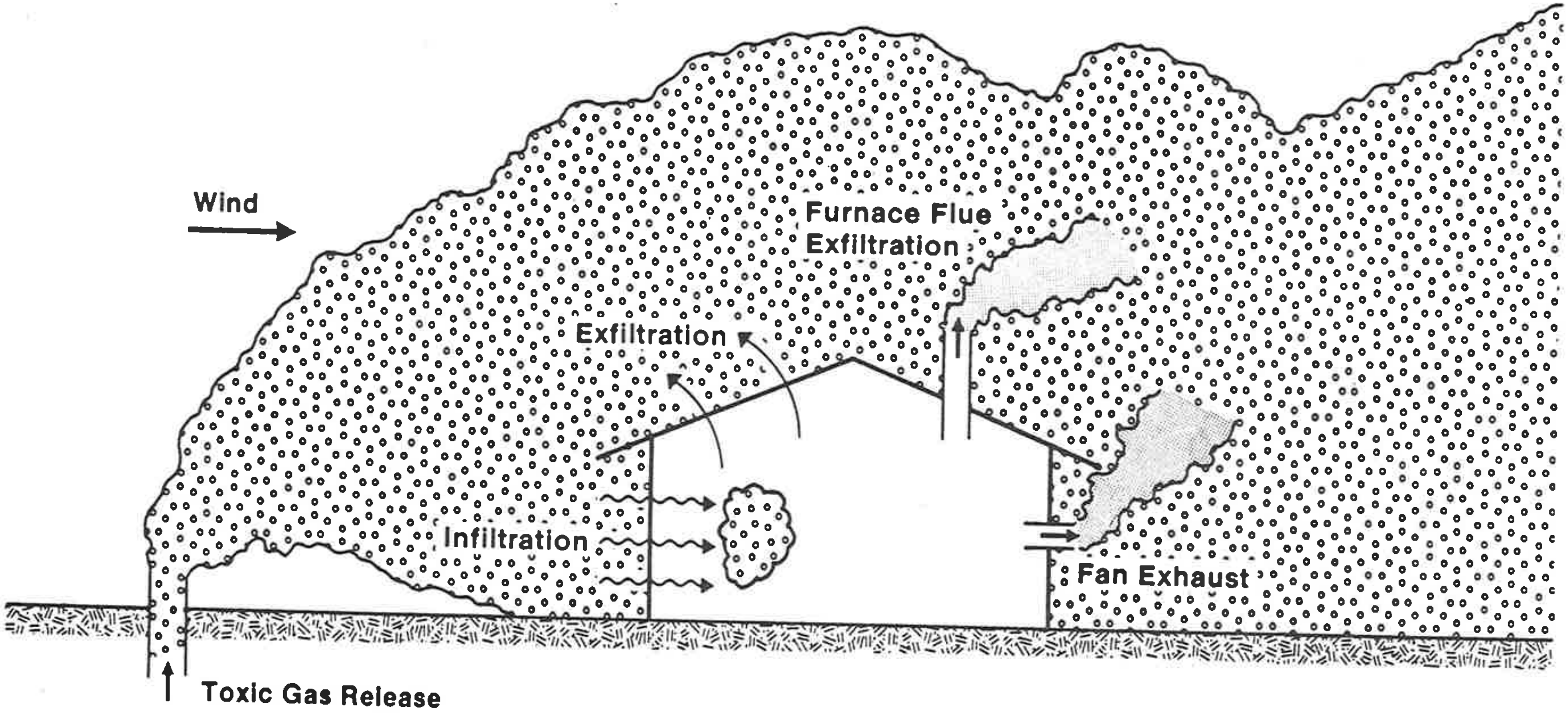

Figure 1 Infiltration of contaminated outside air into a building

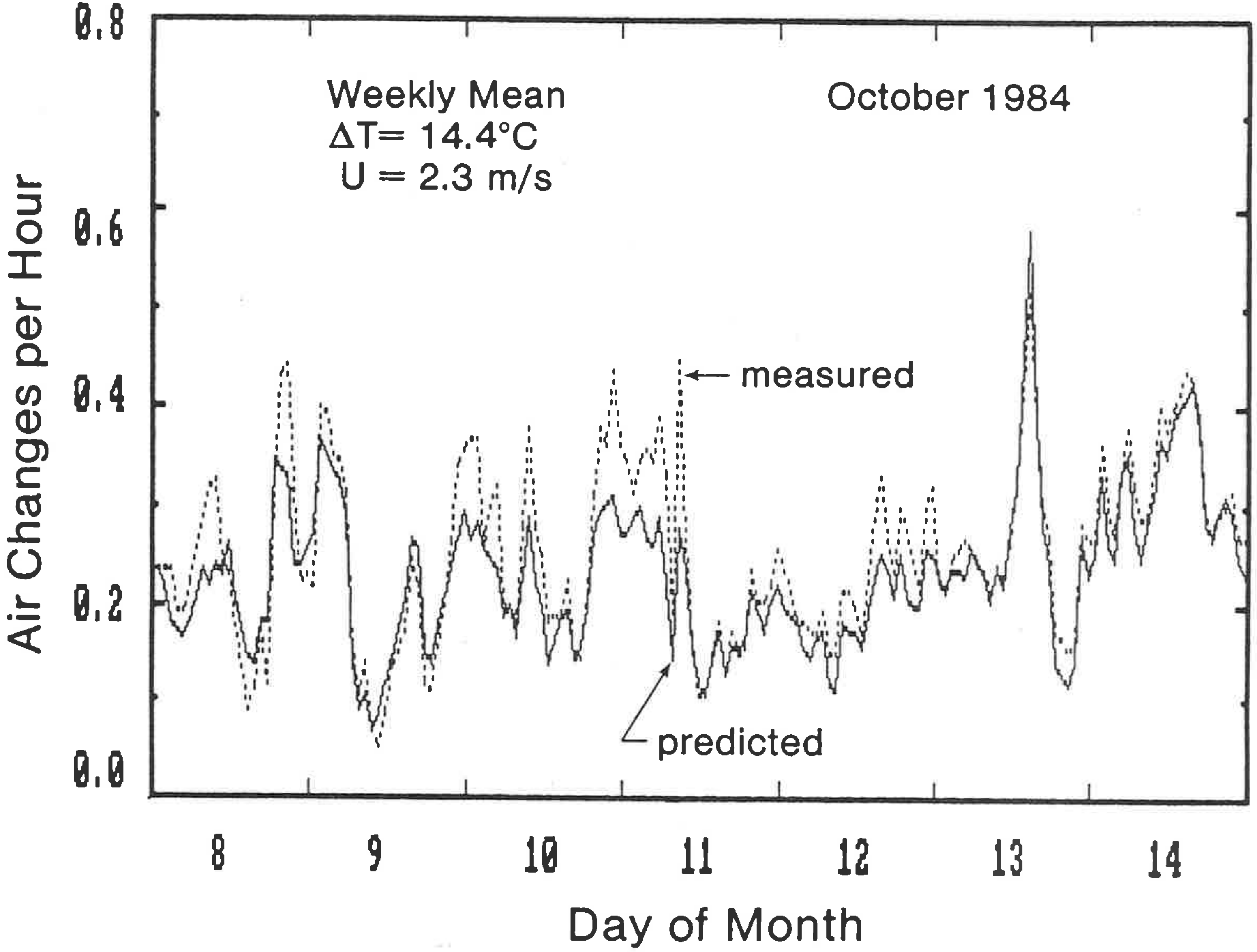

Figure 2 Measured and predicted outside air infiltration rates in a test house in Edmonton. From Yuill et al. and Wilson (1985)

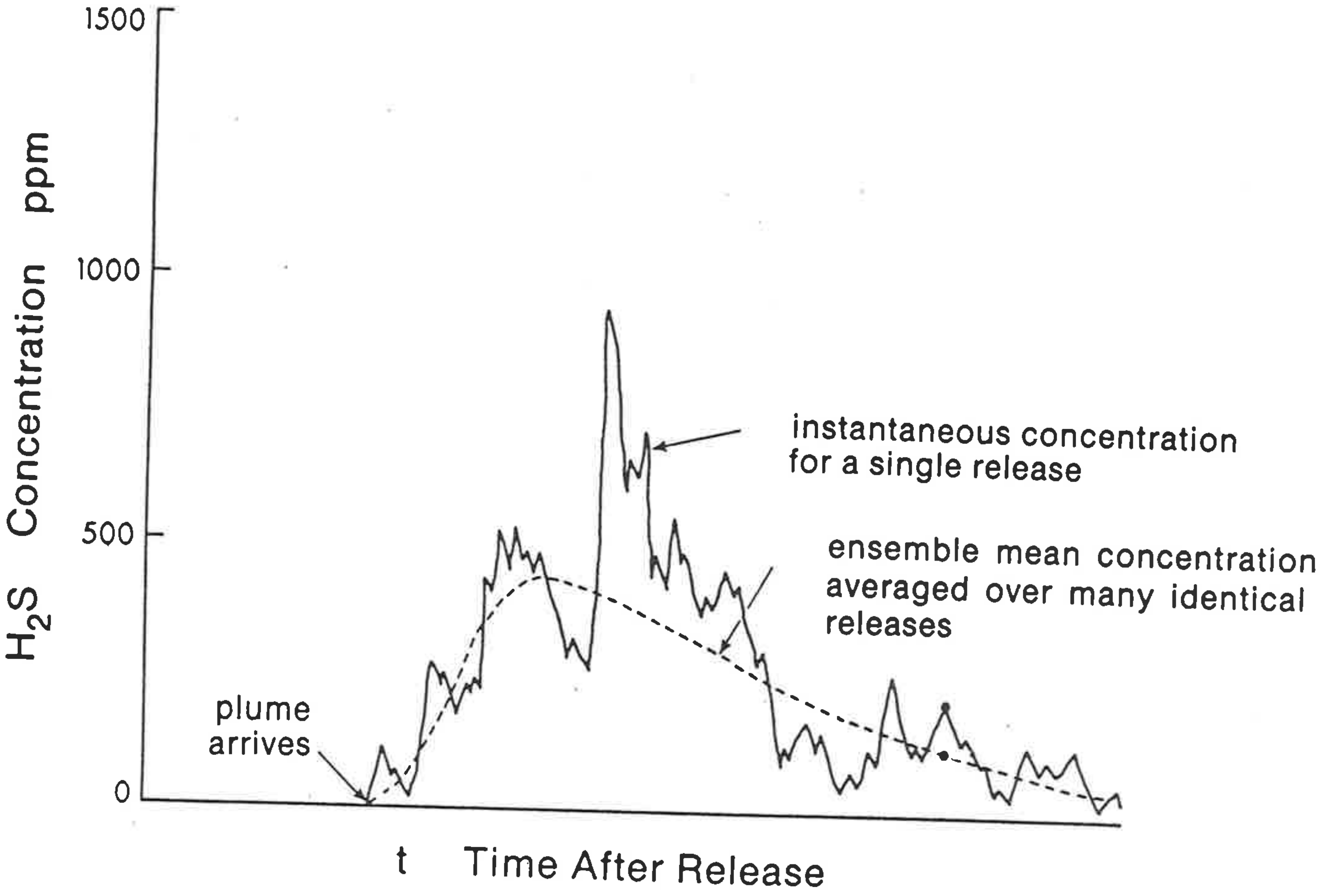

Figure 3 Single individual concentration-time profiles and variation from the idealized ensemble average.

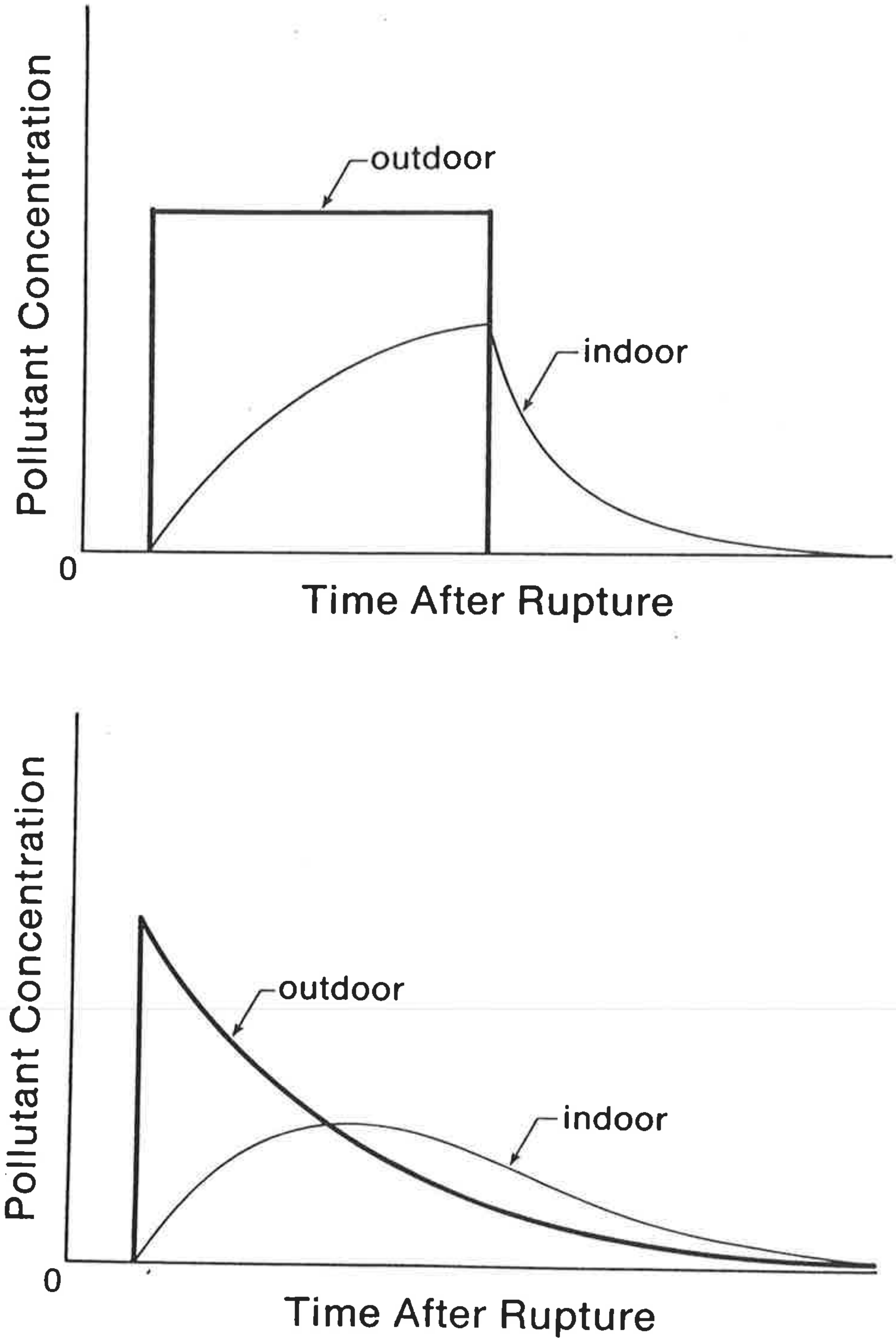

Figure 4 Indoor-outdoor concentrations for two types of non-turbulent time varying outdoor concentration.

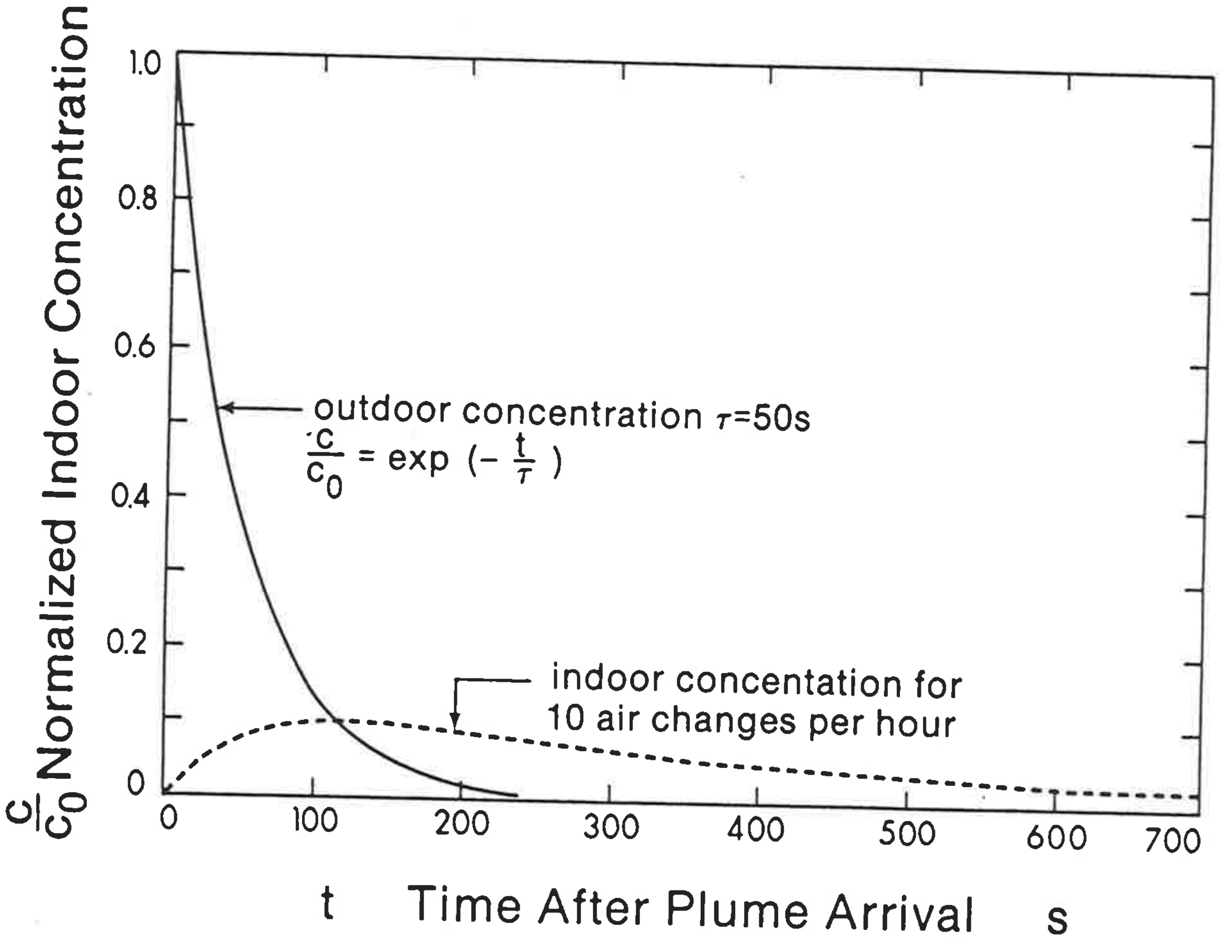

Figure 5 Protection afforded by staying indoors during a short decaying exposure in a well ventilated building. From Wilson (1979)

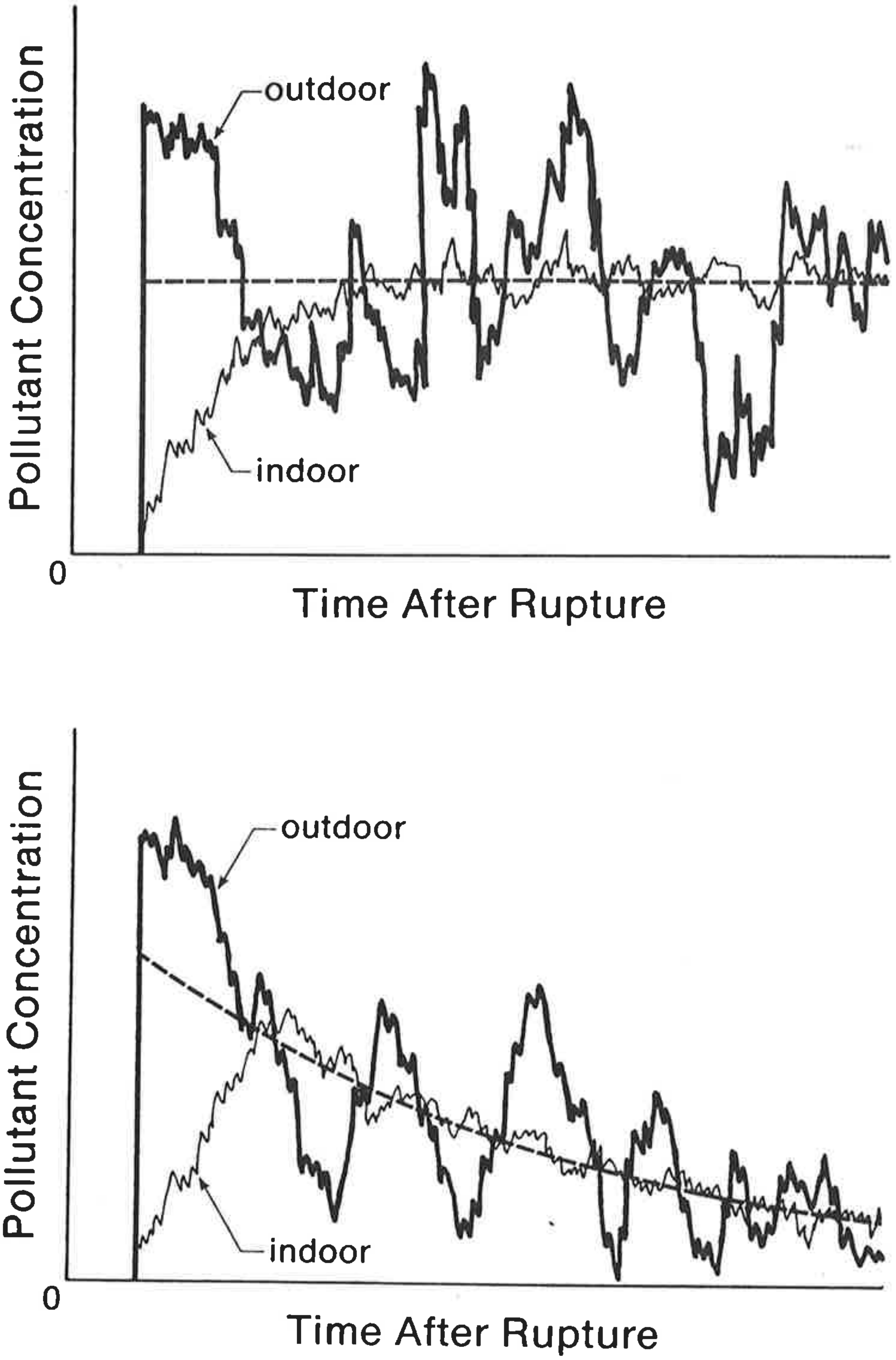

Figure 6 Building infiltration turnover time reduces peak indoor concentration from turbulent fluctuations in outdoor concentration for steady (well blowout) and decreasing (pipeline rupture) release rate.

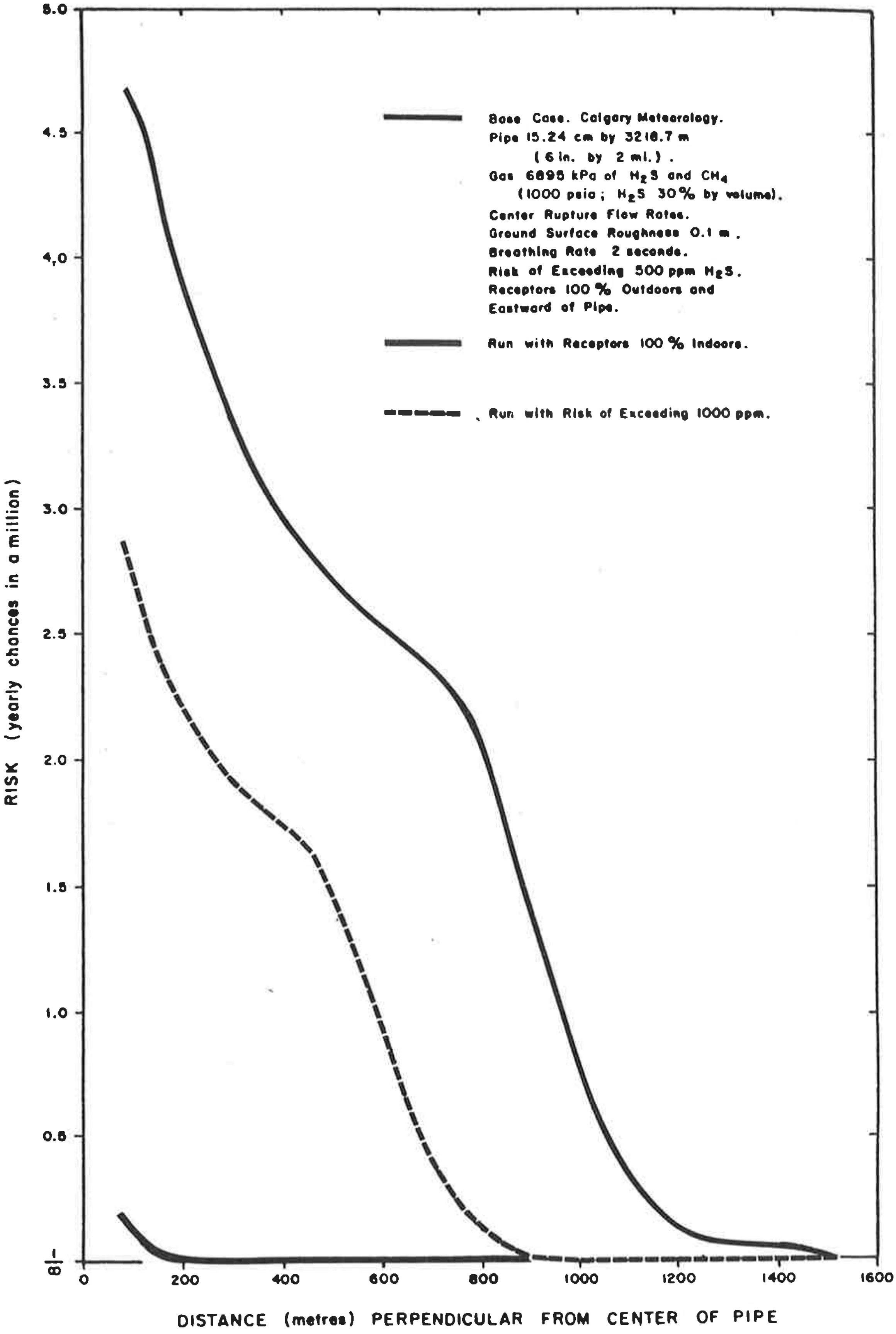

Figure 7 Annual risk of exposure to high H_2S concentrations from a pipeline rupture is greatly decreased by staying inside a building with time constant of 0.10 hr. in daytime and 0.25 hr. night. From Choukolas (1980).