Calculated Chemical Contributions to Extinguishment by Halocarbons

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ABSTRACT

Sheinson and Driscoll **[1]** and Sheinson, Penner-Hahn, and Indritz [2] have presented a method to quantify suppression action pathways for extinguishing agents. We have taken this method, recast the calculation in a slightly different form, and have determined the relative physical and chemical contributions for a large number of halocarbons using extinguishment concentrations determined with the NMERI Standard cup burner **[3]** and vapor-phase heat capacities. Trends, expected and unexpected, are discussed.

INTRODUCTION

Some researches believe that extinguishment by all agents is dominated by heat absorption, and that many of the effects attributed to chemical mechanisms may be thermodynamic rather than kinetic **(4).** These conclusions, however, are not accepted by most researchers, who believe that the "radical trap" mechanism explains fire extinguishment by the halons and other highly effective agents.

A number of approaches can **be** used used to estimate the physical and chemical contributions to extinguishment by an agent (see, e.g., [5]). Here, we estimate the purely physical component of agent effectiveness by comparing the amount of agent required to raise the heat capacity of an enclosed atmosphere to the concentration required for extinguishment by cooling alone compared to the measured extinguishment concentration. The flame-spread rate for burning material is a strong inverse function of the heat capacity per mole of oxygen of the oxidizing atmosphere. As a result, if the heat capacity of an atmosphere is raised to approximately **209** J/mol-K per mole of O_2 present, combustion is not supported **[6, 7]**. This criterion can be used to calculate the concentration of a given agent required to suppress a fire by heat absorption only. The difference between the calculated and actual concentrations can then be attributed to suppression mechanisms other than purely physical (i.e., chemical suppression).

METHODOLOGY

When a total-flooding agent is discharged into an enclosed volume and the pressure is maintained constant by leakage, the oxygen concentration decreases. Regardless of the agent used, the O_2 concentration (C_{O2}) and the agent concentration (C_a), both in mole or volume percent (mol % and vol %), are related by Equation 1. This equation assumes ambient air containing 21 vol % O_2 (i.e., before addition of agent, $C_{O2} = 21$ vol %).

$$C_a = -4.7619(C_{O2}) + 100 \qquad [1]$$

Three calculations are required to determine the agent concentration, C_a, required to raise the total heat capacity of an enclosed area to 209 J/mol-K/mole of O_2. (The heat capacity assumed affects values calculated but does not affect the rank ordering of agents.) (1) The mole or volume percent (identical for mixtures of ideal gases) of agent required to impart a heat capacity of 209 J/mol-K/mole of O_2 at 298K and constant pressure while maintaining a constant oxygen concentration (e.g., 20 mol %) is calculated. In other words, the oxygen concentration is held constant at 20 mol % and the nitrogen/argon (N_2/Ar) concentration is decreased as agent is added. (2) A second calculation is made assuming a different constant O_2 concentration (e.g., 16 mol %). (3) These data are then used to calculate, for each agent, the equation of the line that represents an atmosphere where combustion cannot be sustained. A sample calculation is given below for HFC-125 (pentafluoroethane, CHF_2CF_3).

At 298K and 1 atmosphere pressure, the vapor-phase heat capacity (Cp) of HFC-125 is 96.1 J/mol K. Under normal conditions, the composition of ambient air is approximately 21 mol % oxygen, 78 mol % nitrogen, and 1 mol % argon. The heat capacity of oxygen (O_2) is 29.37 J/mol-K, that of nitrogen (N_2) is 29.15 J/mol K, and that of argon (Ar) is 20.800 J/mol-K [8]. The average heat capacity of N_2/Ar in the ratio found in air (78 mol %/1 mol %) is calculated as 29.04 J/mol-K. Thus, the heat capacity of a mixture of HFC-125, O_2, and N_2/Ar is given by $f_{125}(96.1) + f_{O2}(29.37) + f_{N2/Ar}(29.04)$ J/mol-K, where f_a is the mole fraction of component a. This must be set equal to the heat capacity of 209 J/mol-K/mole of O_2. Thus for 1 mole of mixture, $f_{125}(96.02) + f_{O2}(29.37) + f_{N2/Ar}(29.04) = 209 f_{O2}$. If f_{O2} is maintained at 0.20, this gives Equation 2, whose solution yields $f_{125} = 0.1892$ (18.92 mol %). The same procedure for an oxygen concentration of 16 mol % gives $f_{125} = 0.0648$ (6.48 mol %).

$$f_{125}(96.1) + 0.20(29.37) + (1\text{-}0.20\text{-}f_{125})(29.04) = 209(0.20) \quad [2]$$

The relation between the HFC-125 and O_2 concentrations (C_{125} and C_{O2}) is linear and can be written in the form $y = mx + b$, where y is C_{125}, x is C_{O2}, m is the slope of the line, and b is the y intercept. The two (x, y) data pairs calculated earlier are (20, 18.92) and (16, 6.48). The slope is given by $m = (18.92\text{-}6.48)/(20\text{-}16) = 3.11$ and the y-intercept is $b = 6.48 - (3.11)(16) = -43.31$. Thus, the equation relating the concentration of HFC-125 to the concentration of O_2 for an atmosphere that will not support combustion due to its heat capacity is

$$C_{125} = 3.11(C_{O2}) - 43.31 \quad [3]$$

This line defines a family of mixtures containing HFC-125, O_2, and N_2/Ar. Only one mixture on this line can be formed by discharging HFC-125 into an enclosed volume. That unique mixture is the intersect of the HFC-125 line described by Equation 3 and the oxygen depletion line defined by Equation 1 with $C_a = C_{125}$. The intersection of these two lines is found from the simultaneous Equations 1 and 3. For HFC-125, $C_{O2} = 18.21$ mol % and $C_{125} = 13.33$ mol %.

RESULTS AND ANALYSIS

Table 1 contains cup burner extinguishment concentrations for n-heptane fuel and heat capacity data for a series of halocarbon compounds. The cup burner values were taken from the original data as reported in Reference 3 with, in some cases, one fewer decimal place. The heat capacity data are from DuPont or the NMERI/CGET Chemical Options Database, which is compiled from a variety of sources. In all cases, agreement between DuPont and NMERI/CGET values was good; however, where both data were available, the DuPont data were used.

TABLE 1. CUP BURNER AND HEAT CAPACITY DATA

CAS No.	Halocarbon No.	Formula	Cup Burner, vol (mol) %	Cp at 298K, J/mol-K
353-59-3	BCFC-12B1	$CBrClF_2$	3.22	74.7
75-61-6	BFC-12B2	CBr_2F_2	2.17	'77.8
75-63-8	BFC-13B1	$CBrF_3$	2.9	69.8
56-23-5	cc-10	CCl_4	7.61	83.4
75-69-4	CFC-11	CCl_3F	7.75	78.1
76-13-1	CFC-113	CCl_2FCClF_2	6.19	121.4
354-58-5	CFC-113a	CCl_3CF_3	6.19	120.5
76-14-2	CFC-I 14	$CClF_2CClF_2$	6.41	116.3
374-07-2	CFC-114a	CCl_2FCF_3	6.41	115.9
76-15-3	CFC-115	$CClF_2CF_3$	6.28	110.9
75-71-8	CFC-12	CCl_2F_2	7.64	72.4
75-72-9	CFC-13	$CClF_3$	7.22	66.9
76-16-4	FC-I 16	CF_3CF_3	7.8	106.4
75-73-0	FC-14	CF_4	13.79	61
76-19-7	FC-218	$CF_3CF_2CF_3$	6.11	149
355-25-9	FC-3-1-10	$CF_3CF_2CF_2CF_3$	5	191
115-25-3	FC-C3 18	$-CF_2CF_2CF_2CF_2-$	7.19	159
2314-97-8	FIC-1311	CF_3I	3.02	70.88
754-34-7	FIC-217caI1	$CF_3CF_2CF_2I$	3.04	'197
354-06-3	HBCFC-123aB1α	$CBrF_2CHClF$	3.17	103
354-04-1	HBFC-123aB2	$CHBrFCBrF_2$	2.01	106
1868-53-7	HBFC-21B2	$CHBr_2F$	1.77	65
1511-62-2	HBFC-22B1	$CHBrF_2$	4.41	59.6
630-20-6	HCC-130a	CCl_3CH_2Cl	[b]7.96	104.2
75-34-3	HCC-150a	CH_3CHCl_2	8.6	76.3
67-66-3	HCC-20	$CHCl_3$	10.5	65.4
78-87-5	HCC-270da	$CH_3CHClCH_2Cl$	[b]4.6	96.7
142-28-9	HCC-27Ofa	$CH_2ClCH_2CH_2Cl$	[b]5.46	93.8
75-29-6	HCC-280da	$CH_3CHClCH_3$	3.2	85.6
540-54-5	HCC-28Ofa	$CH_3CH_2CH_2Cl$	3.32	82.9
75-09-2	HCC-30	CH_2Cl_2	14.1	50.9
354-14-3	HCFC-121	CCl_2FCHCl_2	b7.77	114.1
354-15-4	HCFC-122a	$CCl_2FCHClF$	6.3	109.7
306-83-2	HCFC-123	$CHCl_2CF_3$	[b]7.1	102.5
354-23-4	HCFC-123a	$CHClFCClF_2$	[b]8.3	104.3

2837-89-0	HCFC-124	$CHClFCF_3$	6.7	98.9
1649-08-7	HCFC-132b	$CH_2ClCClF_2$	7.85	94.2
75-88-7	HCFC-133a	CH_2ClCF_3	7.59	89.1
430-57-9	HCFC-141	$CHFClCH_2Cl$	18.72	82.1
1717-00-6	HCFC-141b	CH_3CCl_2F	[b]12.5	88.7
75-45-6	HCFC-22	$CHClF_2$	11.6	57.1
593-70-4	HCFC-31	CH_2ClF	b20	47.3
354-33-6	HFC-125	CHF_2CF_3	9.41	96.1
359-35-3	HFC-134	CHF_2CHF_2	11.2	83.7
811-97-2	HFC-134a	CH_2FCF_3	10.47	86.3
2252-84-8	HFC-227ca	$CHF_2CF_2CF_3$	6.5	137.7
431-89-0	HFC-227ea	CF_3CHFCF_3	6.3	136.6
75-46-7	HFC-23	CHF_3	12.6	51.1
431-63-0	HFC-236ea	$CF_3CHFCHF_2$	6.6	128.1
690-39-1	HFC-236fa	$CF_3CH_2CF_3$	5.6	126
1814-88-6	HFC-245cb	$CF_3CF_2CH_3$	8.2	120.2
40723-63-5	HFC-254cb	$CHF_2CF_2CH_3$	[b]10.1	107.6
62126-90-3	HFC-272ea	$CH_2FCHFCH_3$	[b]5.6	88.8
75-10-5	HFC-32	CH_2F_2	8.75	42.7

[a]Reliability uncertain.

[b]Limited confidence.

[c]Estimated.

Table 2 gives the extinguishment concentrations calculated based on heat capacity alone, the observed extinguishment concentrations, and the ratio of the calculated concentration to that observed (termed the "extinguishment ratio" throughout this paper).

TABLE 2. EXPERIMENTAL AND CALCULATED EXTINGUISHMENT CONCENTRATIONS

Halocarbon No.	Formula	Extinguishment Concentration vol %		Extinguishment Ratio
		Calculated	Observed	Calc/Obs
HBFC-21B2	$CHBr_2F$	18.52	1.77	10.47
BFC-12B2	CBr_2F_2	15.96	2.17	7.36
HBFC-123aB2	$CHBrFCBrF_2$	12.24	2.01	6.09
BFC-13B1	$CBrF_3$	17.47	2.9	6.02
FIC-1311	CF_3I	17.25	3.02	5.71
BCFC-12B1	$CBrClF_2$	16.52	3.22	5.13
HCC-280da	$CH_3CHClCH_3$	14.72	3.2	4.60
HCC-28Ofa	$CH_3CH_2CH_2Cl$	15.13	3.32	4.56
HBFC-22B1	$CHBrF_2$	19.87	4.41	4.51
HBCFC-123aBla	$CBrF_2CHClF$	12.55	3.17	3.96
HFC-32	CH_2F_2	25.71	8.75	2.94
HCC-270da	$CH_3CHClCH_2Cl$	13.26	4.6	2.88
HFC-272ea	$CH_2FCHFCH_3$	14.27	5.6	2.55
CFC-13	$CClF_3$	18.09	7.22	2.51
HCC-27Ofa	$CH_2ClCH_2CH_2Cl$	13.61	5.46	2.49
FIC-217caI1	$CF_3CF_2CF_2I$	6.98	3.04	2.30
CFC-12	CCl_2F_2	16.95	7.64	2.22
CFC-11	CCl_3F	15.91	7.75	2.05
cc-10	CCl_4	15.05	7.61	1.98
HCFC-124	$CHClFCF_3$	13.00	6.7	1.94
HCC-150a	CH_3CHCl_2	16.23	8.6	1.89
HCFC-122a	$CCl_2FCHClF$	11.87	6.3	1.88
CFC-115	$CClF_2CF_3$	11.76	6.28	1.87
HCFC-133a	CH_2ClCF_3	14.23	7.59	1.87
HFC-236fa	$CF_3CH_2CF_3$	10.50	5.6	1.87
HFC-23	cHF3	22.43	12.6	1.78
HCFC-123	$CHCl_2CF_3$	12.60	7.1	1.77
HCFC-22	$CHClF_2$	20.56	11.6	1.77
CFC-113a	CCl_3CF_3	10.92	6.19	1.76
CFC-114	$CClF_2CClF_2$	11.27	6.41	1.76
CFC-114a	CCl_2FCF_3	11.31	6.41	1.76
HCC-20	$CHCl_3$	18.43	10.5	1.76
CFC-113	CCl_2FCClF_2	10.85	6.19	1.75

HCFC-132b	$CH_2ClCClF_2$	13.56	7.85	1.73
HCC-30	CH_2Cl_2	22.50	14.1	1.60
HFC-236ea	$CF_3CHFCHF_2$	10.34	6.6	1.57
FC-116	CF_3CF_3	12.19	7.8	1.56
HCC-130a	CCl_3CH_2Cl	12.42	7.96	1.56
HFC-227ea	CF_3CHFCF_3	9.76	6.3	1.55
HCFC-123a	$CHClFCClF_2$	12.41	8.3	1.50
HFC-227ca	$CHF_2CF_2CF_3$	9.69	6.5	1.49
FC-218	$CF_3CF_2CF_3$	9.02	6.11	1.48
HCFC-121	CCl_2FCHCl_2	11.47	7.77	1.48
FC-3-1-10	$CF_3CF_2CF_2CF_3$	7.18	5	1.44
HFC-125	CHF_2CF_3	13.33	9.41	1.42
FC-14	CF_4	19.50	13.79	1.41
HFC-134a	CH_2FCF_3	14.62	10.47	1.40
HFC-134	CHF_2CHF_2	15.01	11.2	1.34
HFC-245cb	$CF_3CF_2CH_3$	10.95	8.2	1.34
HFC-254cb	$CHF_2CF_2CH_3$	12.08	10.1	1.20
HCFC-31	CH_2ClF	23.80	20	1.19
FC-C318	$-CF_2CF_2CF_2CF_2-$	8.50	7.19	1.18
HCFC-141b	CH_3CCl_2F	14.28	12.5	1.14
HCFC-141	$CHFClCH_2Cl$	15.25	18.72	0.81

The data in Table 2 are presented in order of decreasing extinguishment ratio. One would expect this would give an order of decreasing chemical contribution to extinguishment, and inspection of the table indicates that this is generally true. If the assumed heat capacity of 209 J/mol-K/mole of O_2 is correct, a Calc/Obs value of 1.00 indicates no chemical contribution and, except for HCFC-141, 1.00 appears to be a lower limit. Bromine and iodine-containing compounds appear toward the top of the table, and compounds whose extinguishment mechanism is believed to be primarily physical appear toward the bottom. As expected, dibromide compounds are exceedingly effective. FIC-217caIl appears to be out of line; however, the heat capacity of this compound has been estimated [9], and appears to be high. This would make the predicted extinguishment concentration based on heat absorption alone low and would give a low value for the extinguishment ratio.

The large apparent chemical contributions to extinguishment by HCC-280fa ($CH_3CH_2CH_2Cl$) and HCC-280da ($CH_3CHClCH_3$) are surprising. In these flammable compounds, the large number of hydrogen atoms may serve as highly effective free radical scavengers (e.g., Reaction 1). Data for the hydrochlorocarbons (HCCs) indicates that the chemical contribution increases as the atom ratio of hydrogen to chlorine increases (Table 3)

$$RH + \cdot H \rightarrow H_2 + \cdot R \qquad (1)$$

TABLE 3. HCC EXTINGUISHMENT RATIO AS FUNCTION OF H/Cl ATOM RATIO

Halocarbon No.	Formula	WCI Atom Ratio	Calc/Obs Extinguishment Ratio
HCC-280da	$CH_3CHClCH_3$	7.00	4.60
HCC-28Ofa	$CH_3CH_2CH_2Cl$	7.00	4.56
HCC-270da	$CH_3CHClCH_2Cl$	3.00	2.88
HCC-27Ofa	$CH_2ClCH_2CH_2Cl$	3.00	2.49
HCC-150a	CH_3CHCl_2	2.00	1.89
HCC-20	$CHCl_3$	0.33	1.76
HCC-30	CH_2Cl_2	1.00	1.60
HCC-130a	CCl_3CH_2Cl	0.50	1.56

Trends in extinguishment ratio based on the H/F atom ratio in the hydrofluorocarbons (HFCs) is much less clear (Table 4) No trends are immediately apparent even when the data are grouped into methane and ethane derivatives. HFC-32, which is flammable, appears to be particularly anomalous. Its effectiveness does not appear to be due to exceeding the upper flammability limit since the flammability limits for HFC-32 are 12.7 vol % to 33.4 vol % [10]; whereas the cup burner extinguishment concentration is 8.75 vol %. On the other hand, the extreme position of HFC-272ea may well be due to operation of the same mechanism proposed above for the HCCs.

TABLE 4. HFC EXTINGUISHMENT RATIO AS FUNCTION OF H/F ATOM RATIO

Halocarbon No.	Formula	H/F Atom Ratio	Calc/Obs Extinguishment Ratio
HFC-32	CH_2F_2	1.00	2.94
HFC-272ea	$CH_2FCHFCH_3$	3.00	2.55
HFC-236fa	$CF_3CH_2CF_3$	0.33	1.87
HFC-23	CHF_3	0.33	1.78
HFC-236ea	$CF_3CHFCHF_2$	0.33	1.57
HFC-227ea	CF_3CHFCF_3	0.14	1.55
HFC-227ca	$CHF_2CF_2CF_3$	0.14	1.49
HFC-125	CHF_2CF_3	0.20	1.42
HFC-134a	CH_2FCF_3	0.50	1.40
HFC-134	CHF_2CHF_2	0.50	1.34
HFC-245cb	$CF_3CF_2CH_3$	0.60	1.34
HFC-254cb	$CHF_2CF_2CH_3$	1.00	1.20

For the hydrochlorofluorocarbons (HCFCs), any relationship of the extinguishment ratio to the H/Cl and H/halogen atom ratios appears to be totally random (Table 5). There is a very weak indication that extinguishment ratio may decrease (!) as the number of chlorine atoms relative to the number of fluorine atoms increases, though the data are ambiguous and variations in hydrogen content and number of carbon atoms undoubtedly obscure any trends. Of particular interest are the small values of the extinguishment ratio for the isomers of HCFC-141. In the case of HCFC-141b, the extinguishment concentration (12.5 vol %) is well within the flammability envelope (5.6 to 17.7 vol % [11]). The effect of hydrogen content on extinguishment ratio, which appears to be so clear for the HCCs, deserves further investigation.

TABLE 5. HCFC EXTINGUISHMENT RATIO AS FUNCTION OF ATOM RATIOS

Halocarbon No.	Formula	H/Cl Atom Ratio	H/Halogen Atom Ratio	Cl/F Atom Ratio	Calc/Obs Extinguishment Ratio
HCFC-124	$CHClFCF_3$	1.00	0.20	0.25	1.94
HCFC-122a	$CCl_2FCHClF$	0.33	0.20	1.50	1.88
HCFC-133a	CH_2ClCF_3	2.00	0.50	0.33	1.87
HCFC-22	$CHClF_2$	1.00	0.33	0.50	1.77
HCFC-123	$CHCl_2CF_3$	0.50	0.20	0.67	1.77
HCFC-132b	$CH_2ClCClF_2$	1.00	0.50	1.00	1.73
HCFC-123a	$CHClFCClF_2$	0.50	0.20	0.67	1.50
HCFC-121	CCl_2FCHCl_2	0.25	0.20	4.00	1.48
HCFC-31	CH_2ClF	2.00	1.00	1.00	1.19
HCFC-141b	CH_3CCl_2F	1.50	1.00	2.00	1.14
HCFC-141	$CHFClCH_2Cl$	1.00	1.00	2.00	0.81

For fully halogenated compounds, with the exception of the perfluorocarbons, the data show a clear reduction in extinguishment ratio as the chlorine content increases when grouped into methane and ethane derivatives (Table 6). This appears to contradict the general opinion that chlorine provides a small, but significant, chemical contribution to extinguishment. The CFCs have high extinguishment ratios and relatively high extinguishment efficiencies relative to most other agents that operate by primarily physical mechanisms. Work has shown that some CFC blends are actually as good as or better than Halon 1211 in field testing [12].

Comparison of data for isomers indicates that an increase in the number of CF3 groups gives an increase in the extinguishment ratio, indicative of increased chemical contribution (Table 7), though some differences are small. The sole exception is CFC-114 and CFC-114a, which have identical extinguishment ratios. This observation indicates a chemical participation by $\bullet CF_3$ free radicals, the primary subject of another paper in this conference [13]. This may explain why FC-C318 (cyclic C_4F_8), which contains no CF_3 groups, has the smallest extinguishment ratio (indicating the smallest chemical contribution) of any of the perfluorocarbons in Table 2.

TABLE 6. EXTINGUISHMENT RATIO FOR FULLY HALOGENATED COMPOUNDS AS FUNCTION OF Cl/F ATOM RATIO

Halocarbon No.	Formula	Cl/F Atom Ratio	Calc/Obs Extinguishment Ratio
	Methanes		
FC-14	CF_4	0	1.41
CFC-13	$CClF_3$	0.33	2.51
CFC-12	CCl_2F_2	1.00	2.22
CFC-11	CCl_3F	3.00	2.05
CC-10	CCl_4	∞	1.98
	Ethanes		
FC-116	CF_3CF_3	0	1.56
CFC-115	$CClF_2CF_3$	0.20	1.87
CFC-I 14a	CCl_2FCF_3	0.50	1.76
CFC-114	$CClF_2CClF_2$	0.50	I.76
CFC-113a	CCl_3CF_3	1.00	1.76
CFC-I 13	CCl_2FCClF_2	1.00	1.75

TABLE 7. DATA FOR ISOMERS WITH DIFFERENT NUMBERS OF CF_3 GROUPS

Halocarbon No.	Formula	Number of CF_3 Groups	Calc/Obs Extinguishment Ratio
HFC-236fa	$CF_3CH_2CF_3$	2	1.87
HFC-236ea	$CF_3CHFCHF_2$	1	1.57
HCFC-123	$CHCl_2CF_3$	1	1.77
HCFC-123a	$CHClFCClF_2$	0	1.50
CFC-113a	CCl_3CF_3	1	1.76
CFC-113	CCl_2FCClF_2	0	1.75
HFC-227ea	CF_3CHFCF_3	2	1.55
HFC-227ca	$CHF_2CF_2CF_3$	1	1.49
HFC-134a	CH_2FCF_3	1	1.40
HFC-134	CHF_2CHF_2	0	1.34

It has been proposed by others in the past that $\bullet CF_3$ free radicals can act chemically as fire suppressants. Ab initio molecular orbital calculations indicate that fire suppression by perfluoromethylamines is due, in part, to reactions of the trifluoromethyl radical, which can be

easily released from perfluoroalkyl-amine by dissociation of C-N bonds (Reference **14).** The proposed Reactions **2** through **4** are similar to those proposed for bromine in the case of the halons.

$$\bullet CF_3 + \bullet H \rightarrow CF_3H \quad (2)$$

$$CF_3H + \bullet H \rightarrow \bullet CF_3 + H_2 \quad (3)$$

$$CF_3H + \bullet OH \rightarrow \bullet CF_3 + H_2O \quad (4)$$

REFERENCES

1. Sheinson, R. S., and Driscoll, D. C., "Fire Suppression Mechanisms: Agent Testing by Cup Burner," ***Proceedings, International Conference on CFC & Halon Alternatives,*** Washington DC, **10-11** October **1989.**

2. Sheinson, R. S., Penner-Hahn, J. E., and Indritz, D., "The Physical and Chemical Action of Fire Suppressants," ***Fire Safety Journal,*** Vol. **15,** pp. 437-450, **1989.**

3. Moore, T. A., Weitz, C. A., and Tapscott, R. E., **"An** Update **on NMERI** Cup-Burner Test Results," ***Proceedings, Halon Options Technical Working Conference,*** Albuquerque, New Mexico, pp. **551-567, 7-9** May **1996.**

4. C. T. Ewing, J. T. Hughes, and H. W. Carhart, ***Fire and Materials*** **8(3), 148-156 (1984).**

5. Dlugogorski, B. Z., Kennedy, E. M., and Moms, K. A., "Thermal Behaviour of Cup Burners," in ***Proceedings, Interflam '96, 7th International Interflam Conference,*** Cambridge, England, March **26-28, 1996,** Interscience Communications, Ltd., London, pp. 445-457.

6. Huggett, C. M., "Oxygen-Containing Atmospheres," U. S. Patent **3,840,667, 8** October **1974,** assigned to Atlantic Research Corporation.

7. McHale, E. T., "Life Support Without Combustion Hazards," ***Fire Technology,*** Vol. 10, pp. **15-24, 1974.**

8. ***CRC Handbook of Chemistry and Physics***, 68th Ed., Weast, R. C., ed., CRC Press, Inc., Boca Raton, Florida, pp. **D-51** to **D-93, 1987.**

9. Pitts, W. M., Nyden, M. R., Gann, R. G., Mallard, W. G., and Tsang, W., ***Construction of an Exploratory List of Chemicals to Initiate the Search for Halon Alternatives,*** NIST Tech. Note **1279,** Air Force Engineering and Services Laboratory, Tyndall AFB, Florida, National Institute of Standards and Technology, Gaithersburg, Maryland, August **1990.**

10. Amaud, D., Macaudiere, S., Tanguy, J. C., and Radice, P. F., "Properties of Blends Which Can be Used as CFC-502 Substitutes in Refrigeration," ***Proceedings, International CFC and Halon Alternatives Conference,*** Washington, D.C., **29** September-1 October **1992,** pp. 105-114.

11. *BS 4434 : Revision : Specification for Safety and Environmental Aspects in the Design, Construction, and Installation of Refrigerating Appliances and Systems,* BS **4434,** British Standards Institute, 1 February **1995.**

12. Tapscott, R. E., Lee, M. **E.,** Watson, J. D., Nimitz, J. S., and Rodriguez, M. L., ***Next Generation Fire Extinguishing Agent, Phase IV — Foundation for New Training Agent Development,*** ESL-TR-87-03, Vol. **4** of **5, Air** Force Engineering and Services Laboratory, Tyndall Air Force Base, Florida, December **1989.**

13. Williams, **B. A.,** Fleming, J. **W.,** and Sheinson, R. S., "Extinction Studies of Hydrofluorocarbons in Methane/Air and Propane/Air Counterflow Diffusion Flames: The Role of the CF_3 Radical," ***Proceedings, Halon Options Technical Working Conference,*** Albuquerque, New Mexico, **5-7** May **1997.**

14. Fukaya, H., Ono, T, and Abe, T., "New Fire Suppression Mechanism of Perfluoroalkyl-amines," *Journal* ***of Chemical Society Chemical Communications,*** pp. **1207-1208, 1995.**