EFFECT OF AIRPLANE OPERATIONAL PARAMETERS ON CARGO COMPARTMENT FIRE SUPPRESSION SYSTEM EFFECTIVENESS

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Fire suppression in non-accessible cargo compartment on-board commercial airplane is provided by a remotely actuated built-in halon 1301 fire suppression system. The system provides an initial 5% volumetric (minimum) concentration of halon at all operating conditions. Subsequent discharge (dump or metered) maintains 3% volumetric (minimum) concentration for continued safe flight to the nearest landing field. Empty cargo compartment volume and maximum cabin-to-ambient differential pressure leakage is used for system design. This paper examines the effects of operational parameters (altitude, leakage, cargo load) on system's fire suppression effectiveness.

Nomenclature

A = Cargo compartment effective leakage area (in^2).

C = Average volumetric concentration of halon in air by volume (%).

D = Dosage (%.min.)

g = Acceleration due to gravity (ft/sec^2).

H = Altitude (ft).

L = Infiltration or leakage (cfm).

M = Flow Mach Number (-).

P = Pressure (psia).

R = Gas Constant (ft-lb/lb-^{0}R).

S = Specific volume of halon (ft^3/lb)

t = Time (min)

T = Temperature (^{0}F or ^{0}R).

V = Volume (ft^3).

W = Weight (lb)

Subscript

amb	Outside Ambient
c	Cargo compartment
des	design
h	halon 1301
l	Cargo or load
n	Net
sl	Sea-level
t	time

Greek symbols

β	Compartment leakage correction factor
γ	Ratio of Specific heats
δ	Compartment pressure ratio (P_c/P_{sl})
ϕ	Function of indicated variables
λ	Load factor = V_l/V_c
ρ	Density (lb/ft^3)

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Introduction

Five classes of cargo compartments, A through E, are described in Section 25.857 of Part 25 of the Code of Federal Regulations Title 14 (14CFR 25), reference 1. A compartment that is inaccessible in flight and is greater than 1000 cubic feet in volume and or incorporates ventilation is classified Class C. A Class C cargo compartment is required to have

(1) A separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station;
(2) An approved built-in fire extinguishing system controllable from the pilot or flight engineer station;
(3) Means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by crew or passengers;
(4) Means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

Fire detection system requirements are defined in §25.858. Section 25.851(b) identifies the regulations applicable to the design of built-in fire extinguisher system. Each fire extinguisher system is required to be installed so that --

(a) No extinguishing agent likely to enter personnel compartments will be hazardous to the occupants;
(b) No discharge of the extinguisher can cause structural damage;
(c) The capacity of each required built-in extinguishing system is adequate for any fire likely to occur in the compartment.

Federal Aviation Authority (FAA) has determined that a system that provides the following, in an empty cargo compartment, is adequate for any fire likely to occur in the compartment.

(i) Initial average volumetric halon concentration equal to or greater than 5% at all operating conditions (to knock down flaming combustion), and
(ii) A minimum average volumetric halon concentration of 3% during continued flight to the nearest landing field (to maintain the fire suppressed).

Design Methodology

Aviation industry utilizes National Fire Protection Association (NFPA) Standard 12A – Standard on Halon 1301 -- reference 2, as a guide for system design. The halon 1301 weight to achieve the desired initial design concentration, in the hazard volume, is calculated using the following formula.

$$W = \frac{V}{S}\left[\frac{C}{(100-C)}\right] \qquad \text{(Equation 1)}$$

The above formula assumes homogeneous mixing and includes an allowance for leakage from a "tight" enclosure due to agent expansion. It assumes that the halon 1301 and air mixture lost in this manner contains the <u>final</u> design concentration of halon 1301. This represents the worst case from a theoretical standpoint, and provides a built in safety factor to compensate for non-ideal discharge.

The volumetric concentration produced by a given weight of halon 1301 is affected by the enclosure temperature. The airplane cargo compartment is maintained above freezing temperature, by design, to allow transport of animals and perishable goods. The aviation industry uses a design temperature, T_{des}, of 32^0 F (0^0 C). It selects initial halon discharge based on sea-level conditions (lowest specific volume of superheated halon, S_{sl}) and empty cargo compartment volume, V_c. The weight of halon for initial dump, W_{des}, is calculated from equation (1) using design concentration, C_{des}, equal to 5%. This yields

$$W_{des} = \frac{V_c}{19 S_{sl}} \qquad \text{(Equation 2)}$$

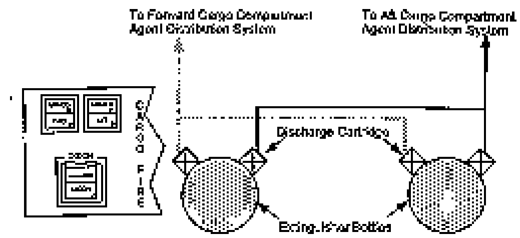
Aviation industry uses the leakage rate, L_{des}, determined by flight test at maximum cabin-to ambient differential pressure, to estimate the instantaneous halon concentration $[C]_{t=t}$ using the following mathematical relation.

$$[C]_{t=t} = [C]_{t=0} * \left\{ e^{\frac{-L_{des} * (t)}{V_c}} \right\} \qquad \text{(Equation 3)}$$

The system incorporates features to automatically (or manually release) supplemental halon in the compartment after a fixed time delay, t_{des}. The time delay is determined from equation (3). It is the time for halon to decay to 3% concentration. This ensures adequate suppression capability during continued flight to the nearest landing field.

The automatic or manual release of supplemental halon may be a halon dump (instantaneous release) or a metered continuous supply (pressure and temperature compensated). Figure 1 show the characteristics of the dump/dump system. Such a system is typically used for small cargo compartment or a short range airplane.

Fig. 1- Dump/Dump Fire Suppression System



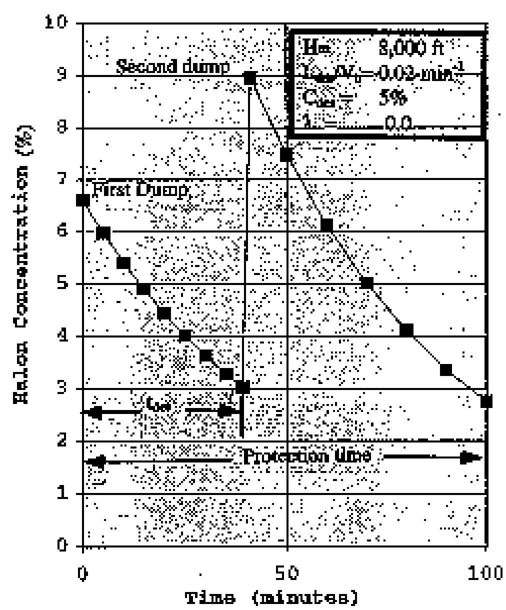
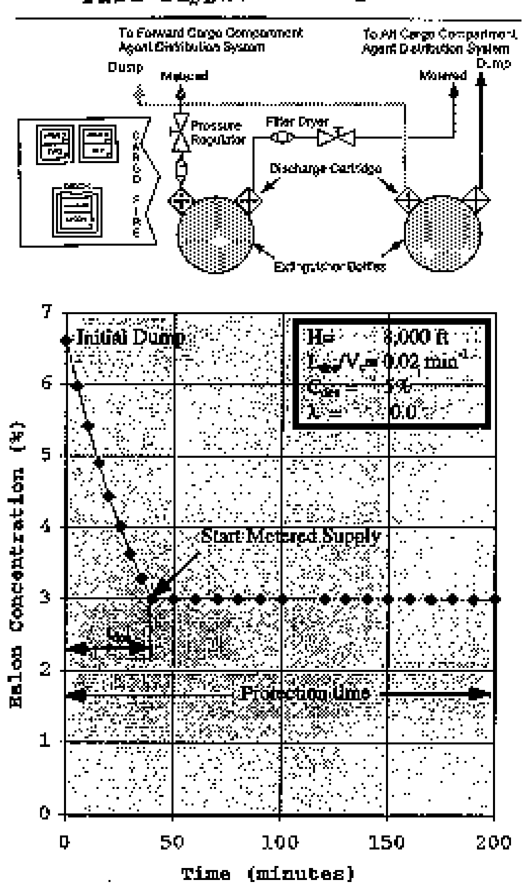


Figure 2 shows the characteristics of a dump/metered-supply system. The dump/ metered-supply system is preferred for large volume cargo compartments and or airplanes that need to fly for long time periods (for example over water) to reach the nearest landing field. It uses less halon to maintain the design 3% concentration. Airplanes that fly long routes over water have systems designed to provide up to 195 minutes of fire suppression capability.

Fig. 2 - Dump/Metered Supply Fire Suppression System



Effects of Operational Parameters

Effects of typical operational parameters on fire suppression system effectiveness are discussed below.

(a) Effect of cargo load and compartment pressure ratio (or altitude) on initial concentration, $[C]_{t=0}$

Assumptions:

(1) Discharged halon = W_{des} = constant

(2) Compartment Temperature = T_{des} =constant

The effect of cargo load on initial concentration is determined using the following relations.

(i) Cargo compartment net volume, Vn,

$$V_n = V_c - V_l = V_c\left\{1 - \frac{V_l}{V_c}\right\} = V_c\{1-\lambda\}$$

(Equation 4)

(ii) Specific volume of superheated halon 1301 at compartment pressure, P_c, and temperature, T_{des}, is given by Equation of State as:

$$S_c = S_{sl} * \left[\frac{P_{sl}}{P_c}\right] = \frac{S_{sl}}{\delta}$$

(Equation 5)

From equation (1) initial halon concentration, $[C]_{t=0}$

$$[C]_{t=0} = 100 * \frac{W_{des} * S_c}{(V_n + W_{des} * S_c)}$$

(Equation 6)

Substitute for W_{des}, V_n, and S_c from (2), (4) and (5) to obtain

$$[C]_{t=0} = \frac{1}{\{1 + 19\delta * (1-\lambda)\}}$$

(Equation 7)

Figure 3 shows the solution of equation 7. Note the rapid increase in initial halon concentration with increase in load factor at all compartment pressure ratios, δ, (or altitudes, H). This occurs due to reduced air volume in the presence of cargo. Initial halon concentration in excess of 20% is evident for load factors equal or greater than 80%.

Increased halon concentration suppresses Class A (combustible solids) fire with greater effectiveness. This results from the following synergetic effects.

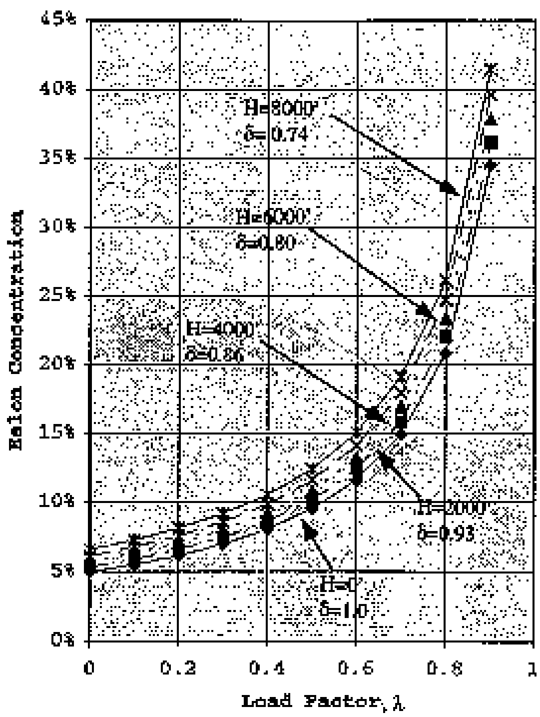
(i) Increased halon molecules in the combustion zone (Law of Mass Action - the instantaneous rate of chemical reaction is proportional to the concentration of reactants at any moment),

(ii) Increased cooling effect (halon absorbs heat and reduces fuel pyrolysis), and

(iii) Reduced oxygen partial pressure due to the high concentration of halon (Dalton's Law of Partial Pressures). The oxygen partial pressure in an 8000 foot altitude compartment (Pc=10.92 psia) is 2.18 and 1.83 psia when the halon concentration is 5 and 20%

respectively. The apparent altitudes (based on oxygen partial pressure) are approximately 9,350 and 13,750 feet respectively.

Fig. 3 - Initial Halon Concentration



In addition, oxygen consumption by fire and dilution of compartment atmosphere by the products of combustion occurs faster, in a compartment of given fixed characteristic leakage, L_{des}, when the load factor is high. This automatically promotes fire suppression.

Thus, it is reasonable to conclude the following.

(i) The installed fire suppression system will suppress a Class A fire with increased effectiveness when the load factor is high. Also, the fire suppression effectiveness will increase as the compartment pressure ratio decreases (or compartment altitude increases). It is probable that the installed system may extinguish some Class A fires (e.g., surface fires) and render others (deep seated) non-hazardous for a longer time.

(ii) The installed fire suppression system will extinguish Class B fires with an increased factor of safety when the load factor is high and or the compartment pressure ratio is low (increased compartment altitude). Extinguishment of a Class B fire requires the halon concentration above a minimum threshold concentration (fuel dependent). For common solvents the concentration is in the range of 3-4 % based on cup burner tests.

(b) Effect of cargo load, compartment pressure ratio and pressure control system algorithm on instantaneous halon concentration, $[C]_{t=t}$

Assumptions:

(1) Compartment effective leakage area, A, is a constant.
(2) Compartment maximum normal altitude = 8000 feet (P_c = 10.92 psia), FAR 25.841(a), reference 1.
(3) Compartment pressure control algorithm - linear with respect to ambient pressure.

From equation (3) at an operating altitude where the compartment leakage is L_c

$$[C]_{t=t} = [C]_{t=0} * e^{\frac{-L_c t}{V_c}} \qquad \text{(Equation 3a)}$$

As the compartment effective leakage area and temperature remain constant, the compartment leakage, L_c, depends on the compartment and outside ambient pressures.

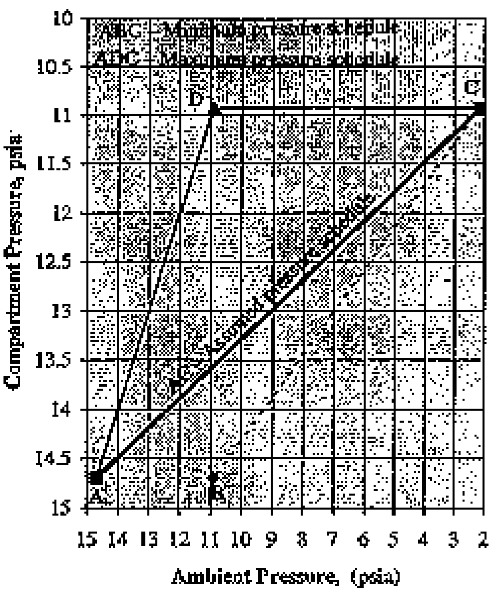
$$L_c = \phi_1[P_c, P_{amb}] \qquad \text{(Equation 8)}$$

Figure 4 shows the pressure control system operating envelope for an airplane of 45,000 feet ceiling altitude. The compartment pressure control system, in the automatic mode, operates within the envelope ABCD. The actual algorithm depends on parameters such as take-off and landing field altitudes, selected compartment ascent and descent rates, limit ascent and descent rate, airplane climb and descent rate, etc. Herein, to simplify analysis, a linear algorithm is assumed.

$$P_c = 0.3012\, P_{amb} + 10.27 \qquad \text{(Equation 9)}$$

$$\frac{P_c}{P_{amb}} = 0.3012 + \frac{10.27}{P_{amb}} \qquad \text{(Equation 9a)}$$

Fig. 4 - Compartment Pressure Control



The compartment leakage correction factor, $\beta = L_c/L_{des}$ can be determined using isentropic flow equations and the equation of state.

$$M = \frac{2}{(\gamma-1)} * \left\{ \frac{P_c}{P_{amb}}^{\left[\frac{\gamma-1}{\gamma}\right]} - 1 \right\}$$

$$= 5.0 * \left\{ \frac{P_c}{P_{amb}}^{.2857} - 1 \right\}$$

Pc/Pamb< 1.893 (Equation 10)

$M = 1.0$, for P_c/P_{amb} = or >1.893 (Equation 10a)

$$W = \frac{\left[\sqrt{\frac{\gamma}{R}}\right] * M}{[1+(\gamma-1)/2\, M^2]^{\frac{\gamma+1}{2(\gamma-1)}}} * \frac{A * P_c}{\sqrt{T_c}}$$

(Equation 11)

$$= 0.9196 * \frac{M}{[1+0.2\, M^2]^3} * \frac{A * P_c}{\sqrt{T_c}}$$

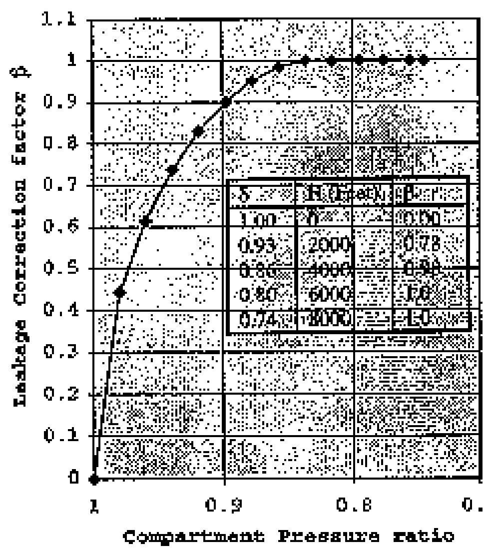
(Equation 11a)

$$\rho_c = 144 * \frac{P_c}{R * T_c}$$ (Equation 12)

$$L_c = \frac{W}{\rho_c} * 60 = \beta * L_{des}$$ (Equation 12b)

Figure 5 shows the relationship between compartment pressure ratio, δ, and the leakage correction factor, β, for the assumed pressure control algorithm.

Fig. 5 - Leakage Correction factor



$\delta = P_c/P_o$

The characteristic decay equation is obtained by substituting known relations in equation (3a).

$$[C]_{\tau=t} = \frac{1}{[1+19\delta(1-\lambda)]} * e^{\frac{-\beta}{(1-\lambda)} * \frac{L_{des} t}{V_c}}$$

(Equation 13)

Figures 6(a) and 6(b) show the solution of equation (13) for several values of λ, β, δ and L_{dc}/V_c.

Fig. 6a -Decay Characteristic

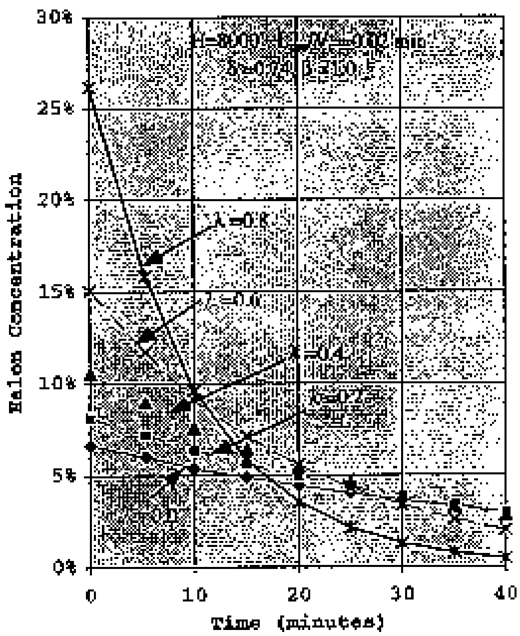
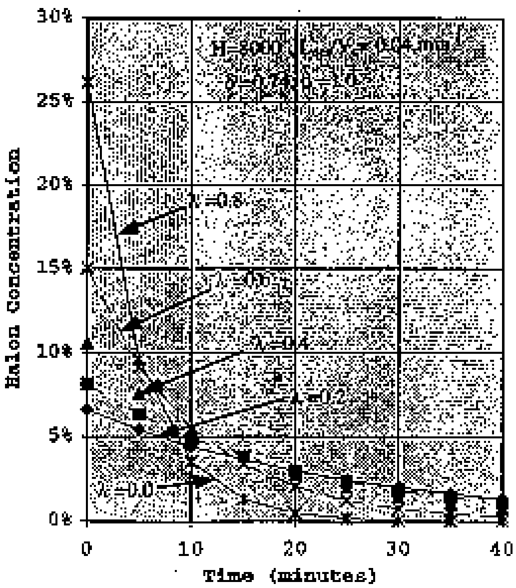


Fig. 6b - Decay characteristic



Refer to Figure 6(a). Note the high initial concentration at high load factors, λ. At a load factor of 0.8 the initial concentration is 26.15% and concentrations above 5% persist in the cargo compartment for t >15 minutes. High concentration and soak time promote increased fire suppression effectiveness against Class A fires.

Figure 6(b) show data similar to figure 6(a) data except it is for a characteristic leakage factor, L_{dc}/V_c, 0.04 min^{-1}. Note the faster decay. This leads to the conclusion that low characteristic leakage factor is important for fire suppression effectiveness.

Figures 7 and 8 show data for conditions of Figure 6(a) but at compartment altitudes of 6,000 and 2,000 feet respectively.

Fig. 7 - Decay Characteristic

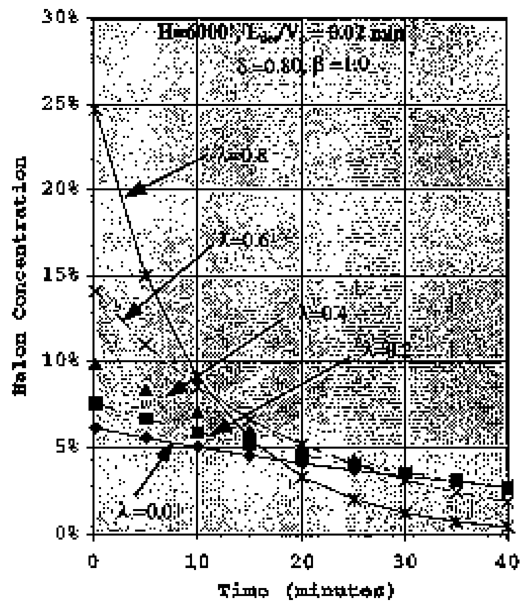


Fig. 8 - Decay Characteristic

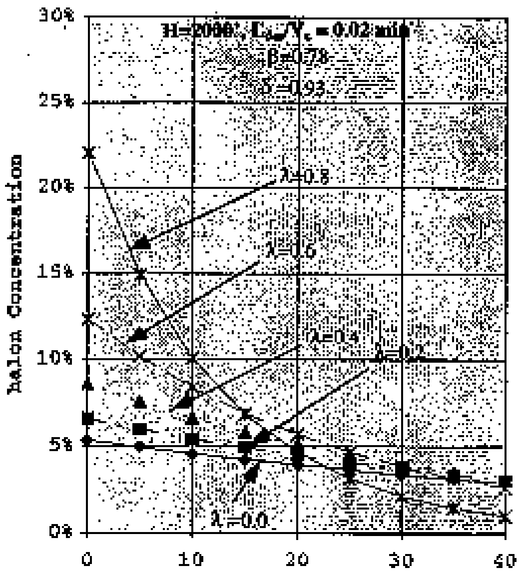
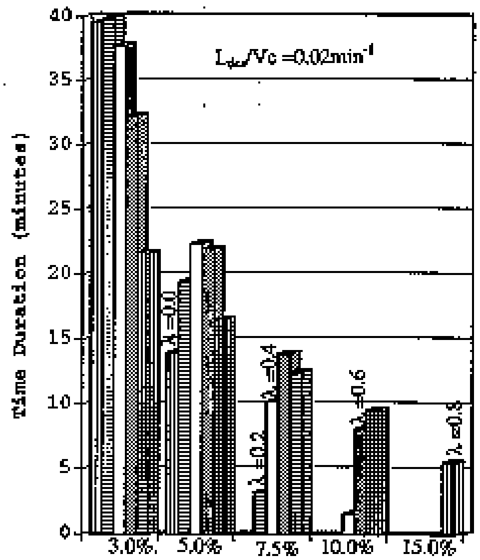


Fig. 9 - Soak Time [H=8000 ft]



(C) Effect of operational parameters on soak time.

The soak time or duration for which the halon concentration is above a desired concentration can be determined from equations (7) and (13)

$$[C]_{t=0} = \frac{1}{\{1+19\delta*(1-\lambda)\}} \qquad \text{(Equation 7)}$$

$$[C]_{t=t} = \frac{1}{[1+19\delta(1-\lambda)]} * e^{\frac{-\beta}{(1-\lambda)} * \frac{L_{ckt}}{V_c} t} \qquad \text{(Equation 13)}$$

Figures 9 and 10 show the soak time for compartment altitudes of 8,000 and 2,000 feet (δ =0.7429 and 0.9298) for a characteristic leakage factor, L_{ckt}/V_c, equal to 0.02 min^{-1}.

Refer to figure 9. Note, long soak periods at high halon concentration result at high load factors. For example, at a compartment altitude of 8,000 feet and load factor of 0.8, the halon concentration is equal to or greater than

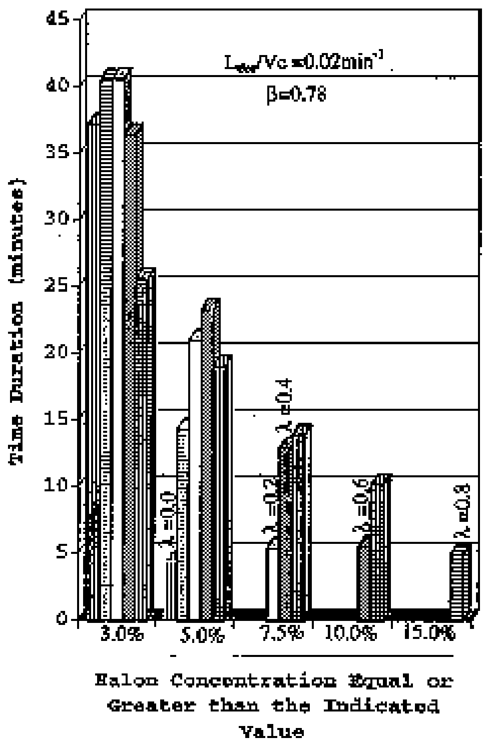
(i) 15% for 5.56 minutes;
(ii) 10% for 9.62 minutes
(iii) 5% for 16.54 minutes, and
(iv) 3% for 21.66 minutes.

[At a load factor of zero, the maximum halon concentration is 6.62 percent and the concentration above 5% lasts for only 14.0 minutes).

Similar characteristics are observed at lower compartment altitudes, Figure 10.

The fire suppression capability of a halon system, when challenged by a Class A fire, depends on halon concentration and soak time, References 3 and 4. Thus, it is reasonable to conclude the installed fire suppression system would be more effective when the load factor is high.

Fig. 10 - Soak Time [H=2000 ft]



(d) Effect of load factor and altitude on time to 3% halon concentration.

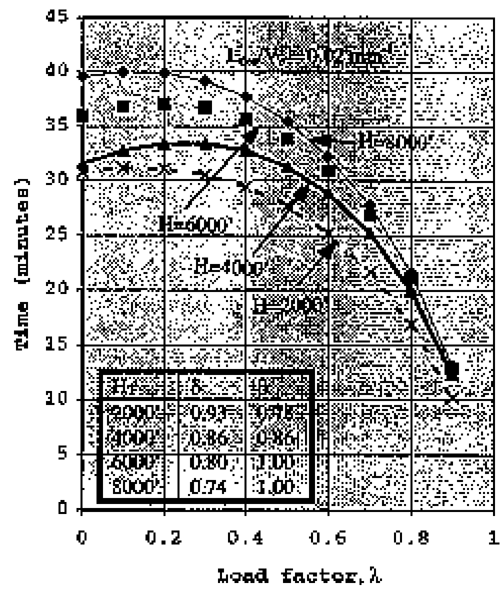
Aviation fire suppression systems incorporate automatic (or manual) features to release supplemental halon in the compartment after a fixed time delay, t_{del}. The release of the supplemental halon may be a dump or metered supply, Figures 1 and 2. The time delay for the supplemental supply is estimated using characteristic leakage, L_{del}, and cargo compartment volume, V_c. This is determined from equation (3) by setting $[C]_{int}$ equal to 3%.

Figure 11 shows the effect of load factors on the time to 3% halon concentration for L_{del}/V_c =0.02 min^{-1} at four compartment altitudes. Note, the following

(1) The halon decays faster to 3% concentration at lower compartment altitudes than at higher compartment altitudes. The figure does not show data for compartment altitudes less than 2,000 feet. At lower altitudes, a reversal in behavior would occur (for the assumed pressure control algorithm) as the leakage correction factor, β, approaches zero, figure 5. The time to 3% halon concentration is theoretically infinite at sea-level as the compartment differential pressure and leakage approache zero. [Theoretically, it will also approach infinity for an unpressurized cargo compartment at all operating altitudes.]

(2) The time to 3% halon concentration first increases slightly with increase in load factor and then starts to decreasing with further increase in load factor. There is no appreciable effect on time to 3% halon concentration for load factors up to 0.35, approximately . Thus, it is reasonable to conclude that load factors up to 0.35 will provide enhanced fire suppression capability. This would result from higher initial halon concentrations that occur at higher load factors, figure 3.

Fig. 11 - Time to 3% Halon Concentration After Initial Dump



(3) The time to 3% halon concentration is approximately 90% of the zero load factor time when the load factor is 0.5. However, the initial halon concentration at a load factor of 0.5 is approximately 90% higher than the zero load factor's initial halon concentration. High halon concentrations are generally accepted to be more effective in suppressing Class A fires; they are known to extinguish surface fires and suppress deep seated fires to a greater degree. It is difficult to authoritatively comment on the state of a typical fire

in a partially loaded (load factor greater than 0.35, approximately) cargo compartment at the time of release of supplemental halon. The halon release being after time delay, t_{del}; estimated for zero load factor configuration, figure 1 and 2. A surface fire will most probably be in an extinguished state. The state of a deep seated fire will depend on several variables, the most important being the ease with which air and halon mixture can get to the fire and products of combustion can get away from the fire. It is reasonable to conclude that the fire will be less hazardous when the load factor is high because of the following:

(i) the compartment is unventilated,

(ii) available air to support combustion in the compartment is less,

(iii) the products of combustion will rapidly dilute the ambient atmosphere (for constant rate of products of combustion release) and reduce oxygen partial pressure (Dalton's Law of Partial Pressure), and

(iv) halon concentrations will be higher and soak times longer,

(4) The time to 3% halon concentration is approximately 55% of the design delay time, t_{des}, when the load factor is 0.8. However, the initial halon concentration at a load factor of 0.8 is approximately 350-400% higher than the zero load factor's initial halon concentration. It is reasonable to conclude that the fire will be less hazardous, at the release of supplemental halon, when the load factor is high. This is concluded based on the data of Figure 3 (initial concentration), Figures 9 and 10 (soak time) and Figure 12 (halon dosage).

(e) <u>Effect on Halon dosage</u>

The halon dosage, D, defined as a product of halon concentration (%) and time (min), can be determined by integrating equation (13) between the limits t=0 to t=t

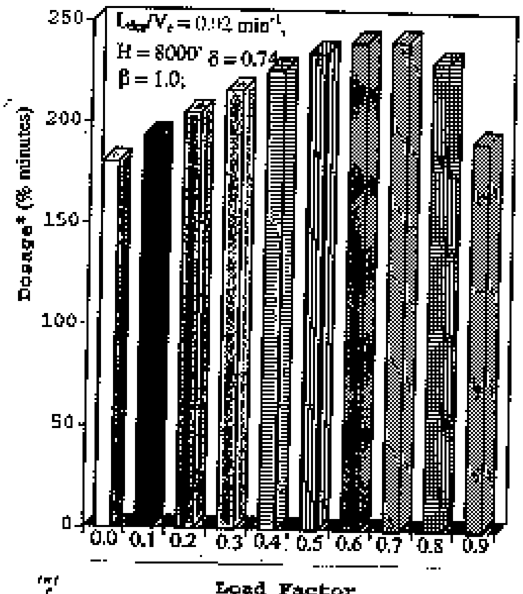
$$D = \int_{t=0}^{t=t} C_{t=t} * dt$$

$$= \frac{1}{\{1+19\delta(1-\lambda)\}} * \int_{t=0}^{t=t} e^{\frac{-\beta}{1-\lambda} * \frac{L_{des}}{V_c} * t} * dt$$

(Equation 14)

Figure 12 shows the estimated dosage (from t=0 to actual time 3% concentration) as a function of load factor. Figure 11 shows the decay time to 3% halon concentration. Note, at high load factor, the fire is exposed to a high concentration and a high dosage. This leads to the conclusion that increased load factors enhance fire suppression effectiveness.

Fig. 12 - Halon Dosage (Product of halon concentration and time)



$* = \int_{t=0}^{t=t} C_{t=t} * dt$ where t is the time to 3% halon concentration.

Conclusion

Methodology used by aviation industry to design cargo compartment fire suppression system is safe and sound. Analysis of halon concentration and residence time leads to the conclusion airplane operational parameters do not compromise fire suppression effectiveness. In fact, it can be reasonably concluded that fire suppression effectiveness increases with increase in cargo loading. Compartment leakage is a critical factor and must not be allowed to exceed the certification characteristic leakage factor, L_{des}/V_c.

Gaseous agents behave similarly in total flood systems. Thus, it can be concluded that the current design methodology, with average concentrations characteristic of the new agent, can be safely used to design non-halon fire suppression systems.

References

1. Code of Federal Regulations (CFR) 14, Part 25. Published by the Office of the Federal Register National Archives and Records Administration.

2. Standard on Halon 1301 Fire Extinguishing Systems. Published by National Fire protection Association (NFPA), 1, Batterymarch Park, PO Box 9101, Quincy, MA 02269-9101.

3. Ford, Charles L, "An appraisal of Halogenated Fire Extinhuishing Agents," E.I. du Pont de Nemours & Company. Proceedings of a symposium held at National Academy of Sciences.

4. Williamson H.V, "Halon 1301- Minimum Concentrations for Extinguishing Deep- Seated Fires," Cardox Division of Chemetron Corporation.