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Appendix 1. Comparison between the ISO standard, SFPE Handbook and AEGL

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The ISO standard (ISO 13571, 2012), the SFPE Handbook (Purser & McAllister, 2016) and the Acute Exposure Guidelines (AEGL) (National Research Council, 2001) have established methods for determining threshold values for when people's possibility of escape and survivability are threatened. These methods are discussed and compared for the individual fire conditions below.

A. Toxic gases

Irritant gases

ISO standard

The ISO standard uses the FEC method for irritant gases to determine the combined influence of irritant gases (HCl, HBr, HF, SO_2, NO_2, acrolein and formaldehyde) on the possibility of escape and survivability. In this method, the sum is taken of the FEC values for the individual irritant gases (see equation 1). The uncertainty of this equation is approx. 50%.

$$FEC_{irr} = \frac{\varphi_{HCl}}{F_{HCl}} + \frac{\varphi_{HBr}}{F_{HBr}} + \frac{\varphi_{HF}}{F_{HF}} + \frac{\varphi_{SO_2}}{F_{SO_2}} + \frac{\varphi_{NO_2}}{F_{NO_2}} + \frac{\varphi_{acroleine}}{F_{acroleine}} + \frac{\varphi_{formaldehyde}}{F_{formaldehyde}} + \sum \frac{\varphi_{irriterend\ gas}}{F_{C_i}}$$

φ the average concentration of the irritant gas in $\mu L \cdot L^{-1}$;

F the concentration of each irritant gas expected to significantly reduce the possibility of escape and survivability, in $\mu L \cdot L^{-1}$.

Equation 1 FEC method for irritant gases

The ISO standard lists threshold values[1] for the irritant gas concentrations which are expected to be life-threatening to people who are exposed to them (F values in equation 1). These threshold values are shown in table 1. The situation becomes life-threatening when the value of FEC_{irr} becomes equal to or greater than sf*1.

SFPE Handbook

The SFPE Handbook uses the FIC method for irritant gases. However, the equation for this method is similar to the equation for the FEC method in the ISO standard (see equation 1). The only difference is that the concentrations are given in ppm[2]. In describing this method, the SFPE Handbook not only mentions threshold values[3] for the irritant gas concentrations for the life-threatening situation[4], but also for the impaired escape situation and fatal situation after 30 minutes (see table 1). Starting from the threshold value for impaired escape, an FIC

[1] These threshold values were determined by analysing data from various sources and guidelines (ISO 13571, 2012).

[2] Based on the general gas law, 1 $\mu L \cdot L^{-1}$ is approximately equal to 1 ppm.

[3] The physiological algorithms in the SFPE Handbook are based partly on experimental data and reported effects with people and partly on animal experiments (Purser & McAllister, 2016).

[4] The literal term used in both the SFPE Handbook and the ISO standard is incapacitation. We have chosen for life-threatening, because the person can no longer save himself or herself and is therefore in a life-threatening situation. Furthermore, 'life-threatening' is a more common term.

value of sf*1 represents an impaired escape and an FIC value of sf*5 represents a life-threatening situation.
In addition to the FIC method, the SFPE Handbook mentions the FLD method to calculate fatal effects of irritant gases. This method is based on a dose rather than a concentration and the FLD value is therefore included in the method for asphyxiant gases (see equation 5). The equation is similar to the equation for the FEC / FIC methods for irritant gases, however the fatal dose as presented in table 1 is used as the threshold value. Here, the exposure time is taken into account for the concentration. An FLD value of sf*1 represents a fatal situation.

Table 1 Threshold values for irritant gas concentrations according to the ISO standard and the SFPE Handbook

	SFPE	SFPE	ISO	SFPE
	Impaired (ppm)	Life-threatening (ppm)		Fatal dose (ppm·min)
HCl	200	900	1000	114,000
HBr	200	900	1000	114,000
HF	200	900	500	87,000
SO_2	24	120	150	12,000
NO_2	70	350	250	1900
NO	-	>1000	-	~30,000
CH_2CHO (acrolein)	4	20	30	4500
HCHO (formaldehyde)	6	30	250	22,500

AEGL

The threshold values of AEGL-1, AEGL-2 and AEGL-3 for the irritant gases with exposure times of 10 and 30 minutes are shown in table 2.[5] Only these two exposure times are shown because the primary concern of this research is the time people have to escape and survive in the event of fire and this often involves short time periods.

[5] The threshold values of the AEGL method cannot directly be related to the classification of threshold values in the SFPE Handbook and the ISO standard because the descriptions of the different levels of the AEGL method differ from the levels described in Table 1. The tables therefore show the levels of the AEGL method.

Table 2 AEGL threshold values for irritant gases

	AEGL-1		AEGL-2		AEGL-3	
	10 min (ppm)	**30 min (ppm)**	**10 min (ppm)**	**30 min (ppm)**	**10 min (ppm)**	**30 min (ppm)**
HCl	1.8	1.8	100	43	620	210
HBr	1.0	1.0	250	83	740	250
HF	1.0	1.0	95	34	170	62
SO_2	0.20	0.20	0.75	0.75	30	30
NO_2	0.50	0.50	20	15	34	25
NO	-	-	-	-	-	-
CH_2CHO (acrolein)	0.03	0.03	0.44	0.18	6.2	2.5
HCHO (formaldehyde)	0.9	0.9	14	14	100	70

Asphyxiant gases

An overview of the concentrations of asphyxiant gases (CO, HCN, low O_2 and CO_2) which can be life-threatening or fatal to a person who is in a state of light activity after exposure for approximately 5 and 30 minutes is shown in table 3 (Purser & McAllister, 2016).

Table 3 Life-threatening and fatal concentrations of asphyxiant gases

	5 min		30 min	
	Life-threatening	Fatal	Life-threatening	Fatal
CO (ppm)	6000-8000	12,000-16,000	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 (%)	7-8	> 10	6-7	> 9

ISO standard

According to the ISO standard, the combined influence of asphyxiant gases can be determined using the FED method in which the sum is taken of the FED values for the individual asphyxiant gases. The general equation for this method is shown in equation 2.

$$FED = \sum_{i=t}^{n} \sum_{t_1}^{t_2} \frac{C_i}{(C \cdot t)_i} \Delta t$$

C_i the average concentration of an asphyxiant gas i in $\mu L \cdot L^{-1}$;

Δt the chosen time increment in minutes;

$(C \cdot t)_i$ the exposure dose ($\mu L \cdot L^{-1} \cdot min$) threatening the possibility of escape and survivability.

Equation 2 General FED method for asphyxiant gases

The ISO standard indicates that CO and HCN are the only asphyxiant gases with a significant effect on the possibility of escape and survivability of people who are exposed to them and therefore only CO and HCN are taken into account in the FED method. However, the possibility of hyperventilation is also taken into account. Therefore, the average concentration of each asphyxiant gas is multiplied by the frequency factor (v_{CO2}) in the FED method (see equation 3). The uncertainty of this equation is approx. 20%.

$$v_{CO_2} = exp\left[\frac{\varphi_{CO_2}}{5}\right]$$

φ_{CO2} the average volume percentage CO_2 during the chosen time increment.

Equation 3 Calculation of the frequency factor (v_{CO2})

The FED method according to the ISO standard in which both CO and HCN and the frequency factor are taken into account is shown in equation 4.[6] The uncertainty of this equation is approx. 35%. The situation becomes life-threatening when the value of FED_{tox} becomes equal to or greater than sf*1.

$$FED_{tox} = \sum_{t_1}^{t_2} \frac{\varphi_{CO} \cdot v_{CO_2}}{35000} \Delta t + \sum_{t_1}^{t_2} \frac{{\varphi_{HCN}}^{2.36} \cdot v_{CO_2}}{1{,}2 \cdot 10^6} \Delta t$$

φ_{CO} the average CO concentration in $\mu L \cdot L^{-1}$ over the chosen time increment;

φ_{HCN} the average HCN concentration in $\mu L \cdot L^{-1}$ over the chosen time increment;

Δt the chosen time increment, in minutes.

Equation 4 FED method for asphyxiant gases according to the ISO standard

SFPE Handbook

The FED method according to the SFPE Handbook takes into account the asphyxiant effect of CO and HCN, and the influence of hyperventilation, as well as the asphyxiant effect of low O_2 and nitrogen oxides, and the fatal dose of irritant gases (see equation 5).[7] However, the direct contribution of nitrogen oxides is often small and field research has shown that low O_2

[6] The threshold value for the CO dose was determined using experiments with juvenile baboons. The threshold value for the HCN dose was determined using experiments with cynomolgus monkeys. Further information can be found in the ISO standard (ISO 13571, 2012).

[7] The physiological algorithms in the SFPE Handbook are based partly on experimental data and reported effects with people and partly on animal experiments (Purser & McAllister, 2016).

and the fatal dose of irritants have little effect on the total FED value. The FED method assumes an adult who is doing light work.

$$F_{IN} = \left(F_{I_{CO}} + F_{I_{Cn}} + F_{I_{NO_x}} + FLD_{irr}\right) \times v_{CO_2} + F_{I_O}$$

F_{ICO} FED value for CO, assuming a life-threatening dose;
F_{ICN} FED value for HCN, assuming a life-threatening dose;
F_{INOx} FED value for nitrogen oxides, assuming a life-threatening dose;
FLD_{irr} FED value for a fatal dose of irritant gases;
v_{CO2} frequency factor;
F_{IO} FED value for low O_2, assuming a life-threatening dose.

Equation 5 FED method for asphyxiant gases according to the SFPE Handbook

According to the SFPE Handbook, an FED_{IN} value of sf*1 represents a life-threatening situation, and an FED_{IN} value of sf*2 represents a fatal situation. The equations below show how to calculate the FED value of CO (see equation 6), HCN (see equation 7), NO_x (see equation 8) and low O_2 (see equation 9).

$$F_{I_{CO}} = 3{,}317 \times 10^{-5} [CO]^{1{,}036} (v_E)(t)/D$$

[CO] CO concentration in ppm;
v_E respiratory ventilation per minute in $L \cdot min^{-1}$, 25 $L \cdot min^{-1}$ for light work;
t exposure time in minutes;
D exposure dose (%COHb) for a life-threatening situation, 30 %COHb for light work.

Equation 6 Calculation of the FED value for CO

$$F_{I_{CN}} = \frac{[CN]^{2{,}36}}{1{,}2 \times 10^6} t$$

[CN] HCN concentration in ppm;
t exposure time in minutes.

Equation 7 Calculation of the FED value for HCN

$$F_{I_{NO_x}} = \frac{[NO_x]t}{1500}$$

$[NO_x]$ nitrogen oxide concentration in ppm;
t exposure time in minutes.

Equation 8 Calculation of the FED value for NO_x

$$F_{I_O} = \frac{t}{exp[8{,}13 - 0{,}54(20{,}9 - [\%O_2])]}$$

[$\%O_2$] O_2 concentration in volume percent (% v/v)

t exposure time in minutes

Equation 9 Calculation of the FED value for low O_2

AEGL

The AEGL assumes the threshold values for asphyxiant gases shown in table 4 for the three levels and exposure times of 10 and 30 minutes.

Table 4 AEGL threshold values for asphyxiant gases

	AEGL-1		AEGL-2		AEGL-3	
	10 min (ppm)	**30 min (ppm)**	**10 min (ppm)**	**30 min (ppm)**	**10 min (ppm)**	**30 min (ppm)**
CO	-	-	420	150	1700	600
HCN	2.5	2.5	17	10	27	21

B. Heat

An overview of the tolerance of exposure to both radiant and convected heat is shown in table 5 (Fire Service Academy, 2015).

Table 5 Tolerance of exposure to radiant and convected heat

Radiant heat		Convected heat	
Radiant heat flux ($kW \cdot m^{-2}$)	**Maximum dwell time**	**Temperature (°C)**	**Maximum dwell time**
15	2 seconds	200	2 minutes
8	5 seconds	150	5 minutes
6	7 seconds	120	7 minutes
2.5	> 30 seconds	110	10 minutes
		100	15 minutes
		90	> 30 minutes

ISO standard

According to the ISO standard, the effect of heat on the possibility of escape and survivability can be considered from the dose of heat that the body is subjected to during a certain period of time. Therefore, this effect can be calculated using the FED method, which takes into account both the effect of radiant heat and that of convected heat.

The ISO standard provides two equations for calculating the effect of radiant heat, i.e. the time until pain is experienced (see equation 10) and the time until second-degree burns develop (see equation 11). The uncertainty of both equations is approx. 25%.

$$t_{Irad} = 4{,}2q^{-1{,}9}$$

q radiant heat flux in $kW \cdot m^{-2}$

Equation 10 Time until pain is experienced due to radiant heat

$$t_{Irad} = 6{,}9q^{-1{,}56}$$

Equation 11 Time until second-degree burns develop due to radiant heat

In addition, the ISO standard suggests two equations for calculating the effect of exposure to convected heat with a humidity of 10%. They distinguish between how much clothing the exposed person is wearing, i.e. the moment when pain is experienced if the person is fully clothed (see equation 12) and if the person is unclothed or lightly clothed (see equation 13). The uncertainty of both equations is approx. 25%.

$$t_{Iconv} = (4{,}1 \times 10^{8})T^{-3{,}61}$$

T the temperature in degrees Celsius.

Equation 12 Exposure to convected heat when fully clothed

$$t_{Iconv} = (5 \times 10^{7})T^{-3{,}4}$$

Equation 13 Exposure to convected heat when unclothed or lightly clothed

Subsequently, the FED method consists of the sum of the FED values for radiant heat and convected heat (t_{Irad} and t_{Iconv} reversed) (see equation 14). If the radiant heat is less than 2.5 $kW \cdot min^{-2}$, the FED value for radiant heat ($1/t_{Irad}$) is equal to 0 in this equation. When FED_{heat} reaches or exceeds a value of sf*1, the situation becomes life-threatening for any people exposed.

$$FED_{heat} = \sum_{t_1}^{t_2} \left(\frac{1}{t_{Irad}} + \frac{1}{t_{Iconv}} \right) \Delta t$$

Equation 14 FED method for exposure to heat

SFPE Handbook
The SFPE Handbook uses the same equation for the FED method for exposure to heat as the ISO standard (see equation 14). However, the equation to calculate the effect of exposure to radiant heat is different (see equation 15). In addition, for the effect of exposure

to convected heat, the SFPE Handbook only presents the equation for people who are unclothed or lightly clothed (see equation 13).

$$t_{Irad} = \frac{r}{q^{1,33}}$$

r radiant heat exposure dose in $(kW \cdot m^{-2})^{4/3}$min

q radiant heat flux in $kW \cdot m^{-2}$

Equation 15 Exposure to radiant heat

The effect of different values for the radiant heat exposure dose are shown in table 6.

Table 6 Effect of radiant heat exposure dose

Effect	r $[(kW \cdot m^{-2})^{4/3}$min]
Severe skin pain	1.33-1.67
Second-degree burns	4.0-12.2
Third-degree burns	16.7

According to the SFPE Handbook, assuming a radiant heat exposure dose for severe skin pain (r = 1.33), a FED value of sf*1 represents impaired escape, a FED value of approx. sf*8 represents second-degree burns and thus a life-threatening situation, and a FED value of approx. sf*12 represents third-degree burns and thus a fatal situation.

C. Visibility

The ISO standard does not state any threshold values for the influence of visibility on the possibility of escape and survivability of exposed people. According to the SFPE Handbook, the effect of visual obscuration due to smoke can be calculated using the FEC method, which distinguishes between small and large rooms (see equation 16). The possibility of escape for the exposed person becomes significantly impaired when the value of FEC_{smoke} becomes equal to or greater than sf*1.

$$FEC_{smoke} = \frac{(OD/m)}{0.2} \; for \; small \; rooms \; or \; \frac{(OD/m)}{0.08} \; for \; large \; rooms$$

OD/m optical density per metre

Equation 16 FEC method for visibility through smoke

An overview of the threshold values for visibility in both small and large rooms, expressed in optical density per metre, is given in table 7.

Table 7 Threshold values for visibility through smoke in buildings

Size of the room	Threshold value (OD/m)	Visibility (m)
Small	0.2	5
Large	0.08	10

D. Conclusion

The possibility of escape and survivability of people exposed to toxic gases, heat and visual obscuration because of smoke due to a fire were examined using the guidelines and threshold values in the ISO standard, the SFPE Handbook and the AEGL. Since the AEGL assumes concentrations at specific exposure times and there will be time-dependent concentrations in the experiments, the AEGL is not easy to apply in the current research. Therefore, the ISO standard and the SFPE Handbook match our purposes better. They have been summarized in table 8. Since the SFPE Handbook discusses the most complete and up-to-date method for determining the possibility of escape and survivability for exposed people, it has been decided to follow the SFPE Handbook in this research.

Table 8 Overview of threshold values according to the ISO standard and the SFPE Handbook

Fire condition	Standard	Method	Impaired	Life-threatening	Fatal
Irritant gases	ISO	FEC_{irr}		sf * 1	
	SFPE	FIC FLD	sf * 1	sf * 5	 sf * 1
Asphyxiant gases	ISO	FED_{tox}		sf * 1	
	SFPE	FED_{IN}		sf * 1	sf * 2
Heat	ISO	FED_{heat}		sf * 1	
	SFPE	FED_{heat}	sf * 1	sf * 8	sf * 12
Visibility	ISO	-			
	SFPE	FEC_{smoke}	sf * 1		

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