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Reliance Industries Limited Patalganga

Training Module

Flare Systems

Module No. TES - TS - P - 014

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1.0 INTRODUCTION

1.1 What is flaring ?

Many industries generate significant amounts of waste streams, such as hydrocarbon vapors, which must be disposed of, on a continuous or intermittent basis. Some of the examples can be like off-spec product or the bypass streams generated during startup operations. Direct discharge of waste gas streams and vapors into the atmosphere is unacceptable due to safety and environmental control considerations.

Gas flaring is a standard operation aimed at converting flammable, toxic and corrosive vapors into environmentally acceptable discharges. Gas flaring converts flammable, toxic or corrosive vapor to less objectionable compounds by means of combustion. Flaring is a critical operation in many plants where design must be based on strict safety principles.

1.2 Why is flaring required ?

In general, proper planning and layout of process plants require that special consideration be given to the design of various safety facilities to prevent catastrophic equipment failure. These facilities are designed to prevent overpressure and to provide for safe disposal of discharged vapors and liquids. Portions of these facilities are also used as an operational tool for safe disposal of hydrocarbons - particularly during start-up and shutdown phases.

Standard pressure relieving devices most often used are safety and relief valves, rupture disks, pressure control valves and equipment blowdown valves. Direct discharge of waste or excess vapors to atmosphere is unacceptable either -

- 1 Because of restrictions imposed by local ordinances or plant practices.
- 2 Concentrations of the contaminants at ground or adjacent platform levels may exceed permissible explosion or toxicological threshold limits.
- 3 Meteorological considerations such as severe temperature inversions of long duration may occur, creating hazardous conditions.

Non hazardous vapors such as low pressure steam are usually discharged directly to the atmosphere. In contrast, hydrocarbon vapors that are discharged on a continuous or intermittent basis can not be directly discharged to the atmosphere and should be disposed of through a closed system, and burnt in a flare.

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1.3 Types of flare

There are basically two types of flare system namely, **Elevated Flares & Ground Flares.**

In an elevated flare system, combustion reactions are carried out at the top of a pipe or stack where the burner and igniter are located. Relieving gases are sent through an elevated stack from a closed collection system and burned off at the top. The flame generated is open in this case. E.g. the flares of PX and LAB plants at RIL - PG.

A ground flare is also similarly equipped except that the combustion takes place at or near ground level. The flare flame is contained in a flare chamber.

Three types of ground flares are in general use -

- 1 The type that uses a water spray to disperse the combustion gases.
- 2 The venturi type that depends on the kinetic energy available in the waste gases to inspire and mix the proper amount of air with the gases.
- 3 Multi Jet ground flares where the flow of the waste gas is distributed through many small burners.

The principle advantages of a Ground Flare system are -

- 1 No structural support is required
- 2 Erection is relatively straight forward and requires light parts
- 3 Maintenance is easy
- 4 Operating costs are negligible
- 5 The flame of the flare is not visible since it is hidden in a box. It requires less steam to produce a smokeless flame since it produces relatively non-luminous flame because of more controlled combustion at the multiple burners.
- 6 Finally, with the exception of the venturi type, it is a fairly quiet system

However, a disadvantage of the ground flares is that they must be well isolated from the remainder of the plant and process lines, thus requiring considerable space and long interconnecting piping. Concentrations of toxic gases are relatively high because of combustion taking place at ground level. A water spray can be a possible solution, but it is often avoided because of

1. high water consumption
2. the possibility of extinguishing the pilot burners

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3. potential water damage to instrumentation.

The venturi type ground flare is almost obsolete because of objectionable high noise levels.

The multi jet type normally used has high initial costs and capacity limited.

In contrast, an Elevated flare requires less ground area. Because of its high elevation, it can be located within a process area or on the periphery of the plant site, since radiation effects and ground level concentrations of pollutants can be maintained within allowable limits. Piping costs tend to be lower due to smaller and shorter pipe runs. Also the distance between the point of discharge from safety valves and the flare stack is less than that in the case of ground flares.

A problem with elevated flares is that initial and operating costs are high. Maintenance is also difficult and tedious. The visibility of the flame is the most serious disadvantage and sometimes causes objections from local community. These systems also require more steam to produce a smokeless flare. A final disadvantage is that noise levels are relatively high.

The selection of the type of flare will be influenced by availability of space, characteristics of the flare gas (i.e. composition, quantity and pressure level), economics including both initial investment and operating cost and concern over public relations with the surrounding community.

In general, elevated flares are most often recommended. In spite of the numerous advances of ground flares, the requirement of the large land area and the associated high initial cost makes it less attractive than elevated systems. However, in some cases, visibility of the flame, depending upon local regulations, could be the determining factor.

There are situations when a ground flare is used in conjunction with a second conventional flare, which may be an elevated system. The ground flare is designed to handle the normal flaring requirement. In the event of major failure, excess flow is automatically diverted by a seal to a second flare. Since, the possibility of a major failure is rather remote, it may not conflict with pollution or local site regulations.

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2.0 COMPONENTS OF THE FLARE SYSTEM

As we know by now, that in a flare system, relieving gases are sent through an elevated stack from a closed collection system and burned off at the top.

Thus, a typical flare system is comprised of the following components :

- 1 Relief, safety and depressurising valves (which relieve the fluid to be flared)
- 2 Pressure - relieving headers that convey discharges from safety valves and pressure control valves in the process unit to the flare.
- 3 Knock out (KO) drum located before the flare stack in order to separate any condensate or liquid from the relieving vapors (it is hazardous to burn liquid droplets).
- 4 Flare stack consisting of riser structure, Molecular seal and burner tip.

The relieving gases from safety relief valves and pressure control valves are collected in a horizontal or vertical knock-out drum through a flare main header. Any condensate carried out alongwith the gases is knocked down here. A constant liquid level is maintained in the boot/drum. The liquid is pumped to a slop tank or is reused in oil recovery facilities. If required, steam is used for winterizing to prevent freezing. The gas from the KO drum is then sent to an elevated flare stack. At the bottom of the stack, normally a liquid seal is maintained. Alternately another seal may be located between the KO drum and the flare stack. A positive water seal is maintained by controlling the level. In cold countries, the water seal is also provided with steam for winterizing.

The stack is comprised of a riser section, molecular seal and burner tip.

1. *Riser structure*

This normally consists of two or more sections. The flare header enters at the bottom section, which can also serve as a flare stack knock cut drum where any condensate carried over from the main knock out drum is collected.

2. *Molecular Seal*

This is welded to the riser section. It provides a seal against entrance of air into the flare stack and minimizes the possibility of a explosive mixture forming in the

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flare system. More information on a molecular seal is given in one of the coming chapters. Briefly, it resembles a bubble cap and creates a seal by using the buoyancy of the purge gas to create a zone where the pressure is greater than atmospheric pressure.

3. *Flare Burner Tip*

The burner tip is sealed to the molecular seal outlet. Accessories on the burner tip include about three or four gas pilots, a similar number of pilot gas/air mixture assemblies, and steam supply nozzles for steam injection.

At the top of the burner tip, pilot burners, which are automatically lighted from a remote place through the igniter line, are positioned. The steam connection is also provided for smokeless flares and a purge gas connection is provided for maintaining an air free system and to prevent flash back by maintaining pressure at the molecular seal higher than the atmospheric pressure. This arrangement prevents air from re-entering the stack from ambient surroundings.

Figure-1 shows a schematic diagram of the entire Flare System.

In the next few chapters, we shall go through the flare system design guidelines, componentwise.

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3.2 Estimating relief rates

Each pressure relief valve should be individually analyzed for any probable causes of over pressure due to operational failures and plant fire.

The valve should be sized for the case that will require the maximum relieving rate. If a fire condition is controlling, two separate safety valves, one for fire condition and the other for operational failure, may be provided since the fire situation is less likely to occur.

Guidelines for determining individual relieving rates are illustrated with an example of a column -

Consider a fractionating column where different causes of overpressure may be analyzed as follows :

1 blocked outlet condition of the overhead vapor line by inadvertent closure :

In this case, it may be assumed that heat input to the reboiler is normal, and the reflux will still be maintained since the overhead receiver has the holding capacity for about 10 minutes. Hence, the relieving capacity of the pressure relief valve may be assumed as the normal vapor load to the overhead condenser. The relieving pressure will be the set pressure of the PRV and the temperature will be the boiling point corresponding to that pressure. Vaporization rate may have to be corrected as the latent heat changes with change in boiling temperature which in turn changes because of change in column pressure. Also the reboiler duty may get affected due to process side changes in pressure and temperature.

2 cooling water failure

The cooling water typically, used as the cold utility in the overhead condenser may stop because of power failure or some other operational problem. Under this situation, overhead vapor will not condense in the condenser and because of the vapor accumulation, the pressure will rise. The reflux can still be maintained for about 10 minutes because of the holding capacity of the accumulator. The relieving capacity of the pressure relief valve will also be the normal vapor rate to the condenser. Vaporization rates may need correction here also.

3 reflux failure

This may be associated with the malfunction of reflux control valve, pump failure, or any other operational problem. In this case, the overhead condenser becomes flooded with condensate. As a result of this, overhead vapor can not condense and pressure starts building up. Once the pressure reaches to the set pressure of PRV,

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the relief occurs. The vaporization rate, here as well, can get affected by rise in pressure.

4. *abnormal heat input by reboilers*

If the reboiler controller malfunctions for any reason, the rate of vaporization may increase. If the vaporization rate exceeds the rate of condensation, the pressure will build up. In this case, the relieving rate should be the difference between the maximum rate of overhead vapor and the maximum rate of condensation of the condenser. In the absence of data, the relieving rate may be assumed to be the normal vapor load to the condenser.

The column can also get subjected to high pressure, if the reboiler is an exchanger, carrying the hot utility (like steam) at higher pressure than the column bottoms pressure and the exchanger tube leaks.

For relief loads due to fire

The surface area of a vessel exposed to fire, and which is effective in generating vapor, is that area wetted by its internal liquid level up to a maximum height limitation of 25 ft. above grade, which is the normal practice based upon the flame length. "GRADE" is defined as any horizontal solid surface on which liquid could accumulate i.e. roofs, solid platform etc. The contents under variable level conditions would ordinarily be taken at the average inventory. Liquid full vessels, horizontal or vertical (such as clay treaters), operate with no vapor space, and the wetted surface in such cases would be the total vessel area within a height of 25 feet above grade. It should be noted that, in such a vessel, at the start of a fire the opening of the pressure relief may be due to thermal expansion of the liquid. However, the PRV should be sized based upon the vapor generated at the relief pressure and the boiling point corresponding to that pressure.

The surface area of typical vessels used in process operations are -

1 *surge and reflux drums*

The wetted surface should be calculated using the high liquid level or 50% of the total vessel surface, whichever greater, since 50% is the normal liquid level in these vessels.

2 *KO drums*

KO Drums usually operate with only a small amount of liquid at the bottom of the drum. If the normal liquid level is not known, the level at the high level alarm should be used to estimate the wetted surface.

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3 *fractionating columns*

Usually fractionation columns operate with a normal liquid level in the bottom of the column plus level on each tray. However, the entire wall of a fractionating column within a fine height limitation of 25 ft. should be considered as wetted.

4 *working storage tanks*

Here the liquid level is independent of operation, and therefore the maximum liquid level should be used for determining the wetted surface. The wetted surfaces of spheres and spheroids are calculated as the area of the bottom half of the vessel or up to a height of 25 ft. which ever gives the greater surface area.

Heat absorbed by vessels

Where suitable drainage is provided to preclude an accumulation of flammable liquids directly under vessel, the total heat input rate to the vessel may be computed as follows :

$$Q = 21,000 F A^{0.82}$$

Where,

Q = Total heat absorbed in BTU/hr

A = Wetted surface in sq.ft.

F = Environment factor

This equation is recommended by the API, RP-520

Using the appropriate value of the wetted surface and the value of factor F tabulated for different thickness of insulation, the heat input may be calculated :

F = 1.0 for bare surface

F = 0.3 for 1" thickness of insulation

F = 0.15 for 2" thickness of insulation

F = 0.075 for 4" thickness of insulation

If insulation exists but the thickness is not known, an F- value of 0.3 is recommended. If drainage is not provided for the area under the vessel (i.e. diked or curbed area around a tank), then vapor relief for fire exposure should be computed using the following heat input criteria.

20,000 BTU/hr/ft² for an uninsulated vessel

10,000 BTU/hr/ft² for 1" insulation

6,000 BTU/hr/ft² for 2" insulation

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3,000 BTU/hr/ft² for 4" insulation

These values are based on the wetted surface upto the normal liquid level, provided the insulation is fire proofed. If insulation is not fire proofed, the vessel should be assumed as bare.

Vapor generated for a fluid below critical point (i.e. at relieving temperature and pressure) the rate of vapor released is -

$$W = Q / \lambda$$

where,

W = Vapor release rate in lbs/Hr

Q = Total heat input BTU/hr

λ = Latent heat of fluid in vessel evaluated at the relief valve inlet pressure, BTU/lb.

No credit is normally taken for the sensible heat capacity of the fluid in the tank

For a fluid above the critical point, i.e. when pressure relief conditions are near or above the critical point, the rate of vapor discharge depends upon the rate at which the fluid will expand as a result of the heat input. The latent heat & vaporization at or near the critical point is almost zero in this case.

More information on the relief rate calculation is available in API 520 and in the training module on the relief valves.

3.3 Maximum vapor load to be flared

After relieving loads of individual PRVs have been calculated, a detailed study is required to determine how these relieving situations are related to each other. The simultaneous occurrence of two or more contingencies (known as double jeopardy) is so unlikely that this situation is not usually considered as a basis for determining the maximum system loads. In determining the maximum load from a single contingency, all directly related contingencies that influence the load must be considered. For example, in a plant where a single boiler or source of steam is used for both, process drives and electric power generation, a failure of steam source (a single contingency) can cause simultaneous loss of power (directly

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related contingency). If the electrical system had an alternate source of supply then only the loss of steam would be considered, provided the elapsed time for power supply source switching was not too long to be ineffective. In this situation, power failure would not be a contingency directly related to the loss of steam.

Since, double jeopardy is not usually considered, the maximum load can be based up on any one of the following contingencies.

- Electrical Power Failure
- Cooling Water failure
- Steam failure
- Instrument Air failure

For the fire case, a cause of fire is normally localized. The whole plant is divided into different fire zones. The flare load is generally calculated based up on one or two related zones. However, it is not unusual to consider the total load.

Another consideration is that the time delay relative to the discharge of individual valves caused by the same and related contingencies should be properly studied while determining the maximum load. A similar line of reasoning will in some cases apply to a fire affecting several vessels where product composition and pressure vary widely.

The method of calculating the time element related to each pressure relief valve is referred to as 'TRANSIENT LOAD ANALYSIS'. This is based upon the non steady state condition in the flare system of a plant during emergency situations. This calculation is tedious but with simplified assumptions, it provides an estimate of the relative time delays of the individual valves.

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4.0 DESIGN OF COLLECTION SYSTEMS

The relieving vapors from different PRVs and depressurising valves must first be collected in individual flare subheaders located near each process area. Sub headers must be interconnected to a main flare header which leads to a knock out drum. Condensates carried over by vapors are separated in this vessel. Vapors leaving the KO drum from top move up the flare stack where they are subsequently burned at the tip.

The no. of main flare headers and the individual sub headers connected to them depends up on the type of vapors handled, temperature and the back pressure limitation of PRVs.

The pressure level of the flare header depends on the type of pressure relief valves used to protect the equipment and the pressure levels of the equipment connected to the flare system. In the conventional type of PRV, the performance depends on the back pressure. A maximum back pressure of 10% of the maximum allowable working pressure is a limit for the conventional type of PRV. For the non-conventional valves like balanced bellows type, piston type or pilot operated type, the maximum allowable back pressure may be taken as high as 40-50% of the valve set pressure.

4.1 Determining the no. of flare headers

The no. of flare headers required depends up on an economic evaluation of system combination & that will result in the minimum piping cost. The following steps outline the procedure for comparative estimations -

- 1 Plot plan layout study - From the plot plan layout, the no. of safety valves in different process areas, the set pressures of safety valves, individual relieving loads of safety valves, relieving temperature of vapors, the nature of vapors (i.e. whether corrosive, condensable or dry etc.) are recorded.
- 2 A single subheader in each process area is drawn up, connecting area PRVs or depressurising valves.
- 3 The sub headers are then connected to give a single main flare header based upon shortest routing.
- 4 The equivalent length of the main flare header is then calculated from the flare stack to the last safety valve, taking in to consideration the straight length of the pipe and approximate equivalent lengths for bends, etc. If the actual location of

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the flare stack is not known by that time, it may be assumed to be 500 ft. from the last piece of equipment.

- 5 A trial estimate is made for determining the diameter of the flare header based up on the max. relieving flare load and considering the back pressure limitation of 10% for conventional valves and 40% for balanced type valves. Note, however, a single main header in many cases, may be too large to be economically feasible.
- 6 The second trial is required for two main flare headers, one collecting the Low Pressure (LP) flares (usually 5 to 10 psig) and the other collecting relatively High Pressure (HP) flares (usually 15 to 20 Psig). The two headers are connected to their individual KO drums. The vapor lines from the KO drums are combined into single header connected to the flare stack.
Maximum simultaneous load in each header must be calculated separately and the pressure drop must also be computed for the entire length of the pipe including combined length from the KO drum to the stack.
The load in a subheader used for the line sizing, need not be same as the load which is utilized for designing the main header or the flare stack.
- 7 The next consideration is the cost of construction materials. This determines the final no. of flare headers. Vapors that normally require expensive materials may be listed as -
 - a Corrosive vapors e.g. H₂S, SO₂
 - b Very high temperature vapors e.g. high temp. gases used for regeneration of catalyst in reactors.
 - c Very low temperature vapors e.g. the relief load from cryogenic system.

Of the three, corrosive vapors are usually piped up in a separate header quite up to the flare stack since such lines are very small and if combined with other streams may run the risk of corroding the much larger and more expensive pipelines.

For a high temperature system, separate sub header may be run up to the point where the temperature drops down to the allowable limit of a less expensive material. It may then be connected to the main flare header. A heat loss calculation is needed in order to properly evaluate this. As a rule of thumb, a heat loss of 10 BTU/hr/ft² may be assumed for a quick estimate for bare pipe. Consideration should also be given to the need for expansion joints. Main flare headers may be as large as 36 to 42" in diameter for a large capacity plant. Expansion joints of such magnitudes may be very expensive, so as to call for a separate small header for the hot flare system.

A flare sub header carrying very low temperature vapors (temperature ranging from 50 deg.F and below) may similarly be combined into a single low temperature flare header and pipe all the way up to the flare stack. Again, since the atmosphere is warmer than pipes, a heat gain calculation may indicate that the cold sub header

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after running a certain distance by themselves may be safely combined either with the low pressure main flare header or the HP main flare header depending upon this operating pressure.

- 8 Wet flare and Dry flare : Some times, relatively hot vapors carrying condensates may be separated from the dry cold vapors. They do not run as separate headers but either LP or HP flare headers may be associated with any one of them. Thus a wet flare header may be in fact the LP header and the dry flare header may be the HP flare or vice versa.
- 9 After the total no. of flare headers has been established, it may be necessary to recheck the vapor load in individual headers since introduction of a separate header may allow subtraction of the flow quantity from earlier header to which it was added initially.

For Example :

A typical coal gasification plant usually has -

- HP wet flare header
- HP dry flare header
- An H₂S header containing vapor which has more than 5% H₂S

4.2 Line sizing for flare headers

Once the relief load is established and the maximum allowable back pressure has been defined, line sizing is reduced to standard flow calculations.

The flare lines carry the vapors which are compressible in nature. The flare lines are also normally long and not fully insulated. Hence, the flow can not be adiabatic flow. Hence, the flare headers are typically sized based upon isothermal compressible flow. This also gives more conservative design.

The criterion used for flare line sizing are -

1. The back pressure developed at the downstream of any PRV connected to the same header should not exceed the allowable limit for that type of PRV.
2. To avoid the sonic velocity and related noise problem, the velocity in the header is limited to 0.6 Mach.

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A quick method for sizing compressible isothermal flow is developed by Lapple. As per this,

For a pure gas -

$$G_{ci} = 12.6 P_o \left[\frac{M^{0.5}}{(2Z-1) T_o} \right]$$

where,

G_{ci} = Max. mass flow or critical mass flow, lb /sec ft²

P_o = absolute upstream pressure, lb/in²

M = molecular weight

T_o = upstream temperature, Rankine

Z = Compressibility factor

The actual mass flow G (lb /sec ft²) is a function of critical mass flow G_{ci} , line resistance N , & ratio of downstream to upstream pressure. This is represented by figure 2. In the area below the line in the figure 2, the (G / G_{ci}) remains constant, which indicates that the sonic flow has been established. Thus, for sizing flare header, the plotted point must be above the line.

$$\text{Line resistance, } N = \frac{4 f L}{D} + \sum K_i$$

where,

L = equivalent length of line, ft.

D = line diameter, ft

f = fanning friction factor

N = line resistance factor, dimensionless

K_i = Resistance coefficients for pipe fittings (see table 1)

Lapple method is useful when upstream pressure of a header is known & downstream pressure is to be calculated. However, to develop pressure profile of the headers as a function of distance from the stack, it is convenient to calculate pressure drop backward, starting from the flare stack exit where pressure is atmospheric. Fig. 3 enables to calculate pressure drop when downstream pressure is known. The following steps summarize sizing flare headers -

1. Approximate pressure at base of flare stack (varies slightly with type of seal used) is taken as 2 psig. This is based on 0.5 psi pressure drop at tip, 0.5 psi pressure

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drop at molecular seal and 1 psi pressure drop due to flow through the stack height.

- 2 Compute pressure in KO drum (2 psig + Delta P in header from stack to KO drum and 0.5 psi Delta P as in KO drum)
- 3 As a first trial, inside pipe diameter is calculated based on 0.6 Mach (60% of the sonic velocity) corresponding to pressure & temperature at base of the stack, i.e. 2 psig and temp = To (as it is assumed to be isothermal flow)

$$\text{sonic velocity, } V_s = 223 * (KT/M)^{0.5}$$

where,

Vs = Sonic velocity, ft/sec

K = Cp/Cv of gas, normally between 1 to 1.8

T = temperature, Rankine

M = molecular weight

The vapor density, ρ (lb/ft³), at pressure P (corresponding flare base i.e. 2+14.7 = 16.7 psia) and temp T (Rankine) with a molecular weight of M, is given as

$$\rho = (M * P) / (R * T) \text{ where, } R = \text{gas constant} = 10.73$$

Now,

$$\frac{W}{\rho * \pi * d_i^2 / 4} = 0.6 * V_s$$

Knowing all other values, the pipe inside diameter (di) is calculated. Knowing di, the Reynolds no. and friction factor can be calculated. Assuming a straight length of pipe for L = 500, line resistance N is calculated. G is calculated based on the di. Gci is calculated based on downstream pressure & is called Gc2. G/Gc2 evaluated & P2/P1 determined from Fig.3 since P2 is known, P1 can be calculated. Pressure at inlet of KO drum is taken as P1+0.5 psi.

- 4 From the KO drum, indicated flare headers can be sized similarly. Based on a Mach no. of 0.6 & density corresponding to (P1 + 0.5) psia, trial diameter can be estimated. The pressure at every intersection between sub header & main header to be calculated with downstream pressure being (P1 + 0.5) psia. Knowing the pressure at the intersection of the sub header & main header, the pressure at the intersection of sub header & discharge pipe of the safety valve is computed. The process continues till discharge pipes and subheaders of all PRVs are sized.

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The sum of all pressure losses starting from flare stack up to the safety valve yields the total back pressure. This back pressure must be lower than the max. back pressure allowed in the system & corresponding to the lowest set pressure of the safety valve.

4.3 Example

The maximum flare load of a system is 1,000,000 lb/hr of vapor. The pressure at the base of the flare stack is 2 psig, the average MW of vapor is 50 and temp is 200 F. The distance from the drum to stack is 500 ft. The line has two 90 degree welding elbows and an orifice with Ki factor of 0.2. The total pressure drop at the knock out drum is 0.5 psi. Determine pressure at inlet of the knockout drum. Also, given are

$$K = C_p/C_v = 1.2$$

$$Z = 1$$

Solution:

$$\begin{aligned}\rho &= (M * P) / (R * T) \\ &= 50 * (2 + 14.7) / (10.73 * (200 + 460)) \\ &= 0.12 \text{ lb/ft}^3\end{aligned}$$

$$\begin{aligned}\frac{W}{\rho * \pi * d_i^2 / 4} &= 0.6 * V_s \\ &= 0.6 * 223 * (KT/M) ** 0.5\end{aligned}$$

$$\frac{1,000,000 * 4}{3600 * 0.12 * 3.14 d^2} = 0.6 * 223 * (1.2 * 660 / 50) ** 0.5$$

Hence, $d = 2.35 \text{ ft} = 28.2''$

This is approximated to 29'' corresponding to standard pipe of 30'', 20 schedule.

Now, we shall calculate pipe resistance factor, N

From table 1, Ki for 90 degree welding elbow is 0.32

$$\text{Thus, } \sum K_i = (2 * 0.32) + 0.2 = 0.84 \quad (\text{orifice } K_i \text{ is } 0.2)$$

A typical Fanning friction factor, $f = 0.004$ (It can be also estimated with help of Re)

$$\text{Line resistance, } N = \frac{4 f L}{D} + \sum K_i$$

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$$= \frac{4 * 0.004 * 500}{29/12} + 0.84$$

$$= 4.15$$

Now, $G = W / (\pi d^2 / 4)$

$$= \frac{1,000,000 * 4}{3600 * 3.14 * (29/12) * (29/12)}$$

$$= 60.6 \text{ lb/sec ft}^2$$

$$G_{c1} = 12.6 P_o \left[\frac{M^{0.5}}{(2Z-1) T_o} \right]$$

P_o will be replaced by downstream pressure, i.e. $2 + 14.7 = 16.7$ psia and figure 3 will be used.

$$G_{c1} = G_{c2} = 12.6 * 16.7 * (50 / (2-1) * 660)^{0.5}$$

$$= 57.9 \text{ lb/secft}^2$$

$$G/G_{c2} = 60.6/57.9 = 1.06$$

At this ratio, and $N = 4.15$, figure 3 gives $P_2/P_1 = 0.56$

$$\text{Hence, } P_1 = 16.7/0.56 = 29.8 \text{ psia}$$

$$\text{Pressure drop} = P_1 - P_2 = 29.8 - 16.7 = 13.1 \text{ psi}$$

This is a very high pressure drop. Typically, it should not exceed 3 psi. Hence, a larger pipe diameter is required.

The above procedure is repeated for higher diameter pipes. It can be seen that, when pipe ID is 41.25" (corresponding to standard OD of 42"),

$$N = 3.1$$

$$G/G_{c2} = 0.49$$

$$P_2/P_1 = 0.87$$

$$P_1 = 19.2$$

and the pressure drop ($P_1 - P_2$) is 2.5 psi, which is acceptable.

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Hence, total pressure drop = Line ΔP + KO drum ΔP
= 2.5 + 0.5 = 3 psi.

Thus, the pressure at inlet of the KO drum is 16.7 + 3, i.e. 19.7 psia or 5 psig.

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5.0 DESIGNING THE FLARESTACK & ACCESSORIES

5.1 KO drum sizing

The hydrocarbon relief streams are mainly vapors, but they may carry some liquid that condense in the collecting lines. A particle that is 150 micron or less, can be burnt in the flare without hazard. Larger particles are removed in the KO drum.

KO drums are either Horizontal or vertical. They are also available in a variety of configurations and arrangements which include -

- 1 Horizontal drum with vapor entering at one end of the vessel & exiting at the top of the opposite end (no internal baffling)
- 2 Horizontal drum with vapor entering at each end on the horizontal axis & a central outlet.
- 3 Horizontal drum with vapor entering in the center & exiting at the two ends on the horizontal axis.
- 4 Vertical drum with vapor entering at the top on a certain diameter & provided with a baffle so that the flow is directed downward. Outlet nozzle is located at the top of the vertical axis.
5. Vertical drum with a tangential nozzle

Selection of the drum arrangement depends on economics. When large liquid volume storage is required & the vapor flow is high, normally a horizontal drum is more economical.

Split entry/exit reduces size of the drum for large flows. As a rule of thumb, when drum diameter exceeds 12 feet, split flow arrangement is normally economical.

KO drums are usually sized by a trial & error method. Liquid particles can drop out when the vapor velocity traveling through the drum is sufficiently low. In other words, the drum must be of sufficient diameter to effect the desired liquid - vapor separation.

The factors considered while designing the knockout drums are -

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- 1 The residence time of the vapor should be equal to or greater than the time required for a liquid droplet to travel the available vertical height at dropout velocity of the liquid particle.
2. Sufficient volume should be provided for the liquid accumulation in the knockout drum.

Horizontal KO drum designing

Tan proposed the following formula to determine size of horizontal drum, valid for particle size of 400 micron.

$$W = 360 * D^2 [(\rho_L - \rho_G) MP/T]^{0.5}$$

Where,

W = vapor flow, lb/hr
 ρ_L = liquid density, lb/ft³
 ρ_G = gas density, lb/ft³
M = molecular weight
T = Vapor temperature, R
P = KO drum pressure, psia
D = KO drum diameter, ft.

If the calculated KO drum diameter for 400 micron particle (D_{400}) is to be converted to liquid particle size of say, X microns, then the new KO drum diameter (D_x) is given as :

$$D_x = D_{400} * ((400/X) ** 0.25)$$

The min. L/D ratio recommended for a split flow horizontal drum is 2.5 for proper separation of liquid particles from vapors.

Vertical KO drum designing

A practical formula for the vapor velocity in vertical KO drums is,

$$V = 0.4 * ((\rho_L - \rho_G) / \rho_G) ** 0.5$$

where,

V = vapor velocity, ft/sec
 ρ_L = liquid density, lb/ft³
 ρ_G = gas density, lb/ft³

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It is also a general practice to assume a liquid holdup time between 10 and 30 minutes. In absence of data, a volume of 2000 gals of liquid can be a good approximation.

5.2 Seal system

Seals are provided in the flare system to prevent flash back . If seal is not provided, a continuous quantum of gas may be bled to the flare to maintain a positive flow. The seals can be of two main types - liquid seal and gas seal.

Liquid seals

Liquid seals are further classified as seal drums and seal pipes. In the former, a liquid seal is used in a seal drum located between the KO drum & flare stack. Seal drums can be horizontal or vertical, the selection mainly depends on the availability of space. Figure 4 shows a horizontal and a vertical seal drum. Instead of a drum, sometimes , a piping seal is used as a seal leg located at the bottom of the stack. This is often an integral part of the stack.

A seal drum maintains a seal of several inches on the inlet flare header, preferably not exceeding 6 inches. More is the height of the seal, more is the back pressure. Sealing liquid is usually water with a continuous flow, the overflow going to the sewer.

In cold regions, a submerged steam header is provided to avoid freezing of sealant water or water may be replaced by liquid such as alcohol, kerosene etc. which do not require continuous flow.

The capacity of the seal drum is usually the volume corresponding to 8-10 ft. of the vapor inlet line. In a vertical drum, the ratio of the inlet pipe cross-sectional area to the vessel free area for gas flow above the liquid should be at least 1:3 to prevent upsetting surges of gas flow to the flare. For this, area for the gas above the liquid surface should be atleast equal to that of a circle having diameter, $D = 2d$, where d is inlet gas pipe diameter.

The height of the vapor space above the liquid level in a vertical drum should be app.2-3 times the diameter (d) to provide disengaging space for entrained seal liquid.

If a horizontal liquid seal vessel is used, a minimum dimension of 3 ft. between liquid level & top of the drum is recommended.

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Seal pipes (Fig.5) located at the base of stack are cheaper than drums, however they can experience pulsation of the gas flow to the flare under very low flow conditions. Also during a large gas release, the water seal may be blown out of the top to the flare stack.

Guidelines for sizing seal legs

- 1 Slope of the inlet line is designed to provide a volume of water below the normal sealing water level equivalent to inlet pipe volume of 10 ft.
- 2 Depth of water seal should not exceed 12" to prevent gas pulsation.
- 3 Seal water level is maintained by a continuous flow of water at about 20 gpm.
- 4 Normal overflow is taken off the bottom of the seal through a seal leg height of which is equivalent to about 175% of the pressure at the base of the stack during maximum vapor release so that gas release at the base of flare is prevented.

Gas seals

A more recent gas seal type of device that has been developed to prevent flash backs in the flare system is 'Molecular' type seal. It uses a purge gas of molecular weight of 28 or less (like N₂, CH₄ or natural gas). Because of the buoyancy of the purge gas, it creates a zone having pressure greater than the atmospheric pressure. The molecular Seal is located at the top of the flare stack immediately below the burner tip, the ambient air can not enter the stack because of this high pressure. (Figure-6). The recommended purge velocity through the molecular seal is about 0.1 ft/sec. If a molecular seal is not used, the recommended velocity is 1 ft/sec, thereby increasing the purge gas requirement.

5.3 Flare burners

The flare burner is located at the tip of the flare stack. The top section is normally about 12 ft long & is called the flare burner tip. The burner diameter is sized on a velocity basis. The flame blow out can occur when the exit velocity of the vapor exceeds 20-30% of the sonic velocity.

Mass flow is given as -

$$W = 3600 * \rho_G * A_c * V$$

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where,

W = mass flow rate, lb/ sr.

ρ_G = gas density, lb/ft³

V = exit velocity, ft/s

A_c = c/s area, ft²

$$\text{Vapor density, } \rho_G = \frac{MP}{10.73 T}$$

Exit velocity corresponding to 20% of sonic velocity

$$V = 1/5 (g KRT/M)^{0.5}$$

$$\text{Flare tip cross-sectional area, } A_c = \frac{0.785}{144} d^2$$

where,

M = molecular weight

P = absolute pressure of vapor = 14.7 psia

T = temperature, R

g = acceleration due to gravity = 32.17 ft/sec²

R = gas constant = 1546 ft lb force/R. mol

$K = \frac{CP}{CV} = 1.2$ (assumed)

d = diameter of flare tip, inches

Combining the above equations and substituting values for g , K , R & P ; we obtain,

$$d^2 = \frac{W}{1370} (T/M)^{0.5}$$

If based on the maximum rate, the diameter may be too large. In such case, the normal flow is used to arrive at value of d and velocity for the maximum flow is kept at maximum 40% of the sonic velocity.

5.4 Example

The flare normal load is 800,000 lb/hr whereas max load is 1,000,000 lb/hr. The vapor temperature is 300 degree F and molecular wt. is 50. What should be diameter of the burner tip ?

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Solution :

$$d^2 = \frac{W}{1370} (T/M)^{0.5}$$

$$= \frac{800,000}{1370} * (760/50)^{0.5}$$

$$\text{Hence, } d = 47.7 \text{ i.e. } 48 \text{ inch.}$$

$$\begin{aligned} \text{Vapor density, } \rho_G &= \frac{MP}{10.73 T} \\ &= 50 * 14.7 / (10.73 * 760) \\ &= 0.09 \text{ lb/ft}^3 \end{aligned}$$

$$\begin{aligned} \text{Max Velocity} &= W / (3600 * \pi * \rho_G * d^2 / 4) \\ &= 1000,000 * 4 / (3600 * 0.09 * 3.14 * (48/12)^2) \dots \text{based on max flow} \\ &= 246 \text{ ft/sec} \end{aligned}$$

$$\begin{aligned} \text{Sonic velocity, } V_s &= (g KRT/M)^{0.5} \\ &= (32.17 * 1.2 * 1546 * 760 / 50)^{0.5} \\ &= 953 \text{ ft/sec} \end{aligned}$$

Thus, the maximum velocity is 25.8 % of the sonic velocity, which is less than the max limit of 40%. Hence, the diameter of burner tip should be 48".

5.5 Flare stack - statutory requirement

The location of flare, is a safety related issue. The flare stack is generally located on the downwind of normally prevailing winds & remote from operating & traffic zones.

In India, as per Petroleum Rules, 1976 (page 49, point 169), no flare shall be situated nearer than 90 meters to any tank, still, pump-house or any facility for the refining, cracking, reforming, blending, storage for handling of petroleum or liquefied petroleum gases other than knock-out drum and condensate recovery pump attached to such flare.

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5.6 Flare stack design

Height of the flare stack depends upon -

- 1 Heat released by the flare gas in BTU/hr
- 2 Characteristics of the flame & flame length
- 3 Emissivity of the flame
- 4 Radiation intensity of the flame in BTU/hr ft²
- 5 Ground level concentration of toxic gases present in the flare stream in the event of a flame blow out.

Flame burning characteristics and flame length are of considerable importance in sizing the flare stack.

Flame burning characteristics are shown in Fig.7 A which identifies zones of the flame spectrum in terms of dimensionless numbers. Figure-7B enables estimations of the critical flame points in each combustion zone. Figure-8 helps to visualize how a flame profile may be superimposed on the loci of Figure-7B. Note that the flame height increases appreciably when combustible gas flow is sufficiently reduced so as to cause a shift back into laminar zone. By designing flare tip which induces premixing of gas and air or selecting a smokeless design which induces partial premixing by agitation with steam, the increased peaking of the flare in the laminar zone may be avoided or materially reduced. This type of flare tip design also reduces the noise level.

Figure-8 should be used alongwith following criteria -

Peak at Reynolds number = 3,000
Valley at Reynolds number = 5,000
Blow off at Mach number = 0.2

Note that the Reynolds number is based on stack diameter. Each of these criteria refers to the gas state before combustion at the exit from the stack tip. The Reynolds number of 3,000 applies to the Peak Loci Curve, the Reynolds number of 5,000 applies to the Valley Loci Curve, and the Blow off Mach number applies to the limit of Valley Loci Curve. The blow off point is reached when the velocity of gas leaving the stack causes the flame to separate from tip, at which point the flame becomes unstable.

For max. stack discharge, a mach number of 0.2 is recommended. From Fig.8 then, corresponding L/D ratio is 118. From the stack diameter D, the flame length L can be determined. Thus,

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$$L = 118 D \quad \text{----- (1)}$$

The thermal radiation and escape time can be estimated from the data in table-2. Values are based on experimental data on the threshold limit of pain to the human body as a function of the radiation intensity in BTU/Hr/ft², generated by a flame.

A safe level of heat radiation intensity for unlimited time exposure has been found to be 440 BTU/hr/ft². It is apparent that a time interval with varying radiation intensity must be allowed, to permit a human to escape from a suddenly released intense heat source. The varying radiation intensity results from an individual increasing his distance from the source of heat.

Assume a person is at the base of a flare stack when heat is suddenly released. The average individual reaction time is between 3 and 5 seconds. Hence, during this short reaction time interval, the full radiated heat intensity will be absorbed. Then follows another short interval (20 ft/sec is normally assumed to be the average escape velocity of a man) during which continually decreasing amounts of heat will be absorbed until safe distance is reached (heat intensity for a safe location is 440 BTU/Hr/sq.ft.)

$$t_a q_a = t_r q_m + t_e \frac{q_M - q_m}{\ln(q_M / q_m)}$$

Where, $t_a = t_r + t_e$

t_a = total time exposed

t_r = reaction time

t_e = escape time

$t_a q_a$ = total heat flow/area for the exposure time

q_M = maximum radiation intensity

q_m = minimum radiation intensity

Figure 9 is a solution to this equation.

The escape time depends on the stack height, H. The following steps outline the approach to determining the flarestack height based upon the radiation intensity.

- 1 Calculate the radiation intensity using the following equation -

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$$q = \frac{fQ}{4\pi X^2} \text{----- (II)}$$

where,

q = radiation intensity, BTU/hr/sq.ft

f = emissivity of the flame

Q = heat generated by the flame, BTU/hr

X = distance from center of flame, Xm feet above grade to point P (Figure-10)

Flame emissivity values for common gases are as follows :

Gas	f
Hydrocarbons	0.4
Propane	0.33
Methane	0.2

A relationship between f and the net calorific value of a gas can be used in the absence of data -

$$f = 0.2 (hc/900)^{1/2}$$

Where hc = net heat value of a gas (LHV) in BTU/scf (60 deg.F, 14.7 psia)

- 2 Calculate the heat flow Q, BTU/hr

$$Q = W * hc * 379/M$$

where,

W = lb/hr of vapors released.

hc = Net heating value of gas in BTU/Scf (60 deg.F, 14.7 Psia)

M = Molecular weight of the gas.

- 3 The formula for the stack height is first derived. Referring to Fig.10, we have -

$$X^2 = X_m^2 + y^2 \text{ and } X_m = [H(H+L)]^{0.5}$$

Where,

X_m = distance (ft) of the point of maximum intensity from grade

H = stack height, ft

L = flame length in ft. = 118 D as per equation I

$$\text{Hence, } X^2 = H(H+L) + y^2 \text{----- (III)}$$

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Hence, from equations II and III, and for max radiation density (q_M) at flare base where $y=0$,

$$q_M = \frac{fQ}{4 \pi H (H + L)}$$

Hence, H is derived as -

$$H = 0.5 \{ [L^2 + (fQ / \pi q_M)]^{0.5} - L \} \quad \text{----- (IV)}$$

The shortest stack is obtained when $q_M = 3,300$ BTU/hr/sq.ft (or from figure 9, at $t_e = 0$)

The limiting safe radial distance from the flame is -

$$X = \left(\frac{fQ}{4 \pi 440} \right)^{1/2} \quad \text{i.e. } X^2 = fQ / 5530$$

and we note that y = radial distance from the base of the stack = $[X^2 - H(H+L)]^{1/2}$

Allowing for the speed of escape (20 ft/sec) we have -

$$y = 20 t_e = [X^2 - H(H+L)]^{1/2} \quad \text{----- (V)}$$

This defines the safety boundary, corresponding to quiescent ambient air. Thus, the stack height H, the limiting heat radiation q_M , and the radial distance, y can be evaluated with a trial and error procedure, by assuming a value of t_e .

The above analysis must be extended to account for the more prevalent case of wind circulation in the vicinity of the flare. For those sections where wind intensity is unknown, it is suggested that an average 20 mph wind be assumed in all directions, which results in increasing the safe circular boundary by the resulting tilt of the flame (Figure 11). The flame tilt and its effect on the safety boundary increase may be determined as follows :

$$\tan \theta = U_w / U$$

where,

U_w = wind velocity

U = flare exit velocity

$$U_w = [X_m - H] \sin \theta \quad \text{and} \quad U_t = (X_m - H) \cos \theta$$

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$$y = [X^2 - (H + (Xm-H)\cos \theta)^2]^{1/2} + (Xm-H) \sin \theta \quad \text{----- (VI)}$$

This formula establishes the limiting boundary for wind circulation. When evaluating wind effects on flame tilt, an average wind intensity should be used in the calculations.

5.7 Alternate method of calculating safety boundary

For high flaring rates, the stack height calculation previously described leads to a very tall stack. Part of the reason for this conservative estimate is that calculations are based up on the thermal effect on bare skin. If proper clothing is provided to personnel before entering the flare stack area and proper shielding is installed at the stack or at the equipment to reduce the radiation effects, the required stack height can be greatly reduced. However, there is a tradeoff in that the safe boundary limit must be increased.

Since heat load of the flare, the flame length, and the safe radiation intensity (440 BTU/hr/sq.ft) remain the same, decreasing the stack height leads to an increase in the safety radius. Another important consideration is the type of support provided for the stack. In general, the higher the stack the greater the structural support costs.

An alternative method of stack sizing is based on the allowable limit for radiation intensity. For operating personnel the allowable intensity is 1500 BTU/hr/sq.ft. , and for equipment it is 3000 BTU/hr/sq.ft.

The 1500 BTU/hr/sq.ft criterion is established from the following basis. In emergency releases, an operation time of 3 to 5 sec. may be assumed. Perhaps 5 to 10 sec. more would elapse before an individual could escape the area via an average velocity of 20 ft/sec. This would result in a total exposure period ranging from 8 to 15 sec. only. The time to pain threshold corresponding to 1500 BTU/hr/sq.ft. is 16 sec. before the individual could escape to a safe place. The effect of radiation on equipment is shown in figure-12. The temperature of metal equipment increases with exposure time and higher the radiation heat intensity, the greater the temp. Curve 1 in figure 13 shows the theoretical equilibrium temps. for metal equipment, based on a view factor of 0.5 . The actual temp. on surfaces facing the flame the flame will be between curves 1 & 2.

The temperature of the vessels containing liquid or flowing vapors may be lower because of cooling effects. Curve-2 applies to materials having a low heat conductivity coefficient e.g. wood. In this case, equilibrium temperatures are reached within a shorter time as compared with metal objects. Dehydration of wood takes place at about 500 deg.F, decomposition at 700 deg.F, and ignition at

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around 800 deg .F, corresponding to heat intensities of 1300, 3000 and 4000 BTU/hr/sq.ft respectively. This means that wooden structures and vegetation exposed to heat intensities of 3000 to 4000 BTU/hr/sq.ft. and higher may catch fire and burn. Paint on equipment also may also be damaged.

Therefore, it is recommended that equipment located in this area be protected by proper heat shielding or emergency water sprays .

The following steps outline calculations by the alternate method :

- 1 From equation II, the radial distance from the flame at $Q = 1500$ BTU/hr/sq.ft. is calculated.
- 2 The safe radial distance at $Q = 440$ BTU/hr/sq.ft. is calculated from the same equation
- 3 A suitable value for Q is assumed at the base of the stack. $Q = 3000$ BTU/hr/sq.ft. is a good start since protective shielding will be provided in this case at the stack.
- 4 From equation IV, H is calculated.

Figure-14 illustrates the different heat intensity loci that should be examined.

5.8 Example

The flare normal load is 800,000 lb/hr whereas max load is 1,000,000 lb/hr. The vapor temperature is 300 degree F and molecular wt. is 50. Stack diameter is 48". Average wind velocity is 20 mph and net heating value is 1500 BTU/scf). Calculate the stack height and the safe boundary.

Solution :

$$\begin{aligned} \text{Total heat released, } Q &= W * h_c * 379/M && \text{----- equation as given earlier} \\ &= 1,000,000 * 1500 * 379/ 50 && \text{---- max flow considered} \\ &= 11370 \times 10^6 \text{ BTU / hr.} \end{aligned}$$

$$\begin{aligned} \text{Flame emmisivity, } f &= 0.2 (hc/900)^{1/2} && \text{----- equation as given earlier} \\ &= 0.2 (1500/900)^{1/2} \\ &= 0.258 \end{aligned}$$

$$\text{Radiation intensity, } q = \frac{fQ}{4 \pi X^2} \quad \text{-----as per equation (II)}$$

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$$440 = 0.258 * 11370 * 10^6 / (4 \pm X^2) \text{ -- 440 is safe intensity value}$$

Hence, safe radial distance, $X = 728.6 \text{ ft.}$

The flame length, $L = 118 D$ -----as per equation (I)

$$= 118 * 4 \text{ ---- as the stack diameter is 48" i.e. 4 ft.}$$

$$= 472 \text{ ft}$$

The stack height, $H = 0.5 \{ [L^2 + (10^6 / \pi q_M)]^{0.5} - L \}$ --as per equation (IV)

For shortest stack, escape time, $t_e = 0$. Figure 9 gives corresponding value of $q_M = 3300 \text{ BTU/hr/sq ft.}$

$$\text{Hence, } H = 119.6 \text{ ft} = 120 \text{ ft.}$$

This is the shortest possible stack height, but is not a practical height as it assumes $t_e = 0$.

If a reasonable escape time i.e. $t_e = 30 \text{ sec.}$ is assumed, then figure 9 gives $q_M = 1330 \text{ BTU/hr/sq ft.}$ Then, $H = 245 \text{ ft}$ (as per equation IV)

$$\text{Now } 20 t_e = [X^2 - H(H+L)]^{1/2} \text{ ----as per equation (V)}$$

We have, $X = \text{safe radial distance} = 728.6 \text{ ft.}$

$$H = 245 \text{ ft}$$

$$L = 472 \text{ ft}$$

Hence, $t_e = 29.8 \text{ sec.}$ This is almost same as the assumption of $t_e = 30 \text{ sec.}$

Hence, the selected flare height is 245 ft.

Now, let us calculate the wind effect on the safe boundary around the flare stack.

$$\text{Wind velocity, } U_w = 20 \text{ mph} = 29.3 \text{ ft/sec}$$

$$\begin{aligned} \text{Gas density} &= \text{Mole. Wt} * \text{abs. Pressure in psia} / (10.73 * \text{temp in R}) \\ &= 50 * 14.7 / (10.73 * 760) \\ &= 0.09 \text{ lb/ft}^3 \end{aligned}$$

$$\begin{aligned} \text{The gas exit velocity, } U &= 1,000,000 * 4 / (\pi * 4 * 4 * 0.09 * 3600) \\ &= 245 \text{ ft/sec} \end{aligned}$$

$$\begin{aligned} \text{Now, } \tan \theta &= U_w / U \\ &= 29.3 / 245 = 0.1196 \end{aligned}$$

$$\text{Hence, } \theta = 6.82, \sin \theta = 0.1187, \cos \theta = 0.99$$

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$$X_m = [H * (H+L)]^{0.5} = 419 \text{ ft}$$

$$X_m - H = 419 - 245 = 174 \text{ ft}$$

$$\text{Now, } y = [X^2 - (H + (X_m - H) \cos \theta)^2]^{1/2} + (X_m - H) \sin \theta$$

Substituting the values, we get y = safe radial distance from the base of stack = 618 ft.

5.9 Estimating ground level concentrations

After the stack height has been established from radiation intensity values, the maximum permissible ground level concentration of toxic gases in the event of a flame blow out should be evaluated. Table 3 represents toxicological threshold limit as allowed by the environmental protection agency (EPA).

Estimated ground level concentrations should be based on the emergency condition of flame blowout. The calculation is normally done for a range of climatological conditions at the plant site.

For a rough estimate, the following empirical formula may be used :

$$C_{\max} = \frac{3697 \text{ VM Dz}}{\mu H^2 Dy}$$

$$X_{\max} = (H/Dz)^{2/(2-N)}$$

Where,

$C_{\max}$ = Concentration at grade in ppm (volume)

V = Specific volume of toxic gas, cu ft per lb

M = Weight discharge of pollutant component in tons per day

Dz = Vertical diffusion coefficient

μ = Air velocity at grade, mph

H = Stack height, ft.

Dy = Horizontal diffusion Coefficient

$X_{\max}$ = Distance from stack to the point of maximum concentration, ft.

N = Environmental factor

The following values are taken from API manual

$$Dz = 0.13, Dy = 0.13, N = 0.25$$

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5.10 Stack support

There are generally three types of flare stack supports : Guyed type, Derrick and Self supporting.

As a rough guide to the economics of these three types of flare structures, the comparative costs for material and labor as functions of stack height are tabulated as follows -

Capital investment (Equipment only)

	Up to 150 ft	150 to 200 ft	Above 200 ft.
Least expensive	Derrick type Self supporting	Derrick type Guyed	Guyed Derrick
Most expensive	Guyed	Self supporting	Self supporting

Installation Labor

Least expensive	Self supporting Guyed	Derrick (Self supporting Guyed)*	Guyed Derrick
Most expensive	Derrick		Self Supporting

* denotes that both options of around the same cost.

5.11 Pilot burners

To ensure ignition of flare gases, continuous pilots with a means of remote ignition are recommended for all flares. Generally the pilot system consists of three components - a continuous pilot, an ON/OFF pilot and an igniter. The most commonly used type of igniter is the flame front propagation type which utilizes a spark from a remote location to ignite a flammable mixture. The ON/OFF type is used only to ensure ignition of the continuous pilot. Pilot igniter controls are located near the base of elevated flares and atleast 100 ft. away from ground flares.

The number of pilot systems required per flare is largely a function of the wind conditions. A minimum of two pilot systems is recommended while normally three pilot systems are used. They are uniformly placed around the top of the flare.

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Typical flare pilot systems for an elevated flare stack is shown in figure-15. The same type of assembly installed horizontally may be used for ground flares.

The pilot is piped to the top of the flare stack via a 2" venturi burner. Nozzles are provided at the end of the pipe. In some designs, nozzles are hooded and should the flame blow out, the heat of the nozzle will immediately reignite it.

In the pilot igniter system, the gas pipe is connected to a 3" venturi type burner, which is located at the bottom of the stack. The fuel gas flows through a nozzle to inspirate air to form a combustible mixture. The igniter with spark gap is located approx. 3 ft above the burner. When the igniter button is pushed, the resulting spark ignites the gas air mixture. The flame front generated travels up the pipe at the top of the flare and ignites the gas from the pilot nozzles.

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6.0 OTHER DESIGN CONSIDERATIONS

6.1 Materials Of Construction

Following table outlines materials of construction for different components of the flare system.

Component	Material of construction
<u>Piping & KO Drum</u>	
Up to - 20 deg.F	Conventional carbon steel
Up to - 50 deg.F	Special low temp. carbon steel
-150 deg.F & below	18-8 stainless steel
Above 750 deg.F	High temp. resistant alloy
<u>Stack</u>	
Bottom section	Gunitite line (cemented for corrosion resistance)
Burner tips (about 10 ft)	Stainless steel lined with refractories
Section upto 20 ft. below burner tips	High temp. resistant refractories
Other sections of the stack	Special low temp. carbon steel
Structural members, hardware and bolting	Should be hot dip galvanized after fabrication

6.2 Steam requirement for smokeless operation

A flame is referred to as being luminous when incandescent carbon particles are present in it. When these particles cool, they form smoke. Smoke formation mainly occurs in fuel rich systems where a low hydrogen atom concentration suppresses the smoke.

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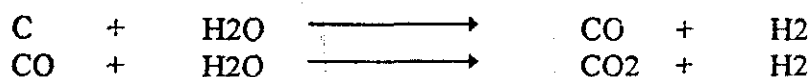
Prevention of smoke in flares is normally accomplished in three different ways :

- 1 By the addition of steam
2. By making a premix of fuel and air before combustion so as to provide sufficient oxygen for efficient combustion.
- 3 By distribution of the flow of raw gases through number of small burners.

Among these methods, the addition of steam is most commonly used to produce a smokeless flare for economy and superior performance. In steam addition, the raw gas is preheated before it enters the combustion zone of the flare. If the temperature is high enough, cracking of the hydrocarbons may occur. This produces free hydrogen and carbon. When the cracked hydrocarbons travel to the combustion zone, hydrogen reacts much faster than carbon. Unless the carbon particles are burned away, they cool down and form smoke. Consequently, in order to prevent smoke, either the hydrogen atom concentration must be decreased to ensure uniform burning of both hydrogen and carbon or enough oxygen must be provided for complete combustion.

There are several theories which try to explain the chemistry of smokeless flares, using steam. One of them assumes that the steam separates the hydrocarbon molecules, thereby minimizing polymerization reactions and forms oxygen compounds that burn at reduced rate and temperature, so as to prevent cracking.

Another theory, claims that steam reacts with carbon particles forming CO, CO₂ and H₂, thereby removing the carbon which forms smoke after cooling. Following reactions are expected to take place as per this theory,



The latter reaction is also known as water gas shift reaction.

Following empirical formula is recommended for evaluating the requirement of steam for producing a smokeless flame as a function of the flow rate of hydrocarbon and their molecular weight.

$$W_s = W_h [0.68 - (10.8 / M)]$$

where,

W_s = Steam rate, lbs/hr

W_h = Hydrocarbon rate, lbs/hr

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M = Molecular weight of hydrocarbon

It may be observed from this that the higher the mol. wt., the higher the required steam. This may be associated with the theory that the higher the mol. wt. the lower the ratio of steam to CO₂ after combustion, resulting in a greater tendency to smoke.

Since, steam consumption is rather high (about 0.464 lb/lb of hydrocarbons with mol. wt.50), it is too expensive to provide for smokeless burning for the max. flare load. Normally, 20% of the max. flare load is designed for smokeless burning. This is well supported by the fact that massive failure is very rare and in 90% of occurrences, smokeless flares are produced.

6.3 Fuel requirement

Fuel gas supply to the pilots and igniters must have high reliability. Since, normal plant fuel sources may be upset or lost in the plant upsets, it is desirable to provide a backup system connected to the most reliable alternate fuel source with provision for automatic cut in on low pressure. The flare fuel system should be carefully checked to ensure that hydrates are not present to cause problems. Because of small lines, long exposed runs and large vertical rises up the stack, use of liquid knock out pot is frequently warranted to remove condensates that may have collected in the fuel line especially during winter. It is a good practice to provide a low pressure alarm on fuel supply after the last regulator, which will warn the operator.

6.4 Purging of flare lines

Any gas or mixture of gases that can not reach dew point at any condition of ambient temperature can be used as a purge for flare system. Nitrogen, Methane or Natural gas are normally used as purge gases.

Purging is normally of two types : Normal purging and emergency purging

Normal purging is used continuously and admitted to the flare system at the end of each sub header and at the bottom of the molecular seal at the flare stack. When the molecular seal is used, it is that purge volume which will create a velocity of 0.1 ft /sec. at the flare tip. When a molecular seal is not provided, the exit velocity is 1 ft/sec. The purge volume depends upon the wind velocity at the flare elevation. These velocity criteria are based on a wind velocity of 15 mph and vary as the square of the wind velocity.

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Emergency purging is used to compensate for thermal shrinkage. After cessation of hot vent gas flow, the system residual gas will shrink as it cools to the ambient temperature. It normally takes about 15 minutes to reach equilibrium. Unless the purge is admitted to the system, the shrink will draw air back in to the flare header. The shrink problem can be overcome by sensing the system temperature and adding makeup gas at a rate commensurate with the system volume and the max. anticipated gas temperature.

6.5 Noise pollution

Noise pollution from flares has for too long been an inconvenience, accepted in petrochemical plants as an inevitable byproduct of flaring process. It has been established that major individual source of noise from flare is usually at the flare tip itself. This is especially true when the flare tip is of the type used for smokeless flaring of hydrocarbon gases utilizing steam injection.

Basically noise is created because of two reasons, steam energy losses at the high pressure steam injectors and unsteadiness in the combustion process.

Ground flares are normally quieter than elevated flares. This is probably due to the fact that the flame contained inside a box is protected from wind effects and the stabilizing effect of the heat re-radiated from the refractory walls reduces the random characteristics of combustion. The walls themselves will absorb some of the sound energy.

Sophisticated design of flare tips have greatly reduced the noise pollution. In some designs, combustion efficiency has been greatly increased by remixing of air with gas before they are combusted. Steam is also premixed with air and gas before gases leave the flare tip. Some of the turbulent noise energy is thus shielded by the tip itself.

6.6 Stress relief and winterizing

The major stress to which the discharge piping of a relief system is subjected, are results of thermal strains from entry of cold or hot gases. Temperature fluctuations are normally very wide. In majority of situations, it is usually possible to maintain stress levels within allowable limits over the full temperature range by providing an expansion joint or expansion with a cold or hot spring. Special attention to stresses is recommended where piping constructed of carbon steel is used for metal temps. as low as -50 deg. F.

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Design of discharge piping requires careful analysis of the possible thermal and mechanical stresses imposed on the pressure relief valves. Proper anchors, supports and provision for flexibility of discharge piping can prevent these stresses.

Winterizing of the flare system depends upon the severity of ambient temperatures. It is normal practice to slope the flare headers towards knock out drum 1/4 in per 10 ft of run. This enables condensate to flow into KO drum, thereby reducing the possibility of pipe freeze up due to lengthy exposure to low ambient temperature. KO drums are usually provided with a submerged steam heater in order to prevent freezing. Where a water seal is used, a similar arrangement is warranted. In some cold climate areas, flare headers containing water are steam traced and insulated.

6.7 Instrumentation and controls

Typical flare system instrumentation and controls are as follows -

- 1 To ensure smokeless burning, a suitable control system is provided to regulate steam injection into flare tip. Normally, a flow sensor is provided on the main flare header. The flow sensor is in ratio control with the steam. Alternatively, the luminosity of flame is measured by a flame monitoring device, which sets the steam flow in order to maintain the smokeless operation of the flare.
- 2 Thermocouples are provided for the pilots with an alarm in the control room.
- 3 An oxygen analyzer with an alarm is normally provided to indicate the pressure of the air or oxygen in the flare system.
- 4 The KO drum is level controlled in order to maintain a constant level for providing a seal and to prevent the pump from running dry. The KO drum pump, many a times can cut in automatically at high level of KO drum. It also typically, has a AUTO standby pump.
5. A flare video monitor is provided in the control room which helps to observe smokeless operation as well as to identify the abnormal releases in the flare headers.

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7.0 FLARE OPERATIONS

7.1 Startup

The flare startup and shutdown procedures may differ from a plant to plant depending on the flare system it has. Here are some general guidelines, which are followed when starting up or shutting down a flare system.

Initial checkout

- 1 After completion of construction, the system should be thoroughly flushed with water to remove scale and debris. Pressure testing should be conducted where required. Special attention should be given to all flanged joints, valves and connections. All leaks found should be repaired and re-tested.
- 2 The flare KO drum pump should be checked for ease of operation and correct rotation.
- 3 All instruments should be checked for proper connections and performance
- 4 Equipment such as flare tip, molecular seal, flare front generator, water seal, flow sensor and all associated piping should be given final check.

System purge

The flare system must be purged of air before the pilots are ignited, otherwise there is danger of a severe explosion. After the flare system has been purged of air (less than 2% O₂), the pilots are lighted as follows :

- 1 All valves in the flare front generator are closed.
- 2 Plant air and fuel gas lines up to flare front generator should be blown down to remove any line condensate before gas or air is admitted.
- 3 Push the ignition button and check for a spark at the sight port.
- 4 Open valves for the flare front generator to pilot No.1 and fuel gas to all pilots.
- 5 Open the gas supply to approx. 10 psig by observing the pressure gauges.
- 6 Purge for 3 minutes. Then push igniter button to light the pilot. Then light pilot No.2 & 3 in the same manner.

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7.2 Shutdown

The total flare system can only be shutdown and isolated after all the process units are shut down, drained of hydrocarbons, depressurised and purged as necessary. Then flare system is purged with nitrogen before opening up the KO drum, molecular seal etc. for any maintenance.

Individual process units or pipes of equipment can be isolated from operating flare system after they are shutdown by closing block valves and installing blinds, when maintenance is required.

7.3 Inspection

The flare inspection is carried out generally in the plant turnaround.

In the inspection, the flare tip and the pilot burners, the steam nozzles etc. are checked and replaced if required. UT testing is done for the flare shell welds. The flare shell thickness is measured at different locations. General visual inspection is also carried out.

The guy ropes are checked for proper tension and are re-tensioned if required. The guy anchor points are also checked. The guy ropes are greased.

The straightness of the flare stack is also checked. In the PX plant of RIL -PG, it was found that the guy ropes were not adequate for flare stack support. Hence, the stack support is being modified to a Derrick type.

7.4 Normal operation

During the normal operation, the shift crew monitors the flare and ensures that it is smokeless. The flame length is monitored to identify abnormal releases in the flare system. In the normal operation, the amount of vapors flared can be monitored. As this is the material wasted, efforts are to be taken to minimize the normal load which is flared.

The KO drum level and the flare header purge gas minimum flow is ensured during the normal operation. The operations crew also ensures that the seal liquid rate (and hence, the seal) is maintained for the liquid seal system. It is also checked that the pumpout pump of the KO drum is always available.

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8.0 FLARES AT RIL - PG

In Patalganga complex of RIL, there are two flares - one each in PX and LAB plants. The detailed information of both the flare systems is available with respective plants. Here is a brief introduction to both flare systems.

8.1 Flare System in PX

The flare in the PX plant is designed to handle maximum flow rate of 500,000 kg/hr of hydrocarbons. This load can arise when there is plant wide electricity failure. The normal operating flow in the flare design is 640 kg/hr. The flare has a molecular seal, with height of 15 ft and diameter of 80". Minimum purge gas required is 7.21 nm³/hr. The riser height is 305 ft and the riser diameter is 42". The flare tip is from 'John Zink' and is of 310SS. There are 3 pilot burners and 21 steam jets. It uses LP (6 bar g) steam for smokeless operation.

The system had a ZOOM control (Zink Optically Operated Monitor) for ensuring the smokeless operation in the original design. This was supposed to monitor the luminosity of flame by a remotely located detector and adjust the steam for smokeless operation. But it is not commissioned as some of the critical components of the control system are not available. Currently, the steam control to the flare is on 'manual'.

The stack has guyed rope type of support, but it has been found inadequate. Hence, the support is being changed to Derrick type.

8.2 Flare System in LAB

The flare in the LAB plant has maximum design load of 265,000 kg/hr of hydrocarbons. The flare has a molecular seal as well as a water seal. The molecular seal has a diameter of 1.37 m. The water seal drum has a diameter of 1.8 m and the height of 5 m. Minimum purge gas required is 9 nm³/hr. The riser height is 80 m and the diameter is 24". The flare tip is from 'John Zink' and is of SUS 310S. There are 3 pilot burners. The steam used for smokeless flame is at 28 bar g. The steam rate is controlled manually. The support is of guyed rope type.

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9.0 TABLES AND FIGURES

Table - I - Resistance coefficient K for various pipe fittings

Fitting	K	Fitting	K		
Globe valve, open	9.7	90° double-miter elbow	0.59		
Typical depressuring valve, open	8.5	Screwed tee through run	0.50		
Angle valve, open	4.6	Fabricated tee through run	0.50		
Swing check valve, open	2.3	Lateral through run	0.50		
180° close screwed return	1.95	90° triple-miter elbow	0.46		
Screwed or fabricated tee through branch	1.72	45° single-miter elbow	0.46		
90° single-miter elbow	1.72	180° welding return	0.43		
Welding tee through branch	1.37	45° screwed elbow	0.43		
90° standard screwed elbow	0.93	Welding tee through run	0.38		
60° single-miter elbow	0.93	90° welding elbow	0.32		
45° lateral through branch	0.76	45° welding elbow	0.21		
90° long-sweep elbow	0.59	Gate valve, open	0.21		
Contractions (USASI)	0	0.2	0.4	0.6	0.8
Contractions (sudden)	—	—	0.21	0.135	0.039
Enlargements (USASI)	0.5	0.46	0.38	0.29	0.12
Enlargements (sudden)	—	—	0.9	0.5	0.11
	0.0	0.95	0.74	0.41	0.11

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Table 2 - Heat radiation and escape time

Radiation intensity (BTU/hr/ft ²)	Time to pain threshold (Seconds)
440	∞
550	60
740	40
920	30
1500	16
2200	9
3000	6
3700	4
6300	2

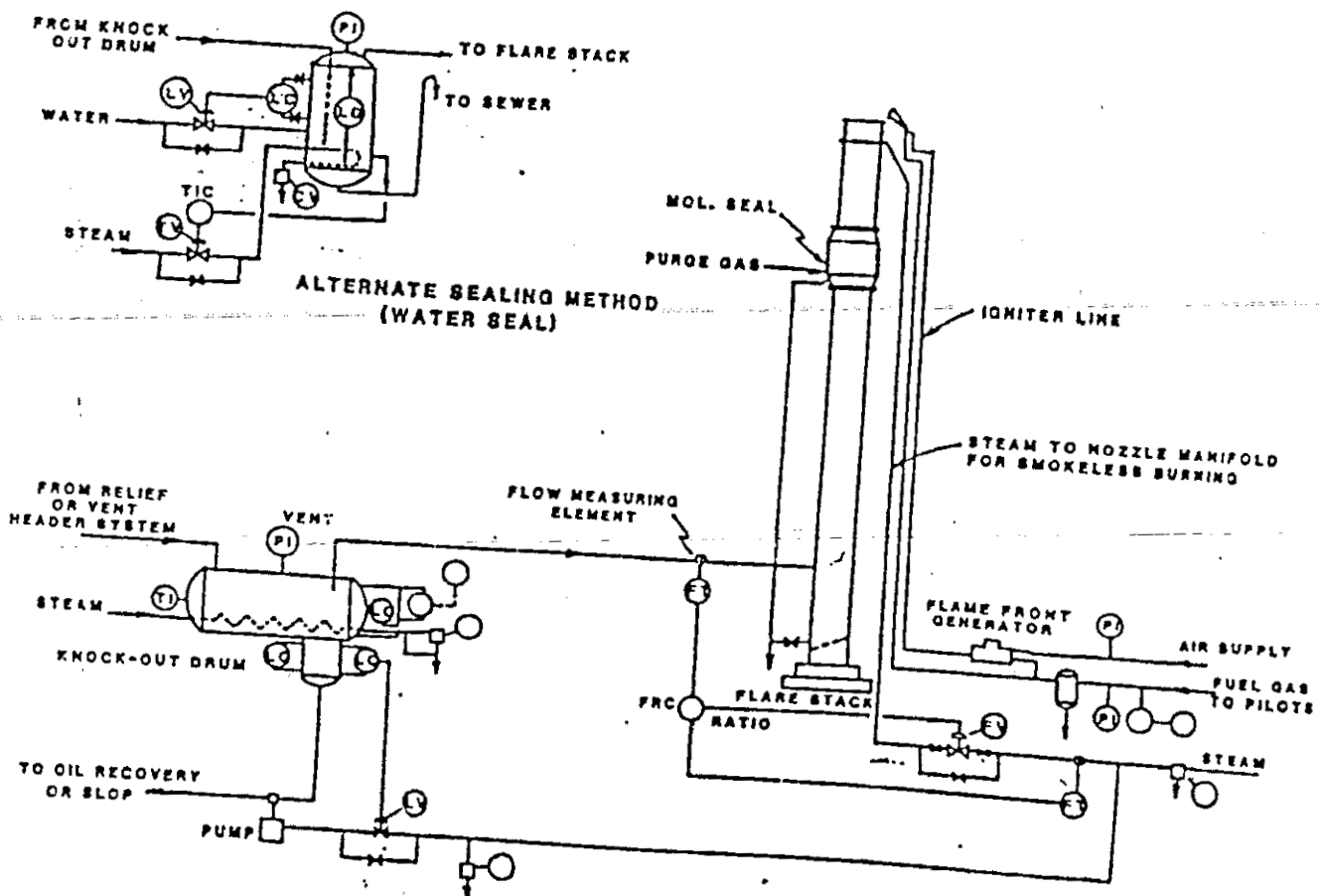
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Table 3 - Threshold limits for some toxic substances - gases and vapors

Gas or Vapor	PPM (v/v)	Gas or Vapor	PPM
Acetaldehyde	200	Dimethylsulfate	1
Acetic acid	10	Diethylene dioxide	100
Acetic anhydride	5	Ethyl acetate	400
Acetone	1,000	Ethyl alcohol (ethanol)	1,000
Acrolein	0.5	Ethylamine	25
Acrylonitrile	20	Ethylbenzene	200
Ammonia	100	Ethyl bromide	200
Amyl acetate	200	Ethyl chloride	1,000
Amyl alcohol	100	Ethyl ether	400
Aniline	5	Ethylene chlorohydrin	5
Arsenic	0.05	Ethylenediamine	10
Benzene	35	Ethylene dibromide	25
Benzyl chloride	1	Ethylene dichloride	100
Bromide	1	Ethylene oxide	100
Butadiene	1,000	Fluorine	0.1
Butyl alcohol	100	Formaldehyde	5
Butylamine	5	Gasoline	500
Carbon dioxide	5,000	Hydrazine	1
Carbon disulfide	20	Hydrogen selenide	0.05
Carbon monoxide	100	Hydrogen sulfide	20
Carbon tetrachloride	25	Isodiaz	0.1
Chlorine	1	Isophorene	25
Chlorobenzene	75	Isopropylamine	5
Chloroform	100	Mesityl oxide	50
Cresol (all isomers)	5	Methyl acetate	200
Cyclohexane	400	Methyl acetylene	1,000
Cyclohexanol	100	Methyl alcohol	200
Cyclohexanone	100	Methyl bromide	20
Cyclohexene	400	2-Methoxyethanol	25
Cyclopropane	400	Methyl chloride	100
Diacetone alcohol	50	Methylcyclohexane	500
O-Dichlorobenzene	50	Methylcyclohexanol	100
1,1-Dichloroethane	100	Methylcyclohexanone	100
Diethylamine	25	Methyl formate	100
Diisobutyl ketone	50	Methyl amyl alcohol	25
Dimethylaniline	5		

FIGURES

Figure 1 - Schematic of typical flare gas system

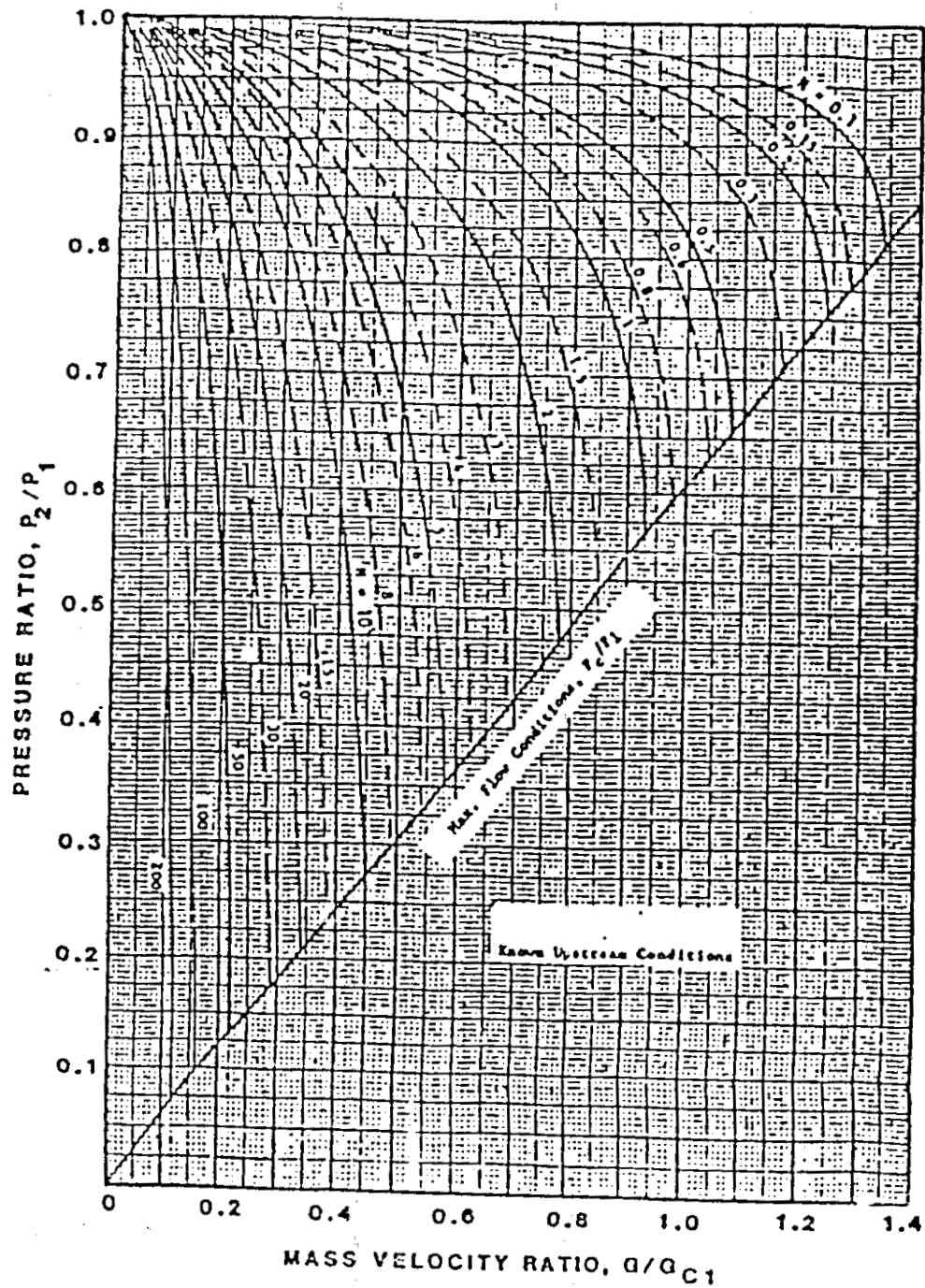


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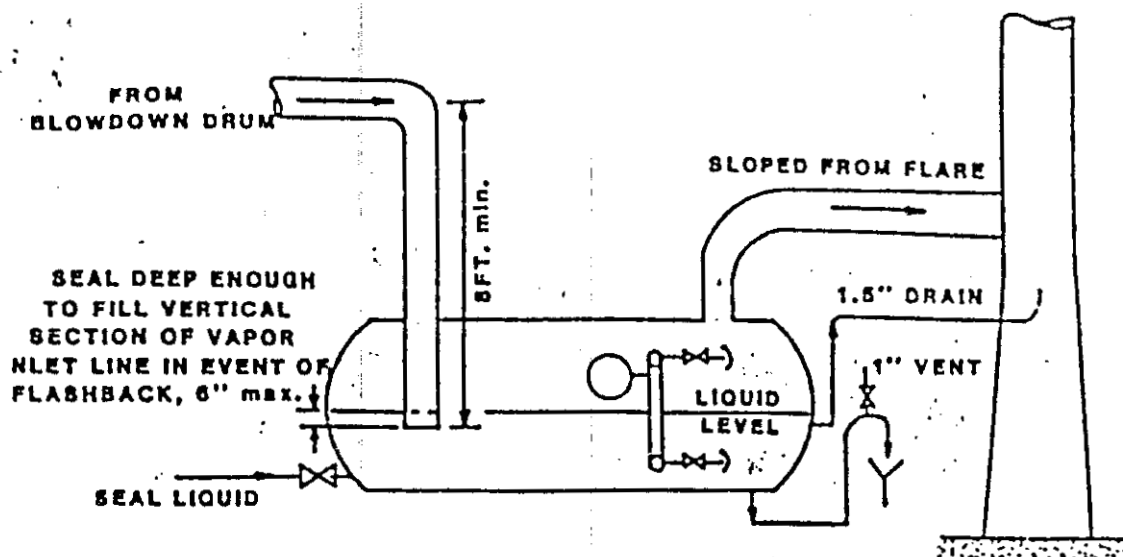
Figure 2 - Pressure drop chart (known upstream conditions - by Lapple)



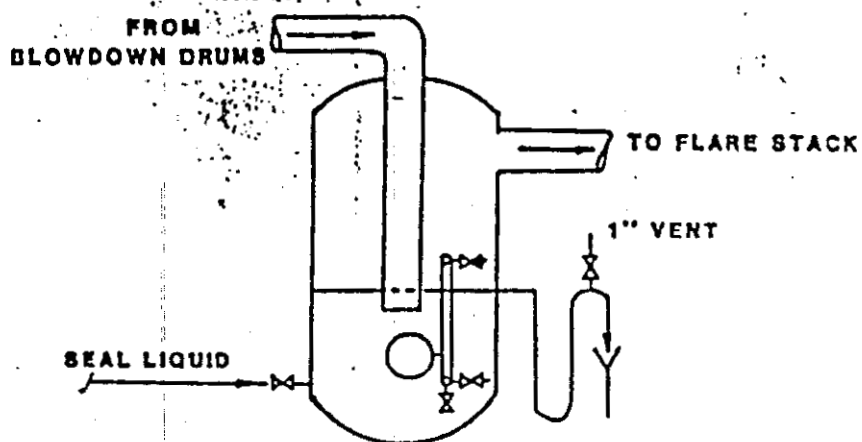
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Figure 4 - (A) Horizontal seal drum (B) Vertical seal drum



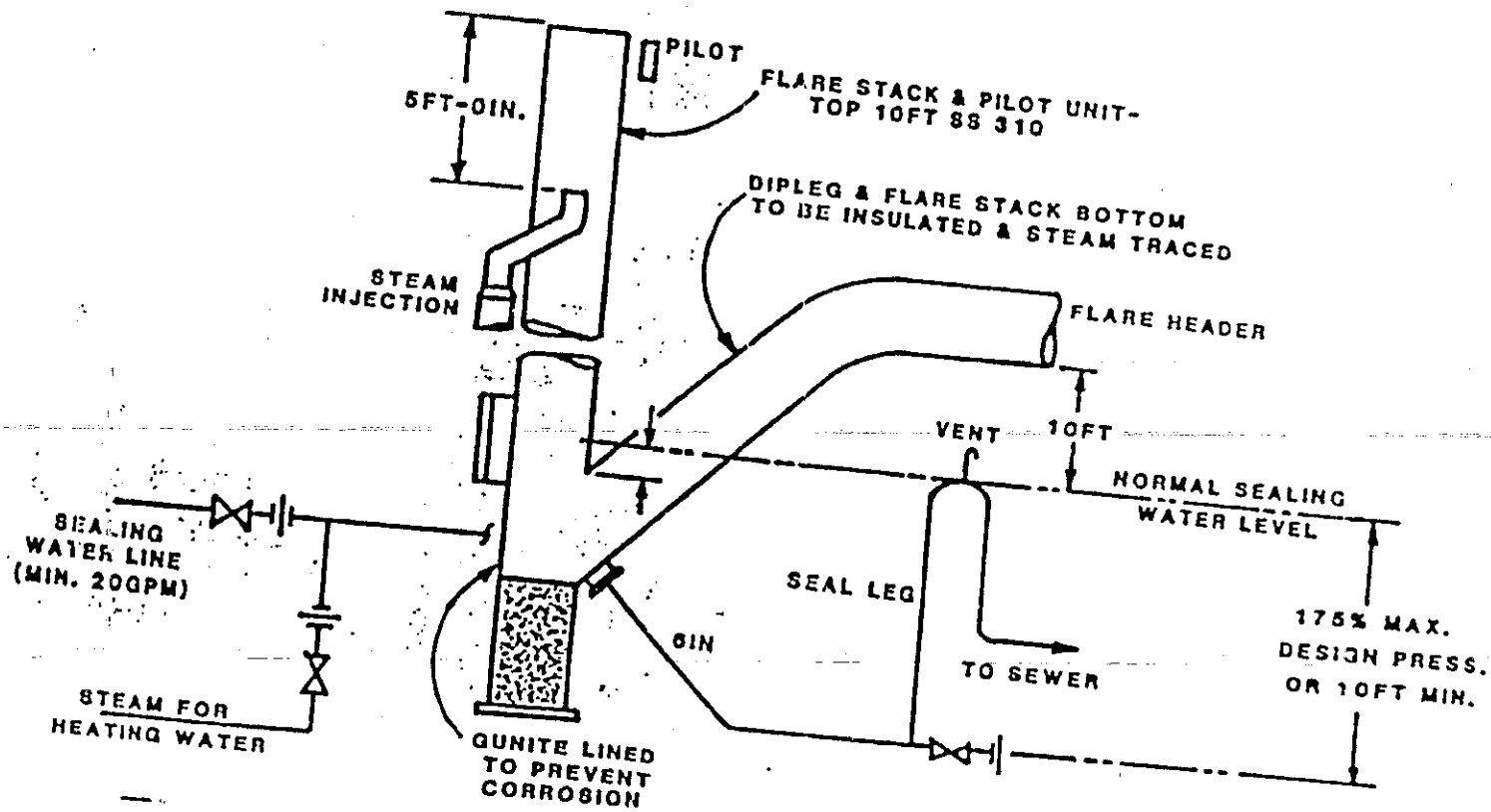
(A)



(B)

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Figure 5 - Seal leg arrangement



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Figure 6 - Molecular seal

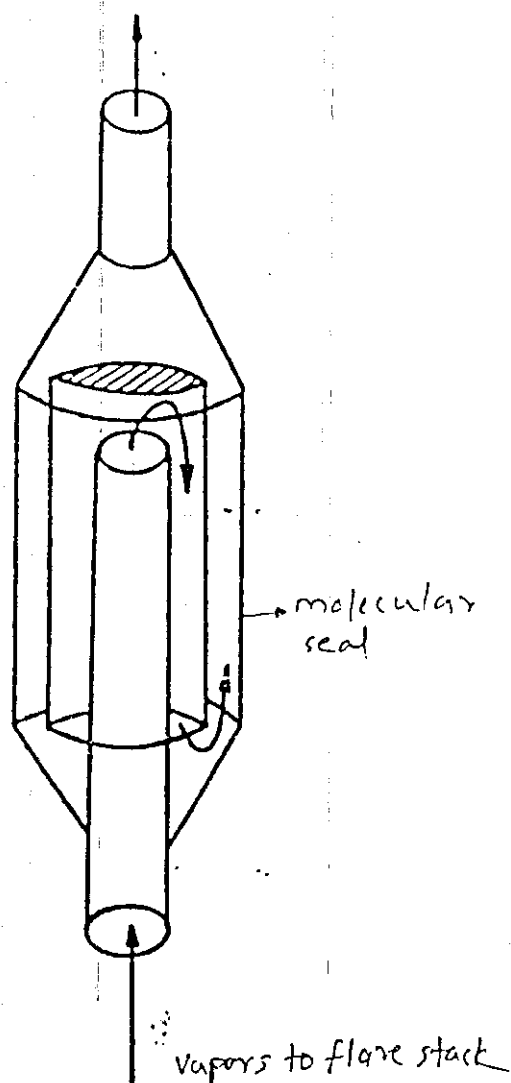
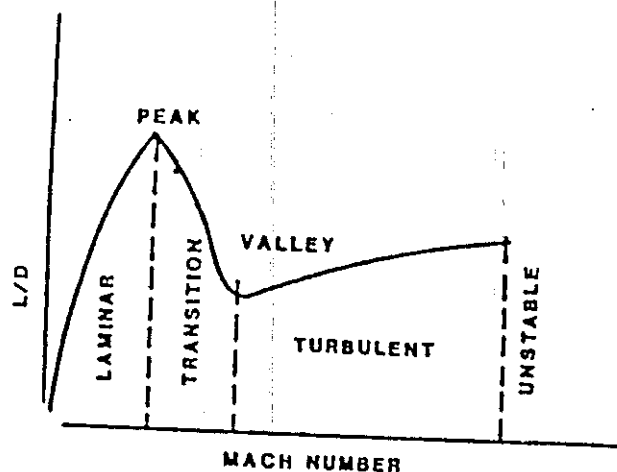
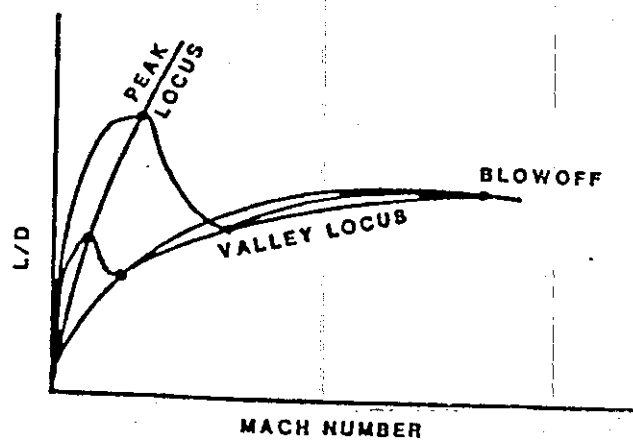


Figure 7 - (A) Burning characteristics of flames from circular ducts discharging vertically into quiescent air without premixing

(B) Plot of (L/D) versus mach number



(A)



(B)

Figure 8 - Superimposition of typical flame characteristics on the locus curves

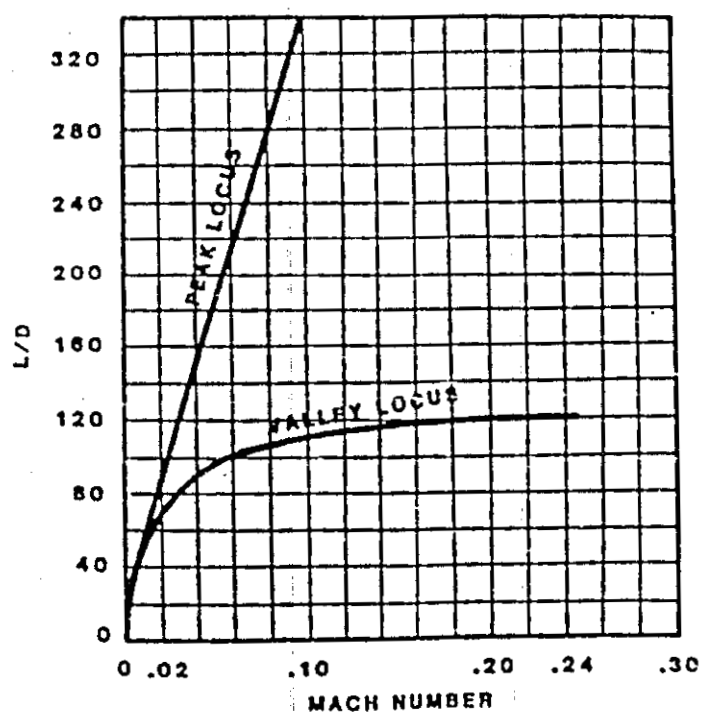


Figure 9 - Plot of maximum radiation intensity versus escape time, assuming 5 second reaction time.

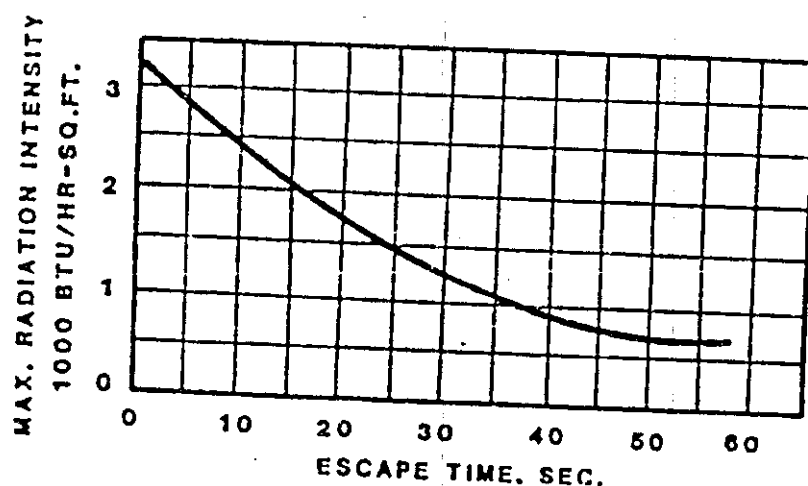


Figure 10 - Flare stack and flame in stagnant surroundings

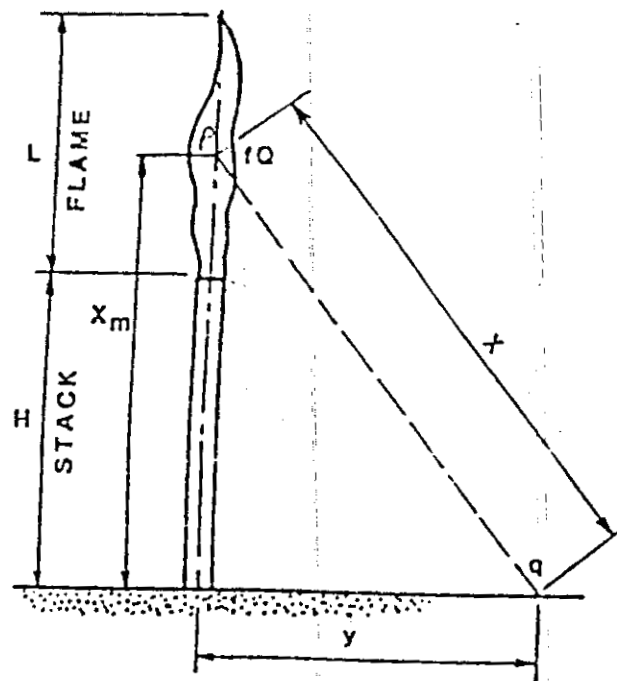
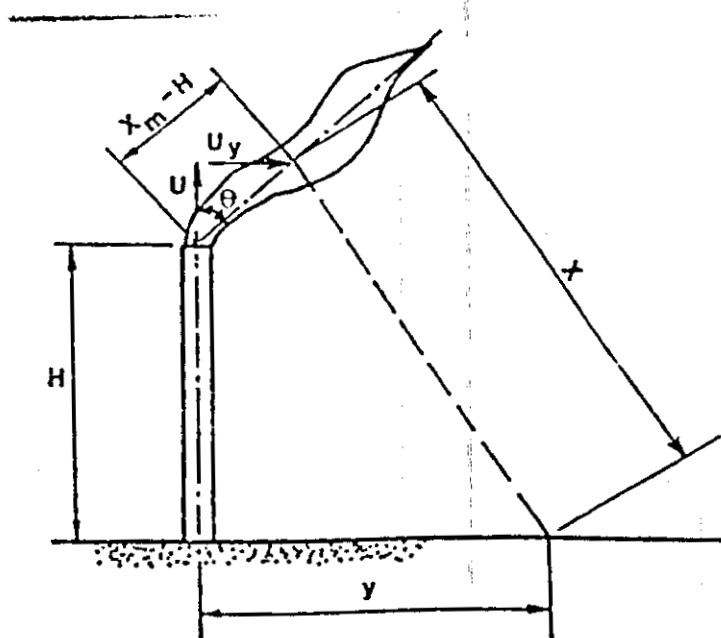
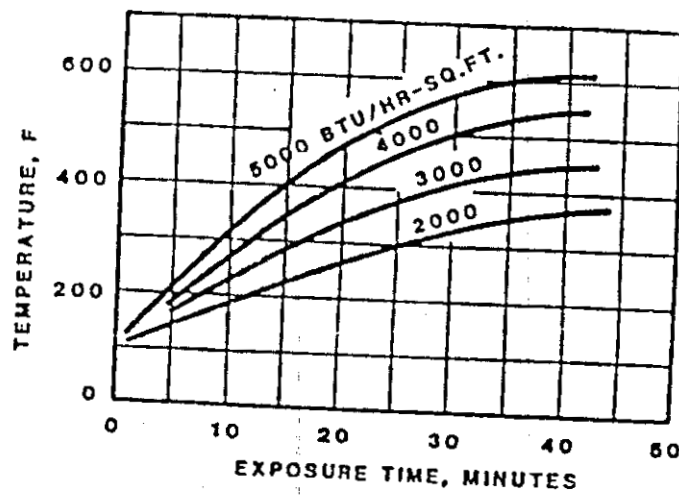


Figure 11 - Flare stack and flame in wind blown surroundings



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Figure 12 - Plot of temperature of steel equipment versus exposure time for different radiant heat intensities. Curves are based on 0.25" plate thickness with an effective emissivity of 10 and view factor of 0.5. Cooling caused by convection etc. are neglected.



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Figure 13 - Plot of equilibrium temperature versus radiant heat intensity. The curve 1 is for metal equipment while curve 2 is for wood.

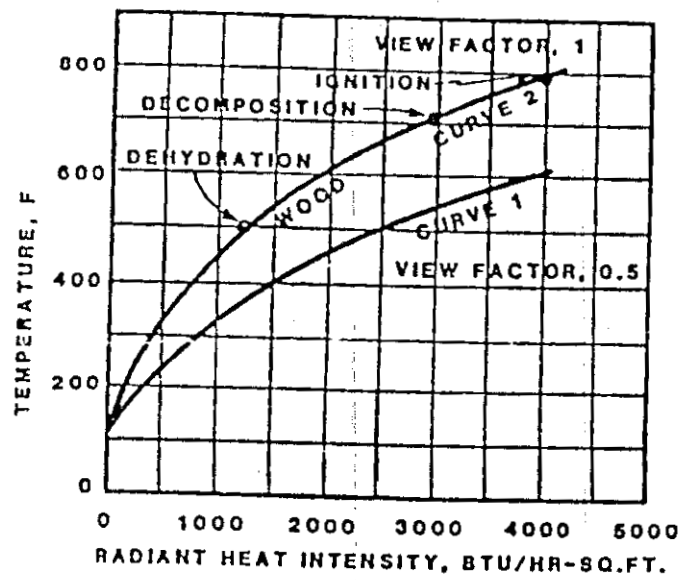


Figure 14 - Contours of radiant heat intensity

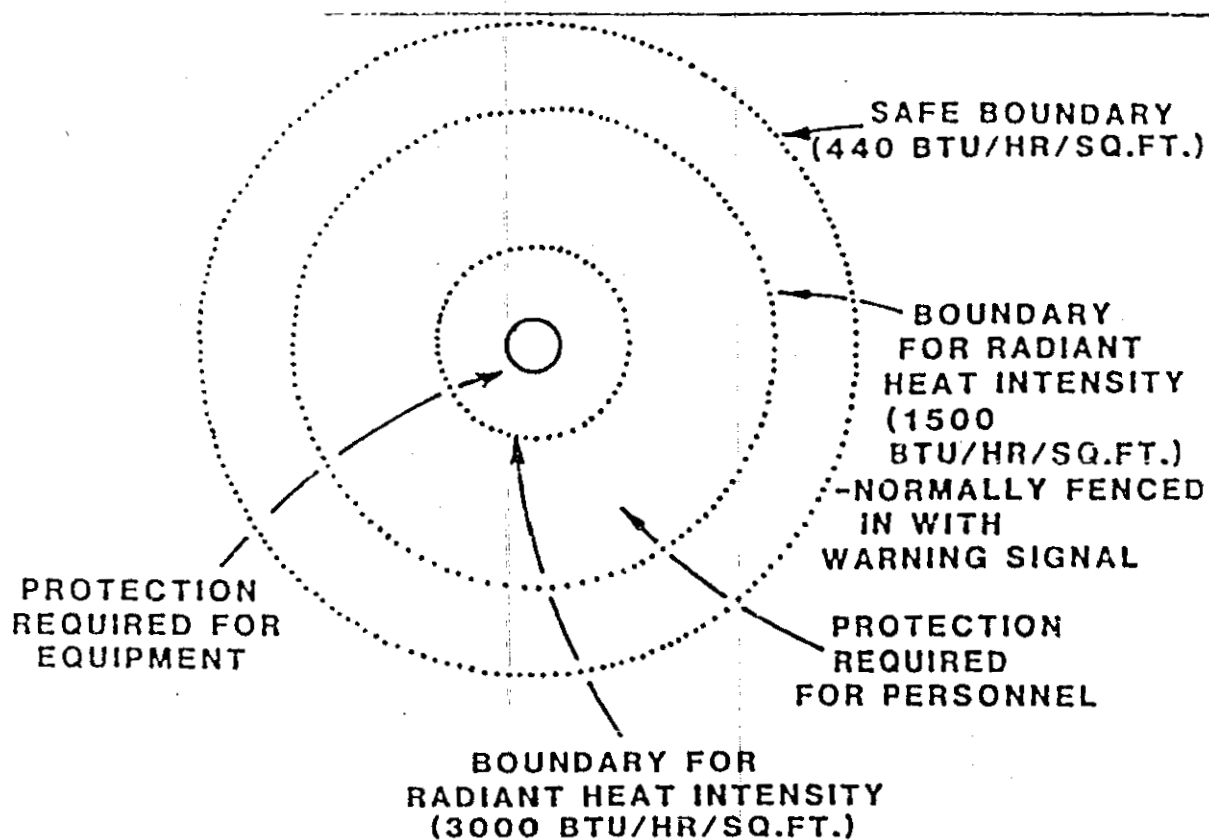
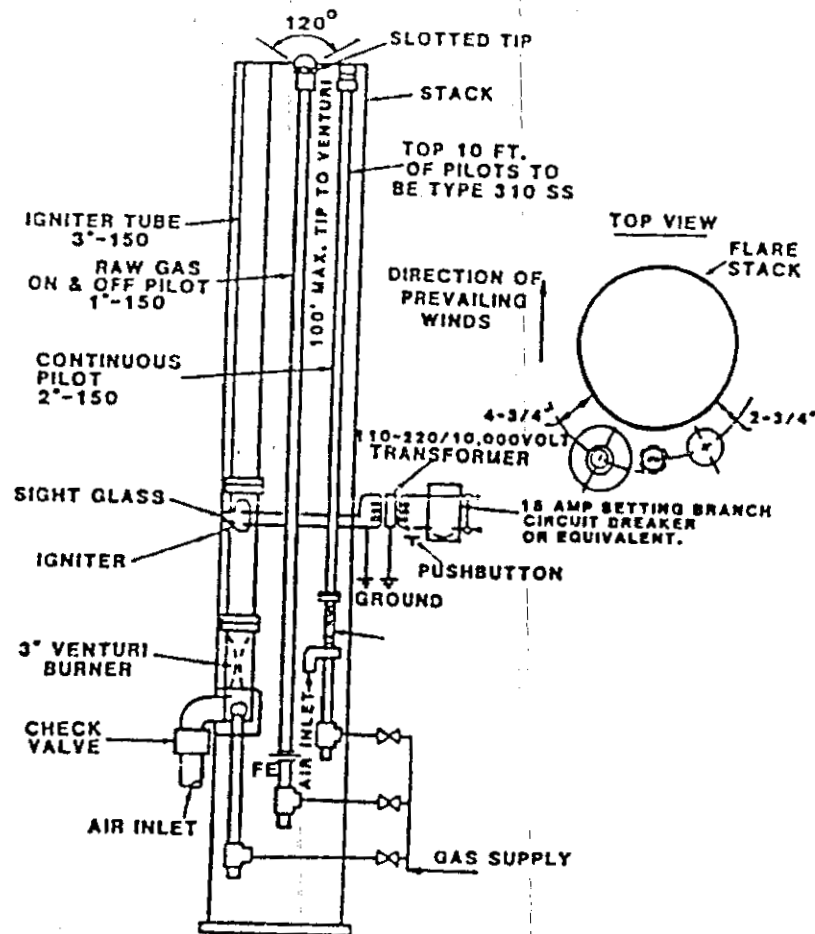


Figure 15 - Typical flare pilot and igniter



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10.0 REFERENCES

Following references have been used while preparing this module -

1. Flare Gas Systems Pocket Handbook by K. Banerjee, N. P. Cheremisinoff et. al.
2. Engineering Design Seminar, conducted by UOP (1994) - volume 5
3. American Petroleum Institute, Refinery Practices, 520 and 521.

Information regarding statutory requirement and LAB flare system has been obtained from Mr. A. E. Patil (TS) and Mr. U. D. Deshpande (TS).

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11.0 QUESTIONNAIRE FOR VALIDATION

Following is a list of some of the questions which can be useful for validation of training on this module.

1. What is flaring ? Why is it required ?
2. What are different types of flares? What are the advantages and disadvantages associated with them ?
3. What are the components of a typical flare system ?
4. what are the causes which lead to overpressurization of a process system ?
5. How is the relieving load calculated in case of a external fire ?
6. How is the maximum load to be flared is arrived at ?
7. Describe the guidelines to estimate no. of flare headers in a plant.
8. Outline briefly the method of sizing the lines in a flare system.
9. How are the horizontal and vertical flare KO drums designed ?
10. What are the types of seals used in the flare system ?
11. What are the guidelines for seal leg sizing?
12. Describe the molecular seal which is utilized in the flare system.
13. How is the flare burner tip diameter is arrived at ?
14. What are the parameters which determine the flare stack height?
15. Explain briefly how the flare stack height and safe boundary is arrived at.
16. How are the ground level concentrations determined in case of flame blow out ?
17. What are different types of the stack supports ?
18. How is smokeless flame achieved in a flare system ?
19. how is the steam requirement for smokeless flare operation calculated ?

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20. What are the types of flare purging ? Why is purging required ?
21. What is typical instrumentation and control associated with a flare system ?
22. What are the steps in startup and shutdown of a flare system ?
23. What are the inspection checks carried out on the flare stack ?
24. What are the things, operations crew should monitor in the normal operation of the flare ?

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PATALGANGA TRAINING SYSTEM

Topic : Flare Systems

Module No. : TES-TS-P-014

Category : A1

Level : JMC

Location : Site

Sr. No.	CONTENTS	Author	Resources	Available	Learning		Validation		Trainer
				Y/N	Method	Hrs #	Method	Hrs #	
1	Requirement of flaring & types of flares	MGM	Chapter 1.0	Y	Self study	1	Quiz		
2	Components of the flare system	MGM	Chapter 2.0	Y	Self study	1	Quiz		
3	Determining vapour loads to be flared	MGM	Chapter 3.0	Y	Self study	2	Quiz		
4	Design of collection systems	MGM	Chapter 4.0	Y	Self study	2	Quiz/problem solving		
5	Designing the flarestack & accessories	MGM	Chapter 5.0	Y	Self study	6	Quiz/problem solving		
6	Other design considerations	MGM	Chapter 6.0	Y	Self study	2	Quiz		
7	Flare operations	MGM	Chapter 7.0	Y	Self study	2	Quiz		
8	Flares at RIL - PG	MGM	Chapter 8.0	Y	Self study	1	Quiz		
				(Total)		17	(Total)	2	

* - To be finalised

- Guestimated