## A thermal view on the synergistic effect of fire suppressants

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#### Abstract:

Starting from the flammability diagram, a thermal theory is proposed to scale various critical concentrations in combustion. By the analogy between ignition and suppression, the flammability limits are extrapolated to the Minimum Extinguishing Concentration. Thus the suppressibility of a fuel will be evaluated from its flammability, while the suppression capability of an agent will be evaluated using the CB value. By setting up the thermal balance at extinguishing, the synergistic effect can also be explained by an adjustable flame temperature factor. This thermal mechanism will guide the future work on selection new combination of binary agents.

# Keywords: adiabatic flame temperature, flammability limits, oxygen index, minimum extinguishing concentration, synergistic effect

#### 1. Introduction

After 20 years of searching for an effective fire-extinguishing agent to phase-out halons, an ideal agent with all the desirable properties of halon 1301 is difficult to find. Attention has been paid to the combination of two or more agents, with the purpose of taking favoring advantages of each agent. Lott et al. (1994) study the synergistic effect between chemical and physical fire-suppressant agents. Their extinguishment factor (or suppression fraction) is adopted by Vahdat et al. (2003) and Zhang et al. (2007) for expressing the synergism between chemical and physical agents. They found the chemical effect is most dominant at lower concentrations, without further work on a coherent theory. Sheinson et al. (1989) tried to isolate the physical and chemical contributions of all agents by allocating suppressant factor to each functional group in each agent. However, they improperly assume that the physical and chemical effects are additive, which is contrary to the findings of Tucker et al. (1981).

Historically, such a chemical effect was explained as a different mechanism than any thermal agents, which was based on the analysis of combustion tube data at Purdue University (Fryberg, 1950; Malcom, 1950). Then the "free radical" mechanism is widely accepted as the fourth component of a fire tetrahedron (Haessler, 1974), and widely accepted in any fire-related textbooks. However, while much has been learned about the chemistry of fire, this "radical trap" theory cannot be used to explain the extinction phenomena alone. Numerous research work show that the effectiveness of halogens are in direct proportion to their atomic weight. This fact has invalidated the "radical trap" theory (Larsen, 2005). Ewing et al. (1984, 1989) further found more evidence of thermal mechanisms in their systematic work on dry chemicals. Noto et al. (1998) found that this chemical effect is only significant at small concentrations, while the experimental work of Tucker et al. (1981) shown that the agent (Halon 1301) extinguishing concentration is a linear function of local oxygen concentration, while the linearity breaks down at lower oxygen concentrations. Williams (1981) and Saito et al. (1995) used the raised flame temperature to explain the synergistic effect, which is further explored here for a thermal

theory to explain the suppression mechanisms associated with any total-flooding agents. Following the previous thermal view on the chemical effect, this work will check the thermal mechanism against various critical phenomena.

The paper is organized as following. The flammability diagram is checked first with a thermal theory. Critical concentrations are found to be interchangeable based on the flammability information. Next, the fuels are ranked based their flammability. The agents can also be ranked by a device-dependent coefficient. Finally, the synergistic effect is modeled using this thermal theory.

#### 2. A thermal view on critical phenomena

In combustion science, all critical behaviors are the result of competition between heat source (heat of combustion) and heat sink (energy absorption by fuel/oxidizer/inertants). Though the chain branching theory explains some phenomena in combustion (Glassman, 1995), the conservation of energy still applies to all critical behaviors. Now the physical view explains the critical behavior from a thermal perspective, while the chemical theory introduces the threshold of reaction (flame temperature) for the energy balance to take place. In order to understand various critical phenomena (flammability, inertion and extinguishment), we have to begin with the flammability diagram.

## 2.1. A closer look at flammability diagram

Following the previous work (Ma, 2011), the idealistic flammability diagram can be composed from material properties. Starting with a typical combustion system, the following equations are used.  $C_{a}H_{b}O_{c} + C_{a} \cdot (O_{2} + 3.773N_{2}) + C_{d} \cdot D \rightarrow a \cdot CO_{2} + 0.5b \cdot H_{2}O + 3.773a \cdot N_{2} + C_{d} \cdot D$  (1)

$$+C_{o} \cdot (O_{2} + 3.7/3N_{2}) + C_{d} \cdot D \to a \cdot CO_{2} + 0.5b \cdot H_{2}O + 3.7/3a \cdot N_{2} + C_{d} \cdot D$$
(1)  
$$C_{o} = a + b/4 - c/2$$

$$C_{st} = 1 + 4.773 \cdot C_o$$
(2)

where D stands for diluent,  $C_o$  is the oxygen coefficient or a stoichiometric oxygen number representing chemistry, and  $C_y$  is the stoichiometric number.

Now, a diluent with a concentration of  $y_d$  and a quenching potential of  $Q_D$  is introduced into a combustion system. The energy balance for such a binary system at LFL and UFL are expressed as

$$x_{L} = \frac{1 - (1 - Q_{D}) \cdot x_{D}}{1 - Q_{F} + C_{O} \cdot H_{O}} = x_{L,0} \cdot \left[1 - (1 - Q_{D}) \cdot x_{D}\right]$$
(3)

$$x_{\upsilon} = x_{\upsilon,0} - (x_{\upsilon,0} + \frac{Q_{D}}{Q_{F} - 1 + H_{O} / 4.773}) \cdot x_{D}$$
(4)

Here, subscript 0 is used for the initial flammability limits without any diluent. These two curves produce LFL and UFL lines in a flammability diagram (Figure 1). The idealistic inerting concentration is found to be the cross-point of  $x_L$  and  $x_U$  curves. An additional curve, the stoichiometric line, is governed by the reaction stoichiometry (equation 2) can also be derived.

$$x_{st} = \frac{1 - x_D}{1 + 4.773 \cdot C_O} = x_{st,0} (1 - x_D)$$
(5)

It is not surprising to see that the inerting point falls also on the stoichiometric line.

Real flammability diagrams introduced two discrepancies from the above idealistic flammability curves. First, the flame at extinction is no longer diffusion flame at ignition, but somewhat premixed, which has a different flame structure than a diffusion flame at ignition (LFL or UFL). When the critical

flame temperature (threshold or barrier) is raised, a smaller concentration of inertant is needed to bring about extinction. As Beyler summarizes (1988), the flame temperature is higher at extinction (premixed flame) than at ignition (diffusion flame), due to a distorted flame structure. So the Nitrogen Point/Inertion Point (NP/IP) is smaller than the cross point. Macek (1979) has discussed this bias in more depth. The deviation at the inertion point comes from several reasons: incomplete reaction, increased critical flame temperature, increased radiative heat loss terms, etc.

Second, with a few exceptions, the stoichiometric line is not of complete reaction to CO<sub>2</sub>, but the incomplete reaction to CO instead. That means, the flame at extinction is biased toward the CO sthoichiometric line (equation 6) instead of CO<sub>2</sub> stoichiometric line (equation 2). This shift is attributed to incomplete combustion and to preferential diffusion of reactants (Beyler, 1988).

$$C_o = a/2 + b/4 - c/2$$

$$C_{st} = 1 + 4.773 \cdot C_o$$
(6)



Figure 5. Flammability diagram for propane.

Besides the Nitrogen Point or Inerting Point (NP/IP), the above diagram also shows some critical points compared by Beyler (1988). LL is the Lower Flammability Limit. SL is the cross point between Stoichiometric line and the flammability curve. Oxygen Index (OI) or Limiting Oxygen Index (LOI) is tangent point on the flammability curve. Since OI is so close to NP/IP, NP/IP can be used to estimate OI directly.

From this diagram, all critical points are results of the competition between heating and quenching, with a critical role played by the adiabatic flame temperature (AFT). This thermal view will be applied to thermal agents first, before moving to the synergistic effect.

#### **2.2.** From ignition to inertion

Since the quenching potential is different for each agent, we can scale the inerting potential for each agent with that of air. Here is an important analogy in this paper. In the flammability test of combustible gases, the excess air (those additional to its stoichiometric requirement) is served as the inerting agent. Then for any interting concentration, the difference comes from the quenching potential and the critical flame temperature. Using two parameters ( $\alpha$  for the agent quenching

potential and  $\beta$  for the change in flame temperature), we can derived the inerting concentration from the published flammability limits.

Here is the estimation procedure from the more fundamental parameters:

- 1. The suppression concentration at ignition is LFL;
- 2. Isolate the contribution of excess air;
- 3. Rescale the contribution of the new agent as compared to the properties of air;
- 4. Find the inerting concentration of the specific fire suppression agent.

$$X_{i,fuel} = LFL \tag{7}$$

$$v_{i,\text{oir}} = \frac{1 - C_{\text{st}} \cdot X_{i,\text{fuel}}}{X_{i,\text{fuel}}}$$
(8)

$$v_{i,agent} = \frac{v_{i,air}}{\alpha \cdot \beta} \tag{9}$$

$$X_{i,agent} = \frac{V_{i,agent}}{1 + V_{air} + V_{i,agent}}$$
(10)

Here  $v_{i,air}$  is the inerting agent-fuel-ratio of air, which is converted into  $v_{i,agent}$  by 2 scaling factors. The quenching factor  $\alpha$  is used to compare the inerting potential between agent and air which can be derived from the enthalpy values between ambient and critical flame temperature (see the table in Ma, 2011). The thermal factor  $\beta$  is the contribution of raised flame temperature, which is nearly constant for a thermal agent in a specific flame structure.

$$\alpha_{i} = \frac{\left(H_{AFT}^{0} - H_{298.15}^{0}\right)_{i}}{\left(H_{AFT}^{0} - H_{298.15}^{0}\right)_{air}}$$
(11)

$$\beta_{i} = \frac{\left(T_{AFT}\right)_{extinction}}{\left(T_{AFT}\right)_{ignition}}$$
(12)



Figure 2 shows the prediction of inerting concentration of a typical thermal agent, Carbon Dioxide. Without temperature correction, the isothermal inertion point is predicted (figure 2(a)). This inerting concentration is over-predicted due to isothermal processes. With a constant  $\beta$  to compensate the raised flame temperature change at extinction, the inerting concentrations are better predicted (Figure 2(b)).

#### **2.3. From ignition to LOC**

Similarly, Limiting Oxygen Concentration (LOC or OI, Oxygen Index)can be predicted using LFL information. Figure 1 shows that LOC is close to NP/IP, so the OI can be estimated from NP/IP values directly (equation 13). This conversion has already been used in a textbook (Crowl, 2007)



Figure 3. Prediction of OI under Nitrogen(left) and CO2 (right) inerting

## 2.4. From inertion to extinguishment

The fire suppression community dislikes the concept of minimum inertion concentration (MIC), since it is too conservative and the real-world fuels are seldom in gaseous state, instead they are condensed fuels. That means the evaporation/pyrolysis process may dominate the critical behavior. So cup-burner is used to find the minimum extinguishment concentration (MEC), which is always smaller than MIC, with other suppression mechanisms in action.

LFL measurement is based on the test apparatus close to the measurement of inerting concentration (adiabatic process), so more conservative inerting concentrations are predicted. Once the thermal theory for stagnant premixed flame is established, we can have a new look at the cupburner test.

Comparing the premixed flame, the reaction rates in diffusion flames are 1) limited by mass transfer rates to the reaction zone; 2) dependent on a bluff body to stabilize the physical position of the flame base (otherwise the flame lifts off and extinguishes); 3) velocity profiles at the point of attachment of the flame base to the stabilizer (tending to blow off flame).

If checking the flame structure in a numerical prediction of cup-burner Heptane flame (Takahashi et. al. 2006), there is a small spot near the rim of the burner, which is premixed in nature. Due to this local flow structure, the premixed flame spot helps the diffusion flame to stabilize. Without this hot spot, the diffusion flame will be lift-off, as found in a series of numerical experiments by Takahashi et al. (2006). The heat transfer process in that premixed flame zone dominates the extinction of the total flame, so it needs further research.

Without detail information about the local flow and heat transfer information, we can only estimate the heat loss part using an index  $\gamma$ . The reason for using enthalpy surplus  $\Delta H_c - \Delta H_p$  instead of other choices is that we can use  $\gamma$  along with  $\alpha$  and  $\beta$ , since they have the same scaling role on the quenching potential of the agent. Using try and error, we found that  $\gamma = 1.28$  for the agents in figure 5. Here is a list of input parameters for predicting CB values for suppressing Heptane flame from LFL.

		<u> </u>	J	<b>j</b>	- ] -
	IG01	IG55	IG541	<b>N</b> 2	CO <sub>2</sub>
Quenching factor ( $lpha$ )	0.632	0.812	0.898	0.992	1.615
Loss factor ( $\gamma$ )	1.282	1.282	1.282	1.282	1.282

Table 2. Input parameters for predicting CB values of Heptane flame.



Figure 4. Comparison with CB-test values for Heptane

Figure 4 shows the predicted inerting concentration ( $\gamma = 1$ ) and extinction concentration (CB value)( $\gamma = 1.282$ ). The difference is accounted by the loss factor  $\gamma$ . This factor is closely related to the premixed flame near the rim of fuel supply. This flame serves duplicate purpose: maintain high temperature for flame propagation and preheating the fuel. Using a simple constant, this loss factor can be converted into the inerting effect as well. Unfortunately, this constant is fuel-dependent, depending on the local flow, heat transfer and fuel chemistry. It is only possible to use this value on the combination of a specific fuel and a thermal agent. When the chemical effect is involved, the synergistic effect is not additive, so the contribution cannot be accounted by a simple factor.

Next, the variation on fuel dependency will be studied using its flammability data.

## 3. Screening the fuel suppressibility

For each inquiry on the design concentration choice for a series of chemicals, the proposed task to the fire suppression engineer/consultant is to find the most hazardous material, and use its extinction concentration as the 'worst-case' level for the choice of extinguishing concentration. With the knowledge of material properties (or flammability limits), we can explain the reason why some fuels are more difficult to suppress than others.

Here a new index is introduced to explain the competition between quenching and heating using the flammability information in equation 12. Note this is a dimensional index with a unit of kJ<sup>-1</sup>.

$$SI = \frac{\text{Excess Air for Quenching}}{\text{Total Energy for Heating}} = \frac{1 - x_{L} \cdot (1 + C_{st})}{\Delta H_{C} \cdot x_{L}}$$
(12)





A screening of fuels (liquid fuels listed in Babrauskas's ignition handbook, 2003) is shown in figure 5. It is observed that the fires from halogenated fuels are easy to suppress, while partially oxidized fuels are difficult to suppress.

Using this flammability-derived suppression index of fuel, we can predict the minimum extinguishing concentrations of carbon dioxide in figure 6. The general trend is a linear dependency, while there is some discrepancy involved. The three under-prediction fuels are acetone, Benzene, and Propene, while the over-prediction fuel is carbon monoxide. The rest fuels are following a straight line. Using suppression index, it is possible to extrapolate the MEC (or CB value) of a thermal agent on Heptane to other fuels as well. This also confirms the thermal nature of a thermal agent on a liquid fire.



Figure 6. Minimum extinguishment concentration for carbon dioxide

#### 4. Screening the agent effectiveness

With the thermal theory discussed above, the agent effectiveness of a certain fire suppressing agent can be compared based on their air-equivalent-value. However, the most useful data are the CB values for most agents on Heptane. Heptane, as a fuel, has a complete thermal signature embedded in its lower flammability limits. By establishing the analogy between ignition and suppression, the equivalent-air-index of a certain agent can be derived. This equivalent-air-index can be scaled by the molecular weight to remove the mass-dependency, so a suppression index of the agent is derived. Here is the definition (derived in Appendix A).

$$SI = \frac{\frac{1 - x_E}{x_E} \cdot \left(\frac{1 - C_{st} \cdot x_L}{C_{st} \cdot x_L}\right)}{MW}$$
(13)

The result (listed in appendix B and in figure 7) shows, most agents have a mass-based index around 0.046 (the Nitrogen line, expressed as the thick dash-dot-dot line), while those smaller values are due to the fact that the agent is partially combustible (releasing energy) or Argon-related. Argon has single-atom molecules, so its specific heat is significantly smaller than others. For some below average fuels, they inert the combustion while releasing some energy, so their suppression effectiveness is compromised under the Nitrogen line.



*Figure 7. Screening of fire suppression effectiveness for different agents based on their CB value on Heptane.* 

On the other side, there are several above-average exceptions which are really chemical-assisted. Haloginated Methane (Halon 1301) has an abnormal effectiveness over others, which is found to be the radical scavenging effects due to some ions. The super-reactivity of such ions is also the reason for the ban of Halon (due to its long-term hazards to the ozone layer).

For most agents, mass-weighted effectiveness is roughly same, showing their inherent inerting nature on the combustion process. This result also confirms Hamins's study (1994), where most new agents are inerting the flame than stopping the reaction chemically.

#### 5. The synergistic effect

It is long believed that the raised flame temperature can explain the synergistic effect of a chemical agent like Halon 1301 (Williams, 1981). The mechanisms can be schematically explained in figure 8. As thermal agents will not change the critical flame temperature, a critical fraction of diluent is needed to remove the extra energy, making the reaction not sustainable. However, with a raised critical adiabatic flame temperature, the energy absorption potential of fuel and oxygen are also raised, so the true contribution of the new chemical agent can be smaller. Since this agent bring up the

contribution of existing components, its thermal contribution can be smaller than expected. This is called the synergistic effect of a chemical. Both Williams (1981) and Sato et al. (1994) explained this mechanism with a raised flame temperature. However, a simple framework of capturing this synergism is still missing.



Figure 8. The synergistic effect of raised flame temperature.

Base on this reasoning, we can estimate the temperature change necessary to explain the synergistic effect. First, the thermal balance at LFL is set up as the baseline.

$$\boldsymbol{x}_{L} \cdot \boldsymbol{Q}_{F} + (1 - \boldsymbol{x}_{L}) = \boldsymbol{x}_{L} \cdot \boldsymbol{H}_{F}$$
(14)

Submitting LFL and UFL of Heptane (Ma, 2011), we have the thermal signature as  $Q_F = 10.77$ ,  $H_F = 93.1$ , which means one unit of fuel can absorb 10.77 units of equivalent-air energy for raising air temperature from ambient to ignition flame temperature and release 93.1 units of equivalent-air energy. These two potentials will be used to estimate the flame temperature change at suppression.

Second, the thermal balance at suppression is set up as

$$\left[x_{L} \cdot Q_{F} + x_{D1} \cdot Q_{D1} + x_{D2} \cdot Q_{D2} + (1 - x_{L} - x_{D1} - x_{D2})\right] \cdot \chi = x_{L} \cdot \frac{H_{F}}{\chi}$$
(15)

Here  $\chi$  designates the change of temperature from baseline (critical suppression temperature, usually 1800K). When the critical flame temperature is raised by  $\chi$ , the quenching potential of all species are raised by  $\chi$ , and the heating potential of the fuel is reduced by  $\chi$ .



Figure 9. The experimental data by Lott et al. and the temperature change using the thermal theory.

Use the binary-agent experimental data of Lott et al. (1994), we can derive the variation of  $\chi$  shown in Figure 9 (b). The maximum change is 16%, which means that the slight variation of flame

temperature can explain the synergistic effect of a chemical agent from the thermal perspective. The chemical agent will contribute less by mass as the contributions from other agents are increased due to the raised critical flame temperature. This is the thermal explanation of the magic "radical trap" theory. For the application of a chemical agent in the case of Lott et al. (1996), initial 30% of chemical agent is raising the flame temperature, while the rest is contributing more like a thermal agent at raised critical flame temperature. This thermal theory can be used to guide further work on generic binary agents, such as dry chemical/nitrogen, mist/additive, aerosol/propellant etc.

#### 6. Conclusion

This work tries to check some critical combustion behavior using a consistent thermal theory. Flammability diagram provides the most useful information at ignition. By setting up the analogy between ignition and suppression, the flammability information can be tailored to estimate the Inerting concentration, Oxygen Index, Minimum Extinguishing Concentration etc. Flammability information can also be used to derive the suppressibility of any liquid fuel, which can be used to extrapolate to find the various MECs of a thermal agent. Combined with the flammability limits of Heptane, the MEC of any agent on Heptane (or CB value) can be used to rank all agents. It is found that most agents work thermally, while the chemical agents have exceptional behavior due to a synergistic effect.

By establishing the thermal balance at ignition and at suppression, the role of synergistic effect in the chemical agent is further explored. Using published data on a binary (including both thermal and chemical) agent, it is found that a mere change of 16% in flame temperature is enough to explain the reduction in synergistic index. This treatment confirms with the existing view that most agents work thermally (by mass), while the chemical effect is synergistic and reflected in critical flame temperature change. By combining the thermal agent and the chemical agent, it is possible to reduce the consumption of chemical agents, since most of them are working thermally. This will guide further work on design binary agents.

## Nomenclature

CAFT, Critical Adiabatic Flame Temperature (K)

 ${\it C}_{\it o}$  , the oxygen coefficient in a reaction, dimensionless

 $C_{\rm st}$  , the stoichiometric number for a reaction, dimensionless

 $H_{\scriptscriptstyle O}$ , the heating potential of oxygen based on air, dimensionless

 $H_{\scriptscriptstyle F}$  , the heating potential of fuel based on air, dimensionless

LFL, Lower Flammability Limit (volume ratio), % or dimensionless

LCR, Le Chatelier's Rule

OI, Oxygen Index

MEC, Minimum Extinguishing Concentration

 ${\it Q}_{\rm \scriptscriptstyle D}$  , the quenching potential of diluent based on air, dimensionless

 $Q_{\scriptscriptstyle F}$  , the quenching potential of fuel based on air, dimensionless

 $T_a$ , ambient temperature (K)

UFL, Upper Flammability Limit (volume ratio), % or dimensionless

- $x_{L}$ , Lower Flammability Limit (volume ratio), % or dimensionless
- $x_{st}$ , stoichiometric fuel/air volume concentration, % or dimensionless
- $x_v$ , Upper Flammability Limit (volume ratio), % or dimensionless
- lpha , quenching potential of a thermal agent, retrieved from NIST chemistry webbook
- $\beta$ , contribution of flame temperature change, from ignition (diffusion flame )to extinction (premixed flame)
- $\gamma$  , contribution of wall and other heat transfer effects on extinction
- $\chi$  , changes of critical flame temperature for synergistic effect

## Subscripts

- a, ambient
- d, diluent
- i, component of a mixture
- m, sum of a mixture
- st, stoichiometric
- AF, Adiabatic Flame
- L, lower flammable limit
- U, upper flammable limit
- D, diluent-based potential to air potential
- F, fuel-based potential to air potential

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Appendix A: The suppression index of an agent

First, we establish the volume balance for LFL in (a.1)

$$C_{st} \cdot x_{L} + x_{a} = 1 \tag{a.1}$$

Here  $x_a$  is the concentration of excess air not reacting at ignition (or at the lower flammability limit). So we have

$$\boldsymbol{x}_a = 1 - \boldsymbol{C}_{st} \cdot \boldsymbol{x}_L \tag{a.2}$$

Now we assume the suppression is similar to the above ignition process, but using a new thermal agent to replace the excess air. This new agent has a quenching potential of R times that of air. So the volume concentration of the new agent is scaled-down by R.

$$x_i = \frac{x_o}{R}$$
(a.3)

Now we have the extinction concentration defined as

$$\boldsymbol{x}_{E} = \frac{\boldsymbol{x}_{i}}{\boldsymbol{C}_{st} \cdot \boldsymbol{x}_{L} + \boldsymbol{x}_{i}} = \frac{1 - \boldsymbol{C}_{st} \cdot \boldsymbol{x}_{L}}{\boldsymbol{R} \cdot \boldsymbol{C}_{st} \cdot \boldsymbol{x}_{L} + 1 - \boldsymbol{C}_{st} \cdot \boldsymbol{x}_{L}}$$
(a.4)

Rearrange the terms, we have

$$R = \frac{1 - x_{E}}{x_{E}} \cdot \left(\frac{1 - C_{st} \cdot x_{L}}{C_{st} \cdot x_{L}}\right)$$
(a.5)

For nitrogen, the CB value is  $x_{E} = 0.32$ . Plugging the flammability data of Heptane,  $x_{L} = 0.012$ ,  $C_{st} = 53.4$ , we have R=1.194 for Nitrogen. This is more than its quenching potential  $\alpha = 0.992$ . The difference is the contribution of cup-burner test configuration (use  $\chi$  to represent in this work), i.e., the flow effect, the wall cooling effect, the raised flame temperature effect, etc. Cup-burner test doesnot control the energy loss terms, while the flammability test does control such terms. In order to compare all fire suppressing agents, R is scaled by the molecular weight. Then we have a new suppression index defined as

$$SI = \frac{\frac{1 - x_{E}}{x_{E}} \cdot \left(\frac{1 - C_{st} \cdot x_{L}}{C_{st} \cdot x_{L}}\right)}{MW}$$
(a.6)

Since this index is normalized by mass, it shows the mass-averaged agent effectiveness. As expected, most agents are working by mass, with some exceptions due to synergistic effects.

chemical name	trade name	designation	formula	FEC	R	MW (g/mol)	MB index
Argon		IG01	Ar	41.0	0.8083	39.9500	0.0202
Neon			Ne	37.0	0.9564	20.1800	0.0474
N2/CO2	Argonit e	IG55	N2+Ar	36.5	0.9772	33.9750	0.0288
N2/Ar/CO2	Inergen	IG541	N2+Ar+CO2	34.2	1.0807	29.2990	0.0369
nitrogen			N2	32.0	1.1937	28.0100	0.0426
Carbon dioxide			CO2	21.0	2.1131	44.0000	0.0480
Silicum Tetrafluoride			SiF4	13.0	3.7592	104.0800	0.0361
Trifluoromethane	FE-13	HFC-23	CHF3	12.9	3.7927	70.0100	0.0542
Ethane, 1,1,1,2-tetrafluoro-			CH2FCF3	10.0	5.0555	102.0300	0.0495

Appendix B: List of suppression index

Suppression theory

Pentafluoroethane	FE-25	HFC-125	CH2FCF3	8.7	5.8948	120.0200	0.0491
1,1,1,2,3,3-Hexafluoropropane		HFC-236fa	CF3CH2CF3	6.5	8.0801	152.0400	0.0531
1,1,1,2,3,3,3-							
Heptafluoropropane	FM200	HFC-227ea	CF3CHFCF3	6.2	8.4983	170.0000	0.0500
Carbon tetrafluoride			CF4	16.0	2.9490	84.0000	0.0351
Ethane, hexafluoro-			C2F6	8.1	6.3731	138.0100	0.0462
Propene, hexafluoro-			C3F6	7.3	7.1331	150.0200	0.0475
Propane, octafluoro-			C3F8	6.3	8.3545	188.0200	0.0444
Octafluorocyclobutane			C4F8	6.3	8.3545	200.0300	0.0418
Perfluoro-n-butane	CEA- 410	FC-3-1-10	C4F10	5.3	10.0368	238.0300	0.0422
Methane, chlorodifluoro-			CHF2CI	12.0	4.1193	86.4700	0.0476
Methane, dichlorofluoro-			CHCl2F	11.0	4.5448	102.9200	0.0442
			CF2CHCI	10.0	5.0555	116.4700	0.0434
		Fc-124a	CHFCICF3	7.0	7.4628	136.4800	0.0547
	Halon1						
Methane, bromotrifluoro-	301		CF3Br	3.1	17.5583	148.9300	0.1179
Methane, dibromodifluoro-			CF2BR2	2.6	21.0429	209.8200	0.1003
Ethene, bromo-			CH2CHBR	3.5	15.4874	106.9500	0.1448
Ethene, bromotrifluoro-			CF2CFBR	6.3	8.3545	160.9200	0.0519
1-Bromo-2,2-difluoroethylene			CF2CHBR	6.0	8.8003	142.9300	0.0616
Methane, trifluoroiodo-		FIC-13I1	CF3I	3.2	16.9920	195.9100	0.0867
Sulfur chloride pentafluoride			SF5CI	13.0	3.7592	162.5100	0.0231
Sulfur hexafluoride			SF6	11.0	4.5448	146.0600	0.0311
Sulfur fluoride			S2F10	10.5	4.7880	254.1200	0.0188
Ethane, hexafluoro-			C2F6	7.9	6.5486	138.0100	0.0475
Methane, chlorotrifluoro			CF3Cl	6.9	7.5791	104.4600	0.0726
Propane, octafluoro-		FC-218	C3F8	6.1	8.6468	188.0200	0.0460
Sulfur bromide fluoride			SF5Br	4.2	12.8125	206.9600	0.0619
Chlorotetrafluoroethane	FE-24	HCFC-124	C2HCIF4	6.6	7.9492	136.4800	0.0582
Dichlorotrifluoroethane (4.75%) Chlorodifluoromethane (82%) Chlorotetrafluroethane (9.5%) Isopropenyl-1-	NAF-		CHCL2CF3 CHCIF2				
methylcyclohexene (3.75%)	SIII	HCFC Blend A	CHCIFCF3	9.9	5.1122	92.9000	0.0550
	Halotro n II	HFC-125, and CO2		11.3	4.4092	99.4000	0.0444
	novec1		CF3CF2C(O)C(				
	230	FK-5-1-12	CF3)2	4.5	11.9209	316.0000	0.0377