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DESIGN CALCULATIONS FOR A HALON 1301 DISTRIBUTION TUBE FOR AN AIRCRAFT CABIN FIRE EXTINGUISHING SYSTEM

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16. Abstract

Theoretical calculations were performed to aid in the design of a perforated tube that will uniformly distribute Halon 1301 throughout the unventilated passenger cabin of a commercial air transport. Conditions for the calculations were those of a passenger cabin of a DC-7 fuselage, with a volume of 4000 cubic feet and a length of 72 feet, being used as a test article for evaluating the performance of such a system. Four separate calculations were made to determine the (1) size and number of orifices in the tube required for various Halon 1301 discharge rates; (2) pressure drop as a function of tube diameter and discharge rates; (3) time required to fill the tube with Halon 1301 for various tube diameters; and (4) cabin temperature and pressure after completion of Halon 1301 discharge. The first calculations indicated that for a given discharge time, the required orifice diameter decreased slightly with increasing orifice number for a large number of orifices (about 40 - 50). The pressure drop was shown to be a strong function of both tube diameter and discharge time; however, practical tube diameters could be selected to assure a negligible pressure loss - a system feature which allows orifices equally spaced with the same diameter. It was demonstrated that the fill time would be less than 10 percent of most normally used discharge times - another desired system feature. Thermodynamic calculations predicted a 38°F cabin temperature after complete discharge of agent with an initial cabin temperature of 70°F and relative humidity of 50 percent.

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LIST OF SYMBOLS

A	Tubing cross-sectional area
A_{orf}	Orifice area
C_1	Constant used in Equation (7)
C_2	Constant used in Equation (7)
C_v	Specific heat at constant volume, 0.71 $\frac{BTU}{lb_m\text{-}°R}$ for air
D	Orifice diameter
g_c	Conversion factor, 32.2 $\frac{lb_m\text{-}ft}{lb_f\text{-}sec^2}$
h	Enthalpy per unit mass
h_f	Friction head loss
k	Ratio of specific heats, 1.4 for air
L	Length of each tube, 36 feet
m	Mass
$\dot{m}$	Mass flow rate
M	Molecular weight
N	Number of orifices
p	Pressure
p_i	Initial pressure in tubing, 1 atm
p_T	Storage pressure of Halon 1301, 360 psig
Δp	Pressure drop along tubing
Q	Heat required to evaporate, expand, and raise temperature of Halon 1301 (Equation 24)
R	Gas Constant
t	Time

t_d	Time to discharge Halon 1301
T	Temperature
u	Internal energy per unit mass
U	Internal energy
v	Specific volume
V	Volume
V_i	Initial volume of tubing
x	Distance along tubing
$\dot{x}$	Velocity
$\ddot{x}$	Acceleration
ε	Approximate length of accelerating fluid in Halon 1301 reservoir
ρ	Density
ϕ	Relative humidity in cabin
ω	Humidity ratio, defined as the mass of water vapor divided by the mass of dry air

Subscripts

0	Initial boundary conditions
1	Conditions before Halon 1301 discharge
2	Conditions after Halon 1301 discharge
g	Saturated water vapor properties
ℓ	Liquid water
v	Water vapor

INTRODUCTION

Purpose.

The purpose of this theoretical analysis was to aid in the design of a perforated tube that will uniformly distribute Halon 1301 throughout an unventilated passenger cabin of a commercial air transport. The desired volumetric concentration of Halon 1301 is 5 percent and a uniform distribution of agent must be obtained in a relatively short period of time in order to assure rapid fire extinguishment.

Background.

After the survivable crash of a commercial air transport, an external fuel fire may result if any components of the fuel system are ruptured. The fire will usually spread and eventually involve the passenger cabin, imposing an immediate threat to the safe evacuation of passengers. A study of survivable accidents which have occurred in the past reveals that a cabin fire may occur immediately at first impact or at a later time, depending on such unpredictable variables as the extent and location of fuel leakage, fuselage structural damage, wind speed and direction, terrain, number and location of opened emergency exits, etc. In order to provide a safer cabin environment in case of fire, the FAA adopted regulations in 1947 concerning the allowable flammability of interior materials. Keeping apace of material development technology, the FAA has continually updated and made more severe the flammability limits and has also issued in July 1969 an Advanced Notice of Proposed Rule Making intended to restrict the smoke generated by cabin materials upon exposure to flames or radiant heat. The laboratory test methods used to show compliance with FAA present flammability and future smoke regulations involve relatively small ignition sources. However, if the ignition or fire source is large enough, <u>all</u> organic materials will burn and smoke with varying degree. In the post-crash situation where the fuel fire is usually quite large, additional cabin protection could be provided by an automatic fire extinguishing system. Twenty-four-hour readiness of such a system would also protect the cabin against fires that might initiate during servicing, maintenance, overhaul and ramp parking. Major losses under these conditions have been occurring at the rate of about one to two aircraft per year.

The fire extinguishing agent bromotrifluoromethane ($CBrF_3$), or Halon 1301, has been gaining increasing usage for the protection of highcost installations and aircraft. A recent article in Fire Journal (Reference 1) stated, "Probably the 'hottest' item in fire protection today is the continued application of Halon 1301 in fixed extinguishing systems." Currently, Halon 1301 fire extinguishing systems are being used to protect electronic computer data processing rooms, museums, and in aircraft such as the B-747, DC-10, L-1011, and P-3 during assembly. Halon 1301 is enjoying its wide popularity not only because of its effective and efficient fire suppression capability, but also because of its low toxicity in the concentrations required for fire extinguishment.

Although the aviation industry has had considerable experience over the past 20 years in the development and use of Halon 1301 protection systems for the extinguishment of fires occurring within the engine nacelle, no comprehensive quantitative study has been made to determine the usefulness of a permanent system for the protection of the passenger cabin of a commercial air transport during a survivable post-crash fire. To achieve this end, a project has been initiated at the National Aviation Facilities Experimental Center (NAFEC) entitled, "Develop Transport Cabin Fire Control Partitions and Fire Suppression Systems." One of the objectives of the fire suppression system phase of this project is to evaluate the effectiveness of a Halon 1301, perforated tube dispensing system. Tests will be performed in the fully-furnished passenger cabin of a DC-7 fuselage, which has an air volume of 4000 cubic feet. The perforated tube fire suppression system consists of a 72-foot-long tube running along the cabin ceiling and connected to Halon 1301 storage containers at each end of the fuselage (Figure 1). Each storage container is superpressurized to 360 psig with nitrogen.

The topics to be discussed in this theoretical analysis of the perforated tube extinguishing system are (1) the relationship between orifice size and number of orifices; (2) the pressure drop along the length of tubing; (3) the time required to fill the tube with Halon 1301; and (4) the cabin temperature and pressure after discharge of Halon 1301.

DISCUSSION

Size and Number of Orifices in the Tube Required for Various Halon 1301 Discharge Rates

In the design of a tube having uniform orifices for discharging Halon 1301, one should consider the relation between orifice diameter (D), number of orifices (N), and discharge time (t_d). For an agent container storage pressure of 360 psig and zero pressure loss to the orifice, the mass flow rate of Halon 1301 ($\dot{m}$) per orifice area (see Reference 2) may be expressed as

$$\frac{\dot{m}/N}{A_{orf}} = 65.5 \text{ lb}_m/\text{sec-in}^2 \qquad (1)$$

This experimental data was obtained for the discharge of Halon 1301 through a nozzle and is used for lack of any similar experimentation with orifices.

Since

$$\dot{m} = m/t_d \qquad (2)$$

and

$$A_{orf} = \pi D^2/4 \qquad (2A)$$

Substituting Equations (2) and (2A) into Equation (1) and solving for D, one obtains that

$$D = 0.139\sqrt{m/Nt_d} \qquad (3)$$

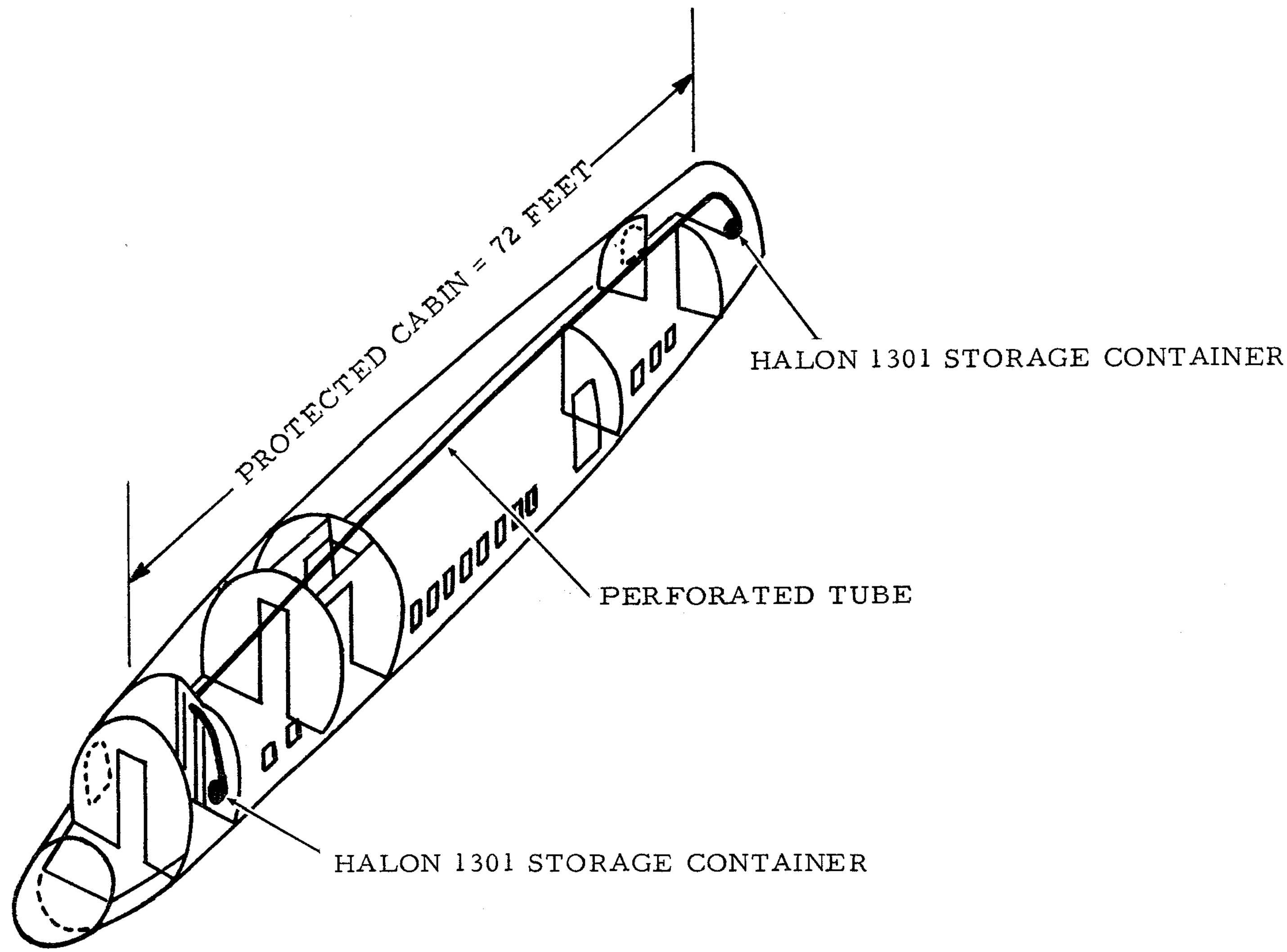


FIGURE 1. LOCATION OF PERFORATED TUBE IN PROTECTED CABIN OF DC-7 FUSELAGE

The mass of Halon 1301 may be calculated from the ideal gas law

$$m = pV/RT \tag{4}$$

For Halon 1301, which has a molecular weight of 149

$$R = 1545/M \ \frac{ft - lb_f}{lb_m - °R}$$

$$= 10.37 \ \frac{ft - lb_f}{lb_m - °R} \tag{5}$$

Considering that the Halon 1301 must occupy 5 percent of the cabin air volume (4000 ft^3)

$$V = (.05)\ (4000\ ft^3)$$

$$= 200\ ft^3 \tag{6}$$

From Equations 4, 5, and 6, and assuming p = 14.7 psi and T = 70°F

$$m = \frac{(14.7\ \frac{lb_f}{in^2})\ (200\ ft^3)\ (144\ \frac{in^2}{ft^2})}{(10.37\ \frac{ft - lb_f}{lb_m - °R})\ (530°R)}$$

or

$$m \simeq 80\ lb_m$$

Thus, if two Halon containers are used, each must contain approximately 40 pounds of agent.

Equation 3 gives the relationship between discharge time, number of orifices, and orifice diameter (Figure 2). From Figure 2, for any given discharge time the orifice diameter required decreases slower with increasing number of orifices the larger the number of orifices. This trend is favorable because a large number of orifices tends to spread the extinguishing agent uniformly throughout the cabin. Furthermore, a small diameter jet of agent will have a higher surface area to volume ratio, thus increasing the agent evaporation process. For example, for a nominal 10 second discharge, 50 orifices with a 0.394-inch diameter should not only adequately spread the agent, but should be easy to make and cause no significant structural weakening of the tubing.

Pressure Drop as a Function of Tube Diameter and Discharge Rate.

In further considering the design of a Halon 1301 fire protection system, it is highly desirable to have a negligible pressure drop along the length of tubing in order to rapidly achieve a uniform distribution of agent throughout the cabin. From a log-log graph of pressure gradient versus mass flow rate for the flow of Halon 1301 in copper tubing (Reference 2),

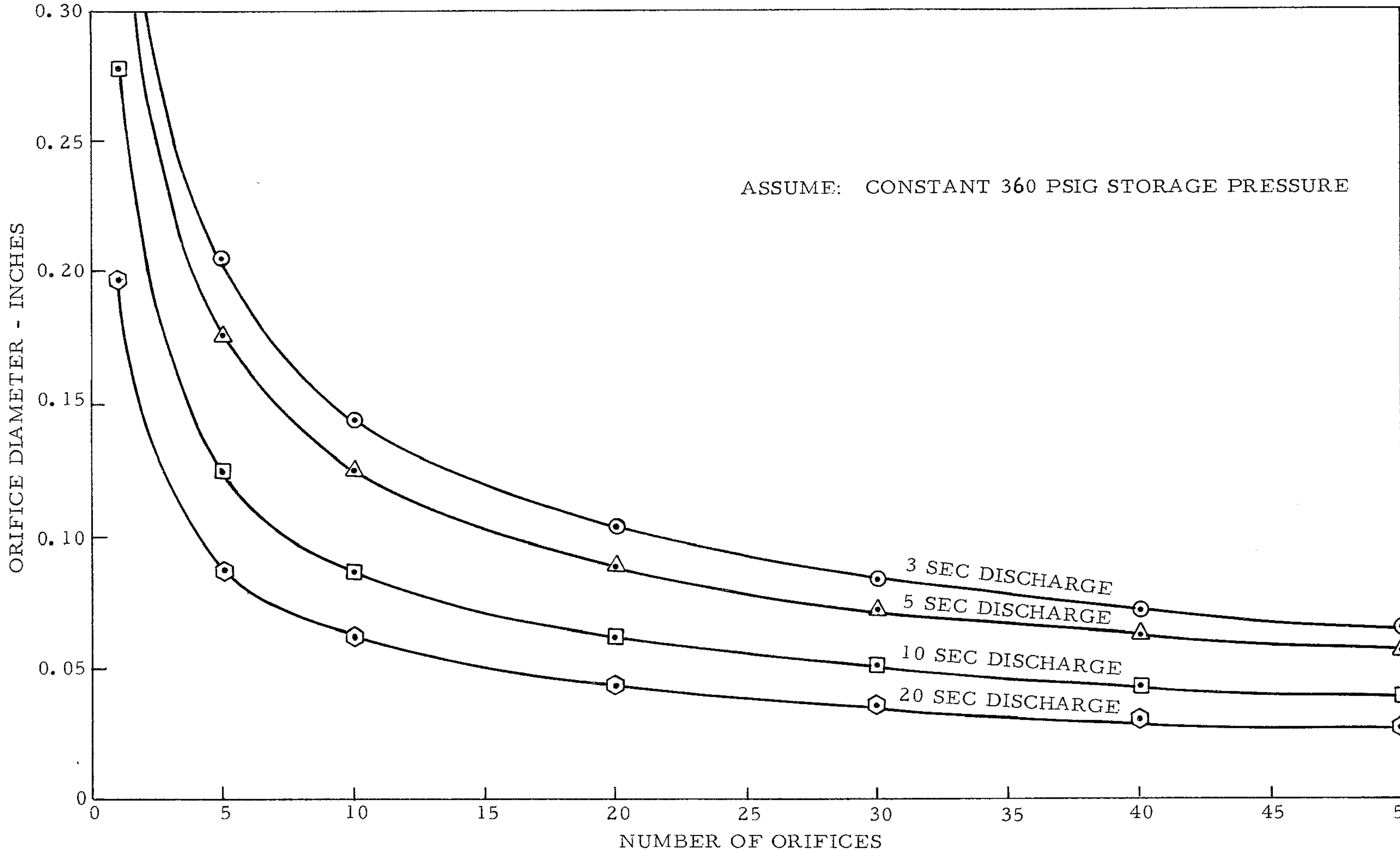


FIGURE 2. VARIATION OF ORIFICE DIAMETER WITH NUMBER OF ORIFICES FOR A 40-POUND DISCHARGE OF HALON 1301

one may linearize the relationship between $\log_{10} \frac{dp}{dx}$ and $\log_{10} \dot{m}$ in the region of expected mass flow rate. Thus, for any given diameter tubing and region of mass flow rate, the constants C_1 and C_2 may be determined such that

$$\log_{10} \frac{dp}{dx} = C_1 \log_{10} \dot{m} + C_2 \tag{7}$$

or

$$\frac{dp}{dx} = 10^{(C_1 \log_{10} \dot{m} + C_2)}$$

$$\frac{dp}{dx} = 10^{C_2} (\dot{m})^{C_1} \tag{8}$$

The constants C_1 and C_2 were determined to be

Tubing Inside Diameter (inches)	C_1	C_2
0.25	2.60	1.34
0.50	2.56	-0.67
0.70	2.45	-1.43
1.00	2.32	-2.28
1.20	2.18	-2.63
1.50	1.98	-2.99

If an infinite number of small orifices are assumed to exist along the tubing, the horizontal mass flow rate through the tubing at any given distance x along the tubing for a uniform discharge rate of agent (Figure 3) is related to the initial mass flow rate by

$$\dot{m}(x) = \dot{m}_0 \left(\frac{L-x}{L}\right) \tag{9}$$

The length of pipe L was considered to be 36 feet, since for the system used each agent container filled only half the total length of tubing.
The initial mass flow rate is given by

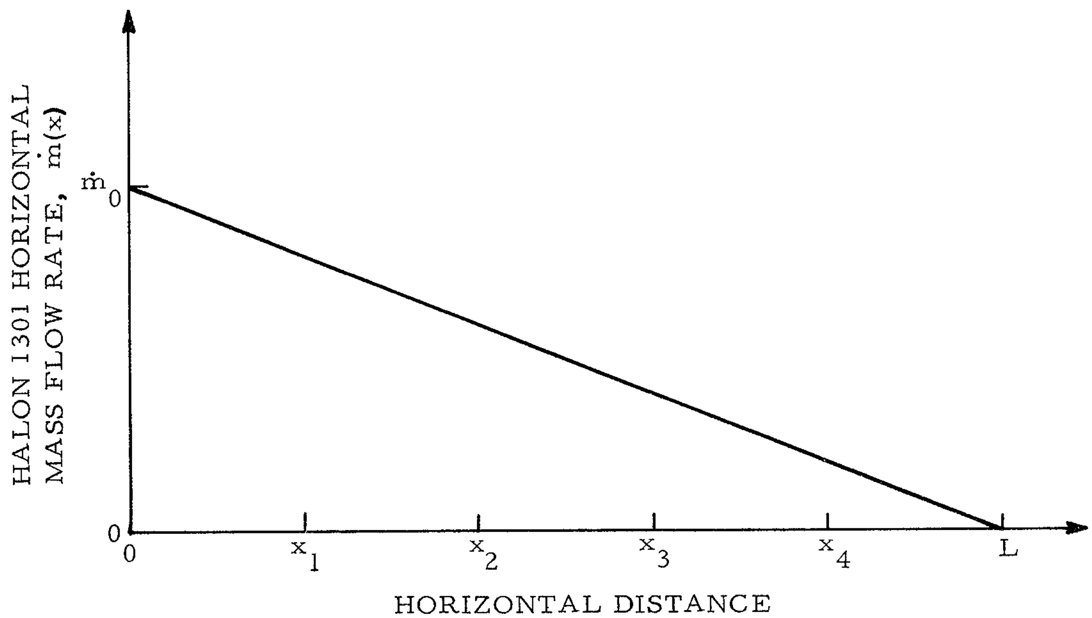
$$\dot{m}_0 = \frac{40 \text{ lb}_m}{t_d} \tag{10}$$

The total pressure drop along the tube is

$$\Delta p = \int_0^L \frac{dp}{dx} dx \tag{11}$$

Substituting Equations 8, 9 and 10 into Equation 11 gives

$$\Delta p = \int_0^L 10^{C_2} \left[\left(\frac{40}{t_d}\right)\left(\frac{L-x}{L}\right)\right]^{C_1} dx$$



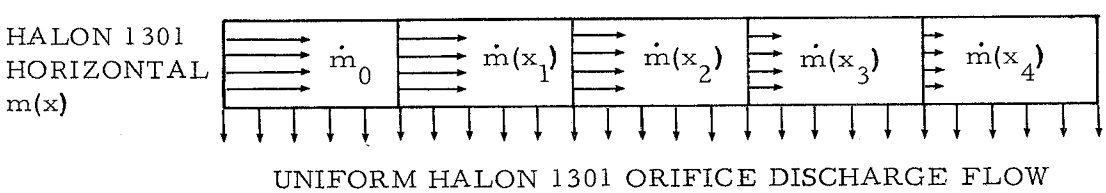


FIGURE 3. ASSUMED HORIZONTAL MASS FLOW RATE DISTRIBUTION OF HALON 1301 WITHIN PERFORATED TUBING

After integration

$$\Delta p = \left(\frac{40}{Lt_d}\right)^{C_1}\left(\frac{10^{C_2}}{C_1+1}\right)\left(L^{C_1+1}\right) \tag{12}$$

The total pressure drop along the tubing was calculated using Equation 12 for different tube diameters and discharge rates (times), and is plotted in Figure 4. Examination of Figure 4 indicates that the pressure drop is a very strong function of both tube diameter and discharge rate. As can readily be seen, very small diameter tubes cause pressure drops higher than those available - the Halon 1301 is stored at only 360 psig. Even pressure drops as low as 160 psi cannot be tolerated since Halon 1301 at 70°F evaporates at 200 psi, and the resulting two-phase agent discharge would not effectively promote the turbulent mixing with air required to produce a uniform Halon 1301/air mixture throughout the cabin, as industrial experience has demonstrated is the case when the agent discharges as a liquid. Another unfavorable chacteristic of not having the agent discharge as a liquid is the substantial increase in discharge time.

Since a small pressure drop is required to achieve uniform agent distribution, one would want a large diameter pipe for any given discharge rate. Alternatively, for any given pressure drop, a longer discharge time allows a smaller diameter pipe to be used. This is structurally desirable since a smaller diameter pipe has less surface area and thus can more easily withstand the high internal pressure without necessitating a thick wall with its unwanted weight increase. A longer discharge rate, however, is unacceptable if quick fire extinquishment is needed. For a nominal 10 second discharge recommended by the National Fire Protection Association (Reference 2), inside diameters less than about 0.70 inches would produce high pressure drops, while inside diameters greater than 1.00 inch would result in a relatively small pressure drop.

<u>Time Required to Fill the Agent Discharge Tube with Halon 1301 for Various Tube Diameters</u>

To rapidly extinguish a fire, it is essential that the tube fill and discharge quickly. In addition, it is desirable that a negligible amount of agent be discharged during the transient fill-up process in order to prevent a non-uniform distribution of agent within the cabin. In Appendix A, a numerical method is described for calculating the time to fill a tube with Halon 1301, taking into consideration unsteady acceleration of the fluid, friction effects, pressure loss due to the fluid velocity, and compression of the air ahead of the advancing fluid. However, any possible two-phase flow boundary layer effects were neglected.

In order to better understand the fluid mechanics taking place within the tube, graphs of displacement, velocity, and acceleration (Figures 5 and 6) were made for a nominal 10-second discharge from a one-inch-inside-diameter tube. From these curves, the agent is seen to have a tremendous initial acceleration because of the large storage pressure. After approximately

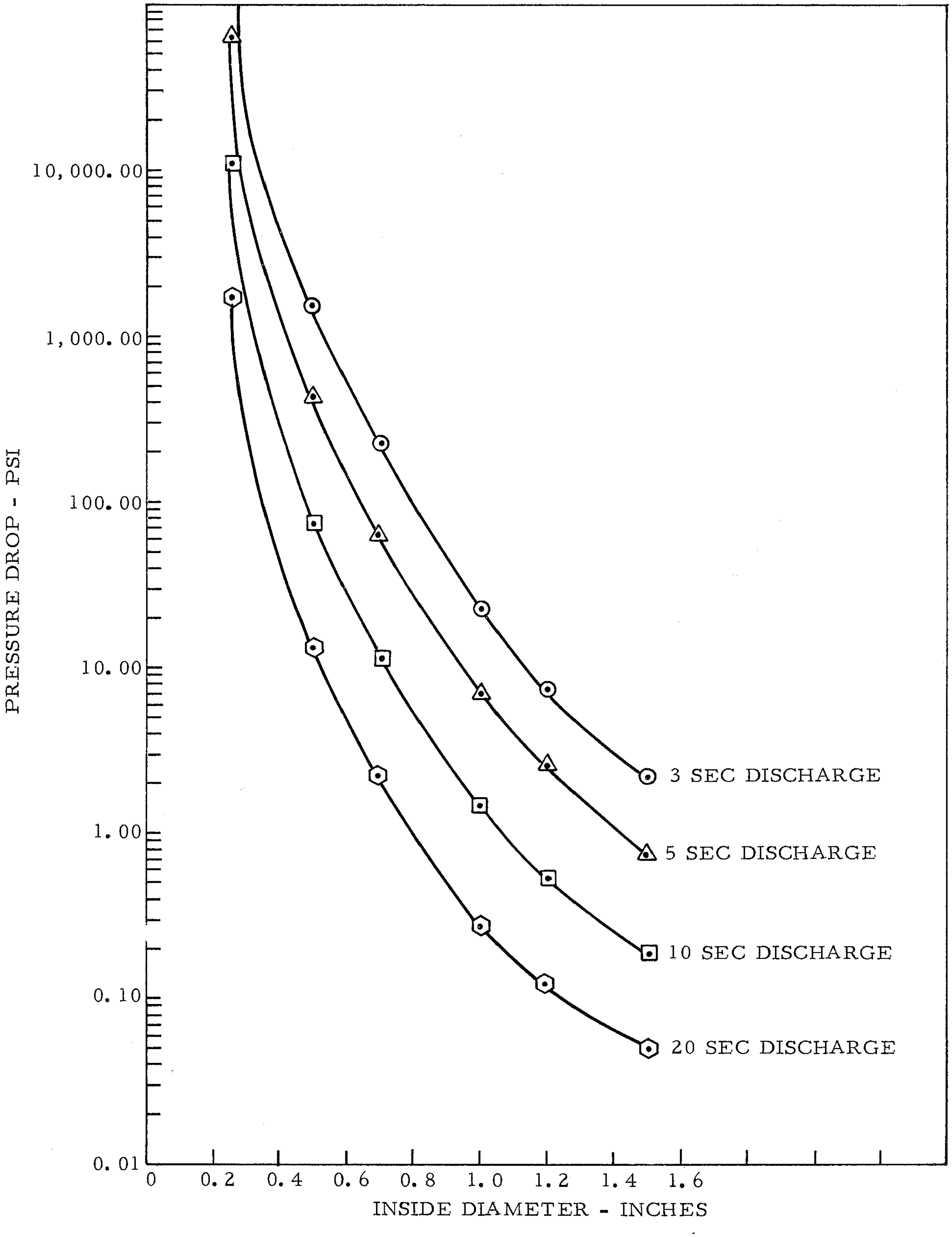


FIGURE 4. VARIATION OF PRESSURE DROP WITH DIAMETER RESULTING FROM A 40-POUND DISCHARGE OF HALON 1301 FROM A COPPER TUBE 36 FEET LONG

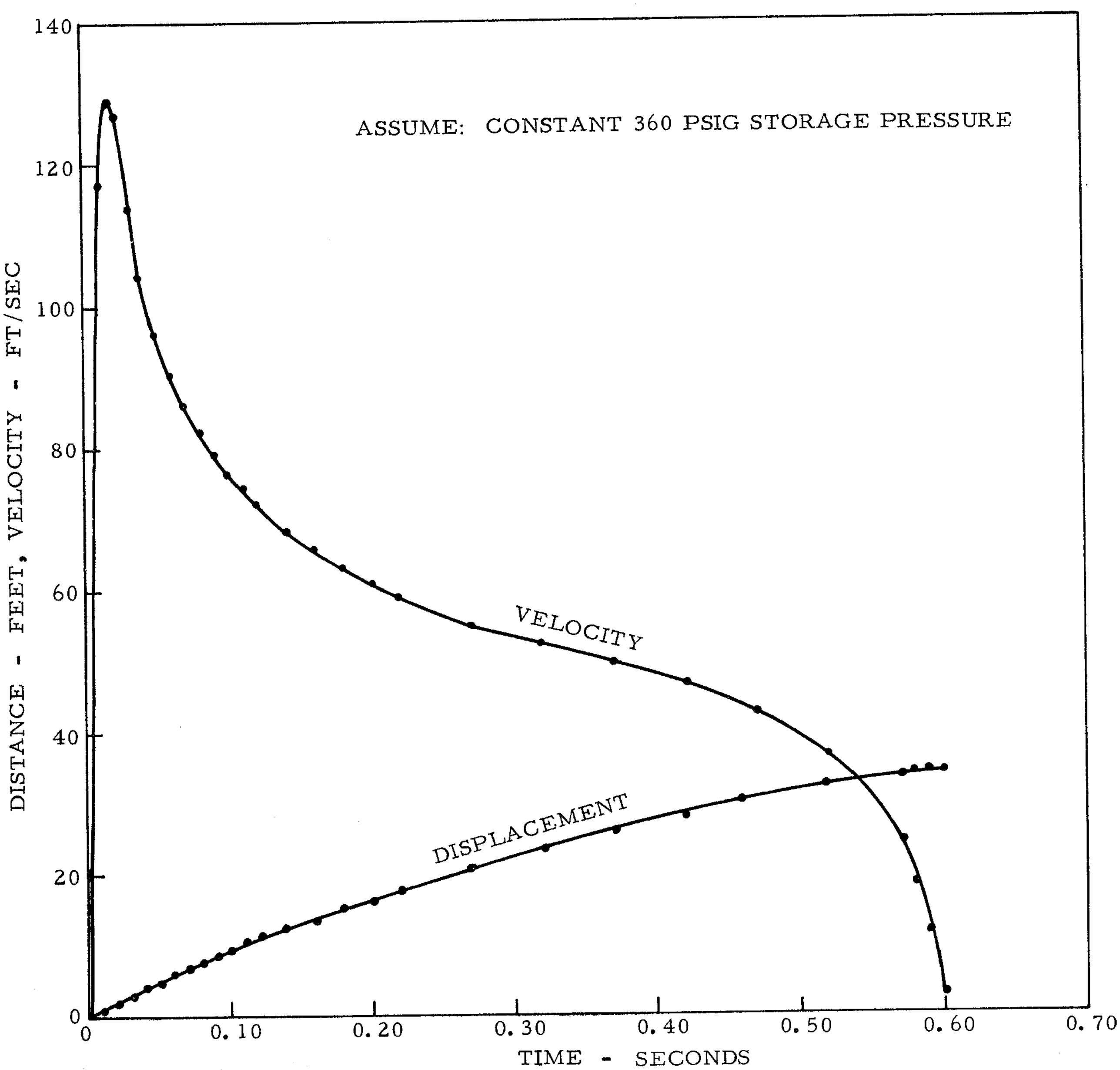


FIGURE 5. HALON 1301 DISPLACEMENT AND VELOCITY FOR UNSTEADY FILLING OF A 36-FOOT, 1-INCH-INSIDE DIAMETER COPPER TUBE

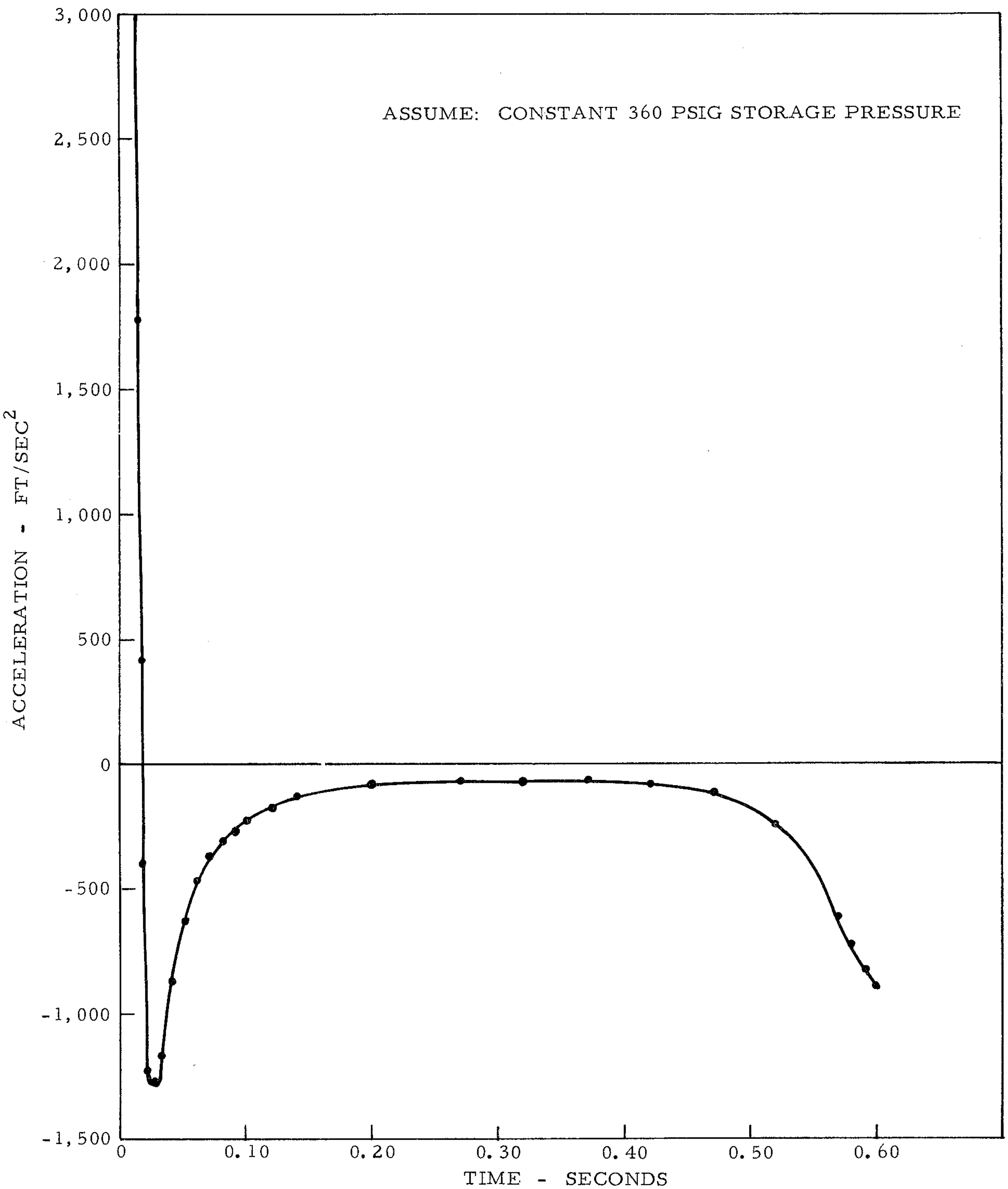


FIGURE 6. HALON 1301 ACCELERATION FOR UNSTEADY FILLING A 36-FOOT, 1-INCH-INSIDE DIAMETER COPPER TUBE

0.015 seconds, however, the acceleration reaches zero as friction effects become dominant, acting to slow the agent down from its maximum velocity. As the agent slows down further, the friction effects, which are a strong function of mass flow rate, become less important and the deceleration is seen to decrease. At $t \approx 0.45$ seconds, the compression of the air within the tubing ahead of the advancing agent is seen to become more important and eventually stops the agent at $t \approx 0.60$ seconds and $x \approx 34$ feet. It should be noted that the deceleration of agent due to compression of air within the tubing is somewhat less than that indicated on the graph, since a certain amount of air escapes through the tube orifices. However, the air does not appreciably compress until the agent is far down the tube where there are only a few orifices remaining from which the air may escape. Thus, unless dealing with large fill-up times, the air compression assumption is valid.

From Figure 7, the time required to fill the tube with Halon 1301 is seen to greatly increase as the tube diameter decreases. The change in fill time is seen to become small as larger diameter tubes are used. Although not shown on the graph, the fill time asymptotically approaches 0.22 seconds as the diameter becomes very large. Smaller diameter tubes are desirable, however, because of their previously mentioned structural strength and low weight. Since larger fill times delay fire extinguishment and may cause an uneven distribution of agent from leakage through the orifices during filling, one should use the smallest diameter tube for any allowable fill time. If an arbitrary fill time to discharge time ratio of 1:10 is chosen, the minimum allowable inside diameter for a 10-second discharge is 0.82 inches.

Cabin Temperature and Pressure After Completion of Halon 1301 Discharge

A calculation procedure for predicting the cabin temperature and pressure after the complete discharge of Halon 1301 is described in Appendix B. Assuming that the initial cabin temperature and pressure are 70°F and 14.7 psia, the following final cabin temperatures and pressures were calculated for two different initial relative humidities :

ϕ_1	T_2 (°F)	p_2 (psia)
0.50	38.3	14.48
0.75	47.1	14.78

As can be seen, the final cabin temperature is strongly dependent upon the initial relative humidity inside the cabin, whereas the final pressure remains approximately one atmosphere (slightly less for 50 percent relative humidity and slightly more for 75 percent relative humidity). It should be noted that the cabin will become uncomfortably moist after completion of agent discharge, since the relative humidity rises to 100 percent and misting occurs, possibly causing low visibility and wet, slippery conditions. Unfortunately, although a low initial relative humidity causes less misting, it also causes a greater temperature drop, thus adding to passenger discomfort if the system inadvertently discharges.

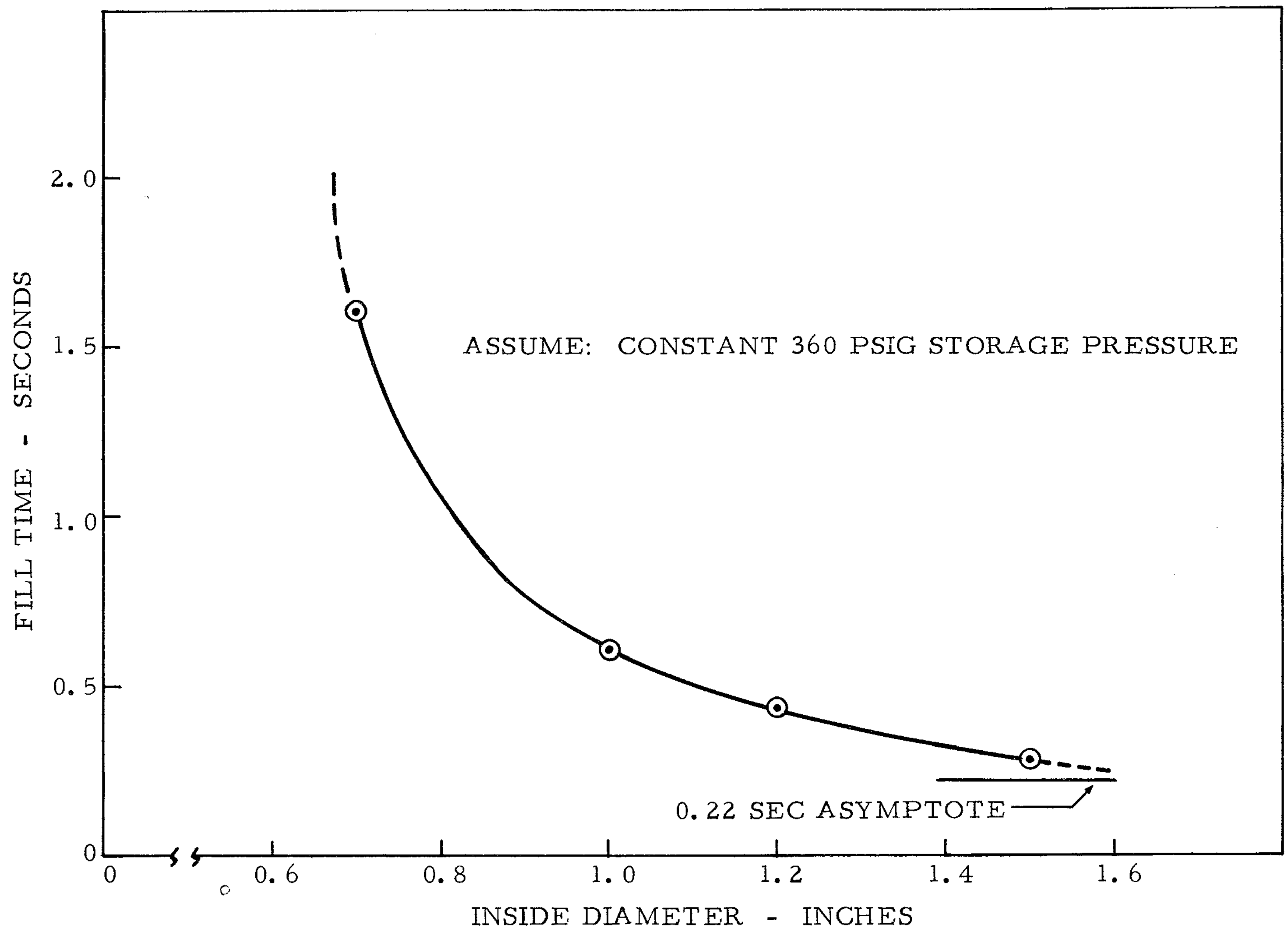


FIGURE 7. VARIATION OF FILL TIME WITH INSIDE DIAMETER FOR FILLING A 36-FOOT TUBE WITH 40 POUNDS OF HALON 1301

SUMMARY OF RESULTS

1. For a design discharge time, the orifice diameter becomes significantly reduced and relatively invariant for a large number of orifices. For example, if a 40-pound discharge of Halon 1301 is desired over a period of 10 seconds, the orifice diameter will be reduced from 0.124 to 0.0719 inches (42 percent) when the number of orifices is increased from 5 to 15; however, if the number of orifices is increased from 40 to 50, the orifice diameter will be only reduced from 0.0439 to 0.0394 inches (10.2 percent).

2. The pressure drop along a perforated tube discharging Halon 1301 is a very strong function of both tube diameter and discharge time. For example, if 40 pounds of agent is discharged from a 36-foot tube in 10 seconds, the pressure drop will be reduced from 70 to 1.5 when the tube diameter is increased from 0.5 to 1.0 inch. Similarly, if 40 pounds of agent is discharged from a 36-foot tube with a 0.8 inch diameter, the pressure drop will be increased from 1 to 100 psi when the discharge time is reduced from 20 to 3 seconds.

3. If a 40-pound liquid discharge of Halon 1301 is desired along the entire length of a 36-foot tube (maximum allowable pressure drop is 160 psi for a 360 psi storage pressure), the minimum inside tube diameter for discharge times of 20, 10, 5 and 3 seconds is 0.32, 0.43, 0.58 and 0.74 inches, respectively.

4. If a 40-pound discharge of Halon 1301 is desired at constant pressure (assuming that a 10 psi pressure drop is negligible) along the entire length of a 36-foot tube, the minimum inside tube diameter for discharge times of 20, 10, 5 and 3 seconds is 0.52, 0.71, 0.94 and 1.14 inches, respectively.

5. The time required to fill a 36-foot tube with 40 pounds of Halon 1301 increases drastically for tube diameters smaller than about 0.7 inches. As the tube diameter is increased from this value, the fill time gradually decreases and asymptotically approaches 0.22 seconds.

6. The final temperature inside a 4000-cubic-foot cabin after the discharge of 80 pounds of Halon 1301 is dependent upon the initial relative humidity. If the initial temperature is 70 °F and the initial relative humidities are 50 percent and 75 percent, then the final temperatures will be 38.3 and 47.1°F, respectively.

CONCLUSIONS

Based upon the results of the theoretical calculations for the conditions and assumptions used, it is concluded that:

1. A practical tube diameter can be selected for any normally used discharge duration such that a negligible pressure drop occurs along the length of tubing. Since it is desirable to have the same discharge flow rate from each orifice in order to expeditiously achieve a uniform agent distribution throughout the cabin, a constant tube pressure allows the designer to use orifices with equivalent area and spacing, thus considerably simplifying the orifice arrangement which would have to be graduated if a pressure loss existed along the line.

2. A practical tube diameter can be selected such that the time required to fill the tubing with agent is 10 percent or less than most normally used discharge durations (2 - 10 seconds). Rapid filling of the tube is also necessary to expeditiously achieve a uniform agent distribution throughout the cabin by assuring that the total mass of agent discharged from each orifice will be nearly equal; i.e., a negligible amount of agent will be discharged during the filling process.

3. The required orifice diameter for a large number of orifices (about 50) is well within the range of available drill sizes. A large number of orifices is advantageous in order to uniformly distribute the agent, hasten the agent vaporization process and decrease the possibility of direct agent impingement upon passengers.

4. The minimum possible temperature near any passengers after the complete vaporization of Halon 1301, assuming an initial cabin temperature of 70°F and relative humidity of 50 percent, is about 38°F. In reality, the coldest temperatures are obviously expected near the orifices during discharge with the actual temperature felt by any seated passengers being warmer than the calculated minimum because of heat losses from cabin surfaces contacted by the agent.

APPENDIX A

CALCULATION PROCEDURE FOR PREDICTING THE TIME REQUIRED TO FILL A TUBE WITH HALON 1301 FOR VARIOUS TUBE DIAMETERS

Ignoring any two phase flow effects that may exist, the generalized Bernoulli equation for non-steady, non-ideal fluids is (Reference 3)

$$\frac{p_T}{\rho} = \frac{\dot{x}^2}{2g_c} + \frac{p}{\rho} + \frac{1}{g_c}\int_0^x \ddot{x}dx + \frac{h_f}{\rho} \tag{13}$$

The friction head loss h_f is given by Equation 11

$$h_f = \Delta p = \int_0^x \frac{dp}{dx}\, dx \tag{14}$$

As opposed to the steady state problem discussed earlier, $\frac{dp}{dx}$ for this case is constant for any given x (any loss of agent through orifices during filling is neglected) and may thus be taken outside the integral sign. The pressure gradient $\frac{dp}{dx}$ is given by Equation 8 with

$$\dot{m} = \rho A\dot{x} \tag{15}$$

Substituting Equations 8 and 15 into Equation 14 gives

$$h_f = x10^{C_2}(\rho A\dot{x})^{C_1} \tag{16}$$

For isentropic compression of the air ahead of the advancing fluid (Reference 4), the air pressure p may be written as

$$\frac{p_i}{p} = \left(\frac{V}{V_i}\right)^k = \left(\frac{L-x}{L}\right)^k \tag{17}$$

or

$$p = p_i \left(\frac{L}{L-x}\right)^k \tag{18}$$

Since the liquid Halon 1301 may be considered an incompressible fluid, $\ddot{x}$ is uniform for any x at a given time and may thus be taken outside the integral sign in Equation 13. Also, if one considers the acceleration of a length ε of fluid in the reservoir, the integral term in Equation 13 becomes

$$\frac{1}{g_c}\int_0^x \ddot{x}dx = \frac{\ddot{x}}{g_c}\int_{-\varepsilon}^x dx \tag{19}$$

$$\frac{1}{g_c}\int_0^x \ddot{x}\,dx = \frac{\ddot{x}(x+\varepsilon)}{g_c} \tag{20}$$

By substituting Equations 16, 18 and 20 into Equation 13, one obtains

$$\frac{p_T}{\rho} = \frac{\dot{x}^2}{2g_c} + \frac{p_i}{\rho}\left(\frac{L}{L-x}\right)^k + \frac{\ddot{x}(x+\varepsilon)}{g_c} + \frac{x10^{C_2}\,(\rho A\dot{x})^{C_1}}{\rho} \tag{21}$$

Solving for $\ddot{x}$ gives

$$\ddot{x} = \frac{g_c}{\rho(x+\varepsilon)}\left[p_T - \frac{\rho\dot{x}^2}{2g_c} - p_i\left(\frac{L}{L-x}\right)^k - x10^{C_2}\,(\rho A\dot{x})^{C_1}\right] \tag{22}$$

For the region of expected mass flow rate, the following values of C_1 and C_2 were obtained (Reference 1)

Inside Diameter (Inches)	C_1	C_2
0.7	2.57	-1.43
1.0	2.57	-2.59
1.2	2.55	-2.99
1.5	2.44	-3.44

An approximate value of $\varepsilon = 1$ foot was chosen, as it was felt that this approximately represented the amount of fluid that must be initially accelerated. Computer studies showed that the value of ε could be either raised or lowered an order of magnitude without significantly affecting the calculated fill time. A value of $\varepsilon > 0$ must be chosen, since $\varepsilon = 0$ would lead to an infinite acceleration at $x = 0$.

The final differential equation (22) was solved with a computer utilizing the following simple numerical technique

1) At $t = t_0 = 0$, $x_0 = 0$

   $\dot{x}_0 = 0$

   $\ddot{x}_0$ was calculated from Equation 22 using x_0 and $\dot{x}_0$

2) At $t = t_1$, $x_1 = \frac{1}{2}\ddot{x}_0\,(t_1 - t_0)^2$

   $\dot{x}_1 = \ddot{x}_0\,(t_1 - t_0)$

   $\ddot{x}_1$ was calculated from Equation 22 using x_1 and $\dot{x}_1$

3) At $t = t_2$,

$$x_2 = x_1 + \dot{x}_1 \, (t_2 - t_1) + \frac{1}{2} \ddot{x}_1 \, (t_2 - t_1)$$

$$\dot{x}_2 = \dot{x}_1 + \ddot{x}_1 \, (t_2 - t_1)$$

$\ddot{x}_2$ was calculated from Equation 22 using x_2 and $\dot{x}_2$

. . . .

n+1) At $t = t_n$,

$$x_n = x_{n-1} + \dot{x}_{n-1} \, (t_n - t_{n-1}) + \frac{1}{2} \ddot{x}_{n-1} (t_n - t_{n-1})^2$$

$$\dot{x}_n = \dot{x}_{n-1} + \ddot{x}_{n-1} \, (t_n - t_{n-1})$$

$\ddot{x}_n$ was calculated from Equation 22 using x_n and $\dot{x}_n$

The various times t_1, t_2, t_3, ... t_n were chosen to give relatively small time increments $t_2 - t_1$, $t_3 - t_2$ ... $t_n - t_{n-1}$ (typically on the order of .001 second) such that the solution converged closely to the same value when smaller time increments were used. The pipe was considered full when $\dot{x}_n = 0$; i.e., when the flow of Halon 1301 ceased.

APPENDIX B

CALCULATION PROCEDURE FOR PREDICTING THE CABIN TEMPERATURE AND PRESSURE AFTER COMPLETION OF HALON 1301 DISCHARGE

The following information is known (the subscripts 1 and 2 denote, respectively, conditions before and after discharge of agent):

$$V_{cabin} = 4000 \text{ ft}^3$$

$$T_{1,air} = 70°F$$

$$p_{1,air} = 14.7 \text{ psi}$$

$$m_{1301} = 80 \text{ lb}_m$$

$$T_{1,1301} = 70°F$$

$$p_{1,1301} = 360 \text{ psig}$$

The first law of thermodynamics for this constant volume process reduces to (the subscripts v and ℓ denote respectively water vapor and water liquid)

$$Q = m_{air}C_{v,air}(T_2-T_1) + (m_2u_2)_v + (m_2u_2)_\ell - (m_1u_1)_v \tag{23}$$

where Q is the heat used to evaporate, expand, and raise the temperature of the Halon 1301; i.e.,

$$\begin{aligned} Q &= (U_1 - U_2)_{1301} \\ &= m_{1301}\left[(h_1-p_1v_1) - (h_2-p_2v_2)\right]_{1301} \end{aligned} \tag{24}$$

A solution to Equations 23 and 24 was found by assuming a final temperature T_2 and comparing Equations 23 and 24. When the difference between the two equations was zero, the solution was obtained.

From the ideal gas law

$$\begin{aligned} (p_2v_2)_{1301} &= (R\ T_2)_{1301} \\ &= \left(\frac{1545}{149}\frac{\text{ft-lb}_f}{\text{lb}_m\text{-°R}}\right)\left(\frac{\text{BTU}}{778 \text{ ft-lb}_f}\right)T_2 \end{aligned}$$

or

$$(p_2v_2)_{1301} = (1.337 \times 10^{-2} \ \frac{BTU}{lbm\text{-}°R})T_2 \tag{25}$$

As a liquid at 70°F and 360 psig

$$(p_1v_1)_{1301} = (.01 \ \frac{ft^3}{lb_m}) \ (360 \ \frac{lbf}{in^2}) \ (144 \ \frac{in^2}{ft^2})(\frac{BTU}{778 \ ft\text{-}lbf})$$

or

$$(p_1v_1)_{1301} = 0.67 \ BTU/lb_m \tag{26}$$

From Reference 5

$$C_{v,air} = 0.171 \ \frac{BTU}{lb_m\text{-}°R} \tag{27}$$

and from Reference 6

$$(h_1)_{1301} = 20.08 \ BTU/lb_m \tag{28}$$

Case 1 . Relative Humidity =50 percent ($\phi_1 = 0.50$)

At T_1=70°F and ϕ_1=0.50, from a psychrometric chart

$$\omega_1 = 0.00775 \ \frac{lb_m \text{ water vapor}}{lb_m \text{ dry air}}$$

$$v_{1,\text{dry air}} = 13.52 \ ft^3/lb_m$$

Therefore

$$m_{1,\text{dry air}} = V_{cabin}/v_{1,\text{dry air}}$$

$$= \frac{4000 \ ft^3}{13.52 \ ft^3/lb_m}$$

or

$$m_{1,\text{dry air}} = 303.03 \ lb_m \tag{29}$$

From Reference 5

$$m_{v1} = \omega_1 m_{1,\text{dry air}} = (0.00775 \ \frac{lb_m \text{ water vapor}}{lb_m \text{ dry air}})(303.03 \ lb_m \text{ dry air})$$

$$= 2.348 \ lb_m \tag{30}$$

The internal energy of the water vapor is equal to the internal energy of saturated vapor at the same temperature. Therefore

$$m_{v1} = \omega_1 m_{1,\text{dry air}}$$

$$u_{v1} = u_{g1} = h_{g1} - p_v v_{g1}$$

$$= 1092.3 \frac{\text{BTU}}{\text{lb}_m \text{ water vapor}} - \frac{(0.3631 \frac{\text{lbf}}{\text{in}^2})(144 \frac{\text{in}^2}{\text{ft}^2})(867.9 \frac{\text{ft}^3}{\text{lb}_m \text{ water vapor}})}{778 \frac{\text{ft-lbf}}{\text{BTU}}}$$

$$u_{v1} = 1034.1 \text{ BTU/lb}_m \tag{31}$$

Assuming $T_2 = 35°F$ and a saturated vapor ($\phi_2 = 1.00$)

$$u_{v2} = 1077.1 \frac{\text{BTU}}{\text{lb}_m \text{ water vapor}} - \frac{(.09995 \frac{\text{lbf}}{\text{in}^2})(144 \frac{\text{in}^2}{\text{ft}^2})(2947 \frac{\text{ft}^3}{\text{lb}_m \text{ water vapor}})}{778 \frac{\text{ft-lbf}}{\text{BTU}}}$$

$$u_{v2} = 1022.6 \text{ BTU/lb}_m \tag{32}$$

From a psychrometric chart at $T_2 = 35°F$ and $\Phi_2 = 1.00$

$$\omega_2 = .0044 \frac{\text{lb}_m \text{ water vapor}}{\text{lb}_m \text{ dry air}}$$

Therefore $m_{v2} = \omega_2 m_{1,\text{dry air}}$

$$= (.0044 \frac{\text{lb}_m \text{ water vapor}}{\text{lb}_m \text{ dry air}})(303.03 \text{ lb}_m \text{ dry air})$$

$$m_{v2} = 1.333 \text{ lb}_m \tag{33}$$

and

$$m_{\ell 2} = m_{v1} - m_{v2}$$
$$= 2.348 - 1.333$$
$$m_{\ell 2} = 1.015 \text{ lb}_m \tag{34}$$

For a saturated liquid at 35°F

$$u_{\ell 2} = 3.02 \text{ BTU/lb}_m \tag{35}$$

As a gas at low pressure and at 35°F, using Reference 6

$$(h_2)_{1301} = 56.98 \text{ BTU/lb}_m \tag{36}$$

From Equation 25 at $T_2 = 35°F = 495°R$

$$(p_2 v_2)_{1301} = 6.62 \text{ BTU/lb}_m \tag{37}$$

Substituting Equations (26-37) into the difference between Equations (24) and (23) gives

$$\text{Equation (24) - Equation (23)} = 400\ \text{BTU/lb}_m \tag{38}$$

As seen from the results shown in Table B-1, similar calculations were performed for $\phi_1 = 0.50$ and assuming that $T_2 = 40°F$. Since the last row in the table, Equation 24 - Equation 23, had opposite signs for $T_2 = 35°F$ and $T_2 = 40°F$, a solution to the difference between these equations existed in between the assumed temperatures of 35°F and 40°F. By interpolation it was determined that $T_2 = 38.3°F$. Using a similar calculation procedure for $\phi_1 = 0.75$, with the important values shown in Table 1, it was determined that $T_2 = 47.1°F$.

If $\phi_1 = 0.50$, the final pressure due to dry air is

$$p_{2,\text{dry air}} = (p_1 - p_{g_1}\phi_1)\left(\frac{T_2}{T_1}\right)$$

$$= \left[\left(14.7\ \frac{\text{lbf}}{\text{in}^2}\right) - \left(0.3631\ \frac{\text{lbf}}{\text{in}^2}\right)(0.50)\right]\left(\frac{498.3°R}{530.3°R}\right)$$

$$= 13.65\ \text{psia} \tag{39}$$

Also $\quad p_{v2} = p_{g2} = 0.11\ \text{psia}$ $\hfill (40)$

and $\quad p_{2,1301} = \left(\frac{R\ T_2}{v_2}\right)_{1301}$

$$= \left(\frac{1545}{149}\ \frac{\text{ft-lb}_f}{\text{lb}_m\text{-}°R}\right)\left(\frac{498.3°R}{50\ \text{ft}^3/\text{lb}_m}\right)\left(\frac{\text{ft}^2}{144\ \text{in}^2}\right)$$

$$p_{2,1301} = 0.72\ \text{psia} \tag{41}$$

Since $p_2 = p_{2,\text{dry air}} + p_{v2} + p_{2,1301}$ adding Equations 39, 40, and 41 gives

$$p_2 = 14.48\ \text{psia}$$

Similar calculations for $\phi_1 = 0.75$ and $T_2 = 47.1°F$ gives

$$p_{2,\text{dry air}} = 13.90\ \text{psia}$$

$$p_{v2} = 0.15\ \text{psia}$$

$$p_{2,1301} = 0.73\ \text{psia}$$

Thus, $\quad p_2 = (13.90 + 0.15 + 0.73)\ \text{psia}$

$$p_2 = 14.78\ \text{psia}$$

It should be noted that the psychrometric chart used to calculate ω_2 and v_2 in the above computations is intended to be used at atmospheric pressure only. The final pressures, 14.48 psia and 14.78 psia, however, were close enough to 14.7 psia to permit the use of the psychrometric chart for these calculations.

TABLE B-1. RESULTS OF THEORETICAL CALCULATIONS FOR PREDICTING THE CABIN TEMPERATURE AND PRESSURE AFTER THE DISCHARGE OF HALON 1301

	$\phi_1 = 0.50$		$\phi_1 = 0.75$	
	T_2=35°F	T_2=40°F	T_2=45°F	T_2=50°F
$m_{dry\ air}$ (lb_m)	303.03	303.03	294.11	294.11
m_{v1} (lb_m)	2.348	2.348	3.450	3.450
m_{v2} (lb_m)	1.333	1.636	1.912	2.294
u_{v2} (BTU/lb_m)	1022.6	1024.3	1026.0	1027.6
$m_{\ell 2}$ (lb_m)	1.015	0.712	1.538	1.156
$u_{\ell 2}$ (BTU/lb_m)	3.02	8.05	13.06	18.07
ω_2	0.0044	0.0054	0.0065	0.0078
$(h_2)_{1301}$ (BTU/lb_m)	56.98	57.51	58.04	58.59
$(p_2 v_2)_{1301}$ (BTU/lb_m)	6.62	6.69	6.75	6.82
Equation 23(BTU)	-2876	-2305	-2843	-2195
Equation 24(BTU)	-2476	-2513	-2550	-2589
Equation 24 - Equation 23(BTU)	400	-208	293	-394

APPENDIX C

REFERENCES

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