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Fractional effective dose model for post-crash aircraft survivability

Louise C. Speitel

Federal Aviation Administration Technical Center, AAR-422, US Department of Transportation, Atlantic City International Airport, Atlantic City, NJ 08405 USA

Abstract

The development of a survival model for post-crash aircraft cabin fires is described in this paper. Its development is based on an extensive review of the literature on the toxicity of combustion gases and on thermal hazards. This model is to be used as a predictive tool to gauge human survivability in full scale aircraft cabin fire tests. The extensive literature search was conducted for carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN), low oxygen, hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen bromide (HBr), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), acrolein (CH_2CHCHO), and heat exposures. Those studies by various investigators of exposures to single and mixed gases on humans, primates, rats, and mice at different physical activity levels were compared. Regression equations were derived from those studies to give the best fit to the gas exposure concentration and duration data. The equation judged to best model the human escaping from an aircraft cabin was selected for each gas. This survival model uses incapacitation data to obtain a fractional effective dose (FED) for incapacitation (FED_I) and lethality data, inclusive of post exposure deaths, to obtain a FED for lethality (FED_L). The exposure time required for either FED_I or FED_L to reach unity, using a projected set of gas concentrations, represents the exposure time available to escape from the specified fire environment or to survive post exposure, respectively. The effect of CO_2 in increasing the uptake of other gases was factored into the concentration term in the FED equation for all gases with the exception of CO_2 and oxygen. Higher respiratory minute volumes due to CO_2 exposure were found to be an important factor in predicting the time available to escape. This FED-based model can be applied to the evaluation of the toxicity of smoke in computer modeling of aircraft fire situations.

Keywords: Aircraft survivability; Survival model; Toxicity model; Fractional effective dose; Inhalation toxicity

1. Introduction

The inhalation toxicity of combustion gases has been studied over the years by many investigators. In those studies, various animal species were used to evaluate effects of single and mixed gases on different toxicopharmacological endpoints at many physical activity levels. Because of the diversity of the accumulated data, there exists a need to compile and evaluate those data to obtain

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a better understanding of human response over a wide concentration range for both pure single and mixed gases. A literature review of such relevant studies was conducted, and the salient data points from the studies were summarized and compared. The findings from those investigations were subsequently incorporated into equations to predict survival time in toxic gas atmospheres. This paper describes the development of the survival model based on those equations. The details of the basis of this model can be obtained in Speitel's report (1995).

2. Method

Time to incapacitation (t_i) is probably the best single measure of the ability to escape from an aircraft fire environment, based on the premise that physical incapacitation effectively signals the end of the individual's voluntary activity. Lethality, inclusive of post exposure deaths, is the best measure of extended survival after escape and is particularly useful for describing the hazards from the irritant gases, such as hydrogen fluoride (HF), hydrogen chloride (HCl), hydrogen bromide (HBr), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). An LC_{50} value is the concentration of a gas for a given exposure duration ($t_{exposure}$) producing deaths of 50% of the experimental animals either during- or post-exposure. The corresponding exposure time for any LC_{50} gas concentration is designated $t_{exposure}$. Exposure to high concentrations of these gases may not prevent escape, but may result in subsequent death due to the damage to the respiratory system. The LC_{50}s are less than the incapacitation concentrations for these gases.

After an extensive search of the current literature dealing with animal and human exposures to combustion gases and elevated temperatures, data in selected references were used to develop a combined hazard survival model to predict survivability in specified fire scenarios. A number of animal species have been tested at different physical activity levels by many investigators. In this present study, regression equations, giving the best fit to the gas exposure concentration and duration data, were selected or developed for animal exposure studies that had previously been reported by other investigators, using a wide range of gas exposure concentrations. Laboratory animals in those investigations were also subjected to different physical activities. An overall picture on how this complex assortment of data was related was obtained by a direct comparison of the predicted times to effect. The goal was to develop an equation or equations that would best approximate the time to effect for a man engaging in light physical activity. From an analysis of these comparative data, the best approximations were selected for use in this new Federal Aviation Administration (FAA) Combined Hazard Survival Model.

The Combined Hazard Survival Model used incapacitation data to obtain a fractional effective dose (FED) for incapacitation (FED_I) and lethality data, inclusive of post exposure deaths, to obtain a fractional effective dose for lethality (FED_L). The time when either FED_I or FED_L reaches unity determines the exposure time available to escape from an aircraft cabin fire or to survive post exposure, respectively. The FED for a constant concentration (C) of the gas toxicant is the dose received up to exposure time t divided by the Ct dose required to cause an effect (incapacitation or lethality). This effect is predicted to occur when FED_{Effect} is equal to 1. For a constant concentration of toxicant:

$$FED_{Effect} = \frac{\text{dose received at time } t}{Ct \text{ dose to cause effect}} = \frac{Ct}{Ct_{effect}} = \frac{t}{t_{effect}} \quad (1)$$

If the concentration varies with time, the fractional doses for a pure gas can be summed for each min of a j min exposure, assuming concentrations are constant within each min (Purser, 1988):

$$FED_{Effect} = \frac{1}{t_{effect\ 1}} + \frac{1}{t_{effect\ 2}} + \frac{1}{t_{effect\ 3}} + \cdots + \frac{1}{t_{effect\ j}} \quad (2)$$

Or more generally,

$$FED_{Effect} = \int_0^t \frac{dt}{t_{effect}} \text{ where } t_{effect} = f(C) \quad (3)$$

Table 1
Studies utilized in the development of the FAA Combined Hazard Survival Model

Test subjects	Activity levels	Combustion gases	References
Monkeys	Seated	HCN	Purser, 1988
Monkeys	Active	CO, CO_2	Purser and Berrill, 1983; Purser, 1988
Rats	Motor driven wheel	CO, HCN, HCl, acrolein	Crane et al., 1985; Crane et al., 1986; Crane et al., 1989
Mice	Motor driven wheel	CO, HCN, HCl, NO_2, O_2, CO_2	Sakurai, 1989
Baboons, rats	Escape task	CO, HCl, acrolein	Kaplan et al., 1984; Kaplan et al., 1985
Rats	Resting	Acrolein	Skogg, 1950
Mice	Resting	Acrolein	Pattle and Cullumbine, 1956
Rats	Restrained	CO, HCN, HCl	Hartzell et al., 1985a; Hartzell et al., 1985b
Rats	Restrained	CO, HCN, NO_2, CO_2	Levin et al., 1987; Levin et al., 1988; Levin et al., 1989
Humans	Light work	CO	Stewart et al., 1970; Purser, 1988
Humans	Resting (at altitude)	O_2	Luft, 1965
Rats	Unrestrained	NO_2	Gray et al., 1954
Mice	Unrestrained	SO_2	Bitron and Aharonson, 1978
Rats	Unrestrained	NO_2	Higgins et al., 1971
Rats	Resting	NO_2, acrolein	Speitel, 1995[a]
Humans	Resting	CO_2, heat	Blockley, 1964; Blockley, 1973[a]
Humans	Resting	CO_2, O_2, heat	Purser, 1988[a]
Humans	Resting	Heat	Crane, 1978[a]
Humans	Resting	O_2, CO_2	Speitel, 1995[a]

[a]These investigators reviewed the literature and compiled data obtained from the works of others.

The expression for $t_{\rm effect}$ can be obtained from the selected regression equations for that gas.

The FED_I can be calculated for a mixture of n gases and heat. For any mixture of n gases, assuming the hazards of each gas are additive:

$$FED_I = FED_{I\,Gases} + FED_{I\,Heat} \quad (4)$$

$$FED_I = \sum_{k=1}^{n} \int_0^t \frac{dt}{t_{Ik}} + \int_0^t \frac{dt}{t_{I\,Heat}} \quad (5)$$

where t_{Ik} is the t_I for gas number k of n gases

$$FED_I = \int_0^t \frac{dt}{t_{I1}} + \int_0^t \frac{dt}{t_{I2}} + \cdots + \int_0^t \frac{dt}{t_{In}} + \int_0^t \frac{dt}{t_{I\,Heat}} \quad (6)$$

Two separate models were used independently to determine the combined hazard. The FED_I model used t_I data for gases and heat to determine the ability to escape from a burning aircraft cabin. The FED_L model used $t_{\rm exposure}$ data, inclusive of post exposure deaths, to determine the ability to survive post-exposure. Regression equations for t_I and $t_{\rm exposure}$ were selected with a preference for active animals with a level of activity that best approximated an escape task. All regression equations for t_I were based on active animals with the exceptions of carbon dioxide (CO_2), oxygen (O_2), and heat, while for $t_{\rm exposure}$ they were based on inactive animals. Equations based on primate data were selected wherever possible. Crane's (Crane, 1978) regression equation for $t_{I\,Heat}$ was selected as it represented a more realistic exposure, i.e., it was based on data using clothed subjects as opposed to nude subjects.

Carbon dioxide is known to be a respiratory stimulant which increases the rate of uptake of other fire gases. Higher respiratory minute volumes (RMVs) due to CO_2 inhalation were found to be an important factor in predicting time to incapacitation or death. Therefore, the important assumption was made in developing the model that the increased uptake of other gases (except CO_2 and O_2) matches the predicted RMV increase due to CO_2. This assumption was based on the observations that: (i) the apparent increased uptake of carbon monoxide (CO) in presence of 5% CO_2 in rat LC_{50} data for 5–60 min exposures ranged from 1.2- to 1.6-fold, respectively, (ii) the

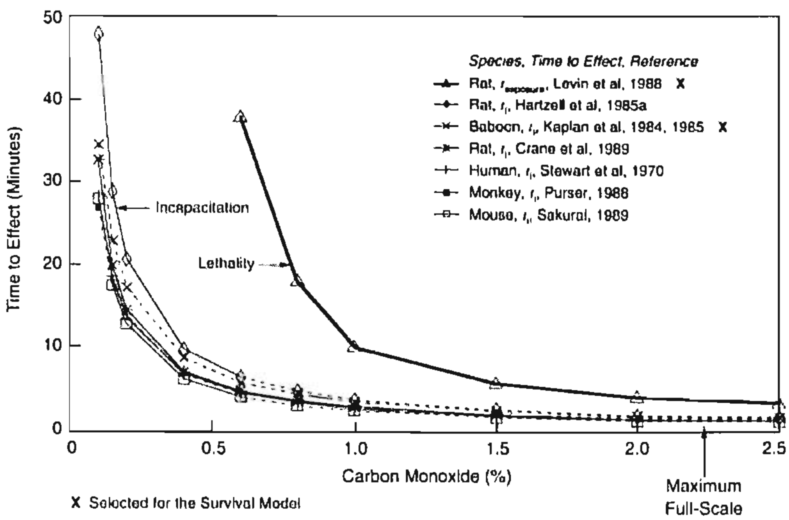

Fig. 1. Comparison of predicted times to effect for carbon-monoxide.

rate of formation of carboxyhemoglobin (COHb) before saturation in rats was 1.5 times greater for 2500 ppm CO in the presence of 5.25% CO_2 than in its absence (Levin et al., 1987), and (iii) the RMV for rats exposed to 5% CO_2 was a factor of 2.2 greater than control rats. The actual uptake of CO in presence of CO_2 was greater than in its absence, but did not match the predicted 2.2-fold increase. Erring on the side of safety, it was assumed in the model that CO uptake matched the predicted RMV increase in humans. In contrast, a quantitative uptake was observed for rats

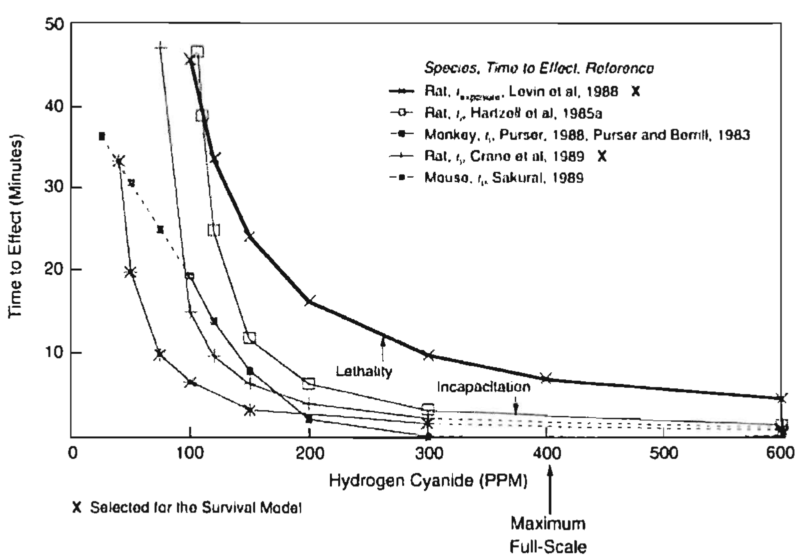

Fig. 2. Comparison of predicted times to effect for hydrogen-cyanide.

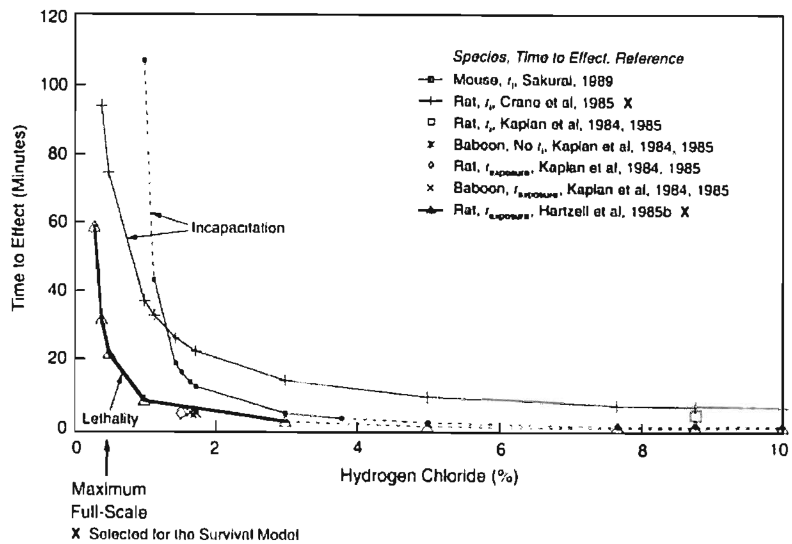

Fig. 3. Comparison of predicted times to effect for hydrogen-chloride.

exposed to NO_2 in the presence of 5% CO_2. The uptake of NO_2 in the presence of 5% CO_2 results in an LC_{50} 2.2 fold lower than in the absence of CO_2 (Levin et al., 1989). This enhanced uptake of NO_2 matches the RMV increase in rats in the presence of 5% CO_2 (2.2 vs. 2.2). One can conclude from this that other water soluble gases, expected to be quantitatively absorbed by the body, may also result in LC_{50}s and C_is (incapacitating concentration corresponding to t_i) reduced

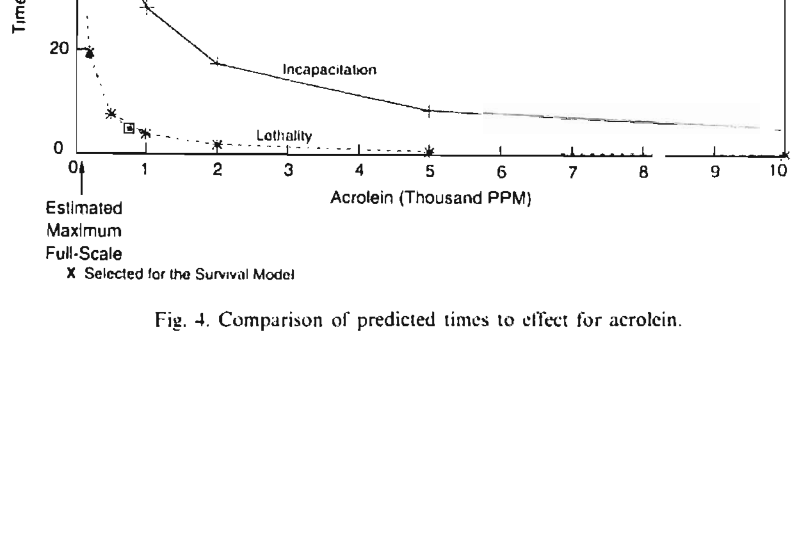

Fig. 4. Comparison of predicted times to effect for acrolein.

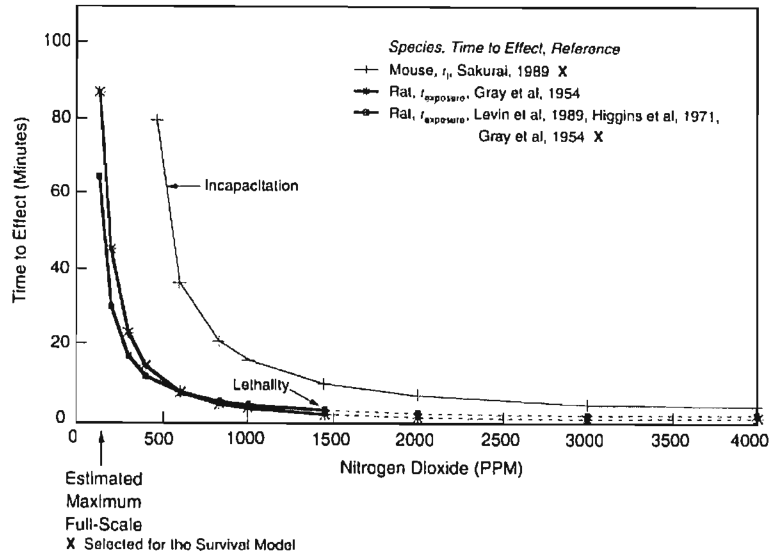

Fig. 5. Comparison of predicted times to effect for nitrogen-dioxide.

by the V_{CO_2} factor. Other water soluble gases include HF, HCl, HBr, SO_2, and HCN. Carbon dioxide has been shown to have a marked beneficial effect of elevating cerebral P_{O_2} levels for low inspired levels of O_2 in monkeys (Karl et al., 1978). The relationship between time to effect and levels of O_2 and CO_2 is not known for a range of CO_2 concentrations. Erring on the side of safety, the beneficial effect of CO_2 on low O_2 exposures was not considered in this new survival model.

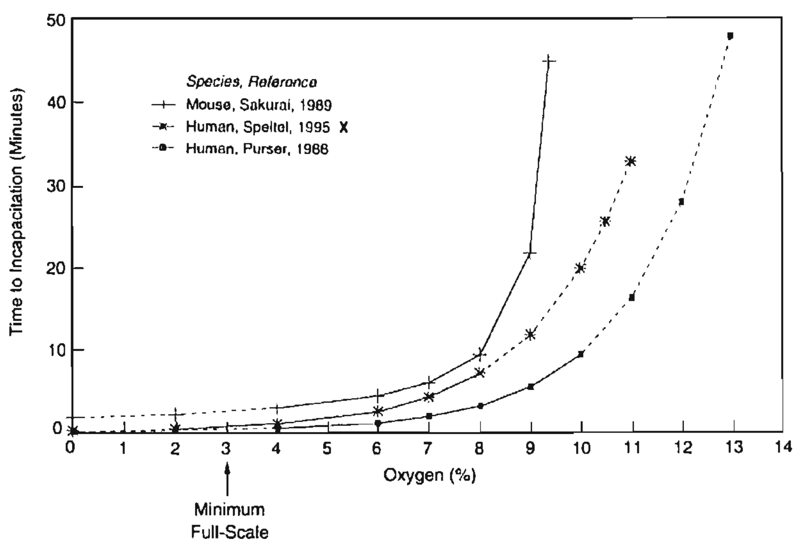

Fig. 6. Comparison of predicted times to incapacitation for low oxygen.

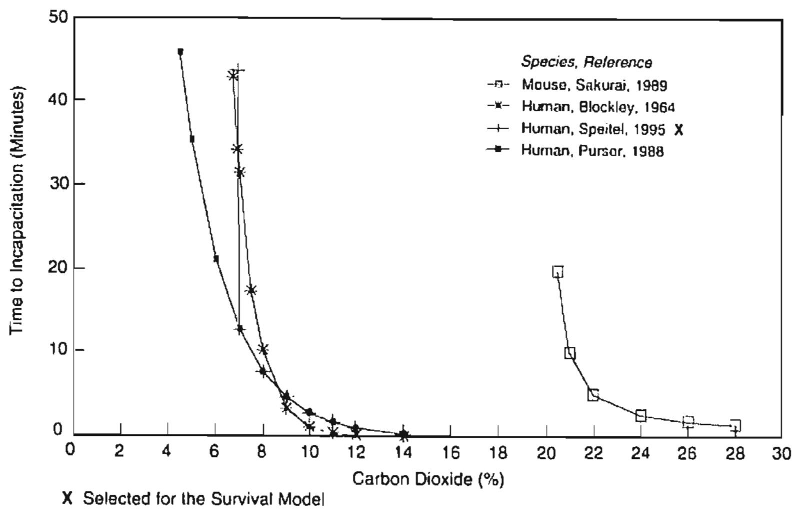

Fig. 7. Comparison of predicted times to incapacitation for carbon-dioxide.

The increase in RMV due to the presence of CO_2 V_{CO_2} is species dependent. In the presence of 5% CO_2, V_{CO_2} (rat) = 2.2 (Lai et al., 1981); V_{CO_2} (guinea pig) = 2.2 (Wong and Alaric, 1982); V_{CO_2} (hamster) = 2 (Chapin, 1954); V_{CO_2} (monkey) = 3 (Purser, 1988); V_{CO_2} (man) = 3.45 (Purser, 1988). In the presence of 10% CO_2, V_{CO_2} (hamster) = 3 (Chapin, 1954); V_{CO_2} (anesthetized baboon) = 5.5 (Kaplan et al., 1988); V_{CO_2} (man) = 12.0 (Purser, 1988).

The multiplication factor V_{CO_2} developed by (Purser, 1988) and based on human exposure data was selected for the enhanced uptake of other gases and was factored into the concentration term in the regression equation for each hazard with the exceptions of CO_2, O_2, and temperature.

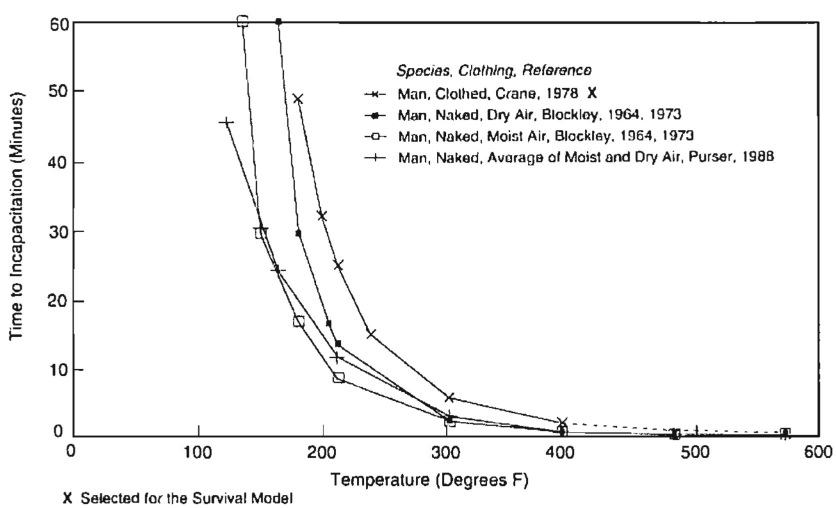

Fig. 8. Comparison of predicted times to incapacitation for heat.

Table 2
Predicted combustion gas concentrations that produce a 5-min time to effect[a]

Gas (unit)	Incapacitation		Lethality (LC_{50})	
	Without CO_2	With 5% CO_2	Without CO_2	With 5% CO_2
CO (%)	0.685	0.194	1.66	0.48
HCN* (ppm)	176	51	560	162
HCl* (ppm)	168300	48783	15900	4609
HF* (ppm)	7663	22213	7227	2095
HBr* (ppm)	168300	48783	15900	4609
Acrolein* (ppm)	10928	3168	783	227
CO_2 (%)	8.8	8.8	ND	ND
O_2 (%)	7.3	7.3	ND	ND
NO_2^* (ppm)	2570	745	852	247
SO_2^* (ppm)	ND	ND	2115	613
Temperature (°C)	156	156	ND	ND

[a]The constant V_{CO_2} = 1 in the absence of CO_2, while it is equal to 3.45 in the presence of 5% CO_2; ND = not determined; ppm = parts per million, volume/volume; % = percent by volume.
*These gases cause post exposure lethality.

$$V_{CO_2} = \frac{\exp(0.2496 \times C_{CO_2} + 1.9086)}{6.8}$$

where $C_{CO_2} = \%CO_2$ (7)

3. Results and discussion

Studies utilized in the development of this model are referenced in Table 1, including test species, physical activity levels, and specific combustion gases. Comparisons of the predicted exposure times to effect (incapacitation and death) are illustrated for each hazard respectively in Figs. 1–8. The maximum gas concentrations observed in full scale aircraft cabin fire tests conducted at the FAA Technical Center and the predictive equations selected for the survival model are also noted for each gas. The author has referenced

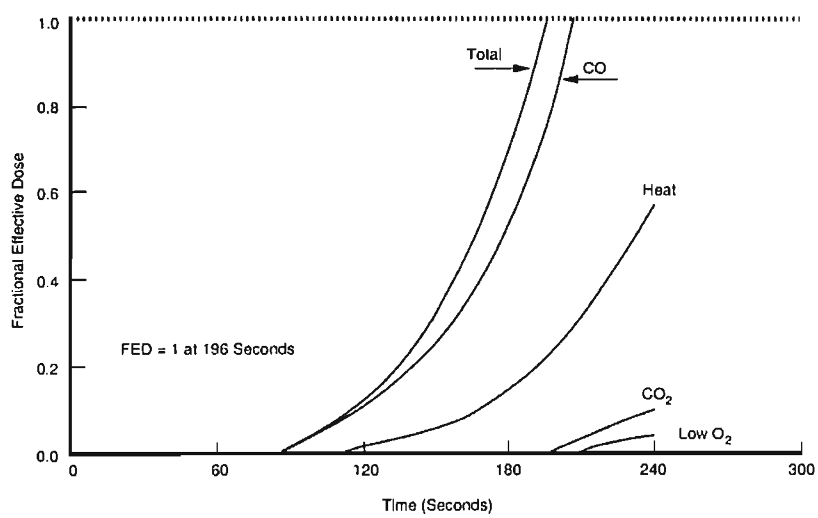

Fig. 9. Typical survival curve for a wide-body fuselage based on FED_I model.

additional exposure studies over narrow concentration ranges of gases to increase the level of confidence for the selected regression equations and provided regression equations and/or reasonable limits when they were not given by the investigators (Speitel, 1995).

The incapacitating concentrations of CO and hydrogen cyanide (HCN) can be seen to decrease with increasing activity level. However, from the predictive equations in restrained rats (Hartzell et al., 1985a) and in active rats (Crane et al., 1989), the incapacitating concentration was 1.4 times greater for the restrained than the active rat using Crane's activity protocol for t_is ranging from 5 to 60 min for CO and HCN.

The FED model derived from the regression equations is shown below. Time is expressed in min and temperature in degrees C for the FED_I and FED_L equations.

$$FED_I$$

$$= FED_{I\ Gases} + FED_{I\ Heat}$$

$$= FED_{I\ CO} + FED_{I\ HCN} + FED_{I\ HCl} + FED_{I\ HF} + FED_{I\ HBr} + FED_{I\ Acrolein} + FED_{I CO_2} + FED_{I\ NO_2} + FED_{I\ Low\ O_2} + FED_{I\ Heat}$$

$$= \frac{1}{3.4250}\int (V_{CO_2} \times C_{CO})\,dt \quad \text{when } V_{CO_2} \times C_{CO} > 0.01\%$$

$$+ \int \frac{(V_{CO_2} \times C_{HCN} - 63)\,dt}{564} \quad \text{when } V_{CO_2} \times C_{HCN} > 63\text{ppm}$$

$$+ \int \frac{dt}{3.0 + [(3.36 \times 10^5)/(V_{CO_2} \times C_{HCl} - 300)]} \quad \text{when } V_{CO_2} \times C_{HCl} > 300\text{ppm}$$

$$+ \int \frac{dt}{3.0 + [(1.53 \times 10^5)/(V_{CO_2} \times C_{HF} - 136)]} \quad \text{when } V_{CO_2} \times C_{HF} > 136\text{ppm}$$

$$+ \int \frac{dt}{3.0 + [(3.36 \times 10^5)/(V_{CO_2} \times C_{HBr} - 300)]} \quad \text{when } V_{CO_2} \times C_{HBr} > 300\text{ppm}$$

$$+ \int \frac{dt}{1.5 + [(4.0 \times 10^4)/(V_{CO_2} \times C_{Acrolein} + 500)]} \quad \text{when } V_{CO_2} \times C_{Acrolein} > 300\text{ppm}$$

$$+ \int \frac{(V_{CO_2} \times C_{NO_2} - 290)\,dt}{1.14 \times 10^4} \quad \text{when } V_{CO_2} \times C_{NO_2} > 290\text{ppm}$$

$$+ \int \frac{dt}{\exp(6.1623 - 0.5189 \times C_{CO_2})} \quad \text{when } C_{CO_2} > 7.0\%$$

$$+ \int \frac{dt}{2193.8 - 311.6 \times C_{CO_2}} \quad \text{when } 5.5 \le C_{CO_2} \le 7.0\%$$

$$+ \int \frac{dt}{\exp[8.55 - 0.511(20.9 - \%O_2)]} \quad \text{when } \%O_2 < 11\%$$

$$+ \frac{1}{4.1 \times 10^8}\int T^{3.61}\,dt \quad \text{when } T > 50°\text{C} \qquad (8)$$

It should be emphasized that the FED_I equation for low O_2 is based on data for men at rest. The FED_I for men escaping from an aircraft fire would probably be higher than predicted by the above equation.

$$FED_L$$

$$= FED_{L\ Gases} + FED_{L\ Heat}$$

$$= FED_{L\ CO} + FED_{L\ HCN} + FED_{L\ HCl} + FED_{L\ HF} + FED_{L\ HBr} + FED_{L\ Acrolein} + FED_{L\ SO_2} + FED_{L\ CO_2} + FED_{L\ NO_2} + FED_{L\ Formaldehyde\ (HCHO)} + FED_{L\ Low\ O_2} + FED_{L\ Heat}$$

$$= \int \frac{dt}{[58000/(V_{CO_2} \times C_{CO} - 4000)] + 0.4} \quad \text{when } V_{CO_2} \times C_{CO} > 9000\text{ppm}$$

$$+ \int \frac{dt}{\exp[5.85 - (3.70 \times 10^{-4})(V_{CO_2} \times C_{CO})]} \quad \text{when } 2000\text{ppm} \le V_{CO_2} \times C_{CO} \le 9000\text{ppm}$$

$$+ \frac{1}{2586}\int [(V_{CO_2} \times C_{HCN}) - 43.2]\,dt$$

when $V_{CO_2} \times C_{HCN} \geq 43.2$ppm

$$+ \int \frac{(V_{CO_2} \times C_{HCl} - 1800)\,dt}{70500}$$

when $V_{CO_2} \times C_{HCl} \geq 1800$ppm

$$+ \int \frac{(V_{CO_2} \times C_{HF} - 818)\,dt}{32045}$$

when $V_{CO_2} \times C_{HF} \geq 818$ppm

$$+ \int \frac{(V_{CO_2} \times C_{HBr} - 1800)\,dt}{70500}$$

when $V_{CO_2} \times C_{HBr} \geq 1800$ppm

$$+ \frac{1}{3915}\int (V_{CO_2} \times C_{Acrolein})\,dt$$

when $V_{CO_2} \times C_{Acrolein} > 5$ppm

$$+ \int \frac{dt}{0.633\exp[8.18012 - (2.89037 \times 10^{-3}) \times (V_{CO_2} \times C_{CO_2})]}$$

when $V_{CO_2} \times C_{SO_2} \geq 300$ppm

$$+ \int \frac{(V_{CO_2} \times C_{NO_2} - 71.8)\,dt}{3899}$$

when $V_{CO_2} \times C_{NO_2} > 71.8$ppm

$$+ \frac{1}{32000}\int (V_{CO_2} \times C_{HCHO})\,dt$$

$$+ FED_{L,CO_2}(\text{unknown}) + FED_{L,Low\,O_2}(\text{unknown})$$

$$+ FED_{L,Heat}(\text{unknown}) \quad (9)$$

The FED_L values for all gases given in the above equation were based on data for inactive animals. The FED_L for an individual escaping from an aircraft cabin fire would probably be higher for these gases.

A high approximation for the missing fractional lethal effective doses can be obtained by substituting the FED_I in place of the unknown FED_L for CO_2, low O_2, and heat. Since much higher CO_2 concentrations are needed to cause death than to produce incapacitation, this approximation results in an over-estimation of FED_L.

The enhanced uptake factor, V_{CO_2}, had a marked impact on the predicted time to effect. The sensitivity of the survival model to the V_{CO_2} factor is evident from Table 2.

The Survival model was exercised for full scale aircraft cabin fire tests conducted in the FAA Technical Center's TC-10 test article, a modified DC-10 fuselage, where concentrations of toxic gases, smoke, and temperature were monitored at various locations in the fuselage as a function of time (Marker, 1993). A typical survival curve for this wide body fuselage based on the FED_I model is illustrated in Fig. 9. As is evident from the Fig. 9, toxic gases were the primary contributors to the total FED_I, not the heat. Incapacitation was dictated by the CO_2 enhanced inhalation of CO. It is interesting that although the occurrence of flashover generates a rapid increase of hazards inside the cabin, including high temperatures, at some cabin locations (closer to the fire origin, near the ceiling), survival will be determined by exposures to heat.

The versatility of the FED-based survival model should enhance its use as a predictive tool to determine human survivability in aircraft cabin fire tests and in hypothetical aircraft fire scenarios. Its incorporation into large scale fire modelling programs should improve hazard estimates by better defining the contributions of heat and toxic gas effects.

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