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Stratification and Localization of Halon 1211 Discharged in Occupied Aircraft Compartments

February 2016

Final Report

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16. Abstract

One goal of this analysis is to characterize the stratification and localization of Halon 1211 in aircraft compartments. A second goal is to provide a methodology to determine stratification and localization multiplication factors that can be applied to the safe-use halocarbon concentrations in Advisory Circular (AC) 20-42D to allow the safe use of higher concentrations than currently recommended. The current safe-use concentrations are based on pharmacokinetic-based assessments of gaseous halocarbon concentration decay histories in a ventilated compartment with perfect mixing and instantaneous agent discharge. The AC 20-42D refers to “an upcoming report” (this report) to provide guidance for setting safe halocarbon limits with consideration of stratification and localization. Separate analyses and guidance is provided for a B-737 aircraft and an unpressurized general aviation aircraft. General guidance is provided for application to non-test aircraft.

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LIST OF ACRONYMS

AC	Advisory Circular
GA	General aviation
FAA	Federal Aviation Administration
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
LOAEL	Lowest-observed-adverse-effect level
MF	Multiplication factor
MF_{SL}	Multiplication factor for stratification and localization
MF_V	Ventilation multiplication factor
NDIR	Nondispersive infrared
NOAEL	No-observed-adverse-effect level
PBE	Protective breathing equipment
PBPK	Physiologically based pharmacokinetic
t_{90}	Time to 90% response
v/v	Volume-to-volume ratio
w/v	Weight-to-volume ratio

EXECUTIVE SUMMARY

The safe-use guidance for hand extinguishers in Advisory Circular (AC) 20-42D provides discharge limits for halocarbon extinguishing agents that are safely below the adverse effect level. The AC guidance is based on the assumption of instantaneous perfect mixing in a ventilated aircraft cabin and the resultant peak human arterial blood concentrations predicted for an exposed person not exceeding a target arterial blood concentration, which is considered the threshold for safe use.

Higher than the currently recommended discharge weights in AC 20-42D are expected to be safe because of stratification of the agent and removal through floor-level air returns. Higher Halon 1211 extinguisher charge weights than those based on perfect mixing are also expected to be safe because there is a history of safe use of 5 B:C Halon 1211 extinguishers in small compartments. This report provides the methodology to determine multiplication factors for stratification and localization (MF_{SL}).

Actual halocarbon gas and arterial blood concentrations may be lower than predicted at the nose level of a seated or standing passenger or crew member because of stratification of the agent and removal at the floor-level air-return ducts, or higher than predicted at locations near the agent discharge. A multiplication factor can be applied to the perfect mixing gas concentration (for the air change time of an aircraft compartment) to increase the AC 20-42D safe use weight of an agent to account for stratification and localization based on the position that a reasonably mobile person would be located at the time of discharge. The increased safe-use agent charge weight should be based on a seated passenger or crew member’s nose level position. The halon concentration histories determined by tests were compared to theoretical ventilated perfect mixing concentration histories, which were calculated based on the weight of agent discharged and the air change time of the compartment, assuming normal leakage. Human arterial blood concentration histories were simulated from the Halon 1211 gas concentration histories using a simple kinetic model, which is based on and has been shown to provide good agreement with physiologically based pharmacokinetic modeling. Safe-use guidelines are based on human arterial blood concentrations not exceeding stated target human arterial blood concentrations.

The ratio of the predicted peak arterial blood concentration obtained from assuming perfect mixing in a ventilated compartment to the test-based predicted peak arterial blood concentrations provides a MF_{SL} for each test and each gas sampling position. Based on this data, one can select a multiplication factor that can be applied to the currently recommended concentrations to provide safe concentrations of Halon 1211.

Tests were conducted to determine the distribution, stratification, and localization of Halon 1211 agent discharged from hand extinguishers in a ventilated B-737-275 narrow-body aircraft cabin and flight deck. The discharge locations were selected after considering the most probable fire sources based on a history of fire occurrences. Cabin discharges were directed at an overhead exit light at the aft end of the cabin seating area. Flight deck discharges were directed at the copilot’s window heater and lower instrument panel.

The B-737 cabin discharge test results showed that Halon 1211, being denser than air, accumulated and spread along the floor. The peak airborne concentrations alongside the firefighter at heights of 22″ and 41″, the nose height of a horizontally reclining passenger and seated passenger, respectively, exceeding the perfect mixing concentration by a factor of 3 and 2, respectively. However, the peak airborne concentrations alongside the firefighter, at standing nose height (60 inches) in the cabin, are far less than the ventilated cabin perfect mixing peak concentrations. The concentrations at the two upper positions 12′ behind the firefighter drop off to far below perfect mixing concentrations, whereas the 22″ high position peak concentration exceeds the ventilated perfect mixing peak concentration by a factor of 2. The B-737 flight deck discharge tests show that Halon 1211 concentrations peaked below the ventilated perfect mixing concentration at the pilot's position at 22″, 41″, and 57″.

The MF_{SL} for the cabin tests were 13.7, 0.79, and 0.44 at 60″, 41″, and 22″ heights at the firefighters' position. The MF_{SL} were 80.3, 54.8, and 1.00 at a distance of 12′ behind the firefighter. The MF_{SL} for the flight deck window heater tests—the worst-case test—were determined to be 1.36, 1.60, and 7.23 at 22″, 41″, and 57″ heights, respectively. Multiplication factors were higher for the instrument panel tests at 1.48, 2.41, and 20.5 at 22″, 41″, and 57″ heights, respectively.

Halon 1211 concentrations in the B-737 flight deck exceeded the perfect mixing AC 20-42D safe-use concentrations at the pilot's nose position after applying test-based MF_{SL}. However, safe use is assured if protective breathing equipment is worn.

Pharmacokinetic-based retrospective analyses of test data for Halon 1211 discharges in a ventilated, unpressurized Cessna 210C four-seater aircraft with a wind tunnel air speed of 120 mph were also performed. The Halon 1211 discharge tests were conducted for an empty aircraft and an aircraft loaded with four mannequins and baggage. Tests selected for analysis included 2 discharge targets: under the instrument panel and the copilot's seat. Three ventilation conditions were included in the analysis: overhead vents open, all vents open, and all vents closed.

Cessna 210C discharge tests conducted in an empty aircraft with overhead vents open resulted in multiplication factors at the pilot's nose level of 2.2 and 2.1 when the extinguisher was aimed under the instrument panel and at the copilot's seat, respectively. The tests conducted in an aircraft loaded with four mannequins occupying the seats and baggage loaded in the baggage area resulted in peak arterial concentrations exceeding those of the empty aircraft by a factor of 2.

1. OBJECTIVE

Tests were conducted to determine the stratification and localization of Halon 1211 when a nominal 2.5 lb Halon 1211 extinguisher is discharged in the flight deck and in the rear section of a ventilated B-737-275 narrow-body aircraft cabin. The goal was to provide test-based guidance for safe-use concentrations to account for nonuniform distribution (stratification and localization) of halocarbon streaming agents. This guidance is provided as multiplication factors to the safe-use guidance material in Advisory Circular (AC) 20-42D [1], “Hand Fire Extinguishers for Use in Aircraft.”

2. BACKGROUND

The Federal Aviation Administration (FAA) Aircraft Certification Service recently issued a replacement for AC 20-42C [2], “Hand Fire Extinguishers for Use in Aircraft,” to provide updated guidance on the selection of halocarbon extinguishing agents. The new AC, AC 20-42D, provides limits on the amount of Halon 1211, Halon 1301, hydrochlorofluorocarbon (HCFC) blend B (primarily HCFC-123), and hydrofluorocarbons (HFCs) 227ea and 236fa, which 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 AC safe-use guidance is based on an instantaneous discharge and perfect mixing. AC 20-42D also provides guidance to crewmembers for compartments that do not meet its safe-use guidance to use portable protective breathing equipment (PBE) if available, and follow the guidance in chapter 4, section 2 of this AC.

There is a history of safe use of Halon 1211 extinguishers in aircraft flight decks that have used AC 20-42C guidance. Figure 1 shows the minimum safe volumes for a sea level discharge of a 2.5 lb Halon 1211 extinguisher for a range of ventilation rates provided in AC 20-42D and the expired AC 20-42C. Both ACs are based on the assumption of instantaneous discharge and perfect mixing.

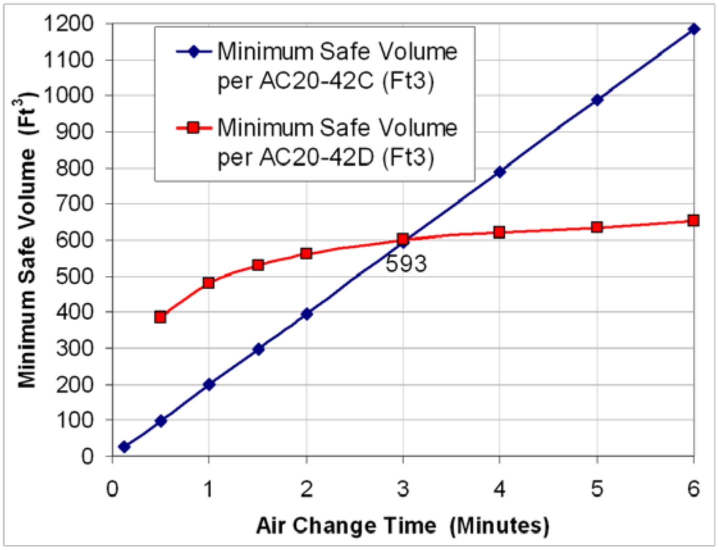


Figure 1. Comparison of minimum safe volumes for 2.5 lb Halon 1211 sea level discharge at various ventilation rates per AC 20-42C and AC 20-42D

The AC 20-42D guidance is based on an updated understanding of halocarbon toxicity. Minimum safe volumes are not linear with dose. Likewise, minimum safe volumes are not linear with air change times, as assumed in AC 20-42C.

The dilemma for small compartments, such as flight decks, is that Halon 1211 concentrations that were previously deemed to meet the old safe-use guidance no longer do so with the new AC. Accounting for stratification and localization increases the safe-use concentrations currently recommended in AC 20-42D in small compartments. If safe-use concentrations are not attained by accounting for stratification and localization, safe use is assured if PBE is used.

The technical basis for the AC 20-42D recommended safe-use limits of halocarbon-extinguishing agents in aircraft is a simple pharmacokinetic-based model that describes the simulated halocarbon concentration history in the blood of humans exposed to a gaseous halocarbon environment [3 and 4]. The pharmacokinetic model is based on rigorous physiologically based pharmacokinetic (PBPK) simulations of halocarbon uptake in the human body and is accurate for short-term exposures in the 0- to 1-minute timeframe [5–7]. The simplified kinetic model, which is calibrated to match the results of the short-term pharmacokinetic model for each chemical, is shown in figure 2.

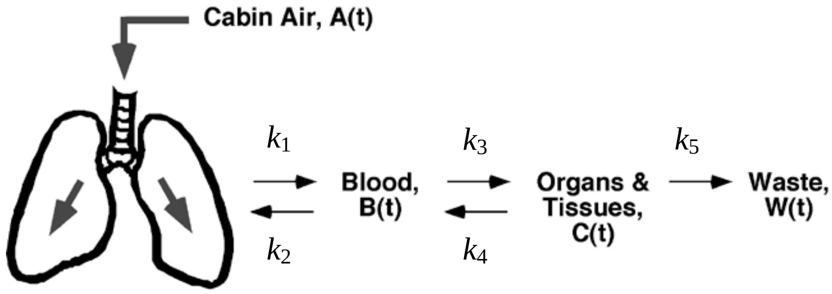


Figure 2. Simplified kinetic model

The rate constants and partition coefficients for the simplified kinetic model are shown in table 1.

Table 1. Rate constants and partition coefficients for kinetic model of halocarbon uptake and elimination from arterial blood [4]

Agent	k_1 (min^{-1})	k_2 (min^{-1})	k_3 (min^{-1})	k_{23} (min^{-1})	k_4 (min^{-1})	P_{BA} ($P_{Blood/Air}$)
Halon 1211[a,b]	0.49	1.3	0.6	1.9	0.50	0.12[c]
Halon 1301	0.27	4.3	0.1	4.4	0.40	0.062
HCFC 123	4.08	4.3	4.2	8.5	0.33	1.16
HFC-227ea	0.16	4.6	0.2	4.8	0.10	0.33
HFC-236fa	0.43	4.08	0.02	4.1	0.01	0.106

a. The rate constants for Halon 1211 are based on a PBPK solution with input parameters that were not referenced (Vinegar [7] may have estimated the input parameters assuming that the safe material concentration is equivalent to the Halon 1211 lowest-observed-adverse-effect level .
b. Compute arterial blood concentration histories using Halon 1301 kinetics as specified in AC 20-42D.
c. Estimated by Lyon and Speitel [4]: $P_{BA} = k_1(k_1/P_{BA})$, where $(k_1/P_{BA}) = 4.2 \pm 0.6\ min^{-1}$ is the average k_1/P_{BA} for the other four halocarbons. Resulting arterial concentration histories matched Vinegar's. However, the source of Vinegar's Halon 1211 $P_{Blood/Air}$ was not referenced.

This simple kinetic model can be used to predict arterial blood concentration histories of a human exposed to changing halocarbon concentrations.

The guidance for both the current and canceled AC is based on the assumption of instantaneous perfect mixing in a ventilated aircraft cabin. The minimum safe compartment volumes for an unventilated compartment per AC 20-42 D are shown in table 2. The minimum safe volumes for Halon 1211 were calculated two ways as indicated in table 2. The lowest-observed-adverse-effect level (LOAEL)-based minimum safe volumes, highlighted in yellow, were used for the stratification and localization evaluation in this paper.

Table 2. Minimum safe compartment volume for one extinguisher in unventilated compartments (from AC 20-42D)

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

a. Agent weight 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 volumes should be corrected for the actual agent weight if different from the agent weight in this figure.
b. Values based on the safe human concentration [3].
c. Values are based on the Halon 1211 no-observed-adverse-effect level concentration of 0.5% volume-to-volume ratio (v/v).
d. Values are based on the Halon 1211 LOAEL concentration of 1.0 % (v/v).
e. Safe human concentrations are not available for Halon 1211 using the same criteria as for other agents. However, the Halon 1211 LoAEL concentration of 1% (v/v) has been shown to be safe for humans. See Speitel and Lyon [3]. Also, the safety factor is smaller than that set for other agents.

Table 3 shows ventilation multiplication factors (MF_V) derived from the simplified kinetic model and adapted in AC 20-42D for ventilated compartments. This table reflects the principle that peak arterial blood concentrations occur early in the exposure to a perfect mixing decaying airborne halocarbon concentration, that the arterial uptake is fairly quick, and that the potential for experiencing peak arterial blood concentrations can occur before the airborne concentrations dissipate much. The toxic effect is measured by the maximum arterial blood concentrations reached relative to a target arterial blood concentration for that halocarbon. The air change times highlighted in yellow are close to the air change times of the B-737 flight deck and cabin Halon 1211 stratification and localization tests discussed in this report.

Table 3. The MF_V (from AC 20-42D)

Agent	Air Change Time, τ (minutes)								
	0.5	1.0	1.5	2.0	3.0	4.0	5.0	6.0	>6 [a]
HCFC Blend B	2.80	2.33	2.14	2.02	1.89	1.79	1.70	1.62	1
Halon 1211 [b]	1.96	**1.57**	1.42	1.34	1.25	**1.21**	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
HFC-236fa [c]	1.98	1.0	1.42	1.34	1.25	1.20	1.17	1.15	1
Halon 1301 [c]	1.96	1.57	1.42	1.34	1.25	1.21	1.17	1.15	1
Test Ventilation: $\tau_{\text{B-737 Flight Deck}}$ = 1.08 min; $\tau_{\text{B-737 Cabin}}$ = 4.13 min									

a. No MF_V is applied if air change time is greater than 6 minutes.
b. Lower MF_V than actual. Based on Halon 1301 MF_V
c. The MF_V are similar for all nonchlorinated halocarbons.

Discharges directed toward low targets are expected to result in higher floor-level concentrations than higher discharges, and are expected to have higher stratification benefits in the higher breathable zones.

Actual halocarbon gas concentrations may be lower than predicted at the nose level of a seated person because of stratification of the agent or higher than predicted because of higher concentrations in the cabin section where the agent is discharged. Stratification and localization of halons were observed in past testing of Halon 1211 discharges in small, nonpressurized general aviation (GA) aircraft [8 and 9], discharges in small pressurized aircraft [10], and discharges in the rear cabin of a C-133 wide-body aircraft [11].

The existence of halocarbon stratification and localization was understood by the drafters of AC 20-42D, yet at the time it was written, there were insufficient data available to provide stratification guidance. There is a provision in AC 20-42D that a report will be published at the FAA Technical Center with a method to adjust safe use concentrations for stratification and localization. That is the intention of this report.

It needs to be emphasized that the guidance in AC 20-42D is conservative and is designed to protect sensitive populations. It is based on canine constant concentration exposures to each halocarbon using a protocol endorsed by the U.S. Environmental Protection Agency. The dogs were pre-dosed with far-higher-than-natural levels of epinephrine (a synthetic adrenalin). The administered epinephrine doses are just below the concentration at which epinephrine alone would cause cardiotoxicity in the experimental animal and are approximately ten times greater than the concentration a human would be likely to secrete under stress. Monte Carlo simulations of blood concentration in the PBPK model at the +2σ level provided a blood concentration that accounts for 95% of the expected human population. The LOAEL and no-observed-adverse-effect level (NOAEL) values are conservative, even in high-stress situations [6, 12, and 13].

The AC 20-42D emphasizes that extinguishing a fire is of primary importance. Any concerns about agent toxicity are secondary in an airborne aircraft. Failure to extinguish an on-board fire can result in the loss of the aircraft and its occupants.

Approved extinguishing agents for use in aircraft per AC 20-42D includeHCFC Blend B , which is primarily HCFC-123; HFC-227ea; HFC-236fa; and Halon 1211. Required extinguishers must pass the minimum performance standard (MPS) for handhelds [14, 3, and 13], which prescribes tests to assure that these agents have the same firefighting ability as Halon 1211 when used as flooding or streaming agents. A narrow volatility range is needed to pass both tests Table 4 shows the boiling points and vapor pressures of the agents listed in AC 20-42D. For blends such as HCFC Blend B, the properties are also shown for the primary and most toxic component, HCFC-123.

Table 4. Boiling points and vapor pressures of agents listed in AC 20-42D [3]

Agent and Most Toxic Component	Formula	Boiling Point	Vapor Pressure at 25°C (bar)
HCFC Blend B (HCFC-123, Argon, PFC-14)	CF_3CHCl_2, Ar, CF_4	81°F (27°C)	6.6
HCFC-123	CF_3CHCl_2	82°F (28 °C)	0.9
HFC-227ea	CF_3CHFCF_3	2°F (-16°C	4.6
HFC-236fa	$CF_3CH_2CF_3$	30°F (-1°C)	2.7
Halon 1211	CF_2ClBr	26°F (-3°C)	2.8
Halon 1301	CF_3Br	-72°F (-58°C)	16.0

As a first approximation, the multiplication factors for stratification and localization (MF_{SL}) developed for Halon 1211 in this report should safely apply to single component agents with a boiling point equal to Halon 1211 and higher and a vapor pressure at 25°C less than or equal to Halon 1211's vapor pressure. For blended agents, the properties of the predominant and most toxic components should be the basis for the agent's MF_{SL}.

For example, for HCFC Blend B, HCFC-123's properties need only be considered. The agents in this table that can safely use Halon 1211's MF_{SL} are HCFC Blend B and HFC-236fa.

This report describes testing conducted to determine the stratification and localization of Halon 1211 when discharged in the rear of a ventilated B-737-275 narrow-body aircraft cabin, and for two flight deck discharge scenarios. Flight deck discharges were directed at the copilot's lower instrument panel and at the copilot's window heater.

The kinetic model was applied to the test Halon 1211 gas-concentration histories to obtain simulated arterial blood concentration histories for each gas-sampling position. The MF_{SL} for increased extinguisher safe-use charge weights were determined by comparing the peak test-based simulated arterial blood concentrations to the theoretical peak perfect mixing simulated arterial blood concentrations, which were calculated using the same air change time and agent discharge weight for a known compartment free-space volume.

This report retrospectively examines the Halon 1211 stratification and localization data for Halon 1211 hand extinguisher discharge tests conducted in a small four-seater Cessna Model 210C aircraft mounted in a wind tunnel in both empty and loaded test configurations [8 and 9]. Halon 1301 pharmacokinetic-based kinetics are used to convert Halon 1211 gas concentration histories to Halon 1211 human arterial blood concentration histories. The predicted test-based human arterial blood concentration histories—and the predicted perfect mixing arterial blood concentrations simulated for vents open and closed at various positions in the test Cessna aircraft—are compared to the perfect mixing arterial blood concentration.

3. EXPERIMENTAL: B-737

Testing was conducted to determine the stratification and localization of Halon 1211 when a nominal 2.5 lb Halon 1211 extinguisher is discharged in the flight deck and in the rear section of a ventilated B-737-275 narrow-body aircraft cabin. A discharge scenario was selected. One air pack was used to provide the ventilation for the aircraft. All overhead vents were closed. The ventilation in each compartment was determined by test. There is no recirculation in this B-737 aircraft.

Air returns are centered 3″ off the floor along the cabin sidewall baseboards.

3.1 THE B-737-275 TEST ARTICLE AND INSTRUMENTATION

3.1.1 The B-737-275 Test Article

The aircraft used in testing was a B-737-275. This is a pressurized aircraft with two air pack units. One auxiliary power unit powered air pack (air pack # 2) was used. The aircraft is shown in figure 3 and its interior configuration is shown in figure 4. The ceiling height in the passenger seating area is 85″.

Figure 3. The B-737-275 test aircraft

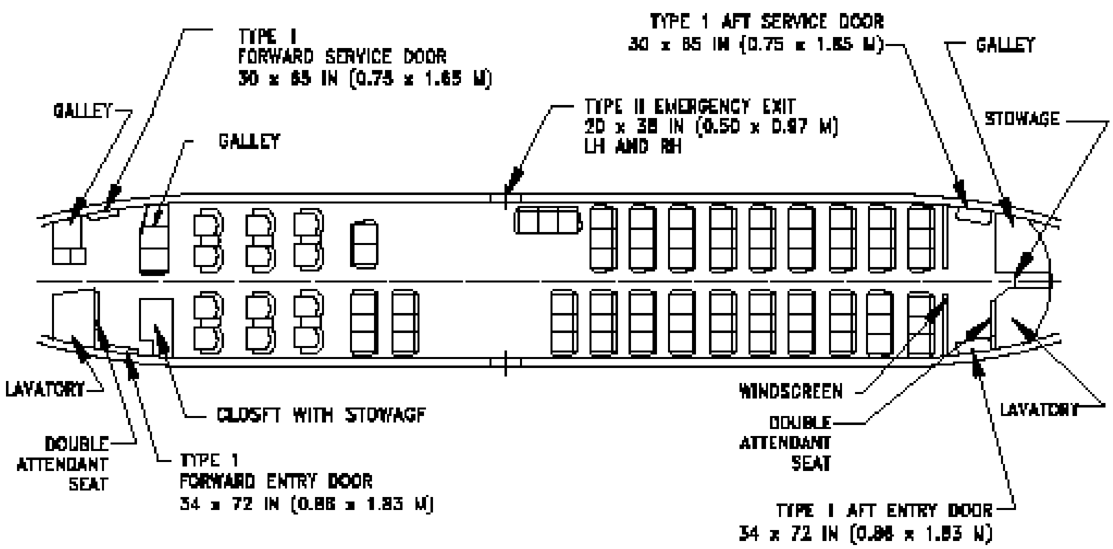


Figure 4. The B-737-275 interior configuration

The passenger cabin is 630″ long x 137″ wide.

Total Cabin Volume = Front Galley volume + Passenger Seating Area volume + Rear Galley volume

$$= 215 \text{ ft}^3 + 3315 \text{ ft}^3 + 323 \text{ ft}^3 = 3853 \text{ ft}^3$$

The 3853 ft^3 cabin volume includes the front and rear galleys and the passenger seating area. The 12 first class seats, 68 coach seats, and 86 feet of overhead storage and other enclosed areas were subtracted to obtain this value. The volume of the firefighter and gear, 6 ft^3, was subtracted to give a free-space volume of 3847 ft^3. The cabin ceiling height measured 85″.

The flight-deck cabin volume was measured and calculated to be 129 ft^3 after subtracting the volume of enclosed structures and seats. The volume of the firefighter and gear, 6 ft^3, was subtracted, to give a free-space volume of 123 ft^3. The flight-deck ceiling measured 65″ at the highest point.

Air returns are along the cabin sidewall baseboards, centered 3″ off the floor. All air ports above the seats were closed. Air entered the cabin from continuous registers along the top center of the aircraft. There are no recirculation systems in this aircraft.

3.1.2 Gas Analyzers

Nondispersive infrared (NDIR) analyzers were used to monitor Halon 1211 and carbon dioxide gas concentrations. Three Emerson-Rosemount Analytical NGA-2000 MLT-4 Halon 1301 analyzers and three carbon dioxide NDIR NGA-2000 analyzers were used. Optical filters were used to minimize interference from water vapor. All analyzers utilize Luft detectors, which measure the common absorbance with the analyte. All analyzers were calibrated for the analyte gases at multiple concentrations within the concentration range of the analysis.

3.1.3 Gas Sample Lines

Lines to each of the three analyzers were prepared to the same length for all cabin tests. The tree supporting the three sample line probes was repositioned for each cabin test, using the same flexible sample lines. Shorter equal-length sample lines were used for flight-deck tests. The line length was minimized by repositioning the gas sampling trailer alongside the point of measurement to provide short transit times for both the cabin and flight deck test series. The transit times matched for the three sampling positions for each sample point in each test series. All sample line infiltrations into the plane were with Swagelok bulkhead fittings. Sample filters were not used, resulting in short time to 90% response (t_{90}) times.

3.2 HALON 1211 DISCHARGE TESTS IN CABIN

The following tests were performed to characterize the stratification and localization of 2.5 lb halon extinguishers discharged in the B-737-275 cabin.

3.2.1 Halon 1211 Extinguisher Directed at Overhead Exit Light

The firefighter was positioned in the passenger seating area alongside the sampling station, 6 ft from the face of an overhead exit light leading to the rear galley. The extinguisher nozzle was positioned approximately 6″ in front of the firefighter. The agent was discharged using a side-to-side sweeping motion from the left edge of the exit sign to the blue light. This scenario was used for tests 1–4 as shown in figures 5–7.

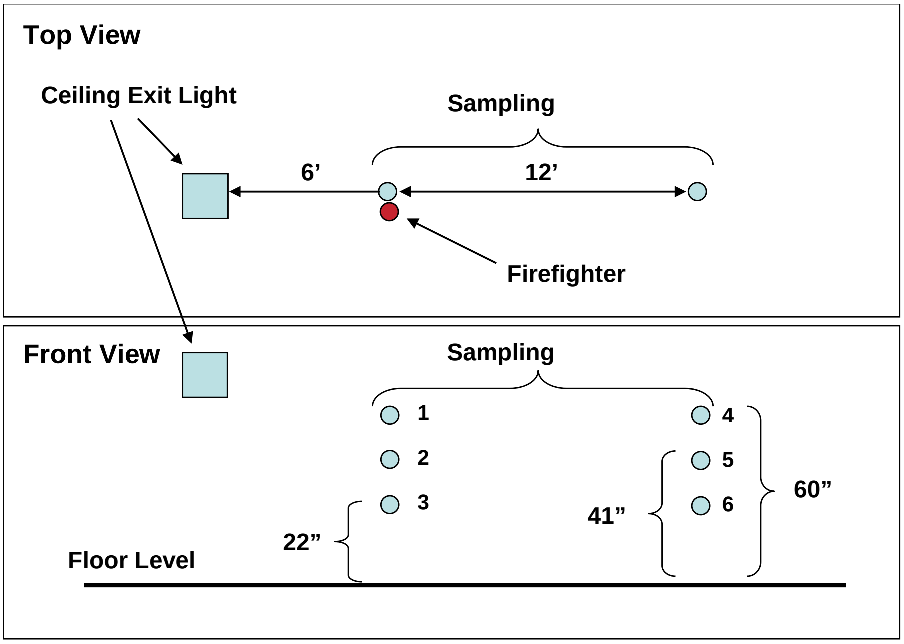


Figure 5. The B-737 test setup for one Halon 1211 extinguisher aimed upward and aft with firefighter positioned 6 ft from the overhead exit ceiling light, Tests 1–4

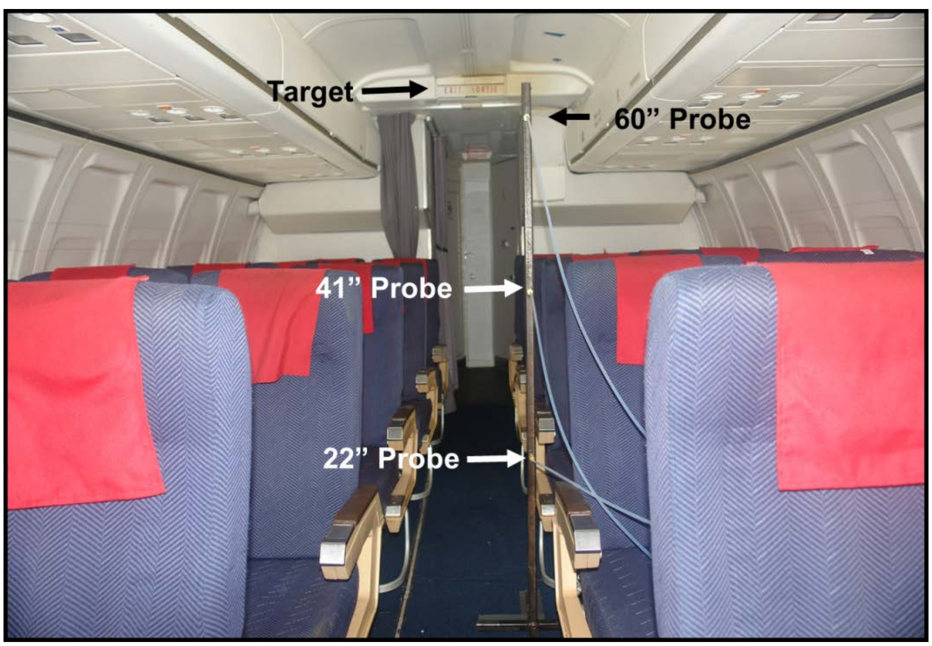


Figure 6. Target and sample probe positions

Figure 7. The target is the left edge of the overhead exit light to the blue button

Tests were run with all doors closed, all cargo compartment liners in place, and the flight deck door closed.

Halon 1211 was measured at two sampling stations at three heights. Because only three gas analyzers were available, the sampling tree was repositioned for each test. The sampling tree was positioned at 6 ft (at the firefighter’s position) and 18 ft forward of the front face of the rear overhead light. Two discharge tests were performed at each sample tree position.

The sample tree had three sample probes at equally spaced heights: 60″ (the nose level of a 5′6″ person), 41″ (the nose level of a seated person), and 22″ (the nose level of an individual resting horizontally).

Data acquisition was initiated 60 seconds prior to discharge. This enabled determination of the baseline noise level and analyzer drift.

3.2.2 Agent Weights and Discharge Times

The extinguisher was fully discharged during each Halon 1211 discharge test and the weight was determined before and after discharge. Discharge times were noted based on the time until a complete discharge and the Underwriters Laboratories discharge time-measurement technique, using the first significant sign of stream change, which is usually accompanied by a sound change and is referred to by some in the industry as “time to hiccup.”

The agent weights and discharge times for the cabin tests are indicated in table 5.

Table 5. Weight and duration of agent discharged for cabin tests

Test	Weight of Agent (lb)	Discharge Time(s) (Time to "hiccup")	Discharge Time- to empty - (Seconds)
1	2.64	15	20
2	2.60	16	22
3	2.47	11	17
4	2.47	11	21

3.3 HALON 1211 DISCHARGE TESTS IN THE FLIGHT DECK

The following test scenarios were performed to characterize the stratification and localization of 2.5 lb Halon 1211 extinguishers discharged in the B-737-275 flight deck. The extinguisher was centered in the same position for both test scenarios—behind the center console. Two discharge tests were conducted for each target. The first target was the copilot's window heater and the second target was the copilot's lower instrument panel. The positioning of the targets, the extinguisher nozzle, and sampling probes positions are shown in figures 8–10. The target section of the lower instrument panel is outlined with duct tape. The agent was discharged using a side-to-side sweeping motion.

Figure 8. The B-737 flight deck test setup

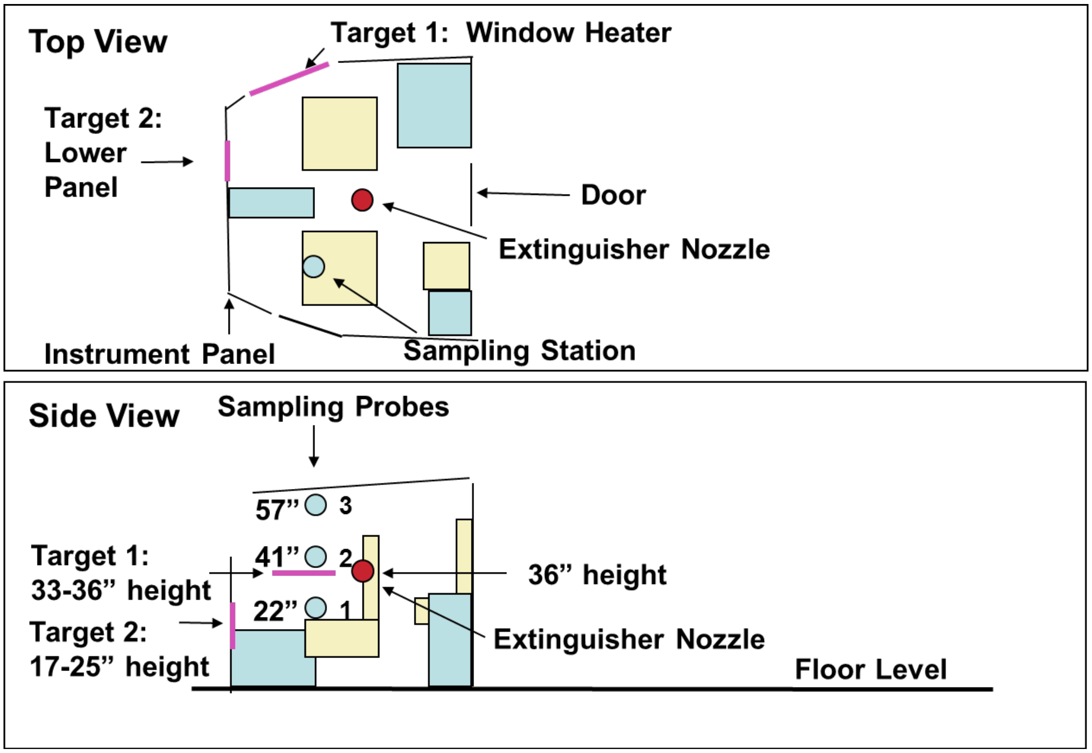


Figure 9. The B-737 flight deck test setup

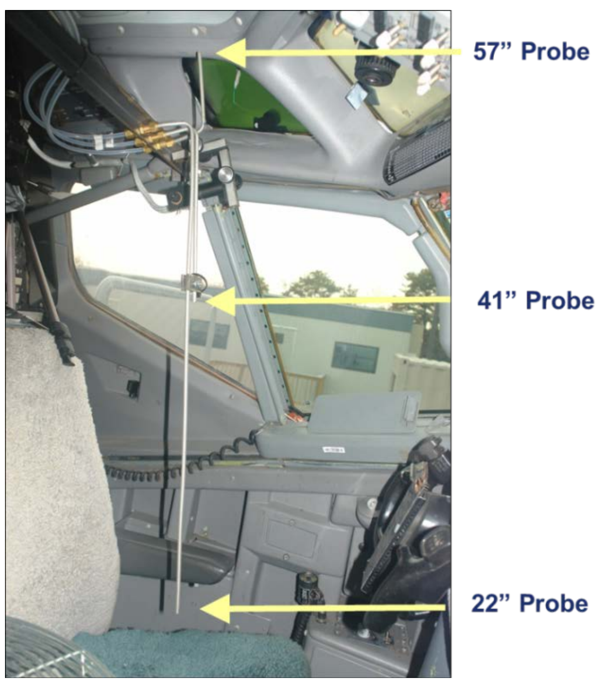


Figure 10. Flight deck sampling probes at pilot’s position

Halon 1211 gas concentrations were measured at the pilot's nose position at a height of 57″ (an inch below the ceiling), 41″ (the nose level of a seated person), and 22″ (the theoretical nose level of an individual resting horizontally with his or her head on the seat; see figures 9 and 10.).

3.3.1 Halon 1211 Extinguisher Directed at Copilot's Window Heater

This scenario was used for flight deck tests 1 and 5, as shown in figure 11.

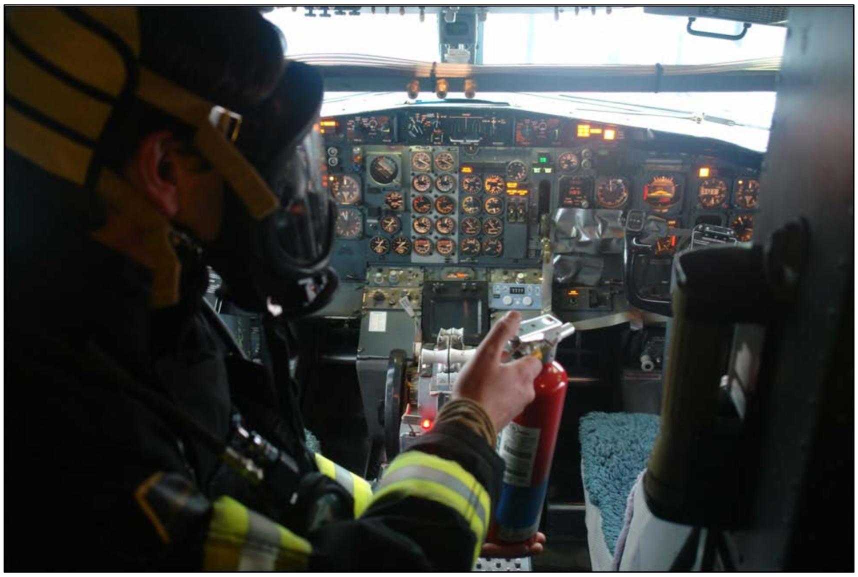


Figure 11. Firefighter directing extinguisher at copilot's window heater

3.3.2 Halon 1211 Extinguisher Directed at Copilot's Lower Instrument Panel

This scenario was used for flight deck tests 3 and 4, as shown in figure 12.

Figure 12. Firefighter directing extinguisher at copilot's lower instrument panel

The target area is outlined with gray duct tape in figure 12.

3.3.3 Agent Weights and Discharge Times

The agent weights and discharge times for the flight deck tests are shown in table 6.

Table 6. Weight and duration of agent discharge for flight deck tests

Test	Weight of Agent (lb)	Discharge Time (s) (Time to "hiccup")	Discharge Time (s) (Time to exhaustion)
1	2.63	18	30
3	2.52	10	15
4	2.47	12	19
5	2.57	10	15

3.4 AIR CHANGE TIME TEST DESCRIPTIONS

3.4.1 Cabin Air Change Time

Eight fans were positioned as shown in figure 13. Six small fans were positioned in the center aisle floor, facing upward, evenly dispersed on the centerline of the seating area of the cabin. The small fans had 18″ diameter blades. A large fan was positioned at each galley exit, one facing the other. The blade diameters were 28″ and 26″, respectively. The height from hub to floor was 47″ and 55″, respectively. Two firefighters were positioned on the starboard side of the cabin, 10 ft from the cabin seating area forward and aft walls. The seating area of the cabin was 50 ft long. The firefighters were positioned alongside the starboard window, shooting over the tops of the

44″ high seats to avoid the center aisle fan updraft. The trajectory was as high as possible to maximize the throw range and to distribute the agent high to promote mixing.

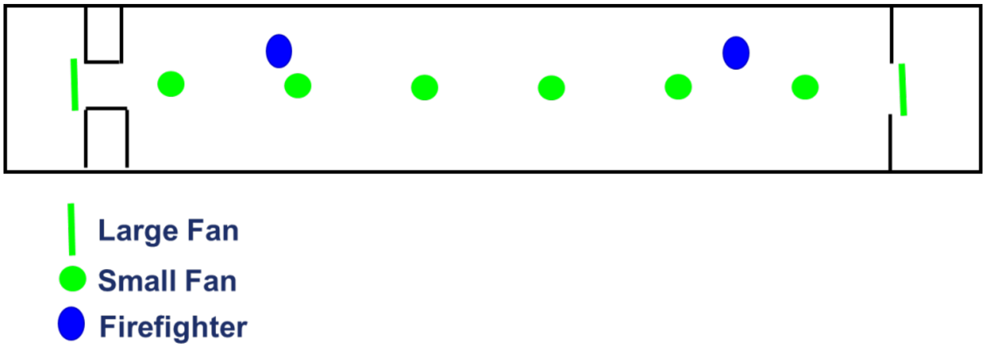


Figure 13. The B-737 setup to determine the cabin air change time: positions of fans and firefighters

Each firefighter was equipped with a nominal 20 lb CO_2 fire extinguisher. The test started 2 minutes prior to agent discharge. The firefighters aimed the extinguishers toward each other for the first 9 seconds of discharge. At 9 seconds into the discharge, they quickly rotated slightly less than 180 degrees, continuing to discharge the agent during the inboard rotation. After rotation, the agent was directed a bit closer to the exit, but mostly at the bulkhead, to avoid blowback of the agent by the exit fan. Discharge was terminated 30 seconds into the discharge for test 3 and at 40 seconds into the discharge for test 5, whether or not there was any remaining agent in the extinguisher.

One gas-sampling probe was positioned at each of the three stations. The stations were positioned 5 ft from the forward and aft end of the cabin seating area, a few inches outboard of the center aisle edge. Probes were positioned either 3″ from the ceiling at a height of 78″ off the floor or 3″ off the floor. Tests were conducted with probes positioned high – low – high, respectvely, or low – high – low, respectively, for each test. The positions of the sampling stations are shown in figure 14. The weights and discharge times are shown in table 7.

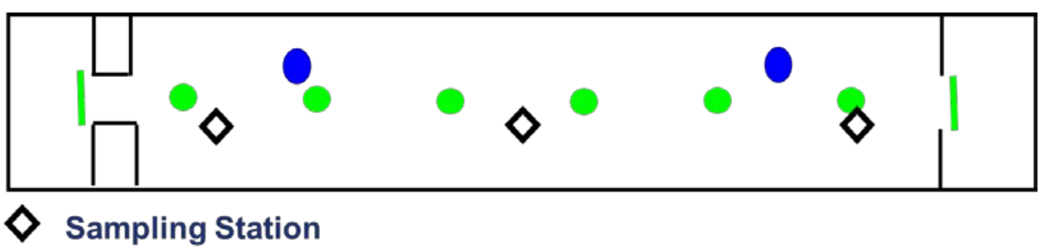


Figure 14. The B-737 setup to determine the cabin air change time with sampling stations

Table 7. Weight and duration of CO_2 discharge for cabin air change time determination

Test	Weight of agent discharged by aft firefighter (lb)	Weight of agent discharged by forward firefighter (lb)	Total weight of agent discharged (lb)
3	18.10	14.95	16.52
5	18.25	19.10	18.67

3.4.2 Flight Deck Air Change Time

One fan and three sample probes were positioned as indicated in figure 15. The fan stood on the center console and was facing upward to mix the CO_2. The fan had 18″ diameter blades. The sampling tree was located directly aft of the center console. The heights of the probes were 3″, 32″, and 60″, respectively. The firefighter was positioned behind the pilot's seat facing forward. The agent was aimed at a fabric curtain, which draped over the instrument panel. Discharge was initiated 120 seconds into the test. The CO_2 discharge was stopped at approximately 2 1/2 seconds into the discharge.

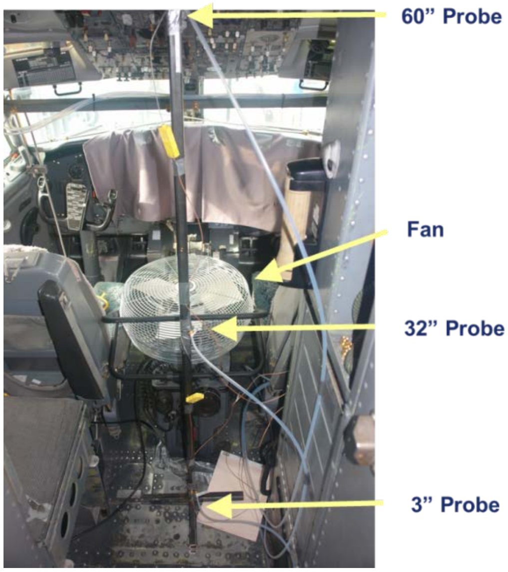


Figure 15. The B-737 setup to determine the flight deck air change time

4. METHODS: B-737

4.1 DETERMINE ARTERIAL BLOOD CONCENTRATION HISTORIES

Arterial blood concentration histories were calculated from the Halon 1211 gas concentration histories. A simple kinetic model, described by Speitel and Lyon [3 and 4], converts gas concentration histories to simulated arterial blood concentration histories. This simple kinetic model approximates a particular PBPK solution, which accurately simulates pharmacokinetic data down to the 0–1 minute range. When arterial blood concentrations are found to exceed the target arterial blood concentration for exposure to a given gas, the recommended safety exposure has been exceeded.

The general equation for changing halocarbon arterial blood concentrations is shown in equation 1, in which $B(t)$ is the arterial blood concentration as a function of halocarbon gaseous concentration and time and $A(x)$ is the gaseous concentration as a function of time. The units of $A(x)$ are mgL^{-1}. The rate constants are shown in table 1 [3 and 4]. The partition coefficients are also shown in table 1.

$$
\begin{aligned}
B(t) = k_1 \int_0^t A(x) e^{-k_{23}(t-x)} dx + \\
k_3 k_4 P_{BA} \int_0^t \left(\int_0^t A(x) e^{-k_4(t-x)} dx \right) e^{-k_{23}(t-y)} dy
\end{aligned}
\tag{1}
$$

This equation can be rewritten into a form that can be executed programmatically or in a Microsoft® Excel® spreadsheet. See equation 2.

$$
\begin{aligned}
B(t) = k_1 e^{-k_{23}t} \int_0^t A(x) e^{k_{23}x} dx + \\
k_3 k_4 P_{BA} e^{-k_4 t} e^{-k_{23}t} \int_0^t \left(\int_0^t A(x) e^{k_4 x} dx \right) e^{k_{23}y} dy
\end{aligned}
\tag{2}
$$

4.1.1 Estimate Halon 1211 Arterial Blood Concentration Histories Using Halon 1301 Kinetics

Halon 1211 arterial blood concentration histories can be estimated using Halon 1301 kinetics.

Halon 1211 kinetics cannot be used directly because the input parameters are unavailable. The AC 20-42D guidance for Halon 1211 is based on an assumed Halon 1211 safe-use concentration of 1.0% and the use of Halon 1301 kinetics (conservative) to obtain an estimated kinetic solution for $B(t)$, for which the target arterial blood concentration for safe use for a sedentary subject is 22.2 mgL^{-1} (the target arterial concentration is 21.3 mgL^{-1} for an active subject). The target arterial blood concentration is the arterial blood concentration at 5 minutes that is predicted using PBPK modeling, for a human exposed to the safe human concentration of a halocarbon for 5 minutes [3 and 4].

Halon 1301 (nonchlorinated halocarbon) kinetics, expressed as $B(t)/B_{safe}$, are more conservative than Halon 1211 estimated kinetics and HCFC-123 kinetics for each air change time, as seen in figure 16. The $B(t)/B_{safe}$ for Halon 1301 rises quicker than it rises for the chlorinated halocarbons HCFC-123 and Halon 1211.

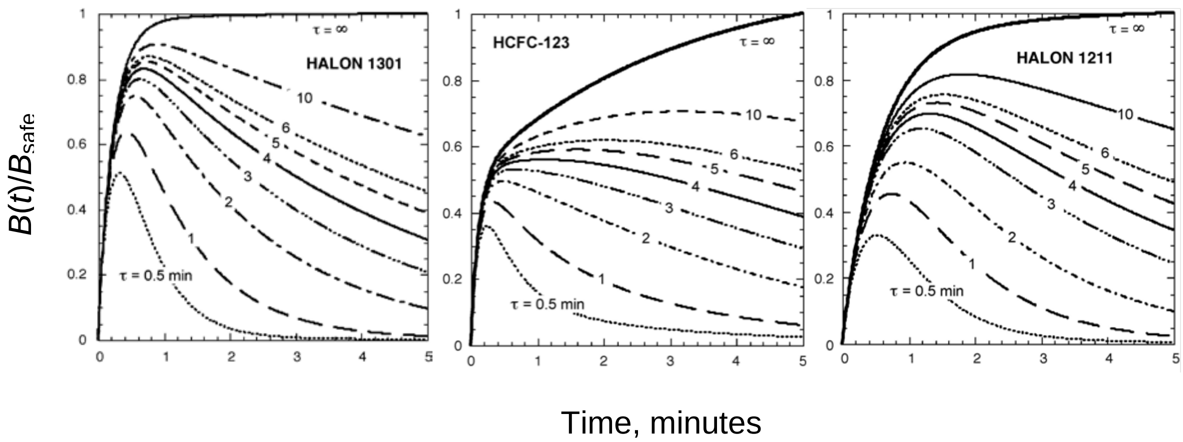


Figure 16. Ratio of the arterial blood concentration of Halon 1301 and the chlorinated halocarbons HCFC-123 and Halon 1211 to the target value B_{safe} for simulated human exposures to A_{safe} in a ventilated cabin at the indicated air exchange times [3 and 4] (Halon 1211 curves are based on nonreferenced data and are not used in safety computations)

The kinetic solutions for $B(t)$ in equations 1 and 2 are based on the gaseous concentration of agent $A(t)$, expressed in units of mgL^{-1}. Because Halon 1301 kinetics are being used, the Halon 1301 equivalent toxicological concentration of Halon 1211 gas, expressed in units of $mg_{Halon\ 1301}L^{-1}$, is used in equation 2 to determine $B(t)_{Halon\ 1301}$. A conversion factor, $B_{safe\ Halon\ 1211}/B_{safe\ Halon\ 1301}$, is then applied to $B(t)_{Halon\ 1301}$ to determine $B(t)_{Halon\ 1211}$ based on Halon 1301 kinetics.

4.1.2 Determine Halon 1301 Toxicologically Equivalent Gaseous Concentration Histories

The Halon 1301 equivalent toxicological concentration histories of Halon 1211 gas, expressed in units of $mg_{Halon\ 1301}L^{-1}$, are determined as follows:

1. Determine the Halon 1301 toxicological equivalent % volume-to-volume ratio (v/v) concentration histories of Halon 1211 gas, $A(t)_{Halon1301}$ (%v/v), by multiplying the Halon 1211 gas volume percent concentrations by the ratio of the safe use gaseous concentrations of Halon 1301 to Halon 1211, as shown in equation 3:

$$A(x)_{Halon\ 1301}\ (\%v/v) = A(x)_{Halon\ 1211}\ (\%v/v) \times (6.25\%v/v)/(1.0\%v/v) \tag{3}$$

2. The Halon 1301 gas volume percent concentration histories, $A(t)_{Halon\ 1301}$ (%v/v), are converted to mg/L Halon 1301 by multiplying the Halon 1301 concentration histories (% v/v) x .01 x 1/*s* , where *s* is the specific volume of the Halon 1301 at 70°F. Table 8 shows the conversion factors. Ideal gas equations should not be used because halocarbons are not ideal gases and occupy a greater volume per unit mass than ideal gases.

Table 8. Conversion factors for halocarbon concentration (%v/v) to mgL^{-1}

Agent	Specific Volume of Agent (ft^3/lb) at 1 atm and 70ºF	Specific Volume of Agent (L/mg) at 1 atm and 70ºF	Conversion Factor: %(v/v) gas to mgL^{-1} gas 0.01/(%v/v) x 1/(*s* (L/mg)), Units = mgL^{-1}(%v/v)$^{-1}$
HCFC Blend B	2.597	0.00016213	61.68
HFC-227ea	2.2075	0.0001378	72.56
HFC-236fa	2.4574	0.00015341	65.18
Halon 1211	2.248	0.00014034	71.26
Halon 1301	2.5605	0.00015985	62.56

1) Note that 1% v/v Halon 1301 is equivalent to 62.56mg/L Halon 1301 gas.

Measured gaseous concentration histories of Halon 1211 (%v/v) can now be converted to toxicologically equivalent Halon 1301 (mg/L) gaseous concentration histories as follows:

$$A(t)_{Halon\ 1301}\ (\text{mg/L}) = A(t)_{Halon\ 1211}(\%\text{v/v})) \times [(6.25\%\ \text{Halon 1301})/(1.0\%\ \text{Halon 1211}] \times [(62.56\text{mg/L Halon 1301})/(1\%\ \text{Halon 1301})] \quad (4)$$

Simplifying:

$$A(t)_{Halon\ 1301}\ (\text{mg/L}) = (A(t)_{Halon\ 1211}\ \%\text{v/v}) \times [(391\text{mg/L Halon 1301}) / (1.0\%\text{v/v Halon 1211})] \quad (5)$$

4.1.3 Determine Toxicologically Equivalent Halon 1301 Arterial Concentration Histories Derived From $A(t)_{Halon\ 1301}$ (mg/L)

The Halon 1301 mgL^{-1} arterial blood concentration histories are determined from equation 6 using the Halon 1301 rate constants and partition coefficients in table 1 and the equivalent toxicological Halon 1301 gas concentration histories expressed in units of mg/L from equation 5.

$$\begin{aligned} B(t)_{Halon1301} &= k_1 e^{-k_{23}t}\int_0^t A_{Halon1301}(x)e^{k_{23}x}dx + \\ & k_3 k_4 P_{BA} e^{-k_4 t} e^{-k_{23}t}\int_0^t\left(\int_0^t A_{Halon1301}(x)e^{k_4 x}dx\right)e^{k_{23}y}dy \end{aligned} \tag{6}$$

4.1.4 Determine Halon 1211 Arterial Blood Concentration Histories for Halon 1211 Exposure Based on Halon 1301 Kinetics

The arterial blood concentration $B(t)_{Halon\ 1301}$ can be converted to toxicologically equivalent arterial blood concentrations $B(t)_{Halon\ 1211}$ by multiplying $B(t)_{Halon\ 1301}$ by the ratio of the target arterial concentration of Halon 1211 to the target arterial blood concentration of Halon 1301, as shown in equation 7:

$$B(t)_{Halon1211} = B(t)_{Halon1301} \times \frac{21.3mg_{Halon1211}/L}{25.7mg_{Halon1301}/L} \tag{7}$$

Note: In this report, the target arterial concentration of Halon 1211 is set at 21.3 mg/L, the target for an active individual. The target for an inactive individual exposed to Halon 1211 is 22.2mg/L.

4.2 DETERMINE MF_{SL}

The MF_{SL} are based on the maximum computed arterial blood concentrations for an exposure, $B_{max\ Halon\ 1211}$, assuming an exposure of 5 minutes or less. The $B_{max\ Halon\ 1211}$ is the maximum $B(t)$ obtained in equation 7.

Compare B_{max} for theoretical perfect mixing (ventilated) to test (ventilated B_{max}). This MF_{SL} will be a multiplier for the maximum agent weight-to-volume ratio (w/v) in AC 20-42D, after MF_V is applied (see equations 8 and 9).

$$MF_{Halon1211_{Stratification\,\&\,Localization}} = \frac{B_{\max Halon1211}(Ventilated, PerfectMixing)}{B_{\max Halon1211}(Ventilated, Stratification, Localization)} \tag{8}$$

Simplifying equation 8:

$$MF_{Halon1211_{Stratification\,\&Localization}} = \frac{B_{\max\,Halon1301}(Ventilated\,,PerfectMixing)}{B_{\max\,Halon1301}(Ventilated\,,Stratification,Localization)} \tag{9}$$

The target arterial concentration of 21.3 mg/L Halon 1211 was used in the analyses (note that equation 7 does not affect the MF_{SL} calculated in equation 9 because it is factored out in the calculation). All Halon 1211 arterial concentrations simulated and plotted for the Halon 1211 discharge tests referenced in this report are using the Halon 1301 kinetics.

4.3 DETERMINE PERFECT MIXING GASEOUS CONCENTRATION

The free space volume of the compartment and the agent charge weight must be known.

4.3.1 No Ventilation

The initial gaseous concentration after disharge can be determined from the agent charge weight, assuming instantaneous perfect mixing.

The agent concentration (expressed in units of weight/volume) in an aircraft compartment is based on the weight of the agent and the free space volume in that compartment. The weight-to-compartment volume ratio, $\left(\frac{W}{V}\right)_{safe}$ (lb/ft^3) can be determined [3]. Equation 10 includes an allowance for the normal leakage from a tight enclosure due to agent expansion [3]. Instantaneous discharge and uniform dispersion are assumed.

$$\left(\frac{W}{V}\right)_{safe} = \frac{1}{(S \times H)} \times \frac{A_{0safe}}{(100 - A_{0safe})} \tag{10}$$

Rearranging, one can solve for A_{0Safe} or, more generally, for A_0 in equation 11:

$$A_0 = \frac{100}{\left(\frac{V}{W \times S \times H}\right) + 1} \tag{11}$$

where:

- A_o is the initial discharge concentration (%v/v).
- S is specific volume of the agent at sea level and 70°F (21.1°C); units are ft^3/lb, as shown in table 9.
- H is the altitude correction factor for S, as shown in table 5, and 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 9. Specific volume of halocarbon agents

Agent	Specific Volume of Agent (ft^3/lb) at 1 Atmosphere and 70°F
HCFC Blend B	2.597[a]
Halon 1211	2.248[b,c]
Halon 1301	2.5605[b,d]

a. Obtained from the manufacturer.
b. Obtained from a past U.S. manufacturer. Halons are no longer manufactured in the United States.
c. The NFPA 12B, standard on Halon 1211 fire-extinguishing systems, 1990 edition (NFPA 12B is no longer an active standard).
d. The NFPA 12A, standard on Halon 1301 fire-extinguishing systems, 2009 edition.

4.3.2 With Ventilation

Assume that an instantaneous discharge of a fire extinguisher at $t = 0$ produces a uniform initial concentration A_0. Equation 12 describes a halocarbon air concentration history that decreases exponentially with time because of dilution of the cabin air with fresh air, assuming perfect mixing and a constant ventilation rate:

$$A(t) = A_0 e^{-t/\tau} \tag{12}$$

Substituting equation 12 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 $t = 0$, as well as perfect mixing.

5. CABIN TEST RESULTS AND DISCUSSION: B-737

5.1 DETERMINE CABIN AIR CHANGE TIMES

To determine the air change time, two CO_2 extinguishers were discharged 120 seconds into the test. All eight fans were running to promote mixing, as described in section 3.4.1. All ventilation systems were run using the same parameters as the test series. One air pack (air pack #2) was used. The resultant CO_2 concentration histories for each probe position and the average of the three probes are shown in figures 17–19.

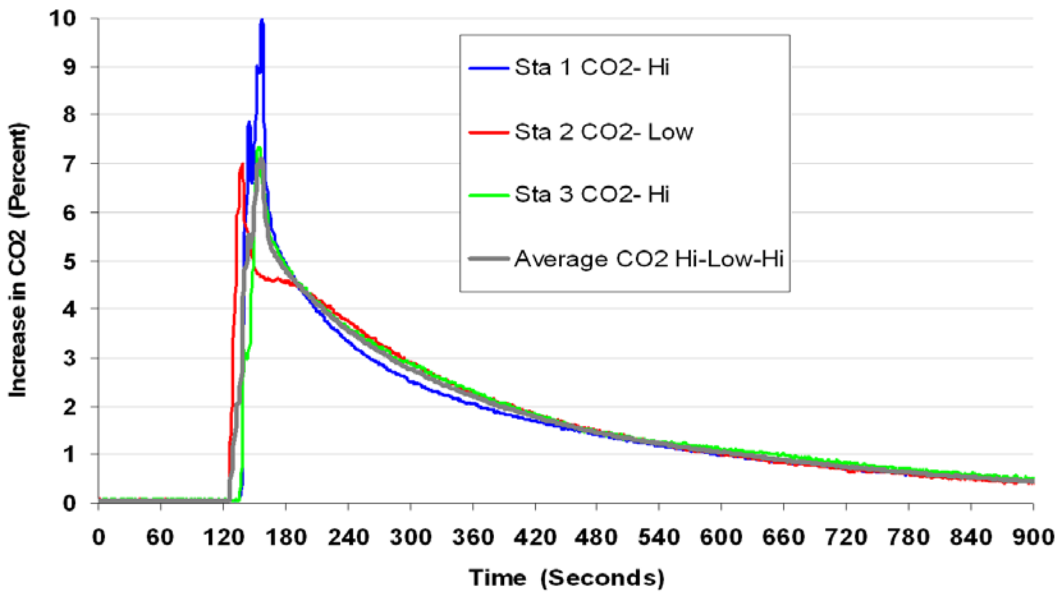


Figure 17. The CO_2 histories for CO_2 discharge Test 3: high, low, high

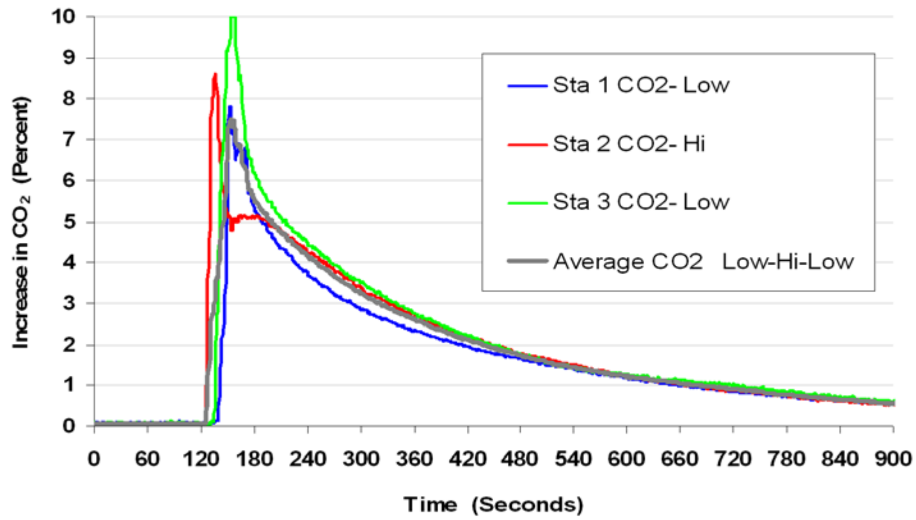


Figure 18. The CO_2 histories for CO_2 discharge Test 5: low, high, low

The average concentrations shown in figures 17 and 18 for CO_2 discharge tests 3 and 5 were each normalized for a 40 lb total discharge. The normalized CO_2 concentration histories are shown in figure 19 along with the average concentration history. Starting at the time of convergence of 195 seconds, the time for one air change was determined from the average curve. Solving equation 12 when $t = \tau$, $C/C_0 = 0.368$. The time for the agent concentration to drop to 0.368 times the 195 seconds concentration (the time for one air change) was determined to be 248 seconds or 4.13 minutes and the volumetric flow rate of fresh air into the cabin = $F = V/\underline{\tau}$ = 3847 ft^3/4.13 min. = 931 ft^3/min.

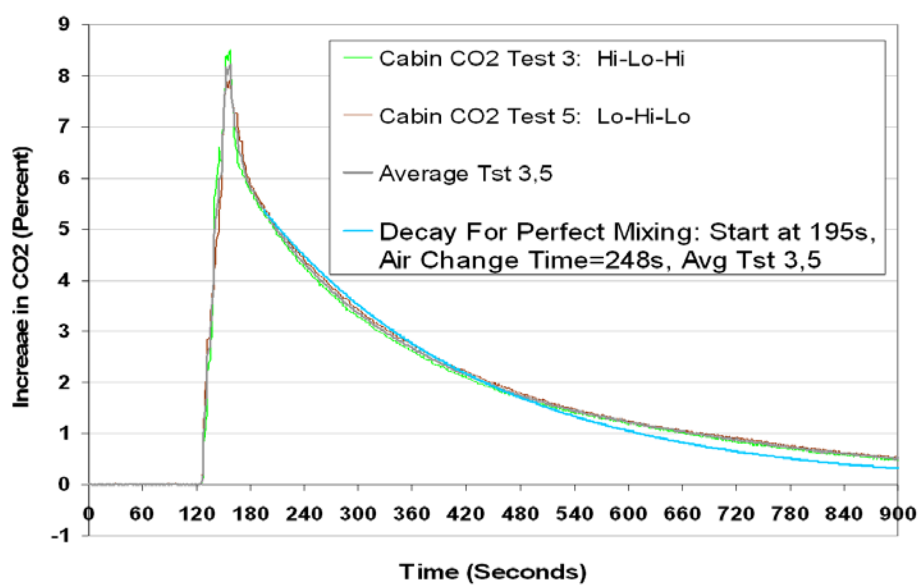
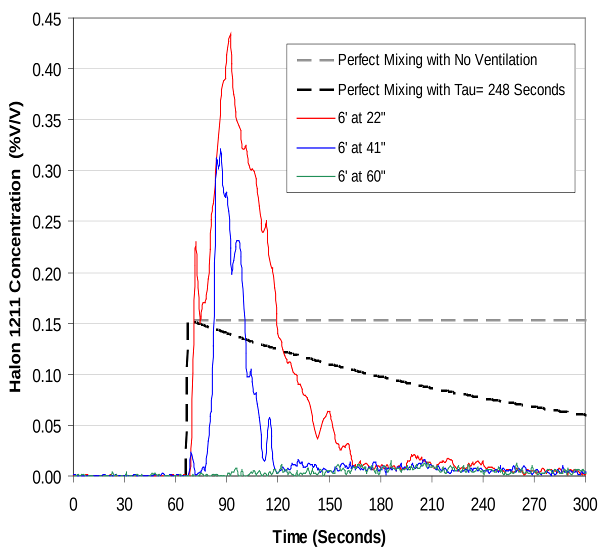


Figure 19. The CO_2 concentration histories normalized for a 40-pound total discharge (the cabin air change time determination is based on average of the normalized data for CO_2 discharge tests 3 and 5)

5.2 HALON 1211 DISCHARGE TESTS IN CABIN: ONE HALON 1211 EXTINGUISHER DIRECTED AT OVERHEAD LIGHT 6 FEET FROM FIREFIGHTER

Figures 20–23 show the concentration histories along with the perfect mixing decay curve for the scenario shown in figures 5 and 6 (tests 1–4). Side-by-side comparisons show the Halon 1211 concentrations and the corresponding computed arterial blood concentrations obtained using Halon 1301 kinetics. The plotted concentration histories are based on the agent weight discharged.



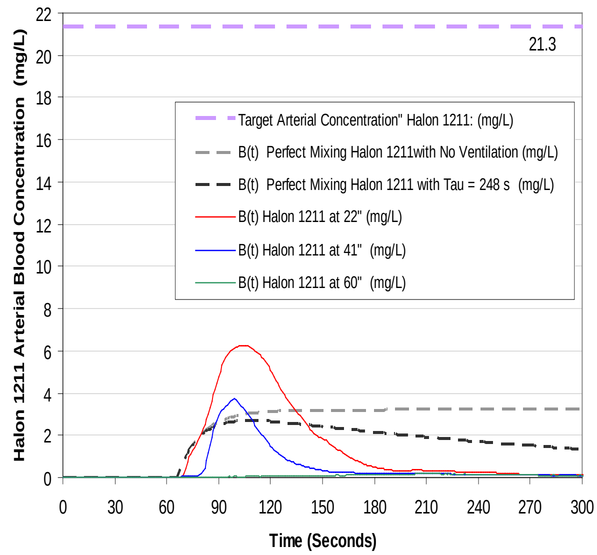


Figure 20. Concentration histories for one Halon 1211 extinguisher discharged at overhead light (sample station is 6 feet from the target, alongside firefighter); Test 1: agent discharged at 60 seconds (figures are based on Halon 1301 kinetics)

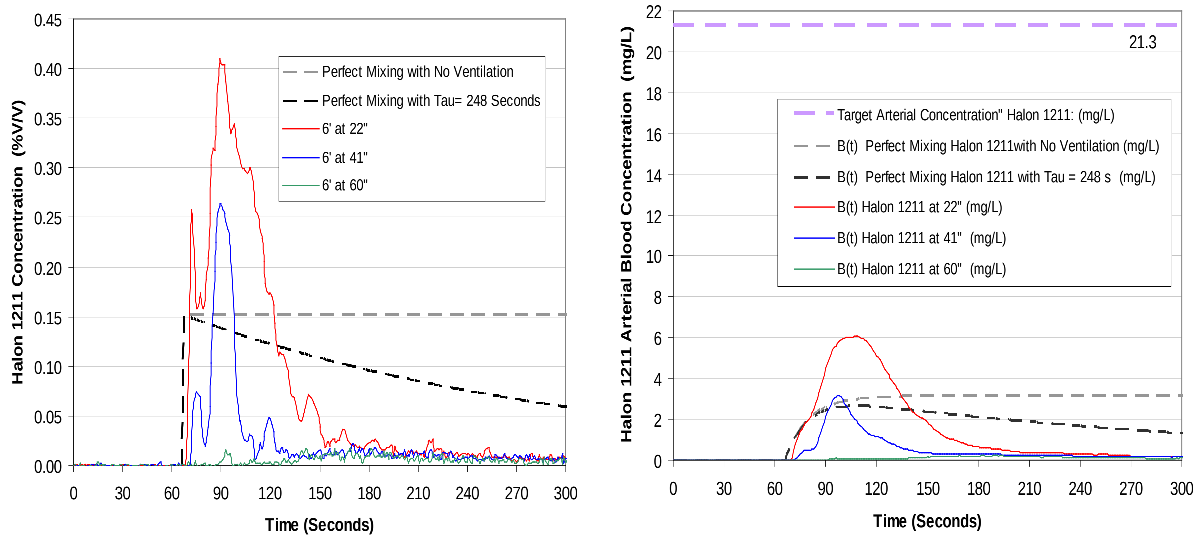


Figure 21. Concentration histories for one Halon 1211 extinguisher discharged at overhead light (sample station is 6 feet from the target, alongside firefighter); Test 2: agent discharged at 60 seconds into test (arterial concentrations are based on Halon 1301 kinetics)

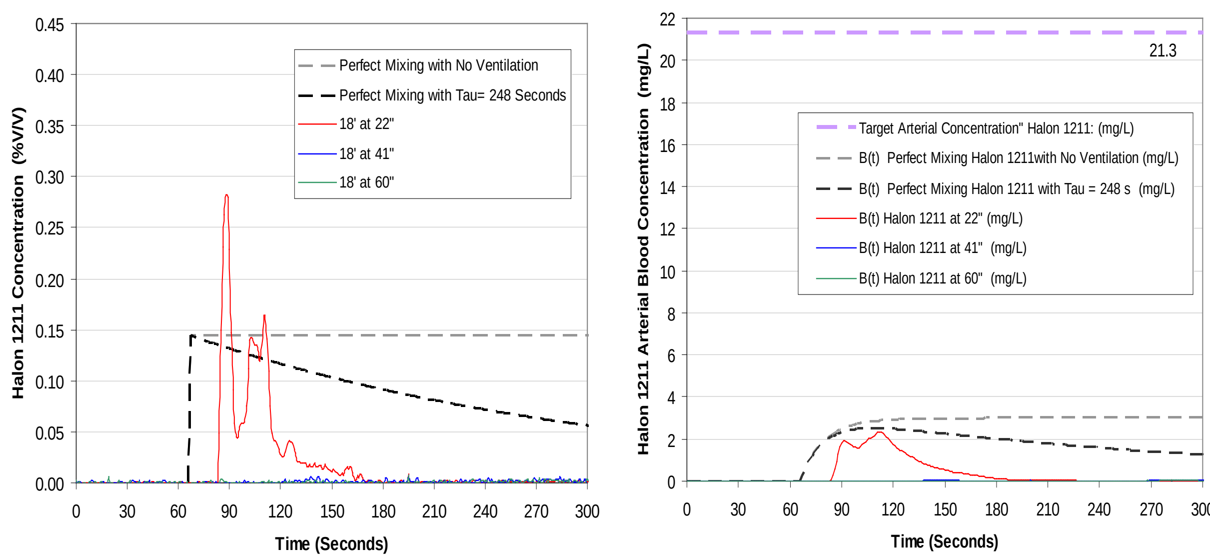


Figure 22. Concentration histories for one Halon 1211 extinguisher discharged at overhead light (sample station 18 feet from target); Test 3: agent discharged at 60 seconds (arterial concentrations are based on Halon 1301 kinetics)

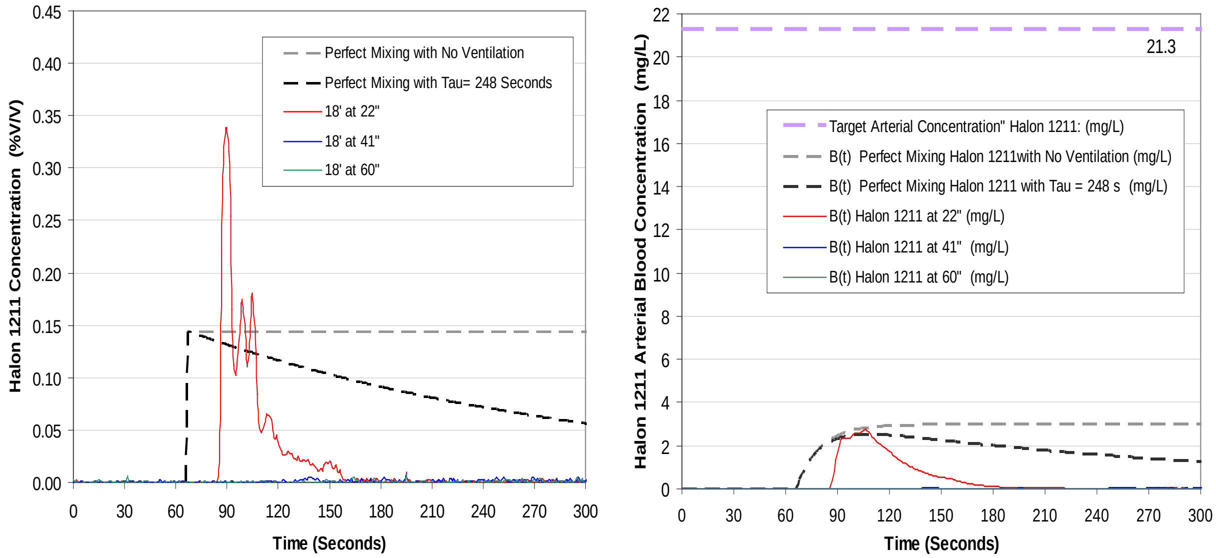


Figure 23. Concentration histories for one Halon 1211 extinguisher discharged at overhead (sample station 18 feet from the target); Test 4: agent discharged at 60 seconds (arterial concentrations are based on Halon 1301 kinetics)

The agent was discharged 60 seconds into the test. The perfect mixing decay curves with and without ventilation were computed. The theoretical discharge time for the instantaneous, perfect mixing decay curves are set to 60 seconds plus the transit time (determined by test). Transit time corrections were not made to the plotted test data. The transit times and t_{90} were 7 seconds and 5 seconds, respectively. Transit times were determined by switching from a bag of Halon 1211 and air at the sampling line inputs in the plane and monitoring the resulting gas concentration histories.

Significant initial stratification and localization can be seen alongside the firefighter. The peak Halon 1211 gas concentration at 22″ and 41″ off the floor for the two stations ranges from 2 to 3 times the peak perfect mixing concentration, as seen for the duplicate tests shown in figures 20 and 21. The peak Halon 1211 gaseous concentrations at 60″ are more than 20-fold lower than at the 41″ sampling height. The simulated Halon 1211 arterial blood concentrations for the discharge tests slightly exceed the perfect mixing peak arterial blood concentration for the 41″ sampling height. The Halon 1211 arterial concentrations at the 22″ height exceed the peak perfect mixing ventilated arterial concentrations by a factor of almost 2. Note that all Halon 1211 arterial concentrations are well below the target arterial blood concentration of 21.3 mg/L and, therefore, far below the safety threshold.

The Halon 1211 concentrations are far lower 12′ behind the firefighter than alongside the firefighter. The peak Halon 1211 gas and arterial blood concentrations at 41″ (the nose level of a seated person) and at 60″ (the nose level of a standing person) are close to zero as can be seen from the duplicate tests shown in figures 22 and 23. The measured peak arterial blood concentrations are slightly lower than or match the perfect mixing peak arterial blood concentration for the 22″ sampling height. Note that they are well below the target arterial blood concentration and, therefore, far below the safety threshold.

5.3 DETERMINE MF_{SL} FOR HALON 1211 IN THE B-737 CABIN

The MF_{SL} for the B-737 cabin tests were determined from the peak arterial blood concentrations using the methodology in section 4.3. Cabin multiplication factors obtained using Halon 1301 kinetics are shown in table 10 and figure 24.

Table 10. The MF_{SL} for one Halon 1211 extinguisher discharged at rear cabin overhead exit sign (the firefighter was positioned 6 feet from the target)

Test	Distance From Target (Feet)	MF_{SL} Based on Halon 1301 Kinetics		
		22″ Height	41″ Height	60″ Height
1	6	0.43	0.73	15.2
2	6	0.44	0.84	12.2
Average	6	0.44	0.79	13.7
3	18	1.08	48.8	61.5
4	18	0.92	60.9	99.1
Average	18	1.00	54.9	80.3

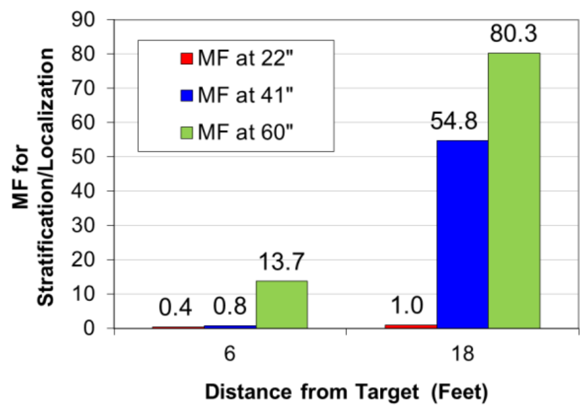


Figure 24. Average MF_{SL} for one Halon 1211 extinguisher discharged at rear cabin overhead exit sign (the firefighter was positioned 6 feet and 18 feet from the target)

Figure 24 shows that for the firefighter, who is located 6 feet from the target with a nose level of 60″, the simulated Halon 1211 arterial blood concentrations are 13.7-fold less than predicted for perfect mixing conditions. The simulated arterial blood concentrations for the nose level of the individual in the seated position alongside the firefighter was 1.2-fold more than predicted. The multiplication factors in figure 24 are much larger 12 feet behind the firefighter, indicating that the hazard is localized in the area of discharge.

6. FLIGHT DECK TEST RESULTS AND DISCUSSION: B-737

6.1 DETERMINE FLIGHT DECK AIR CHANGE TIME

The flight deck air change time was determined as described in section 3.4.2. A CO_2 extinguisher was discharged for 2 1/2 seconds to determine the air change time. Discharge was initiated 120 seconds into the test.

The CO_2 concentration histories measured at three heights are shown in figure 25, along with the average concentration history. Starting at the time of convergence of 138 seconds, the time for one air change was determined from the average curve. Solving equation 12 when $t = \tau$, $C/C_0 = 0.368$. The time for the agent concentration to drop to 0.368 times the 138 second concentration (the time for one air change) was determined to be 65 seconds or 1.08 minutes and the volumetric flow rate of fresh air into the cabin = $F = V/\tau$ = 123 ft^3/1.08 min. = 114 ft^3/min.

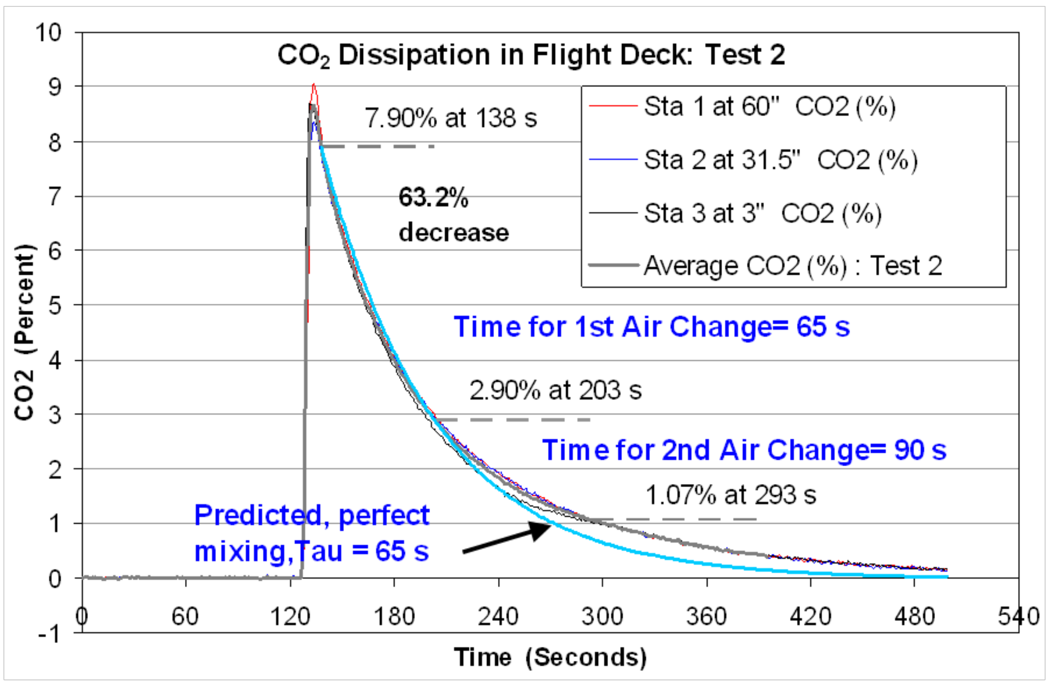


Figure 25. Flight deck air change time determination based on CO_2 discharge Test 2

6.2 HALON 1211 EXTINGUISHER DIRECTED AT COPILOT'S WINDOW HEATER

The concentration histories, along with the perfect mixing decay curve for the extinguisher discharged at the copilot's window heater, are shown in figures 26 and 27. The plotted concentration histories are based on the agent weight discharged. These side-by-side plots show the Halon 1211 gas concentrations and the corresponding computed arterial blood concentrations obtained using Halon 1301 kinetics.

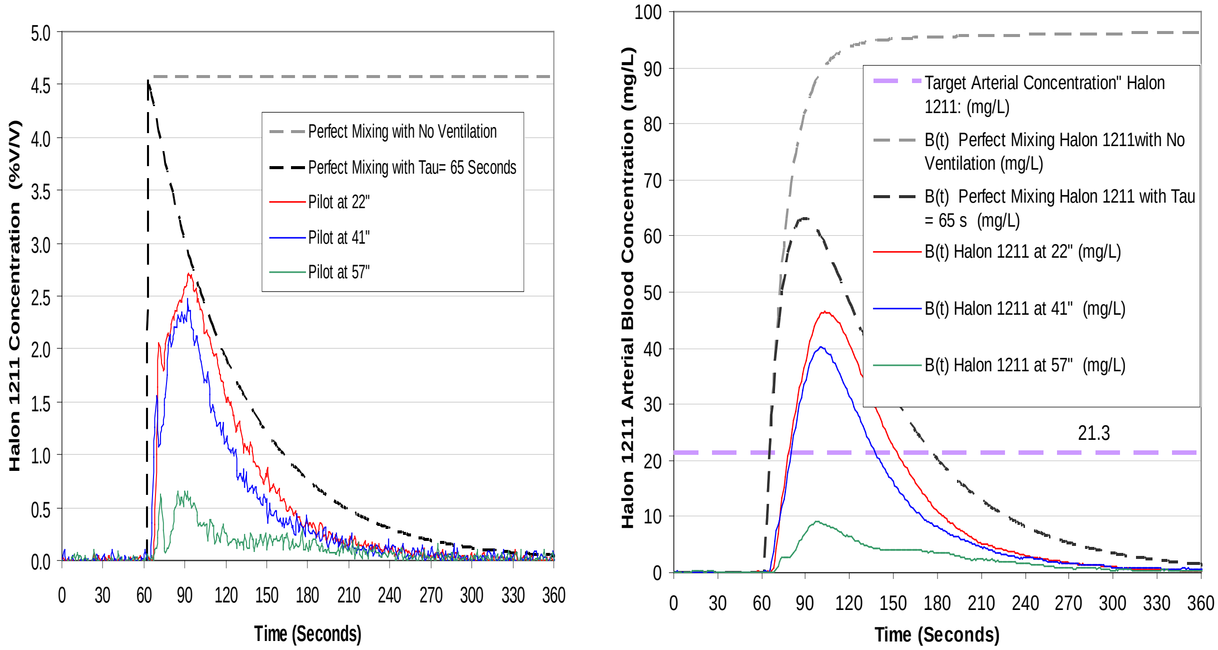


Figure 26. Concentration histories for one Halon 1211 extinguisher discharged at copilot's window heater; Test 1: agent discharged at 60 seconds (arterial concentrations are based on Halon 1301 kinetics)

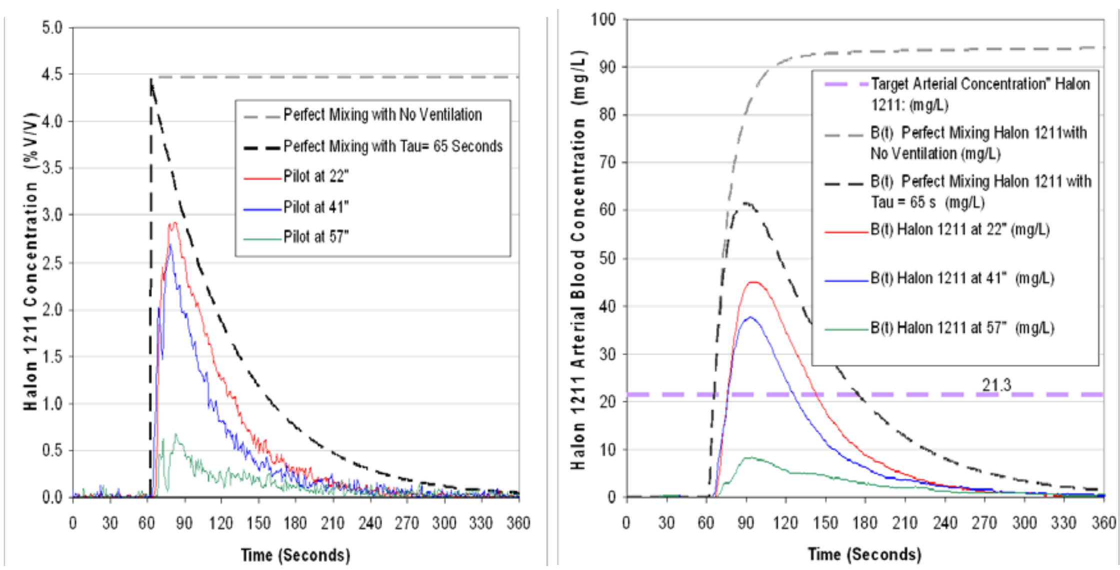


Figure 27. Concentration histories for one Halon 1211 extinguisher discharged at copilot's window heater; Test 5: agent discharged at 60 Seconds (arterial concentrations are based on Halon 1301 kinetics)

The agent was discharged 60 seconds into the test. The perfect mixing decay curves with and without ventilation were computed. The theoretical discharge time for the instantaneous, perfect mixing decay curves are set to 60 seconds plus the transit time (determined by test). Transit time corrections were not made to the plotted test data. The transit times and t_{90} were 3 seconds and 4 seconds, respectively.

Significant initial stratification was seen. All three sampling positions at the pilot's position had a stratification benefit—concentrations less than the perfect mixing concentrations for a ventilated compartment. The peak Halon 1211 gas concentration at 22″ and 41″ off the floor for the two station ranges were similar and were about half the peak perfect mixing concentration. However, the safe use arterial blood concentration was exceeded at the 22″ and 41″ sampling height.

6.3 ONE HALON 1211 EXTINGUISHER DIRECTED AT COPILOT'S LOWER INSTRUMENT PANEL

The concentration histories along with the perfect mixing decay curve for the extinguisher discharged at the copilot's window heater are shown in figures 28 and 29. The plotted concentration histories are based on the agent weight discharged. These side-by-side plots show the Halon 1211 gas concentrations and the corresponding computed arterial blood concentrations obtained using Halon 1301 kinetics.

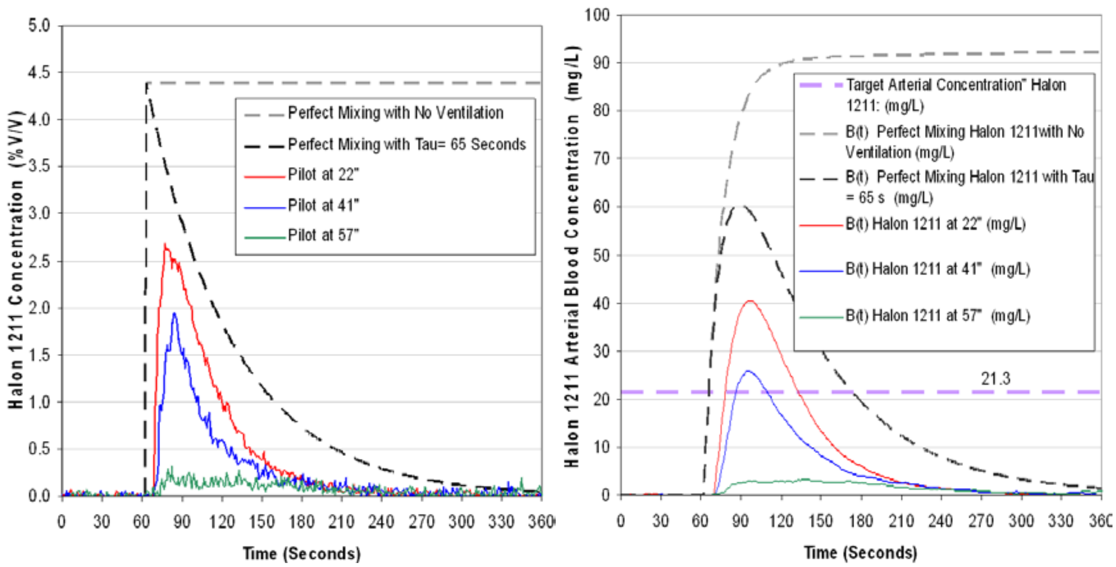


Figure 28. Concentration histories for one Halon 1211 extinguisher discharged at copilot's lower instrument panel; Test 3: agent discharged at 60 seconds (arterial concentrations are based on Halon 1301 kinetics)

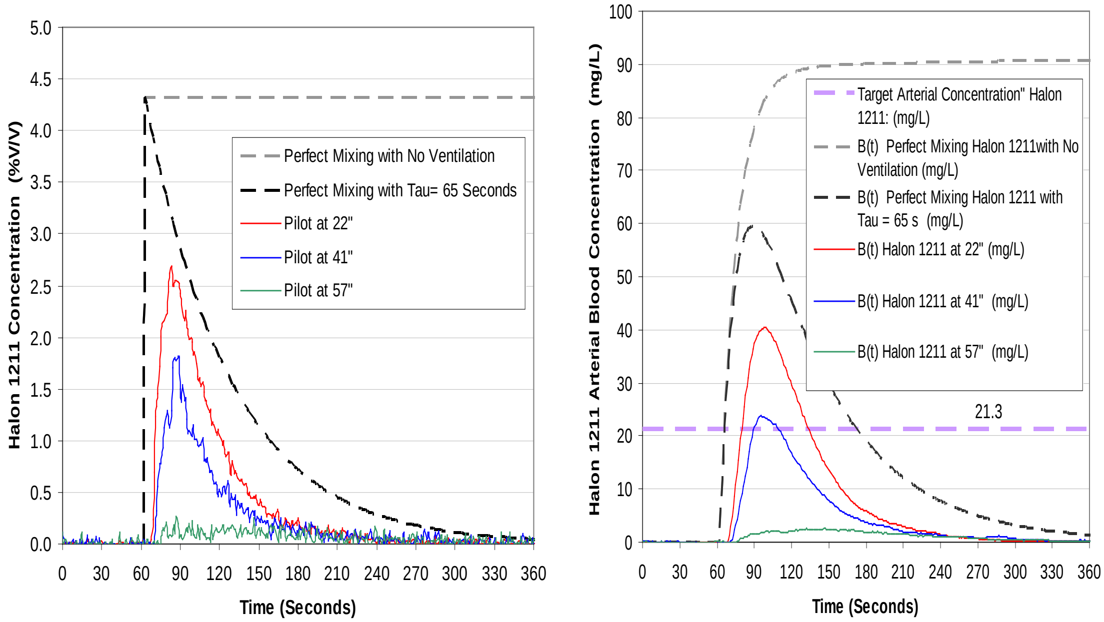


Figure 29. Concentration histories for one Halon 1211 extinguisher discharged at copilot's lower instrument panel; Test 4: agent discharged at 60 seconds (arterial concentrations are based on Halon 1301 kinetics)

The agent was discharged 60 seconds into the test. The perfect mixing decay curves with and without ventilation were computed. The theoretical discharge time for the instantaneous, perfect mixing decay curves are set to 60 seconds plus the line delay (determined by the test). Line delay corrections were not made to the test data.

Significant initial stratification can be seen. All three sampling positions at the pilot's position had a stratification benefit—concentrations less than the perfect mixing concentrations for a ventilated compartment. The peak Halon 1211 gas concentration at 22″ and 41″ off the floor for the two station ranges were similar and were about half the peak perfect mixing concentration. The safe use arterial blood concentration was exceeded at the 22″ sampling height and was slightly exceeded at the 41″ sampling height.

6.4 FLIGHT DECK MF_{SL}

The MF_{SL} for the flight deck tests were determined from the peak arterial blood concentrations using the methodology in section 4.3. Flight deck multiplication factors obtained using Halon 1301 kinetics are shown in table 11 and figure 30.

Table 11. The MF_{SL} for one Halon 1211 extinguisher discharged in the flight deck (the firefighter was positioned behind the center console)

Test	Target	MF_{SL} Based on Halon 1301 Kinetics		
		22″ Height	41″ Height	57″ Height
1	Window Heater	1.36	1.57	6.99
5	Window Heater	1.36	1.63	7.47
Average	Window Heater	1.4	1.6	7.2
3	Instrument Panel	1.49	2.33	18.72
4	Instrument Panel	1.47	2.49	22.27
Average	Instrument Panel	1.5	2.4	20.5

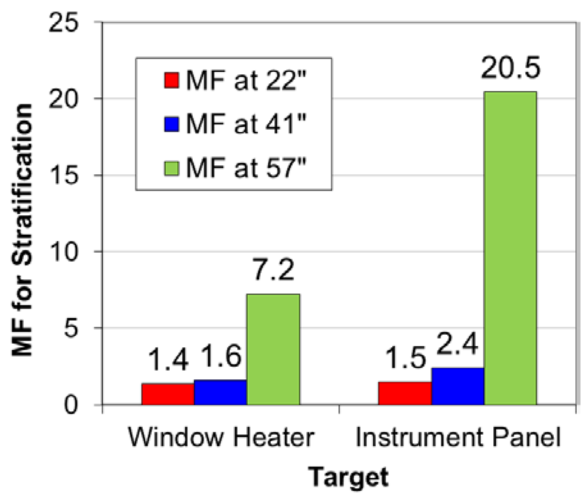


Figure 30. Average MF_{SL} for one Halon 1211 extinguisher discharged at the flight deck window heater and instrument panel (the firefighter was positioned behind the center console)

Figure 30 shows the seated pilot's nose position (41″ in height), and that the simulated peak arterial blood concentrations were 1.6- to 2.4-fold lower than predicted for perfect mixing conditions for Halon 1211 discharges at the window heater and instrument panel, respectively. The predicted peak arterial blood concentrations (57″ in height) were 7.2- to 20.5-fold lower than predicted for perfect mixing. Much higher Halon 1211 concentrations may be safely used than predicted by perfect mixing.

7. RETROSPECTIVE ANALYSIS OF CESSNA 210C TEST DATA

Retrospective analyses were conducted of selected data from 1984 [8] and 1986 [9] FAA technical reports. The historical reports provided stratification and localization test data for Halon 1211 hand extinguishers discharged in a small, four-seat, nonpressurized, ventilated GA aircraft [8]. The Cessna model 210C airplane was mounted in an airflow facility with airspeeds set at 0, 40, 80, 120, and 140 mph. The purpose of reevaluating past test data was to demonstrate the methodology to develop test-based multiplication factors (MF_{SL}) to allow higher concentrations than AC 20-42D guidance provides, accounting for agent stratification and localization in small, unpressurized GA aircraft. This multiplication factor is to be applied to the safe-use w/v along with the MF_V for that agent. This retrospective analysis is based on a better understanding of the pharmacokinetics of the halons [3 and 4].

Halon 1211 extinguishers of a nominal 2.5 lb capacity were discharged remotely at the selected targets for both test series. The tests were conducted with no fire. Selected data for airspeeds of 120 mph were evaluated.

The 1984 test series evaluates halon concentration histories at the target area and at pilot's nose level for an empty aircraft. The targets evaluated were under the copilot's instrument panel and the seat. The overhead vents resulted in ventilation air of 121 cubic ft per minute, providing an air change time of 1.16 minutes for the empty aircraft. Tests were also run with all vents closed and all vents open, including two auxiliary vent doors located on the lower fuselage behind the engine. This ventilating airflow is introduced through the cabin heat and defrost system.

The 1986 series was conducted with four seated mannequins and with baggage loaded in the baggage area, resulting in a reduced and unknown free space volume and an unknown air change time. The air change time is quicker than that for the empty aircraft.

7.1 TEST ARTICLE AND INSTRUMENTATION, 1984 TESTS

7.1.1 Test Article

Figure 31 shows the Cessna 210C airplane mounted in the wind tunnel. The test article is a 1963 model Cessna 210C.

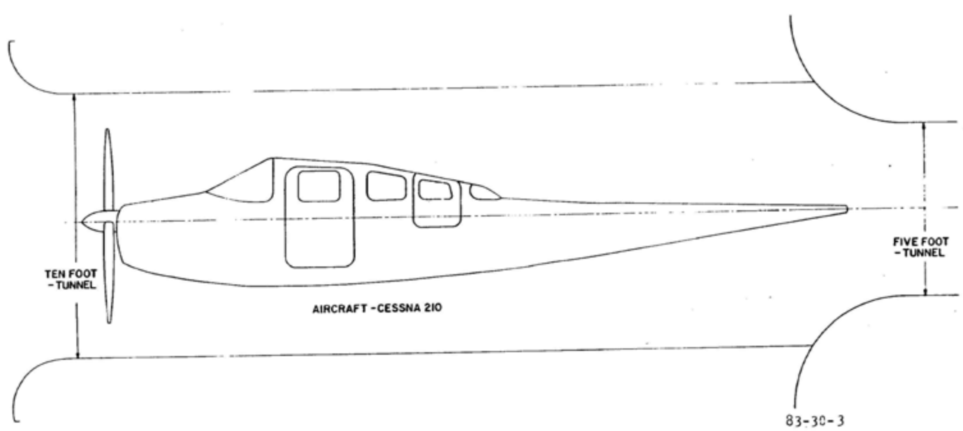


Figure 31. Wind tunnel profile with Cessna 210C

The primary outflow of air is through the tailcone area openings, through which control cables pass.

The cabin volume was 140 ft^3 for the 1984 tests. The time for one air change, τ, was determined by test to be 1.16 minutes at 120 mph air speed, with the front and rear overhead vents open in the empty fuselage. The two overhead front vents were directed toward the pilot's and copilot's faces. All four vents were directed downward and rearward on both test series.

The free space volume is unknown for the 1986 series tests, resulting in an unknown air change time.

7.1.2 Air Flow Measurement

Cabin ventilation airflow visualization studies showed that, with the overhead vents open and directed toward the pilot's and copilot's faces, the direction of the flow was diagonal across the side windows and toward the rear of the aircraft. All flow direction components appeared to be comparable downward and rearward. The smoke visualization indicated that the flow was moving at a fast air-ventilation rate.

The flow exiting the overhead ventilators was measured with pitot-static probes at airspeeds of 120 miles per hour. Airflow through each of the front vents was 32 ft^3/min. Flow through each of the rear vents was 28 ft^3/min. Total flow was 121 ft^3/min. Because the volume of the 210 aircraft is 140 ft^3, the time for an air change in the cabin is 1.16 minutes with the overhead vents open. Halon discharge tests were conducted with three ventilation conditions: overhead vents open, all vents open, and all vents closed. Because the flows at the vents were not measured with all vents open, the air change time cannot be determined for that condition. The air changes may be quicker than calculated because the measurements did not account for air leakage into the aircraft through seals that are not airtight.

7.1.3 Gas Analyzers

Halon 1211 concentrations were measured with Beckman model 865 gas analyzers. The infrared detectors were Luft-based and were filled with Halon 1211 gas. The analyzer included an optical filter to eliminate sensitivity to water vapor for both test series. Calibration gas concentrations of Halon 1211 were 2%, 4%, and 6% by volume for the 1984 test series and 3%, 6%, and 8% for the 1986 test series. It was customary in the mid-80s in the FAA fire test labs to get multipoint calibrations for the entire analyzer range and span the analyzers below the full-scale concentration. Either linearizer boards were used on the analyzer, or linearization corrections were made in the data-acquisition programs. Measured concentrations should be accurate for the entire analyzer range used.

Sample transport lines, sample pumps, and sample flow controls were used. Two analyzers were used in the 1984 test series and three were used in the 1986 test series.

Neat Halon 1211 concentration was measured at the pilot's nose height and at locations in proximity to discharge of the extinguisher. The 1986 test series included a third measurement location: the pilot's and copilot's belt level.

7.2 DISCHARGE TESTS FOR EMPTY AIRCRAFT, 1984 TESTS

Retrospective analysis of 1984 test data included two targets for Halon 1211 discharge: discharge under the instrument panel at the copilot's side and at the copilot's seat. Tests evaluated included three ventilation types: overhead vents open, all vents open, and all vents closed.

Agent discharge weights ranged from 2.55 lbs to 3.15 lbs. Plotted gas and arterial blood concentrations were based on a theoretical 2.5 lb Halon 1211 discharge weight.

Human Halon 1211 arterial blood concentration histories are predicted for the given sampling positions for each test using Halon 1301 kinetics.

7.2.1 Data Summary for Cessna 210C Tests: Empty Aircraft, 1984 Tests

Measured test data are summarized in table 12. The relevant test number, target, weight of the agent discharged, discharge time, ventilation conditions, maximum concentrations in the target area, and the maximum concentration at the pilot's nose height are given.

Ventilation was varied by adjusting the overhead ports and by opening the auxiliary vents. Three ventilation conditions were evaluated at 120 mph wind speed: Overhead vents open with $\tau = 1.16$ minutes, all vents open, and all vents closed. The two latter ventilation conditions do not have a known air change time. The all-vents-open test condition included two auxiliary vent doors, located on the lower fuselage behind the engine. This ventilating airflow is introduced through the cabin heat and defrost system.

Table 12. Data summary for Cessna 210C tests, empty aircraft from 1984 report

					Ventilation					
Fig. No.	Test No.	Target	Discharge Wt. (lbs)	Discharge Time (s)	Over-head Vents Open	All Vents Open	All Vents Closed	Air Change Time, τ (min.)	Max Conc. Target Area (%v/v)	Max Conc. Pilot's Nose (%v/v)
6	4	Under Instrument Panel: Copilot's Side	2.65		x			1.16	7.25	2.05
7	7		2.90	11.0		x			8.00	1.90
8	6		2.95	11.5			x		6.10	1.04
17	17	Copilot's Seat	3.05		x			1.16	6.85	2.20
19	20		2.55	11.0		x			7.25	2.10
20	19		3.15	14.9			x		8.30	1.60

conc. = concentration

7.2.2 Target: Under Instrument Panel—All Vents Open, Closed, Overhead Vents Open

The gas concentrations and the simulated arterial blood concentrations are shown for overhead vents open, all vents open, and all vents closed in figures 32–34, respectively.

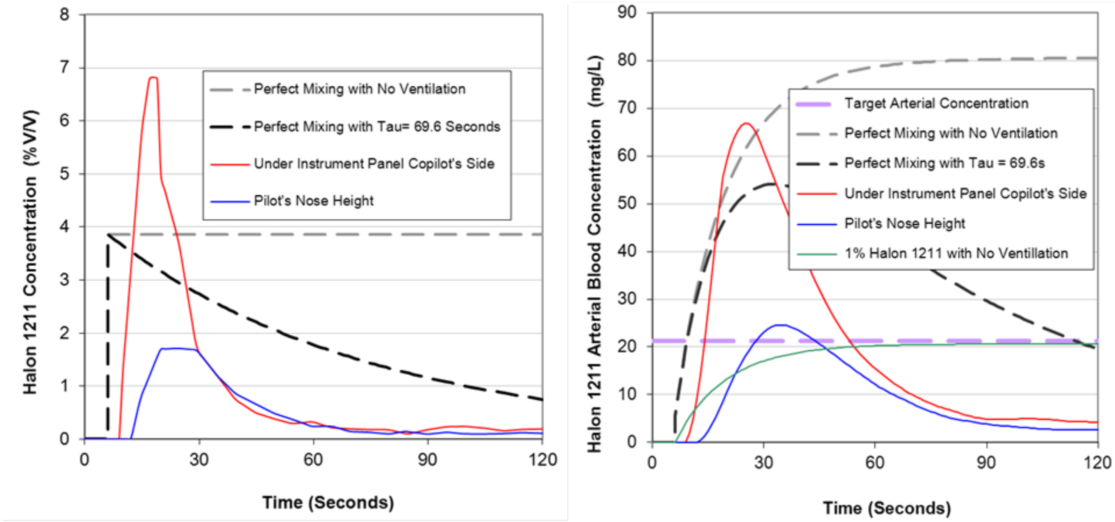


Figure 32. Halon 1211 discharged under instrument panel on copilot's side, overhead vents open, τ = 1.16 Minutes—target area and pilot's nose height (data from 1984 report, figure 6, test 4. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

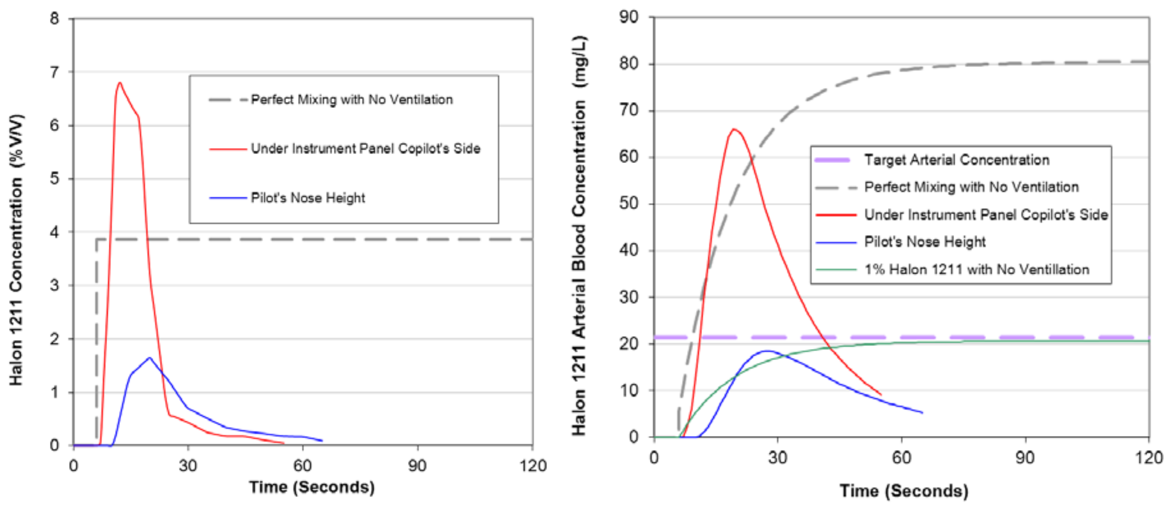


Figure 33. Halon 1211 discharged under instrument panel on copilot's side, all vents open—target area and pilot's nose height (data from 1984 report, figure 7, test 7. Perfect mixing ventilation arterial blood concentration curves not included because τ is unknown. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

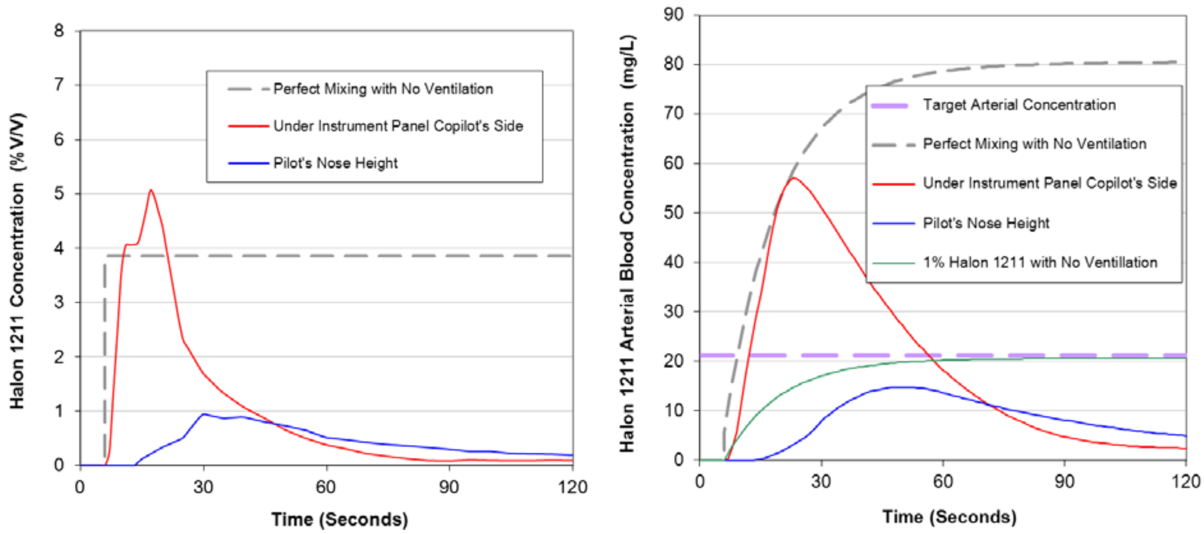


Figure 34. Halon 1211 discharged under instrument panel on copilot's side, all vents closed—target area and pilot's nose height (data from 1984 report, figure 8, test 6. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

Figure 32 shows that the nose-level peak arterial blood concentrations are less than half the predicted peak arterial blood concentrations for perfect mixing at $\tau = 69.6$ s. Nose-level arterial blood concentrations are close to the target arterial blood concentrations.

Lower peak arterial blood concentrations at the pilot's nose height are seen with all vents open by comparing figures 32 and 33. All vents open also results in quicker agent dissipation at both gas monitoring positions.

Comparing figure 34 with figures 32 and 33 shows that the pilot's peak arterial concentrations should be lowest with all vents closed.

7.2.3 Target: Copilot's Seat—All Vents Open, Closed, Overhead Vents Open

The gas concentrations and the simulated arterial blood concentrations for perfect mixing are shown for overhead vents open, all vents open, and all vents closed in figures 35–37, respectively. Figures 35–37 show that the simulated nose level Halon 1211 peak arterial blood concentrations are the lowest when all vents are closed.

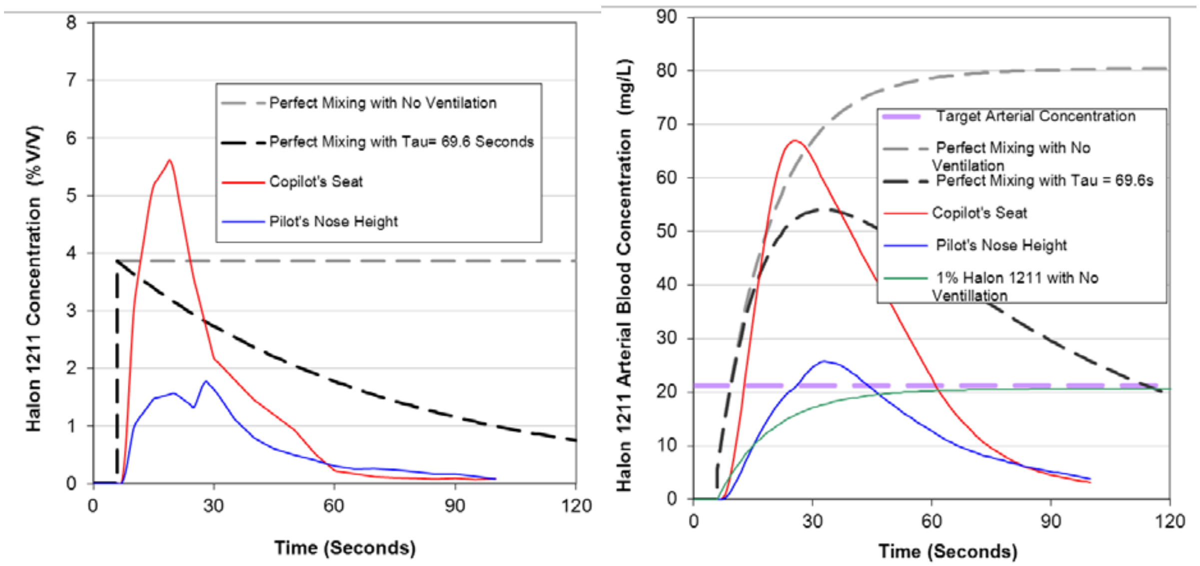


Figure 35. Halon 1211 Discharged on copilot's seat, overhead vents open—target area and pilot's nose height (data from 1984 report, figure 17, test 17. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

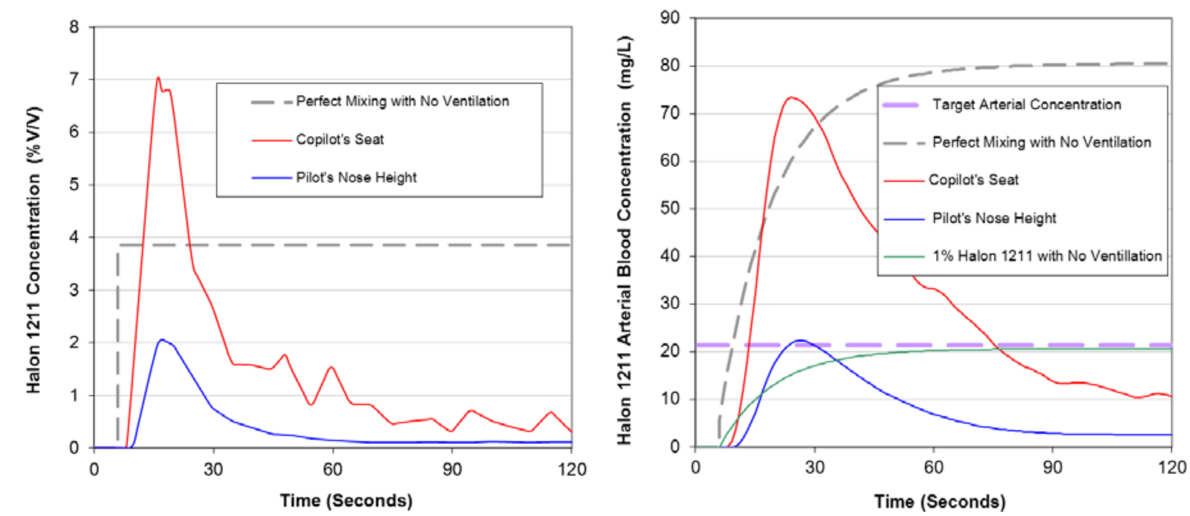


Figure 36. Halon 1211 Discharged on copilot's seat, all vents open—target area and pilot's nose height (data from 1984 report, figure 19, test 20. Perfect mixing ventilation arterial blood concentration curves not included because τ is unknown. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

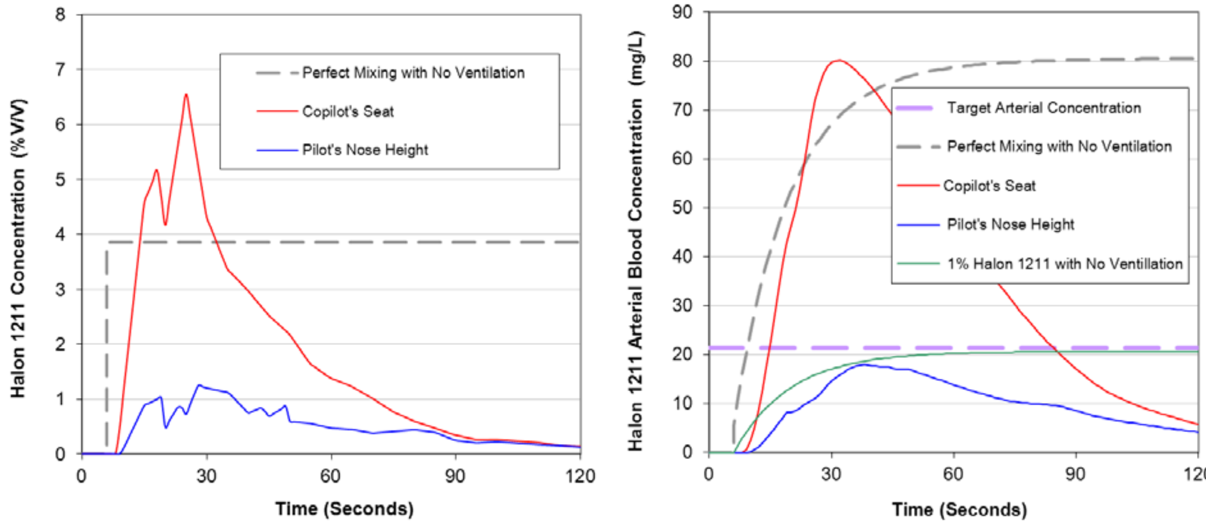


Figure 37. Halon 1211 Discharged on copilot's seat, all vents closed—target area and pilot's nose height (data from 1984 report, figure 20, test 19. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

7.2.4 Comparison of Ventilation Methods: Pilot's Nose Level

Figures 38 and 39 show the effect of ventilation on simulated arterial blood concentration histories at the pilot's nose height.

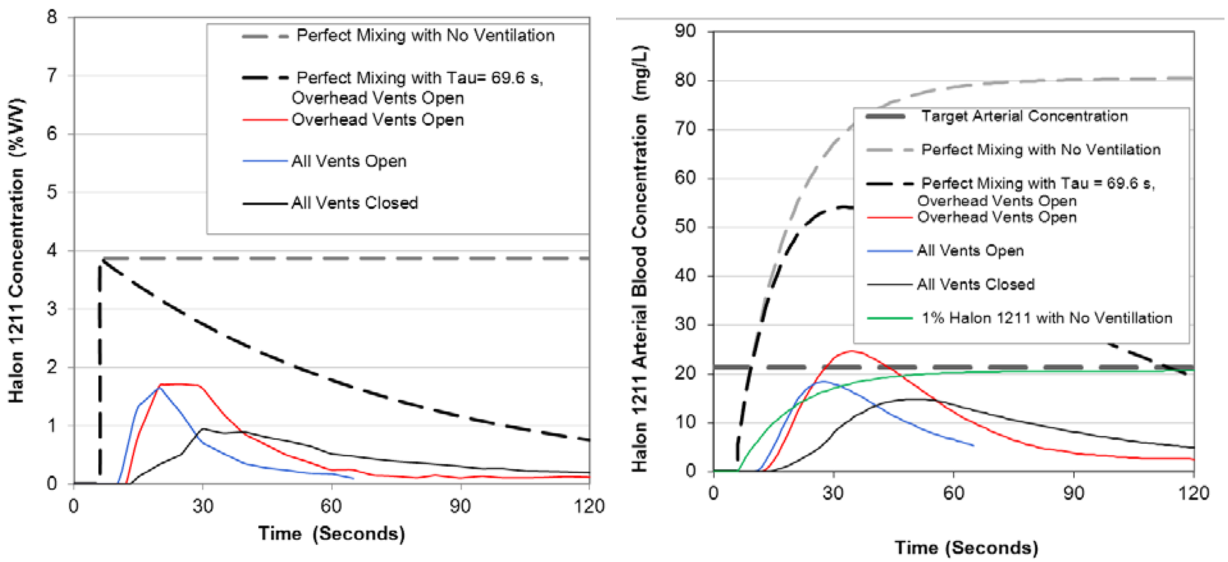


Figure 38. Comparison of Halon 1211 concentrations at pilot's nose height for three ventilation conditions—Halon 1211 discharged under the instrument panel, copilot's side (Data from 1984 report figure 6, test 4; figure 7, test 7; and figure 8, test 6. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

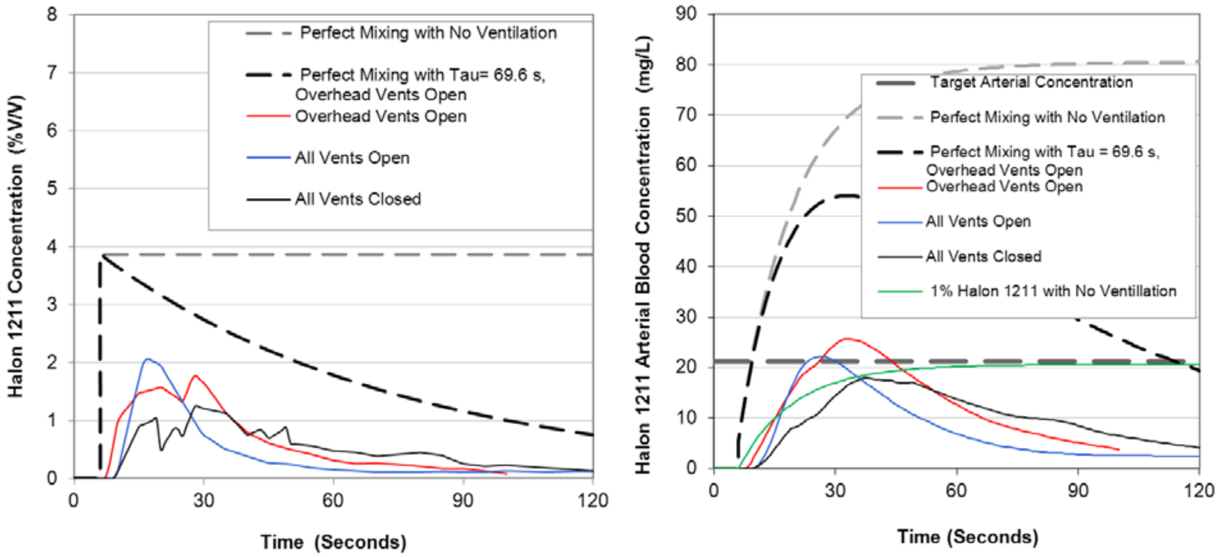


Figure 39. Comparison of Halon 1211 concentrations at pilot's nose height for three ventilation conditions—Halon 1211 discharged on copilot's seat (data from 1984 report, figure 17, test 17; figure 19, test 20; and figure 20, test 19. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

Figure 38 shows the concentration histories for discharge under the instrument panel on the copilot's side. All vents closed resulted in enhanced stratification and the lowest simulated peak arterial blood concentration. The seated pilot is safe for a 2.5 lb Halon 1211 discharge under the instrument panel on the copilot's side for all ventilation conditions.

The concentration histories for discharge onto the copilot's seat are shown in figure 37. All vents closed resulted in enhanced stratification and the lowest simulated peak arterial blood concentration. The seated pilot is safe for a 2.5 lb Halon 1211 discharge onto the copilot's seat for all ventilation conditions.

The predicted peak arterial blood concentrations at the pilot's nose level and the vicinity of the target are shown for discharge directed under the instrument panel in figure 40 and at the copilot's seat in figure 41.

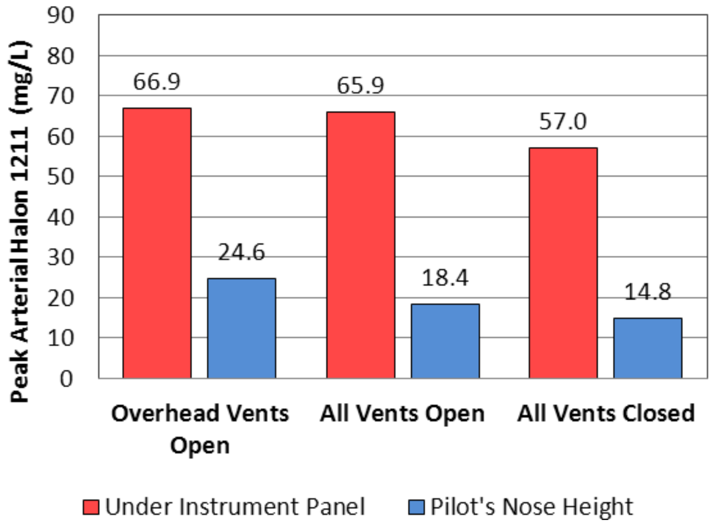


Figure 40. Simulated peak arterial blood concentrations for Halon 1211 directed under the instrument panel, copilot's side: comparison of ventilation methods (data from 1984 report, figures 6–8.)

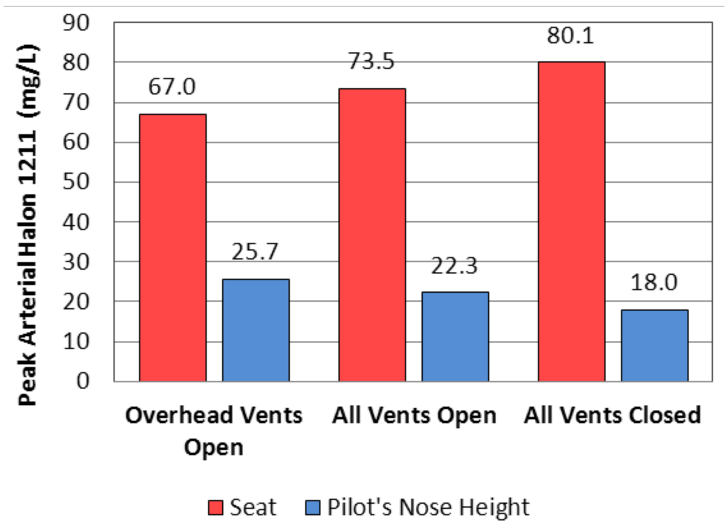


Figure 41. Simulated peak arterial blood concentrations for Halon 1211 directed at copilot's seat: comparison of ventilation methods (data from 1984 report, figures 17, 19, and 20.)

Figures 40 and 41 show that the lowest levels at the pilot's nose were seen with all vents closed. This is probably due to the minimized turbulence with this ventilation condition.

7.2.5 Determine MF_{SL}

The ratio of the perfect mixing simulated peak arterial blood concentration for a 2.5 lb Halon 1211 discharge to the peak experiment-based simulated peak arterial blood concentration is the MF_{SL}. Figure 42 shows multiplication factors indicating the increased safe charge weight due to stratification when overhead vents are open (τ = 1.16 minutes). Overhead vents open is the only ventilation condition for which MF_{SL} can be determined because air-change times were not known for the other ventilation conditions.

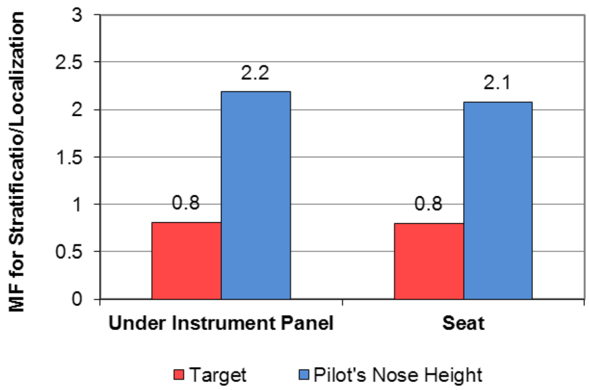


Figure 42. The MF_{SL} to be applied to perfect mixing concentration for empty Cessna 210C with overhead vents open with τ = 1.16 Minutes, windspeed 120 mph (gases measured in vicinity of the target and at the pilot's nose level)

7.3 DISCHARGE TESTS FOR LOADED AIRCRAFT: FOUR MANNEQUINS AND BAGGAGE, 1986 TEST

Four mannequins were used for the pilot and passengers, and baggage was placed in the baggage compartment.

Halon 1211 extinguishers of a nominal 2.5 lb capacity were discharged without fire. The extinguishers were remotely actuated. Retrospective analysis of 1986 test data included one target: under the instrument panel, copilot's side. Tests evaluated included two ventilation types: overhead vents open and all vents closed.

Agent discharge weights ranged from 2.3–2.5 lbs. Plotted gas and arterial blood concentrations were based on a theoretical 2.5 lb Halon 1211 discharge weight.

Human Halon 1211 arterial blood concentration histories are predicted for the given sampling positions for each test using Halon 1301 kinetics.

7.3.1 Data Summary for Cessna 210C Tests: With Four Mannequins and Baggage

Measured test data are summarized in table 13. The relevant figure number, test number, target, weight of the agent discharged, discharge time, ventilation conditions, maximum concentrations in the target area, maximum concentration at the pilot's belt level, and maximum concentration at the pilot's nose height are given.

Table 13. Data summary for Cessna 210C tests with passengers and baggage, from 1986 report

Fig. No.	Test No.	Target	Discharge Wt. (lbs)	Discharge Time (s)	Ventilation			Max Conc. Target Area (%v/v)	Max Conc. Pilot's Belt Level (%v/v)	Max Conc. Pilot's Nose (%v/v)
					Over-head Vents Open	All Vents Closed	Air Change Time, τ (min.)			
7	48	Under Instrument Panel: Copilot's Side	2.5	11	x		<< 1.16*	11+	8.9	4.4
8	47		2.3	—		x	<< 1.16*	11+	10.5	3.0

Two ventilation conditions were evaluated at 120 mph wind speed: Overhead vents open with ventilation of 122 cubic feet per minute, and all vents closed. The free space volume is lower than for the empty aircraft by the volume of the four seated mannequins and the volume of the luggage. Because the free space volume is unknown, the air change time cannot be determined. However, the air change time is quicker than for the empty aircraft.

7.3.2 Target: Under Instrument Panel, Copilot's Side, With Baggage and Mannequins

The gas and simulated arterial blood concentrations are shown for overhead vents open and all vents closed in figures 43 and 44, respectively. The predicted peak arterial blood concentrations at the pilot's nose level, pilot and copilot belt level, and the vicinity of the target are shown for discharge directed under the instrument panel.

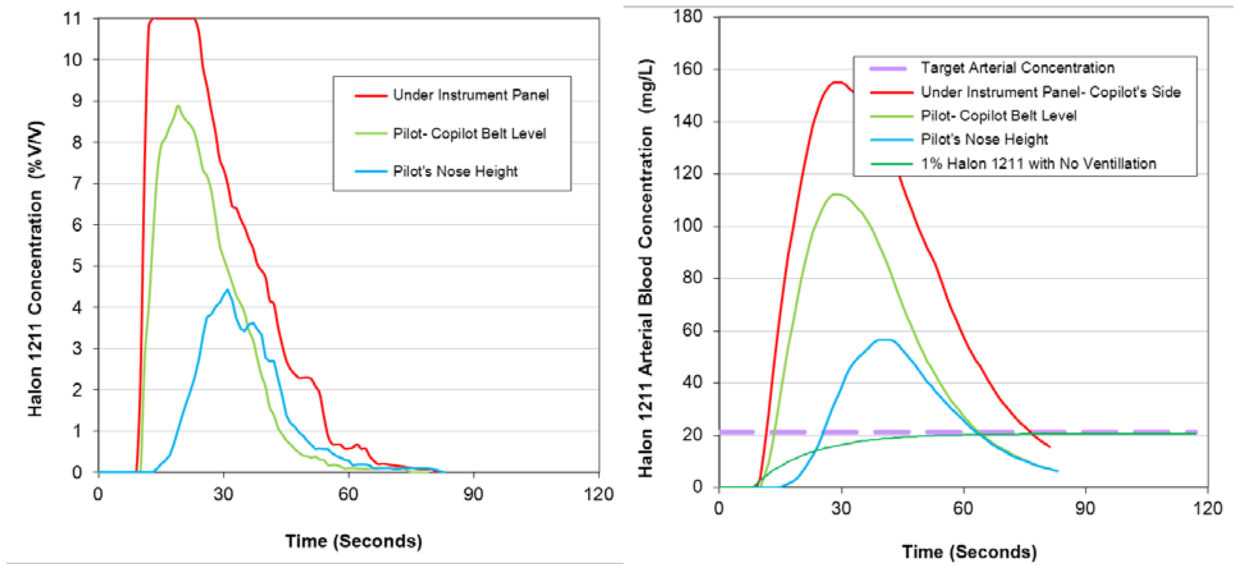


Figure 43. Halon 1211 discharged under instrument panel on copilot's side, overhead vents open (data from 1986 report, figure 7, test 48. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis. Halon 1211 arterial blood concentrations for under the instrument panel are underestimated because the gaseous concentrations were off-scale.)

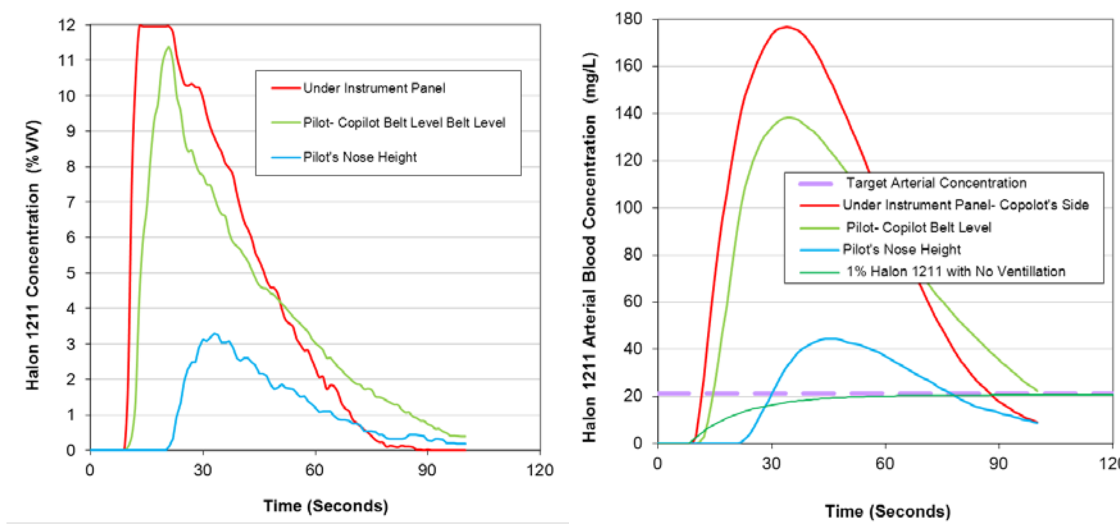


Figure 44. Halon 1211 discharged under instrument panel on copilot's side, all vents closed—target area and pilot's nose height (data from 1986 report, figure 8, test 47. predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis. Halon 1211 arterial blood concentrations for under the instrument panel are underestimated because the gaseous concentrations were offscale.)

Concentrations under the instrument panel exceeded 11% and were offscale in both tests. The arterial blood concentrations, based on offscale gas concentrations, are calculated based on an 11% maximum and are low estimates. Concentrations are far higher in the loaded aircraft than in the empty aircraft. The loaded aircraft has a lower free-space volume and has less stratification, perhaps because of increased turbulence.

7.3.3 Comparison of Ventilation Methods: With Baggage and Mannequins

Figure 45 shows the effect of ventilation on simulated arterial blood concentration histories at the pilot's nose height. As with the empty aircraft, all vents closed in the loaded aircraft resulted in enhanced stratification and the lowest simulated peak arterial blood concentration of both ventilation conditions.

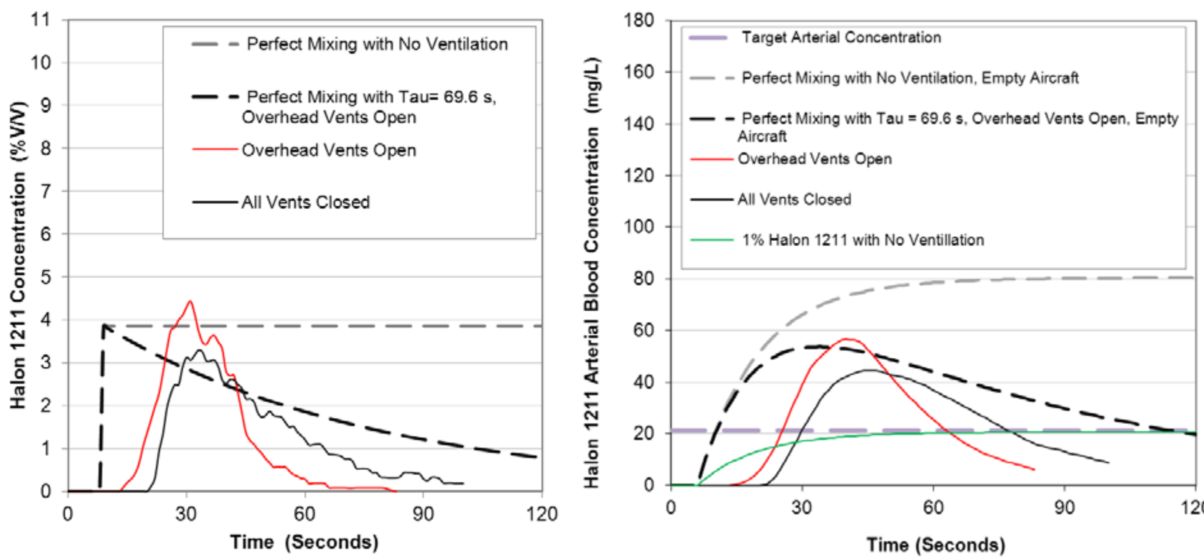


Figure 45. Halon 1211 discharged under the instrument panel, two ventilation conditions—pilot's nose height (data from 1986 report, figures 7 and 8. Predictions of Halon 1211 arterial blood concentrations are based on Halon 1301 kinetics, 2.5 lb discharge basis.)

The predicted peak arterial blood concentrations at the pilot's nose level, belt level, and the vicinity of the target are shown for discharge directed under the instrument panel in figure 46.

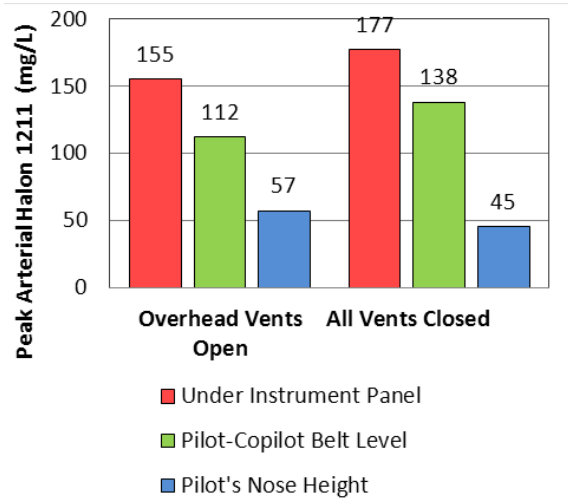


Figure 46. Simulated peak Halon 1211 peak arterial blood concentrations with target under the instrument panel, copilot's side: comparison of ventilation methods (data from 1986 report, figure 7, test 48 and figure 8, test 47. Halon 1211 arterial blood peak concentrations for under the instrument panel are underestimated because the gaseous concentrations were offscale.)

7.4 COMPARISON OF EMPTY AND LOADED CESSNA 210C WITH DISCHARGE UNDER THE INSTRUMENT PANEL, COPILOT'S SIDE

Figure 47 provides a simplified direct comparison of peak Halon 1211 arterial concentrations for the empty and loaded Cessna 210. It shows that loading the Cessna 210C with four mannequins and baggage results in higher peak Halon 1211 arterial concentrations at all measured positions.

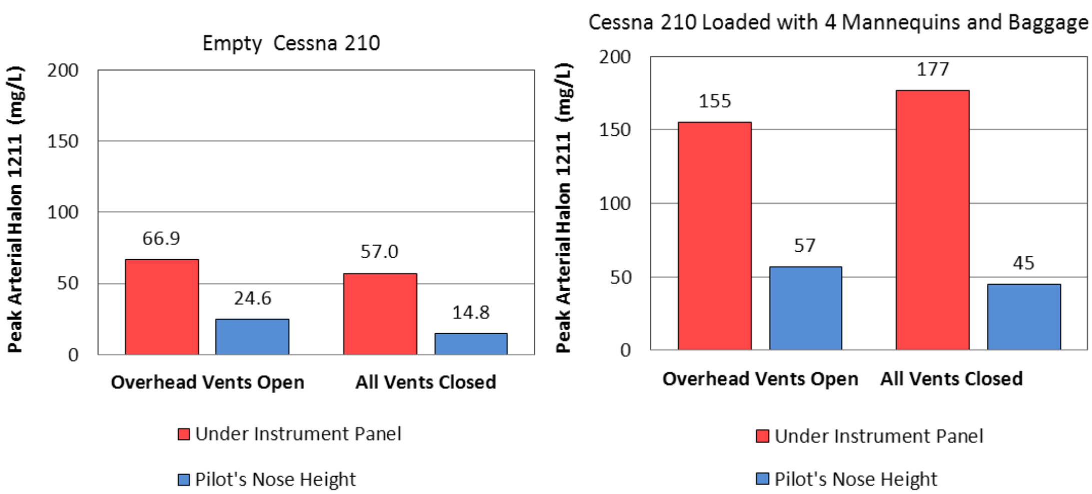


Figure 47. Simulated peak arterial blood concentrations for Halon 1211 directed under the instrument panel, copilot's side: comparison of loading (data from 1984 report, figure 6, test 4; figure 8, test 6; and 1986 report, figure 7, test 48 and figure 8, test 47. Halon 1211 arterial blood concentrations for under the instrument panel are underestimated for the loaded aircraft, as the gaseous concentrations were offscale.)

Figure 48 shows a comparison of Halon 1211 gas and arterial blood concentration histories at the pilot's nose level for the empty and loaded Cessna 210C with overhead vents open.

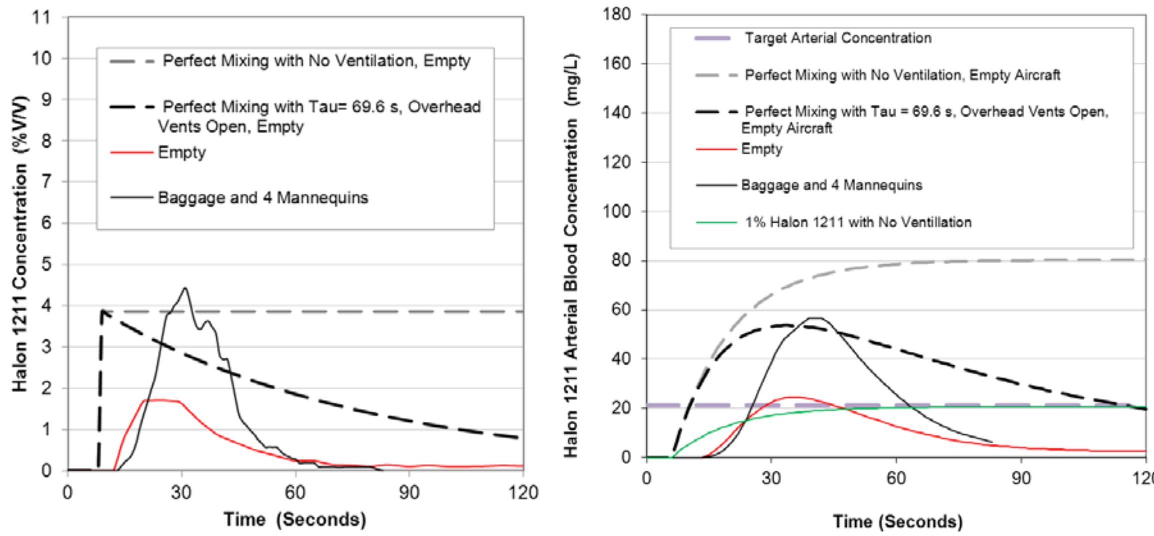


Figure 48. Halon 1211 gas and arterial blood concentration histories at the pilot's nose height for the empty and loaded Cessna 210C with overhead vents open (data from 1984 report, figure 6, test 4 and 1986 report, figure 7, test 48, 2.5 lb discharge basis.)

Figure 49 shows a comparison of Halon 1211 gas and arterial blood concentration histories at the pilot's nose level for the empty and loaded Cessna 210C with overhead vents closed.

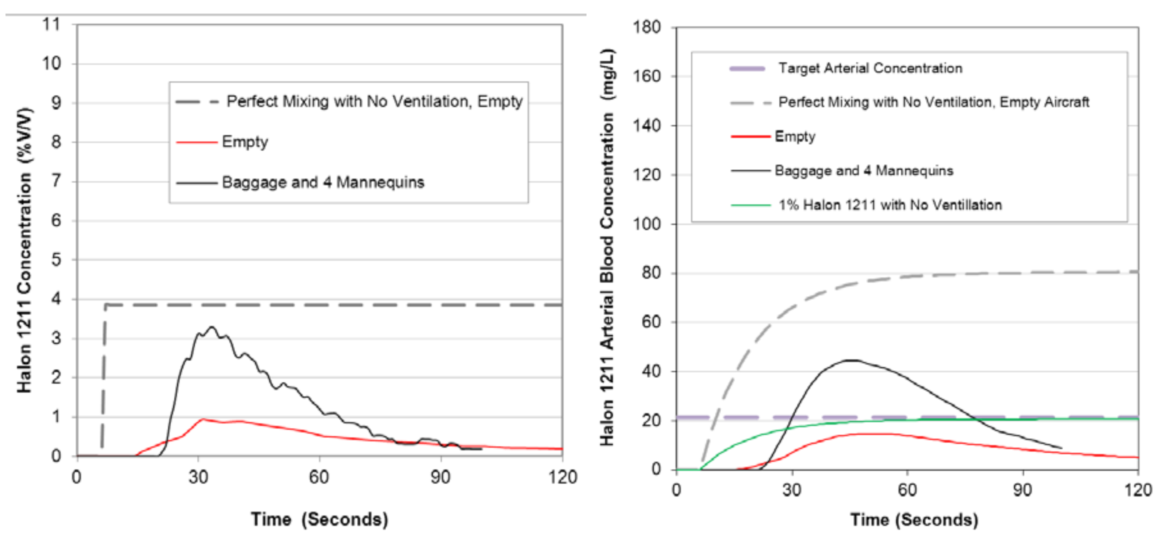


Figure 49. Halon 1211 gas and arterial blood concentration histories at the pilot's nose height for the empty and loaded Cessna 210C with all vents closed (data from 1984 report, figure 8, test 6 and 1986 report, figure 8, test 47, 2.5 lb discharge basis.)

8. APPLICATION

Stratification and localization factors can be safely applied if it is assumed that recirculation systems would be turned off prior to discharge and all passengers would move a safe distance from the location of discharge.

8.1 PRESSURIZED AIRCRAFT

Applying the MF_{SL} will enable the safe use of higher agent charge weights than allowed if perfect mixing is assumed for a ventilated space.

8.1.1 Cabin

8.1.1.1 Calculation of Effective Safe-Use W/V Agent

Because the agent is localized to the area of discharge and the passengers are cleared from the area of discharge, the MF_{SL} may be larger than if perfect mixing is assumed. Figure 50 shows the extrapolated $MF_{SL\text{-}B\text{-}737}$ for the B-737 cabin tests. The $MF_{SL\text{-}B\text{-}737}$ is dependent on the distance from the target; the firefighter is 6′ from the target, as shown in figure 50.

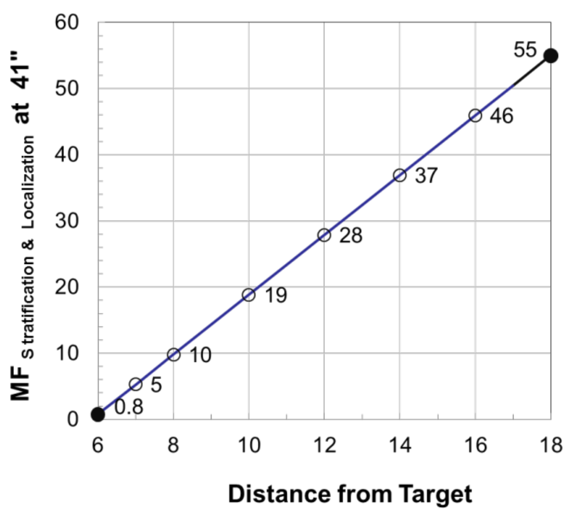


Figure 50. The B-737 cabin $MF_{SL\text{-}B\text{-}737}$ for Halon 1211 at 41″ height, 6 feet from the target (this curve is based on Halon 1301 kinetics, linear extrapolation of two data points)

The shape of the extrapolated curve is unknown. Concentrations are expected to decrease exponentially with distance from the firefighter, so the linear extrapolation of MF_{SL} in figure 50 is conservative. This was confirmed by reviewing preliminary B737 test results with sampling probes at 6, 12, and 18 feet from the target at a 41-inch height using a Statham derivative analyzer.

The MF_{SL} is applied to the perfect mixing ventilated concentration in AC 20-42D to determine the effective safe use w/v of agent. Safety increases markedly with distance from the target and firefighter, as shown in figure 50.

8.1.2 B-737 Flight Deck

Find: Halon 1211 safe use W/V and minimum safe volumes in the test B-737 flight deck for a 2.5 lb discharge.

Given:

1. Air change time, τ = 65 s (1.08 min).

2. Free space volume of the empty flight deck = 129 ft^3.

3. The $MF_{SL\text{-}B\text{-}737}$ obtained from the worst case test data (discharge at the window heater, with the least stratification figure 30 test data, average of 2 tests for the seated pilot at 41″ nose level) is 1.6.

4. The flight deck is normally free of other materials that can decrease the free space volume.

Assume

1. A 95th percentile male of 225 pounds, neutrally buoyant, with a net volume of 102 liters or 3.60 ft^3

2. The total body volumes of maximum possible number of seated flight deck occupants = 3 seats X 3.6 ft^3/seated person= 11 ft^3

3. $P_{\textit{Flight Deck Pressure Altitude}}$ = 8,000 ft

The free space volume of test aircraft with maximum loading = 129 ft^3 - 11 ft^3 = 118ft^3.

Use the Halon 1211 safe-use perfect mixing W/V of 0.00334 lbs/ft^{-3} and MF_V of 1.55 from the tables in AC 20-42D [1, 3].

Safe Use Halon 1211 $W/V_{\textit{Stratification \& Localization}}$ (lbs/ft^3)

= safe use (perfect mixing, unventilated) W/V from AC20-42D tables $\times$ MF_V from AC 20-42 tables $\times$ MF_{SL}

$$= 0.00334 \text{ lbs ft}^{-3} \times 1.55 \times 1.6 = 0.00828 \text{ lbs ft}^{-3}$$

Therefore :

1. The Minimum Safe Volume $_{Stratification\ \&\ Localization}$ or 2.5 lb discharge
= 2.5 lbs Halon 1211/0.00828 lbs ft^{-3} = 302 ft^3

2. Maximum Safe Weight = 0.00828 lbs ft^{-3} $\times$ 118 ft^3 = 0.98 lbs

Alternately, The Minimum Safe Volume $_{Stratification\ \&\ Localization}$ of Halon 1211 (ft^3) can be calculated from the Minimum Safe Volume table in AC 20-42D, in which the minimum safe volume for Halon 1211 at 8,000 ft CPA is 751 ft^3.

Min Safe Volume$_{Stratification\ \&\ Localization}$ of Halon 1211 (ft^3)

$$= \frac{\text{Minimum Safe Volume from AC 20} - \text{42D Tables for Perfect Mixing}}{MF_V \quad \times MF_{SL}}$$

$$= \frac{751\ \text{ft}^3}{1.55 \times 1.6} = 302\ \text{ft}^3 > 118\ \text{ft}^3 \text{ (Free Space Volume of B-737 flight deck with 3 occupants)}$$

The above calculation shows that the Halon 1211 minimum safe volume safety criterion are not met for this B-737 flight deck, even after applying MF_{SL}. Nonetheless, 5:BC protection is recommended, because fire-fighting capability and the importance of extinguishing the fire is paramount. Safe use is assured if PBE or oxygen masks are worn.

8.2 UNPRESSURIZED SMALL AIRCRAFT

Find: Halon 1211 safe use W/V and minimum safe volumes in the test Cessna 210C aircraft for a 2.5 lb discharge.

Given:

1. Air change time, τ = 69.6 s (1.16 min).

2. Free space volume of the empty cabin = 139.9 ft^3.

3. The $MF_{SL\text{-Cessna 210C}}$ obtained from the worst case test data (discharge at the seat, with the least stratification figure 42, for the seated pilot at nose level is 2.1.

4. The cabin is normally free of other materials that can decrease the free space volume.

Assume:

1. The total body volume of maximum possible number of seated flight deck occupants = 4 seats $\times$ 3.6 ft^3/seated person= 14 ft^3.

2. $P_{Flight\ Deck\ Pressure\ Altitude}$ = 12,500 ft, the maximum flying altitude.

Calculate the free space volume of the Cessna 210C aircraft with maximum loading = $140ft^3 - 14ft^3 = 126ft^3$.

Use the Halon 1211 safe-use perfect mixing W/V of 0.00281 lbs/ft^{-3} and MF_V of 1.52 from the tables in AC 20-42D [1 and 3].

Safe Use Halon 1211 $W/V_{\ Stratification\ \&\ Localization}$ (lbs/ft^3)

= safe use (perfect mixing, unventilated) W/V from AC20-42D tables $\times$ MF_V from AC 20-42 tables $\times$ MF_{SL}

$=0.00281 \text{ lbs ft}^{-3} \times 1.52 \times 2.1 = 0.00897 \text{ lbs ft}^{-3}$

Therefore :

1. The Minimum Safe Volume $_{Stratification\ \&\ Localization}$ for 2.5 lb discharge = 2.5 lbs/0.00897 lbs ft^{-3}= 279 ft^3

2. Maximum Safe Weight = 0.00897 lbs ft^{-3} $\times$ 126ft^3 = 1.16 lbs

Alternately, The Minimum Safe Volume $_{Stratification\ \&\ Localization}$ of Halon 1211 (ft^3) can be calculated from the Minimum Safe Volume with perfect mixing, unventilated table in AC 20-42D, where the minimum safe volume for Halon 1211 at 12,500 ft CPA is 895 ft^3.

Min Safe $Volume_{Stratification\ \&\ Localization}$ of Halon 1211 (ft^3)

$$= \frac{895 \text{ ft}^3}{1.52 \times 2.1} = 280 \text{ ft}^3 > 126 \text{ ft}^3 \text{ (Free Space Volume of the Cessna 210C with 4 occupants)}$$

The above calculation shows that the Halon 1211 minimum safe volume safety criterion are not met for this Cessna 210C unpressurized aircraft, even after applying MF_{SL}. Therefore, the occupants should don PBE and the aircraft should be vented immediately after the fire is extinguished.

8.3 SETTING MF_{SL} FOR NON-TEST AIRCRAFT

As a first approximation, the test-based Halon 1211 MF_{SL} can be used for other sized aircraft.

8.4 SETTING MF_{SL} FOR OTHER AGENTS

Physical properties of an agent such as its boiling point and vapor pressure affect stratification and localization.

As a first approximation, the test-based Halon 1211 MF_{SL} can be used for agents other than Halon 1211, if that agent's boiling point is greater than or equal to that of Halon 1211 and that agent's vapor pressure at 25°C is less than or equal to that of Halon 1211. For blends, use the vapor pressure of the predominant and most toxic component. See table 4 for a list of agents and their physical properties.

9. SUMMARY

Significant agent stratification and localization was seen for cabin discharges in the B-737 at the firefighter's position 6 feet from the overhead light (target). The agent dissipated much faster than predicted assuming perfect mixing with cabin ventilation. The effect of stratification and localization was quantified for the B-737 using peak simulated arterial blood concentration as the basis for comparison. Actual Halon 1211 concentrations and simulated perfect mixing concentrations for a ventilated compartment were compared for various sampling positions as were the corresponding simulated arterial blood concentrations.

The resultant MF_{SL} can be applied to the safe use concentrations in references 1 and 3.

At the firefighter's position, a stratification and localization benefit (MF_{SL}=13.7) is seen only at the 60″ probe. The MF_{SL} were 0.8 at the 41″ height and 0.4 at the 22″ height.

A significant MF_{SL} was seen 12 feet behind the firefighter at seated (54.8″) and standing (80.3″) heights. The MF_{SL} was 1.0 at 22″ off the floor.

A significant MF_{SL} was seen for the B-737 flight deck discharge tests at all heights. The MF_{SL} for the window heater discharge tests were 1.4 at 22″, 1.6 at 41″, and 7.2 at 57″ off the floor. The MF_{SL} for the instrument panel discharge tests were 1.5 at 22″, 2.4 at 41″, and 20.5 at 57″ off the floor.

A retrospective analysis of Halon 1211 discharges from a ventilated, nonpressurized, small GA airplane with overhead vents open, likewise, showed a significant MF_{SL} at the pilot's nose level for discharges under the copilot's instrument panel and seat. Comparisons of simulated peak arterial blood concentrations showed that stratification and localization of discharges at two targets resulted in safer-than-predicted arterial blood concentrations at the pilot's nose level. The MF_{SL} for the window heater discharge tests were 1.4 at 22″, 1.6 at 41″, and 7.2 at 57″ off the floor. The MF_{SL} for the instrument panel discharge tests were 1.5 at 22″, 2.4 at 41″, and 20.5 at 57″ off the floor.

A retrospective analysis of subsequent Halon 1211 discharges from that same ventilated, nonpressurized, small GA airplane loaded with luggage and mannequins showed significantly higher Halon 1211 gas concentrations and Halon 1211 arterial blood concentrations than for the empty Cessna under the instrument panel and at the pilot's nose height.

10. CONCLUSION

Halon 1211 gas concentration histories deviate from the predicted gas concentration histories due to the stratification and localization of Halon 1211.

In the B-737 cabin, Halon 1211 concentration decreases as horizontal distance from the target increases. In the cabin and flight deck, Halon 1211 concentration decreases (stratification benefit increases) with height above the floor.

In the small, unpressurized Cessna B-210 airplane, the stratification and localization benefit is significant at the pilot's nose level.

The MF_{SL} can be applied to the perfect mixing safe-use concentration for a particular ventilation condition and particular loading conditions, to allow safe use of higher agent charge weights than would be considered safe for instantaneous perfect mixing of the extinguisher contents.

11. RECOMMENDATIONS

1. Apply Halon 1211 MF_{SL} and the MF_V to the safe-use agent weight, based on a seated-person's nose level exposure.

2. As a first approximation, the test-based MF_{SL} and the MF_V can be applied to the safe-use Halon 1211 concentration in AC 20-42D for other sized aircraft.

3. As a first approximation, the test-based Halon MF_{SL} can be applied to other agents, if the boiling point of the agent is greater than the boiling point of Halon 1211 and if the vapor pressure of the agent at 25°C is less than the vapor pressure of Halon 1211 (see Table 4). For blended agents, the properties of the predominant and most toxic components should be the basis for the agent's MF_{SL}.

4. In compartments where extinguishing agents do not meet the safe-use guidance contained herein, follow the guidelines for the safe use of halocarbon extinguishers contained in AC 20-42D, Chapter 4, Section 2. The critical importance of rapid fire extinguishment is emphasized: "Although exposure to halocarbon agents and their decomposition products are a concern, it is far less of a concern than the consequences of an unextinguished in-flight fire."

12. REFERENCES

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