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Guidelines for Safe Use of Gaseous Halocarbon Extinguishing Agents in Aircraft

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Research and Development Division
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16. Abstract

A kinetic scheme was used to model the human blood concentration history of halocarbon extinguishing agents as a function of agent discharge amount, compartment size, ventilation rate, cabin pressure, and altitude of aircraft. This methodology recommends discharge limits of halon replacement extinguishing agents that produce maximum blood concentrations safely below the adverse effect level. This report provides the technical basis for an update of guidance on the use of hand-held fire extinguishers on aircraft contained in Federal Aviation Administration Advisory Circular 20-42C. Safe-use limits are established for halon replacement extinguishing agents by using an instantaneous blood concentration of halocarbon as a criterion for adverse effect instead of a critical dose (concentration-time product).

17. Key Words

Halocarbon, Inhalation, Toxicity, Safe-use, Halon 1211, Halon 1301, HCFC Blend B, HFC-227ea, HFC-236fa, HCFC-123, Hypoxia, Aircraft, Extinguisher, First-order kinetic modeling, Arterial halocarbon concentration, PBPK modeling, NOAEL, LOAEL, Ventilation, Partition Coefficients

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LIST OF SYMBOLS AND ACRONYMS

HbO	Oxyhemoglobin
CO	Carbon monoxide
COHb	Carboxyhemoglobin
mm Hg	Millimeters of Mercury
$P_{A_{O_2}}$	Alveolar oxygen pressure
P_{O_2}	Oxygen pressure
τ	Time for Air Change
%v/v	Percentage by volume
W/V	Weight-to-compartment volume ratio
AC	Advisory Circular
CPA	Cabin pressure altitude
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
LOAEL	Lowest observable adverse effect level
MF	Multiplication factor
MPS	Minimum Performance Standard
NOAEL	No observable adverse effect level
PBPK	Physiologically based pharmacokinetic
SNAP	Significant New Alternatives Policy
TUC	Time of useful consciousness
UL	Underwriters Laboratories, Inc.

EXECUTIVE SUMMARY

The Federal Aviation Administration Aircraft Certification Service is revising Advisory Circular 20-42C, “Hand Fire Extinguishers for use in Aircraft,” to provide updated guidance on the selection of halocarbon extinguishing agents to avoid problems associated with toxicity. This report recommends limits on the amount of Halon 1211, Halon 1301, hydrochlorofluorocarbon Blend B, and hydrofluorocarbons 227ea and 236fa that can be used to fight fires in ventilated and unventilated aircraft compartments without adverse health effects due to inhalation of the agents themselves or low-oxygen concentration caused by agent displacement. The technical basis for the prescribed safe-use limits of halocarbon extinguishing agents in aircraft is a simplified kinetic model that describes the halocarbon concentration history in the blood of humans exposed to gaseous halocarbon environments. The kinetic model is calibrated against physiologically based pharmacokinetic data for halocarbon blood concentration in humans and is used to calculate the highest weights that can be safely discharged into an aircraft compartment based on compartment volume, cabin pressure altitude, maximum certificated altitude, and cabin air exchange rates.

1. OBJECTIVE.

This report provides technical basis and recommendations for the updated guidance on the safe-use limits of halon and halon-replacement (halocarbon) fire-extinguishing agents in aircraft.

2. BACKGROUND.

Fire-extinguishing agents to replace Halon 1211 in aircraft are being introduced in response to restrictions on the production of ozone-depleting, halogen-containing hydrocarbon (halocarbon) fire-extinguishing agents under the Clean Air Act Amendment of 1990, which was implemented in response to the Montreal Protocol, signed September 16, 1987, as amended [2]. The need for environmentally safe fire extinguishers and the availability of approved hand-held extinguishers containing the halocarbons hydrochlorofluorocarbon (HCFC) Blend B (primarily HCFC-123), hydrofluorocarbon (HFC)-227ea, and HFC-236fa required new guidance material for Halon 1211-replacement hand-held extinguishers [3 and 4].

Halocarbon extinguishing agents are gaseous compounds under normal aircraft operating conditions. They are relatively nontoxic at recommended use concentrations. By comparison, the combustion products of fires, such as carbon monoxide (CO) and hydrogen cyanide, cause hypoxia, manifesting as light-headedness and dizziness at low concentrations and more serious effects at higher concentrations. A quick effective extinguishment of an onboard fire will prevent buildup of combustion products and maintain a safe cabin environment.

However, even for brief exposures, halocarbons can induce cardiac arrhythmia at high concentrations in the bloodstream [4-7] and can induce anesthetic effects for prolonged exposures as they accumulate in the organs and tissues. In the context of the present discussion, a brief or short-term exposure is defined as less than 5 minutes and the blood concentrations of interest for halocarbons are the no observable adverse effect level (NOAEL) and the lowest observable adverse effect level (LOAEL). The NOAEL is the highest concentration of the gaseous halocarbon in the air of the test environment at which none of the test animals exhibits any adverse physiological or toxicological effects. The LOAEL is the lowest concentration of the halocarbon in the test environment at which adverse physiological or toxicological effects are first detected. Consequently, the LOAEL represents a higher concentration of halocarbon in the air than the NOAEL. These limits are determined from gas concentration effect test data for beagle dogs exposed to various constant concentrations of halocarbon for 5 minutes combined with intravenous epinephrine at concentrations well above physiological levels. These exposure limits are conservative because the level of injected epinephrine reaching the dogs' hearts is estimated to be 150 to 1825 times greater than the levels circulating in normally stressed dogs [6 and 7]. In these constant-concentration tests, exposure limits are not based on a particular time (dose) [8]. They are based on the minimum halocarbon concentration in the bloodstream at which cardiac arrhythmias occur in the dogs [6-7 and 9-15].

Based on the similarity between humans and dogs with respect to pharmacology, exposures up to 5 minutes at or below the NOAEL have been determined to be safe for humans by the United States Environmental Protection Agency (EPA), which allows the application of the dog-derived NOAEL for halocarbons directly to humans without application of a dog-to-human adjustment because of the conservative nature of the canine cardiac sensitization test [4-7]. Anesthetic effects have not been observed for dogs exposed to the NOAEL and LOAEL concentrations of the halocarbons in the short-duration tests. However, halocarbons are known to have anesthetic effects in dogs after prolonged exposures; therefore, human exposure should be limited to 5 minutes [16].

Each halocarbon agent has a target arterial blood concentration at which cardiac sensitization occurs for a group of dogs exposed to the LOAEL concentration for 5 minutes. This target arterial concentration has been shown to be the same for the dog and human [6] and provides the link for predicting safe 5-minute human exposure concentrations. Halocarbon gas concentrations exceeding the NOAEL can be safely used if physiologically based pharmacokinetic (PBPK) modeling is used to show that human blood concentrations of halocarbon remain below the target arterial concentration, as described in reference [7]. Table 1 lists the NOAEL, LOAEL, maximum safe 5-minute human exposure concentration, and the target arterial concentration for the halocarbons.

Table 1. NOAEL, LOAEL, Maximum Safe 5-Minute Human Exposure Concentrations, and Target Arterial Concentration for Selected Halocarbons

Agent	NOAEL[a] (%v/v)	LOAEL[a] (%v/v)	Maximum Safe 5-Minute Human Exposure Concentration		A_{safe} (%v/v)	Target Arterial Concentration, B_{safe} (mg/L)
			(%v/v)	(mg/L)		
HCFC-123	1.0	2.0	1.28[b]	78.9	1.28	69.9
HFC-227ea	9.0	10.5	10.84[c]	787	10.84	26.3
HFC-236fa	10.0	15.0	12.75[c]	831	12.75	90.4
Halon 1211	0.5	1.0	N/A[d]	N/A[d]	0.5[d,e] (35.7 mg/L)	11.1[d,e]
					1.0[d,f] (71.3 mg/L)	22.2[d,f]
Halon 1301	5.0	7.5	6.25[c,e]	391	6.25	25.7

[a] NOAEL and LOAEL values for agents approved under the EPA Significant New Alternative Policy (SNAP) program can be obtained from the SNAP program coordinator, U.S. EPA Office of Air and Radiation, or from the public docket for that office. See http://www.epa.gov/ozone/snap/fire/index.html.

[b] Derived from PBPK model [13] with adjustment for Federal Aviation Administration (FAA)-accepted target arterial concentration of 69.9 mg/L for HCFC-123.

[c] Derived from PBPK Model [7].

[d] PBPK method and target arterial concentration does not conform with selection criteria outlined in section 4.1.2. Canine LOAEL arterial blood concentrations and more robust PBPK modeling using referenced partition coefficients, and Monte Carlo Simulations for Halon 1211 are needed to run the PBPK model to meet the specifications set for the other agents.

[e] NOAEL-based, no dog-to-human correction. Exposure for 5 minutes to the NOAEL concentrations are considered safe for humans by the U.S. EPA.

[f] LOAEL-based, no dog-to-human correction.

[g] The target arterial LOAEL blood concentration used in reference 7 was obtained from reference 9.

Pharmacokinetics is the study of the time course of drug and metabolite levels in different fluids, tissues, and organs within the body. PBPK modeling has been used to describe the uptake, distribution, metabolism, and elimination of inhaled halocarbons in the human body and is a quantitative approach to determine human arterial blood concentrations histories [6, 7, and 13-15].

Arterial concentration histories of halocarbon in the bloodstream of humans exposed to constant or varying concentrations of gaseous halocarbons for up to 5 minutes has been simulated using PBPK modeling [6, 7, and 13-15]. Physiological components in the model are the liver, fat, lung, gut, and slowly and rapidly perfused tissues [6, 7, and 13]. The model for the present application includes a respiratory compartment containing a dead-space region and a pulmonary exchange area and a breath-by-breath description of respiratory tract uptake [6] to accurately simulate pharmacokinetic data in the 0- to 1-minute range and Monte Carlo simulations with 1000 iterations to account for ±2 standard deviations ($\pm 2\sigma$) of the simulated human population. Monte Carlo simulations of blood concentration in the PBPK model at the $+2\sigma$ level represent a blood concentration that accounts for 95% of the expected human population.

The arterial blood concentration history PBPK modeling simulation for a 5-minute exposure to a constant Halon 1211 concentration in air at the indicated level is shown in figure 1. The PBPK modeling methodology for Halon 1211 does not meet the same criteria as the PBPK modeling for the other agents in this report. Among the differences is the absence of Monte Carlo simulations. The more conservative PBPF modeling with Monte Carlo $+2\sigma$ arterial blood concentration history simulations for a 5-minute exposure to a constant halocarbon concentration in air at the indicated level are shown in figures 2 though 5 for Halon 1301, HCF 227ea, HFC-236fa, and HCFC-123 [7 and 13]. The HCFC-123 was used to represent Halocarbon Blend B since HCFC-123 is the most toxic component [13]. Figures 1-4 show that the arterial blood concentration of Halon 1211, Halon 1301, HFC-227ea, and HFC-236fa approaches an asymptotic (equilibrium) value at about 5 minutes that is proportional to the exposure concentration. In contrast, the arterial blood concentration of HCFC-123, shown in figure 5, increases continually throughout the exposure. For exposure times greater than a couple of minutes, the arterial blood concentration of HCFC-123 increases at a rate that is roughly proportional to the exposure concentration. These features of the halocarbon blood concentration history must be represented by any model that is used to develop guidance on the safe use of halocarbon extinguishing agents in aircraft cabins.

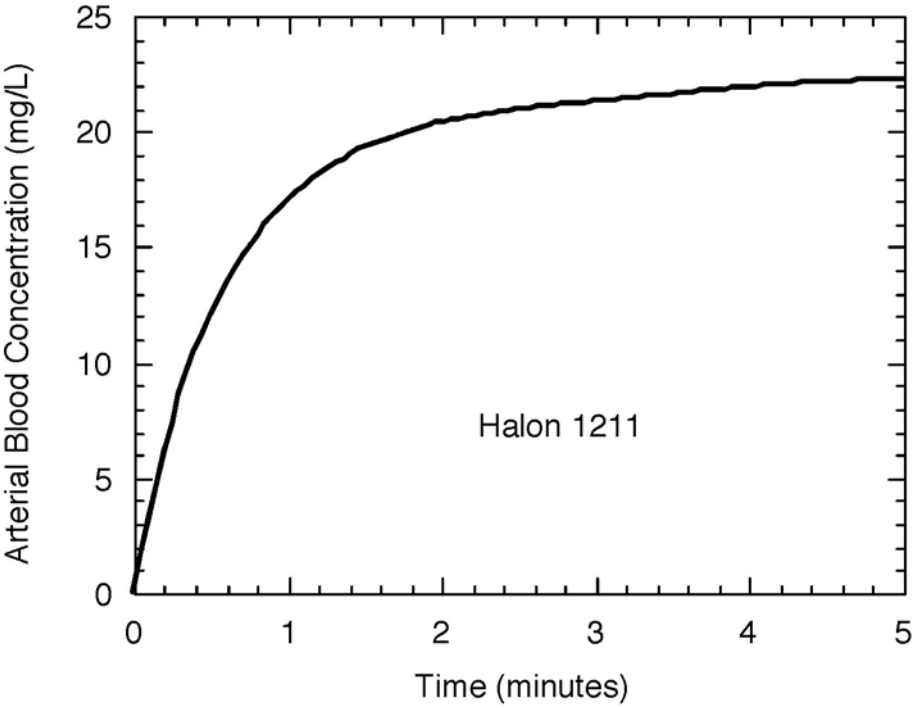


Figure 1. Simulation of Arterial Blood Concentration History for a 5-Minute Human Exposure to a Constant LOAEL Halon 1211 Concentration of 1.0%v/v [6]

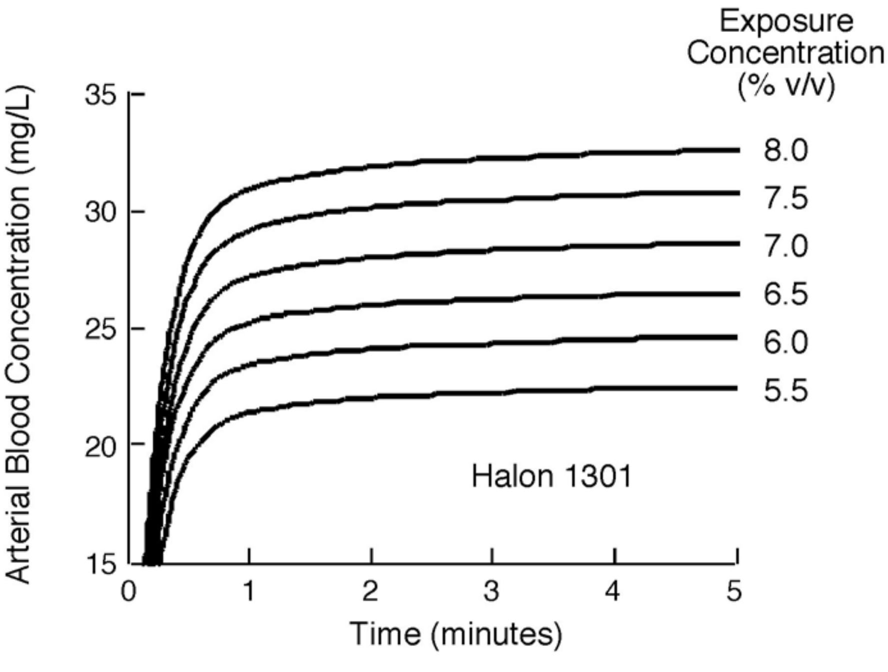


Figure 2. Monte Carlo Simulations of Arterial Blood Concentration Histories for 5-Minute Human Exposures to Constant Halon 1301 Concentrations of 5.5, 6.0, 6.5, 7.0, 7.5, and 8.0%v/v [7]

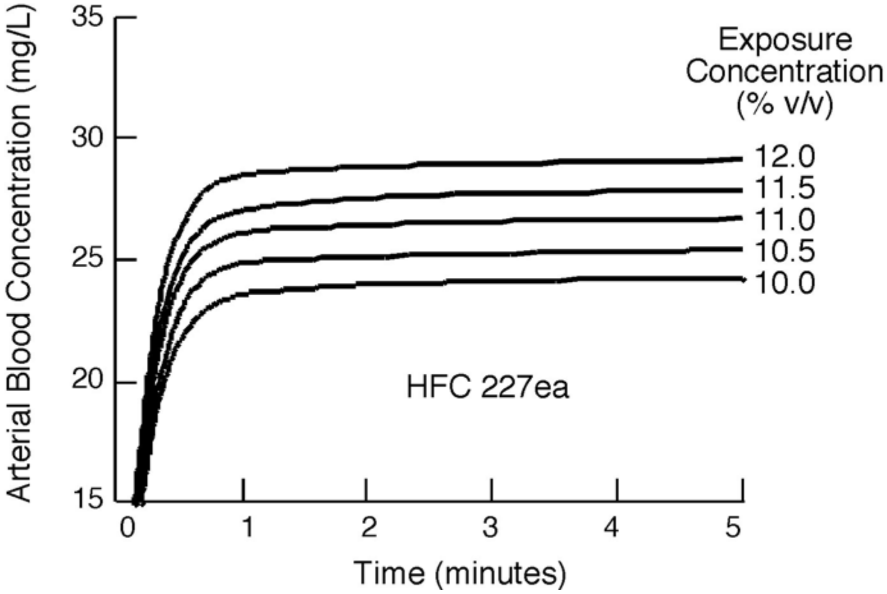


Figure 3. Monte Carlo Simulations of Arterial Blood Concentration Histories for 5-Minute Human Exposures to Constant HFC-227ea Concentrations of 10.0, 10.5, 11.0, 11.5, and 12.0%v/v [7]

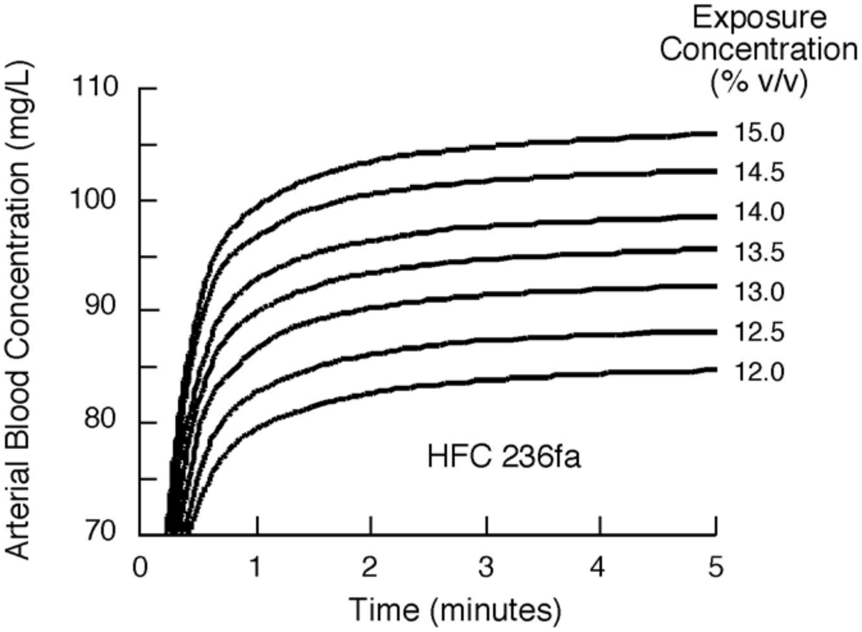


Figure 4. Monte Carlo Simulations of Arterial Blood Concentration Histories for 5-Minute Human Exposures to Constant HFC-236fa Concentrations of 12.0, 12.5, 13.0, 13.5, 14.0, 14.5, and 15.0 %v/v [7]

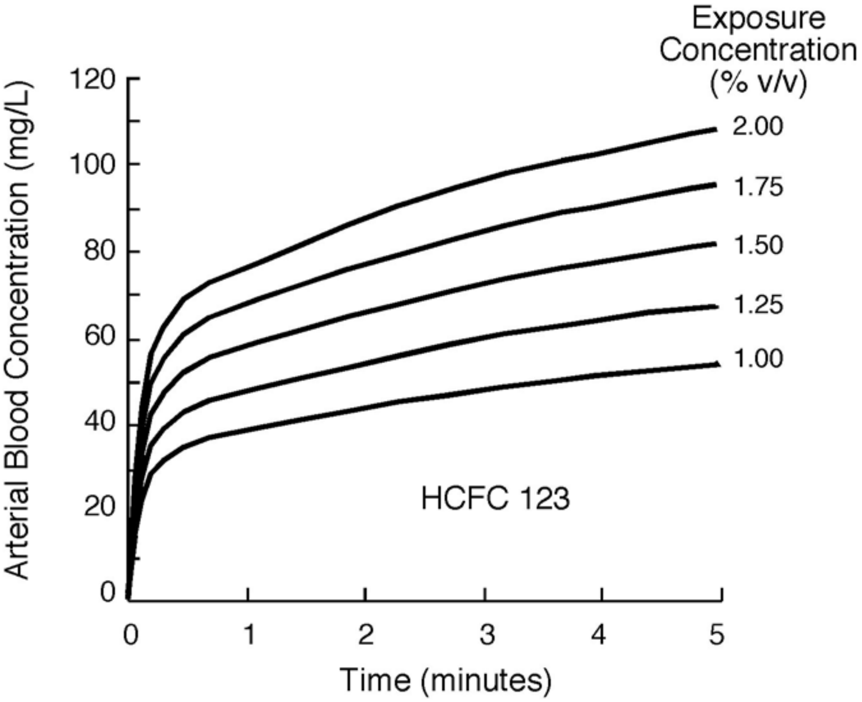


Figure 5. Monte Carlo Simulations of Arterial Blood Concentration Histories for 5-Minute Human Exposures to Constant HCFC-123 Concentrations of 1.0, 1.25, 1.5, 1.75, and 2.0%v/v [13]

Performing PBPK analyses and Monte Carlo simulations are complicated and expensive procedures, requiring a great deal of chemical and physiological data as input to existing models. Very few toxicologists have experience with the specific PBPK models developed for the inhalation of halocarbons. Moreover, the required chemical and physiological data for a particular halocarbon to input into the model may be difficult or impossible to obtain. The objectives of this work were to develop a simplified kinetic model for the transport of halocarbons in the human body, to calibrate the model using existing PBPK-derived human arterial blood history curves for various agents at constant gas concentration, and to apply the model to the calculation of the blood concentration history for a time-varying halocarbon concentration of these agents in air following the discharge of a fire extinguisher in an aircraft cabin. The validated kinetic model, in combination with a toxicity criterion based on the simulated arterial blood concentration reaching the target arterial blood concentration of a halocarbon, provides the technical basis for guidance on the safe use of hand-held fire extinguishers in aircraft.

3. KINETIC MODEL OF HALOCARBON TRANSPORT IN THE BODY.

A kinetic model for the transport of halocarbon in the bloodstream is shown in figure 6. In this kinetic model, halocarbon is transported between cabin air in the lungs and the bloodstream, and between the bloodstream and the organs and tissues with characteristic rate constants k_i. Halocarbon is finally eliminated as waste from the organs and tissues.

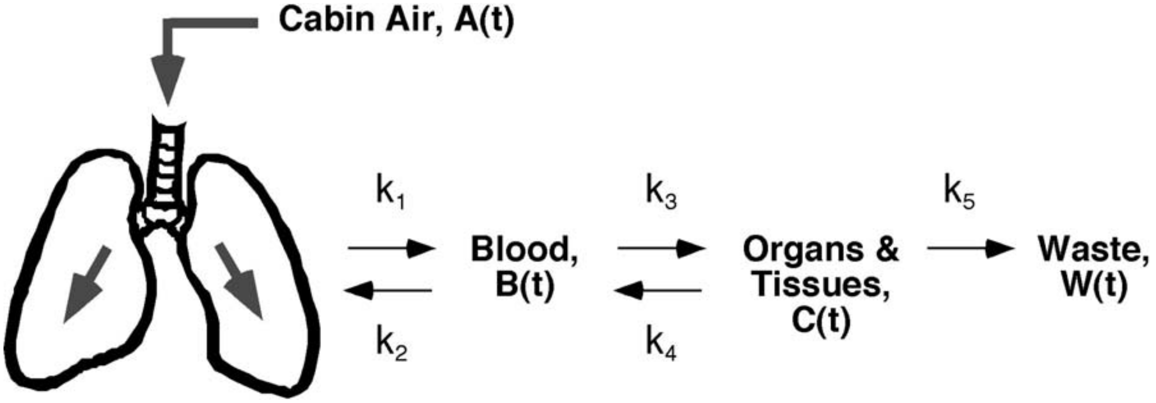


Figure 6. Kinetic Model of Halocarbon Transport in Humans

The kinetic model for halocarbon transport (figure 6) assumes that halocarbon in the cabin air enters the lungs and is transported from the lungs to the bloodstream with rate constant k_1 and the reverse process (i.e., respiration) occurs with rate constant k_2. Halocarbon in the bloodstream is transported to the organs and tissues with a single rate constant k_3 and the reverse process (i.e., from the organs and tissues to the bloodstream) proceeds with rate constant k_4. Halocarbon is metabolized in, or eliminated from, the organs and tissues as waste with rate constant k_5. The kinetic model of figure 6 differs from the PBPK kinetic model by lumping the individual halocarbon exchange reactions between the organs and tissues and blood (see table 2) into a single transport reaction.

In the kinetic scheme of figure 6, the instantaneous concentrations of halocarbon in the cabin air, bloodstream, organs and tissues, and waste, are A, B, C, and W, respectively. If the equilibrium concentrations of halocarbon in the blood and organs and tissues are $B(\infty)$ and $C(\infty)$, respectively, for a constant concentration of halocarbon in the air $A(\mathrm{t}) = A_0$, the partition coefficients for the halocarbon between blood and air ($\mathrm{P_{BA}}$) and between the tissues and air ($\mathrm{P_{CA}}$) are:

$$P_{\mathrm{BA}} = \frac{B(\infty)}{A_0} = \frac{k_1}{k_2}; \qquad P_{\mathrm{CA}} \equiv \frac{C(\infty)}{A_0} \approx \frac{C(\infty)}{B(\infty)}\frac{B(\infty)}{A_0} = \frac{k_3}{k_4}P_{BA} \tag{1}$$

The individual partition coefficients between the organs and tissues and the gaseous halocarbons in the air are shown in table 2 [7 and 13]. These partition coefficients are used in the PBPK model to derive the rate constants for the separate transport processes. In the present kinetic model, the individual partition coefficients are lumped together into a single value $\mathrm{P_{CA}}$ that represents some average of the global transport process between the blood and the organs and tissues.

Table 2. Partition Coefficients (Lognormal Distribution) for Halocarbons in Blood, Organs, and Tissues (Geometric Mean ± Geometric Standard Deviation)

	Parameter	HCFC-123	HFC-227ea	HFC-236fa	Halon 1211	Halon 1301
P_{BA}	Blood/Air	1.16 ±1.01	0.033 ±1.033	0.106 ±1.053	N/A	0.062 ±1.057
P_{CA}	Fat/Air	70 ±1	0.347 ±1.541	0.678 ±1.104	N/A	0.771 ±1.164
	Liver/Air	3.3 ±1.1	0.031 ±1.965	0.106 ±1.075	N/A	0.145 ±1.085
	Richly perfused Tissues/Air	3.3 ±1.1	0.031 ±1.965	0.106 ±1.075	N/A	0.145 ±1.085
	Slowly Perfused Tissues/Air	2.1 ±1.1	0.021 ±5.889	0.091 ±1.067	N/A	0.159 ±1.498

According to figure 6, the rate of accumulation of halocarbon in the arterial blood is the difference between the rate that halocarbon enters the bloodstream by absorption from the lungs and tissues and the rate at which halocarbon leaves the bloodstream by respiration through the lungs and by absorption into the organs and tissues. In figure 6, the concentration of halocarbon in the cabin air $A(t)$, blood $B(t)$, organs and tissues $C(t)$ and waste $W(t)$ are in units of mg/L, and all of the rate constants have units of reciprocal minutes (min^{-1}).

According to the kinetic scheme of halocarbon transport (figure 6), the rate of change of arterial blood concentration of halocarbon with time t for first-order processes is

$$\frac{dB}{dt} = k_1 A - k_2 B - k_3 B + k_4 C \tag{2}$$

Equation 2 states that the rate of increase of halocarbon in the bloodstream increases with the concentration of halocarbon in the air and in the organs and tissues. To solve equation 2, an expression must be found for C in terms of A or B. The rate of change of halocarbon concentration in the organs and tissues from figure 6 is

$$\frac{dC}{dt} = k_3 B - k_4 C - k_5 C \tag{3}$$

The rate of elimination of halocarbon from the organs and tissues to waste is negligible in the time scale of interest (5 minutes), so for practical purposes, $k_5 = 0$. If the blood and air are in rapid equilibrium such that $B(t) = P_{BA}A(t)$, equation 3 can be solved for C using an integrating factor

$$C(t) = \int_0^t k_3 B(x) e^{-k_4(t-x)} dx = k_3 P_{BA} \int_0^t A(x) e^{-k_4(t-x)} dx \tag{4}$$

Substituting equation 4 into equation 2 with $k_{23} = k_2 + k_3$

$$\frac{dB}{dt} + k_{23} B = k_1 A + k_3 k_4 P_{BA} \int_0^t A(x) e^{-k_4(t-x)} dx \tag{5}$$

Equation 5 can be solved for the halocarbon blood concentration history $B(t)$ for an arbitrary, time-varying concentration of halocarbon in the air $A(t)$

$$B(t) = k_1 \int_0^t A(x) e^{-k_{23}(t-x)} dx \ + \ k_3 k_4 P_{BA} \int_0^t \left(\int_0^t A(x) e^{-k_4(t-x)} dx \right) e^{-k_{23}(t-y)} dy \tag{6}$$

Equation 6 is the general solution of the kinetic scheme of figure 6. A few cases are of particular interest.

For a time-varying concentration of halocarbon in a constantly ventilated compartment, such as an aircraft cabin, a particular solution of equation 6 is obtained as follows. If V is the cabin volume, V′ is the volumetric dilution rate of cabin air with fresh air, and τ = v/v′ is the characteristic time for cabin air exchange, the concentration of halocarbon at time t is the solution of

$$-\frac{dA}{dt} = \frac{A}{\tau} \tag{7}$$

Assume that an instantaneous discharge of a fire extinguisher(s) at $t = 0$ produces a uniform initial concentration A_0. Separating terms and integrating equation 7 for an initial condition, $A(0) = A_0$ at $t = 0$

$$A(t) = A_0 e^{-t/\tau} \tag{8}$$

Equation 8 describes a halocarbon air concentration history that decreases exponentially with time due to dilution of the cabin air with fresh air. Substituting equation 8 for $A(t)$ into equation 6 gives the concentration of halocarbon in the bloodstream at time t for a ventilated cabin experiencing an instantaneous discharge of halocarbon extinguishing agent at $t = 0$.

$$B(t) = k_1 A_0 \int_0^t e^{-k_{23}t + (k_{23} - 1/\tau)x} dx \ + \ A_0 k_3 k_4 P_{BA} \int_0^t \left(\int_0^t e^{-k_4 t + (k_4 - 1/\tau)x} dx \right) e^{-k_{23}(t-y)} dy \tag{9}$$

Equation 9 is explicit in time and can be solved exactly for $B(t)$

$$B(t) = A_0 \left\{ \alpha \left(e^{-t/\tau} - e^{-k_{23}t} \right) + \beta \left(e^{-t/\tau} - e^{-k_4 t} \right) \left(1 - e^{-k_{23}t} \right) \right\} \tag{10}$$

The constants in equation 10 are

$$\alpha = \frac{k_1}{k_{23} - 1/\tau}; \qquad \beta = \frac{k_3 k_4 P_{BA}}{(k_4 - 1/\tau) k_{23}} \tag{11}$$

An unventilated compartment is a compartment in which the air exchange rate is zero, or the time constant for air exchange is infinite, $\tau = \infty$, so that the concentration of halocarbon is static (constant). For this condition, the constants (equation 11) reduce to $\alpha = k_1/k_{23}$ and $\beta = k_3 \mathrm{P}_{\mathrm{BA}}/k_{23}$. Equation 11 then becomes

$$B(t) = A_0 \left(1 - e^{-k_{23}t} \right) \left(\alpha + \beta (1 - e^{-k_4 t} \right) \tag{12}$$

Equation 12 requires four parameters—α, k_{23}, k_4, and β—that can be determined from the initial slope of the concentration history and the slope and intercept at long times, as will be described. According to equation 12, the equilibrium of concentration of halocarbon in the arterial blood at $t = \infty$ is $B(\infty) = A_0(\alpha + \beta) = (k_1 + k_3 \mathrm{P}_{\mathrm{BA}})/k_{23}$ from which $\mathrm{P}_{\mathrm{BA}} = B(\infty)/A_0 = k_1/k_2$, as per equation 1.

If halocarbon transport between the tissues and the bloodstream is negligible compared to the air-blood processes, $k_3 = k_4 = 0$, $\beta = 0$, and equation 12 simplifies to

$$B(t) \;=\; A_0 \alpha \left(1 - e^{-k_2 t} \right) = A_0 \frac{k_1}{k_2} \left(1 - e^{-k_2 t} \right) \tag{13}$$

Again, the ratio of the equilibrium concentration of halocarbon in the arterial blood to the concentration in air is $B(\infty)/A_0 = k_1/k_2 = \mathrm{P}_{\mathrm{BA}}$, as per equation 1. The qualitative behavior of the kinetic model for ventilated and unventilated compartments in which transport of halocarbon between the organs and tissues to the bloodstream is allowed (equations 10 and 12) or disallowed (equation 13) is shown in figure 7. The arterial blood concentration histories in figure 7 were evaluated for unit values of k_1, k_2, k_{23}, and A_0, and for $\beta = 1/2$, $\mathrm{k}_4 = 1/10$ (feedback from organs and tissues) or $\beta = 0$ (no feedback), and for $\tau = 3$ minutes (ventilation) or $\tau = \infty$ (no ventilation).

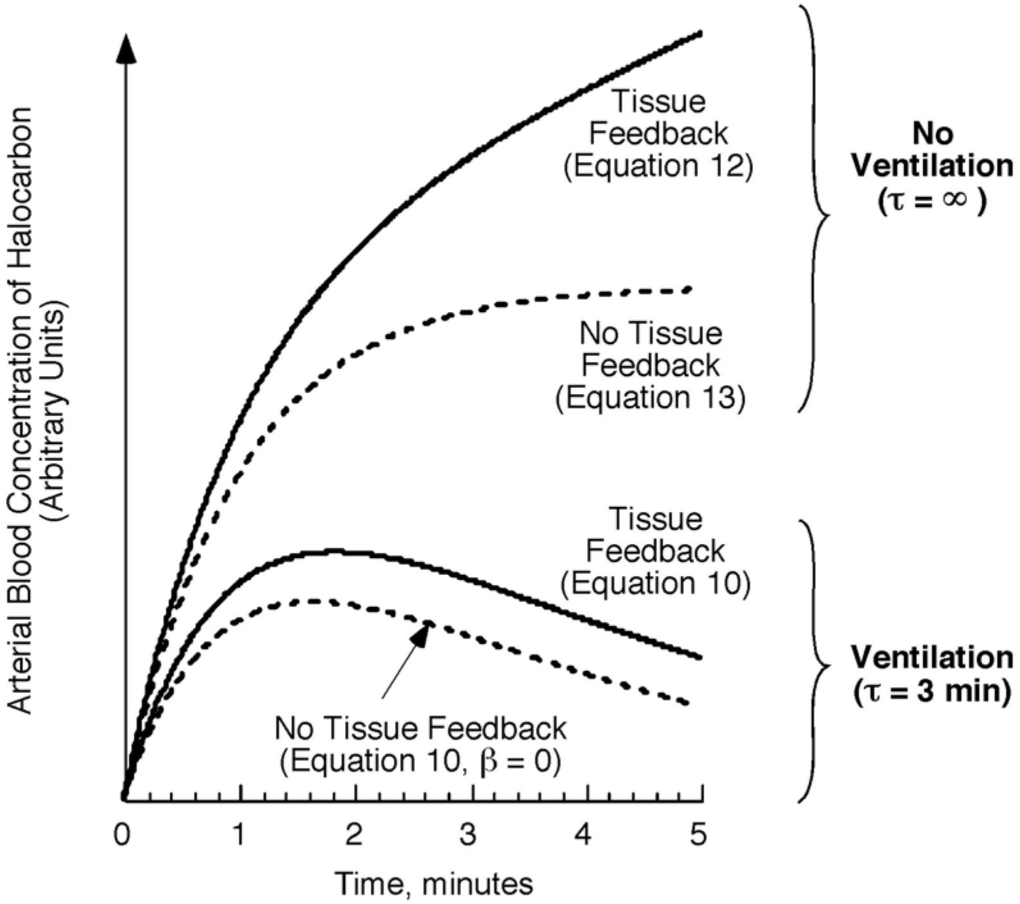


Figure 7. Arterial Blood Concentration Histories for Halocarbon in Ventilated and Unventilated Cabins With and Without Tissue Feedback to the Blood

In the following section, the kinetic model is fit to PBPK data for the halocarbons in figures 1-5. The best-fit values of α, k_{23}, β, and k_4 obtained by the fitting procedure were then used to calculate the arterial blood concentration history for a human in an aircraft cabin in which halocarbon extinguishing agents are discharged, producing an instantaneous and uniform initial concentration A_0. Uniform dispersion is assumed.

3.1 CALIBRATING THE KINETIC MODEL.

The full kinetic model that includes tissue exchange of halocarbon between the bloodstream and the tissues (equations 6, 10, and 12) requires four parameters. If the concentration of halocarbon in the arterial blood is measured (or modeled using PBPK) for a closed compartment ($\tau = \infty$) having a constant concentration of the halocarbon in the air, A_0, equation 12 applies, and the four parameters that need to be determined are α, k_{23}, k_4, and β. These parameters can be determined from the measured or simulated (PBPK) blood concentration history using a robust curve-fitting computer program with initial estimates for the parameters determined by a graphical procedure.

The graphical procedure used as a first estimate of the four model parameters is based on the approximation that, for small k_4, equation 12 reduces to

$$B(t) \approx A_0\left(1-e^{-k_{23}t}\right)\left(\alpha+\beta k_4 t\right) \tag{14}$$

The initial slope $S(0) = S_0$ of a plot of $B(t)$ versus time is $S_0 = A_0k_1$ according to equations 12-14. The intercept and slope at long times are $I = A_0\alpha = (S_0/k_{23}$ and $S_\infty = A_0\beta k_4$, respectively. From these relationships and a numerical value for P_{CA} (from table 2), the four independent parameters needed to describe the blood concentration history in any situation are obtained from the initial slope of the concentration history (S_0) and the slope (S_∞) and intercept (I) at long times:

$$\alpha=\frac{I}{A_0} \qquad k_{23}=\frac{S_0}{I} \qquad k_4=\sqrt{\frac{S_\infty S_0}{A_0\,I\,P_{CA}}} \qquad \beta=\sqrt{\frac{I\,S_\infty P_{CA}}{A_0 S_0}} \tag{15}$$

Figure 8 illustrates the graphical procedure used to obtain the first estimate of these parameters for HCFC-123 from the blood concentration history at a constant exposure concentration in air, $A_0 = 79$ mg/L (1.28%v/v).

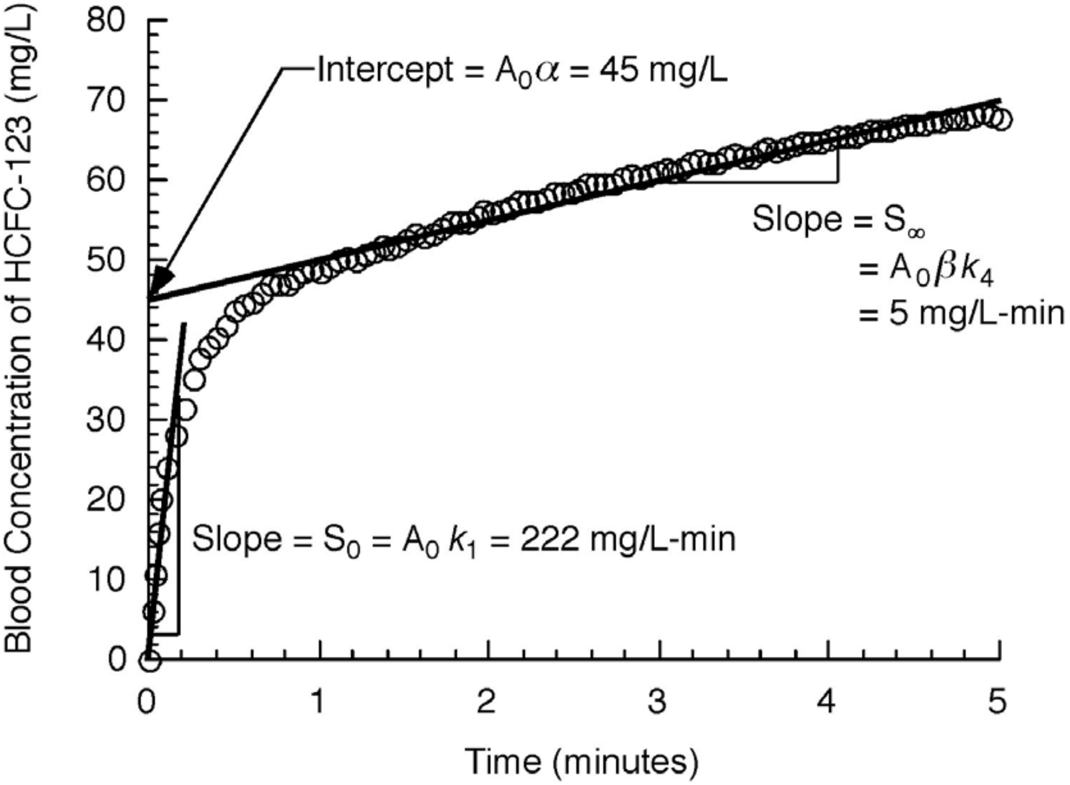


Figure 8. Graphical Procedure Used to Determine Rate Constants for Kinetic Model From Halocarbon Blood Concentration History

The rate constants k_1, k_2, k_3, and k_4 for halocarbons are obtained from the initial estimates for k_4, k_{23}, α, β and the P_{BA} in table 2 using the relationships: $k_1 = \alpha k_{23}$, $k_3 = \langle k_3 \rangle$ = average of $\beta k_{23}/P_{BA}$ and $k_{23} - \langle k_2 \rangle$; $k_2 = \langle k_2 \rangle$ = average of k_1/P_{BA} and $k_{23} - \langle k_3 \rangle$ for each agent. The rate constants are iterated in the formulae (equations 10 and 11) until a best fit is obtained by inspection for a constant concentration of the halocarbon in air, A_0. The optimized values of the rate constants for each agent are listed in table 3 in units of reciprocal minutes based on gas and blood concentrations of halocarbon expressed in units of mg/L. Figures 9-13 show the agreement between the kinetic model with the best-fit parameters in table 3 and the PBPK-derived arterial blood concentrations, $B(t)$, divided by the maximum arterial blood concentration, B_{max}, at the end of the 5-minute exposure to a constant concentration of the agents listed in table 1.

Table 3. Rate Constants for Kinetic Model of Halocarbon Uptake and Elimination

	Source							
	Table 1	Fitted Parameter				Calculated From Fitted Parameters		
Agent	P_{BA}	α	β	k_{23} (min^{-1})	k_4 (min^{-1})	k_3 (min^{-1})	k_2 (min^{-1})	k_1 (min^{-1})
Halon 1211	0.12*	0.26	0.050	1.9	0.50	0.6	1.3	0.49
Halon 1301	0.06	0.06	0.003	4.4	0.40	0.1	4.3	0.27
HFC 227ea	0.03	0.03	0.003	4.8	0.10	0.2	4.6	0.16
HFC 236-fa	0.11	0.10	0.17	4.1	0.01	0.02	4.08	0.43
HCFC 123	1.16	0.48	0.48	8.5	0.33	4.2	4.3	4.08

*$P_{BA} = k_1/\langle k_1/P_{BA} \rangle$, where $\langle k_1/P_{BA} \rangle = 4.2 \pm 0.6$ min^{-1} is the average k_1/P_{BA} for the other 4 halocarbons.

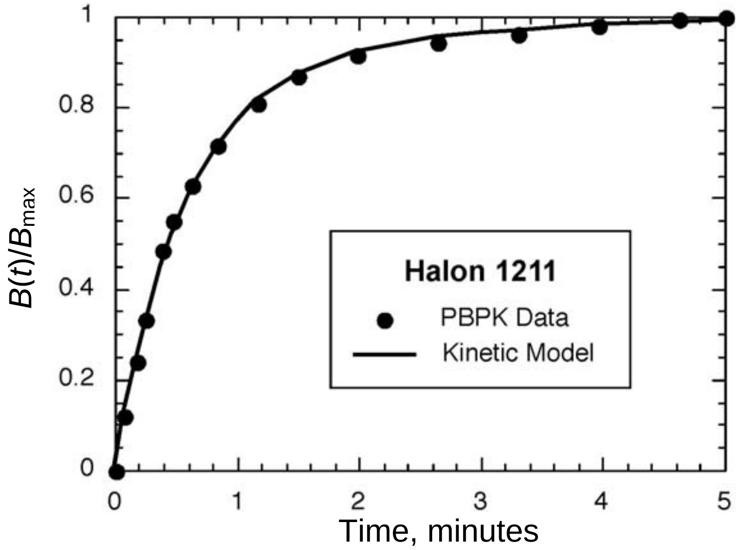


Figure 9. Comparison of Kinetic Model to PBPK Data for Human Arterial Blood Concentration History of Halon 1211 for Simulated Exposure to A_0 = 1%v/v (72 mg/L)

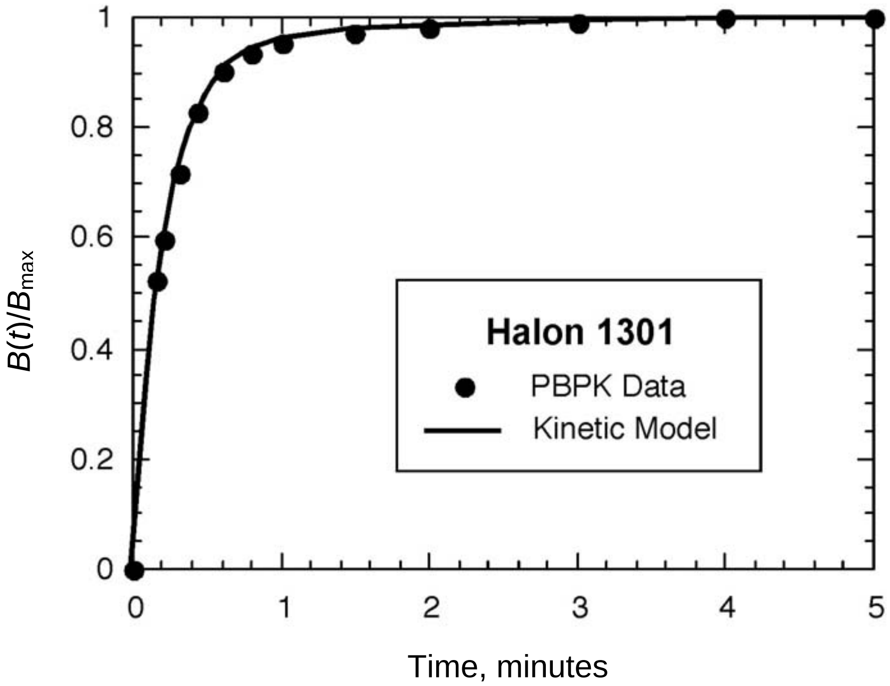


Figure 10. Comparison of Kinetic Model to PBPK Data for Human Arterial Blood Concentration History of Halon 1301 for Simulated Exposure to A_0 = 7.0%v/v (439 mg/L)

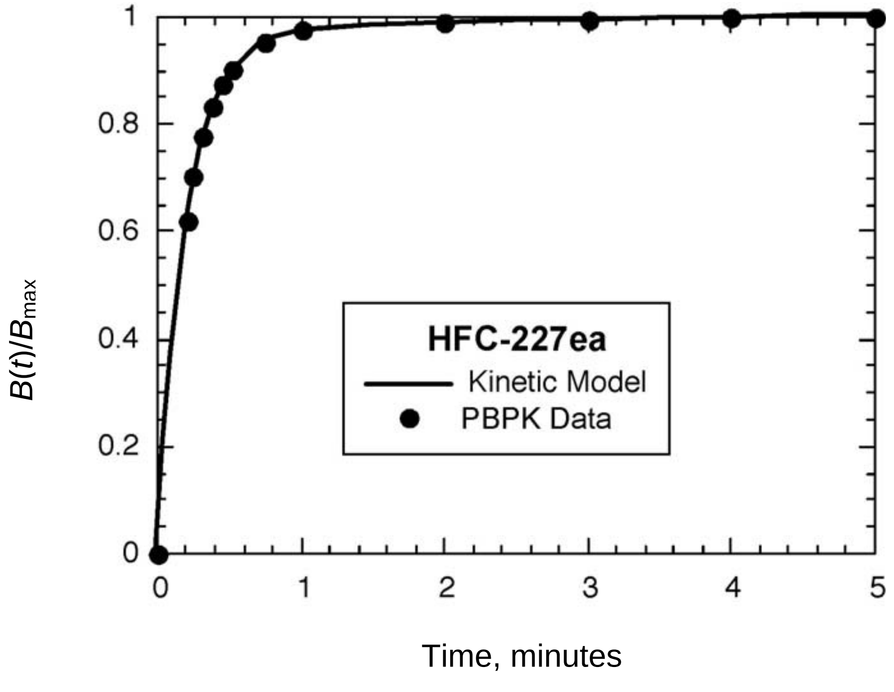


Figure 11. Comparison of Kinetic Model to PBPK Data for Human Arterial Blood Concentration History of HFC 227ea for Simulated Exposure to A_0 = 10%v/v (726 mg/L)

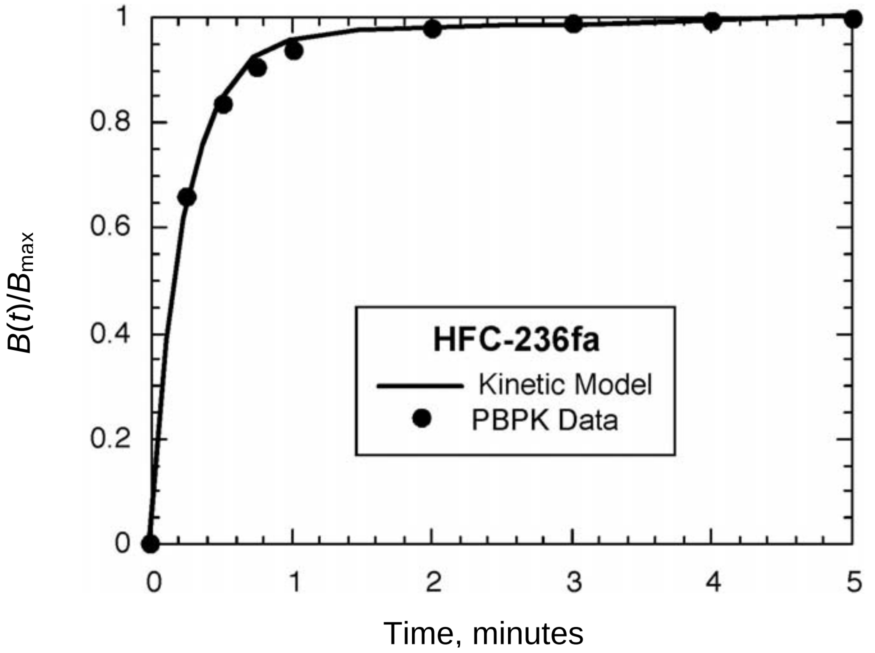


Figure 12. Comparison of Kinetic Model to PBPK Data for Human Arterial Blood Concentration History of HFC-236fa for Simulated Exposure to A_0 = 15%v/v (979 mg/L)

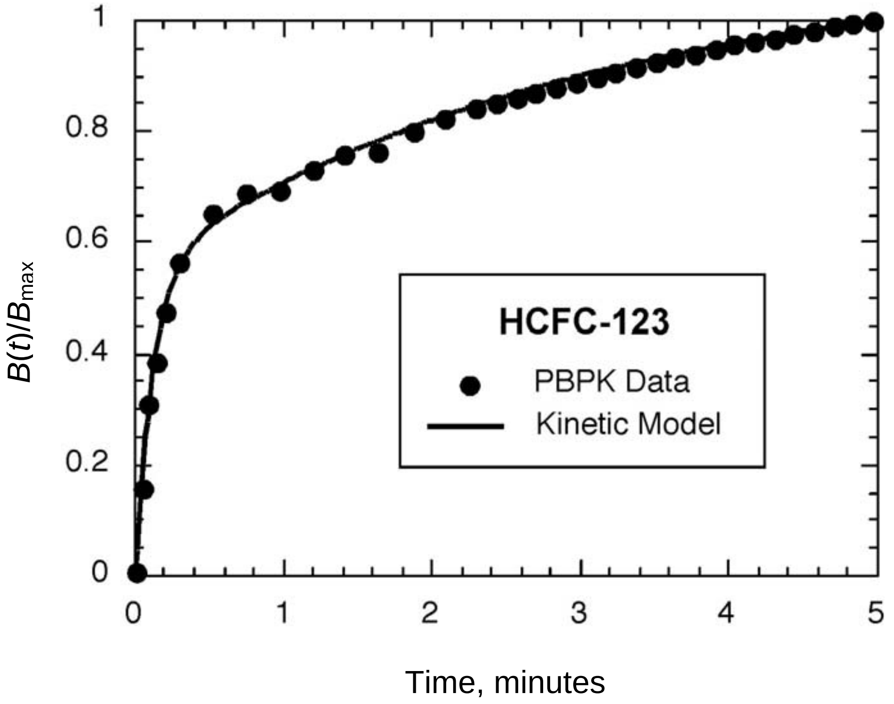


Figure 13. Comparison of Kinetic Model to PBPK Data for Human Arterial Blood Concentration History of HCFC-123 for Simulated Exposure to A_0 = 1.28%v/v (79 mg/L)

3.2 KINETIC MODEL PREDICTIONS FOR VENTILATED COMPARTMENTS.

For the blood concentration history described by equations 10 or 12, the ratio of two blood concentrations, $B_1(t)$ and $B_2(t)$ at any time, t, is independent of the initial halocarbon concentration in air A_0 and is simply the ratio of the time-dependent terms $f_1(t,\tau_1)/f_2(t,\tau_2)$. If $f_2(t,\tau_2) = f_2(5,\infty)$ corresponds to the arterial blood concentration at 5 minutes in an unventilated compartment ($\tau = \infty$) containing halocarbon at the maximum safe-use concentration, A_{safe}, in table 1, then $B_{\max} = B_{\text{safe}}$, then the ratio of the arterial blood concentration at t,τ to the target arterial concentration B_{safe}, is

$$\frac{B(t,\tau)}{B(5,\infty)} = \frac{B(t,\tau)}{B_{\text{safe}}} = \frac{\alpha(e^{-t/\tau} - e^{-k_{23}t}) + \beta(e^{-t/\tau} - e^{-k_4 t})(1 - e^{-k_{23}t})}{\alpha_\infty(1 - e^{-5k_{23}}) + \beta_\infty(1 - e^{-5k_4})(1 - e^{-5k_{23}})} \tag{16}$$

where $\alpha_\infty = \alpha(\tau = \infty)$ and $\beta_{\text{Safe}} = \beta(\tau = \infty)$. The inverse of equation 16 at its maximum point is the ventilation benefit

$$\mathit{Ventilation\ Benefit} = \frac{B_{\text{safe}}}{B(t,\tau)} = \frac{\alpha_\infty(1 - e^{-5k_{23}}) + \beta_\infty(1 - e^{-5k_4})(1 - e^{-5k_{23}})}{\alpha(e^{-t/\tau} - e^{-k_{23}t}) + \beta(e^{-t/\tau} - e^{-k_4 t})(1 - e^{-k_{23}t})} \tag{17}$$

Figures 14-18 show the ratio of the arterial blood concentration of halocarbon in a ventilated compartment at time t for various air exchange times τ to the arterial blood concentration at 5 minutes in an unventilated compartment for an instantaneous discharge of the safe-use concentration (for unventilated aircraft) A_{safe}, as per equation 16. For the special case when the initial concentration is the maximum safe 5-minute human exposure concentration, A_{safe}, $B_{\max}$ is the target arterial concentration, B_{safe}.

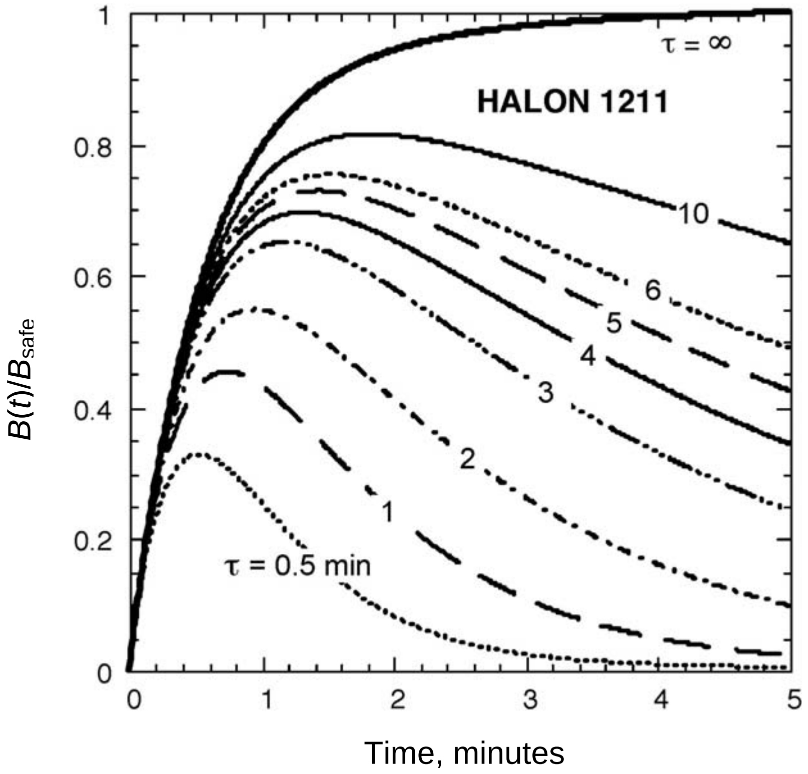


Figure 14. Ratio of the Arterial Blood Concentration of Halon 1211 to the Target Value B_{safe} for Simulated Human Exposures to A_{safe} in a Ventilated Cabin at the Indicated Air Exchange Times

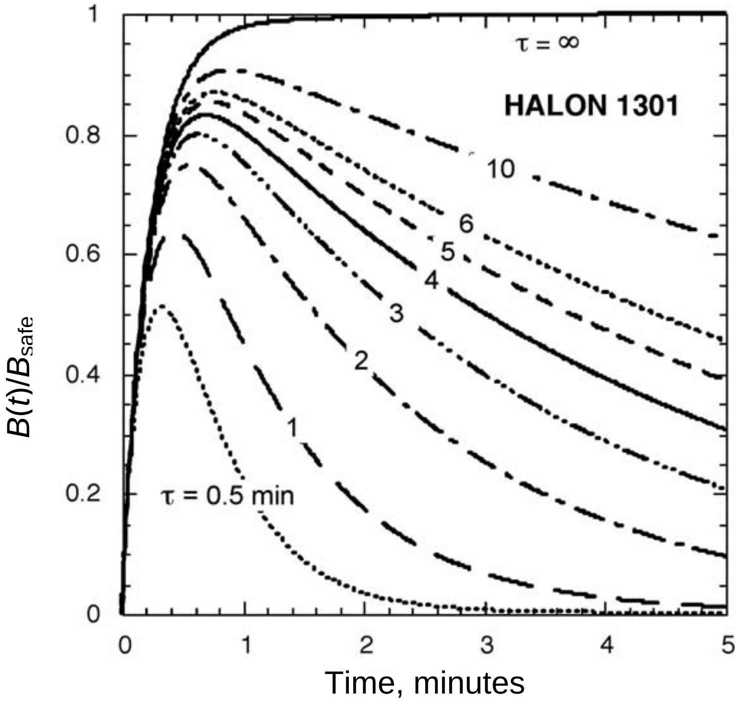


Figure 15. Ratio of the Arterial Blood Concentration of Halon 1301 to the Target Value B_{safe} for Simulated Human Exposures to A_{safe} in a Ventilated Cabin at the Indicated Air Exchange Times

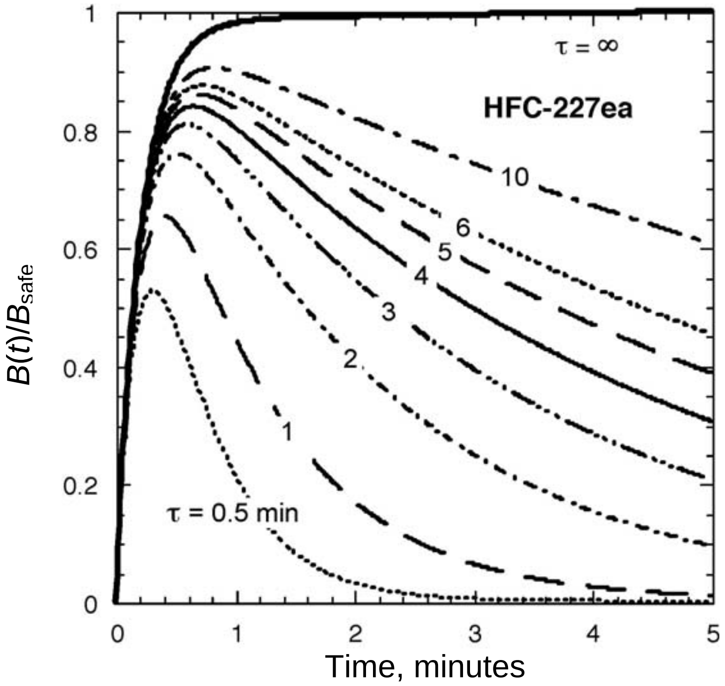


Figure 16. Ratio of the Arterial Blood Concentration of HFC-227ea to the Target Value B_{safe} for Simulated Human Exposures to A_{safe} in a Ventilated Cabin at the Indicated Air Exchange Times

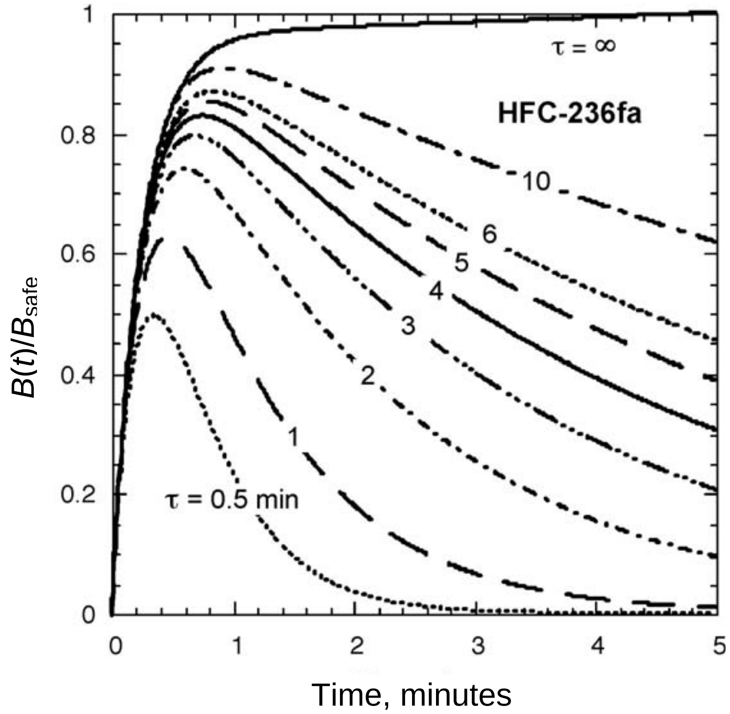


Figure 17. Ratio of the Arterial Blood Concentration of HFC-236fa to the Target Value B_{safe} for Simulated Human Exposures to A_{safe} in a Ventilated Cabin at the Indicated Air Exchange Times

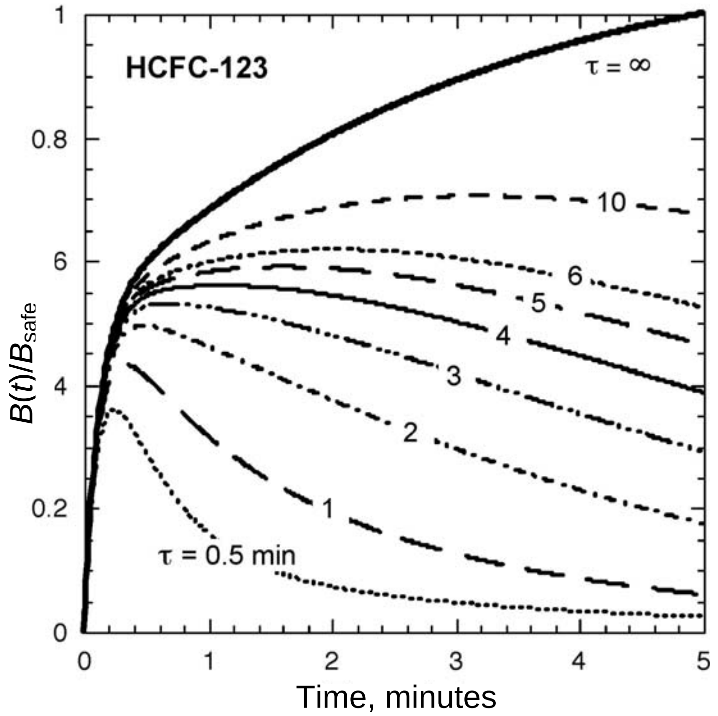


Figure 18. Ratio of the Arterial Blood Concentration of HCFC-123 to the Target Value B_{safe} for Simulated Human Exposures to A_{safe} in a Ventilated Cabin at the Indicated Air Exchange Times

4. RECOMMENDATION FOR SAFE USE OF HALOCARBON EXTINGUISHING AGENTS.

4.1 TECHNICAL BASIS FOR SAFE-USE RECOMMENDATIONS FOR HALOCARBONS.

The following assumptions and criterion were used to develop the guidance for the maximum weight, W, of a fire-extinguishing agent that can be used in a given compartment volume, V, for various altitudes and ventilation rates. The guidance is formulated in terms of the safe agent weight-to-compartment volume ratio (W/V).

4.1.1 Performance Standards of Fire Extinguishers.

Required hand-held extinguishers used in aviation must meet the minimum performance standard (MPS) for hand-held extinguishers. The MPS ensures that extinguishers using halon replacement agents pose no reduction in safety, either in terms of effectiveness in fighting onboard fires or the toxicity of the decomposition products. The MPS was developed by the FAA and the civil aviation community through the FAA-sponsored International Aircraft Systems Fire Protection Working Group [3]. The MPS specifies two extinguisher tests that halon replacement agents must pass: a hidden fire and a seat fire, using gasoline as an accelerant. The effectiveness of the hidden fire test is affected by the hardware used to deliver it. Therefore, approval is granted on an agent/hardware basis.

4.1.2 Toxicity Criterion for Safe Use.

From a regulatory point of view, it is best to set consistent toxicity criteria for all present and future agents used in hand-held extinguishers. Reference 6 provides the methodology and peer-reviewed PBPK evaluation of three of the five agents: Halon 1301, HFC-227ea, and HFC-236fa.

The selection criteria for the target arterial concentration provided in this report is based on the Vinegar, et al., 2000, study [7] and corresponding canine exposure data [9 and 11]. The lowest canine arterial concentration for a group of at least three dogs, measured at 5 minutes into a halocarbon gas exposure at the LOAEL concentration, is the target dose to be used for assessing safe human exposures to aircraft hand-held extinguishing agents. Safe halocarbon gas concentrations are exceeded for both humans and dogs when this target arterial concentration is reached. The target arterial concentrations are shown in table 1.

Halocarbon toxicity is defined to occur at the target arterial blood concentration at which cardiac sensitization occurs. This target arterial concentration, B_{safe} in the kinetic analysis, is obtained from canine halocarbon exposure data. Maximum safe human exposure limits are obtained from this kinetic analysis. These EPA-approved, and peer-reviewed, 5-minute safe human exposure concentrations are obtained from PBPK modeling [7 and 13] of canine LOAEL exposure data (9, 11, and 12) and are shown in table 1.

This safe-use agent W/V guidance minimizes the risk for adverse health effects, including cardiac sensitization and anesthetic effects from potential exposure to an agent. Regulatory and standard-making authorities have used cardiac sensitization thresholds as the criterion for determining acceptability for use in occupied areas [4 and 5]. Cardiac sensitization usually occurs at a lower concentration for halocarbons than other acute toxicity endpoints, such as anesthetic effects and lethality. Cardiac sensitization is particularly important in firefighting. Higher levels of epinephrine (adrenaline) secreted by the body under the physiological stress of a fire event may increase the possibility of sensitization.

It should be noted that after re-evaluation, PBPK-derived safe-use concentrations of Halon 1211 were found to be lower than what was presented in the previous hand-held extinguisher AC (AC 20-42C) [1]. The report authored by Eklund [8] was the basis for the dated AC guidance. Eklund set the safe use at 4 percent • minutes. The assumption was made that a dose of 4 percent for 1 minute was equivalent to a dose of 1 percent for 4 minutes. The robust PBPK modeling techniques used for the development of safe-use guidance were not available when AC 20-42C was written: inhaled halocarbons are rapidly absorbed into the bloodstream, such that the arterial blood concentration for a 5-minute exposure to a constant halocarbon concentration is not much greater than for a 1-minute exposure [6, 7, and 13].

Unlike the halon replacements, human exposure test data is available for halons, albeit limited and mixed [17-19]. Clark reported that human subjects exposed for 1 minute to 4-percent Halon 1211 exhibited marked dizziness and paresthesia (burning and tingling of skin) [18]. A DuPont Haskell Laboaratory report on Halon 1211 references both Clark's and Von Eickstedt's work (unpublished) [19]. Von Eickstedt observed that a 4.1% concentration of Halon 1211 produced no symptoms during 2- to 3-minute exposures. The canine-derived, 5-minute NOAEL and LOAEL Halon 1211 exposure limits are 0.5% and 1%, respectively. However, Halon 1211 has a history of over 25 years of safe use. This safe-use history may be used to justify the 4-percent • minute AC 20-42C limits as acceptable, while this agent is being phased out. More conservative approaches to setting safe-use Halon 1211 limits could be considered.

- Use the nonconforming PBPK modeling for Halon 1211 presented in figure 1, for which canine arterial blood concentration data was not available, partition coefficients were not provided, and a Monte Carlo simulation was not performed [6]. This PBPK modeling was a demonstration of the applicability of the PBPK modeling approach for assessing the safety of exposures to changing Halon 1211 concentrations [6, 14, and 16] does not meet the criteria used for the other agents. Since canine target arterial concentration is not available, the target concentration may be set as follows:

    - Set the target arterial concentration for Halon 1211 based on simulated human exposures to Halon 1211 at the LOAEL concentration of 1.0% [6 and 14], rather than the lowest observed arterial concentration for 5-minute canine exposures at the LOAEL [6]; thus, there is no correction for dog-to-human tolerances, as there is for the other agents evaluated.

    - Set the Halon 1211 target arterial concentration based on the simulated human exposure to Halon 1211 at the NOAEL concentration of 0.5%. (The target arterial concentration would be half the LOAEL-based arterial target concentration, based on PBPK modeling of the more conservative NOAEL 0.5% Halon 1211 human exposure concentration.)

- A conservative aircraft ventilation benefit could be employed. Use the ventilation benefit, A_{safe} (ventilated)/A_{safe} (unventilated), obtained for Halon 1301 as multiplier for the Halon 1211 NOAEL or LOAEL concentrations.

- An even more cautious approach would be to not accept any PBPK modeling and to set the safe-use concentration to the NOAEL, regardless of aircraft compartment ventilation rates.

The canine arterial concentration histories from Huntington Life Science 1998 [11] and Huntington Life Science 2007 [12] were reviewed to ensure consistency in the selection methodology for the target arterial concentration of HCFC Blend B. The target concentration of 83.3 mg/L used by Colton, et al. in reference 13 did not meet the FAA selection criteria. HCFC-123 was found not to conform and was replaced with 69.9 mg/L. The target concentration of 69.9 mg/L is based on the lowest canine 5-minute arterial concentration for three dogs exposed to the LOAEL 2.0% HCFC-123 concentration [12]. The arterial concentration histories for simulated human exposures to constant halocarbon concentrations, obtained by PBPK modeling, are shown for Halon 1301, HCFC-123, HFC-227ea, and HFC-236fa [6 and 13] in figures 2-5. The target arterial concentration is reached 5 minutes into an exposure.

4.1.3 Exposure Time.

The guidance assumes that the time humans are exposed to the maximum safe gaseous halocarbon extinguishing agent concentration A_{safe} in an aircraft cabin is ≤5 minutes. This time limit protects against anesthetic effects associated with prolonged exposures.

4.1.4 Discharge of Halocarbon in the Cabin.

The safe-use guidance in this report is based on the assumption that all extinguishers in a compartment are discharged simultaneously at time $t = 0$ for the following reasons: (1) There are incidences where multiple Halon 1211 hand-held extinguishers have been used to extinguish hidden fires. The extinguishers were used in quick succession such that the arterial concentration would be nearly twice as high as for one discharged extinguisher. (2) An aircraft that seats 30 or more passengers, requiring 2 or more extinguishers, generally has a cabin diameter that is much smaller than its axial length, resulting in an initial uneven distribution of the agent. Even if only one extinguisher is used, the nonuniformity of the agent distribution needs to be considered, especially since most of the arterial uptake of agent occurs in the first 30 seconds (assuming exposure to a constant concentration for 5 minutes).

4.1.5 Dispersion of Halocarbon Extinguishing Agent in the Cabin.

The guidelines for the discharge amount of the various halocarbon extinguishing agents assume an instantaneous discharge and uniform dispersion of agent in the cabin, producing a constant initial concentration A_0 at time $t = 0$ everywhere in the cabin with no subsequent stratification. There is no correction or allowance for agent diffusion or stratification with time. Stratification of discharged halocarbon agents can be either a benefit or liability, depending on the height of an occupant's head above the compartment floor and the attitude of the aircraft. Agent outflow is generally through the floor-level baseboard return air grills, through the cheek area, and outside the aircraft through the outflow valve. These floor-level exhaust grills are beneficial for exhausting the heavier-than-air discharged halocarbon agent when recirculation systems are turned off. This top-to-bottom aircraft ventilation will accelerate the dissipation of the agent in aircraft compartments.

However, if recirculation systems are not immediately turned off, and there is a significant percentage of recirculated air, the agents concentrated at the floor level may be recirculated to the breathing zone of seated passengers. Many aircraft today with 30 or more passenger seats, where two or more extinguishers are required, have recirculating systems that recycle up to approximately 50% of the cabin air. Recirculation systems for aircraft of this size will probably not be turned off within the first 30 seconds of the agent discharge. Most of the agent uptake into the human arterial blood occurs within the first 30 seconds, per figures 1-5 [7 and 13], and the toxic endpoint is directly related to arterial blood concentration. Thus, the uniform dispersion assumption is a reasonable compromise.

4.1.6 Ventilation Benefit.

For unventilated cabins, the maximum safe agent W/V specified in the guidance is based on the PBPK-derived maximum safe constant human exposure concentration, assuming instantaneous discharge, uniform dispersion, and 5-minute exposure. The maximum safe W/V for ventilated cabins is embodied in selector curves calculated using the kinetic model for all halocarbon extinguishing agents. Ventilation benefit calculations were performed for HCFC-123 using the PBPK model and are in reasonable agreement with the kinetic model predictions for this agent. The selector curves are based on the agent, weight, compartment volume, aircraft ventilation rate, and maximum certificated cabin pressure altitude (CPA). Maximum certificated altitude is used for unpressurized aircraft.

4.1.7 Hypoxia.

Low oxygen concentrations in small compartments (cabins) can result from displacement of air by gaseous halocarbon extinguishing agent. Descent, aircraft ventilation, and protective breathing equipment guidance, provided in section 5.5, minimizes exposures to low oxygen concentrations.

4.2 MAXIMUM SAFE WEIGHT-TO-VOLUME RATIOS FOR AIRCRAFT HALOCARBON EXTINGUISHERS.

4.2.1 Single Halocarbon Agent.

The maximum safe agent concentration in an aircraft compartment is based on the combined weight of agent contained in all hand-held extinguishers in that compartment. The maximum safe weight-to-compartment volume ratio, $\left(\frac{W}{V}\right)_{\text{safe}}$ (lb/ft^3) can be determined from equation 18 [5]. Equation 18 includes an allowance for the normal leakage from a tight enclosure due to agent expansion [5]. Instantaneous discharge and uniform dispersion are assumed.

$$\left(\frac{W}{V}\right)_{\text{safe}} = \frac{1}{(S \times H)} \times \frac{A_{0\text{safe}}}{(100 - A_{0\text{safe}})} \tag{18}$$

where:

$A_{0\text{safe}}$ is the maximum safe initial discharge concentration (%v/v), per tables 1 and 8 for unventilated compartments, and table 10 for ventilated compartments.

S = specific volume of the agent at sea level and 70°F (21.1°C), units are ft^3/lb, as shown in table 4.

H is the altitude correction factor for *S,* as shown in table 5. *H* is the ratio of sea level pressure to the pressure at a stated altitude. These pressures were obtained from the ICAO International Standard Atmosphere.

V (ft^3) is the net volume of the compartment, i.e., gross volume minus volume of fixed structures.

Table 4. Specific Volume of Halocarbon Agents

Agent	Specific Volume of Agent (ft^3/lb) at 1 Atmosphere and 70ºF
HCFC Blend B	2.597[a]
HFC-227ea	2.2075[a,b]
HFC-236fa	2.4574[a,b]
Halon 1211	2.248[c,d]
Halon 1301	2.5605[c,e]

[a] Obtained from the manufacturer.
[b] NFPA 2001 Standard on Clean Agent Fire-Extinguishing Systems, 2008 Edition [5].
[c] Obtained from a past U.S. manufacturer. Halons are no longer manufactured in the United States.
[d] NFPA 12B, Standard on Halon 1211 Fire-Extinguishing Systems, 1990 Edition (No longer an active standard).
[e] NFPA 12A, Standard on Halon 1301 Fire-Extinguishing Systems, 2009 Edition.

Table 5. Altitude Correction Factors

Pressure Altitude (ft)	Altitude Correction Factor, *H*
0	1.000
8,000	1.346
12,500	1.604
14,000	1.702
18,000	2.003
25,000	2.695

For pressurized aircraft, use $H = 1.346$ (for 8000 ft CPA). For unpressurized aircraft, use the *H* value at the pressure altitude for the maximum certificated altitude.

Very small aircraft compartments may not meet the maximum safe W/V values presented in the tables and graphs of this report. The importance of having sufficient fire protection far exceeds agent toxicity concerns. Therefore, the installer should choose the safest extinguisher of the required rating. Although exposure to halocarbon agents is a concern, it is far less of a concern than the consequences of an unextinguished, in-flight fire. It is critically important to have an extinguisher available in the event of an in-flight fire. The consequences of an unextinguished fire are the loss of the aircraft and its occupants due to thermal damage to the aircraft and the hazards of burning aircraft materials. These hazards include CO, hydrogen cyanide, smoke, heat, and oxygen depletion. Moreover, a conservative methodology was employed to determine the maximum safe W/V, so the exposure hazard for exceeding the maximum safe W/V values is low when following the guidelines outlined in section 4.1.2.

4.2.2 Halocarbon Blends.

4.2.2.1 Method 1.

The maximum safe W/V for a blend of halocarbon A and halocarbon B can be calculated from the maximum safe W/V ratio of halocarbon A and the maximum safe W/V ratio of halocarbon B, as shown in equation 19.

$$\left(\frac{W_{A+B}}{V}\right)_{Safe} = \chi_A \times \left(\frac{W_A}{V}\right)_{Safe} + \chi_B \times \left(\frac{W_B}{V}\right)_{Safe} \tag{19}$$

where χ_A and χ_B are the mole fractions of halocarbons A and B in the extinguisher and $\chi_A + \chi_B = 1$, regardless of the presence of inert gases in the extinguisher.

By definition

$$\chi_A = \frac{n_A}{n_A + n_B} \text{ and } \chi_B = \frac{n_B}{n_A + n_B}$$

where n_A and n_B are the number of moles of A and B in the extinguisher. n_A and n_B can be expressed in terms of the mass and molecular weights of the agent.

$$n_A = \frac{m_A}{MW_A} \text{ and } n_B = \frac{m_B}{MW_B}$$

where MW_A and MW_B are the molecular weights of A and B in g/mole, and m_A and m_B are the mass of A and B in grams.

The molecular weights of the halocarbon agents and blends are shown in table 6.

Table 6. Molecular Weights of Halocarbon Agents and Blends

Halocarbon	MW (g/mole)
Halon 1211	165
Halon 1301	149
HCFC-123	152
HCFC Blend B	151
HFC-227ea	170
HFC-236fa	152

4.2.2.2 Method 2.

Alternately, in the absence of EPA SNAP-approved NOAEL toxicity data for a particular blend of halocarbon agents *A* and *B*, the maximum safe W/V ratios can be based on the more toxic agent using the total blend weight. For example, the maximum safe W/V for a blend of Halon 1211 and Halon 1301 can by found by assuming the total weight of the blend is Halon 1211 and using the maximum safe W/V of Halon 1211. This is a conservative method that overestimates the maximum safe W/V. The extinguisher manufacturer may choose to use this method if they do not wish to disclose the chemical composition of the blend to the public.

4.3 UNVENTILATED COMPARTMENTS.

Unventilated guidance should be used if

- halocarbon clean-agent extinguishers are installed in a compartment with poor or no ventilation (air change time is unknown or exceeds 6 minutes), and
- the compartment cannot be vented, and
- the occupants cannot leave if the extinguishers are discharged.

The total agent available from all the hand-held extinguishers should not be capable of producing concentrations by volume at 70°F that exceed the agent's safe exposure guidelines.

The safe-exposure guidelines for unventilated compartments are listed below.

- Use the FAA-approved PBPK-derived, 5-minute safe human exposure concentration, if known (table 1).
- If conforming PBPK data is not available, use the NOAEL (table 1). An exception to this rule may be considered if there is a history of safe use, as is the case for Halon 1211. See table 7 for a comparison of concentration limits allowed by the current advisory circular (AC 20-42C) [1] and other safe-use limits.

Table 7. Maximum Safe Exposure Concentrations for Unventilated Compartments

Agent[a]	AC20-42C Unventilated No Egress (%v/v)	AC20-42C Unventilated Egress Within 1 Minute (%v/v)	NOAEL[b] (%v/v)	Maximum Safe 5-Minute Human Exposure Concentration (%v/v)	A_{safe} (%v/v)
HCFC Blend B			1.0	1.28[c]	1.28
HFC-227ea			9.0	10.84[d]	10.84
HFC-236fa			10.0	12.75[d]	12.75
Halon 1211	2	4	0.5	N/A	0.5[f]
			0.5	N/A	1.0[g,h]
Halon 1301	5	10	5.0	6.25[d,i]	6.25

[a] Immediate descent at the maximum safe rate to the lowest practicable altitude, or 8000 feet, is recommended for all unpressurized aircraft to minimize exposure to halocarbon gases and reduce the hazards of low-oxygen hypoxia resulting from the agent displacing oxygen from the air in the compartment. This holds for ventilated and unventilated compartments.

[b] NOAEL values for agents approved under the EPA SNAP program can be obtained from the SNAP program coordinator, U.S. EPA Office of Air and Radiation, or from the public docket for that office. See http://www.epa.gov/ozone/snap/fire/index.html.

[c] Derived from PBPK model [13] with adjustment for FAA-accepted target arterial concentration of 69.9 mg/L for HCFC-123

[d] Derived from PBPK Model [7].

[e] Canine LOAEL arterial blood concentrations, referenced partition coefficients and Monte Carlo Simulations for Halon 1211 are not available and are needed to run the PBPK model to meet the specifications set for the other agents.

[f] The conservative approach is to use the NOAEL concentration. Five-minute exposures to the NOAEL concentration are considered safe for humans by the U.S. EPA.

[g] This method does not conform with the selection criteria outlined in section 4.1.2.

[h] Based on the LOAEL target concentration and figure 1. Nonconforming PBPK approach, nonconforming target concentration, no Monte Carlo Simulation (see section 4.1.2).

[i] The target arterial LOAEL blood concentration used in reference 7 was obtained from reference 9.

4.3.1 Multiplication Factors for Unventilated Compartments Where Egress can be Performed Within 30 Seconds.

Higher charge weights of halocarbons can be used safely in unventilated compartments if egress can be performed in 30 seconds into a halocarbon-free environment. Using a 30-second multiplication factors (MF) would allow:

- Slightly higher agent concentrations in small unventilated compartments in very large aircraft, where egress into a halocarbon-free environment can be performed within 30 seconds.

- Slightly higher agent concentrations when an oxygen mask, which does not provide diluted cabin air to the wearer, is within reach.

- An exposure to the PBPK-derived maximum safe 5-minute human exposure concentration results in a target arterial concentration being reached at 5 minutes. A brief 30-second exposure to that same constant halocarbon concentration results in a 30-second arterial concentration, which is less than the target arterial concentration. The 30-second MF would bring the 30-second arterial blood concentration up to the target arterial concentration, since arterial concentration increases linearly with exposure concentration, as shown in figures 2-5.

- The 30-second MFs are derived by dividing the 5-minute arterial concentration by $B(t)/B\text{max}$ at 30 seconds, as shown in figures 9-13. Note that these 30-second MFs are not much greater than unity for HFC-227ea, HFC-236fa, and Halon 1301. These MFs can be applied to the maximum safe concentration (A_{safe}) in table 1, only if escape into a halocarbon-free environment is assured within 30 seconds. These 30-second MFs and the resulting maximum safe 30-second halocarbon concentrations are shown in table 8.

Table 8. Multiplication Factors and Resultant Maximum Safe 30-Second Halocarbon Concentrations for Unventilated Compartments Where Egress can be Performed Within 30 Seconds

Halocarbon Gas	30-Second MF[a]	Maximum Safe 30-Second Concentration (%v/v)
HCFC Blend B	1.53	1.96
HFC-227ea	1.10	11.9
HFC-236fa	1.19	15.2
Halon 1211	N/A[b]	0.5[c]
Halon 1211	1.73[c,d]	0.87[d]
Halon 1301	1.15	7.19

[a] Applies only to unventilated compartments.

[b] Canine LOAEL arterial blood concentrations, referenced partition coefficients, and Monte Carlo Simulations for Halon 1211 are not available and are needed to run the PBPK model to meet the specifications set for the other agents.

[c] This method does not conform with the selection criteria outlined in section 4.1.2. This conservative approach is to use the NOAEL concentration.

[d] Based on the NOAEL concentration and figure 1. Nonconforming PBPK approach, nonconforming target concentration, no Monte Carlo Simulation (see section 4.1.2).

4.3.2 Maximum Safe Agent W/V for Unventilated Compartments.

For any time (t) into an exposure to a constant halocarbon concentration, the arterial halocarbon concentration is proportional to the halocarbon gas concentration. Thus, the maximum safe exposure concentration, assuming uniform dispersion, can be obtained by multiplying the initial discharge concentration A_0 by the ratio of the target arterial concentration to the 5-minute arterial concentration.

The maximum safe W/V is calculated using the methodology discussed in section 4.2. Computed W/V ratios are shown in table 9 for unventilated compartments. Oxygen masks using diluter-demand regulators and nasal cannula do not fully protect the wearer from inhaling halocarbons because cabin air is inspired by users of both devices. To err on the side of safety, the allowed halocarbon concentrations are computed assuming no protective breathing equipment is used.

Table 9. Maximum Safe Agent W/V for Halocarbon Extinguishers in Unventilated Passenger and Crew Compartments

	Maximum Safe W/V (lb/ft^3)[a,b,c,d,e,f]					
			Unpressurized Aircraft[g]			
Agent	Sea Level (For information only)	Pressurized Aircraft (8,000 ft CPA)	12,500 ft Pressure Altitude [h]	14,000 ft Pressure Altitude [h]	18,000 ft Pressure Altitude[h,i]	25,000 ft Pressure Altitude[i]
HCFC Blend B	0.00499	0.00371	0.00311	0.00293	0.00249	0.00185
HFC-227ea	0.0551	0.0409	0.0344	0.0324	0.0275	0.0205
HFC-236fa	0.0595	0.0442	0.0371	0.0349	0.02970	0.0221
Halon 1211[j]	0.00224	0.00166	0.00139	0.00131	0.00112	0.000829
Halon 1211[k]	0.00449	0.00334	0.00281	0.00264	0.00225	0.00167
Halon 1301	0.0260	0.0193	0.0162	0.0153	0.0130	0.00968

[a] Use this table if air change time is unknown or exceeds 6 minutes.

[b] Maximum safe W/V ratios represent total weight of agent from all extinguishers in the aircraft compartment at 70°F.

[c] W/V multiplication factors (see table 8) can be applied to the data in this table for unventilated compartments if an egress analysis is performed and approved and escape time is <30 seconds.

[d] If the maximum safe W/V is exceeded, use the safest extinguisher of the required rating.

[e] The maximum safe W/V for blends can be determined by the calculation method described in section 4.2.2.

[f] If possible, ventilate immediately, preferably overboard after successfully extinguishing the fire. Increase aircraft ventilation to the highest possible rate, and turn off any air recirculation systems, if equipped.

[g] Descend immediately at the maximum safe rate to an altitude of 8000 ft or an altitude that is as low as practicable.

[h] Using nasal cannula oxygen (allowed up to 18,000 ft) and fingertip-probe oxygen sensor.

[i] Using diluter-demand oxygen mask (allowed up to 25,000 ft) and fingertip-probe oxygen sensor.

[j] Values are based on the NOAEL. All other agents are based on PBPK safe-use concentrations for a 5-minute exposure.

[k] Values are based on the LOAEL.

The maximum safe agent W/V for unventilated compartments can be increased by the MFs listed in table 8 if egress analysis indicates the escape time is less than 30 seconds.

4.4 VENTILATED COMPARTMENTS.

4.4.1 Development of Selector Curves.

The ventilation benefit for each air change time (τ) is the reciprocal of the peak value of $B(t)/B_{\text{safe}}$ per figures 14-18 and is shown in table 10. The maximum safe halocarbon discharge (initial exposure) concentration is the product of the ventilation benefit and the maximum safe 5-minute human concentration, A_{safe}, from table 1.

Table 10. Ventilation Benefit of Agents A_{safe}(Ventilated)/A_{safe}(Unventilated) for Different Cabin Air Exchange Times

	Air Exchange Time, τ (minutes)								
AGENT	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	>6
Halon 1211[b,c]	3.06	2.21	1.90	1.73	1.54	1.44	1.37	1.33	1
Halon 1301[c]	1.96	1.57	1.42	1.34	1.25	1.21	1.17	1.15	1
HFC-236fa[c]	1.98	1.58	1.42	1.34	1.25	1.20	1.17	1.15	1
HFC-227ea[c]	1.90	1.53	1.39	1.32	1.24	1.19	1.16	1.14	1
HCFC-123[c]	2.80	2.33	2.14	2.02	1.89	1.79	1.70	1.62	1
HCFC-123[d]	2.47	2.09	–	1.84	1.74	1.69	1.65	1.63	1

[a] Assume no ventilation.

[b] Nonconforming method (see section 4.1.2). Canine LOAEL arterial blood concentrations, referenced partition coefficients and Monte Carlo Simulations for Halon 1211 are needed to run the PBPK model to meet the specifications set for the other agents. These maximum safe initial discharge concentrations for Halon 1211 were calculated using the kinetic model parameters in table 3 using A_{safe} in table 1.

[c] Obtained from kinetic model.

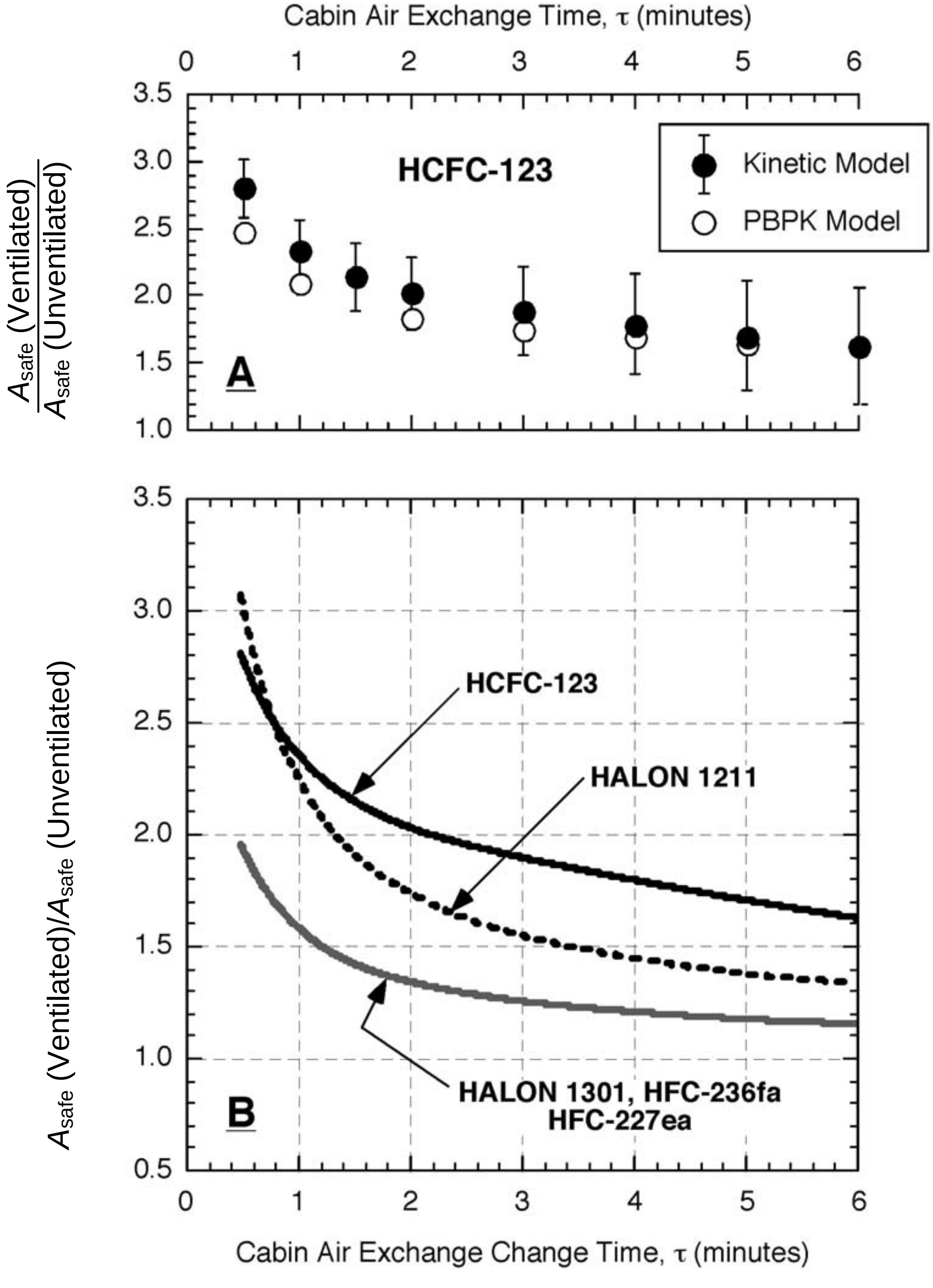
[d] Obtained from PBPK Model of ventilated compartment [13].

A ventilation benefit of 1 was assigned to poorly ventilated compartments, where the air change time exceeds 6 minutes to protect against anesthetic effects that could occur from prolonged exposure to the agent.

Applying the data from table 10, a comparison was made in figure 19 of the aircraft ventilation benefit, A_{safe}(Ventilated)/A_{safe}(Unventilated), provided for these agents, in terms of the increased maximum concentration that can be safely used in a ventilated compartment. Figure 19 shows that the aircraft ventilation benefit is similar for the HFCs and Halon 1301. HCFC-123, the only chlorinated compound evaluated with suitable PBPK data, has a significantly higher aircraft ventilation benefit than the other agents. The Halon 1211 data are based on nonconforming target arterial concentrations and nonconforming PBPK data from table 1.

A technique for providing a conservative aircraft ventilation benefit for Halon 1211 could be employed in the absence of PBPK data that meets the guidelines. Since the chlorinated halocarbons have a significantly greater aircraft ventilation benefit than nonchlorinated halocarbons, one can apply the aircraft ventilation benefit of a nonchlorinated halocarbon to

Halon 1211, a chlorinated halocarbon. For example, multiplying the Halon 1211 NOAEL, 0.5, by the Halon 1301 aircraft ventilation benefit in figure 19 will double the Halon 1211 maximum safe initial discharge concentration, A_{safe}, when the air change time, τ, is 0.5 minute.



(Note: Error bars on kinetic model in 19A are uncertainty associated with range of P_{BA} of table 2.

Figure 19. Ventilation Benefit Versus Cabin Air Exchange Time (A) Comparison of Kinetic Model to PBPK Data for HCFC-123 and (B) Comparison of Different Agents Using Kinetic Model

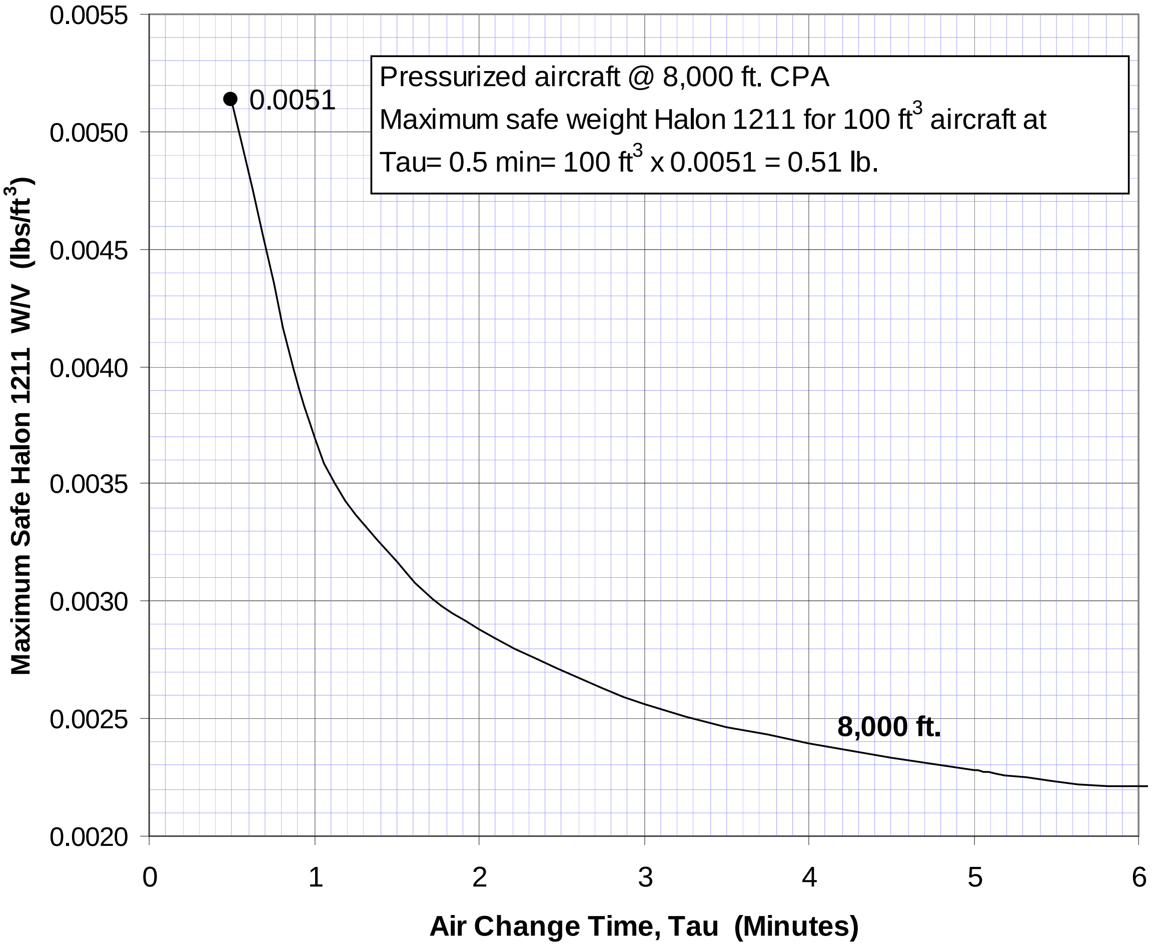
4.4.2 Selector Curves for Maximum Safe W/V in Ventilated Compartments.

Maximum safe W/V ratios for each halocarbon agent can be found by inserting the calculated maximum safe initial discharge concentration from section 4.4.1 into equation 18. The resultant maximum safe W/V ratios are plotted versus the air change times for an 8000-ft cabin pressure altitude for pressurized aircraft and for the maximum certificated altitudes for unpressurized aircraft in figures 20 through 29. The manufacturer of HCFC Blend B selected to calculate the maximum safe W/V as if the entire weight was the most toxic component, HCFC-123, rather than basing it on the individual components (see section 4.2.2.2).

The following guidance should be followed for figures 20 through 29:

- The total weight of agent for all extinguishers in the aircraft compartment is the basis for these maximum safe W/V ratios.
- If the maximum safe W/V is exceeded, use the safest extinguisher of the required rating. Use only the amount of agent necessary to ensure the fire is extinguished. Toxicity concerns are secondary to the importance of extinguishing the fire.
- For aircraft with recirculating ventilation, use the outside air component to determine the air change time.
- Ventilate immediately, preferably overboard after successfully extinguishing the fire. Increase the aircraft ventilation to the highest possible rate, and turn off any air recirculation systems, if equipped.

The NOAEL-based maximum safe W/V selector curves for Halon 1211 are shown in figures 20 and 21. LOAEL-based W/V selector curves would be twice the W/V of the NOAEL-based curves and would provide a lower level of safety.

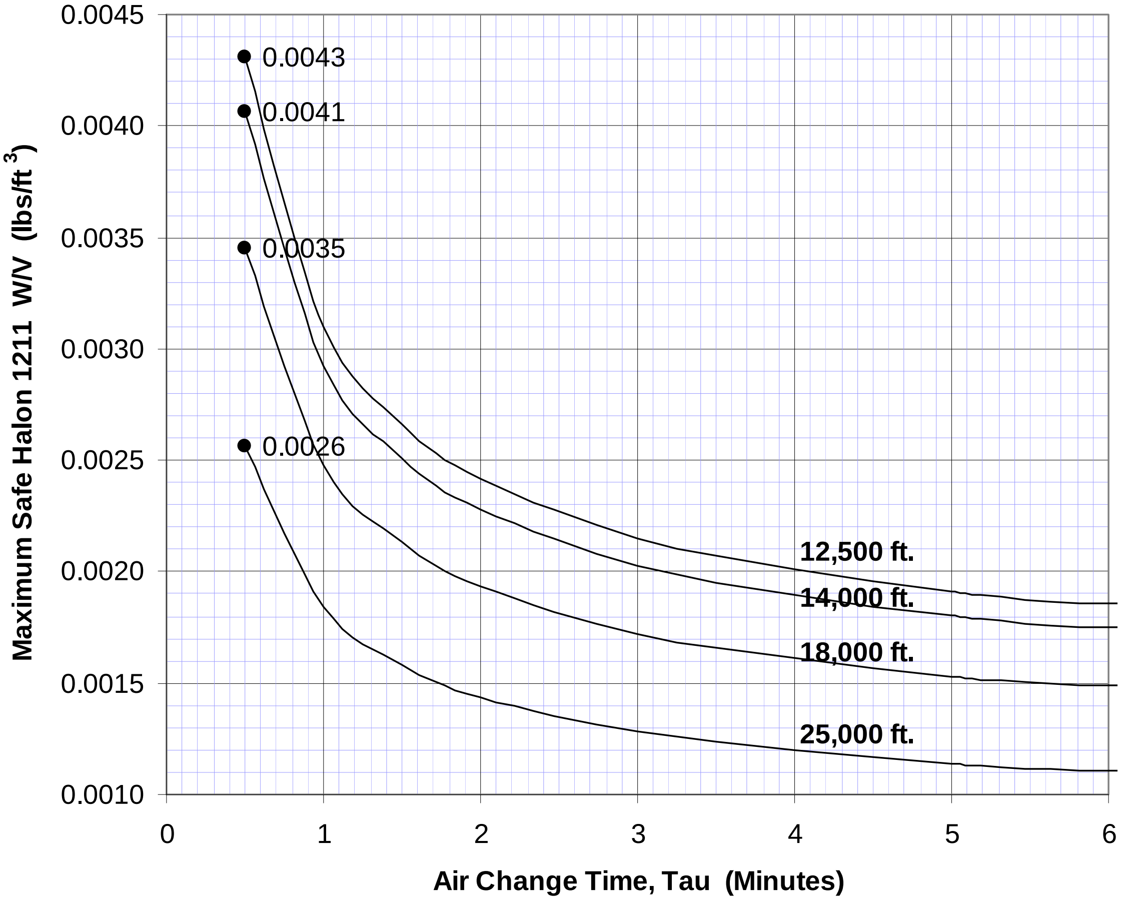


Pressurized aircraft @ 8,000 ft. CPA
Maximum safe weight Halon 1211 for 100 ft^3 aircraft at
Tau= 0.5 min= 100 ft^3 x 0.0051 = 0.51 lb.

Notes:

- Based on figure 1. Nonconforming PBPK approach, nonconforming target concentration based on 0.5% NOAEL, no Monte Carlo Simulation. See section 4.1.2.
- LOAEL-based W/V Halon 1211 selector curves would be twice the W/V of the NOAEL-based curve and would provide a lower level of safety.
- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe Halon 1211 W/V ratio for unventilated pressurized aircraft compartments, as shown in table 9.
- Immediate descent is not necessary for pressurized aircraft.
- The maximum safe W/V for blends of Halon 1211 and 1301 can be found by using the calculation method in section 4.2.2.

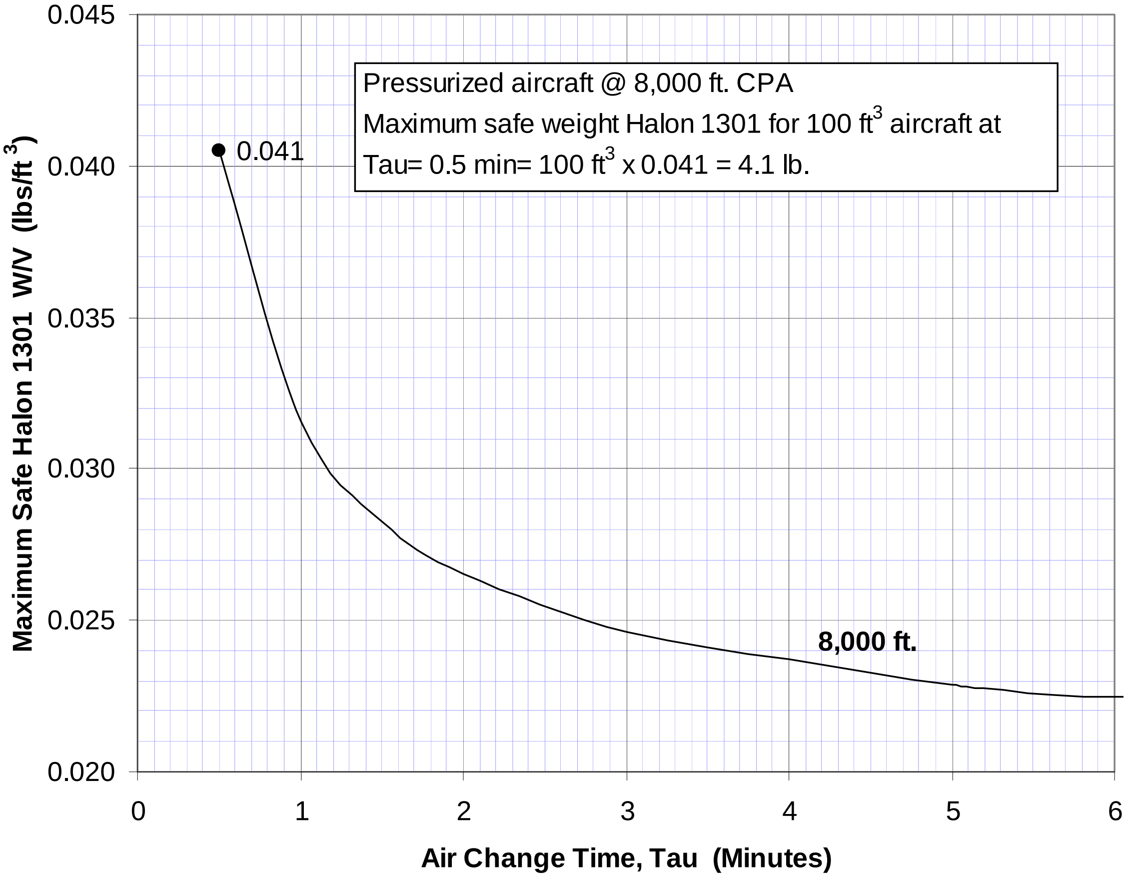
Figure 20. Halon 1211 Maximum Safe W/V Selector for Pressurized Aircraft



Notes:

- Based on figure 1. Nonconforming PBPK approach, nonconforming target concentration based on 0.5% NOAEL, no Monte Carlo simulation. See section 4.1.2.
- NOAEL-based W/V Halon 1211 selector curves would be half the W/V of the LOAEL-based curve and would provide a higher level of safety.
- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe Halon 1211 W/V ratio for unventilated unpressurized aircraft compartments as shown in table 9.
- Immediate descent at the maximum safe rate to the lowest practicable altitude or 8000 ft is recommended for all unpressurized aircraft to minimize exposure to halocarbon gases and reduce hypoxia resulting from the agent displacing oxygen from the air in the compartment.
- Occupants in unpressurized aircraft equipped to fly above 12,500 ft should immediately don oxygen masks or nasal cannula to prevent hypoxia.
- The maximum safe W/V for blends of Halon 1211 and 1301 can be found by using the calculation method in section 4.2.2.

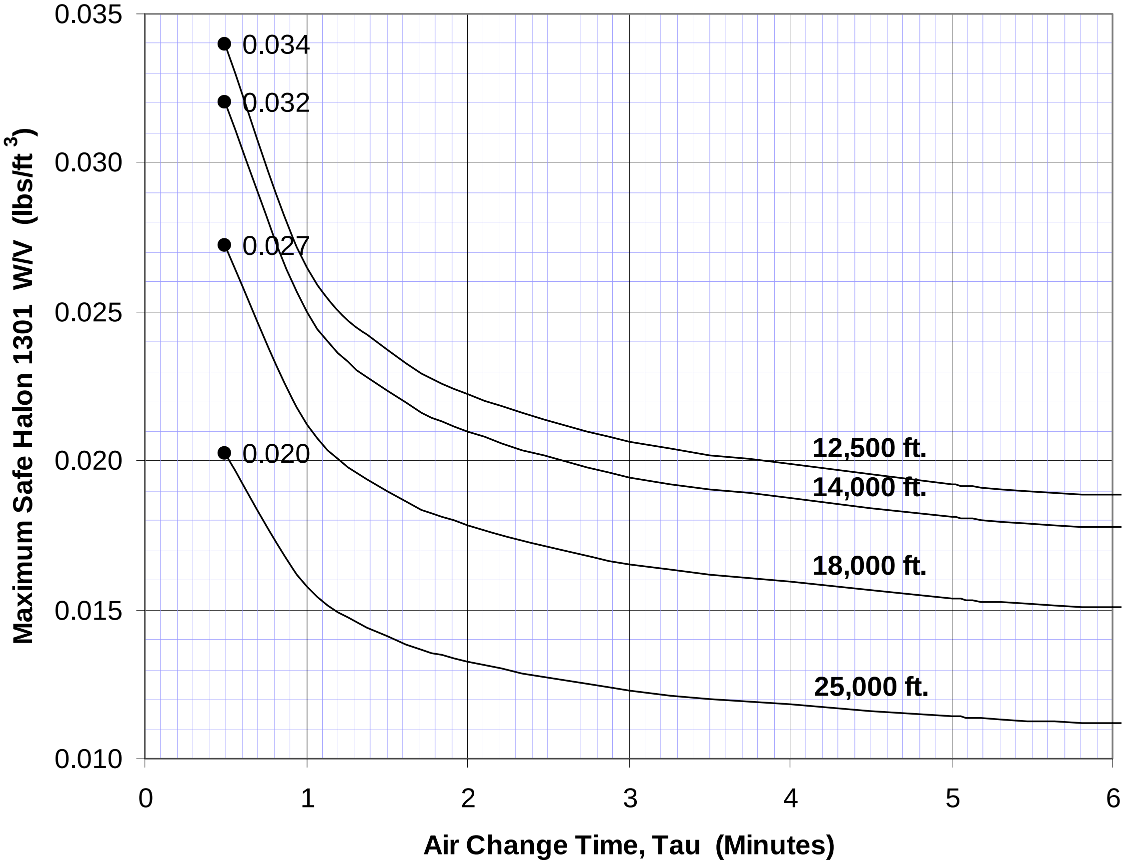
Figure 21. Halon 1211 Maximum Safe W/V Selector for Unpressurized Aircraft Equipped to Fly up to 12,500-, 14,000-, 18,000-, and 25,000-ft Altitudes



Notes:

- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe Halon 1301 W/V ratio for unventilated pressurized aircraft compartments: W/V = 0.0193 lb/ft^3.
- Immediate descent is not necessary for pressurized aircraft.
- The maximum safe W/V for blends of Halon 1211 and 1301 can be found by using the calculation method in section 4.2.2.

Figure 22. Halon 1301 Maximum Safe W/V Selector for Pressurized Aircraft



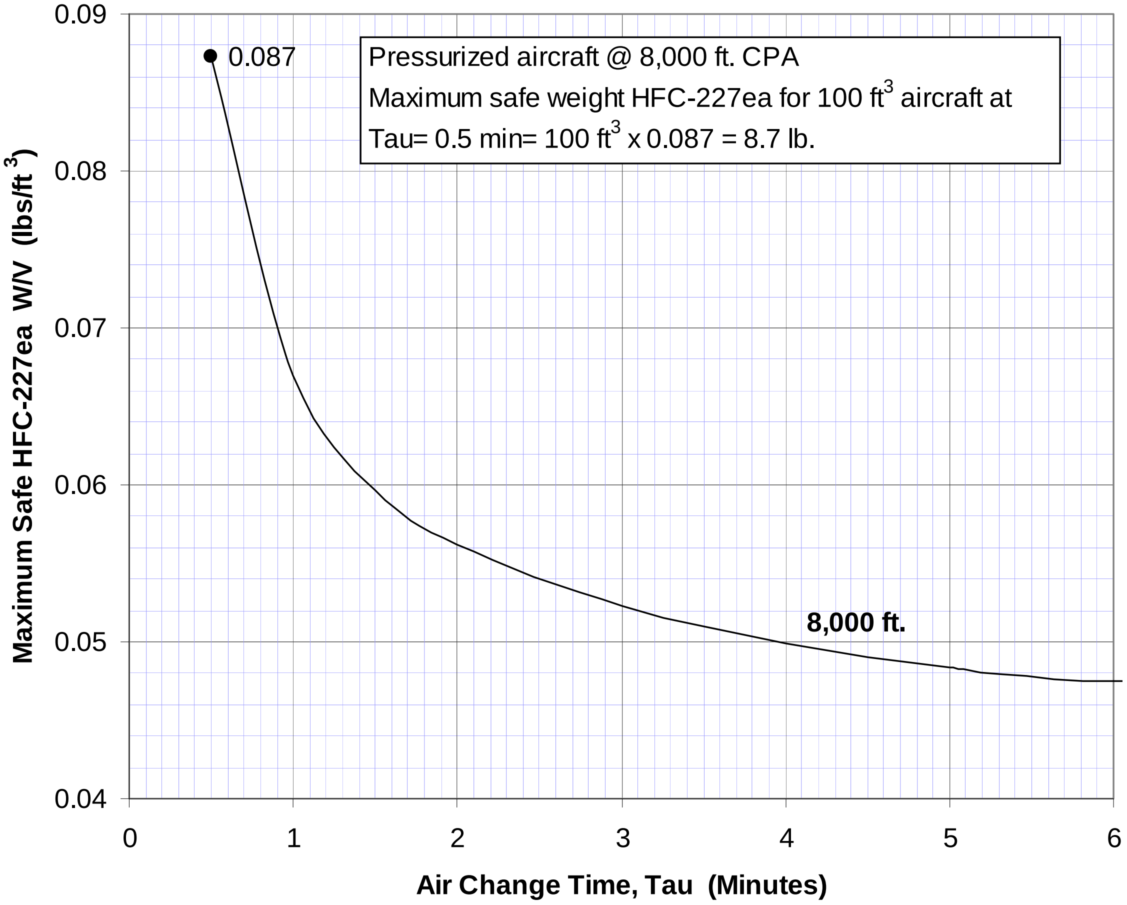
Notes:

- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe Halon 1301 W/V ratio for unventilated, unpressurized aircraft compartments:

  12,500-ft Pressure Altitude: W/V = 0.0162 lb/ft^3
  14,000-ft Pressure Altitude: W/V = 0.0153 lb/ft^3
  18,000-ft Pressure Altitude: W/V = 0.0130 lb/ft^3
  25,000-ft Pressure Altitude: W/V = 0.00968 lb/ft^3

- Immediate descent at the maximum safe rate to the lowest practicable altitude or 8000 ft is recommended for all unpressurized aircraft to minimize exposure to halocarbon gases and reduce hypoxia resulting from the agent displacing oxygen from the air in the compartment.
- Occupants in unpressurized aircraft equipped to fly above 12,500 ft should immediately don oxygen masks or nasal cannula to prevent hypoxia.
- The maximum safe W/V for blends of Halon 1211 and 1301 can be found by using the calculation method in section 4.2.2.

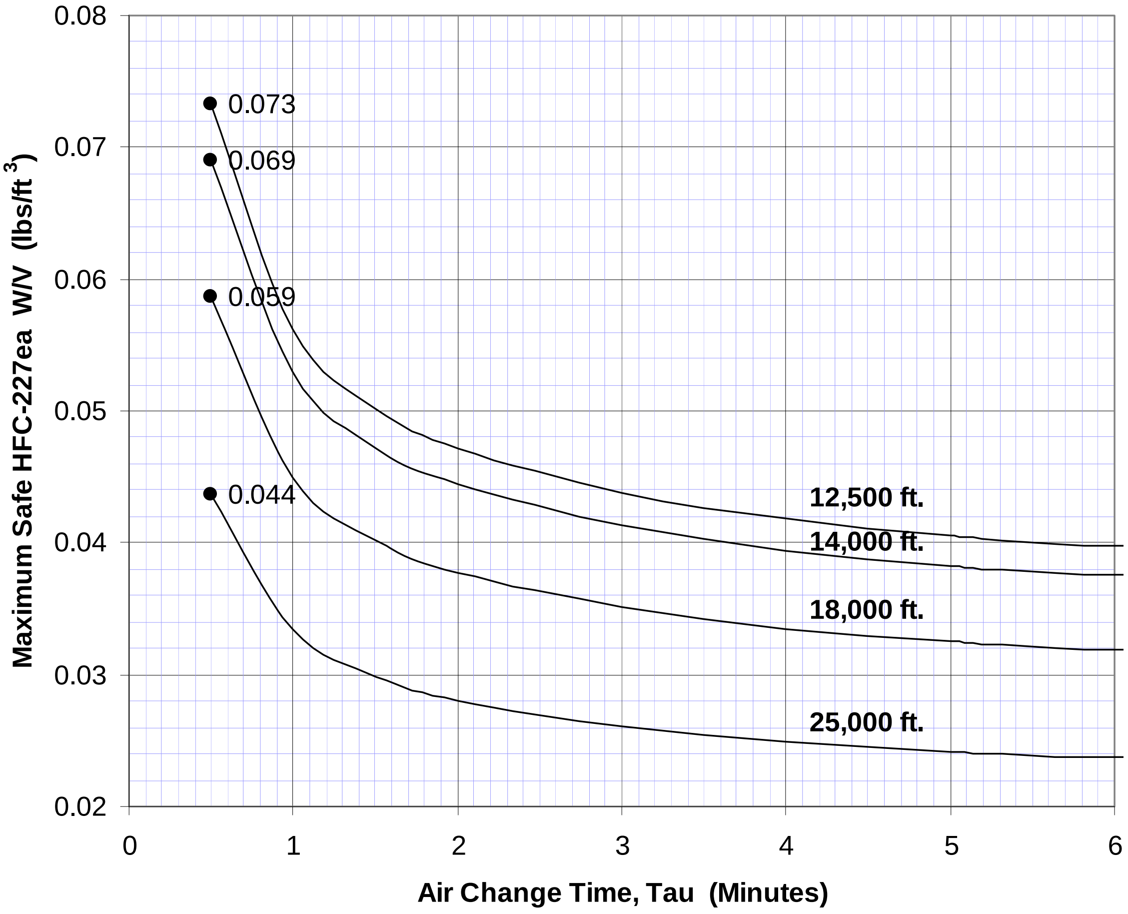
Figure 23. Halon 1301 Maximum Safe W/V Selector for Unpressurized Aircraft Equipped to Fly up to 12,500-, 14,000-, 18,000-, and 25,000-ft Altitudes



Notes:

- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe HFC-227ea W/V ratio for unventilated pressurized aircraft compartments: W/V = 0.0409 lb/ft^3
- Immediate descent is not necessary for pressurized aircraft.

Figure 24. HFC-227ea Maximum Safe W/V Selector for Pressurized Aircraft



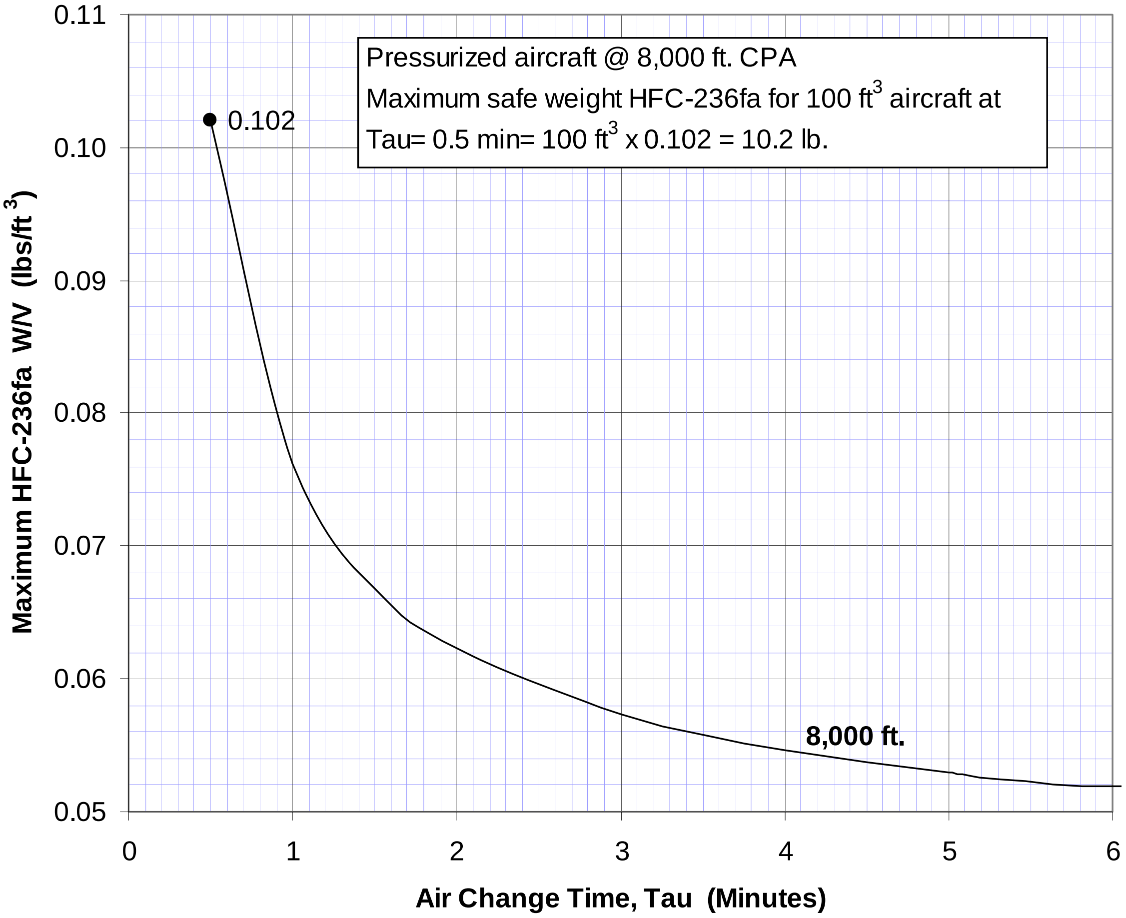
Notes:

- If the air change time is unknown, or exceeds 6 minutes, do not exceed the maximum safe HFC-227ea W/V ratio for unventilated unpressurized aircraft compartments:

  12,500-ft Altitude: W/V = 0.0344 lb/ft^3
  14,000-ft Altitude: W/V = 0.0324 lb/ft^3
  18,000-ft Altitude: W/V = 0.0275 lb/ft^3
  25,000-ft Altitude: W/V = 0.0205 lb/ft^3

- Immediate descent at the maximum safe rate to the lowest practicable altitude or 8000 ft is recommended for all unpressurized aircraft to minimize exposure to halocarbon gases and reduce hypoxia resulting from the agent displacing oxygen from the air in the compartment.
- Occupants in unpressurized aircraft equipped to fly above 12,500 ft should immediately don oxygen masks or nasal cannula to prevent hypoxia.

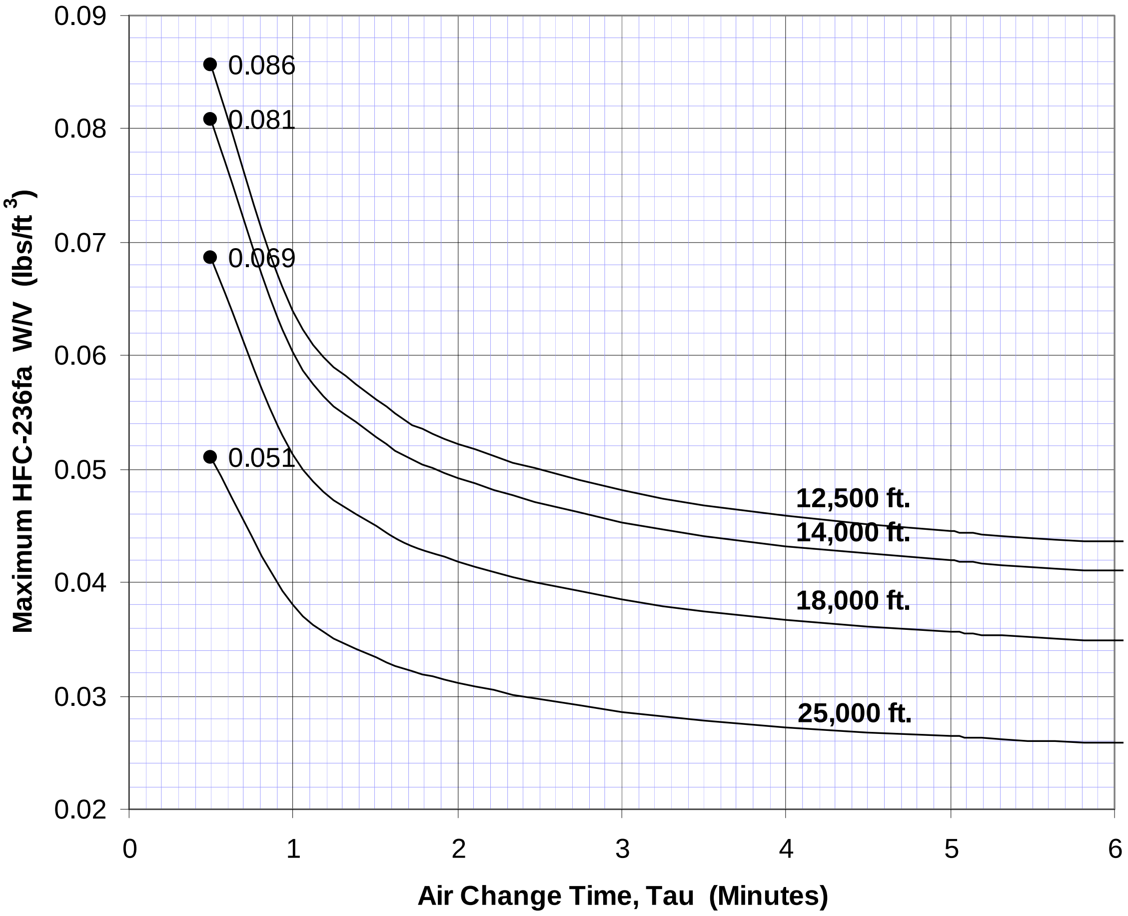
Figure 25. HFC-227ea Maximum Safe W/V Selector for Unpressurized Aircraft Equipped to Fly up to 12,500-, 14,000-, 18,000-, and 25,000-ft Altitudes



Notes:

- If the air change time is unknown, or exceeds 6 minutes, do not exceed the maximum safe HFC-236fa W/V ratio for unventilated pressurized aircraft compartments: W/V = 0.0442 lb/ft^3
- Immediate descent is not necessary for pressurized aircraft.

Figure 26. HFC-236fa Maximum Safe W/V Selector for Pressurized Aircraft



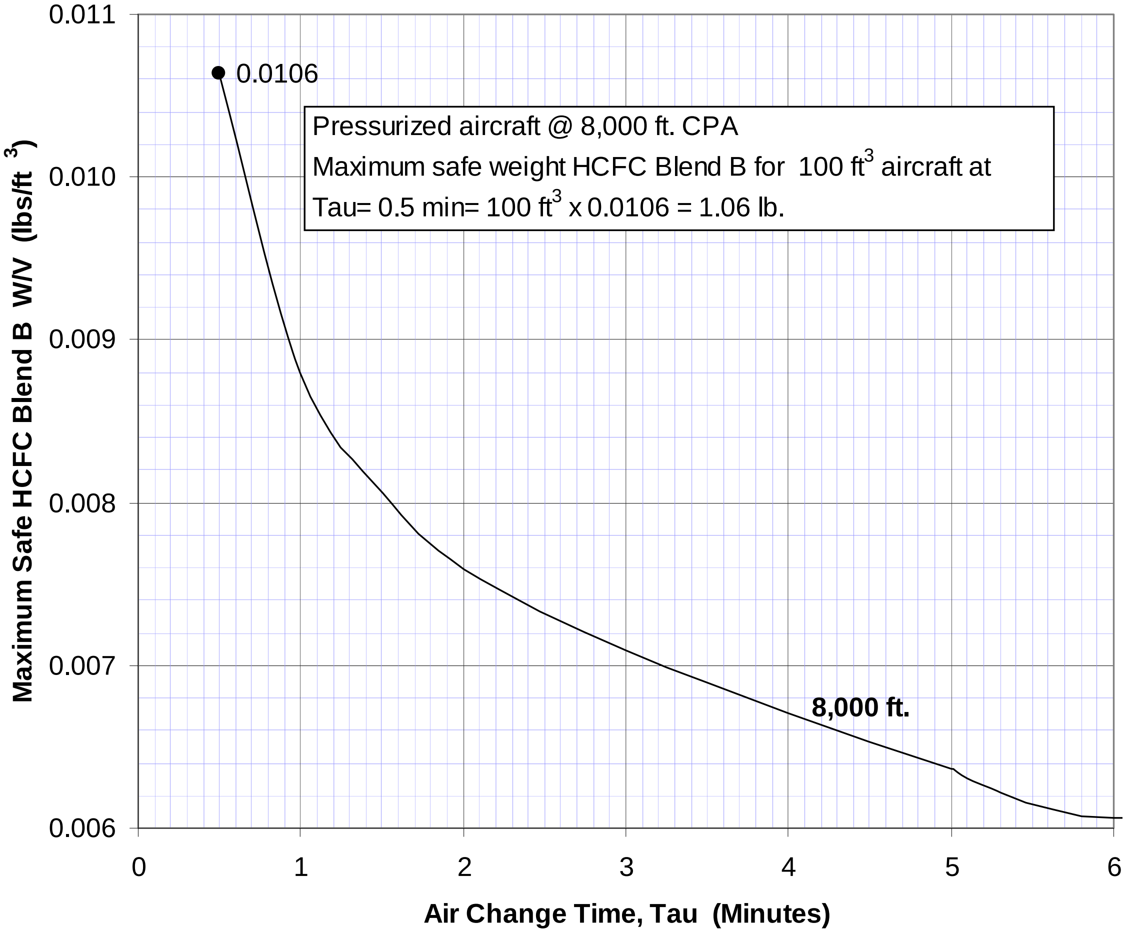
Notes:

- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe HFC-236fa. W/V ratio for unventilated unpressurized aircraft compartments:

  12,500-ft Pressure Altitude: W/V = 0.0371 lb/ft^3
  14,000-ft Pressure Altitude: W/V = 0.0349 lb/ft^3
  18,000-ft Pressure Altitude: W/V = 0.0297 lb/ft^3
  25,000-ft Pressure Altitude: W/V = 0.0221 lb/ft^3

- Immediate descent at the maximum safe rate to the lowest practicable altitude or 8000 ft is recommended for all unpressurized aircraft to minimize exposure to halocarbon gases and reduce hypoxia resulting from the agent displacing oxygen from the air in the compartment.
- Occupants in unpressurized aircraft equipped to fly above 12,500 ft should immediately don oxygen masks or nasal cannula to prevent hypoxia.

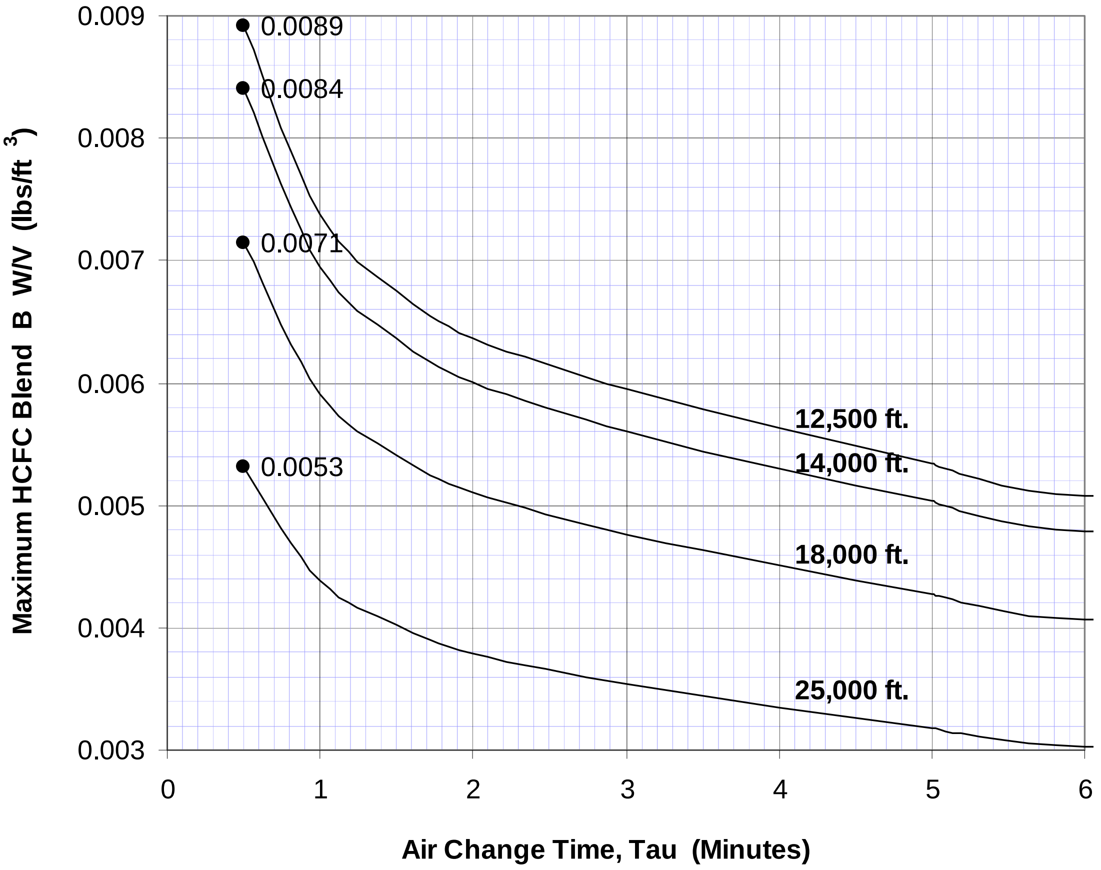
Figure 27. HFC-236fa Maximum Safe W/V Selector for Unpressurized Aircraft Equipped to Fly up to 12,500-, 14,000-, 18,000-, and 25,000-ft Altitudes



Notes:

- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe HCFC Blend B W/V ratio for unventilated pressurized aircraft compartments: W/V = 0.00371 lb/ft^3
- Immediate descent is not necessary for pressurized aircraft.

Figure 28. HCFC Blend B Maximum Safe W/V Selector for Pressurized Aircraft



Notes:

- If the air change time is unknown or exceeds 6 minutes, do not exceed the maximum safe HCFC Blend B W/V ratio for unventilated unpressurized aircraft compartments:

  12,500-ft Pressure Altitude: W/V = 0.00311 lb/ft^3
  14,000-ft Pressure Altitude: W/V = 0.00293 lb/ft^3
  18,000-ft Pressure Altitude: W/V = 0.00249 lb/ft^3
  25,000-ft Pressure Altitude: W/V = 0.00185 lb/ft^3

- Immediate descent at the maximum safe rate to the lowest practicable altitude or 8000 ft is recommended for all unpressurized aircraft to minimize exposure to halocarbon gases and reduce hypoxia resulting from the agent displacing oxygen from the air in the compartment.
- Occupants in unpressurized aircraft equipped to fly above 12,500 ft should immediately don oxygen masks or nasal cannula to prevent hypoxia.

Figure 29. HCFC Blend B Maximum Safe W/V Selector for Unpressurized Aircraft Equipped to Fly up to 12,500-, 14,000-, 18,000-, and 25,000-ft Altitudes

4.5 SELECTION OF THE SAFEST EXTINGUISHER FOR A COMPARTMENT OF A GIVEN VOLUME.

The minimum safe volume is a tool used to compare the toxicity of extinguishers with the same firefighting performance, or the same U.S. Underwriters Laboratories, Inc. (UL), rating. As the minimum safe volume decreases, the toxicity of the agent decreases, and the extinguisher safety increases. The safest extinguisher of a given rating has the lowest minimum safe volume. The minimum safe volume for one extinguisher of a given rating is based on the weight of agent in that extinguisher, as shown in equation 20. The minimum safe volume is obtained by dividing the total agent weight by the maximum safe-use agent W/V for the appropriate altitude and aircraft ventilation.

$$minimum\ safe\ volume = \frac{weight_{agent}}{\left(\frac{W}{V}\right)_{Max\ safe}} \tag{20}$$

where the maximum safe W/V is calculated from equation 18. Computed W/V values are listed in table 9 for unventilated compartments and in figures 20 through 29 for ventilated compartments.

The minimum safe volume for all extinguishers in a compartment is based on the weight of the agent in all of the bottles in an aircraft compartment. It can be calculated as follows:

$$minimum\ safe\ volume_{all\ bottles} = minimum\ safe\ volume_{1bottle} \times \#\,Bottles \tag{21}$$

The minimum safe volume for unventilated aircraft is to be used when the air change time is unknown or exceeds 6 minutes, and when selector graphs for ventilated aircraft are not available for a particular agent.

Table 11 shows the relative toxicity of various UL-rated 5B:C extinguishers in terms of the minimum safe volume in unventilated compartments, assuming uniform dispersion. Halon 1211 is based on the NOAEL and LOAEL concentrations, as maximum safe human concentrations cannot be determined using equivalent methodologies to the other agents. Maximum safe human concentrations are generally between the LOAEL and NOAEL concentrations. The minimum safe volumes for one 5B:C extinguisher in table 11 are based on the agent weight. The minimum safe volume must be calculated for the agent weight in a particular extinguisher.

Table 11. Minimum Safe Compartment Volume for One 5B:C Extinguisher
in Unventilated Compartments

		Minimum Safe Volume for One 5B:C Extinguisher [b,c,d,e] (ft^3)					
			Pressurized Cabin	Unpressurized Cabin			
Extinguisher	Agent Weight[a] (lb)	Sea Level (for info only)	8,000 ft CPA	12,500 ft[f]	14,000 ft[f]	18,000 ft[f,g]	25,000 ft[g]
Halon 1211 [h]	2.5	1116	1502	1790	1908	2232	3016
Halon 1211 [i]	2.5	558	751	895	954	1116	1508
Halon 1301	5.0	192	258	308	327	385	517
HCFC Blend B	5.5	1102	1482	1768	1877	2209	2973
HFC-227ea	5.75	104	141	167	177	209	280
HFC-236fa	4.75	79.8	107	128	136	159	214

[a] The weight of agent for a 5B:C extinguisher is extinguisher dependent. Nozzle design, pressurization differences, and other factors can result in different agent weights for extinguishers using the same agent. The tabulated minimum safe volume should be corrected for the actual agent weight if different from table 9.

[b] Use this table if air change time is unknown or exceeds 6 minutes.

[c] Multiply this number by the number of extinguishers in the aircraft compartment.

[d] The weight of agent for all extinguishers in a compartment should be used to calculate the minimum safe volume. If the minimum safe volume is exceeded, select an extinguisher with the proper rating using an agent that provides an acceptable minimum safe volume.

[e] If the compartment volume is less than the sum of the minimum safe volumes of all extinguishers in the compartment, select the extinguishers with the proper rating using an agent that provides the lowest minimum safe volume.

[f] Nasal cannula oxygen supply.

[g] Diluter-demand oxygen mask.

[h] Values are based on the Halon 1211 NOAEL.

[i] Values based on the Halon 1211 LOAEL.

The number of 5B:C extinguishers that can be safely discharged into a given-sized unventilated aircraft compartment can be calculated by dividing the compartment volume by the sum of the minimum safe volumes of extinguishers in that compartment. The number of extinguishers that can be safely discharged into various-sized aircraft (volumes) are shown in table 12. These calculations are based on the weight of the agent for the extinguishers listed in table 11.

Table 12 provides general guidance only since compartment volumes can vary for aircraft of the same type, and many of the aircraft listed have ventilation systems, enabling higher weights of agent to be safely used.

- Use the compartment volume, the weight of agent in the compartment, and air change time for a particular aircraft. See table 9 and figures 20 to 29 to find the maximum safe W/V for unventilated and ventilated aircraft compartments, respectively.
- Large transport category aircraft have a known ventilation rate. Using the maximum safe W/V guidance for ventilated aircraft in figures 20 through 29 will provide a larger number of extinguishers that can be safely used.

Table 12. Number of 5B:C Extinguishers That can be Safely Discharged in Various-Sized Unventilated Aircraft at 8000-ft Pressure Altitude (Assuming Uniform dispersion, 70°F)[a,b]

Airplane/ Helicopter	Volume[c] (ft^3)	Max No. Seats[c]	Halon 1211 AC 20-42C[d] and U.S. UL1093	Halon 1211[e]	Halon 1211[f]	Halon 1301	HCFC Blend B	HFC-236fa	HFC-227ea
C 152	77	2	0.3[g]	0.05[g]	0.1[g]	0.3[g]	0.05[g]	0.7[g]	0.5[g]
C 210C	140	6	0.5[g]	0.09[g]	0.2[g]	0.5[g]	0.09[g]	1.3	1.0
C 421B	217	10	0.7[g]	0.1[g]	0.3[g]	0.8[g]	0.1[g]	2.0	1.5
S76	204	14	0.7[g]	0.1[g]	0.3[g]	0.8[g]	0.1[g]	1.9	1.4
ERJ135	968	37	3.1	0.6[g]	1.3	3.8	0.7[g]	9.0	6.9
CRJ200	2,015	50	6.5	1.3	2.7	7.8	1.4	19	14
B727-100	5,333	131	17	3.5	7.1	21	3.6	50	38
B767-200	11,265	255	36	7.5	15	43	7.6	105	80
B747	27,899	500	90	18	37	108	19	260	198

[a] Actual allowable number of extinguishers may be greater, as many of these aircraft have fixed ventilation systems. Use figures 20-29 to determine maximum safe W/V for ventilated compartments.

[b] Based on the agent weight in table 11.

[c] Compartment volumes and number of seats can vary for aircraft of the same type.

[d] For information only.

[e] Values are based on NOAEL.

[f] Values are based on the LOAEL.

[g] Less than one 5B:C extinguisher can be safely discharged into that volume.

5. HYPOXIA GUIDANCE.

A separate analysis was developed to provide guidance to minimize human exposure to low-oxygen, partial pressures, which result from the discharge of halocarbon agents in small, unpressurized aircraft compartments. With exposure times beyond 5-10 minutes at the minimum forecast alveolar oxygen pressure, some occupants could be incapacitated. Thus, guidance on minimizing exposure by using aircraft ventilation and rapid descent is important not only for minimizing exposure to the halocarbon agents, but also for minimizing hypoxic hazards in small compartments [20-22].

Title 14 Code of Federal Regulations (14 CFR) 91.122 and 91.211 provide the FAA operational requirements for the use of supplemental oxygen. Unpressurized aircraft are allowed to fly at altitudes of 14,000 ft for up to 30 minutes without the requiring supplemental oxygen and indefinitely at altitudes of 12,500 ft.

5.1 TIME OF USEFUL CONSCIOUSNESS.

Time of useful consciousness (TUC) is the time available for an individual has to put an oxygen mask on without assistance in an environment of inadequate oxygen [22 and 23]. Table 13 shows the TUC for healthy, resting, young pilots at various altitudes. Individual tolerances to hypoxia are extremely variable. Additional factors such as sleep, physical fitness, health, mental health, and the use of medications and drugs influence a pilot's tolerance to hypoxia [20-25]. Any activity would reduce this time [23 and 24].

Table 13. Time of Useful Consciousness at Various Altitudes

Altitude (Feet)	Time of Useful Consciousness (Minutes)^{1,2}	$P_{A_{O_2}}$ (mm Hg)
18,000	20-30	37.8
22,000	10	32.8
25,000	3-5	30.4
28,000	2.5-3	N/A
30,000	1-2	N/A

mm Hg = Millimeters of Mercury

[1] Physical exertion and other factors will reduce this time.

[2] Data taken from the United States Air Force Flight Surgeon's Guide [23]

The National Transportation Safety Board has noted that the studies upon which these times were based were conducted using comfortably seated participants who were expecting a decompression and were asked to perform a repetitive task [26].

5.2 ALVEOLAR OXYGEN PRESSURE AT ALTITUDE.

The ambient pressure, P, ambient oxygen pressure, P_{O_2}, and the alveolar oxygen, water, and carbon dioxide pressure for various altitudes ($P_{A_{O_2}}$, $P_{A_{H_2O}}$, and $P_{A_{CO_2}}$, respectively) are tabulated in table 14. The composition of air changes at different sites along the respiratory tract. Inspired air is warmed, humidified, and becomes saturated to 47 mm H_2O at the normal body temperature of 37°C by the time it reaches the trachea. The total pressure of dry gases in the trachea is 47 mm less than the total pressure of dry ambient air. This 47-mm pressure difference is independent of altitude. Expired CO_2 released by the blood results in high alveolar CO_2 concentrations. These tracheal water and alveolar CO_2 concentrations offset the inhaled oxygen concentration, decreasing the oxygen concentration deep in the lung [20, 23-25].

Table 14. Respiratory Gas Pressures for Various Altitudes*

Altitude (ft)	Ambient Pressure (mm Hg)	Ambient P_{O_2} (mm Hg)	$P_{A_{O_2}}$ (mm Hg)	$P_{A_{H_2O}}$ (mm Hg)	$P_{A_{CO_2}}$ (mm Hg)
0	759.97	159.21	103.0	47.0	40.0
2,000	706.63	148.04	93.8	47.0	39.0
4,000	656.34	137.50	85.1	47.0	38.0
6,000	609.09	127.60	76.8	47.0	37.0
8,000	564.64	118.29	68.9	47.0	36.0
9,000	543.31	113.82	65.0	47.0	35.4
10,000	522.73	109.51	61.2	47.0	35.0
11,000	502.92	105.36	57.8	47.0	34.4
12,000	483.36	101.26	54.3	47.0	33.8
13,000	464.82	97.38	51.0	47.0	33.2
14,000	446.53	93.55	47.9	47.0	32.6
15,000	429.01	89.88	45.0	47.0	32.0
16,000	411.99	86.31	42.0	47.0	31.4
17,000	395.73	84.50	40.0	47.0	31.0
18,000	379.73	79.55	37.8	47.0	30.4
19,000	364.49	76.36	35.9	47.0	30.0
20,000	349.5	73.22	34.3	47.0	29.4
21,000	335.28	70.24	33.5	47.0	29.0
22,000	321.31	67.31	32.8	47.0	28.4
23,000	307.85	64.49	32.0	47.0	28.0
24,000	294.89	61.78	31.2	47.0	27.4
25,000	282.45	59.17	30.4	47.0	27.0

* Data taken from reference 24.

At 18,000 feet, P_{CO_2} equals 30 mm Hg (millimeters of Mercury), P_{H_2O} remains 47 mm Hg, and barometric pressure is 380 mm Hg. At this level, (30 + 47)/380 or 20 percent of the lung volume is occupied by carbon dioxide and water vapor.

For an unacclimatized person, an alveolar oxygen tension of less than 50 mm Hg is considered as approaching a severe state of hypoxia and an oxygen tension of 30 mm Hg is not adequate for supporting consciousness; thus, collapse is imminent [23]. According to Ersting's data, an immediate hypoxic effect is realized at a $P_{A_{O_2}}$ of 55 mm Hg [20] and, as such, constitutes a sound justification for immediate descent [22]. According to Self, the goal should be to get the alveolar $P_{A_{O_2}}$ at or below what it would be at 10,000 feet (61.2 mm Hg). Assume a worst-case scenario, where the nasal cannula or facemask is completely ineffective [22].

5.3 HYPOXIA EVALUATION FOR MAXIMUM SAFE HALOCARBON CONCENTRATIONS.

Figure 30 shows a hypoxia assessment for the discharge of the maximum safe HFC-236fa concentrations for an unpressurized aircraft flying at 12,500 ft, the maximum altitude allowed where supplemental breathing oxygen is not required.

This assessment is based on the maximum safe initial discharge concentrations of HFC-236fa into an aircraft compartment for various aircraft compartment air change times, τ, per table 10. HFC-236fa maximum safe initial discharge concentrations, A_{safe}, are 25.2% when $\tau = 0.5$ minute, 20.1% when $\tau = 1$ minute, 17.1% when $\tau = 2$ minutes, 15.9% when $\tau = 3$ minutes, 15.3% when $\tau = 4$ minutes, 14.9% when $\tau = 5$ minutes, 14.7% when $\tau = 6$ minutes, and 12.75% with no aircraft ventilation (τ = infinity). It illustrates the importance of descending and landing as soon as possible after a fire.

The alveolar pressure histories are plotted as a function of time after discharge. Instantaneous discharge and uniform dispersion are assumed as well as an instantaneous initiation of descent at a rate of 1000 ft/minute to an altitude of 8000 ft. Alveolar oxygen pressure histories are plotted for each air change time. The horizontal dashed lines are drawn to indicate equivalent alveolar oxygen concentrations for pressure altitudes from 8,000-18,000 ft for halocarbon-free air. The dotted black lines indicate the alveolar oxygen pressure history with no agent discharged.

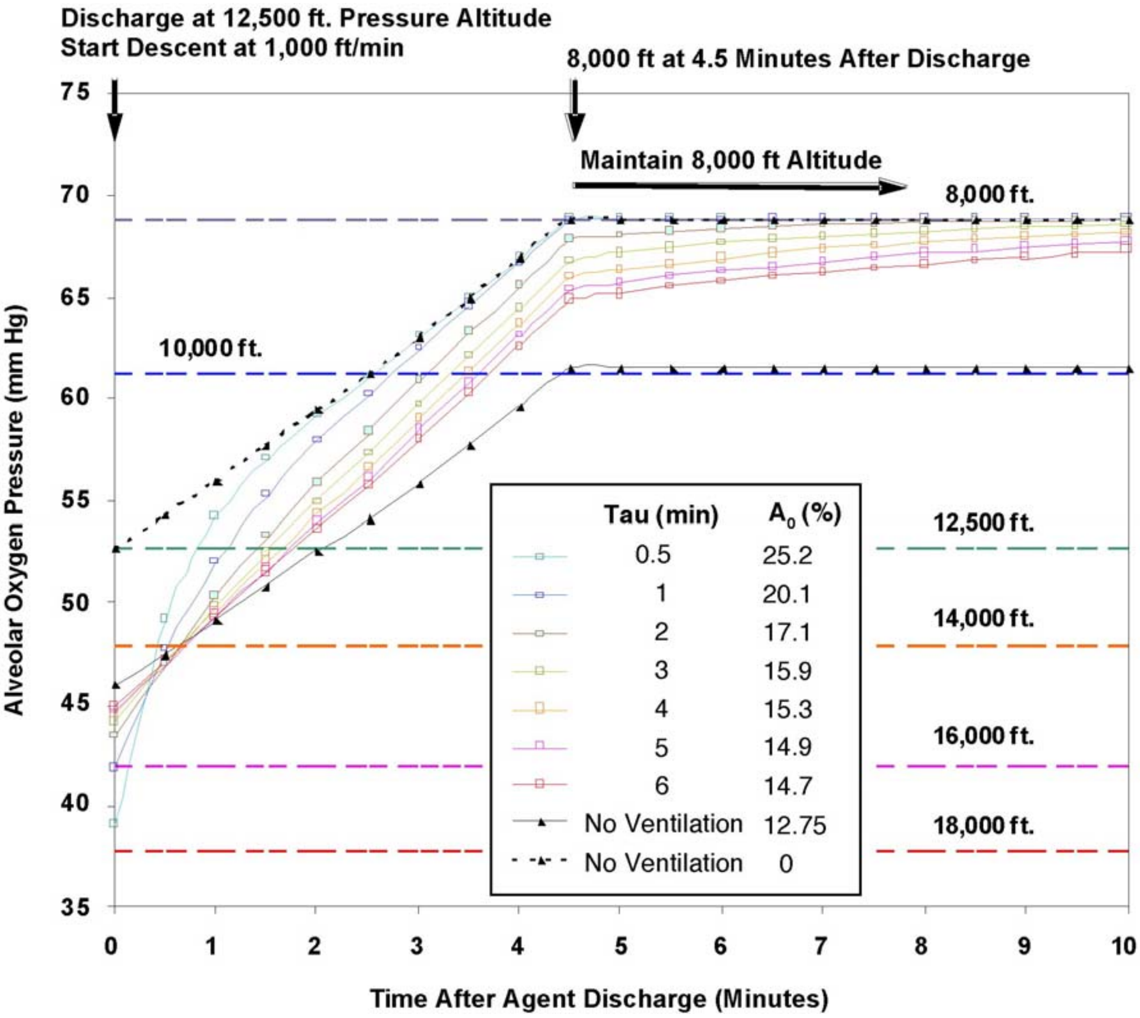


Figure 30. Simulated Alveolar Oxygen Pressure Histories for 12,500-ft Discharges of Maximum Selector Curve HFC-236fa Concentrations Into Unpressurized Aircraft for Various Aircraft Compartment Air Change Times for Healthy Individuals at Rest (Curves are based on uniform dispersion, immediate aircraft ventilation after agent discharge, and descent at 1000 ft per minute, then maintaining an 8000-ft cruising altitude.)

Figure 31 shows a hypoxia assessment for the discharge of the maximum safe HFC-236fa concentrations for a pressurized aircraft with a maximum CPA of 8000 ft, assuming no descent below 8000 ft. There is no descent benefit for pressurized aircraft, unless the aircraft descends to altitudes lower than 8000 ft. This assessment is based on the maximum safe initial discharge concentrations of HFC-236fa into an aircraft compartment, per table 10.

The alveolar pressure histories are plotted as a function of time after discharge. Instantaneous discharge, uniform dispersion, and no descent are assumed. Alveolar oxygen pressure histories are plotted for each air change time. The horizontal dashed lines are drawn to indicate equivalent alveolar oxygen concentrations for altitudes from 8,000-18,000 ft for halocarbon-free air. The dotted black lines indicate the alveolar oxygen pressure history with no agent discharged.

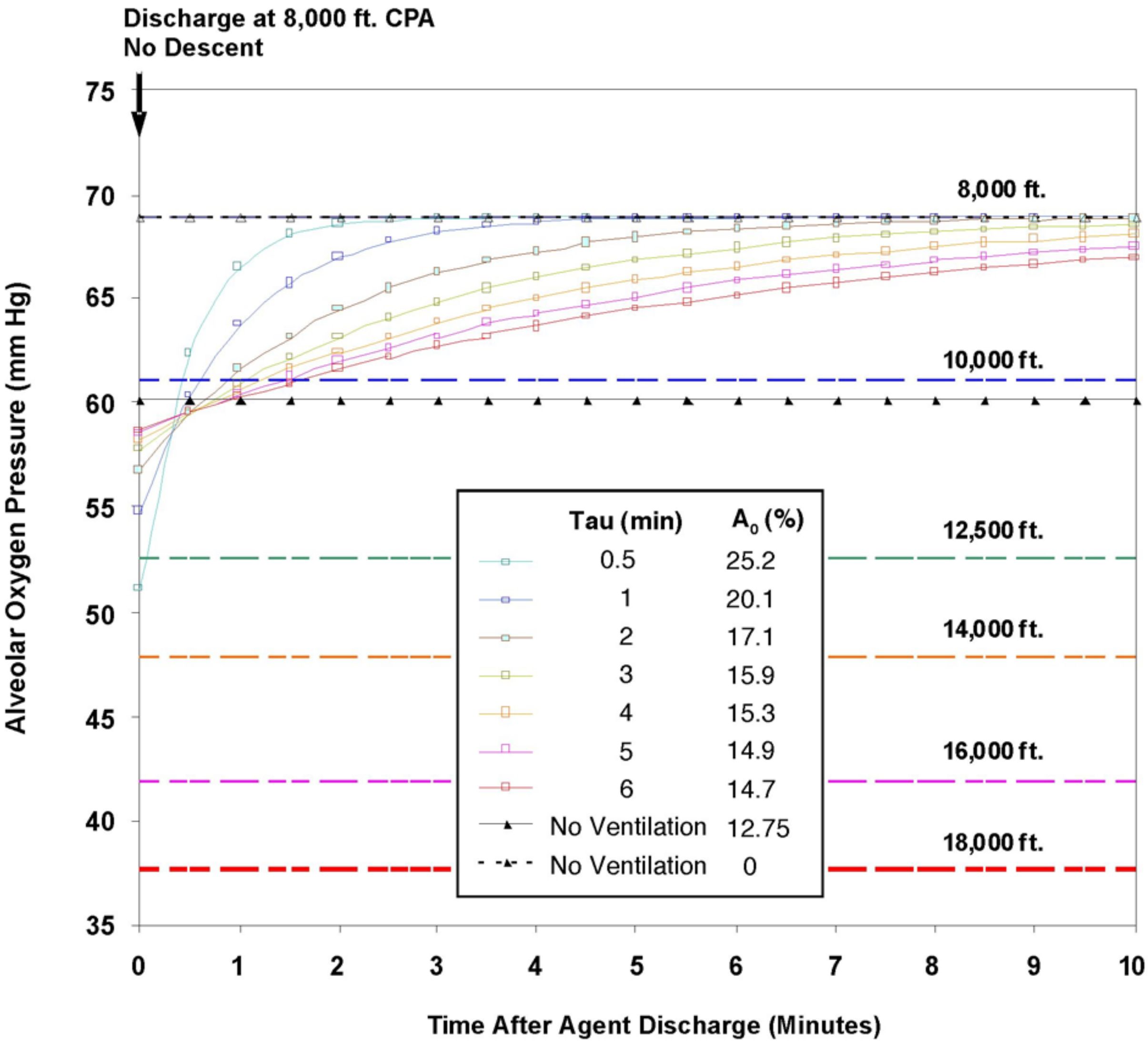


Figure 31. Simulated Alveolar Oxygen Pressure Histories for 8000-ft CPA Discharges of Maximum Selector Curve HFC-236fa Concentrations Into Pressurized Aircraft for Various Aircraft Compartment Air Change Times for Healthy Individuals at Rest (Curves are based on uniform dispersion, immediate aircraft ventilation after agent discharge, and no descent.)

These figures illustrate the benefit of aircraft ventilation and descent for avoiding the potential hazards of hypoxia when high concentrations of halocarbon extinguishing agents are used.

The alveolar oxygen pressures in figures 30 and 31 were calculated every 30 seconds during the exposure using the following steps, where $A_{0\text{safe}}$ is the maximum safe initial discharge concentration of HCFC-236fa for each aircraft compartment air change time. The extinguisher is assumed to discharge at the maximum certificated altitude for an unpressurized aircraft or at the maximum CPA of 8000 ft for a pressurized aircraft. Steps 1 and 2 are performed for air change times, τ of 0.5, 1, 2, 3, 4, 5, 6, and for no aircraft ventilation. The calculations used to create the charts shown in figures 30 and 31 are based on the ambient pressure, ambient P_{O_2}, and $P_{A_{O_2}}$ in table 14. The agent concentration has units of %v/v.

1. Assuming instantaneous discharge, uniform dispersion, and no descent, followed by the instantaneous outboard release of excess pressure, PA_{O_2} is obtained from table 14 for the altitude at which the instantaneous discharge occurred. The maximum safe initial discharge concentration, $A_{0\mathrm{safe}}$, is obtained from tables 1 and 8 for unventilated compartments and from table 10 for ventilated compartments.

$$PA_{O_2}(DischargeAltitude, Agent) = PA_{O_2}(DischargeAltitude, NoAgent) \times \left(\frac{100 - A_{0\mathrm{safe}}}{100} \right)$$

2. Descent Dilution

   a. After the aircraft descends for 0.5 minute and drops 500 feet, the aircraft pressurizes with fresh air:

$$C_{agent2} = C_{\mathrm{safe}} \times \left(\frac{P_{1cabin}}{P_{2cabin}} \right)$$

Note: Skip step 2a for pressurized aircraft. There is no descent dilution for pressurized aircraft at pressure altitudes exceeding the maximum allowed CPA of 8000 feet since:

$$\frac{P_{1cabin}}{P_{2cabin}} = 1$$

   b. Correct for aircraft ventilation, for the aircraft compartment air change time, τ, where $\Delta t = 0.5$ minute. Using equation 18

$$C_{agent_3} = C_{agent_2} \times e^{-\left(\frac{\Delta t}{\tau}\right)}$$

   c. Determine the PA_{O_2} (-500 feet) if no agent was discharged, per table 14.

   d. Dilute the PA_{O_2} from step 4 by $(100\text{-}C_{\mathrm{agent3}})/100$:

$$\mathrm{PA}_{O_2}(-500 feet, Agent) = \mathrm{PA}_{O_2}(-500 feet, NoAgent) \times \left(\frac{100 - C_{agent_3}}{100} \right)$$

   e. Repeat steps 2a through 2d every 30 seconds (every 500 feet into the descent for the first 4.5 minutes) until an altitude of 8000 ft is attained. Then repeat only steps 2b through 2d, maintaining a 8000 ft altitude for an additional 5.5 minutes to obtain the 10-minute alveolar pressure histories.

3. Repeat steps 1 and 2 for each aircraft air change time.

5.4 HYPOXIA DISCUSSION.

Discharging a halocarbon fire extinguisher in an enclosed aircraft cabin can be compared, in some respects, to a decompression event in an aircraft. According to Ersting, et al. [20], flying skills are immediately impaired with alveolar oxygen concentrations below 55 mm Hg and consciousness can be lost within seconds when the alveolar oxygen concentration falls below 30 to 40 mm Hg. Figures 30 and 31 show that the minimum alveolar oxygen partial pressures range from 39 to 46 mm Hg. However, these figures are based on exposures of healthy individuals at rest. At minimal forecast alveolar oxygen pressure for unpressurized aircraft, flying skills may be impaired, and some occupants could be incapacitated. Thus, the guidance on minimizing exposure by using aircraft ventilation and controlled rapid descent is important [21 and 22].

All oxygen systems do not fully protect the wearer from the hazards of hypoxia resulting from the displacement of air by the agent [21 and 22].

- The oxygen flow control for all aircrew oxygen regulators, whether pressure-demand or diluter-demand, is based on pressure altitude, not oxygen partial pressure.

- A flowmeter is used to control oxygen flow for a facemask or nasal cannula. The flowmeter provides a fixed flow and must be adjusted manually to increase flow.

Other issues can prevent oxygen system users from getting full protection from hypoxia.

- Unpressurized aircraft are allowed to use nasal cannula supplementary oxygen systems up to 18,000-ft altitude. These systems provide no protection to a wearer when he or she breathes through the mouth, which can occur at times of stress [21].

- Fingertip probe oxygen sensors are beneficial for oxygen system users in unpressurized aircraft with maximum flying altitudes above 12,500 ft. These devices provide user feedback on the effects of hypoxia and feedback to adjust the oxygen flow to their breathing device to compensate for the hypoxia [21]. However, using pulse oximetry to detect hypoxia in a fire environment may be dangerous. Pulse oximeters show erroneously high readings for individuals that may have inhaled combustion gasses in a fire situation, since it cannot distinguish between hemoglobin bound to CO, carboxyhemoglobin (COHb), and hemoglobin bound to oxygen, oxyhemoglobin (HbO) [22]. Because both oxygen and CO bind with hemoglobin, the absorbance produced will be similar for most pulse oximeters. An individual with CO poisoning is likely to have a normal reading for the percentage of available hemoglobin that is saturated with oxygen, S_{pO_2} [22].

5.5 HOW TO PREVENT HYPOXIA IN UNPRESSURIZED AIRCRAFT.

One can avoid life-threatening hypoxia (low oxygen) hazards that result from the halocarbon agent displacing air in unpressurized aircraft, by following the descent, aircraft ventilation, and supplemental oxygen guidance below [20 and 22].

- Extinguish the fire.

- Don oxygen masks. Occupants of unpressurized aircraft flying at altitudes above 12,500 ft should immediately switch their masks or nasal cannula to the maximum flow of oxygen, if so equipped, to get additional protection during the time it would take to clear the air in the compartment of halocarbon agent and combustion gases. The remaining agent in the compartment after one air change is 36.8% of the starting concentration, 13.5% remains after two air changes, and 5.0% remains after three air changes.

- Descend the aircraft. For example, aircraft with a maximum flying altitude of 12,500 ft are protected from the hazards of hypoxia by immediately descending at a rate of 1,000 ft/minute to an altitude of 8,000 ft or to an altitude that is as low as practicable. Pressurized aircraft have a decent benefit only at pressure altitudes below the CPA. All unpressurized aircraft should descend immediately at the maximum safe rate to 8000 ft or to an altitude that is as low as practicable. Descent is necessary to avoid the life-threatening hazards of hypoxia. Descent dilutes the agent concentration, lowering exposure to the halocarbon agent and combustion gases, while increasing the oxygen concentration. Descent is recommended regardless of the amount of agent used or the ventilation rate.

- Open windows, if so equipped, to increase ventilation.

6. REFERENCES.

1. FAA Advisory Circular AC 20-42C, “Hand Fire Extinguishers for Use in Aircraft,” March 1984.

2. Title 40 Code of Federal Regulations Chapter 1—Environmental Protection Agency, Part 82, Protection of Stratospheric Ozone, Subpart G—Significant New Alternatives Policy Program, and Subpart H—Halon Emissions Reduction.

3. Webster, H., “Development of a Minimum Performance Standard (MPS) for Hand-Held Fire Extinguishers as a Replacement for Halon 1211 on Civilian Transport Category Aircraft,” FAA report DOT/FAA/AR-01/37, August 2002.

4 Tabscott, R.E. and Speitel, L.C, eds., “Options to the Use of Halons for Aircraft Fire Protection Systems—2002 Update,” Task Group on Halon Options, International Halon Replacement Working Group, FAA report DOT/FAA/AR-99/63, February 2002.

5. *NFPA 2001: Standard on Clean Agent Fire-extinguishing systems*, 2008 Edition, NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471.

6. Vinegar, A., Jepson, G.W., and Overton, J.H., "PBPK Modeling of Short-Term (0-5 min) Human Inhalation Exposures to Halogenated Hydrocarbons," *Inhalation Toxicology*, Volume 10, Issue 5, 1998, pp. 411-429.

7. Vinegar, A., Jepson, G.W., Cisneros, M., Rubenstein, R., and Brock, W.J., "Setting Safe Acute Exposure Limits for Halon Replacement Chemicals Using Physiologically Based Pharmacokinetic Modeling," *Inhalation Toxicology*, Volume 12, Issue 8, 2000, pp. 751-763.

8. Eklund, Thor I., "Analysis of Dissipation of Gaseous Extinguisher Agents in Ventilated Compartments," FAA report DOT/FAA/CT-83/1, 1983.

9. Mullin, L.S., Reinhardt, C.F., and Hemingway, R.E., "Cardiac Arrhythmias and Blood Levels Associated With Inhalation of Halon 1301," *American Industrial Hygiene Association Journal*, Volume 40, July 1979, pp. 652-658.

10. Reinhardt, C.F., Azar, A., Maxfield, M.E., Smith, P.E., Jr., and Mullin, L.S, "Cardiac Arrhythmias and Aerosol 'Sniffing'," *Archives of Environmental Health*, 1971, Vol. 22, pp. 265-279.

11. Kenny, T.J., et al., Huntingdon Life Science Ltd., "HFC-236fa, HFC-227ea, HFC-125 and CF3I/ An Inhalation Study to Investigate the Blood Levels of Inhaled Halocarbons in the Beagle Dog," Huntingdon, England, Report IFP 001/984370, 1998.

12. Horrell, P.J., et al., Huntingdon Life Sciences Ltd., "Halotron 1 Measurement of Blood Levels for Cardiac Sensitization Assessment Following Inhalation Administration to Beagle Dogs," Huntingdon, England, November 6, 2007.

13. Colton, B., Gargas, M., and Sweeney, L., "Setting Acute Exposure Limits for the Halotron 1 Clean Agent Onboard Aircraft Using Physiologically Based Pharmacokinetic Modeling," Submitted to Louise Speitel, Federal Aviation Administration, July 16, 2008.

14. Vinegar, A., "Modeling Cardiac Sensitization Potential of Humans Exposed to Halon 1301 or Halon 1211 Aboard Aircraft," *Aviation, Space and Environmental Medicine*, Vol. 72, No. 10, 2001.

15. Vinegar, A., Jepson, G.W., Hammann, S.J., Harper, G., Dierdorf, D.S., and Overton, J.H., "Simulated Blood Levels of CF3I in Personnel Exposed During its Release From an F-15 Jet Engine Nacelle and During Intentional Inhalation," *AIHA Journal*, 1999, Vol. 60, pp. 403-408.

16. Consultation with Dr. Gary Jepson, Senior Fluoroproducts Toxicologist and Manager of the Biochemical and Molecular Toxicology Haskell Laboratory for Health and Environmental Sciences at DuPont, August 2008.

17. Krasner, L.M., "Study of Hand-Held Fire Extinguishers Aboard Civil Aviation Aircraft," FAA report DOT/FAA/CT-82/42, June 1982.

18. Clark, D.G., "The Toxicity of Bromochlorodifluoromethane (BCF) to Animals and Man," Report No. HO/IH/R/279 ICI Ltd., Industrial Hygiene Laboratories, February 1970.

19. Graham, R.C., "Report on Bromochlorodifluoromethane (1211)," DuPont Haskell Laboratory, January 23, 1978.

20. Ersting, J. and King, P., eds., *Aviation Medicine*, Butterworths, London, United Kingdom, 1988.

21. Consultation with Dr. Arnold Angelici, Occupational Medicine Physician at the FAA Civil Aerospace Medical Institute (CAMI).

22. Consultation with Dr. David Self, Physiologist at the FAA Civil Aerospace Medical Institute (CAMI).

23. *USAF Flight Surgeon's Guide*, Chapter 2, "High Altitude Respiratory Physiology," revised by Paul W. Fisher, Ph.D. Document prepared by the Department of Graduate Education at the United States Air Force School of Aerospace Medicine at Brooks Air Force Base for use in the Aerospace Medicine Primary Course, 1996.

24. DeHart, Roy L., ed., *Fundamentals of Aerospace Medicine*, Lea & Febiger, Philadelphia, PA, 1985.

25. Webb, Paul, ed., "Bioastronautics Data Book," Scientific and Technical Information Division, National Aeronautics and Space Administration, Washington DC, 1964.

26. National Transportation Safety Board Recommendation, December 20, 2000, Letter to Jane F. Garvey, Administrator of Federal Aviation Administration.

APPENDIX A—DEFINITIONS AND TERMS

The following definitions and terms apply when following the procedures outlined in this report.

Cabin Pressure Altitude (CPA)—The air pressure in the cabin or compartment of a commercial airliner, specified by regulations, that must not be lower than that found at an altitude of 8000 ft (2438 m) under normal operating conditions, per Title 14 Code of Federal Regulations 25.841(a).

Clean Agent—An electrically nonconducting, volatile, or gaseous fire extinguishant that does not leave a residue upon evaporation. The word agent, as used in this report, means clean agent, unless otherwise indicated.

Compartment—An enclosed space on an aircraft. Examples of compartments are a flight deck, a crew rest, and a cabin. (The aircraft cabin is considered one compartment.)

Flight Crew—The aircraft crew who are responsible for the operations and management of the aircraft flight controls, engines, and systems, including, but not limited to, pilot in command (captain), first officer (copilot), second officer (flight engineer).

Flight Deck—The compartment of the aircraft arranged for use by the flight crew.

Galley—The area of the aircraft for storing, refrigerating, heating, and dispensing of food and beverages.

Halocarbon Agent—An agent that contains, as primary components, one or more organic compounds containing one or more of the elements fluorine, chlorine, bromine, or iodine.

Halocarbon agents are electrically nonconducting, volatile liquids, or gaseous fire extinguishants. As clean agents, they do not leave a residue upon evaporation. These agents are pressurized with inert gases. Halocarbon agents include the halons and halon replacements. Halocarbon agents that are currently commercialized include the hydrochlorofluorocarbons (HCFCs), perfluorocarbons (FCs or PFCs), hydrofluorocarbons (HFCs), fluoroiodocarbons (FICs), and fluoroketones (FKs), as well as the completely halogenated halocarbons (halons). Halocarbon agents are multipurpose class A-, B-, and C-rated agents. They are most effective on Class B and C fires. Extinguishers with greater capacity are also U.S. Underwriters Laboratories, Inc. (UL) listed for Class A fires. To achieve the minimum 1A U.S. UL rating, one of the tests required is the extinguishment of an 8-ft-wide by 8-ft-tall wood panel. Smaller extinguishers do not contain a sufficient amount of agent to extinguish this size of fire. However, they have been shown to be effective against smaller Class A fires, such as seat fires onboard aircraft. The agent manufacturers can provide detailed information on agent characteristics, concentration requirements, health hazards, and extinguishing limitations. Halocarbon agents that are Significant New Alternatives Policy (SNAP) and Federal Aviation Administration (FAA) approved for use on aircraft to replace Halon 1211 in hand-held fire extinguishers include HCFC Blend B, HFC-227ea, and HFC-236fa. Advantages of halocarbon agents include low, cold-shock characteristics on electronic equipment, no degradation of visual acuity, and low pressure.

Halocarbon Blend—A mixture of two or more halocarbon agents in a portable extinguisher.

Halon—Short for "halogenated hydrocarbon." The chemical structure is identified as a four-digit number representing, respectively, the number of carbon, fluorine, chlorine, and bromine atoms present in one molecule. Halon fire-extinguishing agents approved for use include Halon 1211, Halon 1301, and a combination of the two. Both are liquefied gases and typified as clean agents. Halons primarily extinguish fire by chemically interrupting the combustion chain reaction rather than by heat removal or by physically smothering.

Halon 1211—Halon 1211 (bromochlorodifluoromethane, $CBrC1F_2$) is a multipurpose, Class A-, B-, and C-rated agent effective against flammable liquid fires. Due to its relatively high boiling point (-4ºC/+25ºF), Halon 1211 discharges as an 85-percent liquid stream, offering a long agent throw range.

Halon 1301—Halon 1301 (bromotrifluoromethane, $CBrF_3$) is recognized as a multipurpose agent having Class A, B, and C capability in total flooding systems. However, Halon 1301 offers limited Class A capability when used in portable fire extinguishers. The boiling point for this agent is -57.75°C/-71.95°F. Halon 1301 discharges as a gas.

Halon Equivalent Extinguisher—An extinguisher containing a clean agent that meets the minimum performance standard (MPS) for hand-held fire extinguishers (DOT/FAA/AR-01/37). Equivalency does not refer to the weight of the agent. Agent weights for 5B:C listed halon replacement extinguishers may be more than twice the weight of agent in a 5B:C listed halon extinguisher.

Halon Replacement Agents—Any clean agents, which can be either a nonhalon (halocarbon agent) or halon alternative (all other substitute agents), that have SNAP approval by the U.S. Environmental Protection Agency (EPA) and meet the MPS for hand-held fire extinguishers.

Hand-Held Fire Extinguisher—An approved, portable aircraft fire extinguisher, which can be used by aircraft occupants to combat accessible, incipient, onboard fires and hidden in-flight fires per the MPS test.

HCFC Blend B—An extinguishing agent that is a tertiary blend comprised primarily of the chemical 2,2-dichloro-1,1,1-trifluoroethane HCFC-123, (CF_3CHCl_2). Two other gases are blended with the HCFC-123 to enhance flow distribution and fire extinguishing performance. The boiling point of the blend is 27ºC (80.6ºF). Due to its high boiling point, HCFC Blend B discharges primarily as a liquid stream that readily evaporates. It is a multipurpose agent with Class A, B, and C capability.

HFC-227ea—An extinguishing agent that is comprised of the chemical 1,1,1,2,3,3,3-heptafluoropropane (CF_3CHFCF_3). The boiling point of the agent is -16.4ºC (2.5ºF). Due to this boiling point, HFC-227ea is discharged as a mixed liquid and vapor stream that readily evaporates. It is a multipurpose agent with Class A, B, and C capability.

HFC-236fa—An extinguishing agent that is comprised of the chemical 1,1,1,3,3,3 hexafluoropropane ($CF_3CH_2CF_3$). The boiling point of the agent is -1.4ºC (+29.5ºF). Due to its relatively high boiling point, HFC-236fa discharges predominately as a liquid stream that readily evaporates. It is a multipurpose agent with Class A, B, and C capability.

Listed—The equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and is concerned with the evaluation of the products or services. Listing organizations maintain periodic inspection of production of listed equipment or materials or periodic evaluation of services. The listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.

Lowest Observable Adverse Effect Level (LOAEL)—The lowest concentration at which an adverse physiological or toxicological effect has been observed.

Maximum Certificated Occupant Capacity—The maximum number of persons that can be carried for each specific aircraft model as certified by the authority having jurisdiction.

Minimum Performance Standard (MPS) for Hand-Held Extinguishers—Two tests that hand-held extinguishers containing halon replacement agents must pass (DOT/FAA/AR-01/37). These fire tests demonstrate equivalent fire extinguishing effectiveness with the Halon 1211 fire extinguishers currently used in aircraft and assess the toxicity of the decomposition products.

Minimum Safe Volume—The smallest volume (space) into which an extinguisher could be discharged without posing a toxicity hazard. The minimum safe volumes are dependent on the agent, the agent weight, ventilation, and pressure altitude of the discharge. Uniform dispersion is assumed. Safety increases as the minimum safe volume decreases. The minimum safe volumes marked on U.S. UL-listed extinguishers are not applicable for aircraft, as they are based on sea level discharge at +48.9°C (120°F).

No Observed Adverse Effect Level (NOAEL)—The highest concentration at which no adverse physiological or toxicological effect has been observed.

Physiologically Based Pharmacokinetic (PBPK) Model—A mathematical modeling technique for human health risk assessment and investigation of toxicity. The human health concern for halocarbons, including halons, is cardiac sensitization, which occurs at a fixed arterial concentration specific to the agent. The PBPK model estimates the allowable human arterial blood concentration for each halocarbon as a function of time to establish both the concentration of agent and duration to which personnel could be safely exposed. The PBPK modeling approach is endorsed by the U.S. EPA and the National Fire Protection Association.

Pressure Altitude—The indicated altitude when an altimeter is set to an agreed baseline pressure setting.

Rated/Rating—A numerical value assigned to an extinguisher based on its fire-extinguishing capability.

Safe-Use Rankings of Extinguishers—These rankings are based on the minimum safe volumes of extinguishers of the same U.S. UL rating (for the same level of fire protection).

SNAP Program—The Significant New Alternatives Policy Program is the EPA’s program to evaluate and regulate substitutes for ozone-depleting chemicals that are being phased out under the stratospheric ozone protection provisions of the Clean Air Act.

Time of Useful Consciousness—The time available to don an oxygen mask without assistance.

Unventilated—A compartment is considered to be unventilated in this analysis if the air change time is unknown or it exceeds 6 minutes.

Volume Percent (%v/v)—The volume of a gas in liters per 100 liters of the resulting gas mixture.