Safe Separation Distances from Liquid Fuel Fires

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In question is the adequacy of the current method for calculating safe separation distances from large-scale liquid fuel fires. The authors point out the limitations and weaknesses of such calculations and recommend further research.

WHEN a large quantity of a flammable liquid is stored or transported, there is always a possibility of spillage and ignition resulting in a fire that may threaten inhabitants and valuable combustible property within a certain distance from the fire. How spillage and ignition occur and in what order is not important to the objective of this paper. The fuel source may be a ruptured storage tank, an overturned fuel truck, or a derailed tank car. Ignition may be initiated by lightning, a frictional spark, or a welding torch. What is important is a large, liquid fuel spill fire raging and radiating to the surroundings. The objective of this paper is to show the weaknesses and limitations of the method generally used to determine the safe separation distances from such a fire.

DEFINITION OF SAFE SEPARATION DISTANCE

The safe separation distance from a fire is defined as that at which the thermal radiation flux is equal to some prescribed level. This level depends on what one is trying to conserve or protect. The tolerable level for humans varies with the time one allows them to seek shelter. Beuttner[1] gives a value of about 0.035 cal/cm^2 sec (465 Btu/hr ft^2) for the minimum threshold of pain. At 0.05 cal/cm^2 sec (660 Btu/hr ft^2) pain is felt after one minute. In industrial areas, one is generally concerned with the conservation of property and vegetation, which, if ignited, would increase the hazard and spread the fire over a larger area thus compounding the disaster.

NOTE: Adapted from a paper presented at the Central States Section of the Combustion Institute Meeting on Disaster Hazards held at NASA's Manned Spacecraft Center in Houston, Texas, 1970.

Lawson and Simms[2] have shown that the time required for the ignition of different kinds of wood can be related to the radiative flux by the equation

$$(I - I_{crit})\, t^{4/5} = .05 \times 10^{6}\,(k\rho s + 35 \times 10^{-6}) \qquad (1)$$

where

I = radiation flux from the fire (cal/cm^2 sec)
I_{crit} = critical level (cal/cm^2 sec)
t = time to ignition (sec)
k = thermal conductivity (cal/cm sec ° C)
ρ = density (gm/cm^3)
s = specific heat (cal/gm ° C)

They found that the critical intensity, I_{crit}, which is the minimum energy necessary to ignite wood at infinitely long exposures, was between 0.6 and 0.8 cal/cm^2 sec (8000 to 10,600 Btu/ft^2 hr) for nonpiloted (spontaneous) ignition and about 0.3 cal/cm^2 sec for piloted ignition. Since liquid fuel fires do not result in fire brands, which may cause piloted ignition (as do forest fires, for instance), the spontaneous ignition level is generally used to determine safe separation distances.

METHOD OF CALCULATION

To determine the safe separation distance, one calculates the thermal radiation flux at several points away from the fire and then, either by trial and error or by plotting the results, one can find the point at which the hazardous level occurs.

The thermal radiation flux at a particular location is generally determined by the equation:

$$I = \sigma \tau \epsilon F T_f^{4} \qquad (2)$$

where

σ = Stefan-Boltzmann constant (1.38 × 10^{-12} cal/cm^2 sec ° K^4)
τ = atmospheric transmissivity to flame radiation
ϵ = flame emissivity
F = geometric view factor
T_f = average flame temperature (° K)

ATMOSPHERIC TRANSMISSIVITY, τ

The thermal radiation from a fire to surrounding objects will be partially attenuated by absorption and scattering due to water vapor, carbon dioxide, and dust in its path. The fraction of energy transmitted, τ, can be estimated if the path length and attenuant concentrations are known. However, the latter vary widely with weather, season, and terrain conditions; therefore, a conservative (maximum) value for thermal radiation flux can be obtained if a transmissivity of unity is used in Equation 2.

FLAME EMISSIVITY, ϵ

The emissivity of the flame, ϵ, is related to its thickness by Equation 3:

$$\epsilon = 1 - e^{-\kappa D} \qquad (3)$$

where

κ = attenuation or extinction coefficient (cm^{-1})
D = flame thickness (cm)

Experimentally determined liquid fuel attenuation coefficients are given in Table 1. Remember that the attenuation coefficient, and thus the emissivity, of a flame is a complex function of wavelength, partial pressures of the radiating gases (H_2O, CO_2), and concentration of soot, and that Equation 3 is a gross simplification. Fortunately, large fires ($D > 3$m or 10 ft) in most common organic fuels can be treated as black-body emitters with an emissivity of unity.

VIEW FACTOR, *F*

The view factor, F, is the fraction of energy emitted by the radiating source that is intercepted by the element of area under consideration. It can be determined theoretically if the geometric shapes of emitter and receiver and their relative orientation are known. Theoretical expressions and graphs giving the values of F for different configurations are available in the literature[5,6]. Usually, large-scale fires are assumed to be cylindrical or parallelepiped in shape with diameter or width assumed to equal the width of the fuel spill D, and height H equal to the luminous flame height. A vertical element of area along ground level is taken as the recipient of radiation because usually, although not necessarily, it gives a higher value for F (and consequently a higher flux) than a horizontal element would.

FLAME HEIGHT, *H*

The flame height, H, which is needed to evaluate the view factor depends on the type of fuel, the diameter of the spill, and the burning rate. Thomas[7] correlated the results of wood crib fires by the relation

$$\frac{H}{D} = 42\left[\frac{m''}{\rho_o\sqrt{gD}}\right]^{0.61} \tag{4}$$

where

H = luminous flame height (cm)
D = diameter of spill (cm)

TABLE 1. *Attenuation Coefficients for Typical Liquid Fuels*[3,4]

Liquid	κ (*cm*$^{-1}$)
Ethyl alcohol	.0037
Xylene	.012
Hexane	.019
Gasoline	.020
Unsymmetrical dimethyl hydrazine	.025
Benzene	.026
Kerosene	.026
Butane	.027
Liquefied natural gas	.030
Methanol	.046
Liquid hydrogen	.070

m'' = fuel burning rate per unit area (gm/cm^2 sec)
g = gravitational acceleration (980 cm/sec^2)
ρ_o = density of air ($\simeq$1.3 × 10^{-3} gm/cm^3)

Thomas also found that his correlation fitted the data obtained by Blinov and Khudiakov[8] for heavy industrial fuels burning in large pools ($D \leq 22.9$ meters). His correlation, however, overestimated flame heights of large-scale natural forest fires, and its applicability to all liquid fuels is questioned. If an average density of 0.8 gm/cm^3 is assumed for most organic fuels, Equation 4 can be rewritten in terms of a linear regression (burning) rate, $\dot{R}$ (cm/sec), as follows*:

$$H \simeq 258\, D^{0.695} \dot{R}^{0.61} \qquad (5)$$

Calculated flame heights of fuels with different burning rates are shown in Figure 1.

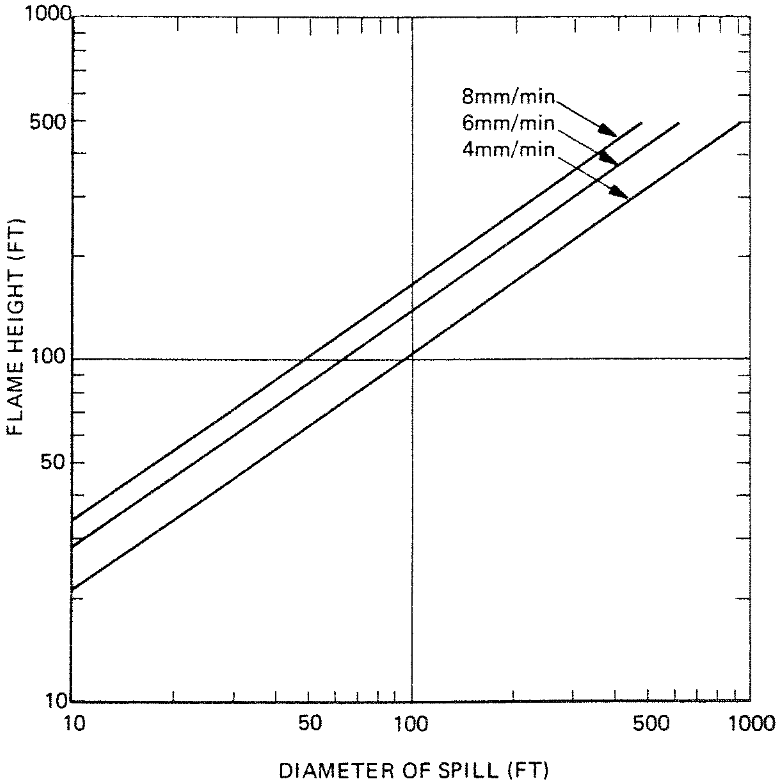

Figure 1. Calculated flame heights for different spill sizes and fuel burning rates.

*For liquids with densities significantly different from 0.8 gm/cm^3 (e.g., liquid methane, where ρ = 0.415 gm/cm^3) the calculated H must be multiplied by $(\rho/0.8)^{0.61}$.

BURNING RATE, $\dot{R}$

The burning rate, $\dot{R}$, is needed to obtain the flame height. In the absence of experimental data in large diameter pools, estimates of this value can be made from a correlation found by Burgess, *et al.*[4]

$$\dot{R} \simeq 1.267 \times 10^{-4} \frac{\Delta H_c}{\Delta H_v} [1 - e^{-\kappa D}] \tag{6}$$

where

$\dot{R}$ = linear burning rate (cm/sec)
ΔH_c = net heat of combustion (cal/gm)
ΔH_v = sensible heat of vaporization(cal/gm)

For heavy industrial fuels, Blinov and Khudiakov[8] found that $\dot{R} \simeq$ 4 mm/min. It is doubtful, however, that this rate is reached by all fuels. Large-scale experiments[9] with liquefied natural gas spills gave burning rates of about 12.5 mm/min.

FLAME TEMPERATURE

An average blackbody temperature is usually assigned to the flame. A typical value of 1600° F or 1700° F is generally used in Equation 2, regardless of the type of fuel.

DISCUSSION OF THE RESULTS

The distances at which the critical radiation flux of 8000 Btu/ft^2 hr is obtained from a cylindrical fire of diameter D and from an optically thick fire of width D were computed from Equation 2 and are plotted in Figure 2. A temperature of 1600° F and a burning rate of 4 mm/min were used in the calculations since they are representative of most heavy industrial fuels (e.g., gasoline, kerosene, diesel oil). However, the results presented in Figure 2 should not be taken as definitive for there are several weaknesses in Equation 2.

FLAME TEMPERATURE

The use of an average blackbody temperature of 1600° F for the flame may be considerably in error, for there can be large temperature variations within the flame. Unfortunately, temperature distributions in liquid fuel fires cannot be predicted theoretically, and only a limited amount of experimental data are available in the literature.

If the temperature distribution within the fire were known, a more accurate form of Equation 2 would be:

$$I = \sigma \sum_{i=1}^{N} \epsilon_i F_i T_i^4 \tag{7}$$

where the flame now has been divided into N zones, each having an average temperature T_i, emissivity ϵ_i, and view factor F_i. Furthermore, each

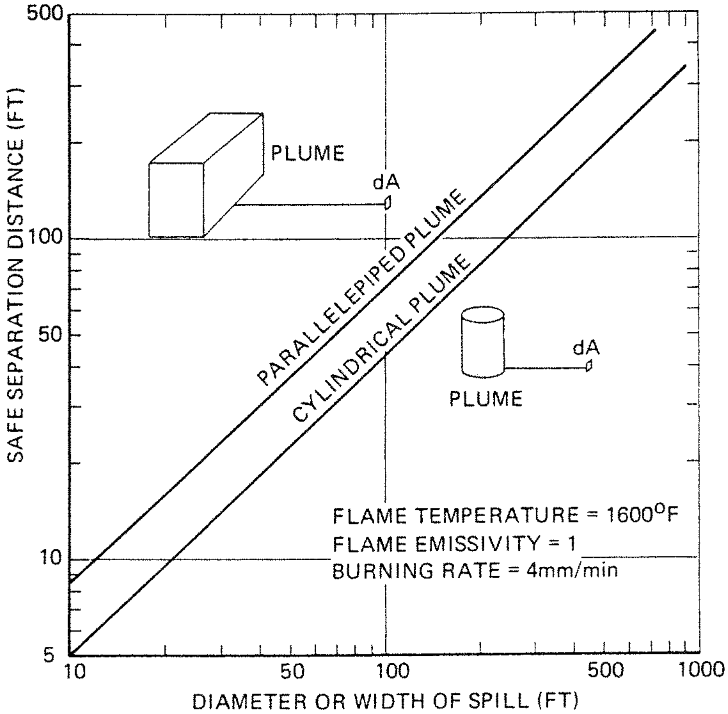

Figure 2. Safe separation distances from fires in typical industrial fuel as a function of the size and shape of the spill.

temperature T_i must be appropriately averaged over the path in the flame from zone i to the receiving point. For a two-dimensional flame of thickness L, having a temperature distribution $T(x)$, the thermal radiation flux is given by

$$I = \int_0^L \sigma \kappa T(x)^4 e^{-\kappa x} dx \tag{8}$$

and the average blackbody temperature of the flame will then be

$$T_f = \sqrt[4]{\frac{I}{\sigma [1-e^{-\kappa L}]}} \tag{9}$$

It can be shown that for a thick flame, in which temperature varies such that $T(x)^4$ is linear with distance x, the average blackbody radiative temperature is equal to the temperature at a distance equal to $\frac{1}{\kappa}$ from the surface. For industrial liquid fuels with $\kappa \simeq 0.025$ cm^{-1}, this distance is 40 cm (16 inches).

The procedure described by Equations 7 and 8 was applied to the experimental temperature profiles obtained by Canfield and Russell[10] with JP-5 fuel burning in an 8- by 16-ft pan. Using an attenuation coefficient

$\kappa = 0.026\ \text{cm}^{-1}$, a blackbody temperature of 1260° F was found to be more representative of the flame radiation than 1600 or 1700° F.

FLAME SHAPE

The flame shape is far from being cylindrical or parallelepiped. Flames tend to neck-in near the bottom and then expand like an inverted cone. Laboratory flames have also been known to vary in shape with the type of fuel burned.[11] It is not known whether or not this is true also for large-scale fires. Another problem that arises in determining the shape of a fire is when the liquid spill is not circular in shape. No data are available for predicting flame heights of elongated spills and other noncircular shapes.

SOOT CLOUD

For most organic fuels, voluminous quantities of soot are generated, so that the luminous portion of the flame is hardly seen by the surroundings. The contribution of the soot cloud to thermal radiation is generally neglected, but it could be significant.

LUMINOUS FLAME HEIGHT

The use of a luminous flame height for a 500-ft fire calculated from a correlation based on experiments in up to 75-ft pools may be grossly in error. For large-scale fires, oxygen starvation in the central regions of the spill may cause cellular fires with downdrafts of air (as has been observed in large forest fires) to feed the central regions. The effects of fire size on soot formation and the luminous flame height are not known.

FLAME PULSATION

Large fires have been known to pulsate and display large radiation bursts from luminous balls of flame appearing at some frequency. Smith[12] made a preliminary analysis to estimate the effect of such bursts on the magnitude of thermal radiation from a fire and concluded that the effect of radiation bursts on heat transfer may be very large.

GEOMETRIC VIEW FACTOR

In evaluating the thermal radiation flux distribution, the interchange view factor between a vertical or horizontal element of area and the flame is found and used in Equation 2. It should be pointed out, however, that neither $F_{vertical}$ nor $F_{horizontal}$ gives the maximum flux at that location. The area element receiving the maximum amount of radiation is that which is positioned with its surface normally displaced from the vertical by an angle equal to $\tan^{-1}(F_{horizontal}/F_{vertical})$ or where the view factor is equal to the vector sum of the vertical and horizontal view factors, i.e.,

$$F_{max} = \sqrt{F^2_{vertical} + F^2_{horizontal}} \tag{10}$$

This calculation becomes important when determining the maximum flux to vegetation where leaves and branches are in random orientation. The use of vertical or horizontal view factors should be limited to building surfaces.

WIND EFFECTS

The effect of wind on large-scale fires and on radiation from such fires has not been investigated. The effect of wind on small (1- to 2-ft diameter), free-burning, liquid pool fires was studied by Pipkin and Sliepcevich.[13] Their model was later modified by Welker and Sliepcevich,[14] and Huffman, Welker, and Sliepcevich.[15] In the final model, the flame angle of tilt from the vertical, θ, was correlated by the equation:

$$\frac{\tan\theta}{\cos\theta} = 3.3\left(\frac{DU}{\nu}\right)^{0.07}\left(\frac{U^2}{gD}\right)^{0.8}\left(\frac{\rho_g}{\rho_a}\right)^{-0.6} \qquad (11)$$

where

D = pan diameter (ft)
U = wind velocity (fps)
ν = kinematic viscosity of air (ft^2/sec)
g = gravitational acceleration (32.2 ft/sec^2)
ρ_g = density of fuel vapor cloud (lb/ft^3), and
ρ_a = density of air (lb/ft^3).

In a study of the effect of wind on the rate of spread of fires in wood cribs, Thomas[16] related the angle of tilt to both the fuel-burning rate per unit width of fire front $\dot{m}'$, and the wind velocity U, by the relation:

$$\cos\theta = 0.7\left[\frac{U}{\left[\frac{g\dot{m}'}{\rho_a}\right]^{1/3}}\right]^{-0.49} \qquad (12)$$

When applied to liquid fuel fires, Equation 12 has been shown to give results which are comparable to those obtained by Equation 11.

It is very doubtful that either equation predicts realistic angles of tilt for very large-scale fires. Unlike 1- or 2-ft pool fires, large-scale fires have considerable influence on local wind velocities at ground level and tend to diminish the effect of natural wind on the flame. Experimental large-scale fires have been known[17] to generate wind speeds of between 30 and 60 fps along the ground, and the upward velocities within the plume can reach comparable magnitudes. Thus the angle of tilt will not be as large as that predicted from small-scale fires.

There is also some confusion as to whether the flame length is lengthened or shortened by wind. It is conceivable that the flame is stretched slightly at low wind velocities. At higher velocities, the resulting turbulence may enhance the mixing of air and fuel vapor leading to complete combustion in a shorter flame length. The experiments of Huffman, *et al.*[15] showed that, for wind speeds less than 10 mph and in pans 1 ft in diameter, the flame length increased with an increase in wind velocity. The same experiments showed that there was little effect of wind on the burning rate of fuel, and, if anything, it was reduced slightly. No data are available for higher wind velocities and larger fires.

Radiation from an inclined flame to a point downwind from the fire may increase or decrease, depending on the position of the receiving point and its view factor with respect to the flame. Huffman's experiments have shown that for a vertical element at a point 15 diameters away from the liquid pool, the rate of incident radiation decreased with an increase in wind velocity. This is to be expected since the view factor is reduced. Although no measurements were made at closer points, one would expect the radiation flux to increase with wind velocity for points located directly below the flame.

RECOMMENDATIONS

We believe that there is a definite need for large-scale spill fire tests employing a variety of liquid fuels. Data from these tests could be used to improve the assumptions made in calculating safe separation distances and to check theoretical predictions. In particular, we feel that the following areas need further investigation:

- The applicability of existing flame height correlations to large-size fires of varying spill shapes and fuels.
- Effective flame temperatures, and their variation with flame height.
- Effect of wind on thermal radiation and geometry of large-scale fires.
- The contribution of soot clouds and radiation bursts to thermal radiation.

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