Chapter 15
Tenability

Abstract One of the most important issues during a fire in a tunnel is the possibility for a safe escape. During an evacuation, tunnel users may be exposed to toxic gases, radiation, high temperatures and dense smoke. In this chapter the most important consequences of exposure to gas components, radiation and convective heat are presented. Examples of asphyxiant and irritant gases and the effect on evacuating people are presented. Different models for estimating time to incapacitation and other endpoints due to exposure are discussed.

Keywords Tenability · Toxicity · Gas concentration · Carbon monoxide · Carbon dioxide · Oxygen · Hydrogen cyanide · Radiation · Convective heat

15.1 Introduction

During a fire, occupants in a building or a tunnel, or passengers in a train can be exposed to heat (high gas temperature or radiation), smoke, or toxic gases (toxicants). This can inhibit evacuation, but also lead to incapacitation and finally death.

The levels of the production of smoke and different species are dependent on mainly three different parameters: the burning material, temperature and the ventilation conditions (oxygen concentration). The latter parameter is not only dependent on the overall availability of oxygen, but also on the spatial/geometrical arrangement of the burning material and the possibility for the oxygen to reach the combustion zone and mix with the pyrolysis gases. This is discussed in more detail in Chap. 7. Further, the effect of smoke on visibility, the escape and walking speed is presented in Chap. 14.

UK statistics show that “smoke” and “burns/smoke” (where the cause of death was ambiguous) cause a significant proportion of the UK fire deaths [1]. There was a peak in fire deaths in the UK in 1979, and since 1985 there has been an almost constant decrease. Some suggested explanations for this reduction are the increased use of fire retarded furniture and the increased availability of low-cost smoke alarms. Also for nonfatal fire injuries the portion of hospital admissions caused by toxic gas inhalation is significant. Although these statistics are not specifically for tunnel

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fires, the effect of smoke is very important for conditions during a tunnel fire and as mentioned above the fire smoke affects the possibilities for a safe escape, both due to reduced visibility and increased risk for incapacitation.

For a long time, carbon monoxide has been seen as the only important toxicant. The reason for this is that it was easily quantified in the blood and was routinely analysed for in forensic investigations. However, it has been shown that also other toxicants are important, for example, hydrogen cyanide and this chapter summarizes the most common fire smoke toxicants, their effects and how to calculate the fraction of an incapacitation dose.

15.2 Combustion Products Related to Toxicity

The different parameters affecting the production of different toxic species are discussed in Chap. 7. In that chapter, it is concluded that the ventilation conditions are important for the chemical production and the hazards. In an under-ventilated fire situation the yield of major toxicants is higher. Furthermore, the total volume of effluents is greater [1]. The fire smoke toxicants can be divided into two groups: asphyxiant (or narcotic) gases and irritant gases. Particulates are also important.

Asphyxiant gases are the gases that prevent the uptake of oxygen or decrease the amount of oxygen delivered to the body tissue (For example, the brain tissue) and thereby cause hypoxia [1, 2]. This can lead to loss of consciousness and death. One can divide this group into two subgroups: simple and chemical asphyxiants, respectively [2]. The first group simply displaces oxygen, leading to a lower oxygen concentration. Examples are nitrogen (N_2) and carbon dioxide (CO_2). Note, however, that CO_2 in a fire situation can have other effects such as increasing the breathing rate leading to a faster inhalation of other more toxic gases. The CO_2 can also have toxic effects at higher concentrations. At concentrations above 7% there is risk for unconsciousness within a few minutes [3]. Chemical asphyxiants, on the other hand, affects a step in the electron transport chain system of the mitochondria, resulting in tissue hypoxia [2]. Examples of chemical asphyxiants are carbon monoxide (CO) and hydrogen cyanide (HCN). In a fire situation also the consumption of oxygen can lead to a low O_2 situation resulting in asphyxiant effects. In most fire situations toxic gases, for example CO, are present in lethal concentration before the oxygen concentration decreases to levels preventing survival. However, there are additive effects and the effects of low O_2 concentrations should be included in calculations of incapacitations.

Irritant gases can affect the eyes and the upper respiratory tract, leading to immediate incapacitation [1], but could also give long-term effects. Examples of irritants are given in Table 15.1.

The smoke also contains particles which are hazardous to health. Particulates in the smoke can prevent escape due to visual obscuration. The decreased visibility due to smoke slows down the walking speed of the people trying to escape from a fire. Furthermore, small particulates can also be inhaled and pose hazards to the

Table 15.1 Examples of asphyxiant and irritant gases

Asphyxiants		Irritants
Simple	Chemical	
Nitrogen (N_2)	Carbon monoxide (CO)	Hydrogen fluoride (HF)
Carbon dioxide (CO_2)	Hydrogen cyanide (HCN)	Hydrogen chloride (HCl)
		Hydrogen bromide (HBr)
		Nitrogen dioxide (NO_2)
		Sulphur dioxide (SO_2)
		Acrolein (C_3H_4O)
		Formaldehyde (CH_2O)

respiratory system. Depending on the size of the particulates, they can enter and affect different parts of the respiratory system. Examples of effects are fluid release and inflammation. Particulates smaller than 0.5 µm can cause interstitial and luminal oedema or enter the blood where they can trigger hazardous immune responses [1]. Particulates can also carry other hazardous species deep into the respiratory system. The particles are not discussed further here, while the visibility and the walking speed are discussed in Chap. 14.

In this introduction, as well as in the rest of this chapter, the main components of fire gases and those with known effects are presented and discussed. There might be other gases that are not often analysed for or with unknown effects that could be important for the overall toxicity in some situations.

15.3 Toxicity

15.3.1 Asphyxiants

Carbon monoxide is an asphyxiant gas and an important gas in connection with a fire. The toxic effect of CO is due to its combination with haemoglobin in the blood to form carboxyhaemoglobin (COHb). In Table 15.2, health effects at different COHb concentrations in the blood are summarized.

The toxicity of CO and its relationship to COHb and effects on the oxygen-carrying blood capacity is well-known, but CO can have other adverse effects, for example interruption of energy production of cells, interference of oxygen delivery and other cellular activities [4]. These latter effects are not as well understood or widely discussed as the binding of CO producing COHb, resulting both in the haemoglobin not being able to transport as much oxygen and the oxygen being more tightly bonded to the haemoglobin. The values in Table 15.2 should be seen as examples and not as exact limits. A concentration of 50 % COHb is often taken as a threshold for lethality [3]. Nelson, however, reports that a larger variety can be expected and that the actual limit depends on the situation [4]. A lower level and

Table 15.2 Summary of health effects at different COHb levels [5]

COHb level [%]	Effect
10	Asymptomatic or headache
20	Dizziness, nausea and dyspnea
30	Visual disturbance
40	Confusion and syncope
50	Seizures and coma
≥60	Cardiopulmonary dysfunction and death

longer exposure can result in effects on the cellular processes and this can lead to fatalities at lower levels of COHb than if a person is subjected to shorter and higher exposures.

While CO decreases the possibilities for the blood to take up, carry and deliver oxygen to the tissues, HCN decreases the ability to use the oxygen delivered to the tissues [3]. By the formation of cyanide ions in the blood, hydrogen cyanide is approximately 25 times more toxic than CO [1]. The dynamics of HCN in the human body are, however, poorly understood and blood cyanide is not analysed as routinely as COHb. This is partly due to difficulties associated with the measurement of HCN in the blood of a fire victim and the decay of HCN levels in the blood after mortality.

Low oxygen concentrations can cause hypoxia effects similar to those caused by CO and HCN. In most cases, heat exposure or toxic cases have reached lethal limits before oxygen concentration has decreased below tenable levels (approximately 6 %) [1]. CO_2 affects the time to incapacitation in two ways. At low concentrations, CO_2 stimulates breathing, that is, increases the breathing rate (RMV = Respiratory minute volume rate). This increases the uptake of other toxic gases. At high concentrations (above approximately 5 %) CO_2 becomes an asphyxiant, although not additive to the effects of CO and HCN.

15.3.2 Irritants

Irritant gases are important when determining the possibility for people to escape from a fire. These gases can be both inorganic (For example, hydrogen chloride (HCl)) and organic (For example, acrolein).

The inorganic irritants halides HCl and HBr dissociate totally in water and are strong acids. Hydrogen fluoride (HF), another halide, is a very irritating gas. Furthermore, nitrogen dioxide (NO_2) can form nitric and nitrous acid when dissolved. These acids can at high concentrations cause pulmonary oedema and death [1]. The effects of different concentrations of HCl and HF are given in Tables 15.3 and 15.4, respectively.

The main effect is irritation of mucous membranes, for example, in the eyes, upper respiratory tract, and to some extent the lungs. The effects include tears and

Table 15.3 Effects of different concentrations of HCl

HCl concentration [ppm]	Effect	References
10	Tolerable exposure	[1]
10–50	Perceived as irritant, but work is possible	[3]
50–100	Tolerable for one hour	[1]
100	Severe irritant effects	[1]
200	Predicted to impair escape in half the human population	[3]
309	Mouse RD_{50}	[3]
900	Incapacitation in half the human population	[3]
1000–2000	Thought to be dangerous for humans for short exposures	[1, 3]
2600	Lethal concentration for mice after 30 min exposure	[1]
3800	Lethal concentration for rats after 30 min exposure	[3]
4700	Lethal concentration for rats after 30 min exposure	[1]
15000	5-min lethal exposure limit concentration in rats and baboons	[3]

Table 15.4 Effects of different concentrations of HF

HF concentration [ppm]	Effect	References
62	30 min AEGL-3	[6, 7]
170	10 min AEGL-3	[6, 7]
200	Predicted to impair escape in half the human population	[3]
500	Incapacitation	[8]
900	Incapacitation in half the population	[3]
2900	30-minute exposure LC_{50} concentration	[3]

reflex blinking, pain in the nose, throat and chest, breath-holding and laryngeal spasm. Another effect is that the gases can cause oedema and inflammation in the lungs, leading to death 6 to 24 h after exposure [3]. In Table 15.5, limiting values are summarized for irritant organic gases as presented by different references.

15.4 Fractional Effective Dose, FED

The general method when estimating the toxicity of a smoke composition is to assume that the effects of the individual toxicants are additive, and in this sum for each toxicant express the concentration as its fraction of the lethal concentration (LC_{50} value), the latter estimated to be lethal for 50 % of the population for a 30 min exposure. To calculate this, one uses the fractional effective dose (FED) which according to ISO 13344 is defined as “ratio of the exposure dose for an asphyxiant toxicant to that exposure dose of the asphyxiant expected to produce a specified

Table 15.5 Limiting values (irritant and lethal concentrations) for irritant organic gases

Substance	IDLH (ppm)	OEL, 15 min (ppm)	RD_{50} Mouse[c] (ppm)	Severe sensory irritancy in humans (ppm)	30-min LC_{50} Mammal (ppm)
Reference	[9]	[10]	[3]	[3]	[3]
Acetaldehyde	2000	50[a]	4946	>1500	20000–128000
Acrolein	2	0.3[a]	1.7	1-5.5	140–170
Acrylonitrile	6	85	10–100	>20	4000–4600
Benzene	500	3[a]	–	–	–
Crotonaldehyde	50	–	10–100	4–45	200–1500
Formaldehyde	20	0.6[b]	3.1	5–10	700–800
Phenol	250	2[a]	10–100	>50	400–700
Styrene	700	20[a]	980	>700	10000–80000
Toluene	500	100[a]	–	–	–
Toluene 2,4-diisocyanate	2.5	0.005[b]	0.20	1.0	100

[a] Short-term value

[b] Ceiling limit value

[c] Where spans are given, ranked according to their reported irritancy in humans [3]

effect on an exposed subject of average susceptibility", that is in this case 50% lethality. This can be described mathematically as

$$FED = \sum_{i=1}^{n} \int_0^t \frac{C_i}{(C \cdot t)_i} dt \tag{15.1}$$

where C_i is the concentration of the toxic component i. One model often used is the N-gas model presented in ISO 13344 [11]:

$$FED = \frac{m \cdot [\mathrm{CO}]}{[\mathrm{CO_2}] - b} + \frac{21 - [\mathrm{O_2}]}{21\text{-}\mathrm{LC}_{50,\mathrm{O_2}}} + \frac{[\mathrm{HCN}]}{\mathrm{LC}_{50,\mathrm{HCN}}} + \frac{[\mathrm{HCl}]}{\mathrm{LC}_{50,\mathrm{HCl}}} + \frac{[\mathrm{HBr}]}{\mathrm{LC}_{50,\mathrm{HBr}}} \tag{15.2}$$

where m is the slope of the CO-vs-CO_2 curve and b is the intercept of the CO-vs-CO_2 curve, which depicts the increasing toxicity of CO as the CO_2 concentration increases. [CO], [CO_2] and [O_2] are concentrations expressed in percent by volume, while [HCN], [HCl] and [HBr] are concentrations expressed in ppm by volume. The values of the gas concentrations are the integrated product values $(C \cdot t)$ over a 30-min test period divided by 30 min. FED in Eq. (15.2) describes the fractional effective dose based on lethality.

The values of the parameters m and b in Eq. (15.2) depend on the concentration of CO_2. If [CO_2] $\leq 5\%$, $m = -18$ and $b = 122000$. If [CO_2] $> 5\%$, $m = 23$ and

Table 15.6 LC_{50} concentrations (30 min) for selected gases common during fires

Compound	Rats (Levin) [12]	Rats (ISO 13344) [3, 11]	Rats [1]	Mice [1]	Primates [1]
CO (ppm)		5700	5300–6600	3500	2500–4000
low O_2 (%)	5.4		7.5	6.7	6–7
HCN (ppm)	150	165	110–200	165	170–230
HCl (ppm)	3700	3800	3800	2600	5000
HBr (ppm)	3000	3800			
HF (ppm)		2900			
SO_2 (ppm)		1400			
NO_2 (ppm)		170			
Acrolein (ppm)		150			
Formaldehyde (ppm)		750			

$b = -38600$. Note that in ISO 13344, the values used as LC_{50}-values in Eq. (15.2) are those presented for rats by Levin (see Table 15.6, where LC_{50} values from other sources are also given). According to ISO 13344, 5700 ppm leads to death (rats) for a 30 min exposure [11].

As can be seen in Eq. (15.2), the effect of the increased respiration rate due to high concentration of CO_2 was only assigned to alter the effect of CO. Purser developed a model where the effect of hyperventilation influences the effect of all the toxic species. Furthermore, carbon dioxide can be toxic by itself and this effect is included as an acidosis factor Z_A.

$$FED = \left(\frac{[\mathrm{CO}]}{\mathrm{LC}_{50,\mathrm{CO}}} + \frac{[\mathrm{CN}]}{\mathrm{LC}_{50,\mathrm{HCN}}} + \frac{[X]}{\mathrm{LC}_{50,X}} + \frac{[Y]}{\mathrm{LC}_{50,Y}} \right) \times V_{\mathrm{CO}_2} + Z_{\mathrm{A}} + \frac{21-[\mathrm{O}_2]}{21\text{-}5.4} \tag{15.3}$$

where [CN] is the HCN concentration, expressed in ppm, corrected for the presence of other nitriles and the protective effect of NO_2, and is given by Eq. (15.4).

$$[\mathrm{CN}] = [\mathrm{HCN}] + [\text{total organic nitriles}] - [\mathrm{NO}_2] \tag{15.4}$$

$[X]$ is the concentration (ppm) of each acid gas irritant and $[Y]$ is the concentration (ppm) of each organic irritant. The multiplication factor for CO_2-driven hyperventilation is expressed as

$$V_{\mathrm{CO}_2} = 1 + \frac{\exp(0.14[\mathrm{CO}_2]) - 1}{2} \tag{15.5}$$

Z_A is an acidosis factor equal to $[CO_2] \times 0.05$.

Table 15.7 Activity dependant variation in parameters for the fractional effective dose for incapacitation by carbon monoxide [13]

Activity	RMV (L/min)	I (%COHb)
Resting or sleeping	8.5	40
Light work—walking to escape	25	30
Heavy work—slow running, walking up stairs	50	20

15.5 Fractional Effective Dose for Incapacitation

In Sect. 15.4, the lethal exposures are discussed. In this section, the focus is the time to incapacitation (or partial incapacitation), that is, the conditions that will lead to incapacitation (and not immediate death), which will prevent evacuation and in turn significantly increase the risk for lethality in the end. For this a fractional effective dose (FED) for incapacitation (or fraction of an incapacitating dose) is calculated. The fraction of an incapacitating dose for all asphyxiant gases (excluding effects of irritants), F_{IN}, can then be written (for a certain time step):

$$F_{IN,n} = \left(F_{I_{CO},n} + F_{I_{CN},n}\right)\cdot V_{CO_2,n} + F_{I_{O_2},n} \tag{15.6}$$

where the total fraction of an incapacitation dose is calculated from the contributions from CO, HCN and low concentration of O_2. In addition, CO_2 affects the breathing rate increasing the effect of CO and HCN. The different contributions are described and explained below.

The calculations are based on the expressions given by Purser [3]:

$$F_{I_{CO},n} = \frac{3.317\cdot 10^{-5}\cdot [\mathrm{CO}]^{1.036}\cdot RMV\cdot \left(t_n - t_{n-1}\right)}{I} \tag{15.7}$$

where F_{I} is the fraction of an incapacitating dose, [CO] is the concentration of CO (in ppm) during the time step, RMV is the breathing rate (25 L/min for light activity), $t_{\mathrm{n}} - t_{\mathrm{n}-1}$ is the length of the time step (min), and I is the COHb (carboxyhaemoglobin) concentration at incapacitation (30 % for light activity). Using values for light work, Eq. (15.7) can be simplified to:

$$F_{I_{CO},n} = 2.7642\cdot 10^{-5}\cdot [\mathrm{CO}]^{1.036}\cdot \left(t_n - t_{n-1}\right) \tag{15.8}$$

Values to be used in Eq. (15.7) for other levels of activity can be found in Table 15.7. Death is likely to occur for COHb above 50 %. Note, however, that the RMV decreases (to approximately 6 L/min) after incapacitation.

For the effect of HCN on the fractional effective dose of incapacitation the following equation has been derived [3]:

$$F_{I_{CN},n} = \frac{t_n - t_{n-1}}{\exp\left(5.396 - 0.023[\mathrm{HCN}]_n\right)} \tag{15.9}$$

where $[\mathrm{HCN}]_n$ is the concentration of HCN (in ppm) during the time step.

Simplified expressions for $F_{I_{CN},n}$ have been developed and Purser suggests the following expression [14]:

$$F_{I_{CN},n} = \frac{\left(t_n - t_{n-1}\right)}{1.2 \cdot 10^6 \cdot [\mathrm{HCN}]^{-2.36}} \tag{15.10}$$

which is also described in ISO 13571 [8].

A correction similar to the one expressed in Eq. (15.4) could be done, that is, considering additional effects of other nitriles and some protective effects of the presence of NO_2. However, their effects are small in comparison to the effect by HCN and Purser suggests that one could ignore the effects of other nitriles and NO_2 and only take the concentration of HCN into account, as described in Eq. (15.10) [14].

To calculate the effect of decreased concentration of oxygen, the following equation can be used [3]:

$$F_{I_{O_2},n} = \frac{t_n - t_{n-1}}{\exp\left(8.13 - 0.54\left(20.9 - [\mathrm{O}_2]\right)\right)} \tag{15.11}$$

where $[O_2]$ is the concentration of O_2 (in vol-%) during the time step.

The fraction of an incapacitating dose for all asphyxiant gases (excluding effects of irritants), F_{IN}, can then be calculated using Eq. (15.6) for each time step with

$$V_{CO_2,n} = \frac{\exp\left(0.1903[\mathrm{CO}_2] + 2.0004\right)}{RMV_r} \tag{15.12}$$

as the multiplying factor for the enhanced uptake of asphyxiant gases (other than CO_2) due to induced hyperventilation where $[CO_2]$ is the concentration of CO_2 (in vol-%) during the time step, and RMV_r is the resting RMV (7.1 L/min is used).

A simplified equation has been suggested [3]:

$$V_{CO_2,n} = \exp\left(\frac{C_{CO_2,n}}{5}\right) \tag{15.13}$$

The total fraction of an incapacitating dose is calculated as the sum of many time steps:

Table 15.8 Summary of tenability limits for incapacitation or death for some in fire gases common asphyxiants [3]

Species	Five minute exposure		Thirty minute exposure	
	Incapacitation	Death	Incapacitation	Death
CO (ppm)	6000–8000	12000–16000	1400–1700	2500–4000
HCN (ppm)	150–200	250–400	90–120	170–230
Low O_2 (%)	10–13	<5	<12	6–7
CO_2 (%)	1–8	>10	6–7	>9

$$FI\left(t = t_N\right) = \sum_{n=2}^{N} F_{IN,n} \tag{15.14}$$

Since the asphyxiant effect of CO_2 is not additive to the effects of the other gases it is not included in Eq. (15.6). However, the fraction of an incapacitating dose of CO_2 can be calculated separately as

$$F_{I_{CO_2},n} = \frac{t_n - t_{n-1}}{\exp\left(6.1623 - 0.5189\left[\mathrm{CO_2}\right]\right)} \tag{15.15}$$

Purser [3] summarized tenability limits for incapacitation or death when exposed to some common asphyxiants in fire gases. These are presented in Table 15.8.

If a situation with constant gas concentrations is assumed the time to incapacitation can be calculated as:

$$t_{IN} = \frac{1}{\left(\dfrac{3.317\cdot 10^{-5}\cdot\left[\mathrm{CO}\right]^{1.036}\cdot RMV}{I} + \dfrac{\left[\mathrm{HCN}\right]^{2.36}}{1.2\cdot 10^{6}\cdot}\right)V_{CO_2} + \dfrac{1}{\exp\left(8.13 - 0.54\left(20.9 - \left[\mathrm{O_2}\right]\right)\right)}} \tag{15.16}$$

Example 15.1 An escaping person is during 5 min exposed to an environment containing 1000 ppm CO, 0.5 % CO_2, and 20.2 % O_2 followed by a period with the composition 5000 ppm CO, 3 % CO_2 and 16.5 % O_2 during an additional 2.5 min. of exposure Calculate the total fraction of an incapacitating dose for the escaping person.

Solution: Since the asphyxiant effect of CO_2 is not additative to the effects of the other gases and becomes an asphyxiant above approximately 5 %, we do not include CO_2 in the calculations more than for the multiplying factor according to Eq. (15.13). This gives together with Eqs. (15.7), (15.10) and (15.11):

$$\begin{aligned} FI &= F_{I,0-5\,\mathrm{min}} + F_{I,5-7.5\,\mathrm{min}} = F_{I_{CO},0-5\,\mathrm{min}}\cdot V_{CO_2,0-5\,\mathrm{min}} + F_{I_{O_2},0-5\,\mathrm{min}} \\ &+ F_{I_{CO},5-7.5\,\mathrm{min}}\cdot V_{CO_2,5-7.5\,\mathrm{min}} + F_{I_{O_2},5-7.5\,\mathrm{min}} = \\ &= 0.177\cdot 1.105 + 0.002 + 0.470\cdot 1.822 + 0.008 = 1.06 \end{aligned}$$

Table 15.9 Required radiant exposure dose for different exposure dose endpoints [3]

r [(kW/m^2)$^{4/3}$]	Exposure dose endpoints
1.33	Tolerance limit, pain, first-degree burns
10	Severe incapacitation and second-degree burns
16.7	Fatal exposure and third-degree burns

This (FI > 1) means that it is probable that the escaping person will be incapacitated before reaching a safe haven.

The discussion above focused on the gas composition. However, the temperature (heat exposure) also affects an escaping occupant. There are mainly three different ways heat exposure can be a threat: body surface burns, hyperthermia and respiratory tract burns. The heat exposure can cause both incapacitation and death due to hyperthermia.

In dry air, respiratory tract burns do not appear without skin burns, that is, the tenability limits for skin burns are in most cases lower than corresponding limits for respiratory tract burns. However, in cases with air saturated with water vapour, respiratory tract burns can occur when inhaling air with a temperature higher than 60 °C [1]. A convective heat flow with a temperature above 120 °C could be very painful and give skin burns within minutes. The tenability limit for radiant heat flux on skin is, according to Purser, approximately 2.5 kW/m^2 [3]. The same level is used in the Swedish building regulations [15]. It has been noted that below this limit, the heat flux can be tolerated for at least several minutes and does not affect the possibilities for evacuation. However, at this level (2.5 kW/m^2) the radiation can be tolerable for approximately 30 s and for a radiation of 10 kW/m^2 the time limit is 4 s [3].

Above the level 2.5 kW/m^2 the time to different effects due to the exposure can be calculated by

$$t_{Irad} = \frac{r}{\dot{q}''^{4/3}} \tag{15.17}$$

where r is the radiant heat exposure dose [(kW/m^2)$^{4/3}$] required to reach a certain endpoint. In Table 15.9, values of r for some endpoints are given [3].

For convective heat, Purser presents a relationship that is the same as the one for a unclothed or lightly clothed person according to SS-ISO 13571:2012 [8]

$$t_{I_{conv\_L},n} = 5 \cdot 10^7 T^{-3.4} \tag{15.18}$$

where T is the gas temperature (°C). In the ISO standard, there is also an expression for exposure of convective heat for a fully clothed person:

$$t_{I_{conv\_F},n} = 4.1 \cdot 10^8 T^{-3.61} \tag{15.19}$$

The convective effect depends on the humidity and Eq. (15.18) tends to follow the 100 % humidity line (worst case). Purser also presented another equation for time tolerance under mid-humidity conditions [3]:

$$t_{tol} = 2 \cdot 10^{31} \cdot T^{-16.963} + 4 \cdot 10^{8} \cdot T^{-3.7561} \tag{15.20}$$

which also fits better to empirical data.

The selected equation for the effect of the convective heat exposure can be used together with Eq. (15.17) to calculate the fractional effective dose of heat:

$$\mathrm{FED} = \int_{t_1}^{t_2} \left(\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}} \right) \Delta t \tag{15.21}$$

15.6 Large-Scale Example of Fraction of an Incapacitation Dose

In 2003, tests were performed in the Runehamar tunnel [16–18] with a set-up simulating a heavy goods vehicle (HGV) with cargo. The tunnel is a 1600 m long abandoned road tunnel. During the four tests performed, different mixtures of cellulosic material and plastics were used as fuel. Gas was sampled at different heights at a measurements station, 458 m from the centre of the fire. Since some of the measurements are only available at the height 2.9 m above the road, all gas concentrations has been evaluated as this height. This is higher than the height representative for a person in the tunnel, but this choice was made to be able to compare the different contributions to the fraction of an incapacitating dose.

The HCN analyses are described by Brandt [19]. The HCN concentrations are affected with some uncertainties. The HCN concentration is, for example, below zero during different time periods in the tests T1, T3 and T4 (only positive values were used in the calculations). Therefore, the total fraction of an incapacitating dose is given both with and without the effect of HCN. For the calculation, Eqs. (15.6), (15.8) and (15.10) were used. In Fig. 15.1, the individual contributions of O_2 and CO, respectively, are presented separately for test T2 (mainly wood pallets and PUR mattresses). In Fig. 15.1, also the fraction of an incapacitating dose due to the asphyxiant effect of CO_2 (Eq. (15.15)) is included. This effect is not additive to the effect of the other gases and is not included in the total fraction of an incapacitating dose.

The HCN concentration significantly affects the time to incapacitation ($F_I = 1$). In these tests, incapacitation is quickly reached (within a few minutes from the start of the increase). In all four tests, significant amounts of HCN were produced. HCN is formed in a fire during combustion of nitrogen-containing materials. In the Runehamar test series, the polyurethane mattresses in test T2 are the most obvious nitrogen source (analyses show 4.6 % (by weight) is nitrogen). Further, the fuel was placed on particle boards in all the tests. The nitrogen content of these boards were

Fig. 15.1 Fraction of an incapacitating dose for asphyxiant gases analysed during test T2 in the Runehamar tunnel 2003 [18]

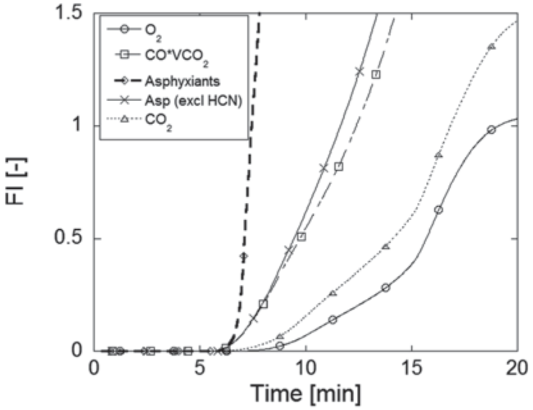
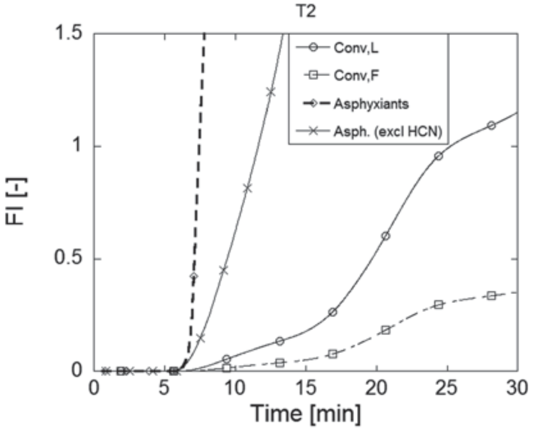


Fig. 15.2 Fraction of an incapacitating dose for convective heat exposure compared with asphyxiant gases for test T2 in the Runehamar tunnel test series from 2003 [18]



not analysed, but a nitrogen content of the order of a few percent has been reported in other cases [20, 21]. Wood also contains nitrogen, but to a lower extent, 0.1 to 0.2 % (by weight) [22, 20, 23]. The formation of HCN is affected by the combustion conditions. High temperatures and under-ventilated or vitiated condition favour the formation of HCN [24–26].

Even without HCN included, incapacitating dose is reached fairly quickly, approximately 5 min after the start of the increase. It should be noted that the transport time is not subtracted, that is, the time in the graphs is the time at the measurement station after ignition.

The fraction of an incapacitating dose (FI) for heat exposure based on the Runehamar test T2 is compared with the results for asphyxiant gases in Fig. 15.2. Incapacitating dose for a lightly clothed person (Conv, L) is reached after 25 min, that is, in T2 the convection curve is far behind the one for asphyxiant gases. In the case with a fully clothed person (Conv, F), the level of incapacitating dose is not reached. It should be remembered that the calculations presented here are based on measurements performed 458 m from the seat of the fire. The effect of the heat exposure will increase closer to the fire. In the work presented by Ingason et al. [27] it was shown that in most cases (scenarios), the temperature and radiation quickly increases above critical values for the occupants in the tunnel. Another conclusion from the same work was that the calculations showed a critical value of 75 MW above which it can be difficult for the occupants in the tunnel to reach the escape routes and survive the fire. If no evacuation is started, only the smallest fire (8 MW) can be survived. During a bus fire (25 MW), critical levels can be reached after long exposure times and for larger fires, the critical values are relatively rapidly reached. The occupants in the cases of no evacuation were assumed to be either 70 or 150 m from the fire.

The results given in this section should be seen as an example of the influence of gas composition and heat on the fraction of an incapacitating dose. The conditions in a specific situation during a fire in a tunnel are very complex and several parameters, for example, the degree of activity of the occupants, affect the results. It should also be noted that age and different kinds of impairment (For example, disease and physical conditions) significantly affects the critical COHb level (COHb levels found in victims) [4]. The results do confirm, however, the importance of the first minutes during a tunnel fire for the ability of the occupants in the tunnel to escape the incident. Note that, the criteria FI = 1 relates to a limit at which 50 % of the population would be expected to experience tenable conditions, while 50 % would be expected to experience compromised tenability [8]. Therefore, it is important to use more conservative numbers for a designer, authority or fire safety engineer. On the other hand, the fast increase (t^2) of many fires means that uncertainties due to variations in the individual susceptibility have a relatively small effect on the predicted times to incapacitation [3].

15.7 Irritant Gas Model

For evaluating the effect of irritant gases, often the concept of fractional effective concentration (FEC) is used. This means that the FEC is determined for each time step for each irritant and the time when the sum of the FEC for each irritant exceeds a certain threshold represents the time when a specific tenability limit is exceeded. This can be expressed as [8]

$$\begin{aligned}\mathrm{FEC} &= \frac{\mathrm{HCl}}{\mathrm{IC_{HCl}}}+\frac{\mathrm{HBr}}{\mathrm{IC_{HBr}}}+\frac{\mathrm{HF}}{\mathrm{IC_{HF}}}+\frac{\mathrm{SO_2}}{\mathrm{IC_{SO_2}}}+\frac{\mathrm{NO_2}}{\mathrm{IC_{NO_2}}}+\\ &+\frac{\mathrm{acrolein}}{\mathrm{IC_{acrolein}}}+\frac{\mathrm{formaldehyde}}{\mathrm{IC_{formaldehyde}}}+\sum\frac{\mathrm{irritant}}{\mathrm{IC_{irritant}}}\end{aligned} \tag{15.22}$$

Table 15.10 IC values for some irritants [8]

Irritant	IC (ppm)
HCl	1000
HBr	1000
HF	500
SO_2	150
NO_2	250
Acrolein	30
Formaldehyde	250

Table 15.11 Yields of some irritant gases from a car fire [28]

Irritant	Yield (g/kg)
HCl	2400
SO_2	5.0
Acrolein	<0.3
Formaldehyde	1.1

where the values of IC (incapacitating concentration) for each irritant represent a concentration (ppm) when the tenability is seriously compromised. In Table 15.10, values are presented for IC for the irritants in Eq. (15.22).

Except for HCl, many of the gases in Eq. (15.22) and Table 15.10 are not analysed for or not detected in most fire tests. Lönnermark and Blomqvist, however, reported yields for some of the species in connection with a car fire test [28]. These yields are presented in Table 15.11.

15.8 Acceptance Criteria

In Sect. 15.5, different aspects of tenability were presented. The fraction of an incapacitation dose can be used when modelling an evacuation situation in performance-based design using advanced computer models or one dimensional dynamic fire development and change in the tunnel environment at different positions. In addition to this, there are several sources of acceptance criteria or acceptable exposure. The main issue is to ensure safe egress. There are several different factors affecting escape from a tunnel. The parameters that will be included here are visibility, gas temperature, radiation and toxic gases. Visibility was also discussed in detail in Chap. 14.

Different acceptance criteria have been suggested for these parameters. In the EU project UPTUN an analysis of different aspects were performed and the values given in Table 15.12 were suggested [29].

Within a Swedish project aiming at developing a proposal for a Swedish performance-based design guide for fire safety in road tunnels different acceptance criteria were also discussed [30]. These are also included in Table 15.12. The Swedish

Table 15.12 Examples of acceptance criteria for different types of exposure

Parameter	UPTUN [29]	FKR-BV12 [30]	TRVR [31]	BBRAD1 [15]
Visibility	≥ 10 m		10 m in unknown env. 5 m in known env. Height below smoke layer > 1.6 m + H × 0.1 m	10 m in spaces > 100 m^2 5 m in spaces ≤ 100 m^2 Height below smoke layer > 1.6 m + H_{room} × 0.1 m
Gas temperature	≤ 60 °C	< 80 °C	< 80 °C	≤ 80 °C
Radiation (kW/m^2)	≤ 2 kW/m^2	< 2.5 kW/m^2	< 2.5 kW/m^2 or short duration of < 10 kW/m^2	≤ 2.5 kW/m^2
Toxic gases	$FI_{tot} < 1$[a]	$[CO_2]$ 5 % $[CO] > 2000$ ppm $[O_2] > 15$ % during max 1 min or FI_{tot} 0.3 (including at least CO, CO_2, O_2 and HCN)		$[CO_2] >$ 5 % $[CO] > 2000$ ppm $[O_2] > 15$ %
Heat			≤ 60 kJ/m^2 + the energy from a radiation of 1 kW/m^2	≤ 60 kJ/m^2 + the energy from a radiation of 1 kW/m^2

[a] In a similar way as described by Eq. (15.6)

Transport Administration (Trafikverket) has published advice related to technical requirements for road and rail tunnels in Sweden [31]. These are presented under TRVR in Table 15.12. For comparison also values to be used for performance-based (analytical) design of buildings in Sweden (BBRAD 1) [15] are included in Table 15.12.

In the UPTUN report, specific acceptance criteria were also given for the fire and rescue services [29]:

- Gas temperature ≤ 100 °C
- Radiation ≤ 5 KW/m^2
- Toxic gases: no limitation due to breathing apparatus (BA)
- Visibility: No limitation due to infra-red cameras

15.9 Summary

Occupants in a tunnel can during escape be exposed to different types of hazards. In this chapter, the most important consequences of exposure to main gas components, radiation and heat are presented. The effects of the most common asphyxiant (CO and HCN) and irritant gases are given. Since one of the most important issues during a fire in a tunnel is the possibility for a safe escape, different exposures affecting the escape are discussed. The effects often depend on both the concentration and the time of exposure. Different models for estimating time to incapacitation and other endpoints due to exposure are discussed. These models are useful when estimating the possibilities for escape from a fire situation. This is exemplified by using data from full-scale fire tests. In some guidelines, there are absolute levels given for exposure and in this chapter some such examples are given and discussed.

References

1. Hull TR, Stec AA (2010) Introduction to fire toxicity. In: Stec A, Hull R (eds) Fire Toxicity. CRC
2. Tan K-H, Wang T-L (2005) Asphyxiants: Simple and Chemical. Annals of Disaster Medicine 4 (1):S35-S40
3. Purser DA (2008) Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. The SFPE Handbook of Fire Protection Engineering, 4th ed. edn. Quincy: National Fire Protection Association., 2–96 -- 2–193
4. Nelson GL (1998) Carbon Monoxide and Fire Toxicity: A Review and Analysis of Recent Work. Fire Technology 34 (1):39–58
5. Varon J, Marik PE, Fromm RE, Gueler A (1999) Carbon Monoxide Poisoning: A Review for Clinicians. The Journal of Emergency Medicine 17 (1):87–93
6. EPA (2012) Acute Exposure Guideline Levels (AEGLs): Hydrogen fluoride Results. United States Environmental Protection Agency, http://www.epa.gov/oppt/aegl/pubs/results53.htm, Updated Jan. 11 2012, Accessed Jan. 14 2014
7. Acute Exposure Guideline Levels for Selected Airborne Chemicals, Volume 4 (2004).
8. ISO (2012) Life-threatening components of fire – Guidelines for the estimation of time to compromised tenability in fires. International Organization for Standardization, SS-ISO 13571:2012
9. IDLH (1994) Documentation for Immediately Dangerous To Life or Health Concentrations (IDLHs) – Chemical Listing and Documentation of Revised IDLH Values (as of 3/1/95). NIOSH
10. AFS (2011) Occupational Exposure Limit Values. The Swedish Work Environment Authority, AFS 2011:18
11. ISO (2004) Estimation of the lethal toxic potency of fire effluents. International Organization for Standardization, ISO 13344, Second edition
12. Levin BC, Paabo M, Gurman JL, Clark HM, Yoklavich MF Further Studies of the Toxicological Effects of different Time Exposures to the Individual and Combined Fire Gases: Carbon Monoxide, Hydrogen Cyanide and Reduced Oxygen. In: Polyurethane ’88, Proceedings of the 31st Society of Plastics Meeting, Lancaster, PA, 1988. Technomic Publishing Co., pp 249–252

13. Purser DA (2010) Toxic hazard calculation models for use with fire effluents data. In: Stec A, Hull R (eds) Fire toxicity. CRC
14. Purser D (2014) Models for toxicity and tenability limits. Personal communication, Jan. 5,
15. BFS (2011) Boverkets allmänna råd om analytisk dimensionering av byggnaders brandskydd. Boverkets Författningsamling, BFS 2011:27 BBRAD 1 (in Swedish)
16. Ingason H, Lönnermark A, Li YZ (2011) Runehamar Tunnel Fire Tests. SP Technicial Research Institute, SP Report 2011:55
17. Ingason H, Lönnermark A (2005) Heat Release Rates from Heavy Goods Vehicle Trailers in Tunnels. Fire Safety Journal 40:646–668
18. Lönnermark A (2005) On the Characteristics of Fires in Tunnels. Doctoral Thesis, Doctoral thesis, Department of Fire Safety Engineering, Lund University, Lund, Sweden
19. Brandt AB Presentation of test result from large scale fire tests at the Runehamar tunnel. In: Ingason H (ed) International Symposium on Catastrophic Tunnel Fires (CTF), SP Report 2004:05, Borås, Sweden, 20–21 November 2003. SP Swedish National Testing and Research Institute, pp 117–120
20. Lighty JS, Pershing DW (1993) Control of Pollutant Emissions from Waste Burning. University of Utah, Project number AQ93-4
21. Risholm-Sundman M, Vestin E (2005) Emissions during combustion of particleboard and glued veneer. Holz als Roh- und Werkstoff 63:179–185
22. Grønli M (1996) A Theoretical and Experimental Study of the Thermal Degradation of Biomass. Doctoral Thesis, The Norwegian University of Science and Technology, Trondheim, Norway
23. Zevenhoven R, Axelsen EP, Kilpinen P, Hupa M Nitrogen oxides from nitrogen-containing waste fuels at FBC conditions – Part 1. In: The 39th IEA FBC meeting, Madrid, Spain, 22–24 November 1999.
24. Simonson M, Tuovinen H, Emanuelsson V (2000) Formation of Hydrogen Cyanide in Fires – A Literature and Experimental Investigation. SP Swedish National Testing and Research Institute, Borås, Sweden
25. Tuovinen H, Blomqvist P (2003) Modelling of Hydrogen Cyanide Formation in Room Fires. SP Swedish National Testing and Research Institute, Borås, Sweden
26. Hansson K-M, Samuelsson J, Tullin C, Åmand L-E (2004) Formation of HNCO, HCN, and NH3 from the pyrolysis of bark and nitrogen-containing model compounds. Combustion and Flame 137:265–277
27. Ingason H, Bergqvist A, Lönnermark A, Frantzich H, Hasselrot K (2005) Räddningsinsatser i vägtunnlar. Räddningsverket,
28. Lönnermark A, Blomqvist P (2006) Emissions from an Automobile Fire. Chemosphere 62:1043–1056
29. Ingason H (ed) (2005) TG2.2– Target criteria. UPTUN Report WP2– task Group 2,
30. Gehandler J, Ingason H, Lönnermark A, Frantzich H, Strömgren M (2013) Performance-based requirements and recommendations for fire safety in road tunnels (FKR-BV12). SP Technical Research Institute of Sweden
31. TRV (2011) TRVR Tunnel 11: Trafikverkets tekniska råd Tunnel. Trafikverket, TRV publ nr 2011:088 (in Swedish)