(12)

DOT/FAA/CT-83/1

Analysis of Dissipation of Gaseous Extinguisher Agents in Ventilated Compartments

Prepared by
Thor I. Eklund

May 1983

Final Report

US Department of Transportation
Federal Aviation Administration
Technical Center
Atlantic City Airport, N.J. 08405

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/CT-83/1	2. Government Accession No. AD-A128 760	3. Recipient's Catalog No.
4. Title and Subtitle ANALYSIS OF DISSIPATION OF GASEOUS EXTINGUISHER AGENTS IN VENTILATED COMPARTMENTS		5. Report Date May 1983
		6. Performing Organization Code ACT-350
7. Author(s) Thor I. Eklund		8. Performing Organization Report No. DOT/FAA/CT-83/1
9. Performing Organization Name and Address Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 181-350-400
12. Sponsoring Agency Name and Address Federal Aviation Administration Technical Center Atlantic City Airport, New Jersey 08405		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

A perfect stirrer model was used to analyze the concentration decay of extinguisher agents in ventilated compartments. The exponential decay curves were integrated over time to yield dosages. In this way, extinguisher agent weights, compartment volumes, and ventilation rates were matched against allowable agent doses to yield selection nomographs for halon 1211, halon 1301, and carbon dioxide. The model predictions were compared with experimental data, and the concept of an effective air-change time was developed for practical application.

17. Key Words	18. Distribution Statement
Halons Ventilation Aircraft Extinguisher Fire	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	25	

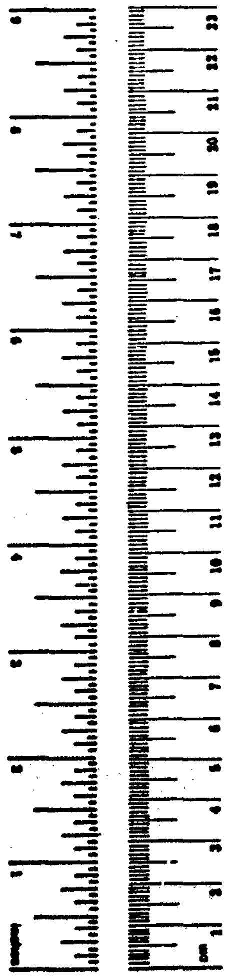
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

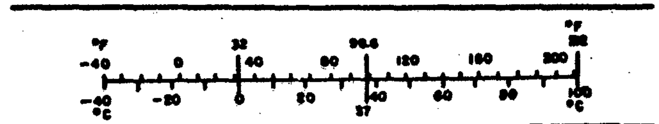
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGMENTS

Several individuals at the Federal Aviation Administration (FAA) Technical Center were helpful in the development and deployment of this approach. Mr. Paul Boris kindly provided his original discrete experimental data so that the theory could be properly evaluated. Mr. C. P. Sarkos gave a presentation to the Associate Administrator for Aviation Standards and this was pivotal to the incorporation of the analytical results in a new Advisory Circular. Mr. Wayne Howell suggested that the analytical results be transformed to nomograph form for optimal usefulness.

TABLE OF CONTENTS

PRECEDING PAGE BLANK-NOT FILMED

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The Federal Aviation Administration recently issued a new advisory circular (AC) on hand-held fire extinguishers. This circular, AC 20-42B, is titled "Hand Fire Extinguishers for Use in Aircraft," and the circular includes three nomographs for proper selection of halon 1211, halon 1301, and carbon dioxide extinguishers for the purpose of avoiding toxicity problems from the neat extinguishing agents.

This report describes the technical basis for the nomographs in the theory of the perfect stirrer. Comparisons with available data are made, and the concept of an effective air-change time is developed for further practical applications. All applications are for ventilated compartments, and this is the crucial deviation from previous guidelines set by standard setting bodies. Most guidance materials, prior to this time, have been applicable only to enclosures where there is no ventilation.

The report reaches three main conclusions. First, conservative estimates of extinguishing agent dissipation yield nomographs which provide a logical method for safely selecting charge weights for hand-held extinguishers. Second, the concept of an effective air-change time can be used to broaden the applications of the perfect stirrer theory. Third, evaluation of exposure doses to an airborne agent involves determination of the following: amount of agent, compartment volume, and ventilation rate.

INTRODUCTION

PURPOSE.

This analysis was developed in order to provide a methodology for the proper selection of portable fire extinguishers in pressurized and ventilated aircraft compartments. This development further provides the methodology employed to generate the selection nomographs for Advisory Circular 20-42B, "Hand Fire Extinguishers for Use in Aircraft."

BACKGROUND.

The Federal Aviation Administration (FAA) has recently encouraged wider use of halogenated hydrocarbon (halon) hand extinguishers in commercial aircraft. This thrust toward acceptance of the halons has been promulgated through official channels by means of a General Notice, correspondence between the FAA Administrator and the airlines, and by a new advisory circular. These documents are in response to needs for improved fire extinguisher capability in the commercial fleet, and the endorsement of halons was based on a recent review of the state-of-the-art of hand-held extinguishers in civil aviation (reference 1), along with recent project results from the FAA Technical Center (references 2 and 3). The project results are from comparisons of halon 1211 with such agents as water, dry chemicals, carbon dioxide, and halon 1301. These tests encompassed both agent effectiveness in fighting specific class A and class B fires, and measurements of gaseous agent concentrations.

The original notices and requests by the FAA for deployment of halon 1211 preceded availability of public documentation on the FAA test and evaluation efforts that supported the recommendations. As such, the recommendations to use halon 1211 were received, in some cases, by the airlines with substantive questions related to realism of any test conditions and questions of neat state and decomposed state toxicity of the extinguishing agents. For the most part, the cumulative data base at the FAA Technical Center was adequate to support the initial General Notice on extinguishers that was promulgated in 1980. Nevertheless, a fact-finding visit by representatives of American airlines in April 1982 to the FAA Technical Center yielded an additional and previously untreated question as to what size extinguisher bottle could be safely used in a specified aircraft compartment. As a result of this question, a technique was developed at the FAA Technical Center for finding safe extinguisher sizes as a function of compartment size and ventilation rate.

Although the technique showed good agreement in its predictions with data published in reference 2, a working paper describing the technique was distributed to key FAA offices and industry personnel for impartial analysis. This working paper, "Selection Criteria for Halon Extinguishers in Ventilated and Habitated Aircraft Compartments," was reviewed in detail for technical soundness by these parties and was recognized as a useful tool if the results could be further formulated into an easily usable format. In July 1982 a request came from the Northwest Mountain Region of the FAA for material that could be used to determine the adequacy of transport category aircraft crew procedures on donning oxygen masks during discharge of hand-held extinguishers in the cockpit. In response to this request, the predictions in the working paper were codified into nomographs for selecting safe quantities of halon 1211 or halon 1301 in ventilated aircraft compartments. Analyses were also developed for carbon dioxide (CO_2) so that a nomograph for

CO_2 could be transmitted to the Northwest Mountain Region. Also, at this time, the Office of Aviation Standards of the FAA was bringing a new advisory circular on hand extinguishers into final form. In August 1982 a decision was made by the Associate Administrator for Aviation Standards to incorporate the nomographs on halon 1211, halon 1301, and CO_2 into this advisory circular, AC-20-42B, "Hand Fire Extinguishers for Use in Aircraft," which was released as an advance copy with the nomographs on August 25, 1982. This advisory circular is a product of an intense effort by personnel of the Office of Airworthiness to upgrade the previous advisory circular on hand extinguishers which was issued in 1980.

Wide acceptance and use of halons for aircraft cabin firefighting has been a relatively slow development because even the neat agents can sometimes pose toxicity problems. For instance, Underwriters' Laboratories, Inc., has developed a standard for halogenated agent fire extinguishers (reference 4) that was first disseminated in 1980 and has an effective date starting January 10, 1983. This standard gives specific guidance on safe sizes for rooms where halons are to be discharged in the following manner: (A) "For Halon 1211, the minimum room volume in cubic feet is determined by multiplying the charge weight of Halon 1211 in pounds by 124.7. This calculation is derived from a maximum concentration of 2 percent of Halon 1211 at a temperature of 120° Fahrenheit (48.9° Centigrade)" and (B) "For Halon 1301, the minimum room volume in cubic feet is determined by multiplying the charge weight of Halon 1301 in pounds by 52.6. This calculation is derived from a maximum concentration of 5 percent at a temperature of 120° Fahrenheit (48.9° Centigrade)." These guidelines refer to rooms and ventilation effects are not included in the analysis. The standard allows 2 1/2 times the Halon 1211 exposure for Halon 1301.

In spite of these potential problems with neat state toxicity of the halons, their effectiveness in extinguishing fires (2 to 3 times better than CO_2) is the significant factor in encouraging the use of halons in appropriate situations. Thus, determining whether a specific ventilated aircraft compartment represents an appropriate situation for a given gaseous extinguishing agent requires an analysis that includes the effect of ventilation on the dosage that an occupant would sustain. The premise here is that a typical person could withstand without any adverse effects various dosages of a given gas. For instance, for halon 1211, a person might safely withstand a volumetric concentration of 4 percent for 1 minute or 1 percent for 4 minutes. In a ventilated compartment, the agent concentration might reach a peak upon completion of agent discharge and then decrease as the compartment sustains continued ventilation. The dosage calculation would be the area under the curve of concentration versus time. In this particular example, the dosage would be acceptable so long as the area under the curve stayed less than 4 percent-minutes.

Evaluation of a variety of literature sources (references 1, 5, 6, 7, and 8) led to selection of the following dosages as acceptable:

(1) halon 1211, 4 percent-minutes
(2) halon 1301, 10 percent-minutes
(3) carbon dioxide, 25 percent-minutes

The selection of 25 percent-minutes for carbon dioxide involved some judgmental consideration. At low concentrations, CO_2 causes accelerated respiration rates, but can be tolerated for quite a time. Thus, over a period of 14 minutes, a concentration of a constant 5 percent might be safely tolerated. However, in cases of rapid ventilation changes, a selection of a dosage of 70 percent-minutes might cause exposure to much higher concentrations for shorter times. This could cause exposure to concentrations that are so high that immediate unconsciousness would result. Thus, a more conservative dosage of CO_2 of 25 percent-minutes was selected.

It should be noted that the Occupational Safety and Health Administration (OSHA) standards (reference 9) state in part 1910.62 the following: "A predischarge employee alarm for alerting employees before system discharge shall be provided on Halon 1211 and carbon dioxide systems with a design concentration of 4 percent or greater and for Halon 1301 systems with a design concentration of 10 percent or greater." Also, part 1910.162 states subsequently "Where egress takes greater than 30 seconds but less than 1 minute, the employer shall not use Halon 1301 in a concentration greater than 10 percent." The latter quotation essentially provides a limit exposure of 10 percent-minutes for Halon 1301. When this is compared with the former quotation, the OSHA standards are implicitly 4 percent-minutes for halon 1211 and 4 percent-minutes for CO_2.

Thus, the OSHA standards are consistent with the halon exposure limits used in the analysis for aircraft. However, the OSHA limits for CO_2 are approximately 6 times lower than the 25 percent-minutes stated previously. Thus, the developments and selection criteria for CO_2 in this report should be used with caution.

OBJECTIVES.

The objective of the effort was to develop a conservative set of plots for safe deployment of hand extinguishers employing agents that are gaseous upon discharge. The plots were to indicate maximum extinguishing agent charge weights that could be used without causing nausea, dizziness, or impaired judgment to compartment occupants as a result of exposure to neat agent.

TECHNIQUE.

The concept from chemical engineering of a perfect stirrer was applied to the discharge of a hand extinguisher in a ventilated compartment. This idealized model assumes instantaneous discharge of the extinguisher, thorough mixing within the compartment, and a loss rate of agent that is a product of ventilation air outflow rate and the instantaneous overall fraction of agent in the compartment.

The analysis is based on a number of specific assumptions and conditions.

(1) The working altitude for the analysis is 8,000 feet above sea level. This is a reasonable maximum cabin altitude of a commercial transport.

(2) The compartment can be treated as a perfect stirrer in generating the concentration versus time profiles.

(3) The integration of concentration over time gives an effective dose that must be maintained below a specified quantity in percent-minutes.

(4) The specified maximum doses are 4 percent-minutes and 10 percent-minutes for halon 1211 and halon 1301, respectively, and these are in the same ratio (2-1/2) as the Underwriters' Laboratories standard cited previously. The specified maximum for CO_2 is 25 percent-minutes.

(5) The temperature for the analysis is set at 72° Fahrenheit.

The starting point for the analysis is Avogadro's principle which states that equal volumes of gases contain the same number of molecules. In a given aircraft compartment, assume an instantaneous discharge of a fire extinguisher so that the compartment is left with A air molecules and H agent molecules. Ventilation occurs through the addition of a air molecules per minute to the compartment and the loss of an equal number of molecules per minute consisting of m air molecules and n agent molecules.

As this process goes forward in time, the number of air molecules in the compartment A' will be A plus the integral of a over time minus the integral of m over time or

$$A + \int a \, dt - \int m \, dt = A' \qquad (1)$$

The number of agent molecules at times after discharge will be given by H'.

$$H - \int n \, dt = H' \qquad (2)$$

The equivalence of inflow and outflow described previously is

$$m + n = a \qquad (3)$$

and the perfect stirrer assumption allows setting a ratio for m and n such that

$$\frac{n}{m} = \frac{H'}{A'} \qquad (4)$$

Equation (3) can be rewritten as

$$H'n + H'm = H'a \qquad (5)$$

and equation (4) can be rewrit en as

$$H'm - A'n = 0 \qquad (6)$$

Equations (5) and (6) can be combined and solved to get

$$n = \frac{H'}{A' + H'} a \qquad (7)$$

Employing equation (2) allows the agent volume concentration to be defined as

$$\frac{H'}{A' + H'} = \frac{H - \int n \, dt}{A' + H'} \qquad (8)$$

Equation (7) can be substituted into equation (8) to yield

$$\frac{H'}{A' + H'} = \frac{H - \int \frac{H'}{A' + H'} a \, dt}{A' + H'} \qquad (9)$$

Also, equations (1), (2), and (3) can be combined to yield the following identity

$$A + H = A' + H' \tag{10}$$

Thus, equation (9) can be rewritten as

$$(A + H) \frac{H'}{A' + H'} = H - \int \frac{H'}{A' + H'} a \, dt \tag{11}$$

Taking the derivative of each side of equation (11) leads to

$$(A+H) \frac{d}{dt} \left\{ \frac{H'}{A' + H'} \right\} = - \frac{H'}{A' + H'} a \tag{12}$$

Using the identity that

$$\frac{d}{dt} \ln \left(\frac{H'}{A' + H'} \right) = \frac{A' + H'}{H'} \frac{d}{dt} \left(\frac{H'}{A' + H'} \right) \tag{13}$$

equation (12) can be written as

$$(A + H) \frac{d}{dt} \ln \left\{ \frac{H'}{A' + H'} \right\} = - a \tag{14}$$

Equation (14) can be integrated to get

$$\frac{H'}{A' + H'} = B \exp \left\{ \frac{-a \ t}{A + H} \right\} \tag{15}$$

At $t = o$, $H'/(A' + H')$ is equal to $H/(A + H)$ and this defines B. Additionally, $H'/(A' + H')$ is simply the volumetric concentration of agent which will hereafter be represented as C. Thus, equation (15) can now be written

$$C = \frac{H}{A + H} \exp \left\{ \frac{-a \ t}{A + H} \right\} \tag{16}$$

Since a is the number of air molecules entering the compartment every minute and A + H is the total number of molecules in the compartment, the time for an air change in the compartment can be identified as τ and it is defined in the following manner

$$\tau = \frac{A+H}{a} \tag{17}$$

Thus, equation (16) can be simply written as

$$C = C_o \exp \left\{ \frac{-t}{\tau} \right\} \tag{18}$$

where C_o is the initial concentration of agent after discharge. The total dosage, D, is simply the integral of equation (18) with time starting at $t = 0$. Thus

$$\int_o^\infty C \, dt = \int_o^\infty C_o \exp \left\{ -t/_\tau \right\} dt \tag{19}$$

or

$$D = \tau C_o \tag{20}$$

Equation (20) states that the total dose, D, is simply the initial agent volumetric concentration times the time for an air change. Given the dosage limits stated earlier, the following relationships can now be stated

$$\tau C_{o\ 1211} \leq .04 \text{ minutes} \qquad (21)$$

$$\tau C_{o\ 1301} \leq .10 \text{ minutes} \qquad (22)$$

$$\tau C_{o\ CO_2} \leq .25 \text{ minutes} \qquad (23)$$

In many aircraft compartments, the volume is known and the ventilation rate is known. Hence, τ is known. Additionally, the initial concentration C_o can be found from the perfect gas law, the conditions specified (8,000 feet altitude and 72° F), the compartment volume, the agent total weight, and the agent molecular weight.

VERIFICATION AND APPLICATION.

A critical verification that must be attempted is the capability of equation (18) to predict the concentration versus time profile that is actually measured. The data chosen for this comparison was from reference 2. Tables 1 and 2 show the concentration data for agent release tests in compartments of 261 cubic feet and 814 cubic feet, respectively. For all tests, the ventilation rate was cited as one air change per minute.

Included as well in tables 1 and 2 are the values predicted from equation (18), based on the noted weight of agent discharge and the conditions of a sea level atmospheric pressure and a temperature of 72° F. The details of this type calculation are shown in appendix A.

Equation (18) can also be written as

$$\frac{C}{C_o} = \exp\left\{\frac{-t}{\tau}\right\} \qquad (24)$$

In this manner the concentration data are normalized against the initial concentration. Tables 3 and 4 show the data from the preceding figures recalculated in normalized fashion along with the predicted numbers from equation (24). The advantage of this approach is that a single theoretical curve, as shown in figure 1, can be used to collapse all test predictions. Also shown in figure 1 are data up to 4 minutes from tables 3 and 4. The curve used in figure 1 is a straight line on a two-cycle semilogarithmic scale. The straight line is the exponential decrease starting with unity at time zero. It is readily apparent that the data do generally follow this curve, although the scatter of the data appears to increase as time progresses.

Considering the relative simplicity of the perfect stirrer approach, the agreement between the experimental data and the predicted data is good. However, note should be taken that the tests which generated the data involved a ventilation pattern wherein air entered one end of the compartment near the bottom and exited on the other end near the top. This bottom to top flow probably aided mixing of the agent with the air in the compartment because of the agent's natural tendency

TABLE 1. AGENT CONCENTRATIONS (261 CU. FT.)

τ = 1 (min) Time (min)	Percent Halon 1211 3.5 lb. Release Experimental	Predicted	Percent Halon 1301 3.1 lb. Release Experimental	Predicted	Percent Halon 1211 16.2 lb. Release Experimental	Predicted	Percent Halon 1301 15.63 lb. Release Experimental	Predicted
0.5	1.65	1.91	2.07	1.88	8.11	8.84	12	9.47
1.0	1.17	1.16	1.89	1.14	5.98	5.36	7.15	5.74
1.5	0.76	.70	1.20	.69	4.42	3.25	4.40	3.48
2.0	0.48	.43	0.84	.42	-	1.97	4.25	2.11
2.5	0.24	.26	-	.25	-	1.20	2.75	1.28
3.0	0.05	.16	-	.15	1.63	.73	1.85	.78
3.5	0	.10	0.42	.09	1.15	.44	1.60	.47
4.0	0	.06	0.31	.06	0.93	.27	0.75	.29
4.5	0	.04	-	.03	0.94	.16	0.45	.17
5.0	0	.02	0.33	.02	0.37	.10	0.25	.11

TABLE 2. AGENT CONCENTRATIONS (814 CU. FT.)

τ = 1 (min) Time (min)	Percent Halon 1211 3.44 lb. Release Experimental	Predicted	Percent Halon 1301 3.19 lb. Release Experimental	Predicted	Percent Halon 1211 15.81 lb. Release Experimental	Predicted	Percent Halon 1301 15.75 lb. Release Experimental	Predicted
0.5	0.37	.60	.23	.62	1.63	2.77	2.02	3.06
1.0	0.17	.37	.25	.38	0.77	1.68	1.40	1.86
1.5	0.11	.22	.14	.23	0.67	1.02	0.89	1.13
2.0	0.09	.13	.10	.14	0.40	.62	0.58	.68
2.5	0.05	.08	.01	.08	0.20	.37	0.19	.41
3.0	0.10	.05	.05	.05	0.18	.23	0.52	.25
3.5	0.02	.03	.03	.03	0.10	.14	0.13	.15
4.0	0.13	.02	.01	.02	0.15	.08	0.07	.09
4.5	0.10	.01	.01	.01	0.04	.05	0.36	.06
5.0	0	.01	0	.01	0.02	.03	0.02	.03

TABLE 3. NORMALIZED AGENT CONCENTRATIONS (261 CU. FT.)

$\tau = 1$ (min) Time (min)	$\frac{C}{C_o} = e^{-t/\tau}$	Measured $\frac{C}{C_o}$ Halon 1211 3.5 lb. Release	Measured $\frac{C}{C_o}$ Halon 1301 3.1 lb. Release	Measured $\frac{C}{C_o}$ Halon 1211 15.2 lb. Release	Measured $\frac{C}{C_o}$ Halon 1301 15.63 lb Release
0.5	.606531	.52	.67	.56	.77
1.0	.367879	.37	.61	.41	.46
1.5	.223130	.24	.39	.30	.28
2.0	.135335	.15	.27	-	.27
2.5	.082085	.08	-	-	.18
3.0	.049787	.02	-	.11	.12
3.5	.030197	0	.14	.08	.10
4.0	.018316	0	.10	.06	.05
4.5	.011109	0	-	.06	.03
5.0	.006738	0	.11	.03	.02

TABLE 4. NORMALIZED AGENT CONCENTRATIONS (814 CU. FT.)

$\tau = 1$ (min) Time (min)	$\frac{C}{C_o} = e^{-t/\tau}$	Measured $\frac{C}{C_o}$ Halon 1211 3.44 lb. Release	Measured $\frac{C}{C_o}$ Halon 1301 3.19 lb. Release	Measured $\frac{C}{C_o}$ Halon 1211 15.81 lb. Release	Measured $\frac{C}{C_o}$ Halon 1301 15.75 lb Release
0.5	.606531	.37	.22	.36	.40
1.0	.367879	.17	.25	.17	.28
1.5	.223130	.11	.13	.15	.18
2.0	.135335	.09	.09	.09	.12
2.5	.082085	.05	.01	.04	.04
3.0	.049787	.10	.05	.04	.10
3.5	.030197	.02	.03	.02	.03
4.0	.018316	.13	.01	.03	.01
4.5	.011109	.10	.01	.01	.07
5.0	.006738	0	0	0	0

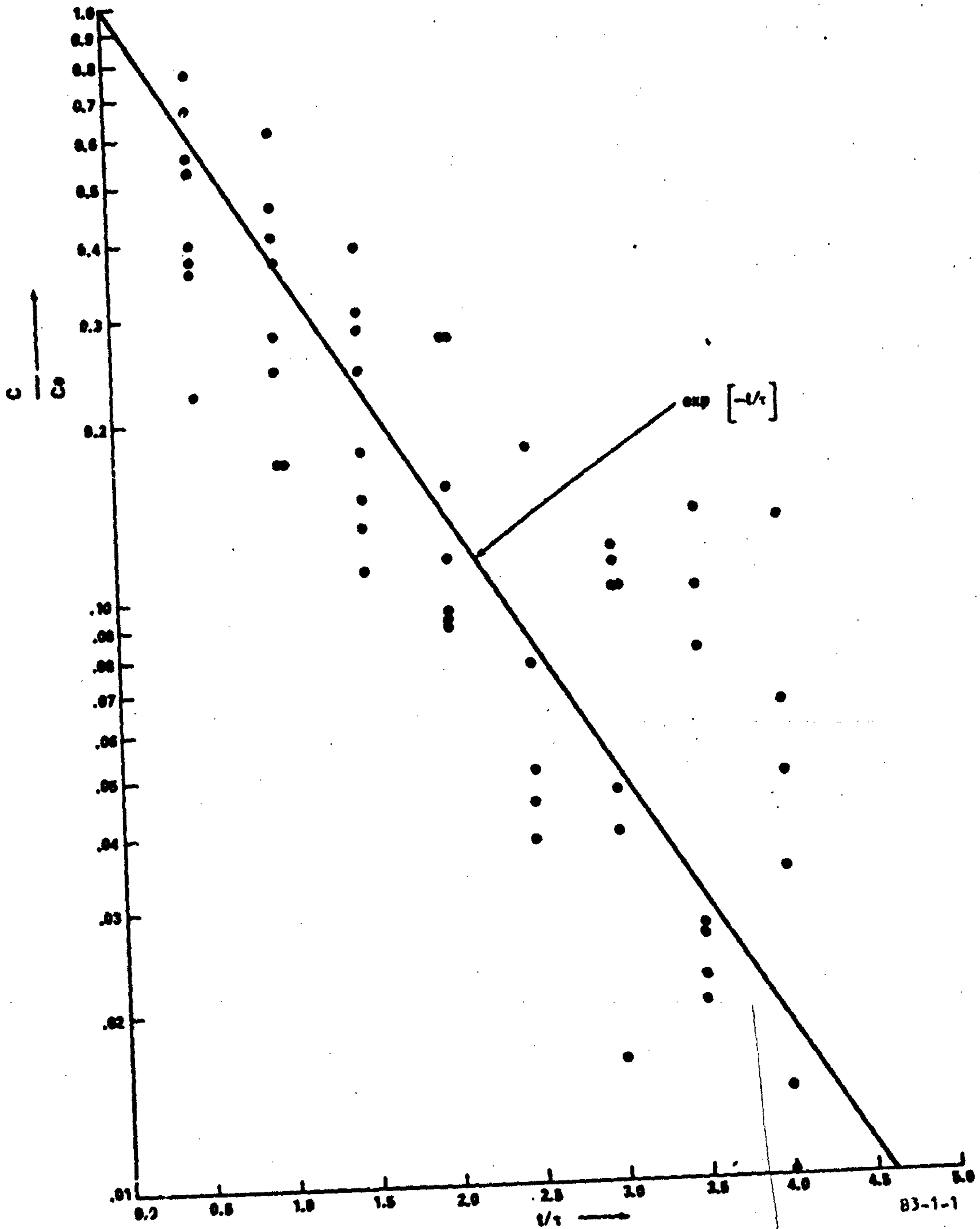


FIGURE 1. AGENT EXPONENTIAL DECAY

to settle to the floor due to density effects. 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 actually be measured. Thus, the predicted dose would be higher than the actual measured dose. Consequently, in this aspect of the physical behavior of the airflow, use of the stirrer concept represents a conservative approach.

Now that a comparison of the technique's predictions with experimental data has been accomplished, equations (21), (22), and (23) can be elaborated to a more useful format. Although the algebraic details are summarized in appendix A, the results can be summarized for the specified conditions of 72° F and 8,000 feet altitude. The initial concentration of agents can be calculated by the following expressions where W is the agent weight in pounds and V is the compartment volume in cubic feet:

$$C_{o\ 1211} = 3.160\ \frac{W}{V} \tag{25}$$

$$C_{o\ 1301} = 3.509\ \frac{W}{V} \tag{26}$$

$$C_{o\ CO_2} = 11.877\ \frac{W}{V} \tag{27}$$

By combining equations (25), (26), and (27) with equations (21), (22), and (23), a set of relations is developed wherein the weight of an agent must be kept below an algebraic product involving the compartment volume V divided by an air-change time τ . When these expressions are set at the maximum allowable agent weight for a given compartment size and ventilation rate, the following relationships can be stated:

$$W_{1211} = .01266\ \frac{V}{\tau} \tag{28}$$

$$W_{1301} = .02850\ \frac{V}{\tau} \tag{29}$$

$$W_{CO_2} = .02105\ \frac{V}{\tau} \tag{30}$$

where W is the maximum allowable agent weight. These equations represent the final product of the use of the perfect stirrer concept for this aircraft application. Because of the algebraic structure of these equations, they lend themselves to formulation in nomograph form. The nomographs are shown in figures 2, 3, and 4. Use of the nomographs involves placing a straight edge across the three vertical scales so that it crosses the compartment volume and ventilation scales at the values appropriate for the aircraft compartment under consideration. Then, the straight edge will automatically intersect the weight scale at the maximum advisable charge weight for the particular agent.

In the process of selecting appropriate extinguishers for a given aircraft application, the results yielded by the nomographs should be only one aspect of the decision process. Other important considerations are found in Advisory Circular 20-42B. A hypothetical example of this might be the choice of an extinguisher for a compartment of 1,000 cubic foot volume and 3 1/3-minutes time for an air change. Use of the nomographs or equations (28) and (30) would lead to the conclusion that one could select 6.3 pounds of CO_2 or 3.8 pounds of halon 1211. Superficially, the conclusion therefore might be that the CO_2 would be the best choice for the

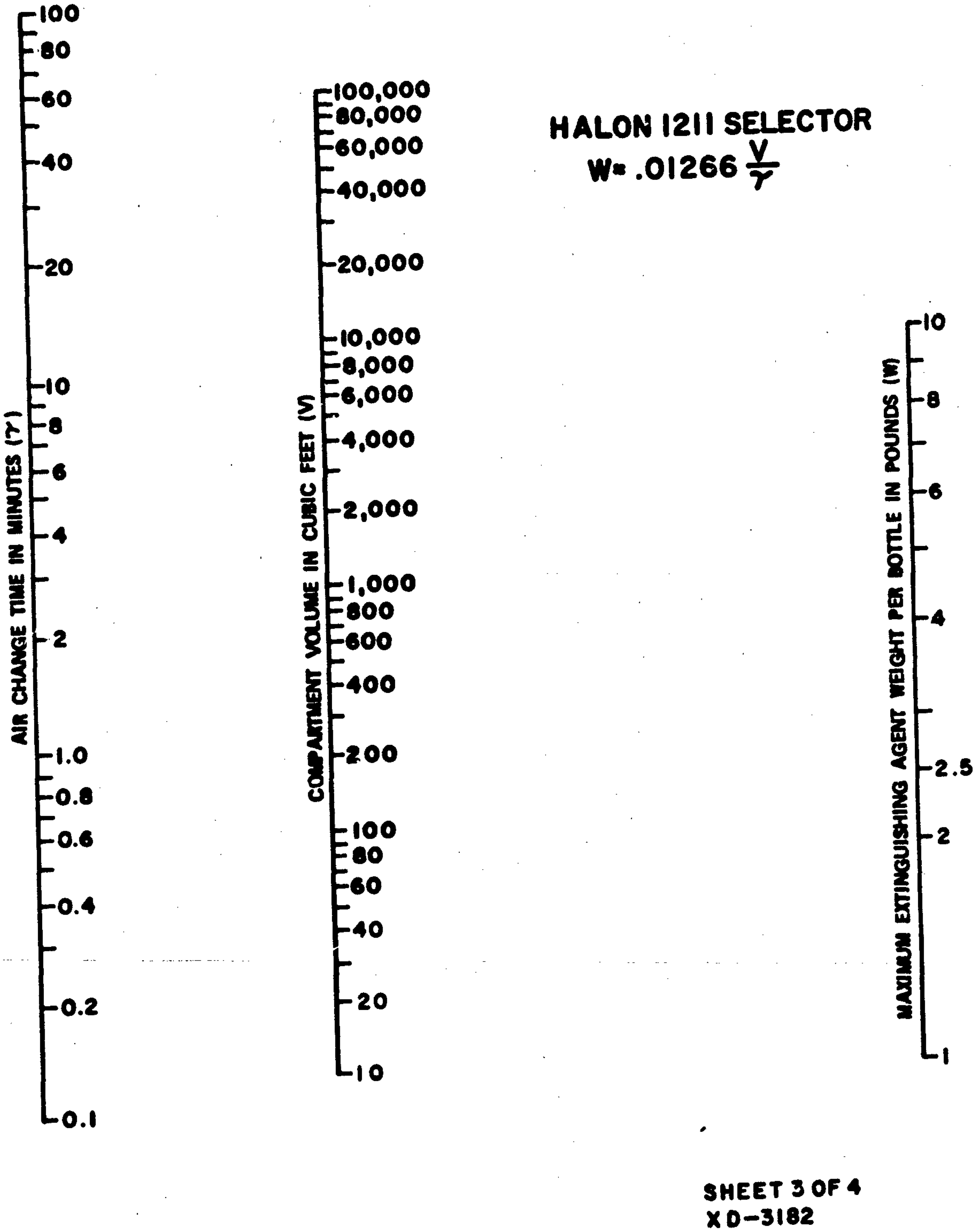


FIGURE 2. HALON 1211 NOMOGRAPH

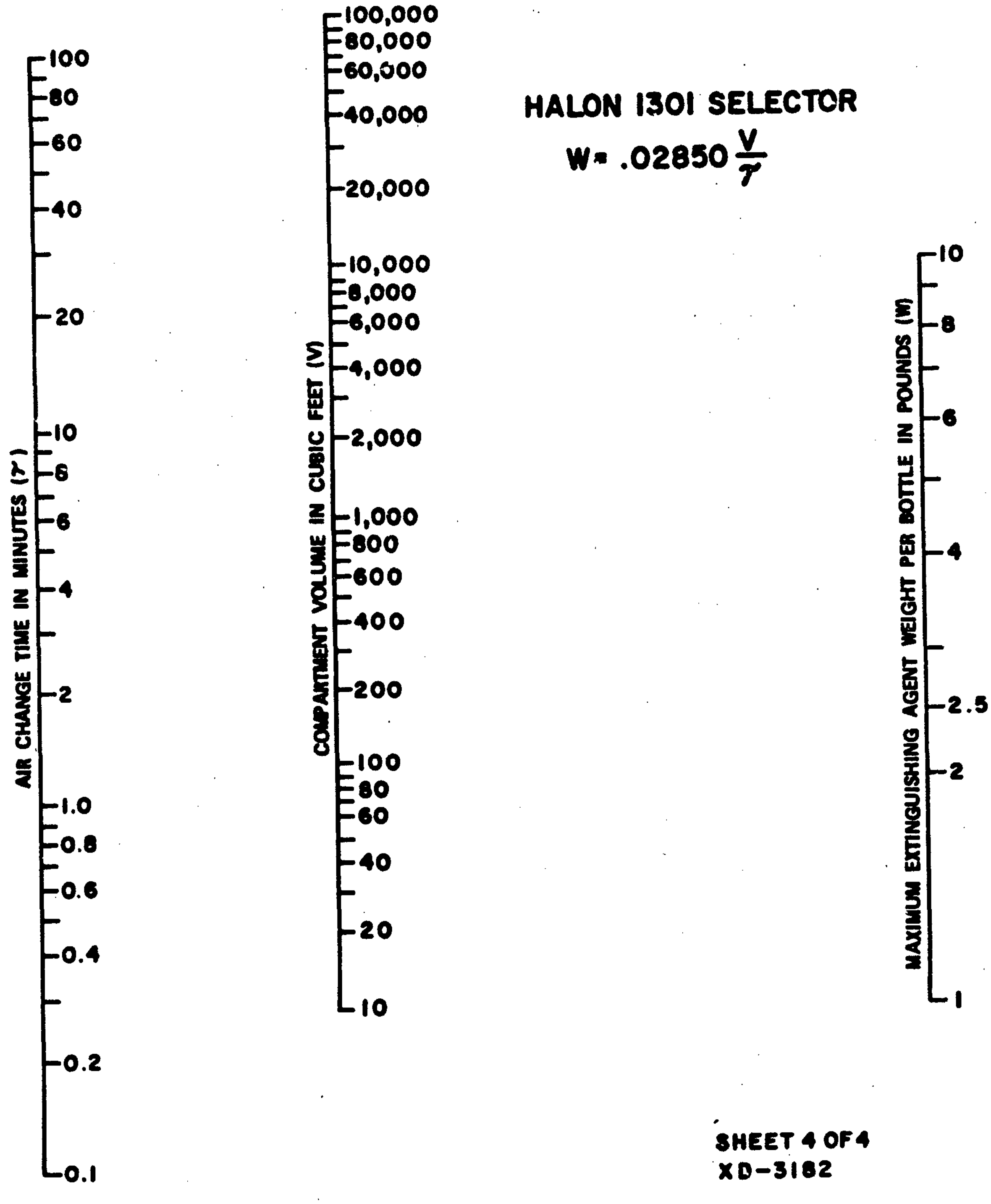


FIGURE 3. HALON 1301 NOMOGRAPH

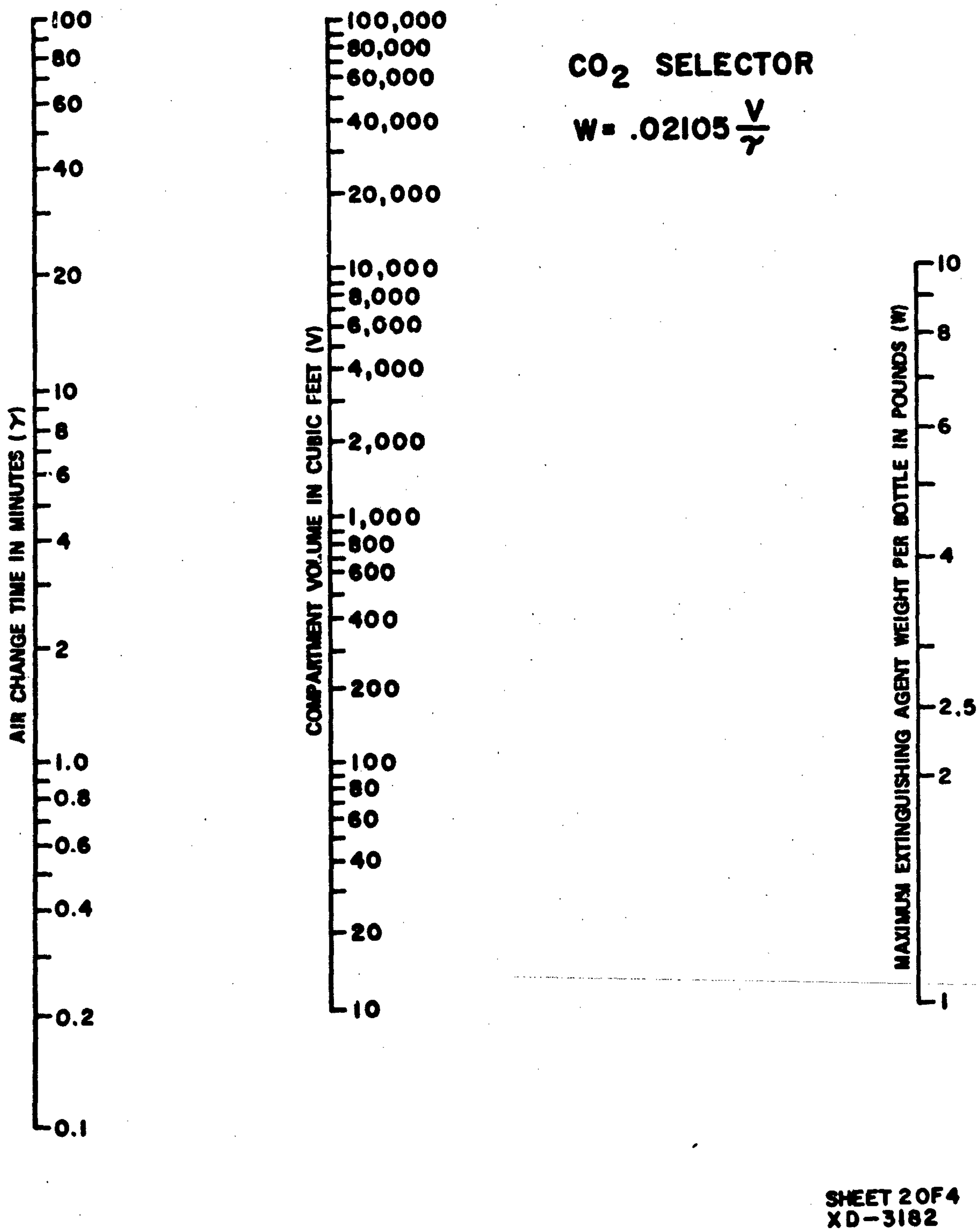


FIGURE 4. CARBON DIOXIDE NOMOGRAPH

application because more could be used. However, AC 20-42B states "halon 1211 is three times as effective as a CO_2 extinguisher having equal weight of agent." Thus, in firefighting effectiveness, the 3.8 pounds of halon 1211 would be equivalent to 11.4 pounds of CO_2. This is almost double the CO_2 allowed by the nomographs. In this hypothetical case, the considerations of both safe doses and agent effectiveness lead to the conclusion that halon 1211 would be the better choice.

EFFECTIVE AIR-CHANGE TIME.

The application of the perfect stirrer to derivation of selection criteria for hand-held extinguishers provides a useful tool for cases where the ventilation rate of a compartment is accurately known as far as time for an air change. This is true in many pressurized aircraft where the ventilation system design is specified as to the airflow into a compartment from the air conditioning system. The selection criteria are particularly useful where the details of the airflow patterns within the compartment are unknown.

In order to increase the usefulness of the selection nomographs to aircraft where ventilation rates are not quantitatively specified in the design and to aircraft configurations where compartment dissipation data is available in detail, an effective air-change time, τ_{eff}, can be defined.

Referring to figure 1 and to tables 3 and 4, one can see that the perfect stirrer theory predicts an exponential decay of agent concentration as time proceeds. From the maximum concentration at the starting point, the concentration will decay to 37 percent of the maximum after one air change, to 5 percent of the maximum after three air changes, to 2 percent of the maximum after four air changes, and so forth. A characteristic of the exponential decrease is that when any point at any time on the curve in figure 1 is selected, the following is true: after one additional air-change time, the concentration will drop by 63 percent over that time for an air change.

What this means is that in cases where the air in a compartment continues to be well mixed during ventilation, data on the decay of an agent in the enclosure will provide the time for an air change, τ. Through picking a concentration point on the decay curve and measuring the time interval before curve decreases to 37 percent of this value, the time for an air change is specified. Whenever such decay data is known or easily generated, a time for an air change can be determined.

In actuality, true perfect stirrer behavior in the ventilation situations of aircraft is unlikely. Most often there will be some deviation from the decay curve predicted by $\exp\{^{-t}/\tau\}$. Thus, in cases where experimental data shows general conformance to the shape of an exponential decay curve (shown in figure 5) the time for decay of the concentration by 63 percent can more properly be defined as the effective air-change time, τ_{eff}. An example of a case where τ_{eff} might be useful is the agent decay in a non-pressurized light aircraft. Such aircraft are ventilated primarily from stagnation ports on the wing leading edge. Other additional venting options may be available in a specific aircraft model. For instance, some aircraft have windows that can be opened to some degree in slow flight. However, the actual times for an air change may not be known in a quantitative sense. This could be determined if a small amount of Halon 1301 were to be discharged such that the initial concentration were less than 5 percent. Such

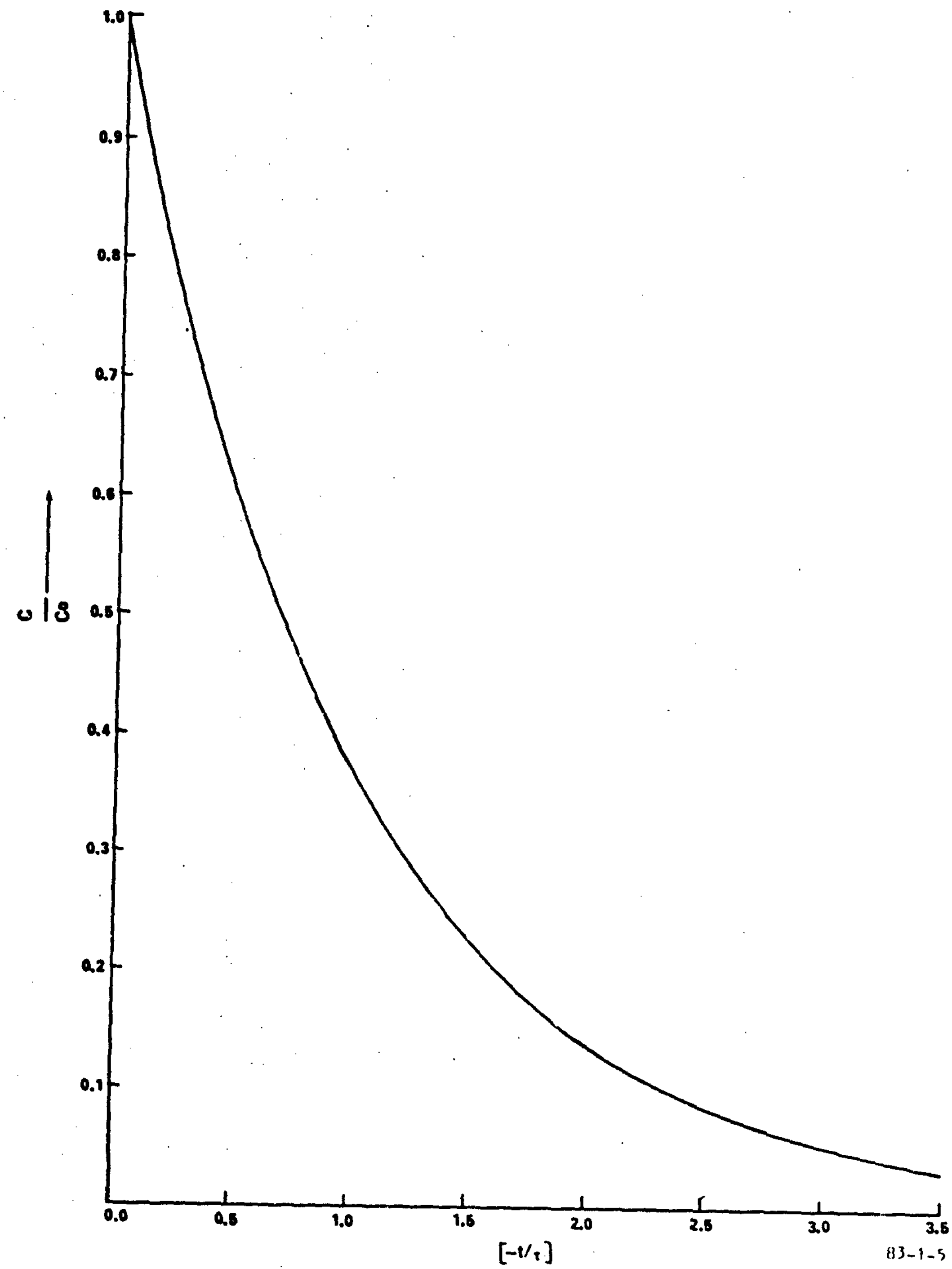


FIGURE 5. CHARACTERISTIC EXPONENTIAL DECAY

a level would be safe in an unventilated environment according to the previously quoted Underwriters' Laboratories standard. Recording the decays of such discharges during a variety of flight ventilation modes allows determination of τ_{eff} in each mode. This compilation of τ_{eff} could serve as the required input to the selection nomographs. For the purpose of extinguisher selection, the measuring point for agent concentration should be pilot nose level. The actual test discharge should be oriented and placed to simulate the orientation and location of hand-held extinguisher in a realistic deployment and discharge action.

A case where the design time for air change is known but where the effective time for air change can be different is in a large compartment. In this case the perfect stirrer predictions should provide a sound basis for evaluating the compartment as a whole but may not give the complete picture of the dosage situation in the immediate vicinity of the discharge. On the one hand, the discharge will tend to be localized relative to a large volume and this would show itself in higher initial concentrations than those predicted by equations (25), (26), and (27). On the other hand, this localized concentration would not be confined. As a result, the dense agent and air mixture would rapidly flow away from the discharge area and the effective air-change time, τ_{eff}, would be less than the design air-change time, τ. An example of this situation is found in the test configuration reported in reference 3. In that configuration, a surplus C-133 was used to simulate a wide-body transport. Ventilation air was supplied though twin overhead perforated ducts within the cabin to simulate in-flight interior airflows.

This C-133 has an interior volume of 13,200 cubic feet and the reported airflow in the testing 4100 cubic feet per minute. Thus, the time for an air change, τ, was 3.2 minutes. In test number 1 wherein halon 1211 was used to extinguish a seat fire, the recorded concentrations of halon 1211 were 55 ppm over the first 30 seconds, 1935 ppm over the next 30 seconds, 1634 ppm from 60 to 90 seconds, 1072 ppm from 90 to 120 seconds, and 260 ppm over the last 30 seconds. These were batch samples representing an average over a 30-second interval so some caution should be taken as to their reflection of the precise shape of the decay profile. Nevertheless, a simple straight line interpolation from data point to data point shows that the peak 1935 ppm value placed at 45 seconds would fall by 63 percent at 118 seconds into the test. This would give an effective air-change time, τ_{eff}, of 73 seconds or a little more than 1 minute. Thus, the effective ventilation rate at 5-foot 6-inch height in the immediate vicinity of the discharge is nearly 3 times higher than the actual compartment ventilation rate. In this case, 2.35 pounds of halon 1211 was discharged. Using 1935 ppm as the peak initial concentration in equation (21), the product of concentration and effective air-change time comes out to be 0.002354 minute which is considerably less than the prescribed 0.04 minute. In fact, the discharge would have to be increased by a factor of 17 to get the maximum dose.

When this type experimental data is available, the preferrable approach is to take the effective air-change time, τ_{eff}, and multiply it times the actual measured peak concentration to get the dose generated by the scenario. This product can then be compared to the recommended doses to determine the level of safety involved in deployed extinguisher charges of the specific size tested.

DISCUSSION

The nomographs provided in figures 2, 3, and 4 are for aircraft compartments of specified size and ventilation rates. The nomographs are conservative in that they are based on uniform mixing of the agent within the compartment. In reality, the three agents (halon 1211, halon 1301, and CO_2) are all dense and ordinarily will tend to concentrate near the floor. Thus, actual human respiratory exposure would, in most cases, be less than predicted by the analysis based on the perfect stirrer. In such cases, the use of the concept of the effective ventilation rate would give a more accurate estimate of exposure dosages.

It should also be noted that the maximum extinguishing agent weight derived from the nomographs could be relaxed to allow higher charge weights in a number of circumstances. For example, availability of appropriate oxygen apparatus for use during discharge of agent clearly can protect occupants from adverse physiological effects. Also, if adequate test data are available, it may be determined that the effective ventilation rate is substantially higher than the actual ventilation rate. Finally, there may be cases wherein temporary impaired judgment, nausea, or dizziness of occupants is tolerable in the face of a major fire threat.

In this entire development, due recognition is given to the controversies associated with safe doses of potentially toxic gases. Exception can and will be taken both to the allowable doses used in this development and to the product assumption which says an exposure of 4 percent for 1 minute is equivalent to an exposure of 1 percent for 4 minutes. Nevertheless, the large quantities of data should be put to use in this area. By making conservative assumptions in an analysis, the data and interpretations, though potentially controversial, at least can be put to use in real applications. Hence, the nomographs are essentially yardsticks which should give the user a good idea how safe a given installation should be.

CONCLUSIONS

The analysis of ventilated compartments using the concept of a perfect stirrer leads to several conclusions.

1. Conservative estimates of extinguishing agent dissipation yield nomographs which provide a logical method of safely selecting charge weights for hand fire extinguishers.

2. An effective ventilation rate concept can be employed to determine ventilation rates when these rates are unknown.

3. Evaluation of exposure dosages to any airborne agent involves a requirement that three quantities be known: amount of agent, compartment volume, and ventilation rate.

REFERENCES

1. Krasner, L. M., Study of Hand-Held Fire Extinguishers Aboard Civil Aviation Aircraft, Federal Aviation Administration Technical Center, Report DOT/ FAA/CT-82/42, June 1982.

2. Boris, P. N. et al, Advanced Fire Extinguishers for Aircraft Habitable Compartments, Report performed by Federal Aviation Administration for Air Force Aero-Propulsion Laboratory, Report AFAPL-TR-79-2036, October 1979.

3. Hill, R. G. et al, In-Flight Aircraft Seat Fire Extinguishing Tests, Federal Aviation Administration Technical Center, DOT/FAA/CT-82/111, December 1982.

4. Standard for Halogenated Agent Fire Extinguishers, Underwriters' Laboratories Inc., UL 1093, First Edition, September 1980.

5. Kimmerle, G., Aspects and Methodology for the Evaluation of Toxicological Parameters during Fire Exposure, University of Utah Polymer Conference Series, 1973.

6. Pryor, A. S. and Yuill, C. H., Mass Fire Life Hazard, OCD Work Unit 2537A, Southwest Research Institute, September 1966.

7. An Appraisal of Halogenated Fire Extinguishing Agents, Proceedings of a Symposium held at National Academy of Sciences, Washington, D.C., 1972.

8. Call, D. W., A Study of Halon 1301 ($CBr\ F_3$) Toxicity Under Simulated Flight Conditions, Aerospace Medicine 44 (2): 202-204, 1973.

9. Occupational Safety and Health Standards for General Industry, Promulgated by the United States Department of Labor, Commercial Clearing House, Inc., 1981.

APPENDIX A

SAMPLE CALCULATIONS

All agent concentration calculations were done in a manner wherein the perfect gas law was utilized as follows:

$$p\ V = n\ RT \tag{A-1}$$

where p is pressure, V is volume, n is the number of gas moles in the volume, R is the universal gas constant, and T is absolute temperature. Equation (A-1) can be rewritten as

$$\frac{V}{n} = \frac{RT}{p} \tag{A-2}$$

to show the volume taken up by 1 mole of gas. Both sides of (A-2) can be divided by M, the molecular weight, to get

$$\frac{V}{nM} = \frac{RT}{pM} \tag{A-3}$$

and this tells the volume of air displaced by a particular agent of known weight.

Thus, a specified weight of agent, w, can be multiplied times either side of equation (A-3) to yield a displaced volume, V_D,

$$V_D = \frac{w\ RT}{pM} \tag{A-4}$$

This relationship can be divided by a compartment volume V_C to get the volumetric concentration C.

$$C = \frac{w\ RT}{V_C\ pM} \tag{A-5}$$

The data comparisons in the text that were plotted in figure 1 (of the text) were based on sea level pressure and a temperature of 72 degrees F. In the nomographs of figures 2, 3, and 4 (of the text), a temperature of 72 degrees F and an altitude of 8,000 feet were used as shown in the following calculation for halon 1211 using equation (A-4):

$$\frac{V_D}{w} = \frac{RT}{pM} \tag{A-6}$$

$$\frac{V_D}{w} = \frac{\left(82.0575\ \frac{cm^3\ atm}{°K\ mole}\right)\left(295.4°K\right)\left(3.5314x10^{-5}\ \frac{ft^3}{cc}\right)}{(.743\ atm)\ (.3646\ lb/mole)} \tag{A-7}$$

$$\frac{V_D}{w} = 3.160\ ft^3/lb \tag{A-8}$$

Thus, for a given weight of extinguisher agent, w, the initial halon concenration is calculated as follows

$$C_o = \left(\frac{w}{V_C}\right)\left(3.160 \quad \frac{ft^3}{lb}\right) \qquad (A-9)$$

which is identical to equation (25).

As is evident in equation (A-7), the molecular weights are needed to perform the calculations. The molecular weights are 165.38 for halon 1211, 148.93 for halon 1301, and 44.01 for carbon dioxide.