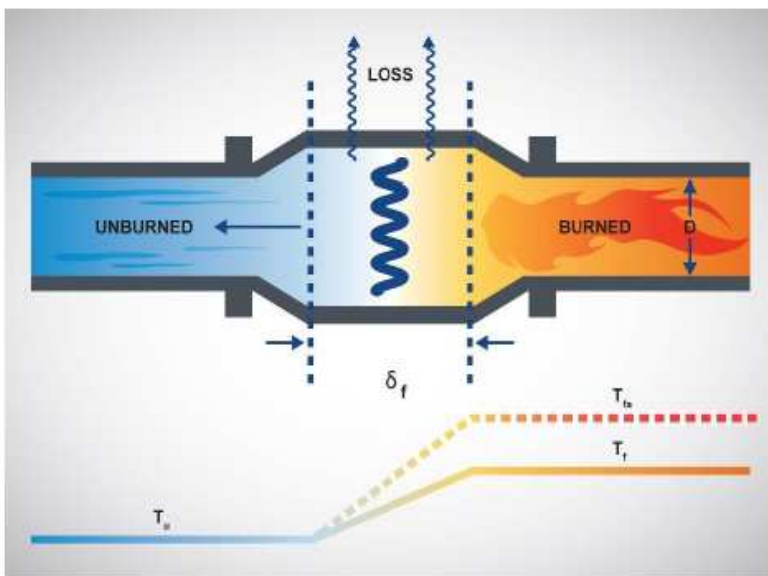




## How Flame Arresters Work



An ioMosaic White Paper

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IO MOSAIC CORPORATION

# **Risk Management and Assessment Practices**

*How Flame Arresters Work*

authored by

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October 30, 2019

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## **Contents**

<b>1</b>	<b>Introduction</b>	<b>2</b>
<b>2</b>	<b>Heat Generation vs. Heat Loss</b>	<b>2</b>
<b>3</b>	<b>Laminar Burning Velocity</b>	<b>4</b>
<b>4</b>	<b>High Flame Speeds</b>	<b>4</b>
<b>5</b>	<b>Maximum Experimental Safe Gap</b>	<b>5</b>
<b>6</b>	<b>Selecting the Right Flame Arrester</b>	<b>6</b>
<b>7</b>	<b>Conclusions</b>	<b>7</b>
<b>A</b>	<b>Laminar Burning Velocities for Selected Materials</b>	<b>9</b>

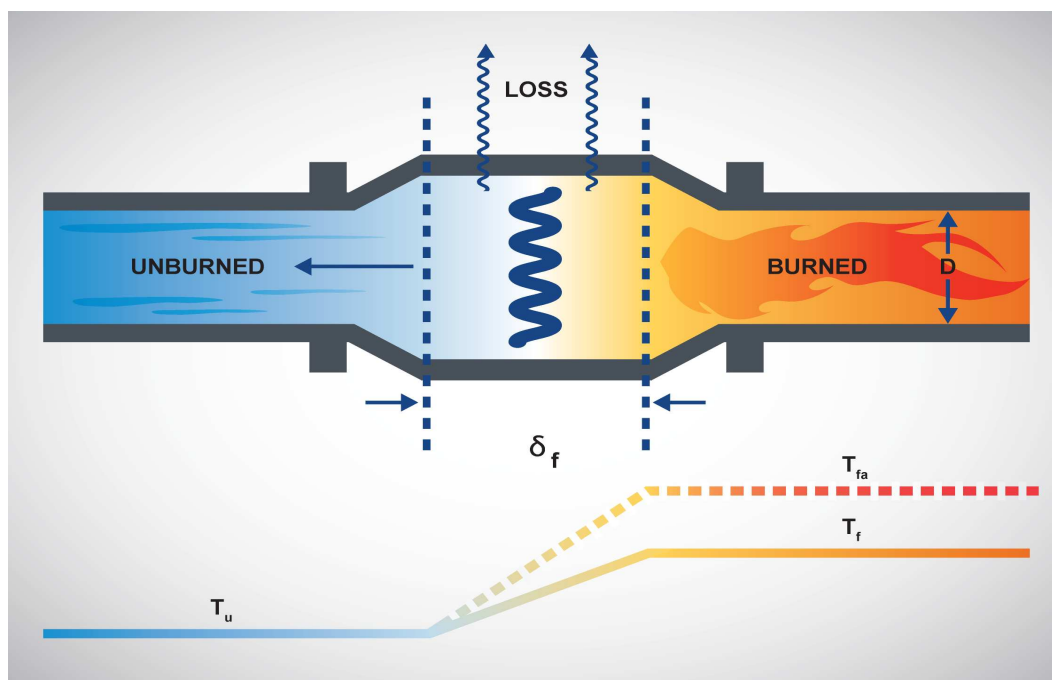
## 1 Introduction

Flame arresters are used in chemical processing facilities to prevent flames from burning into process vessels during either emergency relief or normal operations. Flame arresters<sup>1</sup> work by forcing the flame through one or more narrow passages that are long enough to decelerate the flow and increase the residence time for heat transfer and that are small enough to increase heat loss from the flame surface to prevent the flame from propagating.

Although we can make the flow path tortuous with a very large surface to volume ratio and residence time, we need to consider operational requirements dealing with pressure drop and plugging. Flame arresters will not function properly and will still transmit a flame if they heat up too much. It is a good practice to have a temperature monitored flame arrester that can detect a stabilized flame at the flame-arresting element(s).

Flame arresters can be installed at the end of a relief line and/or directly on a storage tank or process vessel. These arresters are referred to as "End of line flame arresters". They are used to protect against the flame spreading from the outside atmosphere to the inside of the vessel. Flame arresters that are installed in piping systems to protect the downstream equipment from flame propagation and/or a deflagration are referred to as "Inline flame arresters".

Figure 1: Laminar flame propagation in a circular pipe



## 2 Heat Generation vs. Heat Loss

Figure 1 illustrates a laminar flame that is propagating back towards the process. The flame is propagating at a laminar burning velocity  $S_u$  ( $\approx 0.5$  m/s) and as it propagates it consumes unreacted

<sup>1</sup>Flame arresters have some similarities/differences from detonation arresters. Detonation arresters will be discussed in a future publication.

material and loses heat to the pipe wall. The heat production rate by combustion can be calculated as a function of the burning velocity and the theoretical adiabatic flame temperature,  $T_{fa}$ :

$$\dot{Q}_{combustion} = \frac{\pi D^2}{4} \rho_u S_u C_{p_u} (T_{fa} - T_w) \quad (1)$$

The flame also loses heat to the pipe wall over the flame front thickness:

$$\dot{Q}_{loss} = \pi D \delta_f h (T_f - T_w) \quad (2)$$

$$h = \frac{N_u k_u}{D} \quad (3)$$

$$\delta_f = \frac{\alpha_u}{S_u} \quad (4)$$

$$\alpha_u = \frac{k_u}{\rho_u C_{p_u}} \quad (5)$$

where  $N_u$  is the Nusselt number which is measure of convective heat transfer over conductive heat transfer and is typically correlated with Reynolds and Prandtl numbers<sup>2</sup>.  $\alpha_u$  is the thermal diffusivity of the unburnt material,  $h$  is the heat transfer coefficient,  $T_f$  is the actual flame temperature after accounting for heat loss to the wall,  $T_{fa}$  is the theoretical adiabatic flame temperature without any heat loss which depends on the combustion stoichiometry, and  $\delta_f$  is the flame thickness.

We can show by arranging the above equations that the critical value of pipe flow diameter required to arrest or quench a flame is equal to:

$$D \leq \left( \frac{\alpha_u}{S_u} \right) \frac{\sqrt{4N_u \left[ \frac{T_f - T_w}{T_{fa} - T_w} \right]}}{\sqrt{\frac{\dot{Q}_{loss}}{\dot{Q}_{combustion}}}} = \left( \frac{\alpha_u}{S_u} \right) \frac{\sqrt{C}}{\sqrt{\frac{\dot{Q}_{loss}}{\dot{Q}_{combustion}}}} \quad (6)$$

We note from equation 6 that  $D$  decreases with increasing burning velocity. If we assume that the wall temperature is equal to  $T_w = 300$  K, a theoretical adiabatic flame temperature of 2,300 K, an actual flame temperature of 1,400 K at which the flame will not propagate for most hydrocarbon flames (see Melhem [1]), we can show that  $C$  is approximately equal to 9:

$$C = 4N_u \left[ \frac{T_f - T_w}{T_{fa} - T_w} \right] \simeq 4 \times 4 \times \frac{1400 - 300}{2300 - 300} \simeq 8.8 \quad (7)$$

The larger the value of  $\sqrt{\frac{\dot{Q}_{loss}}{\dot{Q}_{combustion}}}$ , the smaller the value of  $D$  becomes. The ratio of heat loss to heat production that is required to stop the flame from propagating typically ranges from 10 to 20 % for hydrocarbon systems. If we take an upper bound of 20 %, we can then show that in order to quench/arrest a flame propagating at laminar burning velocity, the maximum pipe flow diameter should be:

$$D \leq \frac{\sqrt{8.8}}{\sqrt{0.2}} \left( \frac{\alpha_u}{S_u} \right) \leq 6.6 \left( \frac{\alpha_u}{S_u} \right) \quad (8)$$

---

<sup>2</sup>For fully developed laminar flow,  $N_u$  equals 3.66 for constant surface temperature conditions and 4.36 for constant heat flux conditions.

Flame arresters can have flow path geometries that are not circular. Since the hydraulic diameter provides a good representation of surface to volume ratio, it can be substituted for  $D$  in the above equation:

$$D_H \leq 6.6 \left( \frac{\alpha_u}{S_u} \right) \quad (9)$$

The form of Equation 9 is sometimes represented in the literature in terms of a critical Peclet number:

$$N_{Pe} = \left( \frac{S_u}{\alpha_u} \right) D_H \text{ or } D_H \leq N_{Pe} \left( \frac{\alpha_u}{S_u} \right) \quad (10)$$

A critical Peclet number of 42 is reported for propane [2].

### 3 Laminar Burning Velocity

In general the laminar burning velocity can be represented using a power law function of pressure and temperature [3, 4]:

$$S_u = S_{u,o} \left[ \frac{T}{T_o} \right]^\alpha \left[ \frac{P}{P_o} \right]^\beta (1.0 - 2.1Y_{dil}) \text{ for } P \geq P_o \quad (11)$$

$$S_{u,o} = B_m + B_\phi (\phi - \phi_m)^2 \quad (12)$$

$$\alpha = 2.18 - 0.8(\phi - 1) \quad (13)$$

$$\beta = -0.17 + 0.22(\phi - 1) \quad (14)$$

$$\phi = \frac{\left[ \frac{M_{fuel}}{M_{oxidizer}} \right]_{actual}}{\left[ \frac{M_{fuel}}{M_{oxidizer}} \right]_{stoichiometric}} = \frac{\left[ \frac{N_{fuel}}{N_{oxidizer}} \right]_{actual}}{\left[ \frac{N_{fuel}}{N_{oxidizer}} \right]_{stoichiometric}} \quad (15)$$

where  $S_{u,o}$  is the reference laminar burning velocity,  $P_o$  and  $T_o$  are the reference temperature and pressure in absolute units,  $\phi$  is the equivalence ratio,  $B_m$  is maximum flame speed attained at equivalence ratio  $\phi_m$ ,  $B_\phi$  quantifies the dependence of flame speed on equivalence ratio,  $Y_{dil}$  is the mass fraction of diluents,  $\alpha$  is the temperature exponent, and  $\beta$  is the pressure exponent.

If we consider  $\alpha = 2.18$  and  $\beta = -0.17$  to be representative of most hydrocarbon fuels pressure and temperature dependency, then  $D_H$  will decrease with increasing temperature and increase with increasing pressure. Data for laminar burning velocity for a wide variety of fuels is provided in Appendix A.

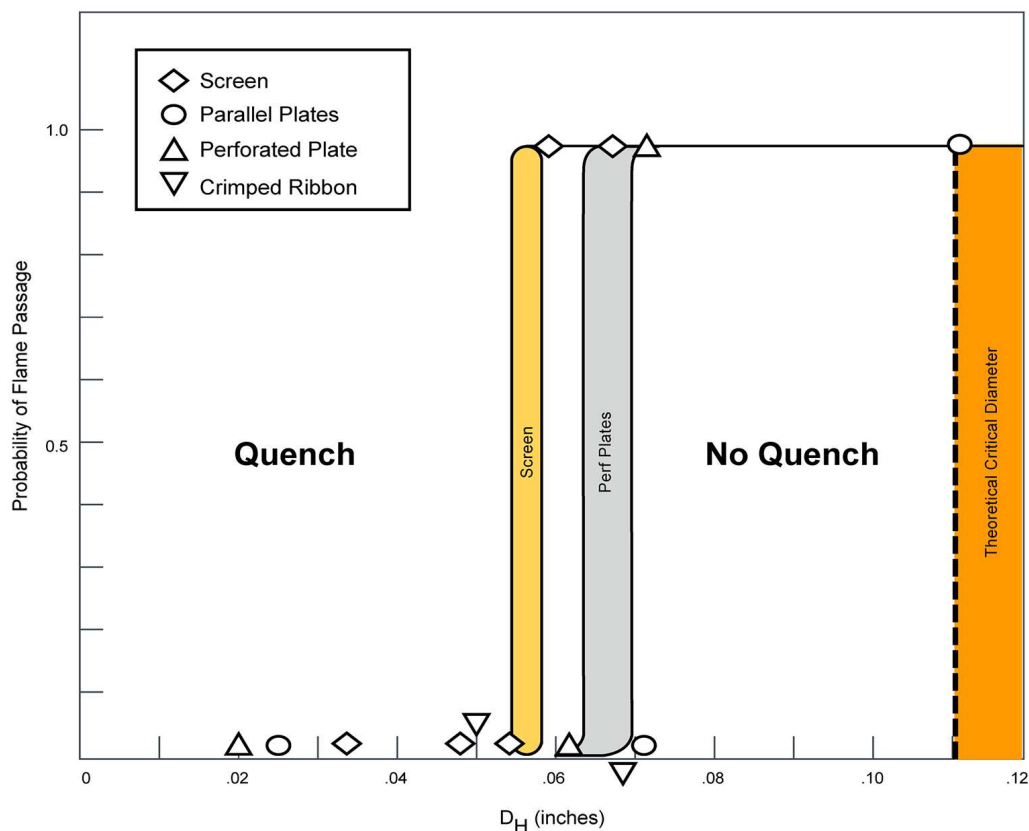
### 4 High Flame Speeds

For high flame speeds, say  $\geq 15$  m/s, the criteria provided by equation 9 is not sufficient. With high flame speeds, the flame arrester has less time to extract heat from the flame. High flame speeds also cause localized overpressure which can cause structural damage to the flame arrester



and can push hot combustion products through the flame arrester. For high flame speeds, the flame arrester needs to have sufficient pressure drop to decelerate the flame and sufficient length to allow extraction of sufficient heat to stop flame propagation.

Figure 2: Flame quench data for methane/air at  $\phi = 1.1$ . Low flame speed, 80 F. [5]



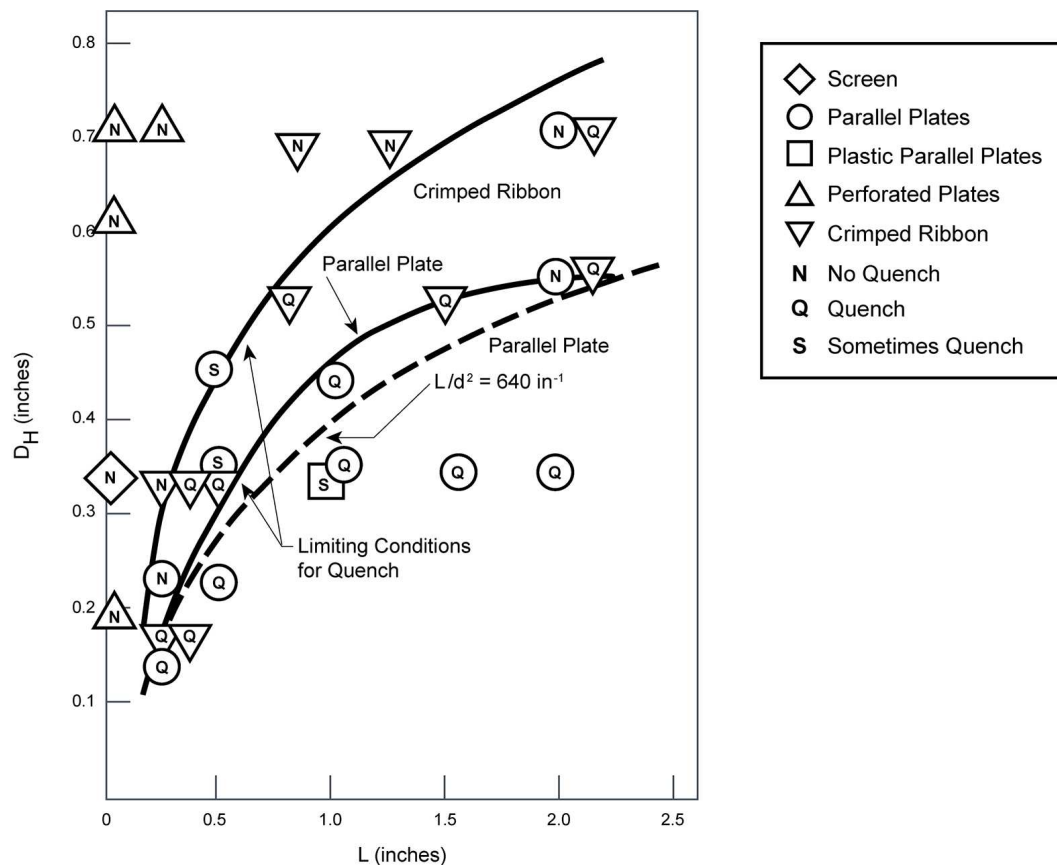
Theoretical analysis and test data show that the critical length correlates with flame speed and critical diameter:

$$L \geq N S_f D_H^n \quad (16)$$

where  $N$  is a constant typically ranging from 20 to 100,  $S_f$  is the actual flame speed, and  $n$  is approximately 2. In the case of methane, it is reported that flame arrester length of 1 inch, and a critical diameter of 0.03 inch will work for both low and high flame speeds at any flammable composition (see Figures 3 and 2).

## 5 Maximum Experimental Safe Gap

The concept of a critical  $D_H$  is essentially the same concept as that of a maximum experimental safe gap (MESG). MESG is measured for flammable gas mixtures as shown in Figure 4. MESG is the distance between two parallel 25-mm long metal surfaces that is found to prevent flame propagation under a specific set of test conditions.

Figure 3: Flame quench data for methane/air at  $\phi = 1.1$ . High speed flame at 67 ft/s [5]

MESG values are used to classify the potential of flammable gases/vapor to produce flame flashback and/or explosions as shown in Table 1. The groups shown in Table 1 are used to select flame arresters.

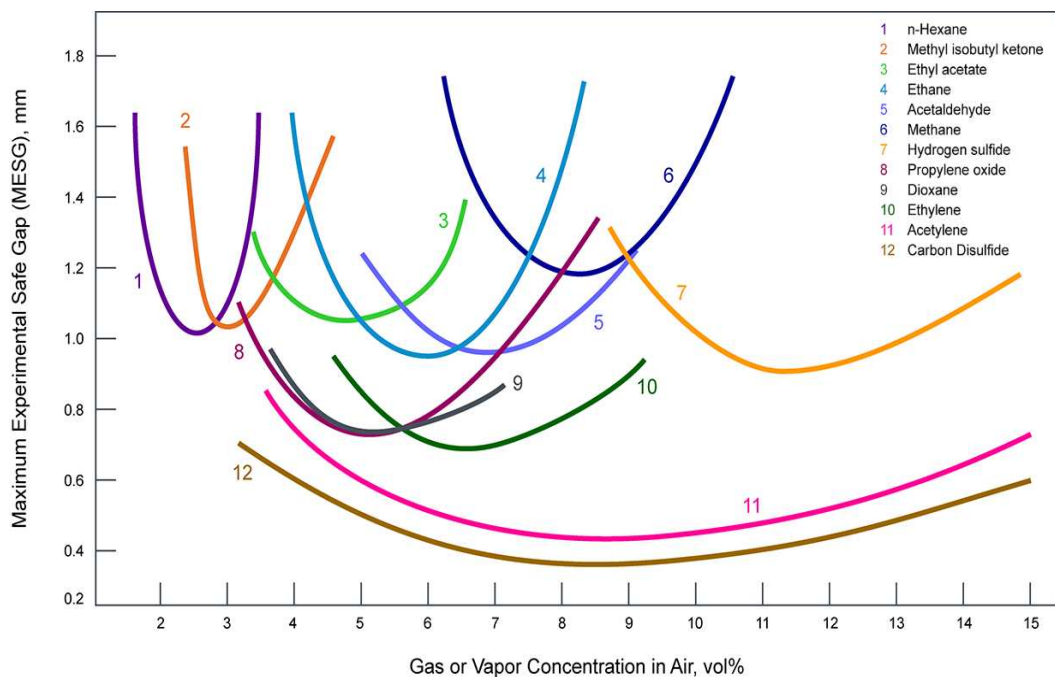
## 6 Selecting the Right Flame Arrester

A flame arrester manufacturer [6] will need information related to service, identity and composition of the flammable gas mixture, physical properties of the gas mixture including molecular weight and density, the expected volumetric and mass flow rate, normal operating and maximum operat-

Table 1: Explosion group classification for flammable gases using MESG [6]

MESG mm	International Electrochemical Commission (IEC)	National Electrical Code (NEC)	Reference Material
1.14	I	-	Methane
> 0.9	IIA	D	Propane
0.5 to 0.9	IIB	C	Ethylene
< 0.5	IIC	B	Hydrogen

Figure 4: Maximum experimental safe gap test data for selected flammable gases [6]

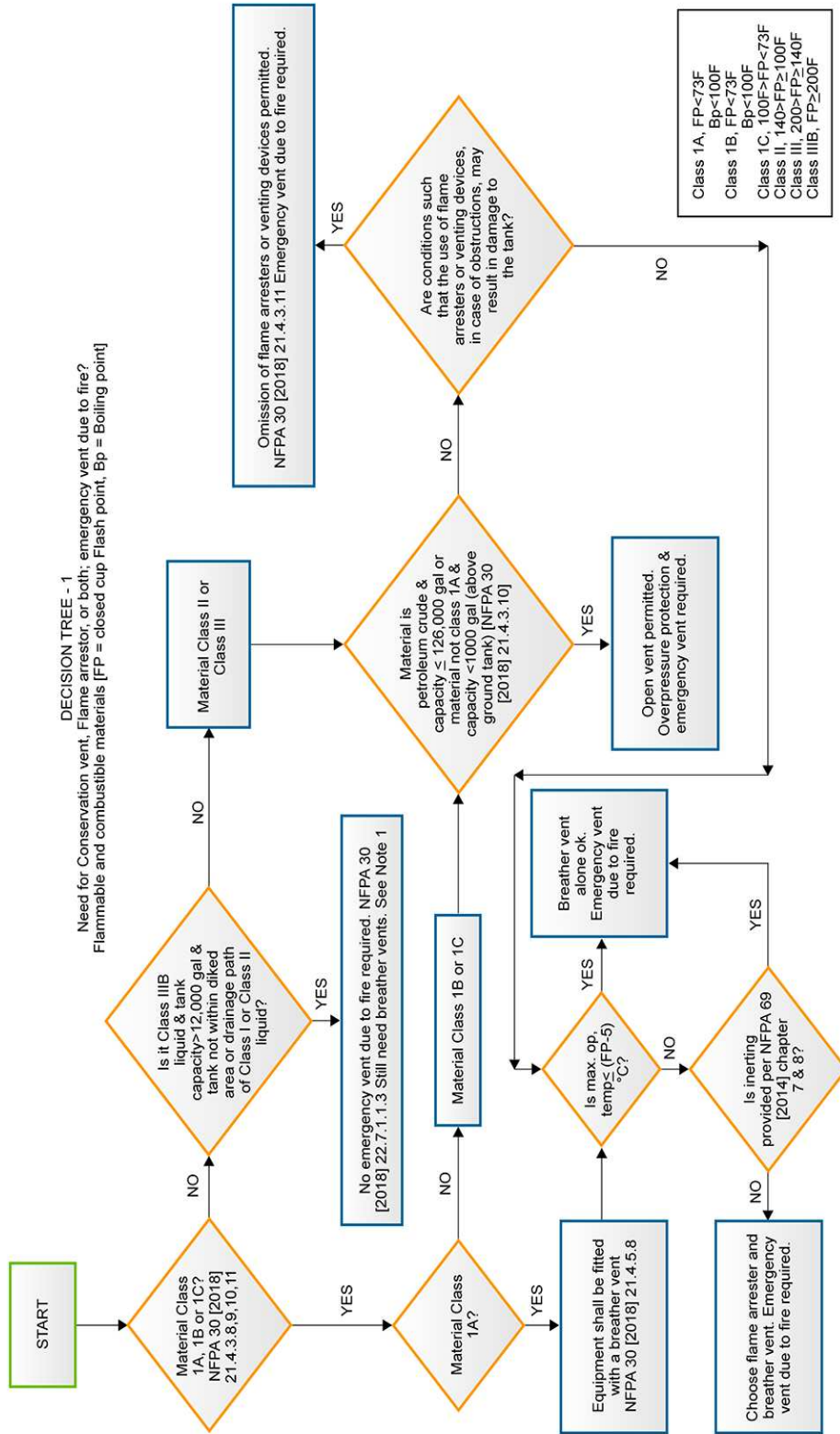


ing temperatures and pressures, pressure drop constraints, type of flame arrester, piping size and connection type, flame arrester housing material, flame arrester elements material of construction, proper flame arrester material of construction that minimizes sparking and electrostatic charging, and most important documentation requirements.

## 7 Conclusions

Selecting the right flame arrester (see Figure 5) requires an understanding of how flame arresters work, physical properties, transport properties, flammability properties of the gas or vapor mixtures, and test data where applicable. While test data may be available for pure components and some limited mixtures at ambient conditions, extrapolation of this data to higher pressures and/or higher temperatures requires careful scaling using detailed chemical equilibrium calculations with computer codes such as SuperChems Expert(TM). Oxygen rich mixtures and mixtures containing materials that can support decomposition flames should be treated with care.

Figure 5: Decision Tree for Selection of Flame Arresters



Notes:

1. Low pressure tanks requiring pressure and vacuum protection require both pressure and vacuum vents. Such vents may be open or breather type.
2. A breather vent may substitute as a flame arrester as long as the pressure side is set to close at or below 1/2" wc and vacuum side has a flame screen. Both pressure & vacuum side must have no piping attached.
3. Every aboveground storage tank shall have an emergency relief vent in the form of construction of a device or devices that will relieve excessive internal pressure caused by an exposure of fire.
4. Open vent or breather vent can serve as an emergency vent also for low pressure tanks. Open vent can serve as an emergency vent for pressure vessels in some states, such as the state of Missouri, USA.
5. All breather vents and flame arresters (independent testing thru third party) require periodic maintenance service.
6. This is a guideline only. The user must use his/her discretion to override the recommended practice, and in so doing, assume responsibility.

## **A Laminar Burning Velocities for Selected Materials**

Table 2: Burning velocities of saturated hydrocarbons at 25 C air-fuel temperature and 1 atm (0.31 mole % H<sub>2</sub>O in air) [7]

Chemical	Equivalence Ratio $\phi$										$S_u$ in cm/s		T and P Exponents	
	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	$S_{max}$	$\phi$ at $S_{max}$	$\alpha$	$\beta$		
Ethane	30.60	36.00	40.60	44.50	47.30	47.30	44.40	37.40	47.60	1.14	2.07	-0.14		
Propane	24.00	29.00	36.50	42.50	43.00	42.50	40.00	27.50	46.40	1.06	2.13	-0.16		
n-Butane	23.00	30.00	37.00	44.80	44.20	41.20	34.40	25.00	44.90	1.03	2.16	-0.16		
Methane	17.00	25.00	33.00	40.50	42.00	37.00	27.00	17.50	44.80	1.08	2.12	-0.15		
n-Pentane	35.00	37.00	39.80	42.20	42.70	39.30	33.90	43.00	42.80	1.05	2.14	-0.16		
n-Heptane	37.50	37.80	39.50	40.10	39.50	36.20	23.50	41.00	41.00	0.98	2.20	-0.17		
2,2,4-Trimethylpentane	33.50	33.00	37.60	39.80	38.40	33.40	24.80	39.90	40.00	0.98	2.20	-0.17		
2,2,3-Trimethylpentane	31.00	31.00	34.80	36.00	36.00	35.20	33.50	36.00	36.00	1.10	2.10	-0.15		
Isopentane														
2,2-Dimethylbutane														
2,2-Dimethylpropane														

Exponents  $\alpha$  and  $\beta$  are calculated for  $\phi$  at  $S_{max}$  according to [3] and [4].

Table 3: Burning velocities of unsaturated hydrocarbons and substituted alkylys at 25 C air-fuel temperature and 1 atm (0.31 mole % H<sub>2</sub>O in air) [7]

Chemical	Equivalence Ratio $\phi$										$S_u$ in cm/s		T and P Exponents	
	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	$S_{max}$	$\phi$ at $S_{max}$	$\alpha$	$\beta$		
Acetylene		107.00	130.00	144.00	151.00	154.00	154.00	152.00	155.00	1.25	1.98	-0.12		
Ethylene	37.00	50.00	60.00	68.00	73.00	72.00	66.50	60.00	73.50	1.13	2.08	-0.14		
Propylene	37.00	48.00	60.00	66.00	70.00	72.00	71.00	65.00						
1,3-Butadiene		62.00	66.60	70.20	72.20	71.20	61.00		72.50	1.14	2.07	-0.14		
n-1-Heptene			42.60	49.60	55.00	57.00	56.90	55.40	57.20	1.23	2.00	-0.12		
Propylene		46.80	50.70	52.30	50.90	47.40	41.60		52.30	1.00	2.18	-0.17		
n-2-Pentene			48.40	51.20	49.90	46.40	40.80		51.20	1.00	2.18	-0.17		
2,2,4-Trimethyl-3-pentene		35.10	42.60	47.80	46.90	42.60	34.90		48.00	1.03	2.16	-0.16		
Methanol		34.60	41.30	42.20	37.40	33.00			42.50	0.98	2.20	-0.17		
Isopropyl alcohol		34.50	42.00	48.00	50.20	47.50	44.40	42.20	50.40	1.08	2.12	-0.15		
Triethylamine		34.40	39.20	41.30	40.60	38.20	36.00	34.20	41.40	1.04	2.15	-0.16		
n-Butyl chloride		32.50	36.70	38.50	38.70	36.20	28.60		38.80	1.06	2.13	-0.16		
Allyl chloride	24.00	30.70	33.80	34.50	32.50	26.90	20.00		34.50	1.00	2.18	-0.17		
Isopropyl mercaptan	30.60	33.00	33.70	32.40	29.60				33.80	0.89	2.27	-0.19		
Ethylamine		30.00	33.50	33.00	26.60				33.80	0.94	2.23	-0.18		
Isopropylamine		28.70	31.40	32.40	31.80	29.40	25.30		32.40	1.00	2.18	-0.17		
n-Propyl chloride		27.00	29.50	30.60	29.80	27.70			30.60	1.01	2.17	-0.17		
Isopropyl chloride		24.70	28.30	27.50	24.10				28.50	0.93	2.24	-0.19		
		24.80	27.00	27.40	25.30				27.60	0.97	2.20	-0.18		

Exponents  $\alpha$  and  $\beta$  are calculated for  $\phi$  at  $S_{max}$  according to [3] and [4].

Table 4: Burning velocities of aromatic compounds and cyclic Compounds at 25 C air-fuel temperature and 1 atm (0.31 mole % H<sub>2</sub>O in air) [7]

Chemical	Equivalence Ratio $\phi$										$S_u$ in cm/s			T and P Exponents	
	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	$S_{max}$	$\phi$ at $S_{max}$	$\alpha$	$\beta$			
Furan	48.00	55.00	60.00	62.50	62.40	60.00			62.90	1.05	2.14	-0.16			
Benzene		39.40	45.60	47.60	44.80	40.20	35.60		47.60	1.00	2.18	-0.17			
Thiophene	33.80	37.40	40.60	43.00	42.20	37.20	24.60		43.20	1.03	2.16	-0.16			
Ethylene oxide	57.20	70.70	83.00	88.80	89.50	87.20	81.00	73.00	89.50	1.07	2.12	-0.15			
Butadiene monoxide		6.60	47.40	57.80	64.00	66.90	66.80	64.50	67.10	1.24	1.99	-0.12			
Propylene oxide	41.60	53.30	62.60	66.50	66.40	62.50	53.80		67.00	1.05	2.14	-0.16			
Dihydropyran	39.00	45.70	51.00	54.50	55.60	52.60	44.30	32.00	55.70	1.08	2.12	-0.15			
Cyclopropane		40.60	49.00	54.20	55.60	53.50	44.00		55.60	1.10	2.10	-0.15			
Tetrahydropyran	44.80	51.00	53.60	51.50	42.30				53.70	0.93	2.24	-0.19			
Tetrahydrofuran			43.20	48.00	50.80	51.60	49.20	44.00	51.60	1.19	2.03	-0.13			
Cyclopentadiene	36.00	41.80	45.70	47.20	45.50	40.60	32.00		47.20	1.00	2.18	-0.17			
Ethylenimine		37.60	43.40	46.00	45.80	43.40	38.90		46.40	1.04	2.15	-0.16			
Cyclopentane	31.00	38.40	43.20	45.30	44.60	41.00	34.00		45.40	1.03	2.16	-0.16			
Cyclohexane			41.30	43.50	43.90	38.00			44.00	1.08	2.12	-0.15			

Exponents  $\alpha$  and  $\beta$  are calculated for  $\phi$  at  $S_{max}$  according to [3] and [4].



Table 5: Burning velocities of selected silanes, aldehydes, ketones, esters, ethers, peroxides, and inorganics at 25 C air-fuel temperature and 1 atm (0.31 mole % H<sub>2</sub>O in air) [7]

Chemical	Equivalence Ratio $\phi$										$S_u$ in cm/s		T and P Exponents	
	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	$S_{max}$	$\phi$ at $S_{max}$	$\alpha$	$\beta$		
	Tetramethylsilane	39.50	49.50	57.30	58.20	57.70	54.50	47.50		58.20	1.01	2.17	-0.17	
Trimethylethoxysilane	34.70	41.00	47.40	50.30	46.50	41.00	35.00		50.30	1.00	2.18	-0.17		
Acrolein	47.00	58.00	66.60	65.90	56.50				67.20	0.95	2.22	-0.18		
Propionaldehyde		37.50	44.30	49.00	49.50	46.00	41.60	37.20	50.00	1.06	2.13	-0.16		
Acetaldehyde		26.60	35.00	41.40	41.40	36.00	30.00		42.20	1.05	2.14	-0.16		
Acetone		40.40	44.20	42.60	38.20				44.40	0.93	2.24	-0.19		
Methyl ethyl ketone		36.00	42.00	43.30	41.50	37.70	33.20		43.40	0.99	2.19	-0.17		
Vinyl acetate	29.00	36.60	39.80	41.40	42.10	41.60	35.20		42.20	1.13	2.08	-0.14		
Ethyl acetate		30.70	35.20	37.00	35.60	30.00			37.00	1.00	2.18	-0.17		
Dimethyl ether		44.80	47.60	48.40	47.50	45.40	42.60		48.60	0.99	2.19	-0.17		
Diethyl ether	30.60	37.00	43.40	48.00	47.60	40.40	32.00		48.20	1.05	2.14	-0.16		
Dimethoxymethane	32.50	38.20	43.20	46.60	48.00	46.60	43.30		48.00	1.10	2.10	-0.15		
Diisopropyl ether		30.70	35.50	38.30	38.60	36.00	31.20		38.90	1.06	2.13	-0.16		
Dimethyl sulfide		29.90	31.90	33.00	30.10	24.80			33.00	1.00	2.18	-0.17		
Di-tert-butyl peroxide		41.00	46.80	50.00	49.60	46.50	42.00	35.50	50.40	1.04	2.15	-0.16		
Hydrogen	102.00	120.00	145.00	170.00	204.00	245.00	213.00	290.00	325.00	1.80	1.54	0.01		
	124.00	150.00	187.00	210.00	230.00	245.00								
Carbon disulfide	50.60	58.00	59.40	58.80	57.00	55.00	52.80	51.60	59.40	0.91	2.25	-0.19		
Carbon monoxide					28.50	32.00	34.80	38.00	52.00	2.05	1.34	0.06		
Hydrogen sulfide	34.80	39.20	40.90	39.10	32.30				40.90	0.90	2.26	-0.19		

Exponents  $\alpha$  and  $\beta$  are calculated for  $\phi$  at  $S_{max}$  according to [3] and [4].

Table 6: Burning velocities of various fuels at 100 C air-fuel temperature and 1 atm (0.31 mole % H<sub>2</sub>O in air) [7]

Chemical	Equivalence Ratio $\phi$										$S_u$ in cm/s			T and P Exponents	
	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	$S_{max}$	$\phi$ at $S_{max}$	$S_{max}$	$\alpha$	$\beta$		
Propargyl alcohol		76.80	100.00	110.00	110.50	108.80	105.00	85.00	110.50	1.08	2.12	-0.15			
Propylene oxide	74.00	86.20	93.00	96.60	97.80	94.00	84.00	71.50	97.90	1.09	2.11	-0.15			
Hydrazine *	87.30	90.50	93.20	94.30	93.00	90.70	87.40	83.70	94.40	0.98	2.20	-0.17			
Furfural	62.00	73.00	83.30	87.00	87.00	84.00	77.00	65.50	87.30	1.05	2.14	-0.16			
Ethyl nitrate	70.20	77.30	84.00	86.40	83.00	72.30			86.40	1.00	2.18	-0.17			
Butadiene monoxide	51.40	57.00	64.50	73.00	79.30	81.00	80.40	76.70	81.10	1.23	2.00	-0.12			
Carbon disulfide	64.00	72.50	76.80	78.40	75.50	71.00	66.00	62.20	78.40	1.00	2.18	-0.17			
n-Butyl ether		67.00	72.60	70.30	65.00				72.70	0.91	2.25	-0.19			
Methanol	50.00	58.50	66.90	71.20	72.00	66.40	58.00	48.80	72.20	1.08	2.12	-0.15			
Diethyl cellosolve	49.50	56.00	63.00	69.00	69.70	65.20			70.40	1.05	2.14	-0.16			
Cyclohexan monoxide	54.50	59.00	63.50	67.70	70.00	64.00			70.00	1.10	2.10	-0.15			
Epichlorohydrin	53.00	59.50	65.00	68.60	70.00	66.00	58.20		70.00	1.10	2.10	-0.15			
n-Pentane		50.00	55.00	61.00	62.00	57.00	49.30	42.40	62.90	1.05	2.14	-0.16			
n-Propyl alcohol	49.00	56.60	62.00	64.60	63.00	50.00	37.40		64.80	1.03	2.16	-0.16			
n-Heptane	41.50	50.00	58.50	63.80	59.50	53.80	46.20	38.80	63.80	1.00	2.18	-0.17			
Ethyl nitrite	54.00	58.80	62.60	63.50	59.00	49.50	42.00	36.70	63.50	1.00	2.18	-0.17			
Pinene	48.50	58.30	62.50	62.10	56.60	50.00			63.00	0.95	2.22	-0.18			
Nitroethane	51.50	57.80	61.40	57.20	46.00	28.00			61.40	0.92	2.24	-0.19			
Iso-octane		50.20	56.80	57.80	53.30	50.50			58.20	0.98	2.20	-0.17			
Pyrrrole		52.00	55.60	56.60	56.10	52.80	48.00	43.10	56.70	1.00	2.18	-0.17			
Aniline		41.50	45.40	46.60	42.90	37.70	32.00		46.80	0.98	2.20	-0.17			
Dimethyl formamide		40.00	43.60	45.80	45.50	40.70	36.70		46.10	1.04	2.15	-0.16			

Exponents  $\alpha$  and  $\beta$  are calculated for  $\phi$  at  $S_{max}$  according to [3] and [4].

## References

- [1] G. A. Melhem. A detailed method for the estimation of mixture flammability limits using chemical equilibrium. *Process Safety Progress*, 16(4), 1997.
- [2] A. N. Gutkowski. Quenching distance and quenching diameter ratio for flames propagating in propane/air mixtures. In *International Conference on Heat Transfer and Fluid Flow*, number 36, 2014.
- [3] M. Metghalchi and J. C. Keck. Laminar burning velocity of propane air mixtures at high temperatures and pressure. *Combustion and Flames*, 38:143–154, 1980.
- [4] M. Metghalchi and J. C. Keck. *Combustion and Flames*, 48:191–210, 1982.
- [5] R. P. Wilson and M. F. Flessner. Design criteria for flame arresters. In *84th AIChE National Meeting*. American Institute of Chemical Engineers, AIChE, 1978.
- [6] M. Davies. Protect your process with the proper flame arrester. *Chemical Engineering Progress*, pages 16–22, 2013.
- [7] Gibbs and Calcote. *Journal of Chem. Eng. Data*, 4:226, 1959.

## About the Author



Dr. Melhem is an internationally known pressure relief and flare systems, chemical reaction systems, process safety, and risk analysis expert. In this regard he has provided consulting, design services, expert testimony, incident investigation, and incident reconstruction for a large number of clients. Since 1988, he has conducted and participated in numerous studies focused on the risks associated with process industries fixed facilities, facility siting, business interruption, and transportation.

Prior to founding ioMosaic Corporation, Dr. Melhem was president of Pyxsys Corporation; a technology subsidiary of Arthur D. Little Inc. Prior to Pyxsys and during his twelve years tenure at Arthur D. Little, Dr. Melhem was a vice president of Arthur D. Little and managing director of its Global Safety and Risk Management Practice and Process Safety and Reaction Engineering Laboratories.

Dr. Melhem holds a Ph.D. and an M.S. in Chemical Engineering, as well as a B.S. in Chemical Engineering with a minor in Industrial Engineering, all from Northeastern University. In addition, he has completed executive training in the areas of Finance and Strategic Sales Management at the Harvard Business School. Dr. Melhem is a Fellow of the American Institute of Chemical Engineers (AIChE) and Vice Chair of the AIChE Design Institute for Emergency Relief Systems (DiERS).

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Through innovation and dedication to continual improvement, ioMosaic has become a leading provider of integrated process safety and risk management solutions. ioMosaic has expertise in a wide variety of areas, including pressure relief systems design, process safety management, expert litigation support, laboratory services, training and software development.

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