Halon 1211
Stratification/
Localization in Aircraft

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Background

Per AC20-42D - Halon 1211, Halotron 1, and BTP are unsafe for use in Boeing airplane flight decks and other small volumes.

AC 20-42D, Chapter 4.4b(3), (4) states that concentrations may be adjusted to account for agent localization/ stratification…a report will be published at the FAA Technical Center with method to adjust safe-use concentrations.
Comparison of Minimum Safe Volumes for 2.5 lb Halon 1211

Minimum Safe Volume per AC20-42C (Ft³)

Minimum Safe Volume per AC20-42D (Ft³)

Air Change Time (Minutes)

Halon 1211 Stratification in Aircraft
**Minimum Safe Compartment Volume for One Extinguisher in Unventilated Compartments (from AC 20-42D)**

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

<sup>a</sup> 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.

<sup>b</sup> Values based on the safe human concentration. See reference report appendix 3, paragraph 7.m.of this AC.

<sup>c</sup> Values are based on the Halon 1211 NOAEL concentration of 0.5% (v/v).

<sup>d</sup> Values are based on the Halon 1211 LOAEL concentration of 1.0% (v/v).

<sup>e</sup> 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 report mentioned in note b above. Also, the safety factor is smaller than that set for other agents.
### Multiplication Factors \((MF_{\text{Ventilated}})\) for Ventilated Compartments \((\text{from AC 20-42D})\)

<table>
<thead>
<tr>
<th>Agent</th>
<th>Air Change Time, (\tau) (minutes)</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>6.0</th>
<th>&gt;6&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCFC Blend B</td>
<td></td>
<td>2.80</td>
<td>2.33</td>
<td>2.14</td>
<td>2.02</td>
<td>1.89</td>
<td>1.79</td>
<td>1.70</td>
<td>1.62</td>
<td>1</td>
</tr>
<tr>
<td>HFC-227ea</td>
<td></td>
<td>1.90</td>
<td>1.53</td>
<td>1.39</td>
<td>1.32</td>
<td>1.24</td>
<td>1.19</td>
<td>1.16</td>
<td>1.14</td>
<td>1</td>
</tr>
<tr>
<td>HFC-236fa</td>
<td></td>
<td>1.98</td>
<td>1.58</td>
<td>1.42</td>
<td>1.34</td>
<td>1.25</td>
<td>1.20</td>
<td>1.17</td>
<td>1.15</td>
<td>1</td>
</tr>
<tr>
<td>Halon 1211&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
<td>1.96</td>
<td>1.57</td>
<td>1.42</td>
<td>1.34</td>
<td>1.25</td>
<td>1.21</td>
<td>1.17</td>
<td>1.15</td>
<td>1</td>
</tr>
<tr>
<td>Halon 1301</td>
<td></td>
<td>1.96</td>
<td>1.57</td>
<td>1.42</td>
<td>1.34</td>
<td>1.25</td>
<td>1.21</td>
<td>1.17</td>
<td>1.15</td>
<td>1</td>
</tr>
</tbody>
</table>

<sup>a</sup> No \(MF_{\text{Ventilated}}\) is applied if air change time is greater than 6 minutes.

<sup>b</sup> More conservative \(MF_{\text{Ventilated}}\) than actual. Based on Halon 1301.
Goal

• Develop test-based multiplication factors to allow higher concentrations than AC 20-42D guidance provides:
  
  ➢ Small aircraft
  ➢ Flight decks
  ➢ Large cabins

• Tests evaluate stratification/localization of Halon 1211 discharged from one extinguisher.
• Determine multiplication factors based on equivalent safety for that test ventilation rate.
Method

• Small aircraft: Use concentration histories from existing reports.

• Flight decks: B 737 Tests

• Large cabins: B 737 Tests

• Multiplication factors (MF) will be based on maximum computed human arterial blood concentrations, B: Compare maximum B for perfect mixing (ventilated) to test (ventilated) maximum B.

• This MF will be a multiplier for the maximum agent W/V in AC 20-42D.

\[ MF(\text{Stratification & Localization}) = \frac{B_{\text{Max}} (\text{Ventilated} - \text{Perfect Mixing})}{B_{\text{Max}} (\text{Ventilated} - \text{Stratification} - \text{Localization})} \]
B-737 Test Article
B 737 Test Article
B 737 Test Article

• The passenger cabin is 630” long x 137” wide (52.5 ft x 11.4ft)

• Total Cabin Volume = Front Galley + Passenger Seating Area + Rear Galley
  = 315 ft³ + 3489 ft³ + 323 ft³
  = 4127 ft³

• The cabin volume includes the front and rear galleys and the passenger seating area.

• The seats, overhead storage and other enclosed areas were subtracted out.

• The flight deck volume is 129 ft³

• The firefighter volume is 5.7 ft³
Cabin Test Plan:

• Discharge one 5 B:C Halon 1211 extinguisher in rear of passenger compartment. Aim at exit light leading to rear galley.

• Sampling stations: 1 Sampling station per discharge test.
  - 6’ horizontally from the target (at firefighter’s position)
  - 18’ Horizontally from the target
  - 3 Heights: 60”, 41” and 22’ (Standing, seated and resting nose height). Extinguisher nozzle is held 6” forward of the sample tree

• Predict maximum arterial concentrations ($B_{\text{Max}}$) for each Halon 1211 discharge test.

• Compare to the maximum arterial concentration that would be obtained if perfect mixing (same compartment, same ventilation).

• Determine multiplication factors for each position
Cabin Test using Luft NDIR Gas Analyzers

Top View

Ceiling Exit Light

Sampling Stations

Firefighter

Front View

Sampling Stations

Floor Level

Halon 1211 Stratification in Aircraft
Cabin Test: Target

Halon 1211 Stratification in Aircraft
Cabin Test

Halon 1211 Stratification in Aircraft
Cabin Test
Cabin Test

Cabin Test 2: Probes 6' from Exit Light

Cabin Test 4: Probes 18' from Exit Light

Halon 1211 Stratification in Aircraft
Cabin Test

Cabin Test 1: Probes 6' from Exit Light

Halon 1211 (Percent)

Time (Seconds)

6' at 60"
6' at 41"
6' at 22"
Perfect Mixing
Tau = 0.5
Tau = 1
Tau = 5

Cabin Test 3: Probes 18' from Exit Light

Halon 1211 (Percent)

Time (Seconds)

18' at 60"
18' at 41"
18' at 22"
Perfect Mixing
Tau = 0.5
B 737 Flight Deck
Flight Deck: Plan:

- Discharge one 5 B:C Halon 1211 extinguisher with side to side sweeping motion.

- Firefighter seated in aft port seat behind pilot. Nozzle height= 36”,
  - Scenerio 1: Target: copilot’s window heater.
    Target: 33” to 36” height, width of target=17”. Target is 38” from nozzle.
  - Scenerio 2: Target: copilot’s instrument panel. 17” to 25” off floor, 10” width, Target distance from centerline: 9” to 19”. Target is 42” from nozzle.

- Sample position: Pilots nose position
  - 3 Heights:
    - 57” Standing
    - 41” Seated
    - 22’ Resting nose height

- Predict maximum arterial concentrations ($B_{Max}$) for each Halon 1211 discharge test.

$$MF(\text{Stratification}&\text{Localization}) = \frac{B_{Max}(\text{Ventilated Perfect Mixing})}{B_{Max}(\text{Ventilated Stratification} - \text{Localization})}$$
Flight Deck Tests using NDIR Gas Analyzers

Top View

Target 1: Window Heater (33” – 36””” height)

Target 2: Lower Panel

Instrument Panel

Sampling Station

Door

Extinguisher Nozzle

Side View

Target 1: 33-36” height

Target 2: 17-25” height

Sampling Probes

Floor Level

36” height

Extinguisher Nozzle
Flight Deck Targets

Halon 1211 Stratification in Aircraft
Flight Deck Sampling Position: Above Pilot’s Seat

Halon 1211 Stratification in Aircraft
Flight Deck Tests: Target: Copilot’s Window Heater
Flight Deck Tests: Target: Copilot’s Window Heater

Flight Deck Test 1: Probes at Pilot’s Position: Discharge at Copilots Window Heater

Flight Deck Test 5: Probes at Pilot’s Position: Discharge at Copilots Window Heater
Flight Deck Tests: Target: Copilot’s Instrument Panel
Flight Deck Tests: Instrument Panel: Copilot’s Side

Flight Deck Test 3: Discharge at Lower Instrument Panel: Copilot’s Side

Flight Deck Test 4: Discharge at Lower Instrument Panel: Copilot’s Side

Halon 1211 Stratification in Aircraft
Flight Deck: Ventilation Rate Measurement

60” Probe
Fan
32” Probe
3” Probe
Flight Deck: Ventilation Rate Measurement

% CO2 from O2 depletion 60"
% CO2 from O2 Depletion 3"
Concentration at 1 air change = 3.7%

Time for one air change = 63 seconds

0.37% CO2
Flight Deck: Ventilation Rate Measurement

Time for 1st air change = 63 s
Time for 2nd air change = 88 s

3.68% CO₂
1.35% CO₂
Flight Deck: Ventilation Rate Measurement

CO₂ Dissipation in Flight Deck: Test 2

- Sta 1 at 60" CO₂ (%)
- Sta 2 at 31.5" CO₂ (%)
- Sta 3 at 3" CO₂ (%)
- Average CO₂ (%) : Test 2

Halon 1211 Stratification in Aircraft
Flight Deck: Ventilation Rate Measurement

CO₂ Dissipation in Flight Deck: Test 2

- Sta 1 at 60" CO₂ (%)
- Sta 2 at 31.5" CO₂ (%)
- Sta 3 at 3" CO₂ (%)
- Average CO₂ (%) : Test 2

Time for 1st Air Change = 65 s
- 7.90% at 138 s
- 63.2% decrease

Time for 2nd Air Change = 90 s
- 2.90% at 203 s
- 1.07% at 293 s

Halon 1211 Stratification in Aircraft
**Flight Deck: Ventilation Rate Measurement**

**CO₂ Dissipation in Flight Deck: Test 2**

- Sta 1 at 60" CO₂ (%): 7.90% at 138 s
- Sta 2 at 31.5" CO₂ (%): 63.2% decrease
- Sta 3 at 3" CO₂ (%): 2.90% at 203 s
- Average CO₂ (%): Test 2
  - Time for 1st Air Change = 65 s
  - Time for 2nd Air Change = 90 s
  - Predicted, perfect mixing, Tau = 65 s

**Halon 1211 Stratification in Aircraft**

Federal Aviation Administration
Summary

- Standing height: MF (Ventilation/Localization) will be very large
  - Flight Deck, 57”: Maximum Halon 1211 Concentrations are 7 to 15 fold lower than initial perfect mixing concentrations
  - Cabin, 60”: Maximum Halon 1211 concentrations are 10 to 20 fold lower than initial perfect mixing concentrations 6” from target. Agent barely detectable at 18’ from target

- Seated Height, 41”
  - Flight Deck: Maximum Halon 1211 Concentrations are 1.6 to 2.4 fold lower than initial perfect mixing concentrations
  - Cabin: Maximum Halon 1211 concentrations are 1.9 to 2.1 fold higher than initial perfect mixing concentrations 6’ from the target. At 18’, the agent is barely detectable.

- Resting Height, 22”
  - Flight Deck: Maximum Halon 1211 Concentrations are 1.5 to 1.7 fold lower than initial perfect mixing concentrations.
  - Cabin: Maximum Halon 1211 concentrations are 2.6 to 2.9 fold higher than initial perfect mixing concentrations 6’ from the target. At 18’ concentrations are 2.0 to 2.4 higher than initial perfect mixing concentrations.
Additional Work

• Run CO2 discharge test for cabin to obtain cabin air change time.

• Calculate the maximum arterial concentrations for test and perfect mixing conditions with ventilation

• Calculate safety factors for each position in each test.
Considerations for Guidance Material

• Corrections need to be made for the maximum anticipated volume of the passengers and crew.

• Note: Test data is based on an non-inhabited cabin and flight deck (firefighter volume is subtracted out).
Conclusions

- Localization is significant in the aft of the cabin for the cabin tests.
- Stratification is significant for both the flight deck and cabin tests.
Simplified Kinetic Model

Simulates human arterial blood concentration histories from inhaled constant or dissipating halocarbon concentrations
Comparison of Kinetic Models for Halon 1301:
Unventilated Compartment ($\tau = \infty$)

![Graph showing the comparison of kinetic models for Halon 1301 in an unventilated compartment. The graph plots $B(t)/B_{max}$ against time in minutes. The data points are shown as black circles, and the kinetic model is represented by a solid line.]

Halon 1301

- PBPK Data
- Kinetic Model

Time, minutes
Arterial Blood Concentration, $B(t)$

General equation for changing Halocarbon Concentrations:

$$B(t) = k_1 \int_{0}^{t} A(x)e^{-k_{23}(t-x)} \, dx +$$

$$k_3 k_4 P_{BA} \int_{0}^{t} \left( \int_{0}^{t} A(x)e^{-k_4(t-x)} \, dx \right) e^{-k_{23}(t-y)} \, dy$$

Method

- Calculate $B(t)$ for each sampling probe

- Multiplication factors (MF) will be based on maximum computed human arterial blood concentrations, $B$

- Compare perfect mixing maximum $B$ (ventilated) to test (ventilated) maximum $B$.

- This MF may be a multiplier for the maximum agent $W/V$ in AC 20-42D.

$$MF(\text{Stratification \& Localization}) = \frac{B_{\text{Max}}(\text{Ventilated} - \text{Perfect Mixing})}{B_{\text{Max}}(\text{Ventilated} - \text{Stratification} - \text{Localization})}$$
Kinetic Model

HALON 1211 Concentration in Blood B(t), mg/L

Time After Discharge, minutes

HALON 1211 Concentration in Air A(t), % v/v

- Air Concentration
- PBPK Model (Vinegar 1998)
- Kinetic Model

Position 1
1st Order Kinetic Modeling of Halon 1301 in Ventilated Compartments

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