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ACCEPTANCE CRITERIA IN FIRE SAFETY ENGINEERING: A REVIEW AND CASE STUDY

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INTRODUCTION

The gradual transition from prescriptive to performance-based regulations has led to a worldwide development of methods and techniques for designing and verifying the fire life safety performance of buildings as well as transportation infrastructure. In the early days of performance based regulation, many countries did not include quantitative performance criteria. In addition, the conditions under which the building/system should be tested were often ill-defined. As a result, many countries have experienced considerable variability in the application of fire safety engineering, and the level of fire safety provided in the resulting buildings/systems can also be expected to vary.

Today, verifying safe egress in a building can be accomplished using several methods, such as qualitative, scenario-based or risk-based. The qualitative methods are often limited to isolated simple scenarios where the effects of any deviation from the prescriptive code can easily be identified, and there is little effect on the overall fire safety in the building. Risk-based methods are better suited for more complex analyses and deviations, but are, on the other hand, often limited by the lack of acceptance criteria and limited input data. Therefore, scenario-based analysis has become common practice when verifying safe egress in a building or transportation infrastructure.

In summary, scenario-based analysis means that a number of fire and evacuation scenarios are identified, analyzed and assessed using more or less advanced calculations. Typically, these include an analysis of people's ability to safely evacuate the infrastructure without being exposed to untenable conditions according to the so-called egress time-line model. In practical terms, this means that the required safe escape time (RSET) is compared to the available safe escape time (ASET), which typically is defined by a number of absolute tenability conditions, for each scenario in more or less independent fire and evacuation calculations or simulations.

More advanced techniques also exist for scenario-based analysis, which offer the possibility to consider the impact of toxic gases on humans. The toxic dose that is absorbed by inhalation can, for example, be calculated by considering the concentration of the gases and the exposure time. A commonly used technique for this is to assess the accumulated dose of irritating and/or toxic gases and compare them to the doses resulting in incapacitation or death according to the so-called fractional effective dose (FED) concept.

Absolute tenability conditions

The ASET is commonly based on absolute values as tenability acceptance criteria. This typically includes evaluating the results from a CFD or two-zone model against a number of pre-defined variables. The variable that reaches the acceptance criteria first will define the ASET. In practice, discrete acceptance criteria, although often conservative, are widely used because they are simple to work with, have low sensitivity to variations in the combustibles, and are generally well accepted.

From a global perspective, a standard set of tenability acceptance criteria does not exist in the fire safety engineering community. This has been previously identified and discussed by Koffel (2014). As an example, the criterion of clear smoke layer height varies between 1.80 to 2.50 meters depending on country (IRCC, 2007). The Confederation of Fire Protection Associations Europe (CFPA Europe) has undertaken efforts to develop common fire safety guidelines for European countries (CFPA, 2018), although specific criteria still varies within the member countries.

Some countries have absolute values as acceptance criteria defined in their regulations. As an example, Table 1 compares tenability criteria for the Swedish building regulations with the New Zealand Building Code (NZBC), which illustrates the above-mentioned variation for different criteria.

Table 1 Comparison of acceptance criteria in the Swedish and New Zealand building regulations.

Criteria	**Swedish building regulations(1)** BBRAD 3	**New Zealand Building Code(1)** C/VM2
Smoke layer above floor level	Smoke layer > 1.6 + (ceiling height)*0.1 [m]	-
Visibility	Visibility > 10 m (spaces > 100 m^2)	Visibility(2) > 10 m (spaces > 100 m^2)
Visibility	Visibility > 5 m (spaces < 100 m^2 or spaces where queuing start early in the evacuation)	Visibility(2) > 5 m (spaces < 100 m^2)
Thermal radiation	Radiation < 2.5 kW/m^2 or a short-term radiation of < 10 kW/m^2 combined with a maximum energy dose of < 60 kJ/m^2 in excess of the energy from a radiation level of 1 kW/m^2	Requirements for radiation exposure along egress routes.
Temperature	Temperature < 80 °C	$FED_{thermal}$ criteria specified
Carbon monoxide toxicity	[CO] < 2000 ppm	FED_{CO} criteria specified
Carbon Dioxide toxicity	[CO_2] < 5%	-
Oxygen availability	[O_2] > 15%	-
FED	-	FED_{CO} < 0.3 $FED_{thermal}$ < 0.3(2)

(1) Criteria assessed at 2.0 meters above the walking surface.
(2) For the NZBC this criteria does not apply if the building is sprinkler protected with fewer than 1000 people.

The Swedish recommendations allow the designer to choose whether smoke layer height or visibility should be used to evaluate the ASET (Boverket, 2013). Generally the visibility criteria is first exceeded and determines the ASET, but the designer has an obligation to demonstrate that the other criteria in Table 1 remain acceptable in that time. Noteworthy is that the Swedish recommendations also provide inputs for the fire size, growth rate, CO, CO_2 and soot yields and the heat of combustion. In the NZBC, tenability values are specified as performance criteria as part of the verification method (Ministry of Buisness Innovation and Employment, 2017). The absolute acceptance level of visibility is the same as in the Swedish recommendations although absolute toxicity and temperature limits are not defined. However, the NZBC differs from the Swedish recommendations since FED_{CO} and $FED_{thermal}$ must also be evaluated, although there are exceptions where only FED_{CO} must be considered. The NZBC also provides specific inputs for the fire scenario similar to the Swedish recommendations.

The Swedish and New Zealand examples highlight the differences in global tenability acceptance criteria. The Swedish recommendations primarily includes absolute tenability criteria that take no account of cumulate effects, whereas the NZBC provides a mix of absolute criteria for visibility and a cumulative FED approach for CO and thermal effects. However, for both these countries the defined acceptance criteria and fire parameters mean that undertaking fire life safety assessments in accordance with the respective regulations is relatively straightforward.

FED tenability acceptance criteria

As discussed in the previous chapter, untenable conditions can be defined by acceptance criteria related to absolute values, for example, impaired visibility. This is particularly true for the fire safety design process linked to traditional buildings. However, as concluded by Nystedt (Nystedt, 2011), some design situations require alternative measures than, for example, visibility to assess the consequences of a certain fire scenario. One such design situation is the fire safety design of transportation infrastructure, such as road and rail tunnels.

As an example, there has been a rather long tradition to apply the FED concept to evaluate life safety in rail tunnels in Sweden. This is due to the fact that the Swedish Rail Administration over a decade ago stipulated that passengers onboard a train, for most scenarios (including fire) should be able to self-evacuate if a train comes to a stop in a tunnel (Banverket, 2007). Regarding asphyxiant gases (CO, CO_2, HCN and low O_2), this was deemed verified if an FED analysis regarding incapacitation[1] could show that the accumulated FED fell below 1.0[2]. Today, the performance criteria for road and rail tunnels regarding self-evacuation is more or less the same, however, the Swedish Transport Administration[3] (formerly the Swedish Rail Administration) does not stipulate explicit acceptance criteria related to the FID analysis typically carried out in the fire safety design process (Trafikverket, 2016) (Trafikverket, 2016). Neither is this stipulated in any regulations related to road or rail tunnels published by the Swedish Transport Agency (Transportstyrelsen, 2015) (EU, 2014). This is similar to the approach taken in NFPA 130 (NFPA, 2017) and NFPA 502 (NFPA, 2017), in which it is described in appendices how the FED concept can be applied for CO and heat in order to verify life safety, but also explicitly stated that the approach is not a part of the requirements of the documents, but is included for informational purposes only.

Thus, in Sweden today, the responsibility lies with the tunnel designer to assess both the methodology to use, which asphyxiant (and/or irritant) gases to consider, as well as the acceptable accumulated dose to verify life safety against (Trafikverket, 2016) (Trafikverket, 2016). In recent tunnel projects in Sweden, this has typically been done by evaluating the effects of CO, CO_2 and low O_2, but not HCN, and self-evacuation has been deemed satisfied when the accumulated FID is below 0.3. This corresponds to a recommendation provided in the Swedish Transport Agency's regulation regarding life safety requirements for metro systems in Sweden (Transportstyrelsen, 2018). Notable

[1] An FED analysis regarding incapacitation is typically expressed as a FID analysis, which is an abbreviation for fractional incapacitation dose.

[2] An accumulated FED corresponding to 1.0 translates to 50 % of the population being susceptible, and, therefore, statistically estimated to experience compromised tenability; 0.3, translates to 11.4 % (ISO, 2012).

[3] The Swedish Transport Administration specifies requirements for, and verifying the safety of, tunnels ordered by the Administration. However, they have no legal mandate. Today, the Swedish Transport Agency has the authority to publish such regulations for tunnels.

is, however, that this contradicts a proposal for a Swedish performance-based design guide for fire safety in road tunnels presented in 2012. In this proposal, it was suggested that the fractional dose for toxic gases should consider at least the effects of CO, CO_2, HCN and low O_2, with an acceptance criteria corresponding to an accumulated FID < 0.3 (Gehandler, Ingason, Lönnermark, & Strömgren, 2013).

Although not as common, recommendations and regulations stipulating tenability criteria assuming a FED concept do exist also for buildings. One example is given by a practice note published by the Society of Fire Safety, NSW Chapter, Engineers Australia (Society of Fire Safety NSW Chapter - Engineers Australia, 2014). In the note it is recommended that a FED methodology to evaluate the tenability conditions for situations where the occupants may be exposed to smoke for longer durations of up to 30 minutes (i.e., similar to a scenario expected in tunnels). A FED criteria corresponding to 1.0 is mentioned as suitable, but no further information regarding which asphyxiant gases to consider is given. Another example is a published document by British Standards, which provides information on engineering methods to verify life safety. Again, no recommendation regarding which gases to consider in a FED analysis is given, but in contrast to the above-mentioned practice note, an accumulated sum of asphyxiant gases < 0.3 is stated to represent an acceptable incidence of incapacitation (BSI, 2004). A final example is the framework for fire safety design for the NZBC (Ministry of Buisness Innovation and Employment, 2017). As a fire modelling rule, it is stated that FED for CO and thermal effects shall be calculated using the procedures described in ISO 13571 (ISO, 2012), and that the FED for CO shall include contributions from CO, CO_2 and O_2 gases. FED thermal shall include radiative and convective effects. Furthermore, it is explicitly stated that evacuating occupants are not exposed to accumulated FEDs greater than 0.3.

Considering the above, it is evident that acceptance criteria regarding asphyxiant gases, evaluated with a FED concept, varies (this is true also for when irritant gases and thermal effects are analysed with the same concept). Thus, there's a fairly well verified and validated technique to assess the consequences using a FED methodology (ISO, 2012), however, the definition of what is tenable conditions, and which aspects (gases) to assess to derive it, seems to vary between sources and countries. Another problem related to the FED concept is that information regarding input to the analysis is scarce. As an example, the basic principle for assessing the asphyxiant component of toxic hazard involves the determination of the exposure dose of each asphyxiant gas, i.e. the integrated area under the concentration-time curve. To model this, reliable information regarding the production of the different species, i.e., the yields, is necessary.

A summary of common combustible items and composition in buildings, as well as the expected combustion products produced when these materials are burnt, have been presented by Jeong (2014). However, the yields of almost all narcotic and irritant products are highly dependent on fire conditions (Stec, Hull, Purser, Blomqvist, & Lebek, 2008). Furthermore, reliable information regarding yields is seldom reported in, for example, test reports of building products, etc. (or are not made publicly available). Exceptions regarding mixed fuels include a report of room-scale tests for both pre- and post-flashover burning of sofas, bookcases and cables, in which detailed yields for CO, CO_2, HCN, HCl, NO_2, acrolein and formaldehyde have been documented (Gann, Averill, Marsh, & Nyden, 2007) (Gann, Averill, Johnsson, Nyden, & Peacock, 2003). Somewhat vaguer information on CO, CO_2 and HCN yields is made available in a report on experiments on upholstered chairs and mattresses performed by SP within the CBUF-project (Gann, o.a., 2001). In addition, Ingason et al. (2015) have summarized yields of CO for some common materials, such as wood, paper, and textiles. Another source of particularly CO and CO_2 yields is a summary of Särdqvist (1993), who reports data from other literature sources. Information about emissions of plastic materials, cables, and other both homo- and heterogeneous fuels can be found in, for example, the SFPE Handbook (Tewarson, 2008). Finally, emissions from fires in vehicles and tunnels is summarized in the Tunnel Fire Dynamics handbook (Ingason, Li, & Lönnermark, 2015).

In some instances, regulations contain recommendations on which yields to assume. As mentioned above, this is, for example, the case with the Swedish National Board of Housing's general recommendations on the analytical design of a building's fire protection[4] (Boverket, 2013). The recommendation includes design values regarding yields for soot, CO and CO_2 for different types of fires, and the recommended yields are based on a material consisting of both wood and plastic. Yield recommendations are also available in the given in the New Zealand Building Code (Ministry of Buisness Innovation and Employment, 2017), but, as for the absolute tenability criteria, differ a bit from the corresponding Swedish recommendations.

PURPOSE, GOALS AND METHODOLOGY

The purpose of the work presented in this paper is to investigate the consequences of applying different methods and acceptance criteria to verify fire life safety. The goals are to identify and discuss:

1. How the fire safety analysis is affected by the verification method used (i.e., assessing against absolute values or by using a FED method)
2. How the fire safety analysis is affected by the selection of acceptance criteria
3. he challenges a designer faces when working with alternative methods and acceptance criteria compared to traditional or regulated approaches

CASE STUDY

A case study method was adopted in order to investigate the above-mentioned aspects. A simple geometry was selected to remove unnecessary complexities for the comparative assessment. It should be noted that the case study was undertaken primarily from a Swedish perspective to fire safety engineering, although the general conclusion and discussions should be applicable to other regions.

Two sets of fire parameters were considered in the case study:

1. The BBRAD 3 fire parameters represent recommended inputs for analytical design within Sweden (Boverket, 2013)
2. The fire parameters based on the above-mentioned NIST tests (Gann, Averill, Marsh, & Nyden, 2007) (Gann, Averill, Johnsson, Nyden, & Peacock, 2003)

The NIST data was selected as it provided the most comprehensive available data for yields of additional species. Furthermore, the NIST sofa data was selected as this represents a reasonable combustible for the scenario considered.

The case study geometry was based on the International Maritime Organization's (IMO) test case 10 (IMO, 2002). This geometry is representative of a cabin arrangement on a passenger ship, but could also represent rooms in a hostel or similar accommodation. The original purpose for selecting the IMO test case 10 was to test exit route allocation for evacuation simulations. This simple geometry was also deemed adequate for the purposes of comparing tenability outcomes with different verification methods and acceptance criteria. The specifics of the geometry are not particularly important for this comparative assessment. However, the geometry selected could involve occupants

[4] BBRAD 3 is used as an abbreviation for this general recommendation in the following text.

asleep at the time that the fire starts. This, and the relatively confined geometry, means that there is the potential that occupants are exposed to the products of combustion prior to their evacuation.

Figure 1 shows the IMO test case 10 geometry overlaid with the FDS model geometry. No ceiling height is given for the IMO test case, as this was not important for its original purpose. A ceiling height of 2.8 meters was, therefore, assumed along with a wall thickness of 0.1 meters. At each exit door an opening of the door width times 0.6 meters height was assumed to avoid under-ventilated conditions and numerical instabilities. The doors to each cabin were assumed open in order to allow smoke to move into the cabins and exposure occupants to the products of combustion.

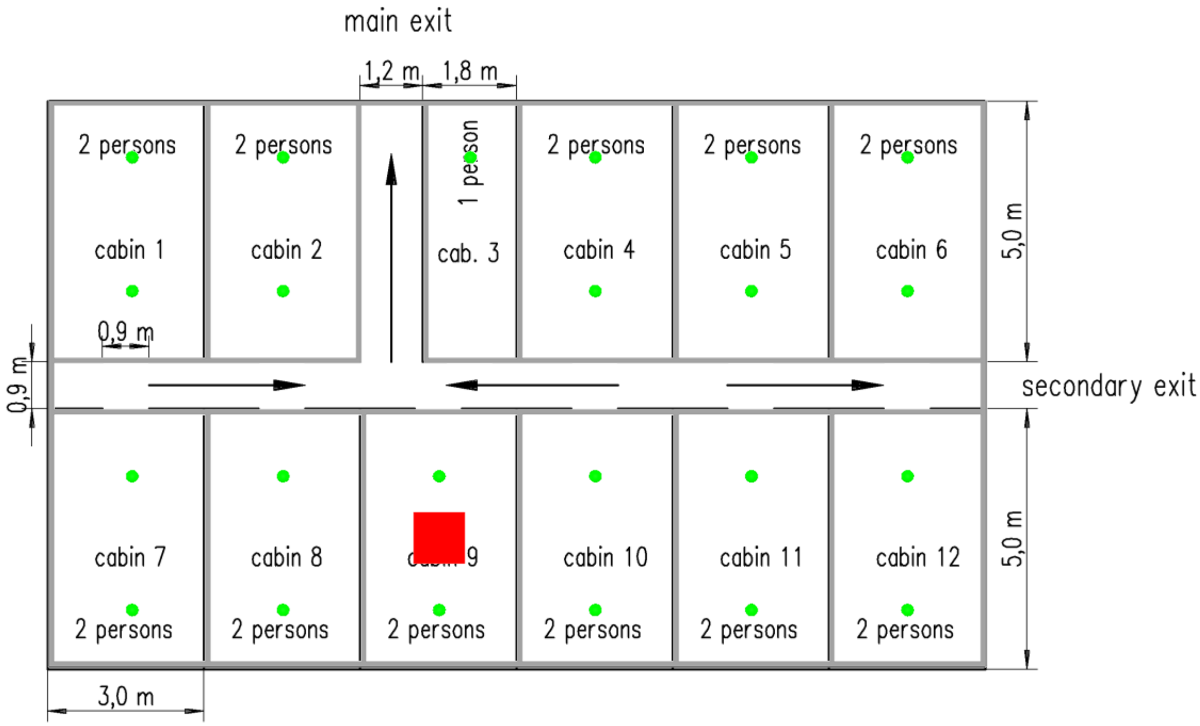

Figure 1: FDS model geometry overlaid on IMO test case 10 (figure 4 from IMO). Green dots are measurement locations (occupants).

FDS version 6.7.0 (McGrattan, Hostikka, McDermott, Floyd, & Manella, 2018) was used for the modelling with the setup generally in accordance with recommendations for CFD modelling in Sweden (BIV, 2013). A cubic grid size of 0.05 meters was used in the fire cabin with cubic grid sizes of 0.1 meters elsewhere. This resulted in resolution parameters of R* = 0.057 and D*/dx = 17.7 around the fire. The visibility factor was set to 8 which corresponds to best practice for Swedish fire life safety assessments with emergency illumination.

The fire was assumed to be nominally located in Cabin 9 as this positioning has the potential to prevent evacuation through the main exit. BBRAD 3 was adopted to define the fire scenarios and requires at least two fire scenarios to be considered (Boverket, 2013). This includes a "worst credible case" scenario where all technical systems function as intended (*fire scenario 1*) and a lower stress scenario where individual technical systems fail (*fire scenario 3*). For the purposes of this case study only fire scenario 1 was considered, which resulted in a fast t-squared 5 MW fire recommended to be used for analyses regarding dwellings, hotels and healthcare facilities.

BBRAD 3 allows fire scenario 1 to be reduced if sprinklers are included (Boverket, 2013). The specifics of this are provided in BBRAD 3 and, assuming sprinkler installation and activation, the resulting HRR curve is illustrated in Figure 2. Activation time of the sprinklers was estimated prior to the modelling using DetactT2 (Evans & Stroup, 1985). The activation time could also have been estimated from the model itself, but the timing is not particularly important for the purposes of the case study, and DetactT2 generally results in conservative activation timings.

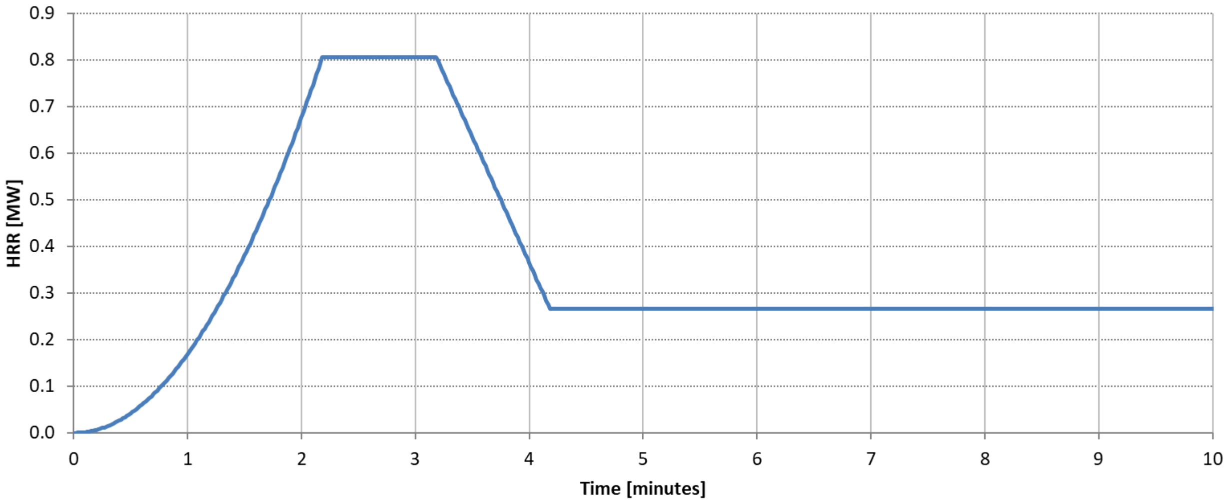

Figure 2: Design fire based on BBRAD 3 with sprinkler activation limiting the fire size.

Table 2 shows the fire parameters used in the modelling. As mentioned above, BBRAD 3 provides inputs for most parameters and variables to be modelled, however, not details of the reaction. Therefore, the reaction was modelled using the BIV recommendations: “simple chemistry” parameters with a reaction of $C_{4.56}H_{6.56}O_{2.34}N_{0.4}$ (BIV, 2013).

Fire parameters for the NIST sofa were based on the original reference (Gann, Averill, Marsh, & Nyden, 2007) (Gann, Averill, Johnsson, Nyden, & Peacock, 2003). However, where inputs were not available these were assumed to be the same as BBRAD 3 fire parameters. The NIST sofa was modelled using “complex stoichiometry” to be able to explicitly specify the gas species, along with the stoichiometry of the reaction. This was necessary due to the addition of HCN, HCl, NO_2, C_3H_4O and CH_2O. The additional species were lumped to minimise the number of scalar transport equations to be solved. The volume fractions introduced as lumped species were calculated from the stoichiometric coefficients of the primitive species (McGrattan, Hostikka, McDermott, Floyd, & Manella, 2018).

The case study did not consider any evacuation modelling. This simplified the comparative assessment and removed complexities with calculating different tenability criteria on moving occupants. IMO test case 10 assumes 23 people distributed throughout the cabins as shown above by Figure 1. Devices were placed in each cabin to represent an occupant location with one measurement location towards the front and one towards the back of each cabin. These devices were located at 2 meters above the floor level with data sampled at 1 second intervals. At each measurement device location the following was recorded: layer height, visibility, radiative heat flux gas, temperature, CO, CO_2, O_2, FED and FIC. For the NIST sofa case the following was also measured: NO_2, HCN, HCl, C_3H_4O and CH_2O.

Table 2: Fire parameters used in the modelling.

Yield	**Units**	**BBRAD 3**	**NIST sofa**[(1)]
Peak fire size (no sprinklers)	MW	5	-[(3)]
Peak fire size (with sprinklers) – see Figure 2	MW	0.8	-[(3)]
Growth rate (t-squared)	kW/m^2	0.047	-[(3)]
Heat of combustion	MJ/kg	20	-[(3)]
Fraction of Hydrogen in soot	-	0.1[(2)]	0.1[(2)]
Yields (per gram of fuel consumed)			
Soot	[g/g]	0.1	-[(3)]
Carbon Dioxide (CO_2)	[g/g]	2.5	1.59
Carbon Monoxide (CO)	[g/g]	0.1	0.0144
Hydrogen Cyanide (HCN)	[g/g]	-	0.0035
Hydrogen Chloride (HCl)	[g/g]	-	0.018
Nitrogen Dioxide (NO_2)	[g/g]	-	0.07
Acrolein (C_3H_4O)	[g/g]	-	0.008
Formaldehyde (CH_2O)	[g/g]	-	0.02

[(1)] Upper limits for the pre-flashover NIST sofa taken as inputs.
[(2)] No value given. FDS default assumed.
[(3)] No value given. BBRAD 3 value assumed.

Table 3 lists the tenability acceptance criteria used for the modelling. Five criteria groups are given by BBRAD 3 and each is tested (Boverket, 2013). The FED and fractional irritant concentration (FIC) are also assessed. For the FED, a nominal acceptance level of less than 0.3 and 1.0 are investigated. For the FIC an acceptance level of less than 1 is considered which corresponds to a tenability endpoint (escape impairment), whereas incapacitation is predicted at higher concentrations (FIC ~3-5) (Purser, 2016).

Table 3: Tenability criteria used for the modelling

ID	**Criteria**	**Level**
1	Smoke layer above floor level	Smoke layer > 1.6 + (ceiling height)*0.1 [m]
2a	Visibility, 2.0 m above floor level	Visibility > 10 m (spaces > 100 m^2)
2b	Visibility, 2.0 m above floor level	Visibility > 5 m (spaces < 100 m^2)
3	Thermal radiation	Radiation < 2.5 kW/m^2
4	Temperature	Temperature < 80 °C
5a	Carbon monoxide toxicity	[CO] < 2000 ppm

ID	Criteria	Level
5b	Carbon Dioxide toxicity	$[CO_2] < 5\%$
5c	Oxygen availability	$[O_2] > 15\%$
6a	FED (not part of BBRAD)	FED < 0.3
6b	FED (not part of BBRAD)	FED < 1.0
7	FIC (not part of BBRAD)	FIC < 1.0

The FED and FIC calculations are based on the methodology defined by the FDS user guide (McGrattan, Hostikka, McDermott, Floyd, & Manella, 2018). For completeness these equations are reproduced below as Equations 1 to 9 and Table 4, however, reference should be made the FDS user guide for full explanation of the methodology.

$$\mathrm{FED_{TOT}} = \left(\mathrm{FED_{CO}} + \mathrm{FED_{CN}} + \mathrm{FED_{NO_x}} + \mathrm{FLD_{irr}}\right) \times \mathrm{HV_{CO_2}} + \mathrm{FED_{O_2}} \qquad \textit{Equation 1}$$

$$\mathrm{FED_{CO}} = \int_0^t 2.764 \times 10^{-5} \left(\mathrm{C_{CO}}(t)\right)^{1.036} dt \qquad \textit{Equation 2}$$

$$\mathrm{FED_{CN}} = \int_0^t \left(\frac{1}{220} \exp\left(\frac{\mathrm{C_{CN}}(t)}{43}\right) - 0.0045\right) dt \qquad \textit{Equation 3}$$

$$\mathrm{C_{CN}} = \mathrm{C_{HCN}} - \mathrm{C_{NO_2}} - \mathrm{C_{NO}} \qquad \textit{Equation 4}$$

$$\mathrm{FED_{NO_x}} = \int_0^t \frac{\mathrm{C_{NO_x}}(t)}{1500} dt \qquad \textit{Equation 5}$$

$$\mathrm{FLD_{irr}} = \int_0^t \left(\frac{\mathrm{C_{HCl}}(t)}{\mathrm{F_{FLD,HCl}}} + \frac{\mathrm{C_{HBr}}(t)}{\mathrm{F_{FLD,HBr}}} + \frac{\mathrm{C_{HF}}(t)}{\mathrm{F_{FLD,HF}}} + \frac{\mathrm{C_{SO_2}}(t)}{\mathrm{F_{FLD,SO_2}}} + \frac{\mathrm{C_{NO_2}}(t)}{\mathrm{F_{FLD,NO_2}}} + \frac{\mathrm{C_{C_3H_4O}}(t)}{\mathrm{F_{FLD,C_3H_4O}}} + \frac{\mathrm{C_{CH_2O}}(t)}{\mathrm{F_{FLD,CH_2O}}}\right) dt \qquad \textit{Equation 6}$$

$$\mathrm{FED_{O_2}} = \int_0^t \frac{dt}{\exp\left[8.13 - 0.54\left(20.9 - \mathrm{C_{O_2}}(t)\right)\right]} \qquad \textit{Equation 7}$$

$$\mathrm{HV_{CO_2}} = \frac{\exp\left[0.1903\,\mathrm{C_{CO_2}}(t) + 2.0004\right]}{7.1} \qquad \textit{Equation 8}$$

$$\mathrm{FIC_{irr}} = \frac{\mathrm{C_{HCl}}(t)}{\mathrm{F_{FIC,HCl}}} + \frac{\mathrm{C_{HBr}}(t)}{\mathrm{F_{FIC,HBr}}} + \frac{\mathrm{C_{HF}}(t)}{\mathrm{F_{FIC,HF}}} + \frac{\mathrm{C_{SO_2}}(t)}{\mathrm{F_{FIC,SO_2}}} + \frac{\mathrm{C_{NO_2}}(t)}{\mathrm{F_{FIC,NO_2}}} + \frac{\mathrm{C_{C_3H_4O}}(t)}{\mathrm{F_{FIC,C_3H_4O}}} + \frac{\mathrm{C_{CH_2O}}(t)}{\mathrm{F_{FIC,CH_2O}}} \qquad \textit{Equation 9}$$

Table 4: Coefficients used for the computation of irritant effects of gases (McGrattan, Hostikka, McDermott, Floyd, & Manella, 2018).

	HCl	HBr	HF	SO_2	NO_2	C_3H_4O	CH_2O
F_{FLD} (ppm × min)	114000	114000	87000	12000	1900	4500	22500
F_{FIC} (ppm)	900	900	900	120	350	20	30

RESULTS

Figure 3 shows outcomes for the BBRAD 3 and NIST sofa fire parameters. These results are presented up to 10 minutes after the fire started. If a data point sits at 10 minutes then it means this particular criterion was acceptable during this period. If a data point sits below 10 minutes then it shows when this particular criteria was lost. This allows a visual representation of all criteria across the 12 cabins (23 occupants). Banding is used to indicate each cabin and the cabin with the fire is shaded red.

For the BBRAD 3 fire parameters (upper plot in Figure 3) it is the layer height and visibility criteria that are first lost. In the fire cabin, temperature and radiation criteria are also exceeded relatively soon into the fire development, which is expected given the close proximity to the fire. Temperature criteria is also exceeded in cabins 7 and 8 soon into the fire development. Apart from these criteria, it is only FED < 0.3 that is exceeded during the first 10 minutes. The time when this occurs varies, but is roughly 4-8 times longer than criteria based on visibility alone.

For the NIST sofa fire parameters (lower plot in Figure 3) it is also the layer height and visibility that are lost soon into the fire development. This occurs at similar times to the BBRAD 3 fire parameters, which is expected given the similar soot yields. However, with the additional species considered in the reaction the FIC criteria is generally exceeded at a similar time to the visibility criteria, noting that a value of unity does not mean that incapacitation occurs (see earlier discussion). Temperature and radiation criteria are generally lost about the same time as the BBRAD 3 reaction, however, FED criteria are lost much sooner in the fire development with the additional species considered.

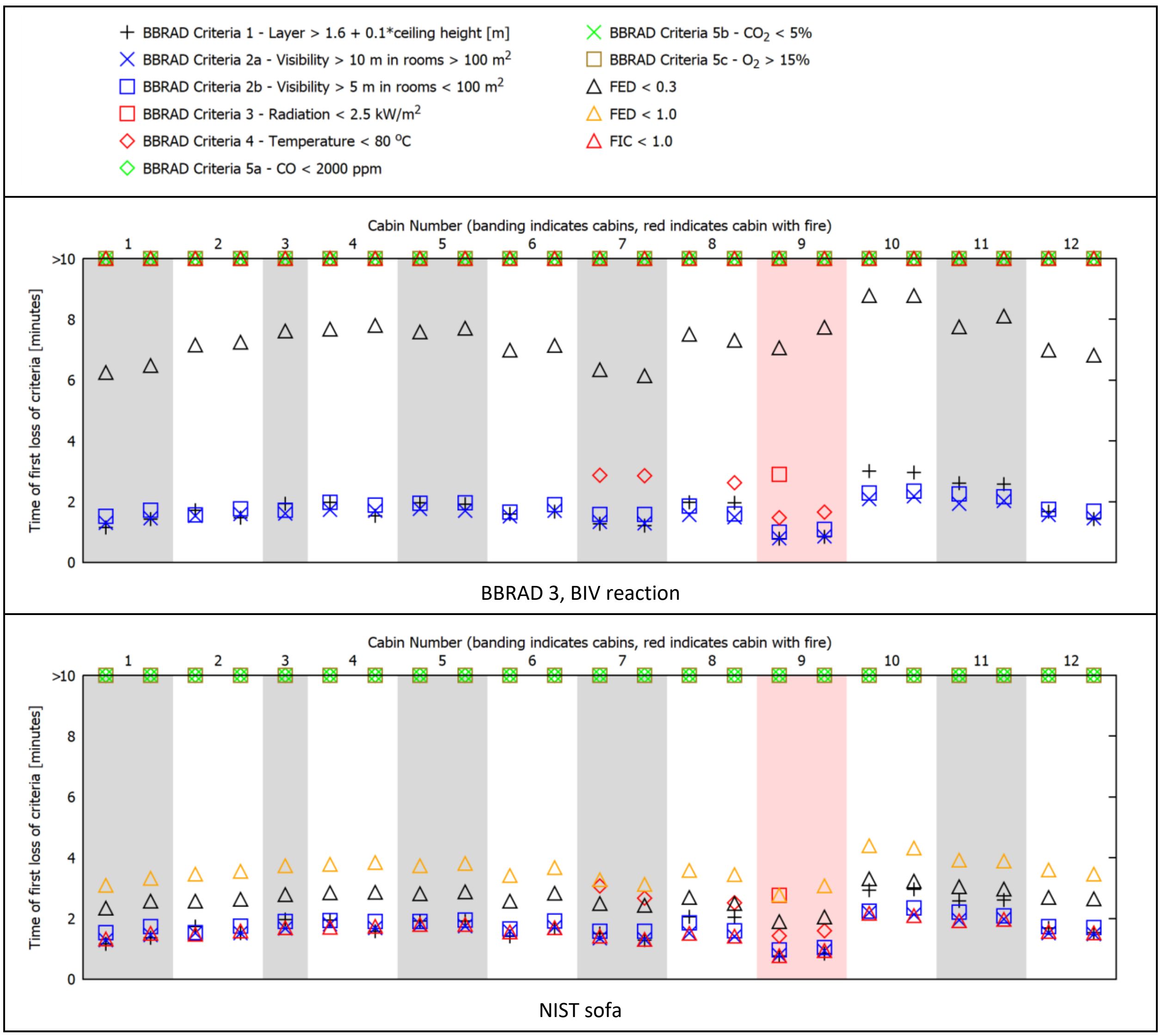

Figure 3: Comparison of all tenability criteria for the BBRAD 3 and NIST sofa fire parameters.

DISCUSSION

Investigations have previously been undertaken regarding the variation in results when applying different verification methods and acceptance criteria to verify fire life safety. Nystedt (2011) discussed the correlation between visibility and FED in sprinklered buildings by using hand-calculations to estimate the burnt mass and resulting visibility, and then calculated the corresponding FED-value for a specific exposure time. He concluded that by the time the common visibility criterion of 10 meters in a room fire is reached, the accumulated FED is still ten times lower than the commonly used criterion corresponding to FED = 0.3.

In this paper, a similar but more refined and detailed case study has been undertaken to illustrate how outcomes vary when applying different methods and acceptance criteria to verify fire life safety. A simple geometry was selected to remove unnecessary complexities for the comparative assessment. The case study results highlight how the fire safety outcome is affected by the use of absolute values or FED methods, and the results are similar to Nystedt's findings. For example, using the BBRAD 3 fire parameters, it was demonstrated that impaired visibility was the first tenability criteria to be exceeded. The time when FED < 0.3 was exceeded varied, but was roughly 4-8 times longer than when basing the ASET on the visibility criterion alone. In contrast, when using fire parameters based on the NIST sofa, additional species are added to the calculation of FED and the difference in time to tenability between visibility > 10 meters and FED < 0.3 became much less, approximately 2-3 times longer for the FED criteria.

The FIC is not relevant for the BBRAD fire parameters as irritants are not considered in the products of combustion. However, for the NIST sofa the introduction of irritants allowed the FIC to be calculated. This showed that FIC < 1 was exceeded at approximately the same time as visibility, which could lead to escape impairment for some occupants. However, incapacitation is not likely to occur for most people until a much higher FIC of ~3-5 (Purser, 2016). Although not illustrated in the results section above, additional analysis of the results reveal that these accumulated levels of FIC where reached before the criterion FID < 1.0.

Both the FED and FIC results highlight the importance of considering the full range of species expected in the products of combustion and that ignoring all or select species may lead to misleading outcomes. As an example, if an FED assessment is based only on asphyxiants (e.g. CO, CO_2 and low O_2), then it may appear that that the time to untenable conditions is much longer than a simple visibility assessment method. As more species are added to the calculation of FED, and inclusion of irritants allow for the FIC assessment, then it could be the case that the simple visibility assessment method gives comparable outcomes to assessment methods based on FED or FIC. This conclusion, however, is somewhat specific to the case study considered and another set of fire parameters may give a different outcome. Ultimately the specifics of a fire and a good understanding of the products of combustion is required to judge the species that should be considered in the assessment.

An interesting topic to discuss is how the fire safety assessment and related conclusions are affected by the selection of verification method and acceptance criteria. In the Swedish context, the designer is provided with specific criteria for layer height and visibility, the latter of which varies by room size. However, the results from the case study show there is little difference in the time to critical conditions for these different visibility criteria. The criteria for layer height and visibility > 10 meters were generally lost at about the same time, with visibility > 5 meters lost soon after. This outcome is likely to be applicable to other confined geometries. Another consideration is the height at which the visibility is assessed. While a height of 2 meters above the walking surface was used for the case study, the assessment height could vary between approximately 1.8 and 2.5 meters in other jurisdictions. This may have some impact on the time to tenability, but it is not likely to result in a step-change in outcomes. Furthermore, influences of the CFD volume discretization are likely to mean there is some tolerance on the layer height and exact time of tenability, although this was not investigated in this study and would require a study of varying grid resolutions.

The choice of FED and FIC criteria are somewhat contentious within the fire safety engineering community. For example, there does not seem to be a uniform agreement on FED criteria and which species make up the FED assessment. In the authors' experiences, a criteria of FED < 0.3 is somewhat typical on projects and there is rarely a requirement for FIC to be considered. The choice of FED < 0.3 may be viewed to be overly conservative, suggesting that FED < 1.0 is more appropriate. It could also be argued, however, that FED < 0.3 is appropriate given the uncertainties in the inputs and that often it is only a limited range of species that are considered. As shown by the case study, the time at which the FED criteria is exceeded might depend on what species are included in the FED calculation.

The mechanics of implementing different assessment methods and acceptance criteria is reasonably well developed from the CFD side. While there are known limitations and simplifications with the fire dynamics models within FDS, the reality is that it is reasonably straightforward to investigate different species in the combustion and assess different criteria. When the designer deviates from the "simple chemistry" model in FDS (which is necessary when they include species such as HCN, HCL, etc.) then they must undertake their own calculations to specify the products of combustion for the "complex chemistry" model. This requires a deeper knowledge of the fuel composition and the reaction stoichiometry. As such, there is a greater risk of user error and the need for tighter quality control, but these can be managed through experience and workflow.

While the CFD implementation is relatively straight-forward, the same cannot necessarily be said for the evacuation modelling. While certain evacuation software allows for any number of species to be included in a subsequent FED/FIC calculation, other evacuation software is limited to specific species or fixed calculation methodologies, with varying approaches to how visibility and irritants affects movement characteristics. These limitation or variations in approach might drive the designer to adopt a certain assessment methodology due to their available software. As such, the assessment criteria might then need to be selected cognizant of the assessment method selected.

Another limitation that the designer must contend with is sourcing input data for the modelling. Within the Swedish context the fire parameters for a typical analytical assessment are provided and the designer needs to exercise little judgement. However, if the designer needs to deviate from these values, or is working in a jurisdiction without well-defined inputs, then the onus is on them to develop reasonable inputs that are representative of the fire scenario being investigated. It becomes more difficult to find appropriate input data, especially if yields of other narcotic and irritant species than CO and CO_2 are to be considered. The yields are highly dependent on the ventilation conditions of the fire and are also seldom reported. How successful the designer is in sourcing these inputs might depend on the available literature and other resources available to them. Sourcing inputs from the literature that are specific to a particular fire scenario might be difficult, if not impossible, and require judgement or additional calculation. Small or full-scale testing might be possible in some situations (e.g., large infrastructure projects), however, this would not be possible for the vast majority of projects. Similar to the software limitations, it might be the availability to develop the inputs that determines the assessment method and criteria adopted.

From the designers' perspective the two methods used in this case study differ in their complexity. Applying absolute tenability criteria to a project is relatively straight-forward. Using a FED or FIC approach is complicated by knowing what should be included in the calculation of these values and what criteria should be adopted. In jurisdictions where fire parameters, assessment methods and acceptance criteria are explicitly defined there is less judgement that the designer much exercise. This results in less approvals risk for a project as the authority having jurisdiction and the designer have a common framework and set of parameters to work with. The converse is true when the fire parameters, assessment methods and acceptance criteria are less well-defined, which is often the case when it comes to the FED concept.

CONCLUSION

The case study presented in this paper illustrates that the selection of method to verify life safety, as well as the selection of the related acceptance criteria, may have a great effect on the conclusions drawn from such a verification. From a first look, applying an FED methodology seems to lead to less conservative solutions as the ASET becomes longer. However, as the FED methodology assumes an accumulation to an endpoint dose, this is only true when few gases/irritants are considered. A full understanding and implementation of asphyxiant and irritant gases may lead to the opposite, which is also indicated by the case study.

It is clear that a fire safety designer faces several challenges when deviating from prescribed or recommended methods and acceptance criteria. Verified and validated methods to verify life safety exists, but applying one verification method may yield completely different results than another. To this comes the uncertainty regarding appropriate acceptance criteria, and the lack of input data (particularly related to the FED methodology). Aspiring to complex FED calculation methods may be desirable, however, it could be the lack of suitable inputs that puts limitations on the species considered. This could introduce uncertainty if an FED method is appropriate or the exclusion of certain species is leading to a misleading outcome. Ultimately more research is required in this field to develop species yields for a wider range of fire scenarios. This research may also help jurisdictions to develop mandated inputs and acceptance criteria for FED methods similar to those typically used for absolute tenability criteria such as visibility and temperature.

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