Effect of Toxicity in Compartment Fires

By: Rajiv Kumar, Sunil K. Sharma and
Narendra Kumar
Fire Research Division Central Building Research Institute
(Council of Scientific and Industrial Research)
Roorkee (India)

INTRODUCTION

It has long been recognized that exposure to toxic smoke products is one of the major hazard confronting people in fires.Toxic chemical species produced during fire result in environmental contamination, injury which may be fatal as well as damage to buildings through corrosion and contamination.

It has been observed in experimental studies on compartment fire that the fire smoke contains a number of potentially toxic gases. Their quantity considerably depends upon the temperatures and oxygen supply to the compartment. Toxic gases are composed of asphyxiant gas such as carbon mono oxide, carbon di oxide and deficient oxygen in all the fires, hydrogen cyanide gas in fires related to modern synthetic materials, and irritants like acrolein and hydrogen chloride acid gas. The asphyxiant &/or irritants, individually and additively, contribute to incapacitation / death of the occupant. Carbon monoxide (CO) is the most common fire toxicant. More than half of the fire fatalities occur due to its inhalation. Though the carbon monoxide concentrations as low as 4000 ppm (0.4 % by volume) can be fatal for one hour exposure, levels of several percents have been observed in full scale compartment fires. A complete toxicity assessment should not only include the toxicity of CO but also the synergistic effects of other combustion products such as elevated CO_2 and deficient O_2 levels. Now a days, there is tremendous increase in injuries and casualties due to smoke and toxic fumes. It is probably due to:

(i) increased use of synthetic materials as furnishings and upholstery in buildings.These materials generate combustion products,which are toxic even at very low doses.

(ii) the rate of fire growth and rate of evolution of the common toxic products are more in the modern combustibles being used as compared to those from the traditional materials such as wood, brick and mortar.

Therefore, it is desirable to mitigate toxic hazards in Fires is to control such factors as ignition,flame spread, and rate of smoke evolution.

COMPARTMENT FIRE & IT'S OCCUPANT

During the growth phase of a fire the combustion products; heat & smoke; have little effect on the occupants. During this period, the important factors influencing escape and ultimate survival are largely psycho behavioral or logistic factors, such as how the victim is alerted to the fire and reacts to that knowledge, whether he/ she responds to alarms, attempts to leave or stay to fight the fire, interacts with other individuals, and how the person responds to the geography of the fire environment in effecting an escape.

If occupant could not escape due to alarm failure or physico-behavioural problem before fire becomes fully developed, he is exposed to smoke, heat and toxic products,and his escape capabilities are affected due to irritancy and asphyxiation. During this phase the critically important factors are the toxic nature, concentration and dynamics of the production of combustion products. If the occupant is exposed to these combustion products his breathing becomes laboured and he starts inhaling more of these irritant or toxic gases. Depending upon the rate of intake or respiration rate per minute (RMV), the body parts start getting affected and incapacitation starts. If the exposure is beyond a certain threshold value i.e. lethal concentration, it can result in death. The two major determinant of whether a potential victim can escape or not, are (1) the point at which incapacitation by toxic products is reached, and (2) how these products affect escape capability during the window of time available for escape between ignition and the development of lethal conditions. It is essential therefore, to study the toxic nature of combustion products as they play a major role in incapacitation and even death of a person entrapped in a compartment under fire.

IMPORTANCE OFTOXICITY

In context of fire safety, toxicity studies are required to assess toxic fire hazard in a full-scale scenario in order to:-

1. Carry out fire safety assessment of building design and design proper fire protection system.

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* To whom correspondence should be addressed: e-mail: rajivkgoel@gmail.com

** Research Intern

2. To determine the time to incapacitation / lethality to assess the effect on the victims and for taking proper action for evacuation etc to save life.
3. To evaluate and compare the potential toxic hazard from different materials.
4. To determine the applicability of materials or the products to a particular occupancy based on toxic hazard / potency.

Toxic potency of a substance depends upon how much of the toxicant is required for a given toxic effect. The smaller the amount needed, the more potent the toxic substance. For example, in fires, hydrogen cyanide is about 20 to 40 times more potent than carbon mono oxide; because the amount needed to be inhaled to cause collapse is much smaller.

TOXICITY MEASUREMENT

In majority of laboratory studies on combustion toxicity, animals, primates or rodents are used to measure lethality, principally in terms of the exposure concentration, LC_{50} for individual fire products, or mixtures of thermal decomposition products from individual material. LC_{50} is the concentration of individual or combination of combustion product causing the death of 50 percent of the animals during exposure or within 14 days after it.

Toxicity is expressed in terms of concentration of inhaled toxic product in target organ of the body and time period for which it is maintained. The concentration of asphyxiants and irritants should be measured in the cerebral blood supply or inside brain cells for product and in the mucous lining of the nose and lungs respectively. For estimation of inhaled concentration the important parameters to be taken into consideration are:

1. actual analyzed concentration of the test materials per unit volume of air in the animals' exposure chamber,
2. duration of exposure, and
3. rate of uptake of toxicant.

The inhaled concentrations can be estimated by measuring the volume of air breathed by the animal per minute (the respiratory minute volume, or RMV). However, for accurate calculation of uptake and dose, further measurements, such as blood level concentrations, should be made. In case of droplet aerosols and dust particles, the particle size range in the atmosphere is also measured so that the desirable fraction (the part capable of entering the body) can be calculated.

In case of fire in a compartment, it is not often feasible to measure directly the amount of the toxic products Accumulated in the occupants. Instead, it is preferable to relate toxic effects of the smoke to the concentration of toxic species in the smoke, to which an occupant is supposed to have been exposed. It enables prediction of toxicity to be made on the basis of measurement of the amount of toxic species in the fire smoke.

Toxic hazard from materials / products is governed by the quantity and rate of generation of various toxic combustion products. It can be represented in terms of:

1. Exposure doses (Ct product) of asphyxiant gases to cause incapacitation or death
2. Concentration of irritants to cause in capacitation or death.

EXPOSURE DOSE AND FRACTIONAL EFFECTIVE DOSE

Carbon mono oxide is not the most toxic as compared to many other combustion products. However, it is considered the primary toxic combustion product mainly because of its presence in large quantity at every fire scenario. For the majority of toxic products in a fire atmosphere a given toxic endpoint such as incapacitation or death occurs when the victim has inhaled a particular quantity (Ct) of a toxicant. Thus it is essential to know the quantity of a toxic gas inhaled by a victim in a compartment fire.

The product of concentration and time (Ct product) gives an estimation of the quantity or the toxic dose available. In practice, dose in inhalation toxicology is often expressed as: (1)

Where W is a constant dose, specific for any given effect.

Thus, if is the lethal dose i.e. the product of concentration and the duration of exposure causing lethality. It is given by (2)

is expressed in mg. min / liter. LC_{50} is concentration which results in death of 50% animals when exposed in a test chamber. If LC_{50} or is smaller, the combustion product is greater toxic. For substances of undetermined composition (e.g., burning plastics), the unit of LC_{50} is g m^{-3}. i.e. it is the amount of mass which needs to be dispersed into a volume of 1 m^3 in order to cause a 50% probability of lethality. For substances where the composition is known (e.g. pure gases), the LC_{50} is usually expressed in units of ppmv. 1 ppmv of a gas means that there is one part of gas per million parts of air. The "v" denotes that the parts refer to 'by volume' and not 'by weight'.

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Haber's Rule

Haber's rule states that for most of the toxicants, the toxicity depends upon the dose accumulated and that the product of time and concentration is a constant. Equation (1) and (2) imply a linear uptake the toxic substance with time i.e. a higher concentration requires a shorter time to attain the same biological effect as shown in Figure 1.The time of exposure is also important for determining the effects from toxic gases. This holds true for many substances where the primary target organ is the lung. In the context of combustion toxicology this relationship can be applied to estimate the dose of a lung irritant likely to cause post exposure fire deaths from lung inflammatory responses. An example of such an irritant is carbonyl fluoride, a highly toxic lung irritant produced during the thermal decomposition of PTFE. Carbonyl fluoride has a 1-hr LC_{50} of 0.990 mg/ L. It's 4-hr LC_{50} is exactly one forth i.e. 0.248 mg/L. Most of the gases show deviations from this simple relationship. However, if better data are unavailable it can be used for rough estimation.

Some volatile substances e.g. CO are both taken up and excreted via lungs. In such cases the rate of uptake depends upon the difference between the concentration inhaled, C, and that retained in the body, W, and is an exponential function described by the equation (3)

Where t is the time of exposure, min, and k is constant. This relationship is the basis of Colburn-Forster-Kane (CFK) equation which provides an accurate prediction of the blood carboxyhemoglobin concentration in human (or various animal species) resulting from exposure to a given concentration of carbon monooxide. It approaches the linear Haber's rule (equation 1) when the concentration, C, in the atmosphere is higher than that required to cause incapacitation or death (Figure 2). For short duration exposures at high CO concentrations, up take is approximately linear. This is illustrated by the results from CO experiments on primates. It was observed that at a constant level of activity the animals became unconscious when exposed to approximately 27000 ppm-min of CO at concentrations between 1000 and 8000 ppm (Figure 3). It can be observed from Figure 3 that for 1000 ppm, 2000 ppm, 4000 ppm and 8000 ppm CO concentration incapacitation doses are 26600 ppm-min, 28097 ppm-min, 26868 ppm-min and 26086 ppm-min, respectively when calculated with CFK equation. For such situations it is, therefore, possible to use linear models for CO uptake without serious error.

Fractional Dose

The importance of any toxic gas species to a particular fire must reflect both its toxicity and its actual concentration in that fire. This is the *fractional effective dose* concept and algorithms are available for using it. This can be achieved by integrating the area under the fire profile curve for the toxicant under consideration. When the integral is equal to the toxic dose the victim can be assumed to have received a dose capable of producing the toxic effect. A particular method for making this calculation is the concept of *fractional effective dose* (FED). The Ct product dose for small periods of time during the fire is divided by the Ct product dose causing the toxic effect. These fractional effective doses are then summed during the exposure until the fraction reaches unity, when the toxic effect is predicted to occur. Thus (4)

CONCENTRATIONS OF IRRITANTS

Some toxic effects, however, are dependent upon a concentration instead of dose acquired over a period of time. Thus the irritant effects of smoke products on the eyes and upper respiratory tract (sensory irritation) occur immediately upon exposure, with the severity depending upon the exposure concentration. Therefore, some toxic effect such as sensory irritation, depends upon the immediate concentration of an irritant to which a subject is exposed, rather than the dose a concept of *fractional irritant concentration* (FIC) has been developed which is calculated as below (5)

In case of the asphyxiant effects of hypoxic hypoxia (oxygen lack) and hypercapnia (high CO_2 concentrations), the concentration of the toxicant, is an important determinant of toxicity along with the duration of exposure. When a subject is exposed suddenly to a low oxygen concentration, a finite time is required for the air in the lungs and gases in the blood to equilibrate to the new conditions i.e. effect is dependant to the some extent on "dose". Once equilibrium is established, usually within a few minutes, the severity of the effects depend upon the oxygen concentration and do not then change appreciably with time. This also applies to high CO_2 concentrations. Once equilibrium is established within a few minutes, toxicity is determined by concentration.

For the other main asphyxiant gas in smoke, hydrogen cyanide (HCN), although accumulation of a dose is one factor, the rate of uptake, which depend upon the concentration, is the most important determinant of toxicity. It can be observed in Figure 4 that for higher concentration of HCN i.e 180 ppm.(Ct product 400 ppm.min), incapacitation occurs rapidly after 2 min but

At the lower concentration of 100 ppm, incapacitation occurs only after approximately 20 min., requiring a much higher Ct product dose (2000 ppm. min). This effect leads to the unusual kinked HCN time / concentration curves shown in Figure 4 compared to the smooth curve for CO.

FIRETOXICITY

For fire toxicity data, the exposure period normally used is 30 minutes under specified conditions i.e. comparison of toxic potential is done on the basis of concentration of the gas species considered fatal to man for 30 minutes exposure time. The parameter used for comparison the toxicity is known as 'Toxicity Index'. It is defined as the numerical summation of the toxicity factors of selected gases produced by complete combustion of material in air under conditions specified.

Toxicity Index = (6)

$$\frac{C_g^{1}}{Cf_1}+\frac{C_g^{2}}{Cf_2}+\frac{C_g^{3}}{Cf_3}+\frac{C_g^{4}}{Cf_4}+\cdots\cdots\cdots\cdots\cdots+\frac{C_g^{n}}{Cf_n}$$

Where 1, 2, 3, 4, 5,..........,n represent each gas species in combustion product.

Cf = Concentration of gas considered fatal to man for 30 minutes exposure time (ppm).

C_g = Toxicity factor for each gas in combustion product

The toxicity factors (C_g), are derived from the calculated quantity of each gas that would be produced when 100 g of material is burnt in a volume of 1 m^3 and given by

$$\text{Toxicity Factor } (C_g) = \frac{Cx100xV}{m} \quad \text{ppm} \quad (7)$$

Where C = Concentration of gas in test chamber (ppm)

m = Fire Test mass (g)

V = Volume of test chamber (m^3)

The concentration of asphyxiant species in combustion gases, at which there would be a danger of incapacitation (loss of consciousness) and death after approximately 5 and 30 minutes exposure in a person engaged in light activity are given in Table 1. The concentrations of common irritant like acrolein and hydorogen chloride gas, causing sensory irritation or Death on exposures, are given in Table 2. Acrolein is commonly found irritants in smoke of different materials. Hydrogen chloride acid gas is evolved during the thermal decomposition of polyvinyl chloride (PVC). For other toxicant such as Hydrogen Sulphide (H_2S), Ammonia (NH_3), Formaldehyde (HCHO), etc, the concentration (Cf) used in equation (6) for calculating Toxicity Indices are shown in Table 3. The testing facilities for determining Toxicity Index as per NES 713 and N.C.D. 1409 codes are available in Central Building Research Institute, Roorkee.

Effects of exposure to Toxic Species

The physiological effects of exposure to toxic smoke and heat in fires result in varying degrees of incapacitation which may also lead to death or permanent injury. Incapacitating effects include.

1. Impaired vision resulting from the optical opacity of smoke and from the painful effects of irritant smoke products and heat on the eyes.
2. Respiratory tract pain and breathing difficulties or even respiratory tract injury resulting from the inhalation of irritant hot smoke. In extreme cases this can lead to collapse within a few minutes from asphyxia due to laryngeal spasm and / or bronchoconstriction. Lung inflammation may also occur, usually after few hours, which can also lead to varying degrees of respiratory distress.
3. Asphyxia from the inhalation of toxic gases, resulting in confusion and loss of consciousness.
4. Pain to exposed skin and the upper respiratory tract followed by burns, or hyperthermia, due to the effects of heat, preventing escape, this can lead to collapse.

Up to a certain level of severity, the hazards listed in items 1 through 4 cause a partial incapacitation, by reducing the efficiency and speed of escape or can lead to permanent injury. All except item 1 can be fatal if the degree of exposure is sufficient. These effects lie on a continuum from little or no effects at low levels to relatively severe incapacitation at high levels, with a variable response from different individuals. It is important to make some estimate of effects that are likely to delay escape, which may result in fewer occupants being able to escape during the short time before conditions become so bad that escape is no longer possible. Most important in this context is exposure to optically dense and irritant smoke which tends to be the first hazards confronting fire victims. For more severe exposures a moment may be reached when incapacitation is predicted to be sufficiently bad as to prevent escape. For some forms of incapacitation, such as when asphyxia leads to a rapid change from near normality to loss of consciousness, this moment is relatively easy to define. For other effects a defining moment is less easily characterized, for example, when smoke becomes so irritant that pain and breathing difficulties lead to the cessation of effective escape attempts, or when pain and burns prevent movement. Nevertheless it is considered important to attempt some estimate of the moment when conditions become so severer in terms of these hazards that effective escape attempts are likely to cease, and when occupants are likely to suffer severer incapacitation or injuries.

For hazard assessment due to fire smoke, the major considerations are

1. The time when partially incapacitating effects are likely to occur which might delay escape
2. The time when incapacitating effects are likely to occur which might prevent escape compared with the time required for escape.
3. Whether exposure is likely to results in permanent injury or death.

CONCLUSIONS

Assessment of fire effluent chemistry and toxicity in fires is required for specification of a product for a specific application in buildings. It is also essential for comparison of toxic potential and combustion characteristics with other products as well as for hazard and risk assessment needed for performance-based design. Time to incapacitation or death depends upon the toxic nature while time to escape required by occupants depends upon the design of the building. If the time to evacuate a building is more than the time to incapacitation or death, the building design requires changes to make it safer. Based on toxic characteristics, the evaluation of post-fire contamination including decisions for replacement / refurbishment of smoke damaged items can also be done.

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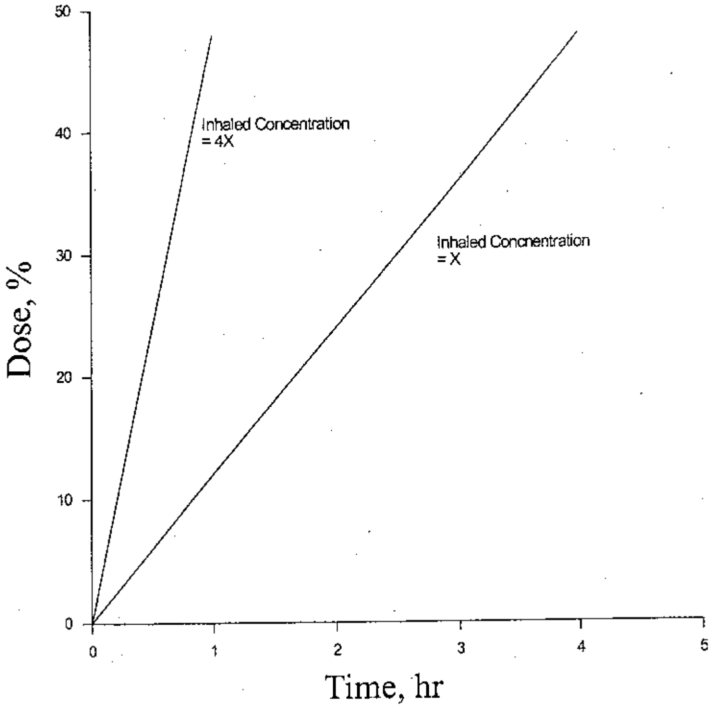
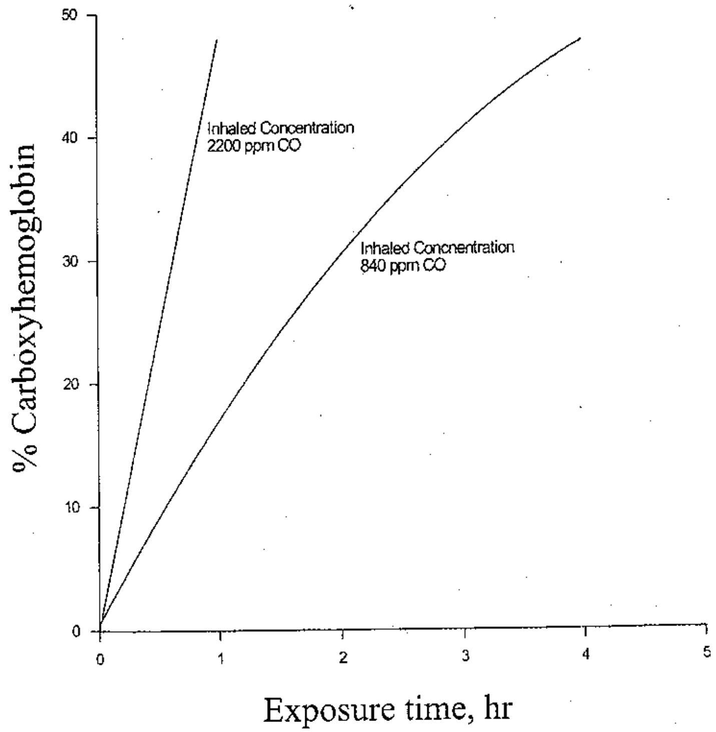


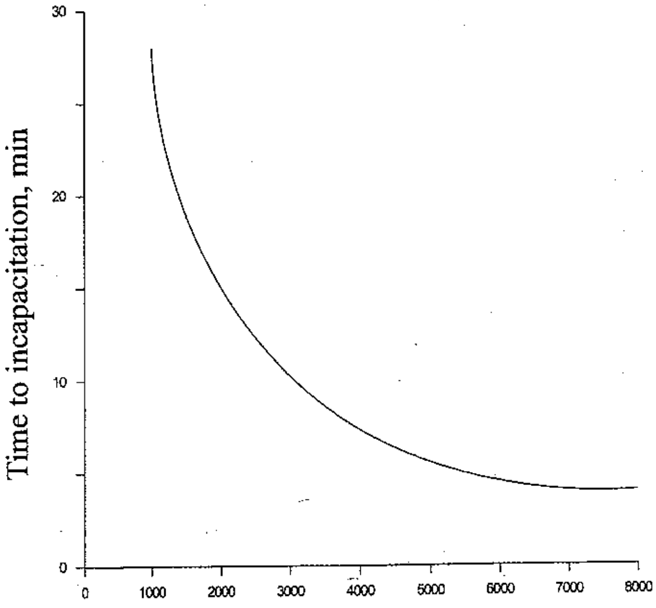
Toxicant following Haber's Rule

Figure I

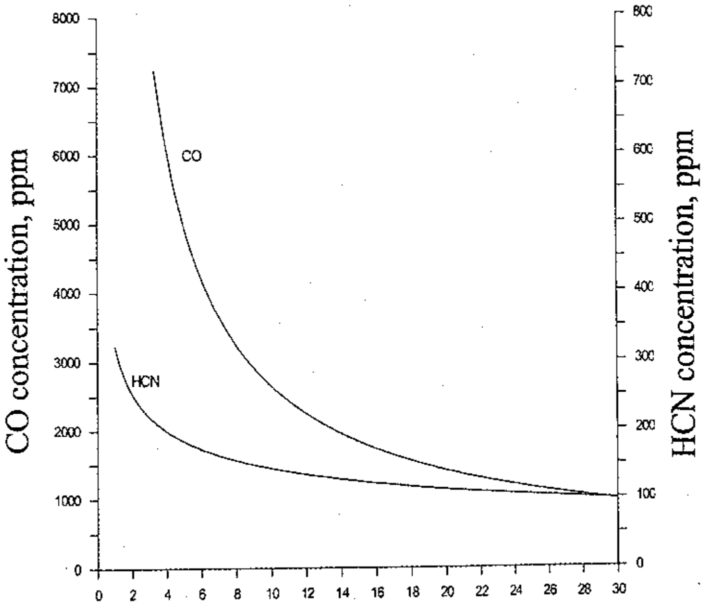


Toxicant (CO) follows Haber's Rule at high concentration for a short time, while at low concentration exposure, it is not linear

Figure 2



CO concentration, ppm
Relationship between time to incapacitation and CO concentration
Figure 3



Time to incapacitation, min
Variation of CO and HCN concentration with time
Figure 4

Table 1. Tenability Limits for Incapacitation or Death from Exposures to Common Asphyxiant Combustion Products

	5 min		30 min	
	Incapacitation	Death	Incapacitation	Death
CO	6000-8000 ppm	12000-16000 ppm	1400-1700 ppm	2500-4000 ppm
HCN	150-200 ppm	250-400 ppm	90-120 ppm	170-230 ppm
Low O_2	10-13%	<5%	<12%	6-7%
CO_2	7-8%	>10%	6-7%	>9%

Table 2 Tenability Limits for Sensory Irritation or Death from Exposures to Common Irritant Products of Combustion

	Sensory Irritation		Death (minutes)		
	a*	b**	5	10	15
Acrolein (ppm)	1-5	5-95	500-1000	150-690	50-135
HCl (ppm)	75-300	300-11000	12000-16000	10000	2000-4000

*At low concentration, unpleasant and quite severely disturbing eyes and upper respiratory tract irritation occurs.
** Severe pain with irritation in eye and upper respiratory tract, blepharospasm, copious lacrymation, and muscus secretion with chest pain occurs at these higher concentrations.

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Table 3 Values of Cf (Concentration fatal to man for 30 minute exposure) for calculating Toxicity Indices of toxicants

Toxicant	Cf (ppm)
Carbon Di Oxide (CO_2)	100, 0000
Carbon Mono Oxide (CO)	4,000
Hydrogen Sulphide (H_2S)	750
Ammonia (NH_3)	750
Formaldehyde (HCHO)	500
Hydrogen Chloride (HCl)	500
Acrylonitrile (CH_2CHCN)	400
Sulphur Di Oxide (SO_2)	400
Nitorgen Oxides ($NO+NO_2$)	250
Phenol (C_6H_5OH)	250
Hydrogen Cyanide (HCN)	150
Hydrgen Bromide (HBr)	150
Hydrogen Fluoride (HF)	100
Phosgene ($COCl_2$)	25

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