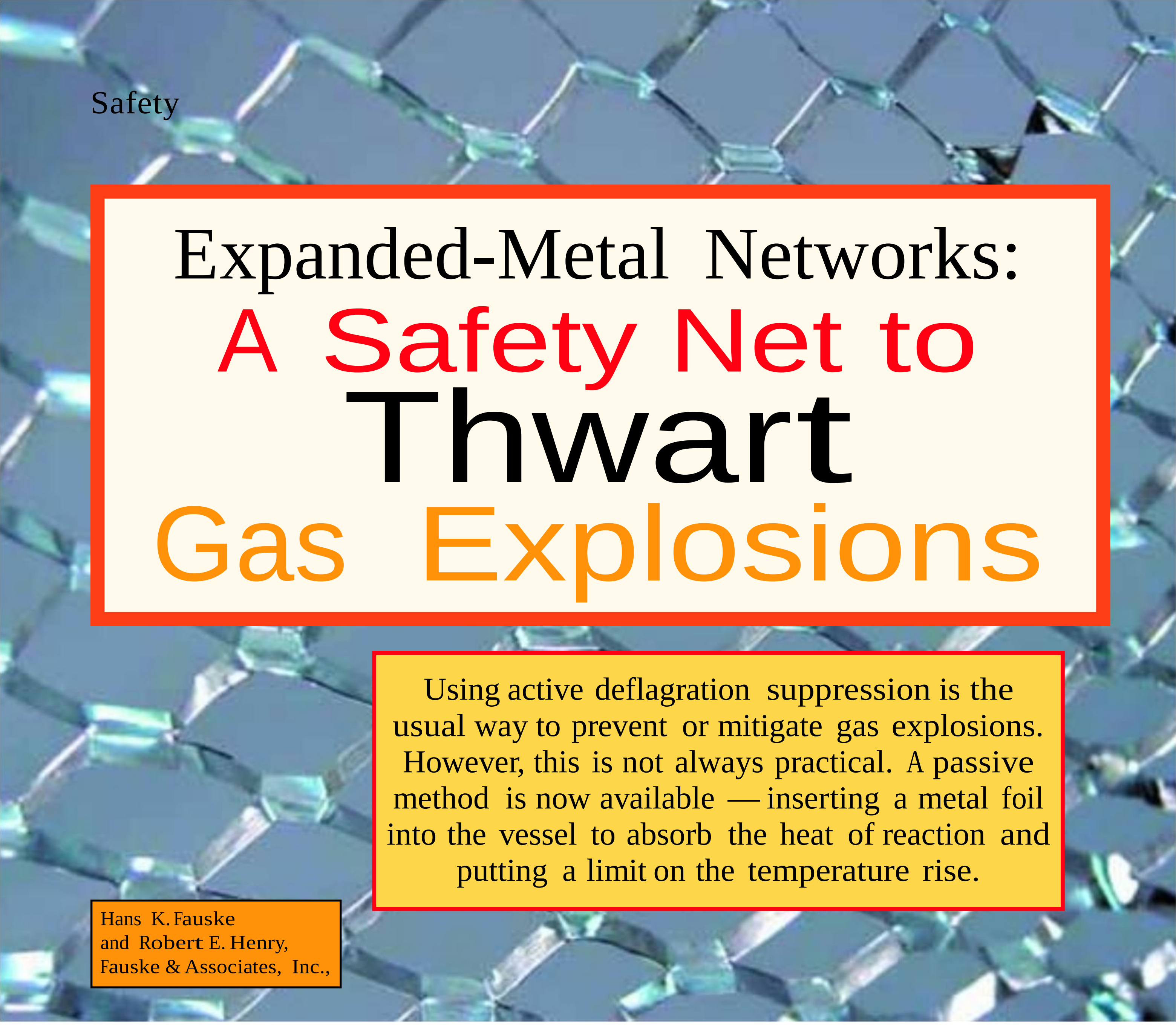

Photo courtesy of Explosion Prevention Systems LLC

Expanded-Metal Networks: A Safety Net to Thwart Gas Explosions

Using active deflagration suppression is the usual way to prevent or mitigate gas explosions. However, this is not always practical. A passive method is now available — inserting a metal foil into the vessel to absorb the heat of reaction and putting a limit on the temperature rise.

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A common standard, from the National Fire Protection Association, NFPA 69 *(1)*, presents various means for preventing confined deflagration incidents including oxidant and fuel concentration-reductions, active deflagration suppression, deflagration pressure-containment, spark detection and extinguishing systems, and isolation methods. However, internal vapor-phase deflagration incidents involving flammable mixtures continue to occur on a regular basis, which can be related to:

• Inerting is not always practical or reliable

• Completely eliminating ignition sources is neither practical nor possible, given the required minimum ignition energy (~ 0.2 mJ) for most hydrocarbon/air mixtures

• Fast-acting flame suppressors are not always practical

• Deflagration venting is not always possible, and

• Total containment is expensive and, often, impractical.

Therefore, in addition to implementing procedures consistent with NFPA 69, the potential for deflagration incidents can be further reduced by considering passive means by using packing material consisting of specially designed expanded-metal products, such as aluminum-alloy foil of low density (30–50 kg/m^3) and high surface area per unit volume (~ 400 m^{-1}). The expanded-metal products have seen some use in fuel tanks and storage containers in Europe, but have seen little application in the U.S. and other countries. We shall present the technical basis for this product's excellent passive explosion suppression/prevention capability in closed containers, and show how it is consistent with available experimental data.

Table 1. Expanded-metal networks characteristics.							
Metal Network	δ, µm	ρ_E, kg/m^3	(A/ V), m^{-1}	D = (A/ V)$^{-1}$, m	α, m^2/ s	t = $(\delta/10^6)^2/\alpha$, s	ϕ
Aluminum	~ 80	~ 40	~ 375	~ 2.6 x 10^{-3}	~ 8 x 10^{-5}	~ 10^{-4}	~ 30
Stainless Steel	~ 25	~ 100	~ 1,070	~ 9 x 10^{-4}	~ 5 x 10^{-6}	~ 10^{-4}	~ 50

Expanded-metal-network characteristics

The expanded-metal products consist primarily of either expanded aluminum-alloy foils (~80 µm thickness and about 40 kg/m^3 density) and stainless steel foils (~25 µm thickness and about 100 kg/m^3 density), *i.e.*, providing high surface areas per unit volume (400–1,000 m^{-1}) and low volumetric displacement (1.3–1.5%). The metal mesh is generally available in several different forms (Figure 1):

• Spherical or cylindrical bodies suitable for packing already-existing smaller-capacity tanks, and

• Rolls of different-sized structures in a network for packing new and large-capacity tanks.

The aluminum and stainless steel materials are chemically inert to most systems of interest, and mechanical stability of the aluminum and steel meshes prevents any significant collapse. Self-compression due to the meshes' own weight is only about 5% for a stack height of 15 m. Some relevant characteristic thermal parameters for the expanded-metal networks are provided in Table 1.

A/V, the network surface area to volume ratio, is given by:

$$A/V = \frac{\rho_E}{\rho_M}\,\frac{2 \times 10^6}{\delta} \qquad (1)$$

In comparison, based upon the characteristic dimension, *D*, *t* for hot, combustible gas products ranges from 10^{-3} s to 10^{-2} s vs. ~10^{-4} s in Table 1. ϕ is the heat-capacity ratio given by:

$$\phi = \rho_E C_M/[1 - (\rho_E/\rho_M)]\rho_g C_g \qquad (2)$$

The large values of ϕ indicated in Table 1 lead to only small temperature increases, assuming temperature equilibration between the network and the combustion reaction products, despite the metal network occupying only about 1.5% of the volume. This temperature increase, ΔT, can be estimated by ignoring the small heat capacity of the combustion reaction-products as follows:

$$\Delta T = \Delta H/(V_{E,M}\,\rho_M C_M) \qquad (3)$$

Values of temperature increases in the aluminum and stainless steel meshes for several stoichiometric fuel/air mixtures are indicated in Table 2. These observations show that these metal networks can easily accommodate the energy release resulting from a stoichiometric fuel/air combustion. Further, the network provides negligible resistance to heat transport, considering that its thermal time-constant is about 10^{-4} s, which is several orders of magnitude less

Figure 1. Two forms of expanded-metal networks. (Courtesy of Explosion Prevention Systems LLC.)

than typical explosion rise-times (Figure 2 *(2)*). The key to effective combustion mitigation and quenching therefore relates to how rapidly the developed combustion energy can be transferred to the metal network's surfaces. Considering that the thermal time constant for the combustion reaction products is on the order of 10^{-2} s, *i.e.*, in the same range as the noted explosion rise-times, the rate of heat transport to the network surfaces by thermal conduction may not be adequate in some cases. However, as illustrated below, the combination of the large surface area provided by the network or the equivalent of the small characteristic

Table 2. Values of ΔT for several fuels and metal networks.			
Fuel	ΔH, J/m^3	**Al** ΔT, K	**Stainless Steel** ΔT, K
Hydrogen	3.19 x 10^6	86	52
Propane	3.67 x 10^6	100	60
n -Hexane	3.75 x 10^6	102	61

Nomenclature

A = network surface area (aluminum), m^2
A/V = network surface area-to-volume ratio, m^{-1}
c = specific heat, J/kg•K
C_g = fuel/air specific heat, J/kg•K
C_M = metal specific heat, J/kg•K
D = characteristic dimension or dia. of expanded-metal network, m
ΔH = energy release from burning 1 m^3 stoichiometric fuel/air mixture, J/m^3
k = thermal conductivity, W/m•K
m_b = mass of the gas that burns, kg
P = final explosion pressure, bar
P_{max} = maximum possible pressure when $m_b = m$, bar
t = characteristic thermal time constant, s
T_{Al} = initial metal-network temperature, K
T_i = instantaneous contact temperature between the metal (aluminum) and the hot reaction products, K
T_H = hot reaction-gas-products temperature, K
ΔT = temperature difference, K
U = flame velocity, m/s
V = total volume of vessel, m^3
V_b = volume of gas that burns, m^3
V_c = volume of vessel that does not contain expanded-metal network, m^3
V_{FM} = volume of fuel/air mixture, m^3
V_T = test volume, m^3

Subscripts
H = hot-gas products
Al = metal (aluminum)

Greek letters
α = thermal diffusivity, m^2/s
β = as defined by Eq. 6
δ = metal foil thickness, µm
ε = emissivity, dimensionless
ϕ = heat-capacity ratio, dimensionless
λ = volumetric fraction occupied by the metal network, dimensionless
ρ = density, kg/m^3
ρ_{Al} = theoretical density of aluminum alloy, kg/m^3
ρ_E = network density, kg/m^3
ρ_g = fuel/air density, kg/m^3
ρ_M = metal density, kg/m^3
σ = Boltzman constant, J/s•m^2•T^4
τ = critical heat-loss fraction, dimensionless

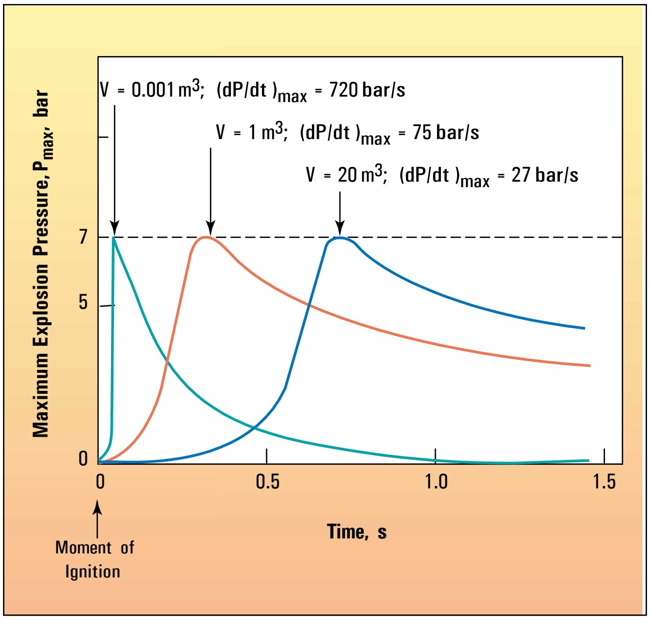

Figure 2. Stoichiometric propane/air explosions in closed vessels (*2*).

Table 3. Critical flame-quenching diameters (3).	
Fuel (U_L, m/s)*	**D_{crit}, m**
Hydrogen (3.1)	7 x 10^{-4}
Acetylene (1.6)	7 x 10^{-4}
Propane (0.45)	2.4 x 10^{-3}
n-Hexane (0.45)	2.4 x 10^{-3}

* U_L is the laminar burn velocity.

dimension, D, together with consideration of radiation-driven heat transport to the network's surfaces appears to assure effective quenching of the combustion flames.

Combustion flame quenching

The suggested quenching characteristics are also consistent with the observation that D in Table 1 is of the same order as the cited critical-flame-quenching diameter for laminar burns (Table 3 *(3)*). Further, the effectiveness of the expanded-metal network in quenching high-temperature flames, such as those produced by igniting stoichiometric hydrocarbon/air mixtures (*i.e.*, resulting in adiabatic flame temperatures of about 2,500 K) can be illustrated as follows. It is well-established that the flame will no longer propagate if the heat-loss rate reaches a critical fraction of the available chemical-heat-release rate *(4, 5)* with the quenching distance proportional to the flame velocity. This observation can be mathematically represented as:

$$\tau\,(1-\lambda)\,\Delta H\,U = (A/V)\,\varepsilon\,\sigma\,T^4\,L \quad (4)$$

Equation 4 shows that radiation is the dominating means for heat transfer from the flame to the expanded-metal-network surfaces. Setting $\tau = 0.15$ *(3)*, $\lambda = 0.015$, $\Delta H = 3.7 \times 10^6$ J/m^3 (representing a stoichiometric propane/air mixture), $A/V = 375$ m^{-1}, $\varepsilon = 0.3$, $T = 2{,}000$ K, the values of L for different flame velocities are provided in Table 4 for the expanded aluminum network. Similarly, with $\lambda = 0.013$, $A/V = 1{,}070$ m^{-1} and $\varepsilon = 0.7$, the corresponding values of L for the stainless steel network are also provided in Table 4.

Note that for the laminar flame, the estimated quenching lengths are of the same order as the characteristic dimensions of the networks $(A/V)^{-1}$, *i.e.*, the expanded-metal networks can be characterized as effective flame quenchers. As such, a 10^{-1} m thick expanded aluminum network layer would appear capable of quenching or decelerating a flame with a turbulence augmentation factor of about 40, *i.e.*, a flame velocity approaching 20 m/s. Similarly, a 10^{-1} m- thick expanded stainless-steel layer would seem capable of quenching or decelerating a 100 m/s flame, *i.e.*, equivalent to a turbulence augmentation factor of about 200.

Finally, in connection with the indicated quenching effectiveness, there is negligible potential for igniting the aluminum network by the high-temperature combustion products (~2,500 K). For the thickness of the aluminum (~80 μm), a relatively high temperature is required to ignite it due to the existing oxide coating. In any case, due to the high heat-capacity ratio, ϕ, and small thermal time constant, t, there is no potential for ignition. The instantaneous contact temperature between the aluminum and the hot reaction products can be estimated from:

$$T_i = \frac{T_{Al} + \beta T_H}{1 + \beta} \tag{5}$$

where T_{Al} = ~300 K, T_H = ~2,500 K, and β is given by:

$$\beta = \left(\frac{(k\rho c)_H}{(k\rho c)_{Al}} \right)^{1/2} \tag{6}$$

Given that the value of β is only about 10^{-3}, we estimate a value of T_i of about 302 K, *i.e.*, a value barely above the initial value of 300 K. Note from Table 2 that the maximum theoretical value cannot exceed about 400 K, which is well below any realistic aluminum ignition-temperature, which would have to be at least equal to the aluminum-melting temperature (~933 K).

Explosion pressure prevention/mitigation

Proper application of expanded-metal networks appears to provide the means to prevent/mitigate dangerous pressure buildups in connection with deflagrations. In the case of mitigation of confined deflagrations, the tanks or vessels containing flammable gas mixtures can be partially or completely fitted with the expanded-metal networks, depending upon the required degree of pressure mitigation (Figure 3).

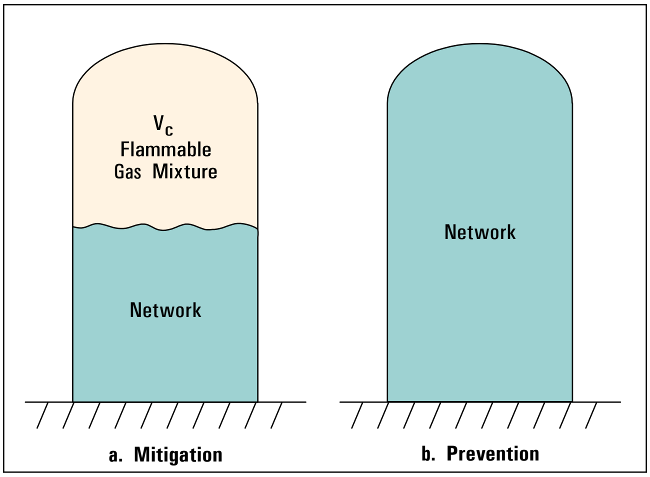

Figure 3. Vessels can be partially or completely filled with metal networks.

The effectiveness of the expanded-aluminum network can be illustrated by starting with the usual assumption invoked in models of closed-vessel deflagrations: the fractional pressure rise is proportional to the mass burned *(6)*:

$$P/P_{max} = m_b/m = V_b/V \tag{7}$$

Assuming that the volume of gas that burns is equal to the volume of the vessel that does not contain the network material, V_c, (Figure 3a) the final pressure can be stated as (ignoring the volume of the network material):

$$P/P_{max} = V_c/V \tag{8}$$

and is illustrated by the straight line in Figure 4. The pressure given by Eq. 8 implies that the combustible gas initially present in the network (*i.e.*, about 98.5% of the total network volume) does not participate in the combustion process. However, it also implies that as the combustible gas in volume V_c is ignited and expands into the network, the subsequent flame penetration, as well as the hot combustion products, are unaffected by the presence of the network, *i.e.*, the metal-network flame-quenching capability is not represented by Eq. 8. However, considering effective flame quenching as the burned gas in volume V_c expands into the volume $(V - V_c)$ containing the network, the actual pressure generation can be approximated by (see the curved line in Figure 4):

$$P/P_{max} = (V_c/V)^2 \tag{9}$$

If the entire volume of the tank is filled by the expanded-metal network (Figure 3b), the explosion potential is eliminated altogether, given the presence of a flammable gas

Table 4. Flame-quenching lengths for stoichiometric propane/air mixtures.

U, m/s	L, m	
	Al	Stainless Steel
0.45 (Laminar)	2×10^{-3}	3.6×10^{-4}
5	2.2×10^{-2}	4.0×10^{-3}
10	4.4×10^{-2}	8.0×10^{-3}
15	6.6×10^{-2}	1.2×10^{-2}
20	8.8×10^{-2}	1.6×10^{-2}

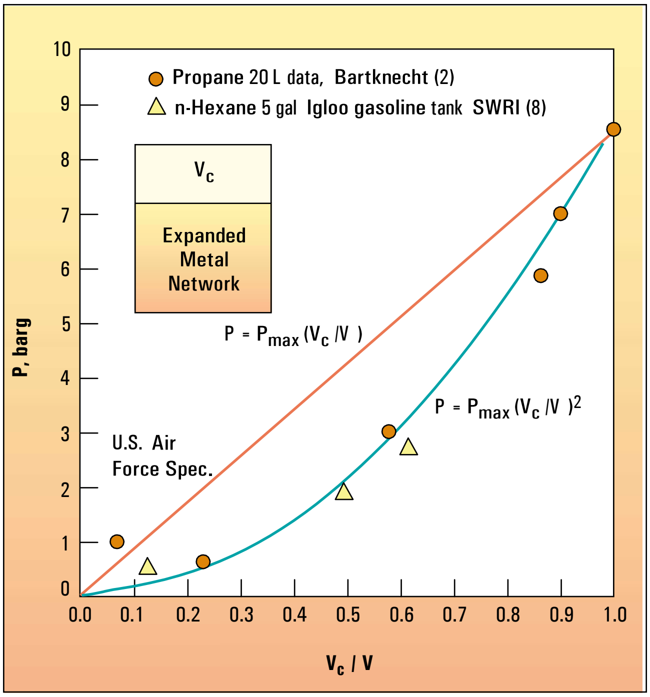

Figure 4. Estimated reduction in explosion pressures due to expanded-metal networks compared with test data.

mixture and an ignition source. As such, note that a significant pressure mitigation is indicated by only partial filling of the metal network, *i.e.*, for $V_c/V = 0.5$, a 75% pressure reduction is indicated. This suggests that considerable uncertainty in the actual fill fraction of the metal network is allowable and still assures effective pressure mitigation.

Deflagration experiments

While extensive visual demonstrations have been performed with containers and vessels filled with expanded-metal networks that illustrate their quenching capability when subjected to fire conditions *(7)*, interpretation of the well-instrumented tests performed by Ciba-Geigy *(2)*, is provided below to confirm the suggested technical basis for their excellent deflagration suppression properties. Using the standard 20-L sphere apparatus for assessing explosivity, deflagration tests were conducted at room temperature and normal pressure over the entire explosion range of propane in air (volume range 2–9.5%) and using various fill fractions of the aluminum metal network (δ = 80 µm and ρ_M of 40 kg/m³). A continuous spark igniting energy of 10 J was used in the test program. The test results are summarized in Table 5 and in Figure 5, clearly illustrating the suppression capability of the aluminum network, represented in terms of the ρ_E network area, *A*.

To compare the above data to the predictions provided in Figure 4, the data in Table 5 are translated from the network surface area *A*, to corresponding vessel fill fractions as follows:

$$V_c/V = 1 - \frac{\left(\dfrac{A \quad \delta \quad \rho_{Al}}{2\ 10^6\ V_T}\right)}{\rho_E} \qquad (10)$$

The translated data are shown in the right-hand column in Table 5 resulting from the *A* values listed with δ = 80 µm, ρ_{Al} = 2,700 kg/m³, ρ_E = 40 kg/m³ and V_T = 0.02 m³. The presentation of the data in this form is illustrated in Figure 4.

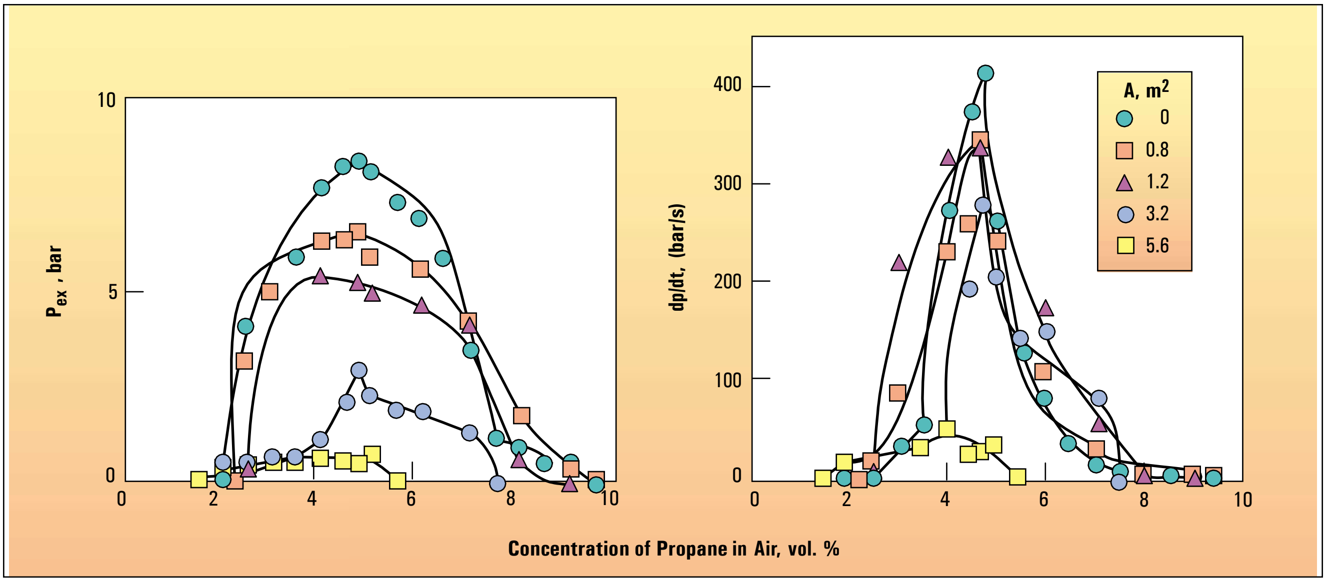

Figure 5. Effects of metal networks on deflagration pressure and pressure-rise rate.

Also included are some data produced by Southwest Research Institute *(8)* representing stoichiometric *n*-hexane/air mixtures. In the absence of the expanded-aluminum network, a 5-gal gasoline tank experienced severe failure due to the resulting deflagration. The experimental data can be seen to be in excellent agreement with the theoretical predictions, confirming the effective flame-quench ability by the expanded-metal network. As such, note that Bartknecht *(2)* suggests that the presence of 8-m² metal network, based upon extrapolation of the data noted in Table 5, would eliminate the propane/air explosion in the 20-L vessel altogether. This is consistent with the analytical prediction in Figure 4, since 8 m² of metal network is equivalent to a value of $V_c/V \sim 0$ according to Eq. 10.

Also, a recent U.S. Air Force Specification for Aircraft Fuel Tanks *(9)* is met by the stoichiometric propane/air data illustrated in Figure 4, which clearly indicates that the aluminum network limits the pressure increase to well below 15 psi for the specified freeboard value of 10%.

The specification calls for δ = 76 µm and ρ_E = 40 kg/m³; combustion pressure increase shall not exceed 15 psi (~1 bar) when V_c = 10 vol. % and the initial pressure = 3 psig (~0.2 barg). Test specification is for a stoichiometric propane/air mixture and an ignition source > 0.25 mJ.

Table 5. Deflagration test results.

Safety Network Area A, m²	Lower Fuel Concentration, vol.%	Upper Fuel Concentration, vol.%	P_{max}, bar	V_c / V
0.0	2.0	9.5	8.5	1.0
0.8	2.25	9.5	6.6	0.89
1.2	2.5	9.0	5.4	0.84
3.2	2.5	7.5	2.9	0.58
5.6	1.5	5.5	0.7	0.25

Concluding remarks

The purpose of this article is to stimulate further use and consideration of the passive means provided by expanded-metal products in eliminating or suppressing vapor-phase deflagration. Moreover, we wish to encourage inclusion of these means in the next edition of the NFPA 69 standard. Relevant experimental data and analytical interpretation provided above clearly justify such consideration. CEP

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