EVALUATION OF CALCULATION METHODOLOGIES FOR THE SAFE USE OF CLEAN AGENTS ONBOARD AIRCRAFT

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The Federal Aviation Administration (FAA) Advisory Circular 20-42C, *Hand Fire Extinguishers For Use In Aircraft*, provides guidance for the safe use of halon 1211, halon 1301, and carbon dioxide handheld extinguishers onboard aircraft. The last time this circular was updated was more than 20 years ago. Since replacements for halon 1211 have come to be available and are fully approved for use onboard aircraft, a committee was formed to update this circular. The committee consists of the FAA, the U.S. Environmental Protection Agency, agent manufacturers, and end users.

There have been numerous discussions within this group as to the proper methodology that should be used to determine the required minimum compartment volumes for safe handling of halon 1211 and its replacements onboard aircraft. One approach was to look toward Physiologically Based PharmocoKinetic (PBPK) modeling to provide guidance. However, PBPK modeling has never been required for handheld extinguishers in the past.

In a typical exposure scenario for a handheld extinguisher, it is assumed that the user of a handheld will immediately leave the area whether the fire is extinguished or not. Currently, each Underwriter's Laboratories (UL) listed clean agent handheld extinguisher carries a minimum required room volume for confined spaces that is based on the agent's Lowest Observable Adverse Effect Level (LOAEL). To calculate the minimum room volume the extinguisher is assumed to be discharged at sea level at a temperature of 120 °F. The agent is assumed to spread homogenously throughout the room and the room is assumed to have no ventilation or leaks. The high temperature would represent a hot building on a summer day. This type of methodology is obviously conservative since it does not account for ventilation, leakage, or stratification, all of which will reduce agent concentrations.

For aircraft applications, it is impossible to leave the plane in-flight. If UL confined space guidelines were used for aircraft, the result would be an overly conservative approach that would create new barriers to replacing halon 1211. Therefore, the task for creating updated guidelines for onboard handheld use should be to create calculation methodologies that provide for safety while not placing too many conservative assumptions into the calculations.

For this report, the main focus will be the use of halon 1211 onboard small aircraft. There are three reasons for this: (1) the baseline of performance and acceptable toxicity level are defined by halon 1211, (2) when evaluating calculation methodologies, small aircraft are the most impacted as commercial aircraft have large enough compartment volumes that over-exposure is not of significant concern, and (3) several reports are available to provide empirical measurements of halon 1211 discharges onboard small aircraft.

CURRENT GUIDANCE

Currently, the UL confined space minimum room volume requirement is 312 ft^3 for the standard 2.5 lb. halon 1211 extinguisher used onboard aircraft. This UL volume was developed before the cardiotox testing became the industry standard. The volume is based on an allowable concentration of 2%vol. versus the 1 % vol. that would be allowed today. If halon 1211 were to be commercialized today, its UL minimum required room volume would be 624 ft^3 for 2.5 lb.

For aircraft, the current guidelines are based on human exposure data and the acceptable dose is set at 4 percent-minutes for halon 1211. Minimum compartment volumes are based on inputting values for the compartment volume and air exchange rate into the perfect stirrer calculation method. This method is presented in detail in Reference 1, which forms the basis of AC 20-42C. The perfect stirrer method assumes that the entire agent amount immediately becomes homogenously mixed in the air, and that fresh air entering the cabin mixes with the existing air thus maintaining higher concentrations as air is ventilated out of the cabin. In the perfect stirrer method, the concentration after each air exchange will be 37 % of the starting concentration. The resulting dose can be found by multiplying the initial agent concentration by the air exchange rate. The calculations for the AC assume an ambient pressure based on an altitude of 8,000 ft and a temperature of 70 °F. Based on the guidelines of the current FAA advisory circular, a small aircraft with a ventilation rate of 1 air exchange per minute would need to have a minimum volume of 197.5 ft^3 for a 2.5 lb. halon 1211 extinguisher to be used.

There was concern about the expected exposure on smaller aircraft as cabin volumes and ventilation rates were not well known. Therefore, the FAA conducted several test series to evaluate discharges onboard smaller pressurized and non-pressurized aircraft (See References 3 5, and 7). The aircraft used in these reports were a four-seat Cessna 210C (139.9 ft^3 volume) and a Cessna C-421B (216.6 ft^3) that could accommodate up to ten people. Reference 3 found that 6 Lb. of halon 1211 could be safely discharged onboard the Cessna 210C to safely stay within the 4 percent-minutes guideline. The report on the Cessna C-421B indicated that "The crew and passenger dose to neat halons was calculated and found to be low in relation to the amount that can be safely tolerated." Both of these reports stated the importance of both ventilation and stratification in lowering the nose level dose.

To recap, the current minimum volumes for the standard 2.5 lb. halon 1211 extinguisher are: 312 ft^3 for UL, 624 ft^3 if UL updated their methodology to reflect the LOAEL concentration, 197.5 ft^3 for the perfect stirrer, and much less than 139.9 ft^3 based on empirical FAA data. Before looking into how PBPK modeling might be used for aircraft related exposures, the stratification noted in References 1, 2, 3, 4, 5, 7, and 8 should be discussed.

STRATIFICATION

The report "Study of Hand-Held Fire Extinguishers Aboard Civil Aviation Aircraft" (Ref. 2) provides a chart that presents a good graphical description of the degree that halon 1211 stratifies. This 1982 report was commissioned by the FAA and written by Factory Mutual. The report provides summaries of several reports concerning empirical halon 1211 and 1301 discharges. One of these summaries included an Imperial Chemical Industries test of a discharge of a 3.0 lb. halon 1211 extinguisher into the cab of a diesel truck. The results of this test are presented in Figure 1 below.

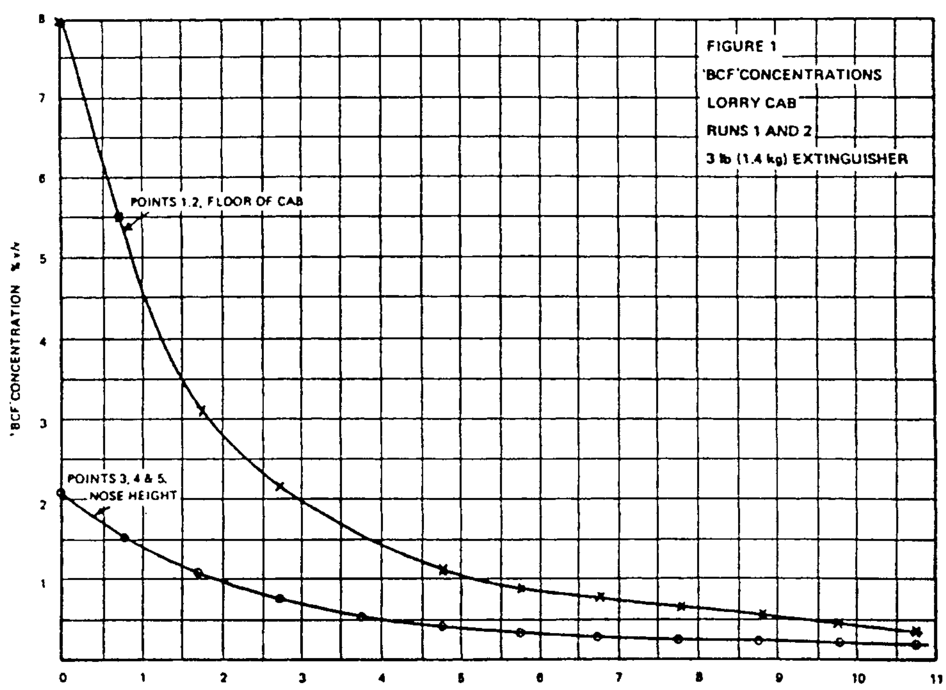

Figure 1. 3 lb. Halon 1211 Handheld Discharge into 97 ft^3 Diesel Truck Cab.

The stratification effect that occurs is immediate with nose level concentrations starting 75 % below concentrations recorded at floor level. If one assumes that this was a totally confined space with no leaks or ventilation, and that the agent was to homogeneously fill the space, the agent concentration would be approximately 7 %vol.

For halon 1211 replacements, Reference 8 provides a graph which illustrates that the higher boiling point agents will have a higher degree of stratification. This is the result of higher vapor densities due to the larger molecules as well as a higher portion of liquid agent dropping to the floor before evaporating. This report by Kidde International Research presented the initial development of the hidden fire test and was commissioned by the Civil Aviation Authority. The purpose of this development work was to create a test fixture that would allow direct flooding capability comparisons between halon 1211 and its replacements. In the testing, a generic constant-pressure discharge apparatus was used to evaluate agent performance. For each agent, the weight discharged was based on determining an equivalence for each agent in relation to 2.5 lb. of halon 1211 based on the agent's cup burner concentration and molecular weight. Not accounting for physical property differences, this should have resulted in the same number of fires extinguished for all agents. Figure 2 below reflects the results from the generic discharge tests.

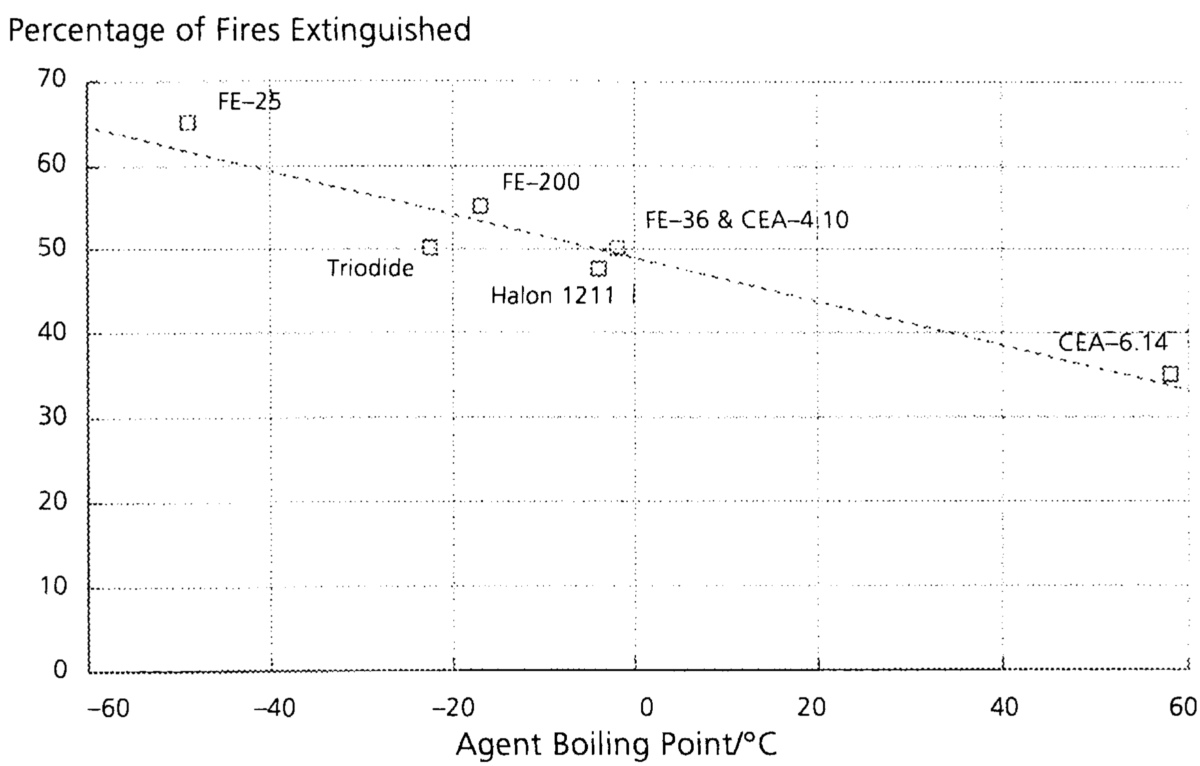

Figure 2. Effect of Agent Volatility.

Based purely on boiling point, it can be seen that the percentage of agent in the air available to extinguish fires will decrease with increasing boiling point. In general the hidden fire test fixture provides a direct measure of an agent's ability to vaporize and to stratify.

During official UL testing of Halotron I (B.P. 27 °C) in the hidden fire test fixture, 5.5 lb. of agent was required to extinguish the same number of cups extinguished by 2.5 lb. of halon 1211.

Based on the differences in molecular weight and cup burner values, the Halotron I agent should have only required 4.2 lb. of agent to extinguish the same number of cups. The other 1.3 lb. is a direct measure of the volatility of Halotron I as compared to halon 1211. When Halotron I was tested in the hidden fire test, throughout the discharge there was liquid dropping to the bottom of the test fixture. It is likely that the agent dropping to the bottom of the test fixture before evaporating includes this 1.3 lb. Due to the vents cut in the side of the test fixture, as the liquid on the bottom of the test fixture evaporated the vapors were quickly removed. Onboard an aircraft the same would be expected and it would be unlikely that this portion of the agent would reach nose level in any significant quantity. However, if using the current methodologies, this 1.3 lb. of agent is assumed to have instantly vaporized and contribute to dose.

It is noted that halon 1211 does not fully vaporize when discharged from a handheld. Reference 4 notes the following, "When they [halon 1211 extinguishers] are utilized in a confined space such as under the instrument panel, liquid is discharged and may splatter on surfaces such as the firewall, instruments, or panels. A short period of time is required for the liquid to become gasified."

EFFECTIVE AIR EXCHANGE RATES

The technical basis (Ref. 1) for AC 20-42C provides an alternative method for allowing estimates of lower doses based on empirically measured stratification. Reference 1 states that "Given the situation in many aircraft compartments where ventilation is from the top to the bottom, the perfect stirrer technique, in those cases, would actually predict higher concentrations at nose level than would be actually measured." The report then provides a methodology for how to determine and use an "effective" air exchange rate versus the standard air exchange rate. The determination of "effective" air exchange rate is based on empirically measured agent concentration drop as measure at nose level. The "effective" air exchange rate is defined as the time it takes for the agent concentration to drop to 37 % of the peak concentration. Due to the layering effect of the agent, the "effective" air exchange rate will always result in a much lower dose to the pilot or passengers. The report indicates that the benefit of using "effective" air exchange rates would be seen the most in small non-pressurized light aircraft where ventilation is primarily from stagnation points on the wing leading edge, or larger aircraft where the large volume will quickly drop the exposure at nose level.

References 3, 5 and 7 empirically measure "effective" air exchange rates for halon 1211. Reference 3 examined discharges onboard a 139.9 ft^3 internal volume four-seat Cessna 210C. In this report, the standard air exchange rate at the 120 mph simulated condition was measured as 1.16 minutes per air change, and the "effective" rate was 0.33 minutes, or 72 % less. This testing incorporated multiple discharge locations to examine the dose impact. Reference 7 was another study onboard the Cessna 210C by individuals involved in Reference 3. In this testing, dummies were placed in the seats and baggage placed in the baggage compartment, which resulted in a higher initial concentrations and also faster "effective" air exchange rates. The "effective" air exchange rate was measured at 0.28 minutes per air change, or 76% less than the standard air exchange rate. This report concludes that "Extinguisher agent stratification and normal flight ventilation are major factors in producing safe conditions in the cabin at the pilot's nose level."

The Cessna C-421B in Reference 5 has a reported internal volume of 216.6 ft^3. When flying at altitudes above 23,000 ft the cabin is pressurized about 5 psi above ambient conditions. Using a compressed air supply, this testing was performed at ground level with the aircraft pressurized at 5.6 psig to simulate higher altitude in-flight conditions. It was noted that the ventilation inlets consisted of both high and low air vents, and the outlet was a single exhaust in the rear of the aircraft. This was believed to better create perfect stirrer conditions. Concentrations in this test were recorded at the test area, knee level, and nose level in multiple discharge locations. The standard air exchange rate was determined to be as 0.78 minutes (47 seconds) per air exchange. However, determination of air exchange rates from smoke dissipation data indicated that the cockpit air changes were faster than that of the cabin area. The standard cockpit exchange rate was measured as 0.53 minutes (32 seconds) per air change, while the cabin rate was measured at 0.98 minutes (58 seconds) per air exchange.

Seat level in this testing was defined as 20 inches high and the nose level measurements were at 37 inches. This implies that the seated individual would have a seat-to-nose height of just 17" which would be representative a child or small adult. Two Cessna C-421B exposures are shown below in Figures 3 and 4. These specific exposures are highlighted because PBPK modeling was performed previously for them.

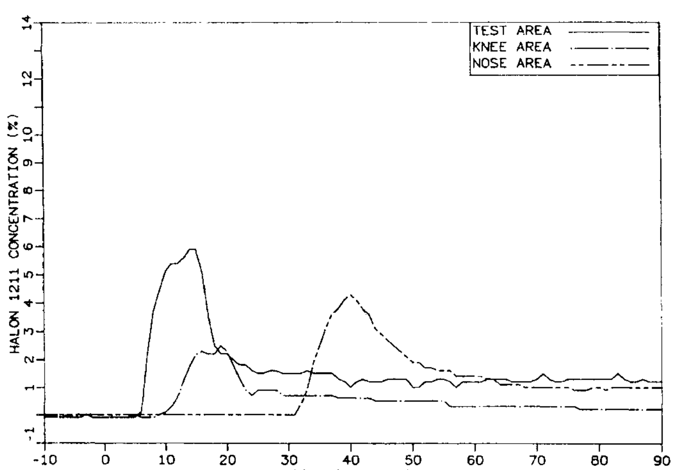

Figure 3. Halon 1211 Handheld Discharge of 2.7 lb. Onboard a Cessna C-421B – Copilot's Seat.

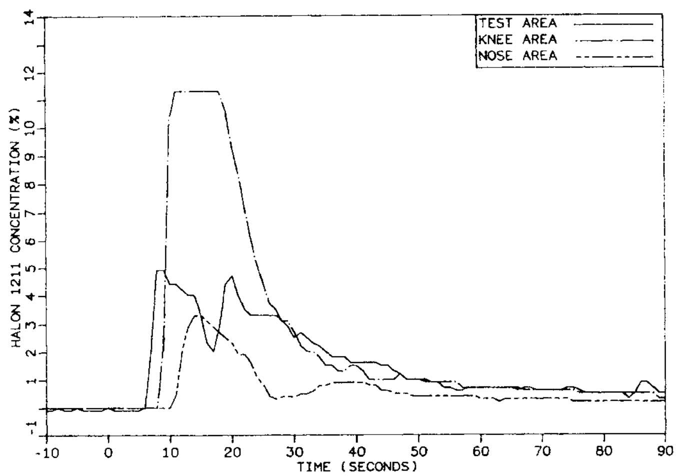

Figure 4. Halon 1211 Handheld Discharge of 2.9Lb. Onboard a Cessna C-421B – Grill Under Copilot's Seat Facing Cabin.

In reviewing the 20 tests that were completed for both halons 1211 and 1301, the test results shown in Figure 3 are suspect and likely should not be considered in further work relating to exposures. Out of the 20 tests, this test was the only one in which the peak concentration at knee level was less than the peak nose concentration. If it was assumed that there was an updraft in this location, the result should also have been observed with halon 1301 and it was not. When halon 1301 was discharged at the copilot's seat the peak nose concentration was measured as 1.9 %vol. and the peak knee concentration as 4.4%vol. which is consistent with other discharges. Furthermore, in all other tests except one, halon 1301 exhibits similar to higher nose level peak concentrations as compared to halon 1211. Based on the other results, including a similar discharge of halon 1211 to the pilot's seat, this test appears to be an anomaly and perhaps the nose and knee concentrations may be transposed. Therefore, Figure 3 will not be further considered.

While the report indicates that the concentration profile should be more in line with perfect mixing estimations, an examination of Figures 4 indicates the agent concentration is dropping much faster than the perfect stirrer method would predict. According to the perfect stirrer method, the nose level concentration would drop from its peak of 3.3 % to 1.2 % over one air exchange of 32 seconds. It appears that this drop in concentration occurs over roughly an 8 second interval. This makes the "effective" air exchange rate 0.13 minutes, a 75 % lower value than the standard cockpit air exchange rate.

For the Cessna C-421B, the average halon 1211 exposure was 0.44 percent-minutes. In three discharge locations there was no recordable dose. Based on the standard air exchange rate of 47 second and the average weight of halon 1211 discharged (2.6 lb.), the perfect stirrer method used in the current FAA advisory circular would estimate the exposure to be 2.95 percent-minutes.

The perfect stirrer method overestimates the average dose by 670 % and overestimates the worst case dose by 210 %. If the perfect stirrer method were employed using the "effective" air exchange rate of 0.13 percent-minutes, the expected dose would be 0.49 percent-minutes. This appears to match reasonably well for the average case.

PBPK MODELING

PBPK modeling has become the industry standard for determining the safe guidelines for halon 1301 alternatives in total flooding systems. The PBPK model models the human uptake of and agent on a breath-by-breath basis with the output of the model being the agent concentration in the arterial bloodstream. This output is then compared to the acceptable blood level that would have been previously determined through dog testing at an agent's LOAEL. It is noted that the dog test to determine the acceptable blood level is so conservative that there are no additional safety factors above and beyond the level measured in the test. Additionally, the PBPK model results will cover 98% of the population, which means that it must take into account individuals that have a much higher than average uptake rate.

The PBPK methodology is quite different than just defining an acceptable dose as does the current FAA advisory circular. At higher concentrations the uptake of the agent into the arterial bloodstream is fairly quick and the result of the PBPK model will quickly reflect an unacceptable dose. As an example, take into account the current allowable 4 percent-minute dose for halon 1211. If this exposure consisted of being exposed to a 1 percent agent concentration for 4 minutes, the PBPK model would indicate that this exposure is acceptable. However, an exposure of 4 percent for 1 minute would not be acceptable. Therefore, the shape of the exposure profile becomes extremely important when performing PBPK modeling.

PBPK modeling was performed in Reference 6 for the empirically measured nose-level exposures shown above in Figures 3 and 4. As noted, it is believed that the concentration profile shown in Figure 3 is not valid and that this test appears to be an anomaly as compared to the other tests in the series. Figure 5 below reflects the PBPK modeling for the nose level concentration profile of Figure 4.

A line at 21 mg/L on the right graph depicts the allowable arterial blood concentration for halon 1211 based on dog testing performed at halon 1211's LOAEL of 1 % vol. As can be seen from the graph, this exposure is acceptable based on PBPK modeling.

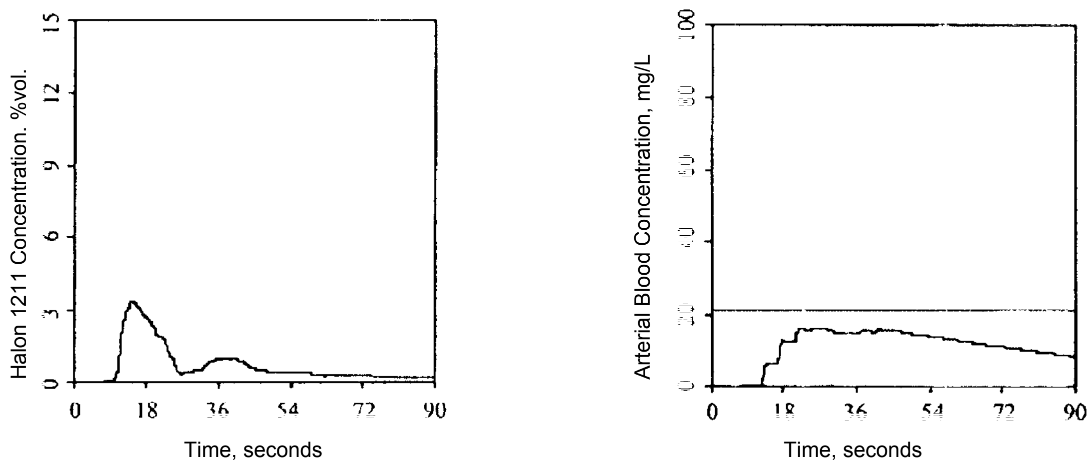

Figure 5. PBPK Modeling of Halon 1211 Handheld Discharge of 2.9 lb. Onboard a Cessna C-421B - Grill Under Copilot's Seat Facing Cabin.

The FAA has developed a simplified method for applying PBPK modeling to various concentration profiles without the requirement for the full model to be run (Ref. 9). The method is based on using results from full model runs conducted at an agent's LOAEL concentration. The equation below reflects the simplified model that can then be created using first order kinetics. The input into this simplified model is the agent concentration and the model determines the uptake and elimination rates based on constants derived from full model results.

The degree of error resulting from using the equations above has not yet been determined, but the equation appears to provide a fair representation of the output from the full PBPK model. Evaluating this simplified model using a constant 1 % vol. of halon 1211 has shown that it will tend to slightly overestimate blood levels for the first few minutes.

$$C(t) \underset{k_u}{\rightarrow} B(t) \underset{k_e}{\rightarrow} W(t)$$

$$\frac{dB}{dt} = k_u C(t) - k_e B(t)$$

Where,

C = Agent concentration, %vol.

B = Arterial blood concentration, mg/L

W = Waste eliminated from blood, mg/L

k_u = uptake rate coefficient (determined as 38.6 for halon 1211)

k_e = elimination rate coefficient (determined as 1.74 for halon 1211)

Based on this simplified model and the perfect stirrer method, the minimum compartment volume for and aircraft that has a standard air exchange every 47 seconds would be 353 ft^3 in order to be acceptable for a 2.5 lb. halon 1211 extinguisher. Using the measured effective air exchange rate of 8 seconds, the minimum volume would need to be 120 ft^3.

Using this simplified PBPK method, three exposures on the Cessna C-421B were examined and are shown below in Figures 6 through 8 (these represent exposures presented in Figures 19, 21, and 25 of Reference 5). In each figure, additional concentration profiles have been added to illustrate the predicted exposures based on perfect mixing with standard ventilation and with the effective ventilation rates. Figure 6 illustrates the same exposure shown above in Figure 5. In the data, the nose level concentrations do not start immediately at the time of discharge. Therefore, in the figures below, the perfect stirrer method curves are set to coincide with the first concentration that is recorded at nose level.

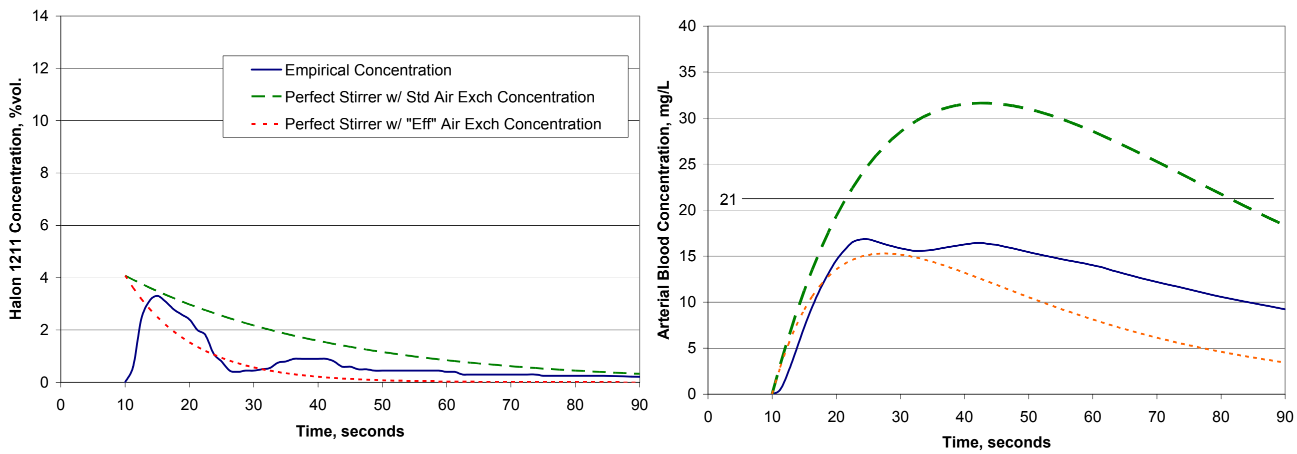

Figure 6. PBPK Modeling of Halon 1211 Handheld Discharge of 2.9 Lb. Onboard a Cessna C-421B - Grill Under Copilot's Seat Facing Cabin.

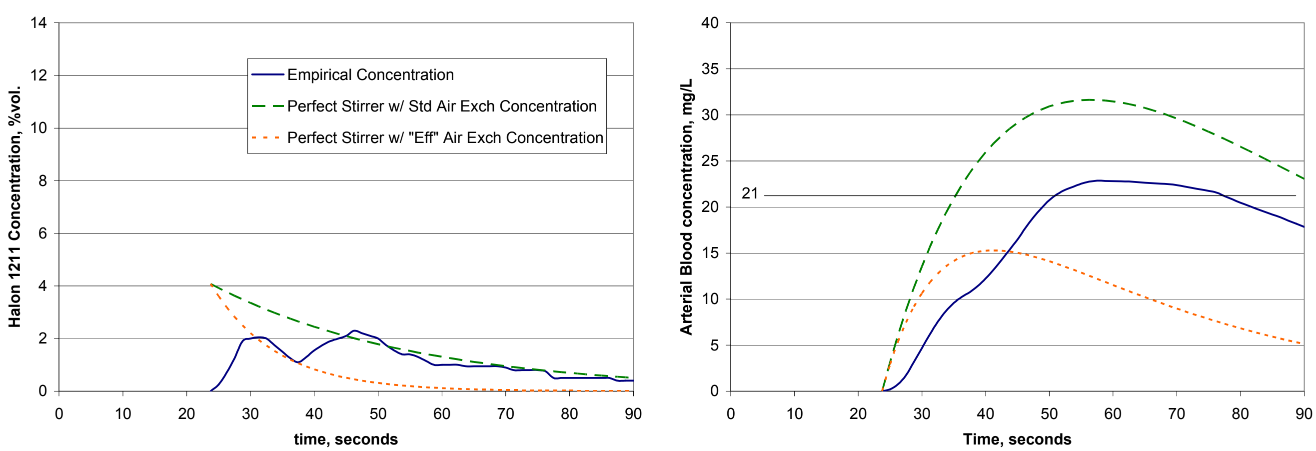

Figure 7. PBPK Modeling of Halon 1211 Handheld Discharge of 2.6 lb. Onboard a Cessna C-421B - Second Cabin Vent Left Side.

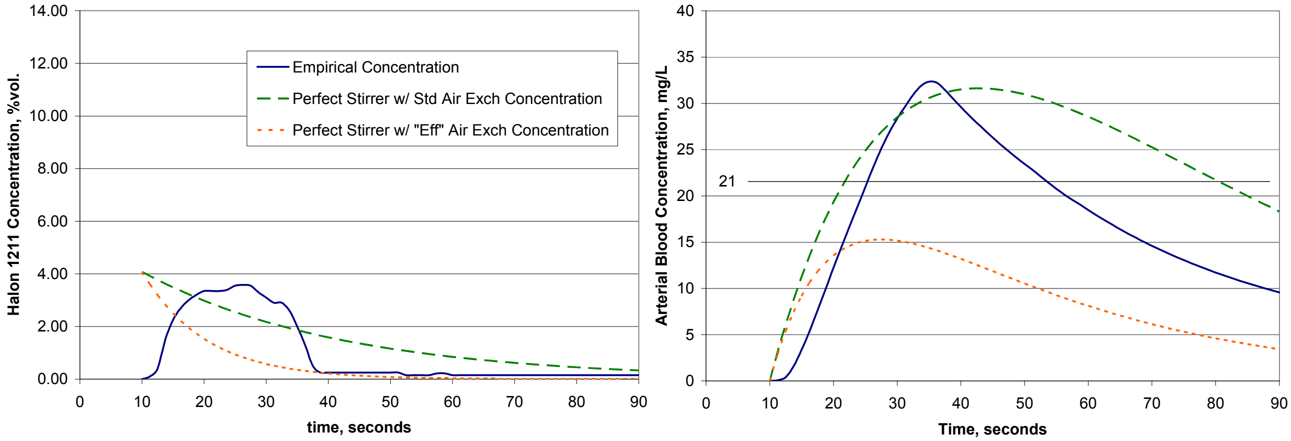

Figure 8. PBPK Modeling of Halon 1211 Handheld Discharge of 2.8 Lb. Onboard a Cessna C-421B - Last Cabin Vent Right Side.

In summary of the testing on the Cessna C-421B, there were 10 halon 1211 tests conducted. As noted previously, the test presented in Figure 4 above will be discounted as an anomaly. Of the remaining 9 test locations: 5 discharges to the instrument panel, circuit breaker, pilot's seat, and the 110 volt outlet at the rear of the cabin resulted in no dose or a low dose at nose level; 2 discharges to the grill under the copilot's seat and cabin vent at floor level before the door on the left side resulted in above average doses of 0.7 and 0.8 percent-minutes, respectively; and 2 discharges into the second cabin vent left side and last cabin vent right side resulted in higher doses of 1.3 and 1.4 percent-minutes, respectively.

The low and above average doses would all result in acceptable exposures. The last two higher exposures appear to be the result of discharging agent toward vents. While the report does not indicate the importance of these vents or hazards that may be associated with them, it can be inferred in these tests that the agent must be being forced back toward the cabin. There was a concentration measurement taken at the test discharge location and it would be expected that the dose at this location would at least initially be the highest. However, when discharging at the vents, the discharge location measurement was lower than the exposure at knee level implying that the agent was being diverted. It is believed that these are return air vents bringing in heated air. The result of discharging toward an incoming air vent would be forced mixing of the agent with the cabin air. Even with this, the exposure resulting from the discharge to the second cabin vent left side just barely exceeds the allowable exposure. Due to the slight conservative nature of the simplified PBPK method, this exposure might be acceptable in the full PBPK model. The concentration profile for the last cabin vent right side creates a steady high concentration of agent for approximately 20 seconds, which is enough time to result in an unacceptable blood concentration. It is noted that the shape of this curve is not predicted by the perfect stirrer method.

Statistics provided in Reference 2 indicate that 86.7 % of small aircraft fires are electrical in origin and another 6% are from smoking materials. For an electrical fire, discharging behind wall panels might be necessary, but unless the vent tubing is damaged a discharge into the vent would not be expected to extinguish a fire within the walls. If the tubing was damaged, the agent exposure profile would not be the same.

A 2.5 lb. halon 1211 extinguisher has been used in small aircraft for over 20 years. Over this period, it was not possible to find one reported case of over-exposure onboard small or large aircraft. This provides some additional evidence that the worst case scenario of discharging in a manner that creates a high airborne concentration is unlikely.

SUMMARY AND CONCLUSIONS

The following observations and conclusions can be drawn:

- FAA reports regarding halon 1211 state that a 2.5 lb. halon 1211 extinguisher is acceptable for general aviation aircraft as small as 139.9 ft^3 (and likely acceptable at half this volume). This result is due to high ventilation rates in small aircraft and stratification of the agent combined with the 4 percent-minutes exposure currently allowed.
- The current guidance that defines the acceptable dose for halon 1211 as 4 percent-minutes is no longer considered valid as it does not account for the profile of the exposure.
- PBPK modeling was developed to provide guidance for the safe use of clean agent total flooding systems. The acceptability of an exposure is based on the calculated agent concentration in the arterial bloodstream and not an overall dose. The agent concentration in the bloodstream is influenced by the shape of the exposure profile.
- For the Cessna C-421B, it has been shown that for instrument panel or circuit breaker fires, expected to be the most common fires onboard this aircraft, the dose is negligible.
- The two highest nose-level exposures onboard the Cessna C-421B are the result of higher airborne air concentrations believed to be due to discharging the agent toward return air vents which mix the agent and push it back into the cabin. Only one of these higher exposures resulted in an unacceptable dose when evaluated using the simplified PBPK model.
- Even though the simplified PBPK modeling of empirically measured nose-level concentration profiles reflects a possibility for overexposure onboard the Cessna C-421B, halon 1211 has a greater than 20 year track record for use onboard aircraft with no overexposures reported for either small or large aircraft. Therefore, the absence of reported over-exposures is either a reflection that discharges into locations that significantly increase mixing are not likely, or it is possibly an artefact of the various conservative inputs into the results presented here. There is a bit of conservatism in each

step along the way: (1) the blood level in dogs is considered conservative enough to use without a safety factor, (2) the PBPK model was developed to cover 98 percent of the population including those individuals with a high agent uptake rate, (3) the nose-level agent concentration is measured at the height of a child or small adult, and (4) the agent must be discharged in such a manner as to forcibly be mixed with air. It takes all of the extremes in the case of the Cessna C-421B in order for the simplified PBPK model result to reflect an unacceptable exposure.

- All current commercialized halon 1211 replacements with UL listings will have a similar to greater propensity to stratify, and on a per pound basis all replacements are at least half as toxic. Therefore, all current commercialized replacements would be expected to have the same acceptability or better than halon 1211 onboard a Cessna C-421B aircraft. Additionally, higher boiling point halon 1211 replacements agents will exhibit a higher degree of stratification/agent drop and additional calculation corrections might be made for these based on hidden fire test results.
- Measured effective air exchange rates, expressed in units of minutes per air exchange, for halon 1211 are 72 % to 76l% less than the standard air exchange rate for the small aircraft examined in FAA reports.
- Exposure models based on perfect mixing using the standard air exchange will significantly overestimate the anticipated exposures. In fact, the use of the PBPK model in conjunction with the standard air exchange rate and the assumption of perfect mixing would reflect that the standard 2.5 lb. halon 1211 extinguisher is not acceptable for typical compartment volumes of general aviation aircraft. However, the use of the "effective" air exchange will not fully cover some exposures. Therefore, in order not to create new barriers for replacing halon 1211 onboard aircraft, it seems reasonable to take a middle position between the two exchange rates.

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