"Making the Flare Safe"

- by David Shore - J.Loss.Prev. Process Ind. Vol. 9, No. 6, pp. 363-381, 1996

Errata

Preamble. The éssential purpose of a flare is to be a safety device for the plant which *it* serves, yet...

formula (5) .... $1/k$ is time constant = $5\ m_t / Q_1$

If additional errors are noted, please contact

David Shore,
Flaregas Corporation, 100 Airport Executive Park, Nanuet. N.Y. 10954. USA
Ph (914)-352-8700 Fx (914)-352-4464

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Making the flare safe

David Shore

Flaregas Corporation, 100 Airport Executive Park, Nanuet, NY 10954, USA

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The paper presents a general review and checklist for many of the safety issues in flare design, specification and operation covering the obvious and not-so-obvious concerns. Common assumptions in flare specification are subjected to explanation and critique relative to their impact on safety. Subjects covered include: selection of height and location of elevated flares; flaring of toxic or noxious materials; flame stability as influenced by gas composition and operational procedures; flaring of unstable or hazardous materials; purging and the use of purge reduction devices; operational considerations to avoid problems; maintenance procedures to minimize risk. Copyright © 1996 Elsevier Science Ltd

Keywords: flares, flames, radiant heat, flame-out, emissions, purge

Preamble

The essential purpose of a flare is to be a safety device for the plant which is serves, yet the use of this device raises a whole series of additional safety concerns connected directly with the act of flaring gas. Many of these concerns are satisfactorily addressed by the correct application of common codes of practice and it is not the purpose of this paper to revamp these well-known and well-tried aspects of design. Rather, the intention here is to expand on these and to cover the lesser known and sometimes forgotten concerns in the hope of raising general awareness of these issues and, hopefully, provide a framework around which additional experience may be assembled.

Where possible, the paper includes tabular or graphical presentations to serve for quick estimations and reference.

In all of these matters, it is important to appreciate that although all of the areas covered are subject to the usual laws of physics and chemistry, the underlying mechanisms are somewhat complex and cannot easily be understood as an exact science. Consequently, industrial treatments rely on approximations and gross estimations, interpretations of which should be made with a constant application of common sense and good engineering judgement. That said, the formulae presented here and in the aforementioned codes do, usually, provide a satisfactory level of accuracy for common usage.

Effects of the flame

Thermal radiation

The basic thermal radiative effects of the elevated flare flame are obvious and addressed in previous texts by a number of other authors. The most commonly used procedure to determine the probable intensity of radiant heat is currently provided by the API in RP-521[1]. This calculation, in common with others, assumes that the flame can be adequately modelled as a point source which then becomes the center for a uniform spherical distribution of radiated heat according to the 'spherical' flame radiation model [equation (1)].

$$R = \sqrt{\frac{\tau Ef Q}{4\pi I}} \tag{1}$$

where R is minimum distance from the 'center' of the flame to the object being considered; τ is atmospheric transmissivity; Ef is flame emissivity (fraction of heat radiated); Q is heat release (based on Nett CV); and I is thermal radiant intensity at point. All units must be consistent.

Flame models. Two alternative methods are provided by RP-521 to estimate the location of the flame 'center'. One of these, which for the sake of recognition we can call the 'API' simple method, relies essentially on momentum effects with no buoyant component and generally indicates a relatively small flame rise. The other procedure was first published by Brzustowski and Sommer[2] and incorporates jet dispersion and small-scale empirical results into the theory. We can designate this the 'BRZ' method. Both methods suffer from an apparent departure from reality at extremely low or high wind speeds and are somewhat tedious if performed long-hand according to the originally published procedures. In the originally published form, the API method used arithmetic summation to estimate flame location. A better, direct solution is obtained from the mathematical integration of the basic formulae producing the result indicated in equation (2).

X = horizontal flame end location

(downwind from tip) — feet

$$= [Lf/A]^2 \times \{Lf - K + ([K^2/A] \times B)]\}$$

z = vertical flame end location (above flare tip) — feet

$$= \{[K\ Lf/A] \times B\} - [K \times X/Lf]$$

$$A = \sqrt{(K^2 + Lf^2)} \qquad (2)$$

$$B = \ln \{[Lf/K] \times (A + Lf)/(A - K)\}$$

where Lf is flame length $= [Q^{0.467}]/135$ (in feet); Q is flame heat release (Btu/h); K is momentum constant $= 1.6\ \pi\ d_o\ (U_o/U_w)$; d_o is discharge diameter (feet); U_o is efflux velocity; U_w is wind speed (fps).

Flame length. API-521 also provides a curve of approximate flame length which tends to be confirmed by experience for estimates at low wind speeds and for common 'pipe' flare designs, although lengths are almost certainly overestimated for wind blown flames and specialty flare tip designs.

Brzustowski calculates flame length as part of the procedure. In general, the BRZ method is not good for very low wind speeds because the flame length becomes much too long to be a practical value. The BRZ method usually gives a flame center a little higher and closer to the flare than the API method. As a result, the radiation levels at grade, immediately below the flare, are sometimes higher with BRZ than with API.

Wind speed. For wind-blown flames, a wind speed of 20 mph (30 fps) is probably the most common and reasonable condition for design, as this creates a fairly significant flame center distortion in both common models, but is still low enough for the selected emissivity to be realistic. Brzustowski *et al.*[3] later show that high exit and wind velocities both tend to reduce overall emissivity. The effect of exit velocity was also demonstrated by Straitz *et al.*[4] Use of the structural design wind speed for flame-lean calculations is unrealistic.

Emissivity. All models to determine radiant heat incorporate a value for radiant 'emissivity' or radiated fraction of total heat. There is not much of a real guide to emissivity in the published information. Formulae by Tan[5] and Kent[6] have fallen into disuse as being unrepresentative of the real case. At the time of writing this paper RP-521 gives no realistic procedure to determine this value other than a short tabulation of empirical data on relatively small flames given by the US Bureau of Mines[7], even though the determination of a statisfactory value is relatively crucial in the selection of flare height. In any event, because none of the flame models will be truly accurate or give identical results for flame position, *the appropriate emissivity can vary from model to model* and a reliance on empirical data obtained using any specific model is implied.

Notwithstanding the relative complexity of the calculation procedure discussed, when used with the same emissivity, API and BRZ calculations often produce strikingly similar results when the API transmissivity is 0.67 as indicated in the 1969 version of RP-521. *Figure 1* shows a typical comparison of results for a 320 ft × 48 inch flare with a design flow of 1,000,000 lb/h; MW 44 hydrocarbons, both with an emissivity of 0.21 and wind-blown at a wind speed of 30 fps (20 mph).

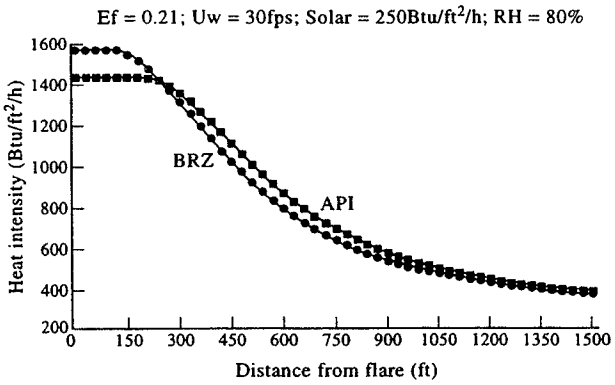

Figure 1 Comparison of heat intensity at grade (320 ft × 48 inches flare at 1,000,000 lb/h)

In summary, the spherical distribution assumption applied with either of the two API flame models seems to be quite satisfactory for practical purposes. Other models[8,9], with varying claims to accuracy, are available, some of them commercially incorporated into computer programs. However, bearing in mind that design wind and flame state are, at best, only rough estimates of true conditions, additional refinements and the introduction of new flame models hardly seems worthwhile for common pipe flare designs. Specialty flare tips, which develop unique flame shapes, may need individual treatment, however.

A proposed model for emissivity

The radiated heat, and hence the emissivity basis, of a flame comes chiefly from two separate sources. First, all the unsymmetrical gas molecules such as water and carbon dioxide will radiate a fraction of their intrinsic heat. This gaseous emissivity may be 10–15%, but the amount of the total heat contained in the H_2O and CO_2 is only about 30–40% of the total, so the effective emissivity of this part, based on the total flame, can be only about 5%. A hydrogen flame which is largely transparent still has a radiative output.

The remainder of the radiation comes from solid particles, usually carbon, which are suspended in the flame and which are all glowing red to white hot. These same particles give the flame its visible color. As each particle is at a relatively constant temperature it behaves like a black body, radiating almost all of its sensible heat. This gives a significant proportion of the radiant heat from the flame and means that a flame with a lot of carbon (smoky) radiates more than a flame with little carbon (clean). This is demonstrably true in the field.

Some gases are more likely to be smoky because they contain a greater proportion of carbon than others or because their cracking temperature is lower than others. In determining carbon proportion we can think of the mass fraction of carbon in the gas molecule because this is a representation of the physical probability of carbon atom collision (and combination) in the flame zone. This relationship has been discussed but not developed by Straitz *et al.*[4] Additional factors which merit consideration are

- reduction in carbon formation as flame turbulence increases[3],
- an increase in carbon development with time, suggesting a diameter dependence, leading to a peak of overall thermal output as carbon production reaches a threshold value beyond which the smoke tends to 'hide' part of the flame[10],
- the unburned carbon reduces the total heat output by about 12,000 Btu/lb.

Design emissivity tends to be selected on a job-by-job basis, using previous experience, as a gauge for the estimation. However, as most of the hydrocarbon processing industry uses API RP-521 as a reference tool, it seems appropriate to produce a 'pseudo-scientific' basis for determining the emissivity with the API and BRZ models, in order to facilitate uniform interpretation. Consideration of the above processes, together with regression analyses on published data and field experience, permits us to suggest the formula in equation (3) for use with the API and BRZ flame models.

$$\text{Emissivity} = Ef = 0.075\ Fi \exp(G\ P) \exp(-1/\sqrt{D}) \quad Ef \text{ limited to 0.4 max or value at } G = 0.05 \tag{3}$$

where Fi = importance factor

= 1.0 for low probability of design relief

= 1.15 for high probability of design relief

D = tip discharge diameter (inches)

G = turbulence factor = $[\text{Mach1}/U_o]^{(0.2)}$

Mach1 = sonic velocity for discharge gas (fps)

U_o = discharge velocity (fps)

P = 'pseudo' solid fraction in the gas

$$= \frac{[12\,\text{C}] + [24\,\text{S}] - [3\,\text{O}] + [3\,\text{O–H}]}{\text{molecular weight of gas}}$$

where C is molar fraction of carbon atoms in total; S is molar fraction of sulphur atoms in total; O is molar fraction of oxygen atoms in total; O–H is molar fraction of O–H bonds in total. For estimates involving unknown conditions, the suggested value for G is $[1/0.2]^{0.2} = 1.38$, the suggested value for D is 60 inches.

One advantage of this formula is that it takes account of inert components, which we know to be beneficial in reducing solid production and corresponding emissivity. Typical evaluations of emissivity for various compositions over a range of velocities are shown in *Figure 2*.

Concurrently, the author wishes to encourage flare operators to generate additional data and help to refine this formula. It is important when obtaining field data to use the supposed flame shape of the appropriate model to determine the flame 'center' as this can vary from the apparent visual center.

Whichever method is used to predict radiant profiles around the flare, the information which is provided must be properly interpreted and understood.

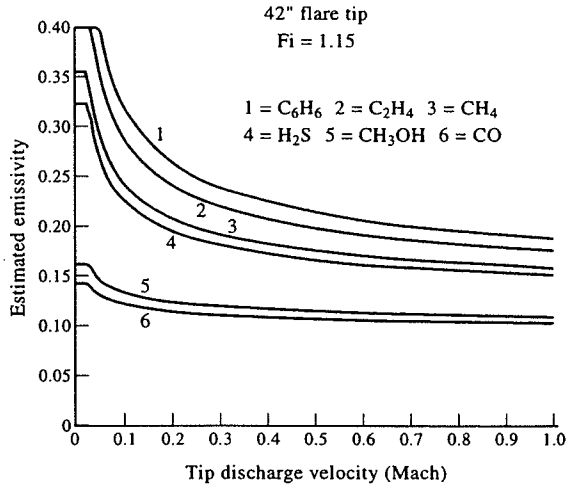

Figure 2 Typical estimated flame emissivities for various gases using proposed emissivity formula [equation (3)]

The effects of radiant heat

Effects on personnel

The effects of heat on personnel were well investigated by Buettner[11]. Largely on the basis of his work a 'safe' level of exposure was proposed by Kent[12] at 1500 Btu/sq.ft.h with the argument that this provided sufficient margin for a timely escape. This value is now widely used as a 'safe' level but unfortunately is not generally very well understood. To be realistic, any radiant heat exposure value should be accompanied by an acceptable exposure time. RP-521 goes a little way toward indicating possible duration of exposure; however, this may be more comprehensively covered in a graphical form as in *Figure 3*. As suggested by the figure, normal clothing can be used to extend exposure times. However, this consideration must be carefully treated. The ability of the clothing to absorb heat (its heat capacity) also means that the clothing will still be hot some time after personnel have escaped from a high risk area and can itself be a risk factor if its mean temperature is too high. A maximum clothing temperature of between 100 and 120°F is suggested in order to avoid possible burns and the lines in the figure represent 120°F warm-up times for clothing of increasing thickness and insulating ability. Normal work clothing, even common 'flameproof' apparel, will only extend the available escape time and should not be considered as a substitute for prudent design.

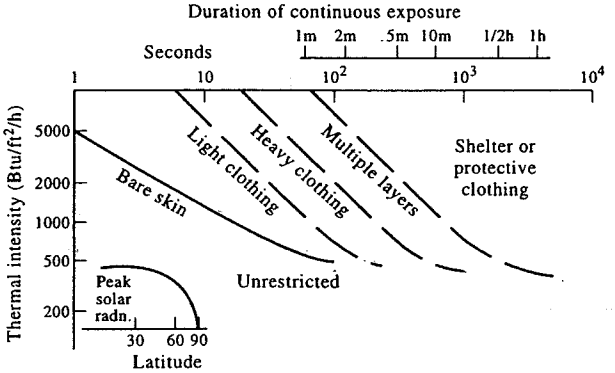

Figure 3 Estimate of protection requirements for exposure to flare flame radiation (head and neck covered)

In the figure, an intensity of less than 500 Btu/sq.ft.h is considered to be suitable for areas with unrestricted access.

Normal solar radiation is additive to thermal radiation from the flare and is included in the recommended exposure times. Initially this might seem to represent a potential problem for working areas where unrestricted access is required at all times; however, although the possibility of solar addition must be considered, it need not be a major source of concern and does not necessarily mean that these areas must be designed for 500 minus the maximum probable solar input. Factors which can also be considered are

(i) the probability of occurrence for any specific design case;
(ii) the probability of occurrence for the peak solar input;
(iii) possible variation of radiant flame intensity for prevailing wind speeds;
(iv) possible variation of intensity for various and prevailing wind directions;
(v) the potential for concurrent convective cooling;
(vi) the true required duration of continuous exposure for personnel with no chance of shielding versus the recommended maximum for the level.

Given these factors, it is quite probable that design case concurrence with solar input will have little or no impact on design locations or flare height for the majority of cases.

For all true levels of radiant heat which allow 1 min or more exposure it is usually realistic to suppose that the discomfort level will eventually drive personnel to seek refuge.

Effects of radiant heat on equipment

The effects of radiated heat on local equipment are often not a significant issue in design of the flare height or location because the possible effects on personnel are more severe. Unfortunately, this generalization can sometimes lead to these effects being ignored only to become a problem subsequent to flare start-up. This is especially true of flares which are remote from personnel areas, which may also be fairly short and run at consistently high rates. In these cases horizontal incoming pipes should be reviewed as their angle of view approaches 90° and they may be elevated on piperacks and consequently be closer to the flame than the flare height alone would suggest. Electrical wiring and instrument signalling cables are particularly at risk as the sheathing is low in conductivity and frequently has a highly absorptive surface which quickly reaches an equilibrium temperature. In some cases, total shielding of equipment or piping is appropriate. This need not be an expensive exercise and even small amounts of modest shielding such as corrugated roofing material can be remarkably effective in preventing heat damage, particularly if designed to encourage an air flow up through the equipment. All equipment falling within the sphere of influence of 500 Btu/sq.fth should be subject to at least a cursory review. Investigation of the effects of this thermal, radiative input on local equipment is effectively a temperature calculation which requires a simple balance of input radiation against radiative and convective cooling. The theory and principles are well known and documented and need not be expanded here. Equation (4) summarizes simple but relevant formulae taken from reference[13].

$$Q_1 = I\,E_s \sin(\theta)\,F_v \tag{4a}$$

where Q_1 is heat absorbed by the equipment (Btu/sq.ft.h); I_1 is incident radiant heat (Btu/sq.ft.h); E_s is surface emissivity; θ is surface angle from normal radiant 'beam'; F_v is view factor or fraction of equipment area exposed.

For maximum equipment temperatures use

$E_s = 1$; $F_v = 0.5$; $\theta = 90°$;

$$Q_2 = 0.172\,E_s\,[T_o/100)^4 - (T_a/100)^4] \tag{4b}$$

$$Q_3 = 0.7383\,[T_o - T_a]^{1.266}\,[2/(T_o + T_a)]^{0.181} \tag{4c}$$

$$Q_4 = [1 + (0.225\,U_w)]\,[T_o - T_a] \tag{4d}$$

where Q_2 is heat radiated by equipment (Btu/sq.ft.h); Q_3 is natural convective heat loss (Btu/sq/ft.h); Q_4 is forced convective heat loss (Btu/sq/ft.h); T_o is equipment (surface) temperature (deg R); T_a is ambient temperature (deg R); U_w is wind speed (fps). At equilibrium $Q_1 = [Q_2 + Q_3]$ or $[Q_2 + Q_4]$.

It must be understood that although this summary will produce a gross estimation of equilibrium temperature at best, more refined calculations are unwarranted given the nature of the flame model, the indeterminate characteristics of the equipment surface and the degree of exposure to both input and cooling factors. For simplicity the conservative model assumes that

- the surface is normal to the input radiation, i.e. view angle = 90°;
- surface emissivity = absorptivity = 1 = 100%;
- exposure is from one side only; i.e. view factor = 0.5 = 50%;
- convective cooling is by natural convection only;

For wind-blown flames, temperatures may be investigated for wind cooled surfaces as well as those cooled by natural convection.

Again, the heat capacity of the equipment will have an effect on the actual temperature as a function of exposure time. Simplistically, we can assume that light, organic materials with low conductivity such as grasses, paper, electrical insulation, etc., reach equilibrium too rapidly for a calculation of period to be relevant. Metal structures and similar, conductive equipment on the other hand may have a significant warm-up period. For quick estimates of probable heating rates, a logarithmic form can be assumed as suggested in equation (5).

$$T = \{(T_o - T_a)\,[1 - \exp(-kt)]\} + T_a \tag{5}$$

T is intermediate temperature (deg R);

t is exposure time (h);

k is time constant = $5\,m_t/Q_1$

m_t is representative thermal mass of equipment per unit area = rho c_o (Btu/sq.ft.deg R); rho is material mass per unit surface area (lb/sq.ft); c_o is specific heat of material

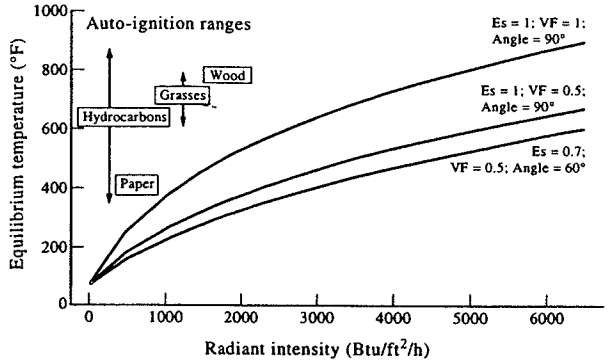

Figure 4 Typical equilibrium temperatures for exposure to radiant heating

(Btu/lb.deg R); Q_1 is rate of heat absorption by the equipment [equation (4)]; T_o is equipment (surface) temperature (deg R); T_a is ambient temperature (deg R).

Tan[5] provided a convenient presentation of typical equilibrium temperatures prepared on the basis and the same approach is used in *Figures 4* and *5*.

Equipment temperatures at/near the flare stack

Some type of reasonable determination of local temperatures in the upper sections of an elevated flare under conditions of radiant heat is important when evaluating the required characteristics of protective coatings or electrical and instrument installations. *Figure 6* provides a practical guide to typical local equilibrium temperatures at the flare tip itself. These are estimates and should not be considered as definitive statements of final metal temperature. Note that, whilst coatings must be able to withstand the greatest estimated temperatures, the majority of the service life will be between ambient and the lowest noted temperatures. Coatings which require a high temperature cure will not automatically receive this cure during service.

Any equipment located in the upper sections of the flare must be designed to withstand the noted temperature ranges. Temperature-sensitive equipment such as electrical or electronic components may not be suitable even if enclosed in a protective box or housing, such as a junction box, as these containers have no ventilation and will absorb the radiated heat uniformly. Any such containers must be either

(a) removed from the affected zone or

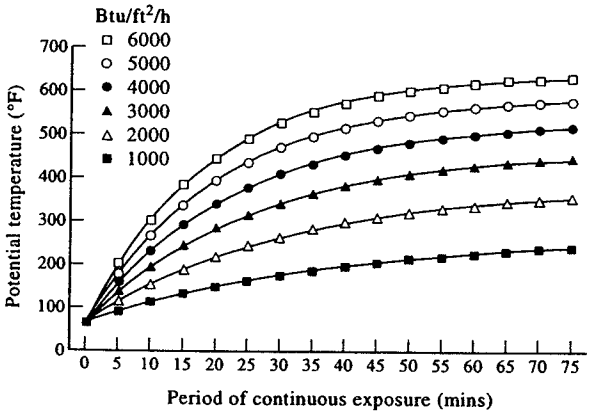

Figure 5 Effect of exposure time on equipment temperature

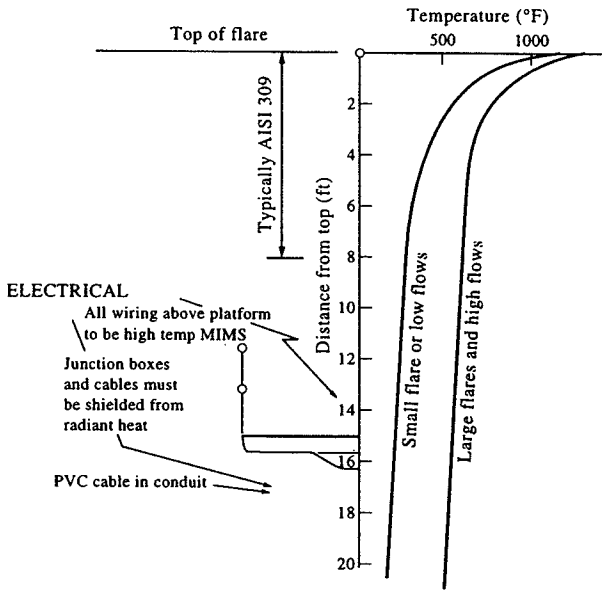

Figure 6 Representative metal temperature range for elevated flare tips

(b) fully protected by a multidirectional radiation shield which provides full shadow for the equipment whilst ensuring a significant air gap and full upward circulation of ambient air.

Experience indicates that junction boxes and conduits installed above the platform are particularly susceptible to heat damage of the contents.

Multiple flare installations

When planning a new flare installation, many of these foregoing considerations may seem obvious and easily covered. It is not uncommon, however, for designers to forget the combined effects of existing flares in the same general location and ignore the effects of heat from these existing units upon the proposed new installation. Maintenance access to both new and old units must be considered together with the plant operator in order to coordinate practical solutions.

Danger of local fire

An additional aspect of local temperature deals with the possibility of creating grass fires because of high radiant heat levels. In general this is a low probability. This does not mean, however, that significant organic growth should be allowed or encouraged around the flare. A much more serious probability exists for burning hydrocarbon liquid or red hot carbon to be discharged at the flare tip. Such incendiary materials can potentially fall as far as a flare height away, although most will fall around the base of the stack. Discharge of hot carbon often accompanies a sudden relief after a prolonged period of relative inactivity, during which time low flows burning inside the flare deposit carbon as described later as 'burn-back'. Similarly, burning hydrocarbon liquid may result from a long-term hydrocarbon build-up in a liquid seal being suddenly displaced by a high relief flow. To avoid the latter, maintain a small continuous purge rate into the flare header to purge the seal dip-leg and remove trapped hydrocarbon. Concurrently, maintain a small sweetening flow of water into the drum to

skim hydrocarbon from the water surface via an overflow. Nozzle and overflow placement should be reviewed during design stages to ensure that skimming is a practical consideration.

The most serious liquid-based fires are usually associated with significant release of liquid hydrocarbon into the flare header and concurrent operator error or lack of attention to level monitors in upstream KO vessels. Operators should be alerted to the potential significance of high liquid level in the KO drum and actively pursue remedies when this occurs. A KO drum should not be located too far from the flare it serves. There is a real possibility that hot reliefs may not have stabilized sufficiently to drop out the majority of their heavier components by the time they reach the drum or, worse, they will pick up liquid from the drum and deposit it later into the flare header.

The effects of the hot gas plume

Temperature of the plume

In some installations, it is impossible to avoid all circumstances in which the hot flue gas plume from the flame might pass across some other piece of equipment such as a distillation column, chimney or tall inhabited building. Although the calculated radiant heat level at these locations may theoretically be tolerable for personnel because of available shielding, the plume itself may create an intolerable condition. Whilst accurate calculation of the plume temperature is impractical, by using common principles of atmospheric dispersion it is possible to estimate the plume temperature range at any downwind location. Making the assumption that a Gaussian-type distribution applies both horizontally and vertically, and that for the length of plume in question the plume centerline is sufficiently far from the ground to avoid plume reflection, we can estimate plume centerline temperature rise.

Turner[14] provided suitable values for horizontal and vertical dispersion coefficients ($sigma_y$ and $sigma_z$) for a range of atmospheric stability categories which are described in *Table 1*. *Table 2* indicates numerical values for temperature calculation within the various stability categories, evaluated to incorporate standard values for $sigma_y$ and $sigma_z$ and corrected to allow for a short sampling time.

The specific plume trajectory beyond the end of the flame may be estimated using the formulae developed by Briggs[15] with suitable adjustments for non-contributory, radiated heat.

Figure 7 provides a graphical representation of these conditions plotted for the neutral stability '*D*' and a 30 fps wind and includes a suggested boundary condition within which the possible effects of the plume should be considered. Stability category '*D*' is chosen as the most representative case for the wind-blown flames which create the worst conditions.

It should be noted also that low flow conditions, with relatively small heat release and plume rise, are potentially more problematic from this standpoint than high flows which have a significant plume rise.

Plume rise and dispersion

A reasonable estimate of plume rise from the flame is also important when designing for dispersion of toxic or noxious discharge from the flare. Typically, compounds containing organically bound sulphur, nitrogen or halogens will all need particular attention to dispersion criteria and estimation of ground-level concentration (g.l.c.). It is suggested that the dispersion calculations might be investigated for

- discharge of an uncombusted relief;
- discharge of a combusted relief with 98% conversion of relief gas to theoretical flue gas and 2% original gas unconverted (to calculate g.l.c. of original gas);
- discharge of a combusted relief with 98% conversion of relief gas to theoretical flue gas and 2% partial conversion to a possible intermediate form (to calculate g.l.c. of intermediate form, e.g. conversion of carbon to CO);
- discharge of a combusted relief with 100% conversion to theoretical flue gas (to calculate g.l.c. of noxious product, e.g. sulphur conversion to SO_2).

For these calculations, the same basis may be used for plume rise as that previously discussed. For preliminary estimates, however, it can be assumed that the plume reaches a maximum height and becomes level when the downwind distance is some multiple of that at which atmospheric turbulence begins to dominate entrainment. Because of downwind variations in the dispersion coefficients $sigma_y$ and $sigma_z$, the combined results of the analysis are too complex to be easily tabulated; however, the complete discussion of plume rise is available in the literature[15]. Maximum g.l.c. occurs at a downwind distance related to plume rise by a constant which results from mathematical differentiation of the dispersion equation.

In the foregoing discussion of dispersion, a calculation which supposes that there is no combustion of flammable materials is only required when there is a specific condition of hazardous relief which warrants the investigation. Reliefs of toxic materials such as hydrogen cyanide or high concentrations of hydrogen sulphide

Table 1 Guide to typical stability categories for flare plume rise estimations[14]

	Daytime solar radiation			Nighttime cloud cover		
Wind speed (fps)	Strong	Mod'te	Slight	O'cast	Light >=50%	Little <=40%
0–6	A	A/B	B	D		
6–10	A/B	B	C	D	E	F
10–16	B	B/C	C	D	D	E
16–20	C	C/D	D	D	D	D
20+	C	D	D	D	D	D

Table 2 Approximate plume rise and plume centerline temperature correlation within 5000 ft of flare

Temperature rise above ambient = $NQ/Uw/X^M$ (°F)

Plume rise = 0.09 $Q^{1/3}$ $X^{2/3}/Uw$ (feet)

Q = Heat release (Btu/h)

X = Downwind distance (ft)

Uw = Wind speed (fps)

N = Stability related constant

M = Distance exponent

Stability	A	B	C	D	E	F
N	0.196	0.164	0.245	0.577	0.557	1.560
M	2.035	1.894	1.835	1.819	1.779	1.752

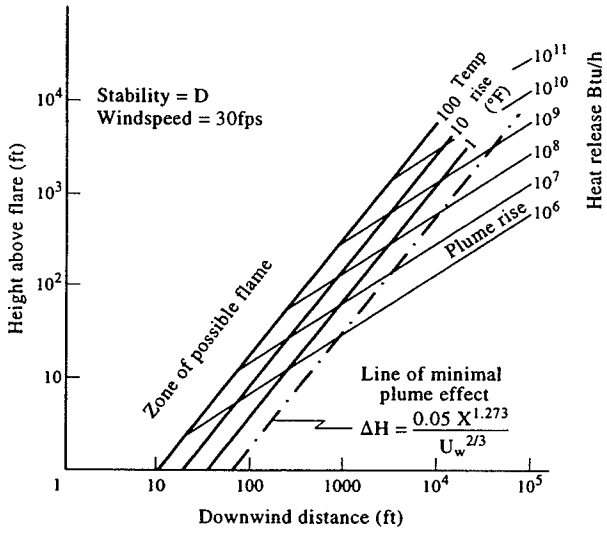

Figure 7 Estimate of flare plume conditions

would, typically, be such cases even though the gases themselves are rich in thermal release and burn well. Other flammable gases which should be similarly investigated are listed in *Table 3* along with their generally accepted exposure limits. It must be noted here that, although this type of dispersion calculation can indicate acceptable ground-level concentrations of pollutants, there may also be total dosage constraints on the amount of any permitted discharge, which should be reviewed with permitting agencies.

Flame stability and efficiency

Although it may be prudent to calculate g.l.c. on the basis of partially combusted material as indicated above, in general gases relieved to flares are rich and flammable and will burn well. However, because of the development of new technologies, as well as an increased awareness of the problems of atmospheric pollution, it is becoming more necessary to be able to flare large quantities of gas which have little or no intrinsic flammability. This is recognized by EPA regulations set out in the Federal Register section 40 CFR 60 and other associated regulations, which dictate acceptable conditions for flaring of hydrocarbons in order to ensure optimum destruction and conversion. These rules were developed primarily from research[16–18] which used low heating value, propane–nitrogen mixtures. Unfortunately the EPA rules tend to be drawn too broadly to truly reflect all possible cases but overall can be a reasonable guide to both flame stability and destruction efficiency for hydrocarbon/inert mixtures.

Stability of the diffusion flare flame

It is not proposed to discuss the basic combustion process in this paper other than to clarify that the basic flare flame is essentially a diffusion flame in which raw gas emerges as a jet, from a nozzle or opening, into the normal atmosphere where it mixes with ambient air. The required mixture of air and gas to permit combustion can only exist at a fairly narrow interface or diffusion zone and the entire combustion process must take place in this zone forming a flame envelope around the emerging raw gas stream. The thickness of the flame envelope is a function of the degree of mixing between the gas and the air and is significantly influenced by natural or induced turbulence and by the momentum and buoyancy forces generated by the gas and air flows and the heat release of the flame. For a flame envelope to exist at all, however, there must be local components of mixture velocity which are less than the basic flame speed for that mixture. In this way, the flame reaction can burn into the mixture. At low nozzle exit velocities, this condition is easily met by transverse velocity components and the flame appears to establish a base quite close to the nozzle. With increasing exit velocity, transverse velocity components become less frequent, the diffusion flame zone becomes thinner and the visible part of the flame seems to lift away from the nozzle. In the extreme case there is no lower flame and the flame base establishes some distance above the nozzle. This is known as a 'flame-lift' or 'lift-off' condition. At this time, the flame is becoming essentially unstable because any disruption of the unburning flow in the lower zone can cause the combustion reaction to be interrupted totally and the flame to be extinguished. Similarly, if the flame does continue to burn above the nozzle, ambient air is entrained into the mixture below the flame zone. This dilutes the total mixture and tends toward a premixed flame rather than a diffusion flame and requiring vertical velocity components to be active in flame stabiliziation, at which time the flame may be even more easily extinguished. This is effectively the 'blow-off' condition.

Table 3 Representative flammability limits and exposure levels for commonly flared gases

Common name		LEL (%)	UEL (%)	STOIC (%)	REL ppm
Carbon dioxide	CO_2	NA	NA	NA	30,000.0
Carbon monoxide	CO	12.5	74.0	29.55	200.0
Methane	CH_4	5.3	14.0	9.50	
Ethane	C_2H_5	3.0	12.5	5.66	
Propane	C_3H_8	2.1	9.5	4.03	1000.0
Butane	C_4H_{10}	1.9	8.5	3.13	
Ethylene	C_2H_4	3.1	32.0	6.54	
Propylene	C_3H_6	2.4	10.3	4.46	
Butylene	C_4H_8	2.0	9.6	4.24	
Butadiene [1.3-]	C_4H_6	2.0	12.0	3.68	
Acetylene	C_2H_2	2.5	81.0*	7.75	
Methyl acetylene	C_3H_4	1.7	?*	4.99	1000.0
Benzene	C_6H_6	1.3	7.9	2.72	1.0 ST
Toluene	C_7H_8	1.2	7.1	2.28	150.0 ST
Ethylene oxide	C_2H_4O	3.0	100.0*	7.75	5.0 C
Propylene oxide	C_3H_6O	2.3	36.0	4.99	20.0
Hydrogen sulphide	H_2S	4.0	44.0	12.26	10.0 C
Methyl mercaptan	CH_3SH	3.9	21.8	6.54	0.5
Ethyl mercaptan	C_2H_5SH	2.8	18.0	4.46	0.5 C
Carbon disulphide	CS_2	1.3	50.0	6.54	10.0 ST
Sulphur dioxide	SO_2	NA	NA	NA	5.0 ST
Hydrogen cyanide	HCN	5.6	40.0	14.38	4.7 ST
Acetonitrile	CH_3CN	3.0	16.0	7.09	60.0 ST
Acrylonitrile	C_2H_3CN	3.0	17.0	5.30	10.0 C
Ammonia	NH_3	15.0	28.0	21.87	35.0 ST
Methylamine	CH_3NH_2	4.9	20.7	8.54	10.0
Monoethylamine	$C_2H_5NH_2$	3.5	14.0	5.30	10.0
Dimethylamine	C_2H_6NH	2.8	14.4	5.30	10.0
Diethylamine	$C_4H_{10}NH$	1.8	10.1	3.02	25.0 ST
Chlorine	Cl_2	NA	NA	NA	1.0 ST
Hydrogen chloride	HCl	NA	NA	NA	5.0 C
Methyl chloride	CH_3Cl	8.1	17.4	10.71	10,000.0
Ethylene dichloride	$C_2H_4Cl_2$	6.2	16.0	6.54	2.0
Vinyl chloride	C_2H_3Cl	3.6	33.0	7.09	5.0 C

LEL% and UEL% (lower and upper explosive limits) and STOIC% (stoichiometric quantity) given as % gas in air.
REL (recommended exposure limits) are given as maximum (C = ceiling) values or 15 min (ST) time-weighted average where available.
Absence of REL indicates no value available.
For full discussion of limits, see ref 31.
* Gases marked can decompose explosively.

These various conditions have been investigated by other authors. Kent[12] related flare tip sizing to the Mach number of the gas on the basis that a lift-off condition due to turbulence develops in an unstabilized hydrocarbon flame around 0.2 Mach. Commercial manufacturers have pushed this limit for common flare designs to approximately 0.5 Mach by using stabilization techniques involving the provision of permanent pilots and creation of recirculation zones which allow small pockets of gas to slow down and burn locally to the rim of the gas exit. These burning pockets are frequently large enough to continue to re-ignite the lifted portion of the flame and reduce the possibility of inadvertent blow-off. The relationship of diameter and Sonic velocity has also been incorporated into the recommendations of RP-521. Currently, more specialized designs are available in which exit velocity is increased to permit sonic discharge velocity whilst maintaining a stable flame.

40 CFR 60.18 limits

In the USA, the EPA regulations which apply to flares have been formulated on the basis of intrinsic calorific value and gas exit speed. These parameters are demonstrated in *Figure 8* and in many cases will supersede the Kent/RP-521 basis of flare tip diameter determination.

The sloping part of the limit for non-assisted and steam-assisted tips is given by the relationship:

Velocity (fps) = $26.6 \times 10^{(CV/850)}$ (400 fps maximum limit).

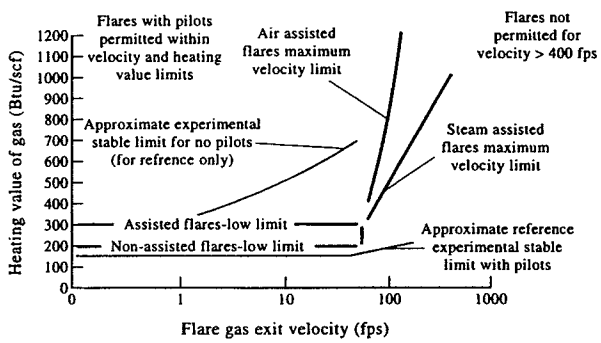

Figure 8 Flare velocity regulations (40 CFR 60.18)

The sloping part of the limit for air assisted tips is given by the relationship:

Velocity (fps) = 28.6 + (0.0867 *CV*)

where *CV* = calorific value (in Btu/scf).

Calorific value for any gas or mixture is limited to a minimum of 300 Btu/scf for assisted flares which use steam or other inert medium to assist smokeless performance and 200 Btu/scf for nonassisted and gas-assisted flares. For EPA or other associated permitting, flare operators should review flare operations to see whether they fall within the regulations.

Limitations on the use of 40 CFR 60

The main problems with the use of the rules of 40 CFR 60.18 are associated with the implicit assumptions that all gas mixtures match the tested gases and that all commercial flare tip designs are similar to the tested units. There are common, specific aberrations in this assumption.

Hydrogen (*CV* = 259 Btu/scf) has the highest flame speed of all common gases and has a very wide range of flammable limits, even when mixed with inert gases, and burns well in mixtures which would not meet the 200 Btu/scf baseline of the regulations. Hydrogen itself does not meet the 300 Btu/scf baseline required for steam and air-assisted flares. This is clearly an aberration in the regulation and frequently leads to unnecessary treatments and grossly oversized flares. Operators should discuss hydrogen cases specifically with regulating authorities and request specific exception for these cases.

Hydrogen sulphide (*CV* = 586 Btu/scf) also burns well but is a toxic gas with a strong odour which can be detected at very low concentrations. It is desirable that the greatest practical destruction of H_2S be achieved when the gas is flared. When burning incompletely, H_2S can make sulphur 'smoke'. As the color of this 'smoke' is a whitish yellow and blends easily with the sky background, it is often not recognized as incomplete combustion as it would be if the color were black. From the EPA test results we know that conversion of H_2S is perhaps two times better than propane, and thus, in a flame which is 99.5% efficient, the specific destruction efficiency of H_2S could be assumed to be 99.67%. Even when the H_2S is fully converted to SO_2, however, there is still an associated odour and concern for threshold levels of toxic effect. The important aspect of adequate dispersion is to create the greatest possible plume rise by ensuring a good total heat input to the flame. Even though H_2S/nitrogen mixtures will remain stable at velocities somewhat higher than hydrocarbon/nitrogen mixtures[18], in order to address these above concerns, the recommended approach is to treat H_2S gas mixtures as assisted flames with a lower calorific value limit of 300 Btu/scf and, wherever practical, add some hydrocarbon to the flame in order to

- increase the number of available radicals in the unburned flame core;
- increase the amount of solid carbon particulate in the flame providing a more radiant core and assisting stability;
- raise the flame temperature and improve the possibility of H_2S destruction;
- raise the total heat in the flame, enhancing the plume rise.

Ammonia (*CV* = 360 Btu/scf) is another relatively lean gas, with strong odour and no solid radical component, which suffers from many of the same problems as H_2S. A similar solution may be adopted when flaring. Practical experience indicates that in a diffusion flame such as a flare, the flame stability of ammonia alone is sometimes questionable. This is probably due to the fact that, at 70°C, the upper and lower limits of flammability for downward propagation of flame meet[19] which means that no flames will propagate downward at low temperatures and all flaring below this temperature must be positively stabilized with pilot flames in order to provide continuous re-ignition for the flare. The limits of flammability for upward propagation remain acceptable even at lower temperatures. There is insufficient specific published data to predict destruction efficiency of NH_3 with a high degree of accuracy. However, the fact that the spontaneous ignition temperature of ammonia (1204°F) is higher than almost all common hydrocarbons suggests that ammonia could represent more than 50% of the total inefficiency in a combined flame. Even though 100% ammonia is above the EPA required low *CV* limit(s) a small hydrocarbon addition to the flame will greatly improve ammonia destruction as well as enhancing plume rise. A minimum figure of between roughly 2 and 5% by weight is suggested. Attention to flare tip design and mode of enrichment can also be extremely beneficial in improving destruction.

Inefficiency in the flare flame

Inefficiencies in the diffusion flame are introduced due to the haphazard and uncontrolled nature of the combustion process. Typically it is possible to witness apparently incomplete combustion in a turbulent hydrocarbon flame by observing the rolling or 'boiling' effects which seem to disappear in a wisp of smoke (i.e. a wisp of pollution).

The use of supplementary flames (pilot burners) at the base of the main flare flame is a major factor in enabling flame stabilization and reducing inefficiency. Pilot flames not only provide a means of initial ignition for the main flame but also continuously re-ignite gases with intrinsically low flammability, assuring continued combustion at the base of the flame and reducing potential raw gas losses.

Research on hydrocarbon flare flames tends to confirm that losses in the form of the original composition are usually negligible. Most of the uncombusted residue of the hydrocarbon flame is likely to be partly combusted material such as carbon (soot), carbon monoxide or the most stable form of hydrocarbon (methane). Oldaender and Siegel[20] found practically no gaseous forms with carbon concurrent with maximum smoking.

A reasonable interpretation of results from the various, limited research which has been performed on relatively large flames leads to the following summary.

(1) Elevated flare flames burn well as long as a stable flame is assured by the presence of (flame-holding) stabilizers and continuously burning pilots.
(2) Combustion efficiencies generally tend to be better than 99% conversion, even when smoking, and most

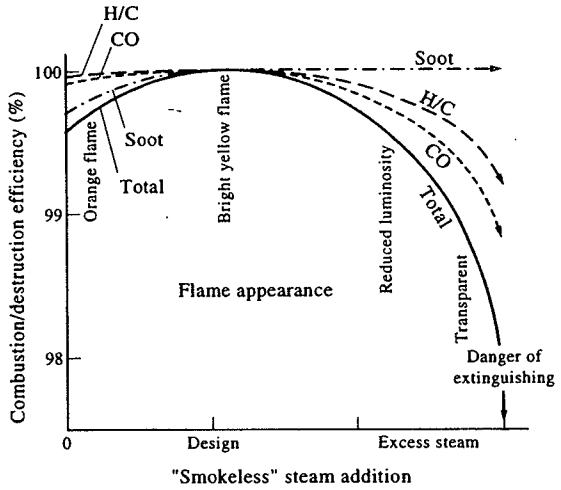

Figure 9 Generalized estimate of smokeless flare flame efficiency

are better than 99.5% conversion even when smoking.

(3) The pollution which results from reduced efficiency seems to produce soot (dirty flames only) or unburned hydrocarbon and carbon monoxide with roughly equal concentration, adding up to the cumulative inefficiency stated above.

(4) Smokeless flares, operating with clean flames, exhibit combustion efficiencies approaching 100% unless over-steamed or over-aired as suggested by *Figure 9*.

- For steam-assisted flares, the steam flow rate affects both the smokeless performance and the combustion efficiency of the flare. Peak efficiency in the reports is related to a clean flame with approximately 0.5 wt/wt steam ratio. Efficiency of oversteamed flames is reduced, although it is still better than 99%.

- For air-assisted flares, the air flow rate affects both the smokeless performance and the combustion efficiency of the flare. Peak efficiency in the reports is related to a clean flame with less than 100% stoichiometric air being provided by blowers. For the tested flare tips, efficiency of over-aired flames reduces significantly, approaching extinction at the LEL (approx. 150% stoichiometric air).

Generalizing the efficiency results in a practical manner for typical refinery applications from an operators viewpoint, the conclusions which may be drawn from the visual picture are indicated in *Tables 4* and *5*.

Table 4 Guide to the estimation of possible flame efficiency based on the visual appearance of a flare flame (assumes hydrocarbon predominance)

Flame appearance	Efficiency
Any combustion reaction	> = 98
Any *visible* hydrocarbon flame	> = 99
Clean, red/yellow	> = 99.5
Clean, sharp, bright yellow/white	Close to 100
Clean, yellow flame with reduced luminosity	> = 99.5
Barely visible (transparent) hydrocarbon flame	> = 99%

Table 5 Flare efficiency—guide to emissions estimation (inefficiency expressed by mass of carbon in the gas)

Total inefficiency (Table 4) < = 2%

Particulate
Depends on nature of original gas and operating conditions;
strongly smoking up to 2%
light smoke
no smoke 0%

Unburned hydrocarbons
0.50% of aromatics (and related hydrocarbons) in original gas;
0.05% of other hydrocarbons in original gas;
40% × residual inefficiency converted to CH_4;

Carbon monoxide—CO
60% × residual inefficiency converted to CO;

Hydrogen sulphide—H_2S
67% × inefficiency for hydrocarbons;
Inefficiencies are expressed by total mass of H_2S;

Nitrogen oxides—NO_x
for hydrocarbon flare flames less than 100 million Btu/h

$$\text{Total } NO_x \text{ (1b/h)} = \frac{(\text{Heat release (Btu/h)})^{1.8}}{25{,}000{,}000{,}000{,}000}$$

for hydrocarbon flare flames greater than 100 million Btu/h

$$\text{Total } NO_x \text{ (1b/h)} = \frac{(\text{Heat release (Btu/h)})^{1}}{10{,}000{,}000}$$

Nitrogen oxides (NO_x) are produced in flare flames to varying degrees. Data are available[18] for hydrocarbon flames less than 100 million Btu/h and suggest a pattern of NO_x production which is nonlinear with heat release. This is contrary to a common practice of applying a linear constant multiplier to heat relase. At rates above 100 million Btu/h, until more data are available, it is suggested to revert back to linearity.

Gases which contain organically bound nitrogen, such as ammonia and amines, when burned alone or in mixtures with hydrocarbon, have a higher NO_x output than hydrocarbons alone. At this time there is no reliable model which predicts these enhanced rates but, in one set of results[18] for ammonia/propane mixtures, NO_x rates were typically perhaps ten times the propane alone values.

Sudden flame-out

Total loss of the flame on an operating flare is, unfortunately, too common not to be a concern. Flame-out is almost always associated with some aspect of operations and usually results from the flare tip conditions being essentially non-flammable rather than from an intrinsic inability of the tip to retain a flame. Nitrogen, water and carbon dioxide are probably the most common culprits. Each of these diluents absorbs heat from, and can quench, the flame. The EPA rules for minimum calorific value, covered previously, apply equally at low flows as well as for maximum design. Operators and designers should review all potential relieving combinations to ensure that flows or non-flammable materials, particularly batch releases of purge, are satisfactorily enriched to exceed the minimum heating value limitation.

Other typical conditions which can lead to this are associated with day-to-day operating procedures.

Manual control of smoke suppression—Smoke suppressing fluids inadvertently left at a high setting follow-

ing a large relief can be too great once the relief flow subsides. Use of some type of automated system related to true demand is suggested.

Oversteaming - a smokeless flare to 'hide' the flame—Maintain a visible flame at all times to prevent flame out and, concurrently, achieve optimum efficiency.

Pilot burners—The use of continuously operating pilot burners, as previously noted, is essential. However, there are circumstances in which pilot can also be extinguished by a flood of non-flammable gases at the tip. In these cases rapid re-ignition of pilots is essential. For many years, pilot ignition has relied mainly on remote flame front generation in a flammable mixture piped to the flare tip from grade. In too many cases the flame front ignition unit is only used during commissioning and has all but become inoperable when needed in a flame-out emergency. To mitigate against this problem, institute procedures which ensure that the panel is re-used frequently to maintain operator confidence and concurrently discover whether panel maintenance is appropriate. 'Re-igniting' pilots which are already in operation is unlikely to create problems with the flare.

Additional measures against flame-out which may be instituted are

(i) automate the ignition sequence using continuous pilot flame monitoring;
(ii) use direct electrical ignition of pilots with flame front only as a back-up system to cover for electrical problems with inaccessible equipment;
(iii) use pilot burners specially adapted for high inert atmospheres wherever high inert purge flows are likely.

Flammability

Flammable limits

The need to determine the flammability of a flared gas mixture is somewhat obviated by the aforementioned calorific value limitations of the EPA regulations. A good association with the basics can, however, be obtained from the references[19,21]. A typical and generic flammability curve for flammable gases mixed with inerts is given in *Figure 10* for reference purposes. The LEL and UEL values required to construct an engineering curve for any specific gas are also well-documented[19], together with a method of combining LEL/UEL values for flammable gas mixtures. Some common values are also listed in *Table 3*.

The effects of temperature on flammable limits should not be ignored. Published values of LEL and UEL for most gases are usually given at a reference temperature of 25°C (77°F). Because the flammable limits relate primarily to the ability of the flame front to raise the temperature of the non-burning part of the mixture to the pyrolysis temperature, they are temperature-dependent and will widen as the mixture temperature increases[21] such that, at the minimum adiabatic flame temperature (approx. 1900°F for paraffinic hydrocarbons), the LEL is zero. The appropriate LEL to use for any gas temperature, assuming eventual combustion air input at ambient temperature, may be found by linear interpolation between the temperature at the published LEL and the minimum adiabatic flame temperature calculated for that mixture. The effect of temperature on flammable limits is typically demonstrated in *Figure 11*. Heating both the air and the gas together will input sufficient energy in the form of sensible heat to effectively permit the minimum energy requirement to be satisfied at a lower temperature. This is the condition commonly known as auto-ignition or spontaneous ignition. Auto-ignition temperatures depend also upon stoichiometry and intrinsic stability and are not readily generalized, although published values are available in the references.

Flame speed

Flame speed is the effective speed of the combustion reaction through the gas mixture and is frequently given as a maximum speed which occurs when the gas is mixed with approximately a stoichiometric quantity of air or oxygen at ambient temperature and pressure. For most hydrocarbons at ambient temperature, a safe maximum assumption would be less than 2 fps but certain gases such as hydrogen, hydrogen sulphide, ethylene oxide, propylene oxide, acetylene, ethylene, carbon monoxide and other rapidly burning gases need special consideration as their combustion properties are outside the normal range. For these gases a general assumption of a 10 fps maximum will suffice for engineering solutions. Flame speeds are also temperature dependent, however, increasing nonlinearly as mixture temperature rises to the relevant auto-ignition point and this matter must be considered when reviewing small reliefs of hot gases.

Flash-back and detonation

Flash-back and detonation are the extreme effects of the flame speed. In the condition of a fully flammable air/gas mixture resident in the flare system with little or no forward speed, we can see that the flame at the tip can travel down into the flare pipe. As it does so, it is accelerated by the building pressure of hot exhaust gases trying to leave the stack and by the reduction in volume of the gases ahead of the flame under the action of pressure waves generated at the flame front and reflected from the closed end of the system. The system pressure builds exponentially and the acceleration culminates in a detonation when the effective flame velocity reaches Mach 1. By the time the detonation is achieved, the reflected pressure in the system could be as high as 40 times the initial (atmospheric) pressure[21] and momentary pressures as great as 100 times the initial pressure might develop in the wave front[22]. The distance into the stack at which the flame reaches Mach 1 depends on geometric considerations of the flare stack and system and cannot easily be formulated here.

Water seals are frequently thought of as a protection against flash-back. Their benefit in this respect is largely a result of isolating the upstream system from the atmospheric air. They do not necessarily assist in suppressing a detonation in the stack and there have been cases where water has been lifted out of a seal into the piping system by the building pressure ahead of the flame front. The potential quench effect of the water may never be

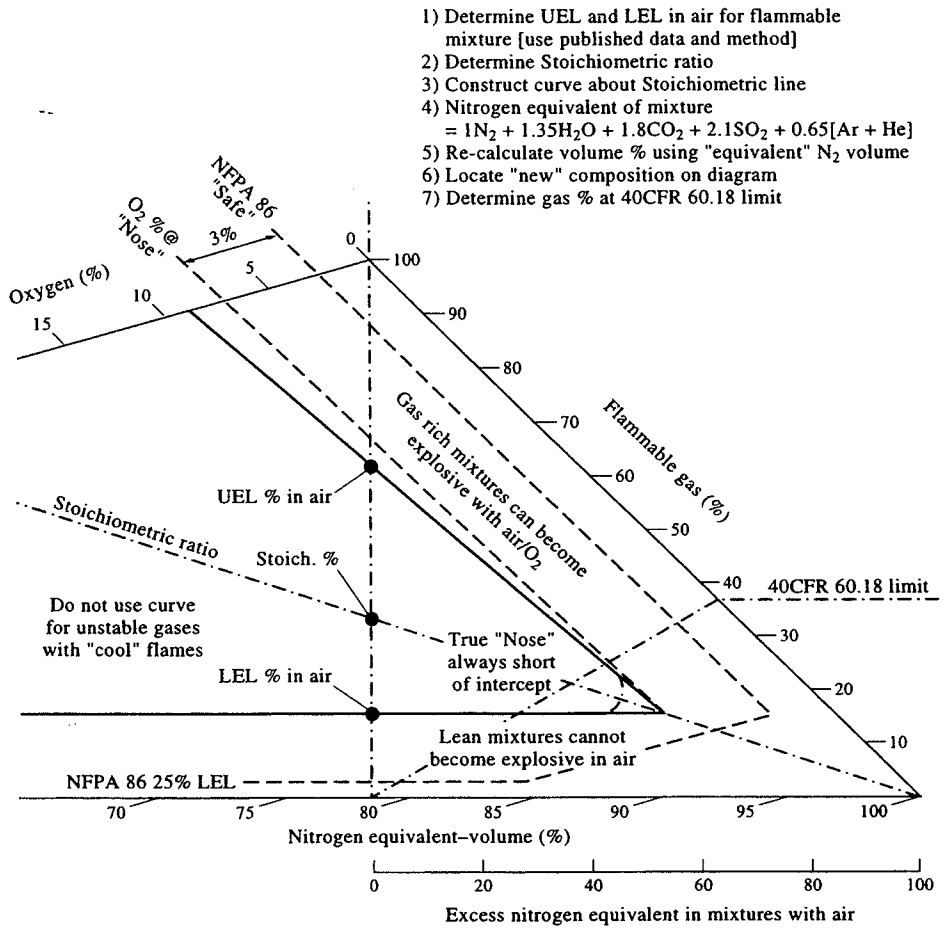

Figure 10 Typical flammability diagram for 'safe' mixture estimation

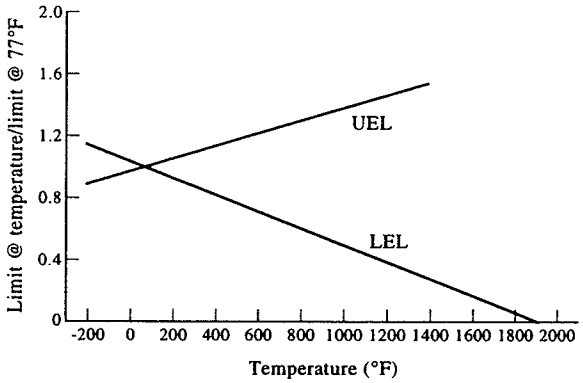

Figure 11 Approximate effect of temperature on flammability limits of paraffins

realized if the detonation pressures develop before the flame front reaches the seal.

Flame arrestors are devices which usually provide a large and conductive contact surface with the flowing medium and have a thermal mass/capacity which can absorb sufficient heat from a flame passing though the arrestor that the flame is cooled to extinguishment. To achieve this cooling effect, most devices use very small apertures or passages intended to raise the ratio of wall contact area to flow area toward or beyond a critical value. Because residence time in the arrestor will be a significant aspect of its success, flame speed is a design factor. Thus, gases with high flame speeds and gases which readily decompose are less easy to manage than more stable aliphatic hydrocarbons with relatively low flame speeds.

Detonation arrestors are specially improved flame arrestors with shock absorbing expansion chambers to break up the sonic shock wave associated with a detonation and also enhance the residence time of the arrestor. Commercial manufacturers usually limit placement of flame arrestors to a maximum distance of 6–10 pipe diameters from the source of ignition, or some other equivalent dimension, beyond which a detonation arrestor is recommended.

In recent years, US Coast Guard rules[23] for handling hydrocarbon vapours have required that detonation arrestors be subjected to an approval testing procedure and many commercial devices now have Coast Guard approval.

As the small passages in these devices can plug over long periods of operation, they are not normally recommended for use in flare systems. When they are required, relatively frequent access for cleaning must be assured.

Designing for internal pressure in the system

Some users specify an internal pressure design for the flare system as a means of protecting the piping and flare from the possibility of mechanical damage in the extreme case that a high, detonation-like pressure

develops. There is, however, wide variation in design pressure specifications.

Notwithstanding the previous discussion of flash-back, the author is unaware of any circumferential rupture failure which has resulted from a detonation-like event in a flare stack. Equipment failures usually occur as longitudinal tensile failure of a circumferential weld joint and almost always coincide with a significant change in the system such as a 90° or 180° bend or sudden contraction. This is probably because the static pressure in the system is not as great as the reflected waveform[21] and tends to indicate that the destructive energy exists primarily in the velocity pressure of the reflected wave. The specific failure location is also probably associated with local configurations and stress raisers. Analysis of one memorable event suggests that the destructive force could easily be associated with a pressure condition in excess to 700 psi, confirming the previously noted pressure range between 40 and 100 atmospheres. Taking this into consideration, we can propose that an appropriate design condition to accommodate the worst potential detonation would be to design piping material cross-section and circumferential joints for the longitudinal forces related to the sonic wave.

Typically for this design, the rules of the ASME Boiler and Pressure vessel code[25] are applied as these provide a framework of calculation procedures and can be used as a means to ensure fabrication quality. Given that a code design considers only uniform static pressure, and that a cylindrical vessel is usually limited by a circumferential stress twice the value of the longitudinal stress, the standard intrinsic safety factors in the allowable code stresses generate an effective factor of safety to failure of 8:1 for the longitudinal stress. Thus, a design pressure specification of 125 psig should adequately protect against catastrophic failure due to a reflected wave pressure up to 1000 psig and should be a satisfactory design basis. There are obvious commercial ramifications associated with the use of this pressure for design of transitions, heads and large vessels and users may choose to avoid detonation risk by operating procedure rather than by specification.

Because most flares actually operate at pressure less than 15 psig, it is not usually necessary to consider the flare as a pressure vessel or to apply this particular internal pressure design concurrent with the structural wind/seismic design. This is simply a cross check calculation which has an infinitesimal probability of concurrence with normal design loadings. Supplementary calculations, such as MDMT at maximum pressure and design pressure adjustments for hydrotest, are usually irrelevant considerations in this design. Furthermore, the code allowable stresses need not be used for the structural design because applicable factors of safety vary and are already incorporated into the standard structural codes.

Purging, minimum flow and burn-back

Many elevated flares spend most of their active service in a pseudo-dormant state. In this condition, elevated flare stacks are generally purged continuously with only a small amount of gas in order to protect them against the possibility of flame flash-back and explosion or detonation. Purge can also represent protection against corrosion or other undesirable conditions, but chiefly addresses the possible mixing of flammable gases with atmospheric air due to buoyancy forces in the stack, bearing in mind that an ignition source may exist at the flare pilots.

Husa purge model

Probably the most notable work to-date has been by Husa[26,27]. His research established a formula to relate the various geometric and physical parameters of the purging problem. The formula is based on the familiar exponential decay curve and seems to be good for the range of conditions encountered in elevated flare stacks. Unfortunately, Husa's recommended calculation of the buoyancy factor for the purge gas can be difficult when compositions of gas mixtures are ill-defined. Husa suggests an upper limit on molecular weight of 28.96 and also reports a potential error factor for the general case formula of approximately 2. Simplification of the general case by prior incorporation of a 2 multiplier to avoid the need for individual analysis will, however, frequently result in significant overestimation of purge gas flow. An alternative estimation of buoyancy factor may be obtained from the relationship shown in *Figure 12* and this is used in subsequent calculations in this paper as summarized in

$$O_2\% = 21 \exp\{- U\,Ls/0.0036\,Fb/D^{1.46}\} \qquad (6)$$

where U = gas velocity (fps)

Ls = distance into stack from open top (feet)

D = stack diameter (inches)

Fb = adjusted buoyancy factor (*Figure 12*)

$= 6.25\,[1-0.75\,(MW/28.96)^{1.5}]$

MW = molecular weight of purge gas.

Husa suggested that 6% oxygen at 25 ft might be an acceptable condition for a 'safe' stack. Almost all common flammable gases and vapours have an Upper Explosive Limit (UEL=gas-rich limit) which is less than 36% gas in air or 13.4% oxygen in the mixture. Additionally, flame run-up distances to produce a detonation in a plain tube are frequently in excess of 25 ft, so, in terms of flare safety against flash-back, Husa's criteria seem to be reasonable. These conditions are, however, fairly arbitrary and the use of an oxygen concentration directly associated with the UEL of the

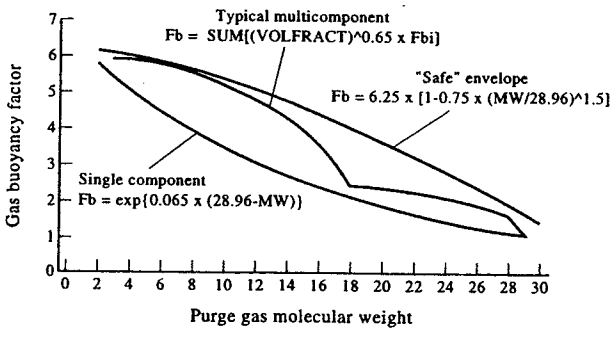

Figure 12 Purge gas buoyancy factor comparison for Husa purge rate formula

flammable gases in the system, as suggested by NFPA-86[28], may be considered appropriate by different users. For safety, it is suggested that the equivalent distance into the stack at which an 'unsafe' level can exist should not exceed a 10 diameter detonation 'run-up' limit, as sometimes used by manufacturers of detonation arrestors.

Inert purge gases

Purging with a non-flammable gas, such as nitrogen, obviously provides an advantage in that the nature of the purge gas itself adequately suppresses any potential for flames to propagate, although it raises a question regarding the validity of the aforementioned oxygen limitation. In order to assess the real value of an inert gas as a continuous purge for an operating flare, it is necessary to consider the effect which any addition of flammable gas will have. In general and approximate terms, the addition of between 5 and 15% by volume of most flammable gases to nitrogen will render the total mixture flammable. The flame propagation speed in the mixture will be somewhat reduced from the normal speed and provide an additional factor of safety although, conversely, the UEL oxygen percentage for lean mixtures also falls significantly. To assure a reasonable degree of safety, the flow rate for a non-flammable purge gases should not be less than about 85% of the equivalent value for a lean mixture of inert and flammable gas. Relieving inert and flammable gases together in a mixture which remains non-flammable raises the additional concern of hydrocarbon release into the atmosphere and may contravene the previously noted EPA regulations.

Flammable purge gases and burn-back

Flammable purge gases are, however, subject to an additional consideration in that the purge rate must be reviewed for the possibility of burn-back of the flame into the top of the flare tip. Normal purge and burn-back flow should not be wrongly assumed to be the same. Operational burn-back can occur in flares purged with flammable gas in service and exhibiting a visible flame or furnished with continuous pilots. At extremely low rates this flame can regress into the tip under the effects of the same buoyant forces as previously discussed, which can be a problem as it may overheat the tip material and can build solid carbon deposits internally. The hot flue gases produced, however, tend to be disruptive to air inflow patterns and it is not easy to predict burn-back using the Husa model. The formula in equation (7), which is derived largely on the basis of experience, can provide a quick approximation of burn-back velocity for typical refinery service, although it may be conservative for gas mixtures with low calorific value due to inert content and slightly underestimates burn-back rates for hydrogen[29].

$$Ub = [(D/MW)^{0.75}\ (LCV)^{0.5}]/1500 \qquad (7)$$

where Ub = approx. burn-back velocity (fps)

D = internal diameter of tip (inches)

LCV = calorific value of gas (Btu/lb)

MW = molecular weight of purge gas.

A good practical guide for empirical determination of purging requirements against burn-back is to use this flame regression condition for assessing stacks which are burning at purge-only rates. Stacks which are safe will show the flames to be clearly visible under purge-only conditions. There may, however, be a tendency for flames to burn slightly low into the tip at low purge rates and then the issue of overheating the flare tip must be separately assessed. Some flare tip designs permit augmentation of the minimum flow using steam in a center nozzle if burn-back overheating is a problem. From a practical point of view, it is important to note that a hydrocarbon flame burning inside the tip will probably make smoke due to incomplete combustion. This can confuse operators who will probably increase the smoke-suppression steam for smokeless flaring and may actually exacerbate the burn-back problem rather than solve it. Smoke produced in a tip due to burn-back has a tendency to appear as a narrow column with either no supporting flame or from the extreme end of a very small flame. Conventional smoking, on the other hand, usually involves large flames with turbulent eddies and smoke production from the upper edges of the flame. Smaller tips do not frequently display pronounced burnback problems.

Maximum purge rate limits

When calculating purge rates, selecting a more conservative oxygen percentage or a lesser depth into the stack than those suggested above will result in greater flow rates. However, in any event, purge rates for common refinery gases need never exceed the burn-back rate with an small factor of safety as deemed appropriate by the operator.

Oxygen content in the flare base

Based on Husa's work, we see that oxygen percentage at any depth into the stack, is inversely proportional to the depth under consideration, as typically shown in *Figure 13*. When checking oxygen levels at the base of a stack, say during initial purging or commissioning operations, this relationship may be usefully employed to permit determination of levels at other elevations in the flare.

Flare 'seals'

Some flares are fitted with devices known as gas 'seals'. In all cases the device is not a 'seal' in the sense that a plug is a seal but is simply a means of reducing the amount of continuous purge gas needed to protect the stack against air infiltration. The existence of the device also makes it possible to define the position of measurement of permissible oxygen in the gas and to set a rate which ensures that this is not exceeded.

Although the underlying issue is the prevention of flash-back, 'seals' are not flame arrestors and should not be thought of as equivalents. As previously explained, a flame arrestor works passively whereas a 'seal' must be properly purged to have any effect. Additionally, a true flame or detonation arrestor can be employed in situations where oxygen rich gas mixtures originate within the plant, whereas 'seals' have no beneficial effect for this condition. 'Seals' are not effective in preventing

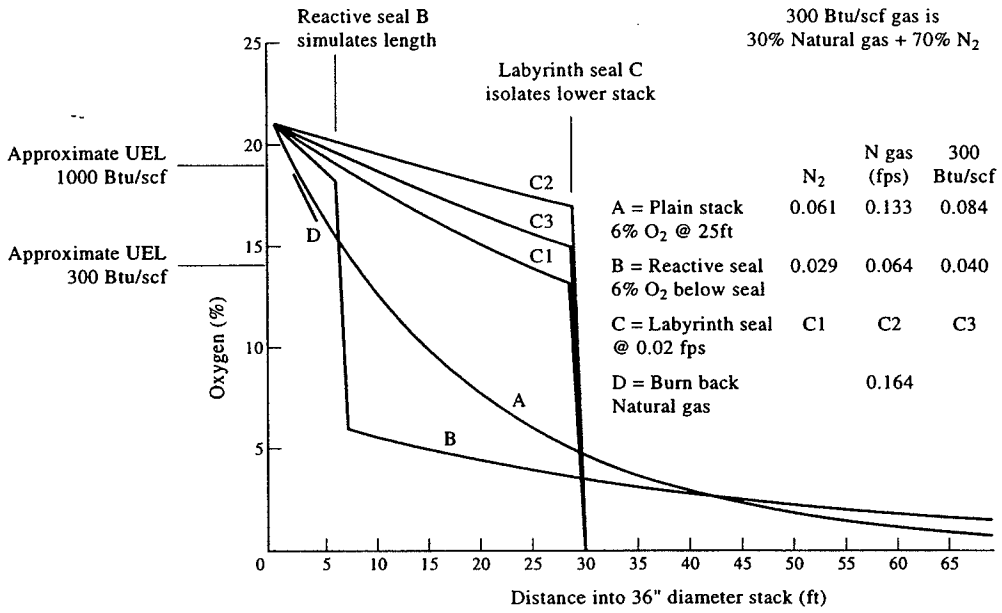

Figure 13 Comparative effects of purge reduction 'seals'

oxygen entry into the flare under conditions of internal suction (negative pressure) caused by thermal contractions of the process gases. Such matters must be considered separately.

As 'sealing' devices add pressure drop to the overall system, the sizing and selection of the equipment becomes an integral part of system sizing as well as a purge consideration.

As previously, the condition being addressed is the prevention of flame flash-back from the flare tip and a subsequent explosion or detonation because of the pressure piling effect in the pipe. All seals may incur a significant flowing pressure loss when compared with the length of plain pipe they actually replace and consequently any flame passing backward through the seal can experience a dramatic change of pressure condition and turbulence. In many cases the total equivalent distance travelled by the flame passing through the seal will approach or exceed the run-up distance limit to an explosive condition. Consequently seals should be sized, selected and located such that the oxygen concentration on the input side is definitely less than the UEL and will not support further passage of a flame.

Labyrinth-type seals cause a path reversal for a length of, usually, 8–10 ft, removing the ability for buoyant movement of air into the stack. In normal operation the only theoretical forward flow required by such a seal is that required to overcome diffusion at the air/gas interface. Although a flow rate as low as 0.01 fps will overcome diffusion alone, in the available space, for common gases, using this rate alone will only maintain a stable interface condition. The turbulent effect of wind and the possible normal variations in atmoshperic pressure and temperature will cause the position of the interface to change such that it may be driven back into the inner sealing leg of the seal. Thus, to ensure a safe condition for the flare, any oxygen interface in the inner leg of the seal must be driven toward the exit. It is, therefore, necessary to exceed the diffusion-based purge rate in this inner sealing leg in order to maintain the interface at the commencement of the final upward leg and, thus, prevent wind and atmospheric effects from pushing the interface progressively backward and overcoming the forward flow rate. The excess purge velocity in the seal effectively becomes an inverse measure of the time taken to restore the position of the interface to the bottom of the upward leg following a displacement due to changing ambient conditions. It should also be noted that the oxygen concentrations in the final outgoing leg may be outside 'safe' concentrations whilst the presence of the inversion leg acts as a barrier, permitting zero oxygen in the incoming leg of the seal. This is also shown in *Figure 13.*

This type of flare seal has a slight additional safety in that loss of the sealing purge gas flow is not an immediate hazard and the stack may remain 'safe' for a short period of time in 'no wind' conditions and for a stable system temperature.

The labyrinth seal's overall usefulness is most apparent in the larger range of tip sizes (greater than 24″) where reductions in long term operating costs override the capital investment in a complicated fabrication. For general safety concerns, any piping which can effectively 'short circuit' the seal, such as an external drain pipe, must be designed to resist both outflow of internal positive pressure and possible inflow of atmospheric air.

Reactive, orifice or baffle-type integral seals: a simplified gas 'seal' may be provided in the form of a reduced diameter or a series of conical baffles in the upper part of a flare gas riser or lower part of the tip. The action of such a seal is two-fold. It presents a smaller cross section area to the upward moving gases thereby reducing the volume of gas needed in order to maintain a fixed purge velocity or momentum. It also acts to reduce the amount of purge because it simulates a length of stack somewhat greater than its true length by presenting an impedance to air flows down into the stack. Typically, a seal of this type may simulate 2–20 stack diameters, depending on its design configuration and minimum diameter. The design is also intended to

allow flows in the correct direction to suffer lesser losses than incoming air flows. It must be remembered that orifice or baffle seals have no factor of safety for cases of loss of purge and that the correct rate of purge must be maintained at all times. On cessation of purge flow, light gases in the flare will immediately commence to decant.

Changing ambient conditions and system contractions

All minimum purge rates are calculated on the assumption that ambient conditions remain fairly stable or, at least, change very gradually. This is true for ambient pressure for which overall rates of change are much less than local wind pressure changes. However, changes introduced by changing ambient temperature, extent of solar radiation, rainfall or wind speed are much more abrupt and less predictable.

Consider the condition of minimum purge flow of 0.10 fps in a 24-inch flare system at a stable daytime temperature of 80°F when a sudden change in the weather drops the ambient temperature by 10°F/h accompanied by heavy rain and strong wind. If the total system volume is roughly 20,000 cu.ft the corresponding reduction in volumetric flow rate will be 0.103 cu.ft/sec or the equivalent of 0.033 fps in the 24-inch line, cutting down the effective purge rate at the tip.

Other, more severe temperature induced system contractions can occur at the result of high temperature reliefs into the flare header. These concentrations may be relatively small, resulting from the simple cooling of the relief header itself as suggested above, or may be as dramatic as the sudden condensation of a single component, such as methanol, over the entire flare header as it reaches a dew point of 148°F.

Different solutions may be used to overcome problems such as those described above. The two most common approaches, used individually or in combination, are

- the use of a water (or other liquid) seal, and
- the use of an automatic temperature/pressure monitoring system.

Water seals

The general characteristics and design requirements of a water seal are too varied to include in detail here; however, the basic functions required of the water seal to fulfill a part in the safety considerations of the flare system are that it should

- hold a positive upstream pressure for all flowing conditions; and
- support an upstream negative without opening the system to the stack.

The positive upstream pressure is usually assured by causing the gas to bubble through the liquid during the low flow conditions.

The upstream negative is usually assured by permitting liquid to be drawn out of the seal as a vertical leg equal to the negative pressure without completely emptying the seal of liquid or uncovering the sealed port.

The magnitude of negative pressure to be so supported should be greater than the maximum negative which could occur naturally due to changing ambient conditions. For the previous example, a total change in ambient temperature, perhaps overnight, of 50°F could potentially generate a negative pressure of roughly −1.36 psi (−38 ins wg). A negative greater than −4.33 psi (120 ins wg) is unlikely to be required in any circumstance.

Additional considerations for the liquid seal which address removal of hydrocarbon from the vessel are discussed in an earlier section of this paper. All overflows, drains and other communication with the outside of the vessel should be designed to hold an internal pressure greater than the maximum positive pressure in the vessel at the maximum design flow and also be reviewed to ensure that negative pressure in the flare system does not adversely affect the integrity of the effective seal. RP-521 suggests a 75% over-design factor for these areas.

Automated 'purge monitoring' controls

The automation of the purge controls to keep a minimum forward flow at all times is a viable option. By monitoring the temperature and pressure conditions in the flare header it is possible to allow supplementary purge gas to flow into the header to overcome the calculated critical cases. Three basic purge conditions must be covered.

- The primary rate is that continuous base rate for the system, as discussed previously, or the specified in-plant purge requirements.
- A low rate supplementary purge may be required to compensate for hot relief conditions during which the piping and containment vessels within the system all become warm. Once heated, the thermal mass of the piping will control the rate of cooling for the gas within the header.
- A high rate purge may be required to compensate for the worst hot relief condition which
- is of sufficiently short duration that heat transfer from the gas to the flare header will control the rate of contraction, or
- contains a sufficient quantity of a single condensible component that a sudden contraction could occur at dew point.

This rate should totally displace the hot gas from the flare header before the major contraction occurs.

The type of monitoring employed in a flare header depends on the basic equipment included in the system. If a liquid seal is furnished, the upstream pressure should always be greater than the minimum break pressure of the water seal. If no liquid seal is furnished the problem becomes a little more complex because any purge gas with a molecular weight less than that of air will record a static head in the flare stack which is less than the static head from an equal height of air. In consequence, the control pressure must be referenced to an equivalent column of purge gas.

Ideally, with or without a water seal, low and high rate purges should be introduced at a location in the flare system as far as possible from the flare stack. In this way the greatest advantage accrues from the displacement purges.

Other dangerous conditions

Process oxygen in the flare line

The most serious and dramatic problems involving flare explosions usually result from the inclusion of air or oxygen in the incoming relief gas stream. This oxygen might be deliberately or inadvertently introduced as part of normal processes of the plant. If so, it is necessary to recognize this possibility during the design stages and plan a strategy for the eventuality that a dangerous (explosive) mixture might occur.

Various actions could be taken, individually or in concert, to accommodate this condition as indicated below

- swamp the system with sufficient flammable gas to bring any possible mixture to a condition richer than the UEL;
- swamp the system with sufficient non-flammable gas to bring any possible mixture to a condition below the flammable limits;
- extinguish the flare flame and pilots;
- use sensitive flame and/or pressure detectors near the flare tip to indicate the onset of a flash-back condition and use the signals generated to trigger a high plug-flow rate of non-flammable material or flame retardant into the relief header;
- include flame arrestors and/or detonation arrestors in the relief line close to the ignition sources.

Any of the above features might be assisted by permanent oxygen monitoring of the relief header at a point as far upstream as possible but downstream of the point at which the oxygen might be introduced. NFPA-86 and Coast Guard regulations 33 CFR 154 prescribe specific actions for purge strategy on equipment covered by these codes.

Maintenance errors

Oxygen may also be inadvertently allowed into the relief header by operator error during maintenance operations. This is probably the largest cause of flare system explosions and is usually due to the header being opened to the atmosphere for valve change-out, whilst subjected to a negative pressure because the gas in the flare stack is lighter than air. Air is sucked into the header and mixes thoroughly with the flammable gas on its way to the flare tip where the flash-back actually occurs. Explosive pressures develop throughout the entire relief system within seconds of the commencement of the flash-back and usually cause significant damage to the first momentum-absorbing weak point in the flare or piping system.

There are a number of positive steps which may be taken in order to minimize the risks during on-line maintenance

(1) If possible, shut down or isolate the section of flare header being serviced.
(2) Keep the plant on the lowest practical and stable throughput to maintain balanced conditions so as not to create any emergency or controlled relief.
(3) If more than one flare is in service on the flare header, select which flare is to be used during the maintenance procedures and raise the water seals on all other units, effectively closing them against flow. Drop out the water seal on the selected flare. This will minimize the system pressure during the procedures.
(4) Add inert gas to the flare header. Use any inert gas lighter than air such as nitrogen, helium or steam in order to reduce the flammability of the hydrocarbon gases and inhibit flash-back.
(5) Maintain a total velocity through the flare tip which exceeds the potential flame speed of the flare. This will prevent the commencement of the flash-back even if the mixture with air falls in the flammable range.
(6) Provided that the velocity constraints [see (5)] are observed, add flammable gas to the flare header using only gases which are lighter than air (e.g. natural gas). If also using inert gas [see (4)] maintain a gas-rich concentration in the header by carefully monitoring the addition of the ballast gases.

Operations without purge

In certain cases where reliefs to a flare are uncommon and infrequent, it may be desired to operate the flare with no continuous purge whatsoever. For this condition the operator must be certain of the possible relief cases and carefully assess the probability of each relief. The stack should definitely be fitted with a water seal or other positive sealing device.

The commencement of each new relief case represents a new start up condition and, in each case, the flow must be guaranteed to sweep all air from the stack ahead of the flammable gas. In practice, this means that the flow velocity must exceed the possible flame speed at all points in the flare system. Start-up may, alternatively, be preceded by a designated inert, pre-operational purge guaranteed to remove the air from the stack.

When the relief flow ceases, the stack is left with a static column of flammable material which quickly develops a burn-back condition and produces sporadic explosions as the gas is replaced by air due to burning and natural decanting. The shut down condition should, therefore, be followed immediately by a designated purge of non-flammable material guaranteed to remove all the flammable gas from the stack. The period of this postoperational purge will depend on the rate of purge selected. At the shortest, 2–3 replacement volumes at a velocity of 5 fps is suggested. The longest possible post-purge would be infinite at the rate prescribed by the Husa formula.

Unstable gases

Some gases demand special consideration because they do not exhibit the same standard characteristics expected of most common hydrocarbons. When flared normally, these gases will combust and react with air just like common hydrocarbons but they are relatively unstable and are also able to decompose, exothermically, to other more stable forms without the need to oxidize in a conventional combustion process. In consequence, they may decompose, sometimes explosively, if exposed to an initiating energy source which is just sufficient to start the decomposition process. This produces a 'cool' flame which may occur at a self-sustaining temperature below

that of a conventional oxidation reaction. Any steady high temperature, pressure or local energy input such as a spark or sudden adiabatic compression can act as an initiator and will start the decomposition process. As with all flames running in pipes, this causes pressure piling and can lead to a subsequent detonation. Lower order olefines, di-olefines and aromatics all have the potential to decompose in this way but the gases most commonly addressed in this regard are ethylene oxide and low order acetylenes.

The normally accepted method of suppressing gaseous decomposition for most unstable gases is by dilution with some other gas which is stable and will not combust at the 'cool' flame temperature. This second gas may, itself, be either non-flammable or flammable.

The minimum quantity of diluent needed to suppress the decomposition depends largely on the specific heat capacity of that diluent, which must be great enough to absorb any exothermic reaction energy and still maintain the overall temperature below the 'cool flame', decomposition minimum. Dilution also reduces the partial pressure of the unstable gas, reducing its own internal energy.

Ethylene oxide (EO) is usually stabilized by maintaining it in a liquid state[30]. This implies handling under pressure, according to the approximate vapor pressure relationship

$$\log_{10} Pv = 5.81 - [2367/Tr]$$

where Pv = vapor pressure (psia)

Tr = temperature (deg R).

For dilution and blanketing, a regression analysis of published data[30] yields the following relationship from which an estimate of diluent requirements may be obtained

Volume Ratio EO/diluent = $[cp/3]^{0.662}$
where cp = diluent specific heat at 1250°F (Btu/lb mol.deg R).

For blanketed liquid storage of EO, however, the blanketing gas mixture is still subject to pressure considerations and, for complete stability, the partial pressure of the EO in the mixture should, ideally, not be less than the equivalent boiling vapor pressure as calculated from the previous formula. The normal relieving condition for EO vapour, however, usually corresponds approximately to the boiling condition at the relieving pressure. At these conditions, dilution or blanketing of EO with sufficient other gas is not always a practical consideration and there may be no guaranteed means of preventing decomposition when exposed to an initiating agent such as a flame or spark. The flame at the flare tip is one such possible initiator.

When flaring EO, the following basic rules should be observed

(1) the velocity of EO in the flare line should be greater than 1 fps; this may be assured by use of a constant line purge, flammable or non-flammable, at a flow rate of 1 fps or greater;
(2) during EO release, tip exit velocity should be at least 10 fps (up to 30 fps is common); this may be assured by adding a base load of gas to the stack which may be flammable only or a mixture of flammable and non-flammable components with a total combined CV not less than 200 Btu/scf;
(3) any continuously flowing gases should be reviewed to ensure that they will be relatively pure, clean, dry and free of sulphur or other contaminants which may cause deposits to form in the flare line as such deposits might, inadvertently, be reactive or catalytic in the EO decomposition;
(4) the diluent gas and all other gases which can enter the flare header should be reviewed for reactivity with EO;
(5) air, acetylene, ammonia, carbon dioxide, and hydrogen sulphide must all be excluded from the mixture;
(6) the flare should be furnished with a dip-leg type liquid seal in the base to assist in sealing the flare line against possible air ingress during a 'dormant' state and to assist in mitigation of any decomposition wave generated at the flare tip. Because of the tendency of EO to hydrolyse if the water pH is not neutral, the addition of ethylene glycol to the water should be considered both as a winterization agent and to suppress the EO water reactions. This will also raise the need for a small water/glycol recirculation system (pump and external tank) to facilitate proper mixing and treatment of the liquid;
(7) raw materials which readily form acetylides, including copper, magnesium and silver, and carbonaceous materials are known to be potential ignition sources, should be avoided in construction;
(8) the internal design of the flare line must be carefully reviewed to ensure that no initiating compressions may be generated.

Acetylene may also decompose spontaneously due to an energy input. An amount of research is available concerning the handling of acetylene which need not be revisited here. It is appropriate to note, however, that pressure energy alone may de-stabilize the gas leading to a deflagration in the line. For gas in steel pipe, heat transfer to the pipe wall will retard the decomposition reaction. Stable pressure thus becomes a function of line size according to the approximate formulae[32].

Decomposition pressure (psia) = $[486/D]^{0.577}$

This means that a flare tip, where the pressure is atmospheric (14.696 psia), the maximum tolerable diameter to inhibit decomposition of 100% acetylene stream is 4 inches. The data[32,33] suggest that diluents and other gases improve the situation by their various abilities to absorb heat energy, as described previously. No specific data are available relating diameter to dilution nor does any clear and simple relationship between specific heat and stable pressure emerge from the available data but it may be noted that, for stability at 100 psig, dilution with nitrogen at a ratio of roughly 1.25 v/v N2/acetylene, or natural gas in a ratio of 0.65 v/v NG/acetylene, is required. With sufficient dilution, the ignition and explosion characteristics of a mixture of 20% acetylene in 80% methane become very similar to those of propane. All of these mixtures would be suitably flammable at a flare tip. For more details on dilution, a literature review is suggested.

Because the heat of formation of acetylene is strongly positive, it needs very little input energy to cause the decomposition which could be started by a loose nut inside a pipeline falling or striking a corner. Also, certain soft metallic compounds, rust and other similar components of the piping can predispose a deflagration of this nature. It is particularly important to totally avoid any compound containing copper, mercury, silver, gold, zinc or brass. This includes any lubricants, coatings, residues and other process fluids.

Precautions with potentially unstable flows should be similar to those previously described for EO, however, because the maximum flame speed of an acetylene/air flame at ambient conditions is 5.25 fps, a baseline purge with fuel gas or an inert medium at a rate of 10 fps is suggested.

At the flare tip exit there is nothing that can be done to prevent the commencement of decomposition because the local energy input is too great and any decomposition of gas as it appraoches the tip exit will also lead to formation of carbon atoms in the gas stream which can eventually create smoking problems. At tip velocities in excess of 6 fps, any particles smaller than 250 microns should continue to be carried into the flame and require smokeless treatment.

There are many other aspects of flare design which are not covered here. However, the author has attempted to touch upon the major areas of concern and hopes that this will stimulate additional thought and understanding amongst flare users and designers.

Although much of this presentation has been tabulated or graphed, it must be remembered that these issues, when applied to flares, represent as much an art as a science. The operational variables in all areas are so diverse that they tend to defy accurate and precise scientific modelling. At best one is only able to produce estimates which enable workable and safe engineering solutions to the various issues.

In conclusion, the author wishes to thank colleagues and associates in the Flare and Hazop field who, by their support and input over the years, have been the effective contributors to this paper, and the management of Flaregas Corporation for their assistance with this presentation.

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