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Technical Options for Protecting Civilians from Toxic Vapors and Gases

C. V. Chester

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Energy Division

TECHNICAL OPTIONS FOR PROTECTING CIVILIANS FROM TOXIC VAPORS AND GASES

C. V. Chester

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Abstract

Costs and quantitative estimates of effectiveness of general technical options for protecting civilians in place against very toxic vapors are provided and compared with possible hazards. Useful protection can be obtained by taking refuge in enclosed spaces if the leak rate is low, cloud passage is quick and it is possible to tell when the cloud has passed.

A variety of charcoal filters and masks are available in the U.S. and abroad which give good protection at reasonable prices if there is some system to warn the people to use the protective equipment. The most cost-effective method of protection found is a mouthpiece respirator which costs less than $14.00 and can be donned in seconds.

Protection for a single room in a residence by a charcoal filter and blower can be obtained for under $1000. In cool weather, the population of a mass shelter can be provided with a charcoal-filtered air supply (of 3 cfm per person) for about $10/person.

Disclaimer

The advertised properties of a number of commercially available devices are tabulated in this report. The information was intended to be representative and what was obtainable with the resources available at the time. The inclusion or exclusion of any commercial product in or from this report is neither an endorsement nor a criticism of the product by the Oak Ridge National Laboratory, Martin-Marietta Energy Systems, Inc., or any agency of the U.S. Government.

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INTRODUCTION

The accident at Bhopal, India in which over 2,000 civilians were killed and more than 20,000 injured by release of 50,000 lb. of methyl isocyanate has sharply increased awareness of the potential of this type of accident. Subsequent smaller releases of the same chemical in plants in this country have persuaded many people both in and out of government that this type of accident needs to be considered in emergency planning.

The possibility of terrorists either causing industrial accidents releasing toxic vapors or acquiring the agents and releasing them at a time and place of their own choosing is also of concern. This type of incident could involve highly toxic chemicals released in areas of higher population density than is normally involved in industrial accidents.

The U. S. Army is currently developing plans to destroy its stockpile of unitary chemical weapons at each of 8 storage locations. The possibility of an accident during storage, onsite transportation, handling, or plant operations must be considered in local emergency planning.

The purpose of this report is to review the technical options, and their associated costs, for protecting civilians from airborne releases of toxic chemicals. Prugh (1985) reviewed aspects of this problem in a publication with comprehensive literature citations. In a study of mitigation of vapor cloud hazards, he considered evacuation prior to cloud arrival, escape from a cloud, protection offered by havens and effectiveness of medical treatment. Evacuation is treated elsewhere in his report. Escape from a cloud is not likely to be an option (without a respirator) for the distances of principal interest in this study (though clearly useful for someone within sight of the release point). Medical treatment is outside the scope of this report.

The chemicals considered here are the military chemical weapons and a few representatives of the more toxic industrial chemicals handled in large quantities. Carbon monoxide is not considered in this review although it is responsible for more deaths than most industrial chemicals. (Carbon monoxide is very slightly lighter than air and does not travel long distances downwind. Its major threat to civilians is its generation inside occupied closed spaces by some combustion process.)

TOXICITIES

Table 1 lists relevant chemical agents and some of the more toxic chemicals used in large quantities in industry. The median lethal concentration times time listed is that product of concentration and exposure time that will kill 50% of resting adults exposed to it, resting adults assumed to be breathing approximately 10 liters per minute. Under vigorous exercise the breathing rate can increase to 40 liters per minute reducing the required concentration time integral for lethality by a factor of 4. The "no deaths" concentration is usually taken as one-tenth the mid-lethal concentration.

WARNING

In order to take protective action in time for it to be effective against toxic chemicals, warning is required. For some chemicals having a strong odor and relatively low toxicity, e.g., chlorine, hydrogen sulfide, or methylisocyanate, the leading edge of the cloud bearing down on an area will have a region of sufficiently low concentration to warn the population of the danger and permit time to take some type of defensive action.

Table 1. Chemical Agent Toxic Properties[1]

Agent	Volatility (mg/m^3, 25^oC)	Median Lethal Concentration X Time (mg/m^3 *min): Respiratory	Median Lethal Concentration X Time (mg/m^3 *min): Percutaneous	Median Incapacitation Concentration X Time (mg/m^3 *min)
Chlorine (CL)	2.2×10^7	19,000	-	1,800
Phosgene (CG)	4×10^6	3,200	-	1,600
Hydrogen Cyanide (AC)	1×10^6	2,000-4,500	-	>2,000
Cyanogen Chloride (CK)	1×10^6	11,000	-	7,000
Sulfur Mustard (HD)[2]	920	1,500	10,000	200
Nitrogen Mustard (HN-1)	2,000	1,500	20,000	200
Lewisite (L)[2]	6,000	1,200-1,500	100,000	300
Mustard Lewisite (HL)	4,200	1,500	>10,000	200
Tabun (GA)[2]	610	400	40,000	300
Sarin (GB)[2]	22,000	100	15,000	35-75
Soman (GD)	3,900	100	1,000	35-75
VX[2]	10.5	100	1,000	50
Methyl Isocyanate		1500		

[1]Taken from U.S. Department of the Army (1975) and WHO (1970).

[2] Chemical agents in the stockpile to be destroyed in this program.

In many cases, the accident releasing the chemical (e.g., train wreck, equipment failure in a chemical plant) will be readily apparent to personnel in the area who could activate an appropriate alarm system and emergency plan if they exist.

Some chemicals, notably the nerve agents, are almost undetectable physiologically at low but lethal concentrations. If the agent is released subtly (unobserved corrosion of a storage cylinder) or clandestinely (as by a terrorist) the only indication that something is amiss may be the collapse of people upwind of the observer, if they can be observed. The system for dealing with this eventuality must include instruments for detecting the agent and providing an appropriate warning. The available and prospective instruments are discussed at length by the National Research Council (June 1984). The requirements of warning systems and how people respond to them is discussed elsewhere (Sorensen 1988).

Table 2 is a partial list of commercially available toxic gas detection equipment. Most are designed to detect nerve agents, but many will detect higher concentrations of other toxic gases. The prices will discourage acquisition by the individual householder.

PROTECTIVE MEASURES

Protective measures which can be considered to reduce the exposure of people to hazardous airborne chemicals can include: (1) distance combined with atmospheric dispersion (e.g. by evacuation); (2) sheltering in sealed enclosures, and (3) supplying air which has been passed through charcoal filters.

Table 2. Monitors Alarms and Detectors

EQUIPMENT	MANUFACTURER	PRINCIPLE	AGENT	SENSITIVITY	APP. PRICE
CAM	Bendix (US) Graseby (UK)	Ion Mobility	Nerve Blister	1 mg/m^3	$ 2000
ACADA (XM22)	Bendix (US)	Ion Mobility	Nerve	0.1 mg/m^3	5000-6000
M8A1	Brunswick (US)	Ionization	Nerve	1 mg/m^3	2500
M43A1	Brunswick (US)	Ionization	Nerve	0.1 mg/m^3	4000-5000
ICAD	Bendix (US)	--	Nerve Blister	0.2-0.5 mg/m^3 5-10 mg/m^3	
ELAC MINI	Honeywell (US)	Passive IR	Nerve	0.1 mg/m^3	
XM21	Honeywell (US)	Passive IR	Nerve	0.3 mg/m^3	30,000- 50,000
TYPE 1306	Bruel & Kjaer (DEN)	Photo Acoustic	Nerve	0.3 mg/m^3	16,000
AP2C	Proengin (FRANCE)	Flame Photometer	Nerve (GD) Blister	5 ug/m^3	
GAS ANALYZER	Sensidyne (US)	Electrochemical	Many		
PORTABLE GAS ANALYZER	Sentex (US)	Gas Chromotograph Electron Capture Photoionization	Many		 14,000 13,000

Source: Company Advertising Brochures. Prices from telephone calls to company sales departments in March-April 1987.

DISTANCE AND ATMOSPHERIC DISPERSION

As a toxic cloud moves downwind it mixes with ever increasing amounts of air, becoming larger and more dilute. Diffusion of the vapor vertically and at right angles to direction of motion reduces the exposure to someone standing in the path of the cloud. Diffusion forward and backwards along the direction of travel in general does not reduce the amount inhaled by someone in the path of the cloud.

The rate of vertical and lateral mixing of the toxic cloud with the surrounding air can vary enormously depending on weather conditions. A bright, sunshiny day promoting convection of the atmosphere close to the ground will cause rapid vertical mixing. A turbulent wind will promote lateral mixing. High windspeeds also reduce the time that a person is immersed in a passing cloud and directly reduces the amount they will inhale for given quantity going by. The worst conditions providing the greatest threat to people at the greatest distance downwind occur under conditions of light, steady winds, a clear night with cooling of the ground to cause vertical stability in the atmosphere and the existence of a temperature inversion not too far above the ground to trap the chemical close to the ground. Conditions very close to these were responsible for the large casualties at the Bhopal incident in India.

Figure 1 shows the downwind hazard from clouds of 1000 kilograms of each of several toxic gases moving at 1 meter per second (approx. 2 miles per hour) in a highly stable atmosphere (Pasquill type E). These conditions also assume an inversion at 750 meters. Calculations use the Army's D2PC code (Whitacre et al, 1986). The dependent variable in Fig. 1 is given as the protection factor offered by protective measures required to prevent 99 percent of the fatalities at each location downwind. For example for GB, to keep the dose down to 1 percent fatalities at 1 kilometer downwind, the population would have to have masks or other protection giving a protection factor of a little less than 700. The

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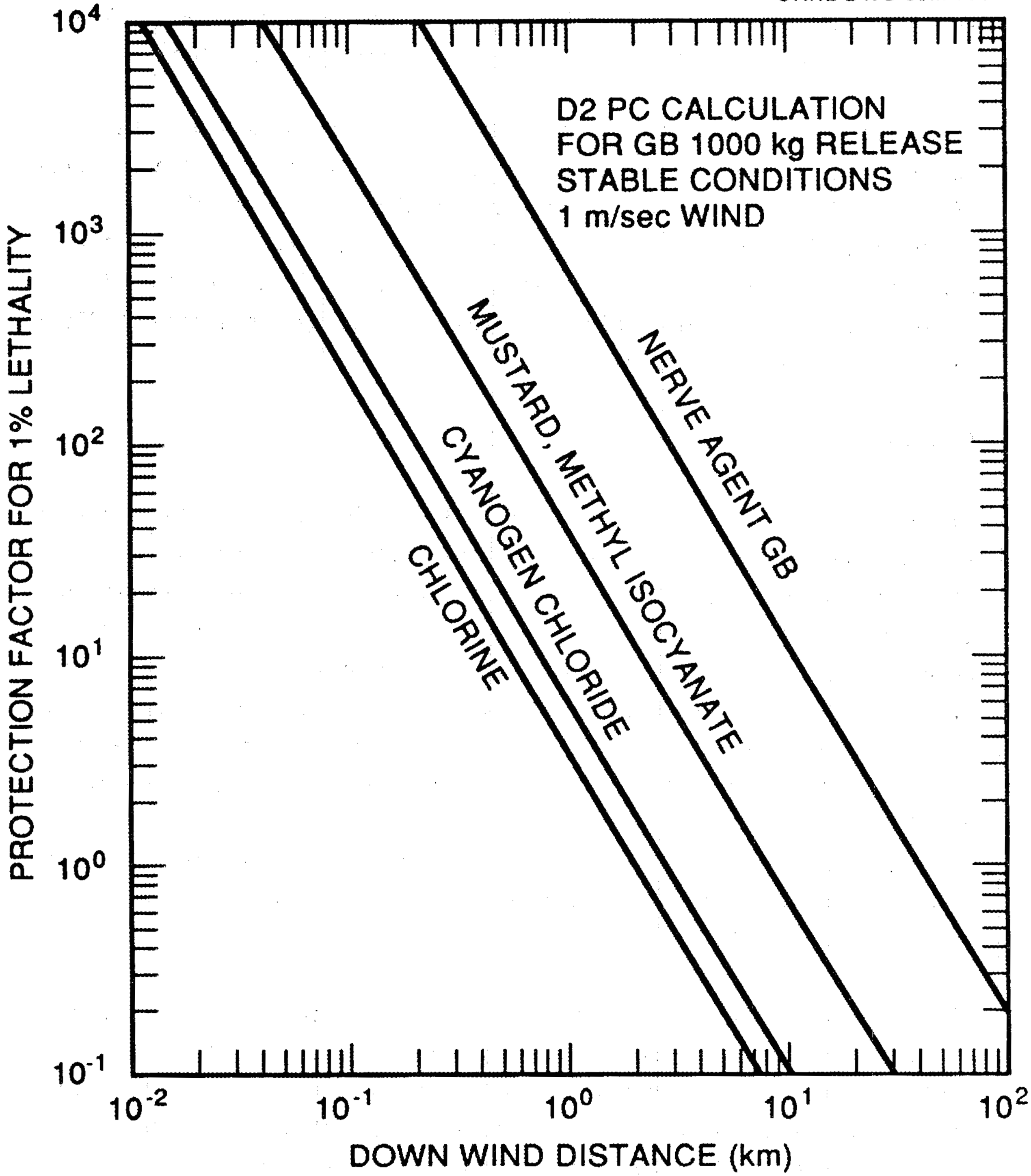

Fig. 1 Dose vs Downwind Distance for Some Very Toxic Gases

protection factor is the ratio of the dose people would get with no mask compared to what they would get if they were wearing a gas mask.

As can be seen from Fig. 1 the requirement for gas masks diminishes rapidly as one gets further away from the point of release of a quantity of agent. Under sunny conditions with a higher wind speed the requirement for protection would decrease even more rapidly. For the purposes of this study, these relatively pessimistic meteorological conditions (1.0 m/s. wind velocity, type E stability, inversion at 750 m) will be assumed in all cases.

EVACUATION

Evacuation is a way of increasing the distance between the population and a hazard and is the countermeasure to toxic chemical releases with which there is the most experience. Sorensen and his colleagues have reviewed the subject thoroughly (1987). It is very effective for slowly (few hours) developing hazards and in areas where emergency plans employing evacuation have been developed. Slowly developing chemical hazards can include a relatively small leak of a volatile toxic chemical, a large spill of a low volatility but highly toxic substance, or a progressive accident (e.g. fire) which doesn't at first cause release of toxic chemicals but has the potential of spreading to nearby equipment, tanks or drums containing toxics. Where small areas are threatened, evacuation can be quite effective.

Situations where taking shelter may be preferable to evacuating include quick release of small quantities of volatile toxic chemicals, or circumstances where an evacuation is likely to result in a traffic jam. This latter is a possibility where the area at risk is large, the population density is high, and the time available is short.

PROTECTION BY LEAKY ENCLOSURES

Given an adequate warning system, it is possible for a population to gain some protection from a passing cloud of toxic vapor by closing up their residence, or a room therein, until the cloud passes. What follows is an attempt to indicate how much protection can be obtained, and under what circumstances.

The protection afforded against chemical agents by closed buildings has been studied extensively by Birensvige (1983 a,b) of the Chemical Systems Laboratory of Aberdeen Proving Ground. He considered many factors beyond the scope of this review: deposition velocity of the agent, re-evaporation and desorption, deposition in cracks, and effects of filtered recirculation system. In addition he developed correlations of infiltration rates with building dimensions, and window and door dimensions.

This work is concerned principally with the countermeasures to protect civilians at some distance from a release of toxic vapor. The principal concern is with vapor rather than aerosol so a very simple infiltration model was used. We are also concerned about the existing stock of U.S. residential housing for which data on infiltration rate and upgrading cost exists.

Our results are consistent with those of Birensvige in that low infiltration rates provide more protection than high infiltration rates and that opening up the enclosed space after the cloud has passed is necessary to minimize the exposure.

We assume an enclosure with an infiltration rate of R air changes/hr immersed in a cloud of constant concentration C_0 for a finite time T. How does the concentration C_i in the room vary with variable time t? We are assuming a physically unrealistic "square" cloud by which the outside concentration C_e increases abruptly to constant concentration C_o as it passes and then decreases abruptly to zero concentration. This simplification is assumed in order to describe the important relationships with mathematical expressions in closed form.

The differential equation describing the situation is

$$\frac{dC_i}{dt} = R(C_e - C_i)$$

which has the well-known solution

for $0<t<T$ $\quad C_e = C_o$

$$C_i = C_o\,(1-e^{-Rt}) \text{ for } 0<t<T$$

for $t>T$ $\quad C_e = 0$

$$C_i = C_o\,e^{-R(t-T)} = C_o\,(e^{RT}-1)e^{-Rt}$$

The quantity proportional to the hazard is the concentration-time integral. At t=T it has the value C_oT outside the enclosure, and inside

$$I_1 = \int_0^T C_i dT = C_o \int_0^T (1-e^{-Rt})dt$$

$$= \frac{C_o}{R}\,[RT - (1 - e^{-RT})]$$

For certain poisons such as hydrogen sulfide, the hazard may be proportional to the peak concentration rather than the time-integral of the concentration (Wilson 1987). For these poisons, enclosures provide a great deal of protection without the necessity of additional ventilation after cloud passage.

For $t>T$

$$I_2 = \int_T^t C_i dt = C_o \int_T^t (e^{+RT}-1)e^{-Rt}\,dt$$

$$= C_o\,(1-e^{RT})\,(e^{-Rt}-e^{-RT})$$

For $t \gg \frac{1}{R}$, $e^{-Rt} \ll 1$

$$I_2 = \frac{C_0}{R} (1-e^{-RT})$$

For all t ,

$$I = I_1 + I_2 = \frac{C_0}{R} [RT - (1-e^{-RT}) + (1-e^{-RT})] = C_0T$$

<u>Thus for a tightly closed house, the concentration time integral inside is exactly that outside if it is kept closed for times long compared to the infiltration time.</u>

If the enclosure can be opened immediately after the cloud passes, the maximum protection is obtained from the enclosure. The concentration-Time integral in this case is

$$I_{min} = \frac{C_0}{R} [RT-(1-e^{-RT})]$$

The ratio of this quantity to the external concentration-time integral, C_0T, is the reciprocal of the protection factor (PF) and is

$$\frac{1}{PF} = 1 - \frac{1}{RT}(1-e^{-RT})$$

The quantity RT is the product of air changes/hr in the enclosure and cloud passage times, in hours. It is the number of times the air could change in the enclosure in the time for the cloud to pass. Large values of RT are obtained for leaky enclosures and extended clouds. As one would expect, the value of the protection factor approaches 1 as RT gets large.

Small values of RT are obtained for tight enclosures and small, fast-moving clouds. In the limit $(1/RT)(1-e^{-RT})$ approaches 1 so (1/PF) approaches 0 as PF becomes very large.

This is seen in Fig. 2, where protection factor is plotted against cloud passage times (T) with air change time (1/R) as a parameter. For large values of air change times (small value of R) and small values of RT, the protection factor becomes large.

These results are in agreement with Prugh (1985) who finds that havens reduce the exposure by about an order of magnitude for a dwelling with an air change rate of one per hour in a cloud lasting 10 minutes. Without explicitly acknowledging it, he apparently assumes that somehow the haven is ventilated or the occupants removed once the cloud has passed.

If a house or room can be sealed to the point where it takes 8 to 16 hrs for an air change, protection factors of 30 to 60 can be obtained if the cloud passes in 30 minutes and the house is then opened. To do this, a system or instrument is required to tell the occupants of the enclosure that the cloud has passed.

Distribution Of Building Leakages

Several investigators report measurements of building infiltration rates in American residences as part of building energy conservation programs (Grot et al 1981, Grimsrud et al 1983). Fig. 3 is a plot (from Nazaroff 1987) of heating season infiltration rates for low-income houses, modern houses, and a weighted aggregate. The infiltration rates are well-approximated by a log-normal distribution.

Schlegel et al (1987) report infiltration rates using the "blower-door technique" as air changes per hour (ACH) at 50 pascals (approximately 5

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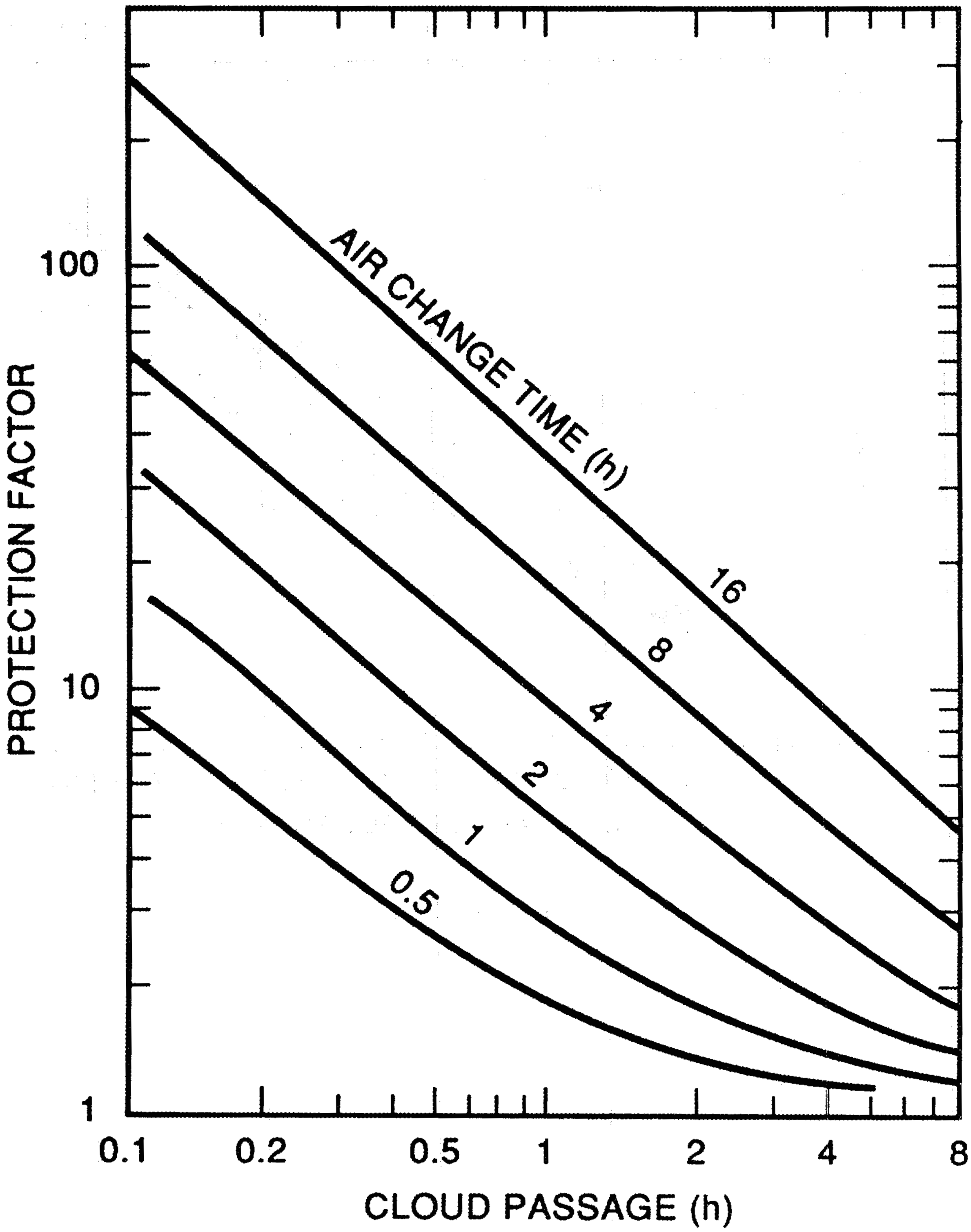

Fig. 2 Protection Factor of Leaky Enclosures

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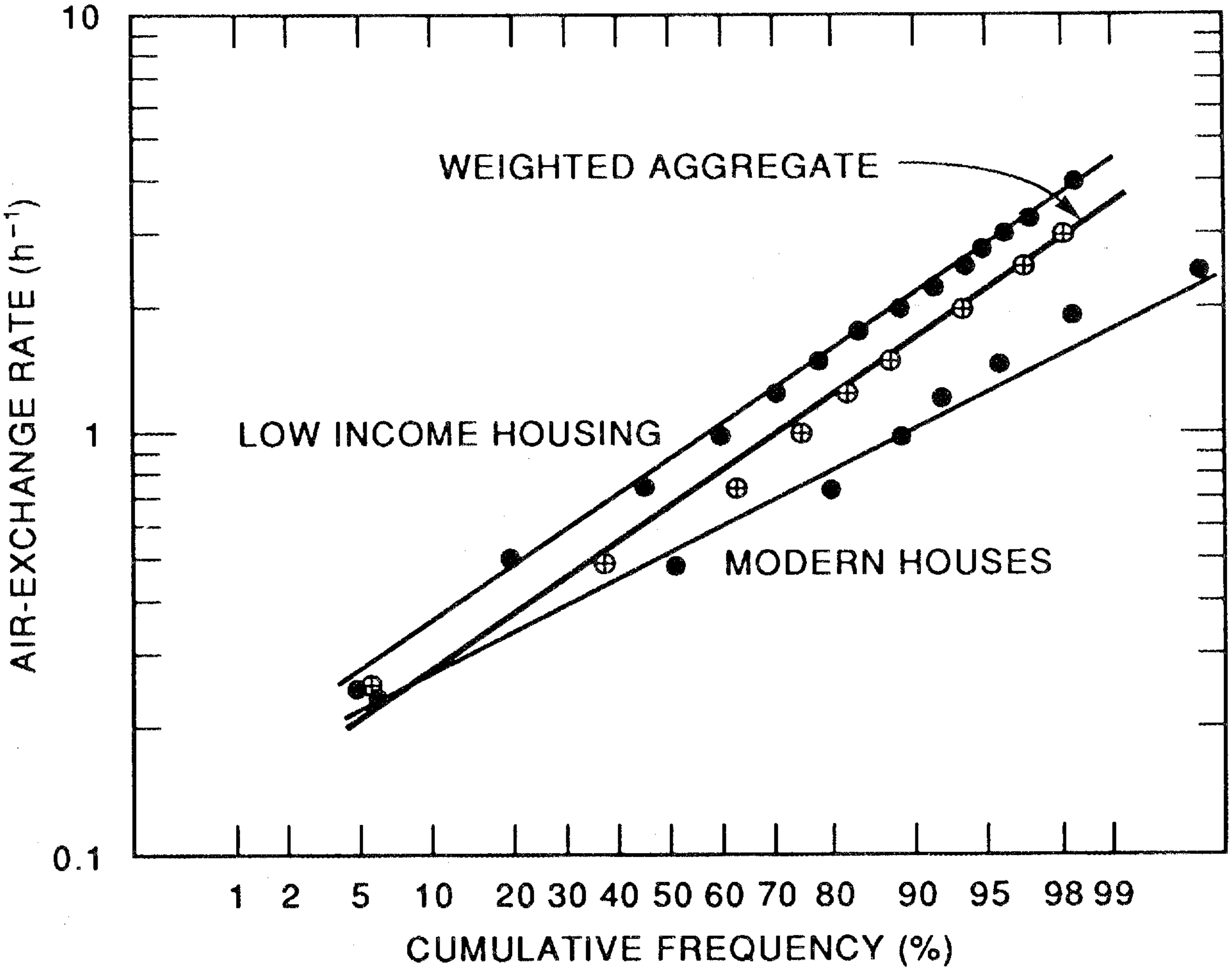

Fig. 3 Infiltration Rates of American Residences

mm water gauge) pressure or ACH50. In this technique, intended to eliminate the variables of temperature difference and windspeed, a house is pressurized with a blower (usually mounted in an exterior doorway) to 50 pascals and the flow rate measured. While this technique is very good for finding leaks, its measurements are not representative of natural infiltration rates. 50 pascals is approximately the stagnation pressure generated by a 20 mph wind striking a flat surface. To estimate the correspondence between ACH50 measurements and average natural infiltration we have compared the air changes per hour at the 50th percentile houses for natural ventilation reported by Nazaroff (1987) (approx. 0.7 ACH) with those of Schlegel et al (ranging from 6.3 to 7.7 ACH). We therefore conclude that a house exhibiting an average of one ACH over a heating season from natural ventilation would leak approximately 10 ACH when pressurized to 50 pascals with the blower door technique.

Estimation Of Infiltration Reduction Cost

Schlegel et al (1987) have measured costs of retrofitting residences to reduce infiltration rates. Fig. 4 is a plot of ACH50 reduction per $100 expenditure and pre-retrofit infiltration. It seems reasonable that the leakier a building is, the less expensive it is to reduce some of the leakage. The relationship should pass through the origin since no improvement in infiltration will be obtained from an incremental investment if the building already has a zero leak rate. The scatter and paucity of the data doesn't warrant any more than a linear approximation.

A least-squares fit of the data in Fig. 4 gives the relation:

ACH50 reduction per $100 expenditure = 0.104 X pre retrofit ACH50

If we define L = leakage
C = cost ($)

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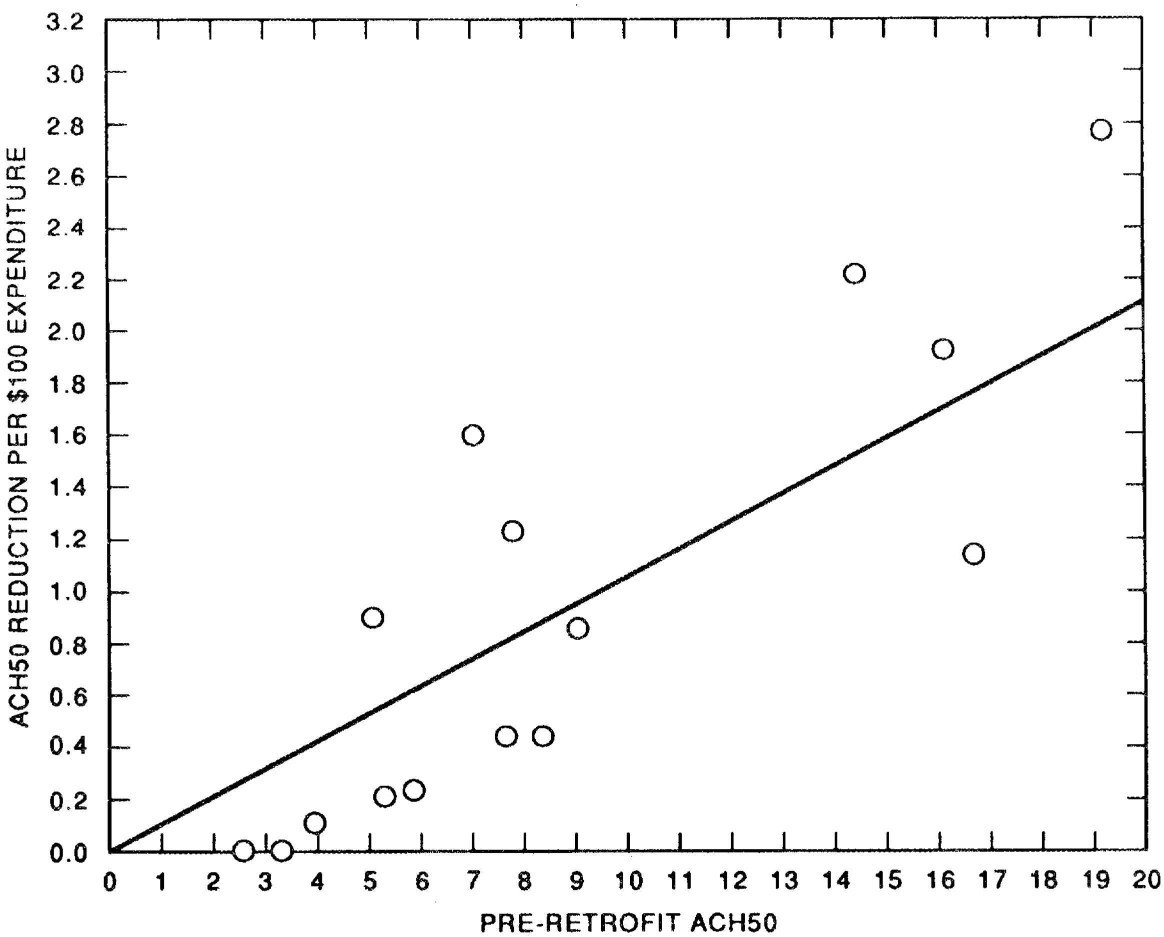

Fig. 4 Leak Reduction Per Unit Cost vs Leakiness

Then this equation becomes

$$-\frac{dL}{dC} = .104L \text{ (C in \$100)}$$

which has the solution

$$C = 960 \ln \frac{L_0}{L_f} \text{ (dollars)}$$

where L_0 = pre retrofit leakage
L_f = post retrofit leakage; air changes/hr.

If L_0 is taken as the leakage in the housing distribution reported by Nazaroff, and the cost is integrated over the housing distribution, the average cost per house for upgrading the whole population to a leakage rate

L_f is

$$C = -370 + 960 \ln \frac{1}{L_f} \text{ where } L_f < 0.6 \text{ air changes/hr, } \frac{1}{L_f} > 1.6 \text{ hr.}$$

This equation is plotted in Fig. 5, in terms of air change times vs upgrading cost.

We conclude that the cost of reducing natural infiltration rates of houses to levels that are interesting from the standpoint of protection from toxic chemical vapors will cost in the vicinity of $1000 per house. This cost will be a slowly varying function (natural logarithm) of the level of protection sought.

Reducing the natural infiltration rate to one air change in 4 hours would result in a decrease in heating and air conditioning costs, the relative decrease being greater for better insulated houses. However, to prevent the accumulation of odors, excessive humidity and in some areas, radon gas, some controlled ventilation would be required. In cold climates an air-to-air heat exchanger could be used. The controlled ventilation can be shut off in an emergency.

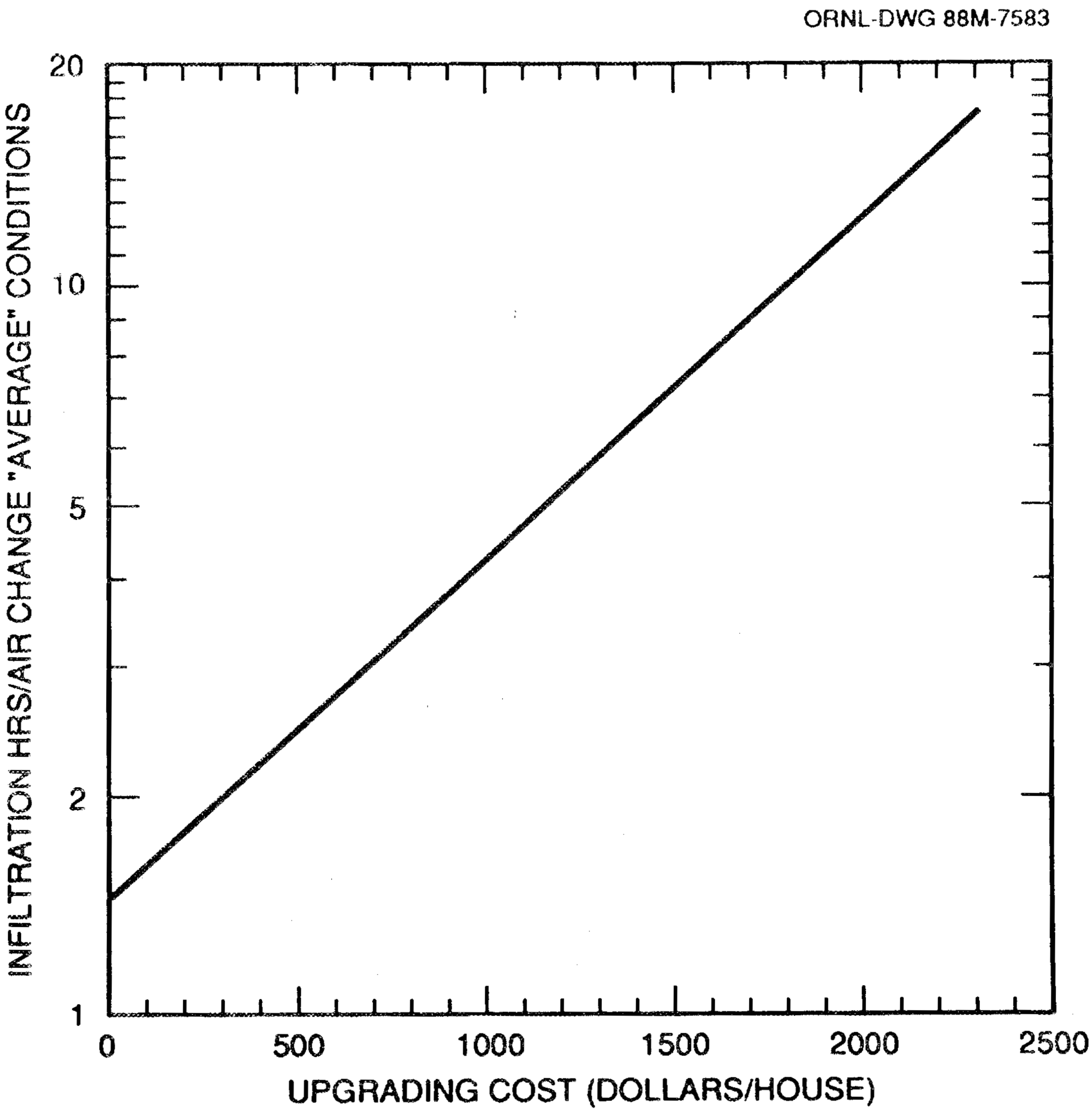

Fig. 5 Reduced Infiltration vs Upgrading Cost (Dollars/House)

Sealing a single room, especially if it were a basement room or an interior room with no windows, would be much less costly, under $200 for many houses.

STORED COMPRESSED AIR OR OXYGEN

For the sake of completeness it must be mentioned that it is possible to protect people from toxic chemicals by providing them with a compressed air or oxygen tank, appropriate regulator valves and a mouthpiece or mask. This equipment is widely available as breathing apparatus for firefighters and other emergency personnel. Underwater apparatus for scuba divers and emergency escape apparatus for workers in chemical plants equipment is highly effective but expensive. Sets of this equipment cost in the neighborhood of $1000 per individual protected.

CHARCOAL FILTRATION

Many toxic gases can be very efficiently removed from air by passing the air through activated charcoal. This is especially effective for higher molecular weight chemicals such as the nerve agent GB. Lighter gases such as chlorine or cyanogen chloride are not taken up as readily and carbon monoxide hardly at all.

Activated charcoal may be impregnated with chemicals which can react with the gases being removed to improve the kinetics of the removal and/or the quantity removed by a given amount of charcoal. Salts of silver, copper, and chromium are commonly used for this purpose.

Military standards for activated charcoal used for chemical protection require that it absorb up to 20% of its weight of GB or 2% of its weight of cyanogen chloride. If charcoal is fresh, and not exposed to moisture it will absorb up to 40% of its weight of GB and up to 10% of its weight of cyanogen chloride.

A common U.S. military standard for charcoal size requires that it pass a 12 mesh sieve and be retained on a 32 mesh sieve. Allowable pressure drops at rated flows through the filters are typically 17 millimeters of water for filters used in gas masks and 5-10 centimeters of water for filter to be used in collective protection. Charcoal filters for the removal of toxic gases usually have fairly shallow depths of charcoal; 10-30 millimeters, depending on application and air flow rate.

Residence Time and Protection Factor

A key variable in comparing charcoal filtration equipment is the superficial residence time. It is the flow rate of air through the filter divided by the volume of the charcoal bed. The protection factor of a filter depends on residence time, adsorbtive capacity of the charcoal which must be determined by test, and the comparison dosage (LD_{50}, LD_{01}, etc.)

A common test for gas mask filters is that they not pass any agent in flow of 30 l/min (0.5 l/sec) of air containing 1 gm/m^3 of GB for 230 min. This corresponds to a minimum breakthrough dosage of 230,000 mg-min/m^3.* If used to protect resting people breathing at 10 l/min., the test filter provides a protection factor of 2300 against GB. (The protection factor for a mask also depends on the in-leakage past the exhaust valves and the seal against the wearer's face.) If the test filter has a charcoal bed volume of 100 cm^3 (0.1l) then the residence time under test conditions is 0.1 l/0.5 l/sec = 0.2 sec. The residence time of the filter will vary with the breathing rate, but so will the lethal dosage (concentration-time integral, mg-min/m^3) so the protection factor for a given filter on a mask is constant for any breathing rate.

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*It is recognized that breakthrough is a gradual and complex phenomenon whose sharpness of onset is dependent upon uniformity of the charcoal bed, the kinetics of sorbtion and residence time. For the purposes of this discussion we make the conservative assumption of abrupt, total breakthrough at the rated exposure time.

The same is not true for charcoal beds driven by a blower. The protection factor must be redefined as

$$PF = \frac{\text{Time for challenge concentration to breakthrough bed}}{\text{Time for unprotected individual to breath a lethal dose}}$$

The breathing rate of the comparison unprotected individual and flow rate through the charcoal are independent, and PF will vary with each. For this discussion, for comparison we will use resting civilians breathing at 10 l/min corresponding to a median lethal dosage of 100 mg-min/m^3 for GB.

Under these circumstances protection factor will depend on bed residence time, which can be varied by varying the blower output. Using the filter described previously, a residence time of 0.2 sec corresponds to a PF of 3450. (See Appendix A for the derivation of simple relations between protection factor and bed parameters.)

Commercial Charcoal Air Filters

Commercial charcoal filters for air purification are usually operated with superficial residence times of 0.125 to 0.3 sec. High quality chemical filters for personnel shelters are designed by the Swiss for prolonged and repeated exposure to toxic weapons and may have residence times longer by a factor of 10 or more with a corresponding increase in cost.

This is demonstrated by Table 3 which is a summary of information on some representative commercial charcoal air filtration equipment.

In the columns labeled "Price" the left column is the price of the filter and the right column is the price of the filter and appropriate blower, and in one case the housing for removable filters. When the price is divided by the unit flow, a wide range of costs is observed: from $3.00

Table 3. Costs of Example Charcoal Air Filtration Equipment

VENDOR	DESCRIPTION AND MODEL NO.	FLOW RATE M^3/HR (CFM)	CHARCOAL VOLUME LITER:	RESIDENCE TIME SEC	PRICE: $U.S. FILTER ONLY	SYSTEM	$/$m^3$Hr ($/CFM)	$/PERSON @3 CFM	$/MASK EQ.
American Air Filter	Type II Tray Absorber	1700 (1000)	141.6	.30	2250	6100	3.8 (6.1)	18	9
P.O. Box 35260		340 (200)		1.5		5600 (est)	16 (28)	85	8.5
Louisville, KY 40232									
Barneby Cheny	Series FE High Efficiency	1420 (840)	49.3	.125	1400	2400 (est)	1.70 (13.00)	8.70	10.4
835 N. Cassaday Ave.	Filter Fold	142 (84)		1.25		1900 (est)	13 (23)	68	8.2
Columbus, OH 43216-2526									
Charcoal Services Corp.	Charcoal air filtration	Various					20 - 34	36-60	
P.O. Box 3	systems						("12-20/CFM")		
Bath, NC 27808									
LUWA Ltd.	LUWA NBC Filter GF40	40 (24)	17.6 l	1.6	689*	1700*	45 (70)	230	21.5
Kanalstrusse 5	GF75	75 (44)	33 l	1.6	952	2000	27 (45)	138	13
CH8152 Glattbrugg	GF150	150 (88)	66 l	1.6	1418	2400	16 (27)	82	17.7
Switzerland	GF200	200 (118)	43.2 l	0.8	1288	2400 (est)	12 (20)	61	11.5
	GF600	600 (353)	264 l	1.6	6440	8000 (est)	13 (23)	65	6.1

*Prices quoted by LUWA March-April 1987 for 1.40 Sw Fr/Dollar.

Source: Company advertising brochure. Prices from telephone calls to company sales departments March-April 1987.

per CFM to $70.00 per CFM. Assuming a shelter tight enough to be pressurized adequately by a flow of 3 CFM per occupant, the cost per occupant shows a proportionate range. However, you get something for the high-cost filters: more charcoal, which translates into more residence time and more protection factor.

If we normalize the prices with respect to protection factor or residence time, the costs become remarkably uniform. The last column is the cost for each 3 CFM of airflow of charcoal filtration systems from the different manufacturers, operated at a flow rate to give a residence time of 0.15 sec. For GB, these conditions would give a protection factor of about 1725. This has been labeled $/mask equivalent.

With the exception of the smallest size of the very high quality Luwa filters, the costs of all systems are within 30 percent of $10.

For protection of U.S. citizens, the huge protection factors provided by the Swiss equipment are probably not warranted. In a peacetime environment, the charcoal filter would presumably be changed after it has been contaminated by a release and hence need not be designed for repeated exposure.

COLLECTIVE PROTECTION

Collective protection using charcoal filtration for civilians can be protected single rooms, whole houses, or mass shelters. In collective protection the technique is to pressurize the sheltered volume with air to approximately 50 mpa (5 mm water gauge) which will prevent in-leakage in winds up to 20 miles per hour. Protection against higher windspeeds would not usually be necessary since at higher wind speeds, turbulence and rapid passage of the cloud severely limit the lethal range of a release.

As reported earlier in this report an average house has a leak rate of 7 air changes per hour under 50 mpa pressure which is about 1000 cubic feet per minute. At $6 per cubic foot per minute of filtration capacity, this would require a $6,000 unit to protect the house.

As indicated in Fig. 5 an investment of $2000 in tightening up the house will reduce its leakage rate by approximately a factor of 10 reducing the air requirement to approximately 100 cubic feet per minute and the investment required in charcoal filtration to approximately $2000 (small systems cost more per unit of capacity).

Reducing the protected area in a house to a single room will result in a proportionate decrease in the cost of protection. A 10 X 12 room selected for minimum window area might be upgradable to 0.7 ACH 50, about 10 cubic feet per minute, for an investment of $100 in upgrading and perhaps $200-$400 for improvised charcoal filtration equipment.

Mass shelter is a term used to describe shelter for hundreds to perhaps thousands of people in designated areas which can be auditoriums or building basements including designated national fallout shelter areas. Minimum ventilation requirements for these areas are 3 cubic feet per minute per occupant to control CO_2 concentration. If the shelter is large and crowded with relatively small wall area per occupant, ventilation must be increased to prevent build-up of body heat in the shelter and eventual heat prostration of the occupants. Figure 6 is a map of calculation of minimum ventilation requirements in large shelters in the U.S. in the summertime to prevent heat prostration. Conditions requiring this level of ventilation at the middle of the day are several days occupancy time and high humidity and temperature. Since chemical emergencies would generally be brief, a few hours at most and not likely to cover much area on hot days (due to the unstable atmosphere), ventilation requirements even in the south can be considerably less.

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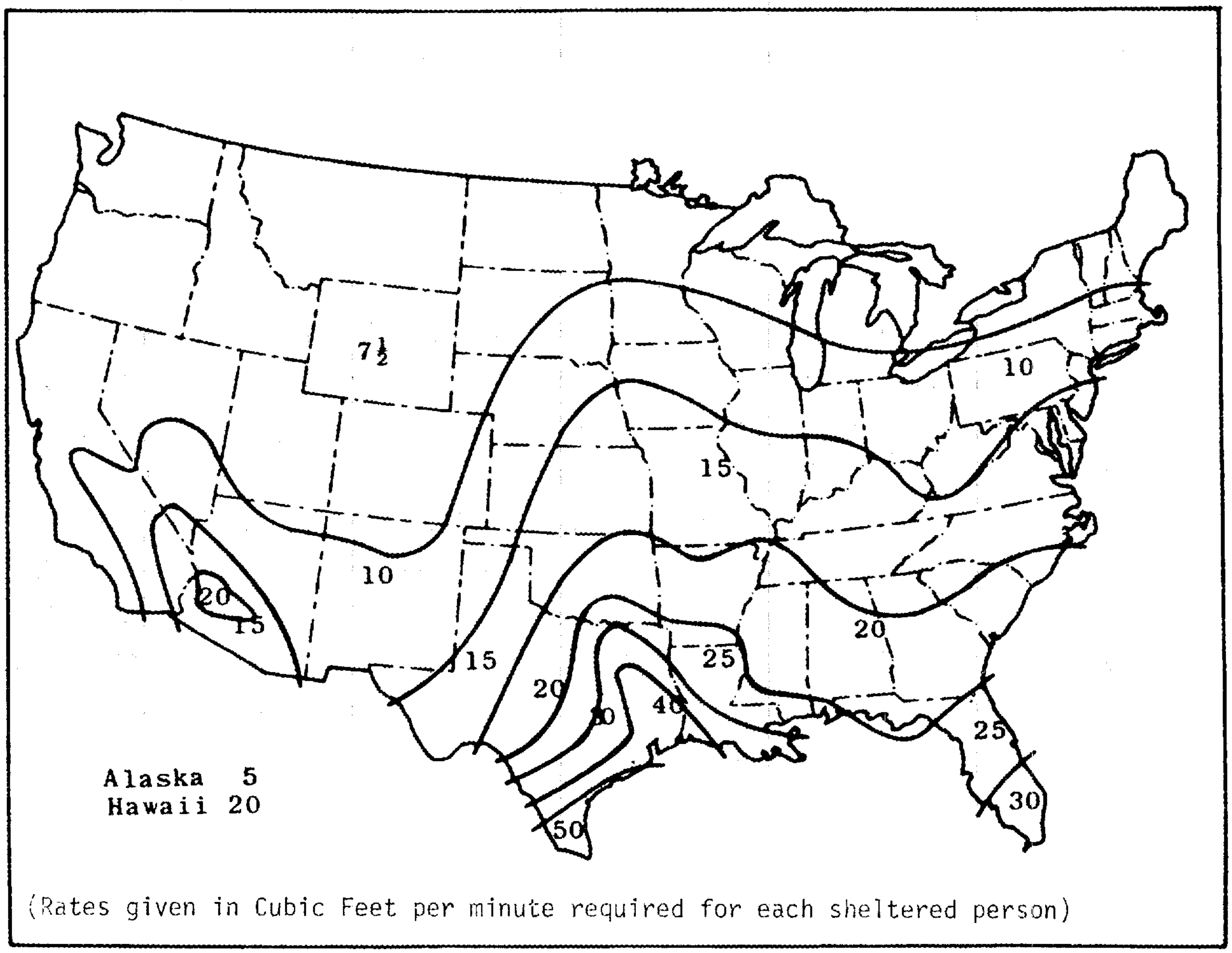

Fig. 6 ZONES OF EQUAL VENTILATION
(Rates given in Cubic Feet per Minute required for each sheltered person)

For large systems one would expect costs in the lower range toward $3 per cfm. One would expect costs per occupant to be in the range of $10, less than the range of costs expected for civilian gas masks. The disadvantage of mass shelter is that people have to move to them in an emergency, which requires time and going out of doors.

INDIVIDUAL PROTECTION

Masks

There is commercially available a wide variety of masks and protective clothing to protect against toxic chemicals (Table 4). In the United States most of this equipment is targeted on the industrial chemical market. In Europe, particularly in Sweden and Switzerland, there is equipment to protect civilians against chemical weapons as well as industrial chemicals. Most of the civilian masks meet military standards of protection containing 90-100 cu. centimeters of charcoal (about 50 grams) giving a filter protection factor of about 2000 against GB and 10-20 against cyanogen chloride. Prices for full face masks range from $30 for a Swedish civilian mask to $80 for Canadian military masks to $165 for American industrial masks.

Protection for Children

More than one manufacturer in Sweden has available a hooded jacket equipped with a battery-operated blower and charcoal filter for small children. One cost quoted is 950 kroner which is approximately $160. Several companies make protective enclosures for infants which are equipped with battery-driven blowers and charcoal filters and costs approximately $220 U.S. equivalent. The Norwegian firm of Helley-Hansen A/S offers a baby bag for the protection of infants which is ventilated by an adults breathing. Air is drawn in through a filter through the baby bag to the adult's mask, and is exhaled from the adults mask. This system has the enormous advantage of not depending on live batteries and

Table 4. Respiratory Protection

EQUIPMENT	NO.	VENDOR	APPROX. PRICE	COMMENT
MOUTHPIECE RESP.	476338	MINE SAFETY APP (US)	$13.55	STANDARD CARTRIDGE
INDUSTRIAL GAS MASK	448934	MINE SAFETY APP. (US)	165.60	
COMBAT MASK	S-10	AVON (UK) STEVE GORMAN (UK)		
COMBAT MASK	S-6	LELAND (UK)	100.00	
COMBAT MASK	CML-B10-C3	CANADIAN ARSENAL (CAN)	80.00	
INDUSTRIAL MASK	SARI ESTO	KERMIRA (FIN)		
FACELET MASK	FACELET	CHARCOAL CLOTH (UK)	$15-20	4 GM CHARCOAL
CIVILIAN FACEMASK	TYPE 33	FORSHEDA (SWEDEN) TRELLEBORG (SWEDEN)	$33- 30	
CHILD'S HOODED JACKET	TYPE 36	FORSHEDA (SWEDEN) TRELLEBORG (SWEDEN)	$150- $200	BATTERY POWERED
INFANT CARRIER	TYPE 39	FORSHEDA (SWEDEN) TRELLEBORG (SWEDEN)	210 240	BATTERY POWERED BATTERY POWERED
INFANT CARRIER	- -	HELLY-HANSEN (NORWAY)	150	VENTILATED BY ADULT MASK

Source: Company sales brochures. Prices by telephone from company sales departments.

avoids the cost of an electric blower. The price in April 1987 was given as 1000 Norwegian kroner which is approximately $140.

The Charcoal Cloth NBC Facelet Mask

The facelet mask is a British development consisting of a charcoal cloth bag held over the nose and mouth by elastic straps. The charcoal cloth which has a density of about 110 grams per square meter is manufactured by pyrolizing and then steam activating rayon cloth. It is claimed to have a more uniform pore size and much higher absorptive capability than conventional granular charcoal. The mask has a total cloth area of about 280 sq. centimeters and contains approximately 3 grams of charcoal cloth. If uniform airflow through the mask is assumed, the cloth would be capable of absorbing about 1200 mg of GB or mustard. This would provide a protection factor against GB of approximately 1200 and against mustard of approximately 80. This is about one-half the protection factor against filter penetration offered by conventional masks. However, the limiting protection factor of both masks and facelet is probably the integrity of air seal against the face which rarely exceeds 1000 and would be very likely less for the facelet. At the quoted price of $15-$20, the facelet would provide very cost-effective protection. Tests need to be made of the uniformity of breakthrough of the charcoal cloth under actual conditions of use. The mask would tend to saturate with moisture very quickly from breathing and its capacity for absorbing chemical agents would be thereby reduced.

An experiment with a sample mask indicated to this writer that there seemed to be an excessively large volume of dead air space between the mask and the face, giving the sensation of recycling a lot of stale air. If the mask performs as advertised it can provide significant protection at an attractive price. It is much more storable than any other respiratory or chemical protection observed. It is much inferior to the mouthpiece respirator in the speed of acquiring protection; it takes a few minutes to extract the mask and its straps from their package and to determine how to attach the straps and put on the mask. With practice, the masks can be put over the nose and mouth very quickly and held in place with the hand.

Mouthpiece Respirator

Possibly the most cost-effective piece of respiratory protective equipment is the mouthpiece respirator sold by Mine Safety Appliance, Inc. Rather than a face mask, it simply has a mouthpiece connected to a filter cartridge by a tube. The mouthpiece is held in the mouth while the nose is held closed by a separate nose clip. The person simply breathes in and out through the mouth. Intake and exhaust valves in the respirator ensure one-way flow through the replaceable charcoal filter. This piece of equipment has two outstanding advantages: the price, $13.55, and the speed and ease with which it can be put into action by untrained people compared to putting on and adjusting a full face mask or even a nose and mouth respirator.

The protection offered by this equipment could be improved if it were augmented by a transparent hood (a plastic bag) which would keep the toxic agent away from the eyes. If the wearer exhales through the nose, the plastic hood can be kept flushed with uncontaminated air.

This equipment has the disadvantage of requiring some physical effort and a fair amount of mental concentration to maintain a tight seal between the lips and the mouthpiece of the respirator. It is intended for use for only a few minutes while the wearer is escaping from a chemical hazard in an industrial plant. If release durations of one hour or more are to be planned for, a face mask will probably be required.

CONCLUSIONS

We have reviewed possible technical measures for the protection in place of civilian populations against the release of a toxic vapor.

Significant protection can be obtained from leaky enclosures if the natural infiltration rate is low enough and cloud passage is fast enough and the enclosure is opened up for additional ventilation or evacuated when the cloud has passed. For example, if a house has a natural infiltration rate of one air change per hour and a toxic cloud goes by in ten minutes and the house is opened up immediately afterwards, the inhabitants of the house will receive 1/10th of the dose of toxic agent they would have received had they been outdoors. If the people remain in the house for a long period of time with it closed up, they will accumulate a dose of toxic agent exactly equal to what they would have received outside. Any system relying on protection by enclosure must include a system for telling the occupants when the cloud has passed and the enclosure may be opened up.

A variety of measures developed in the Department of Energy's Energy Conservation Program are available to reduce the infiltration rate of houses. For an investment of the order of $1000/house the infiltration rate of the house can be reduced be to the neighborhood of 1 air change in 4 hours which will provide significant protection even against very large toxic clouds. A single room in a residence can have its infiltration rate reduced very significantly at a much lower cost, particularly if it is located in the interior of the house or in the basement.

Pressurizing a house with air which has been drawn through a charcoal filter provides a very high degree of protection of the occupants. To pressurize an entire house with filtered air would require an investment of $3000-$5000. The cost of providing a charcoal air filter to pressurize a single room would be significantly lower, possibly under $1000. However, some system would have to be in place to warn the occupants when to turn on the charcoal filtration system. If left on all the time the charcoal would have to be periodically replaced due to the accumulation of organic vapors in the filter.

Pressurizing a mass shelter with air leakage controlled to 3 CFM/occupant can be done for an investment, in charcoal filtration equipment of $10 + 3 per occupant with a protection factor of about 1700. A protection factor of 3400 can be obtained for $20 + 6 per design occupant.

Masks equipped with charcoal filters give very high protection factors (1000-3000) against toxic vapors. They are available to civilians for as little as $30-$33 in Sweden and for the military, $80-$100. An industrial mask in the U.S. can cost $160.

Hoods and baby enclosures equipped with charcoal filters and blowers are available in Europe for prices ranging from $140-$240.

For adults the most cost-effective protection method we have seen is the mouthpiece respirator. Its cost in 1987 was $13.55. It can be donned in seconds faster than any other type of protection, and provides a protection factor comparable to that of a full mask.

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Appendix A

Protection Factor for Blower-Driven Charcoal Filters

We define protection factor as

$$PF = \frac{\text{Time for challenge concentration to breakthrough bed at flow rate}}{\text{Time for unprotected individual outside to breathe a lethal dose}}$$

for some level of breakthrough concentration.

$$PF = \frac{\text{Bed volume X capacity/unit volume}}{\text{Concentration x flow rate}} \Bigg/ \frac{\text{lethal dose (mg)}}{\text{breathing rate x conc.}}$$

$$\frac{\text{Capacity}}{\text{unit volume}} = \frac{\text{Test concentration x test flow rate x test breakthrough time}}{\text{Test charcoal volume}}$$

$$\frac{\text{Test flow rate}}{\text{Test charcoal volume}} = \frac{1}{\text{Test residence time}} = \frac{1}{R_t}$$

Test conc. x test breakthrough time = test conc.-time integral = I_t

$$\frac{\text{Capacity}}{\text{unit volume}} = \frac{I_t}{R_t}$$

$$PF = \frac{\text{Bed Volume}}{\text{Flow Rate}} \cdot \frac{I_t}{R_t} \cdot \frac{1}{\text{concentration}} \Bigg/ \frac{\text{Lethal dose}}{\text{breathing rate}} \cdot \frac{1}{\text{concentration}}$$

$$\frac{\text{Bed Volume}}{\text{Flow Rate}} = \text{Bed residence time} = R_B$$

$$\frac{\text{Lethal Dose}}{\text{Breathing Rate}} = \text{Lethal concentration-time integral} = I_{LD}$$

$$PF = \frac{R_B}{R_t} \cdot \frac{I_t}{I_{LD}} = \frac{R_B}{I_{LD}} \cdot \frac{I_t}{R_t} = \frac{R_B}{I_{LD}} \text{ x charcoal capacity/unit volume}$$

For a charcoal filter of volume/flow rate to give a residence time of R_B filled with charcoal which gave a breakthrough time of 230 min. on a test filter of Residence Time R_t=0.2 Sec challenged by a test concentration to give concentration-time integral I_t of 230 mg-min/l, the protection factor compared to a lethal dosage of .100 mg-min/l is

$$PF = \frac{R_B(\text{sec})}{0.2\ (\text{sec})} \cdot \frac{230\ \text{mg -min/l}}{0.100\ \text{mg -min/l}} = 11500\ R_B\ (\text{sec}) \text{ for 230-min. charcoal}$$

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