# FLARE NETWORK

by: Ali Kiashemshaki

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# Selection of Disposal System

- General Strategy :

1. Review, define, and document all pressure relief systems and relief scenarios.

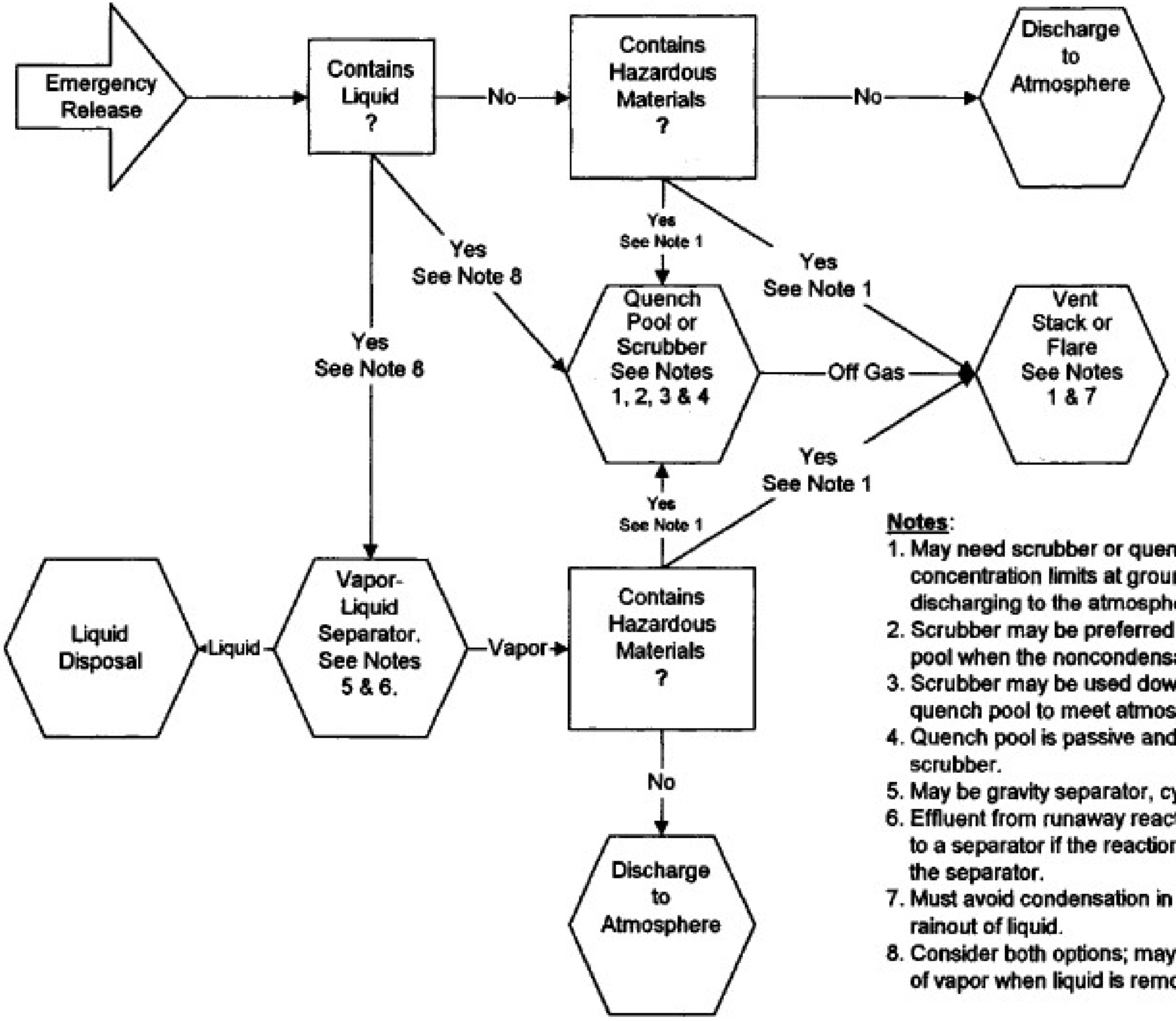
2. Estimate flow rates and quantities of hazardous materials that could be discharged from the pressure relief devices.

3. Evaluate the hazardous natures of released materials, and determine the maximum quantities that can be released directly to the atmosphere, or acceptable ground-level concentrations, considering the potential for fire or explosion, and effects on humans and the environment.

4. Select a treatment process or equipment to restrict the quantities, or ground-level concentrations, released to the atmosphere to meet the limits set in Step 3.

5. Design the equipment and ancillary facilities to meet the requirements of Step 3.

# Selection of Disposal System



<u>**Notes**</u>:

1. May need scrubber or quench pool to meet concentration limits at ground level when discharging to the atmosphere or to a flare.
2. Scrubber may be preferred over a quench pool when the noncondensable concentration is high.
3. Scrubber may be used downstream from quench pool to meet atmospheric discharge limits.
4. Quench pool is passive and lower cost than scrubber.
5. May be gravity separator, cyclone, or dump tank.
6. Effluent from runaway reactions can be discharged to a separator if the reaction will not continue in the separator.
7. Must avoid condensation in stack or flare to avoid rainout of liquid.
8. Consider both options; may get better dispersion of vapor when liquid is removed before quench pool.

# Selection of Disposal System

**Selection of Atmospheric or Closed Discharge for Pressure Relief Valves**

- Discharge to a Grade or sewer system :
  - This method routes the release stream directly to the ground or to a sewer system. The released material is recovered in a sewer treating system or must be cleaned up after a release. This method can generally be used for liquids which are non-hazardous and are not released in large quantities.
- Discharge to a Process Vessel :
  - This method returns a released fluid back into a process system operating at lower pressure than the system from which it was released. This method is attractive for streams that are unsuitable for grade or atmospheric release and usually does not require construction of collection or treating systems.

# Selection of Disposal System

**Selection of Atmospheric or Closed Discharge for Pressure Relief Valves**

- Discharge to a Closed Collection system :
  - This method discharges released fluids to a closed collection system. This system may treat or cool the release stream and either recover some or all of the material or route it to a remote location where it can be safely disposed of. This type of system can be a liquid blowdown system, an incinerator system, a flare system, a burn pit, or a vapor recovery system.

# Selection of Disposal System

**Discharge to Atmosphere**

- Release Criteria :
  - The release must be a vapor and be from a vapor space of a vessel that affords sufficient disengaging area that release of liquid or liquid entrainment by the vapor release is not a concern.
  - The release must be from a pressure device which will open only under emergency conditions. The release must not be a toxic substance. This is intended to mean a substance which is immediately toxic such as hydrogen sulfide or similar materials.
  - The released vapor should not condense or form a mist or droplets that may settle back to grade.

# Selection of Disposal System

**Discharge to Atmosphere**

- Liquid Release :
  - Liquids should never be released to atmosphere, but in some cases liquid releases from pressure relief devices may be directed to a safe containment area at ground level.
  - Cool or warm water streams (less than 60 °C) may be directed to grade irrespective of quantity. Hot water or streams that may flash should be routed to a suitable flash drum.
  - A liquid stream may be considered hazardous because of its potential to flash or vaporize and thereby create a fire or explosion hazard, or because it is toxic, corrosive or otherwise unacceptable to allow it to be released to grade. Such liquids should be routed to a containment system

# Selection of Disposal System

**Discharge to Atmosphere**

Two-Phase Release :

- Releases that may be combined vapor/liquid releases should be treated as liquid releases and routed to the appropriate disposal location.
- Generally, two phase releases are not safe to route directly to atmosphere and should be routed to a closed system. If both the vapor and liquid phases are nonhazardous and the quantity of potential release is acceptable, grade disposal may be considered.

# Selection of Disposal System

**Discharge to Atmosphere**

Prevention of Liquid Release :

- Occasionally, conditions are encountered where a liquid or liquid-bearing release will occur only in very unlikely situations.

  - The potential hazard if the release does occur must be assessed. If an immediately hazardous condition (such as release of volatile liquids to grade) would be created, alternate disposal methods should be considered.
  - If the release occurs, the cause of the release must be readily correctable. If the cause of the release cannot be rapidly and simply eliminated, alternate disposal methods should be considered.
  - Additional controls and interlocks to minimize the chances of a liquid release occurring should be added. These may take the form of a high level cut-off or bypass or back-up control paths to either restrict fluid entering the system or to significantly increase the flow of fluid leaving the system.

# Selection of Disposal System

**Discharge to Atmosphere**

Prevention of Liquid Release :

- An example of this type of application is a feed surge or flash drum which may have a non-volatile liquid release if the drum were to fill up with liquid. If all other potential releases are vapors suitable for release to atmosphere, assuming the risk of a liquid release may be acceptable if the criteria in previous slide are met.

Discharge to Process

- Routing of a pressure relief stream back into a process rather than to the environment or to a disposal system may be the most economical and safest alternative for many streams.

- Considerations :
  - Capacity
  - Destination Pressure
  - Process Upsets
  - In-Service Requirements

# Selection of Disposal System

**Closed Disposal System**

- These collection systems may have sources from normal design releases from processes (such as those from a process into a fuel gas system), emergency controlled releases from pressure control and depressuring systems or emergency releases from pressure relief devices.

- The major disadvantage of closed systems is their cost, the need to provide enough capacity for all potential release cases and the maintenance and operating attention they require.

- Discharge to a Closed System is Required for PR valves in the following categories:

1. PR valves handling materials which are liquid or partially liquid at the valve inlet. An exception to this is made for certain thermal expansion relief.

2. PR valves normally in vapor service, but which under any design contingency may discharge flammable, corrosive or hazardous liquids.

# Selection of Disposal System

## Discharge to a Closed System

3. PR valves located in the vapor space of partially liquid-filled vessels when liquid overfill as a cause of overpressure is a design contingency.

4. PR valves handling, flammable, toxic or corrosive vapors which condense at ambient conditions, e.g., phenol or flammable vapors with an average molecular weight greater than 100 (since they may condense).

5. PR valves in toxic vapor services where discharge to the atmosphere would result in the calculated concentration at any working area (either at grade or an elevated platform) exceeding the Short Term Exposure Limit (STEL).

6. Release of flammable vapors which would result after dilution with air in a fuel-air mixture with a concentration above 50% of Lower Flammability Limit (LFL) at grade or any frequently accessed platform or equipment.

7. Releases of flammable vapors which, if discharged to the atmosphere, would in the event of inadvertent ignition, result in radiant heat densities in excess of the permissible exposure level (6000 Btu/h ft2 or 19 kW/m2) for personnel at grade or a frequently manned platform. Note that increasing the height of the riser to reduce radiant heat densities is an acceptable alternative to discharge to a closed system.

# Selection of Disposal System

## Type of Closed Release Systems

- 1. Conventional Flare System - The majority of pressure relief devices discharges must be routed to the flare through a closed system consisting of laterals, headers, and a blowdown drum.
- 2. Condensable Blowdown Drum with Atmospheric Vent - Releases which can be totally condensed may be routed through a closed release system consisting of laterals, headers and a condensable blowdown drum, which may be vented to the atmosphere provided that the criteria defined in atmospheric release are met.
- 3. Closed Systems for Special Services - Special closed systems are also provided for PR device releases in certain services where operating problems or hazards would result from discharge into the regular flare header. Such services include severely toxic, corrosive, polluting, or high-cost materials; and the following are examples of the special facilities required.
- 4. Segregated H2S Flaring System - Continuous releases (greater than 30 minutes) of hydrogen sulfide are normally routed to a segregated H2S flare system to remove a potential source of plugging from the regular flare system.

# Selection of Disposal System

## Design Temperatures of Closed Release System

- The design temperatures of a header or lateral in the closed release system are set by the extremes of the emergency operating temperatures which can result from any of the streams tied into it.
- The design maximum temperature to be used for analyzing stress in the relief system piping is the highest temperature achieved downstream of the relief valves.
- Generally, fire relief cases establish this design temperature for laterals from the relief valve to the subheader. Fire relief case temperatures are normally not considered in establishing pipe wall thickness.
- The design temperature selected above may be reduced in the downstream piping by calculating heat loss to be ambient air. This may be performed in several zones to reduce the need for large expansion joints associated with elevated temperatures. This credit is to be applied to pipe stress only and not to hydraulic calculations.
- If materials are handled at temperatures below 60°F (15°C) or if they can auto-refrigerate to below 60°F (15°C), a minimum design temperature must also be specified.
- Where laterals of different piping materials are combined, the material of the lower-temperature header is continued for the rest of the combined line, and is also extended back into the other lines for **20 ft (6 m).**

# Selection of Disposal System

## Design Pressure of Closed Release System

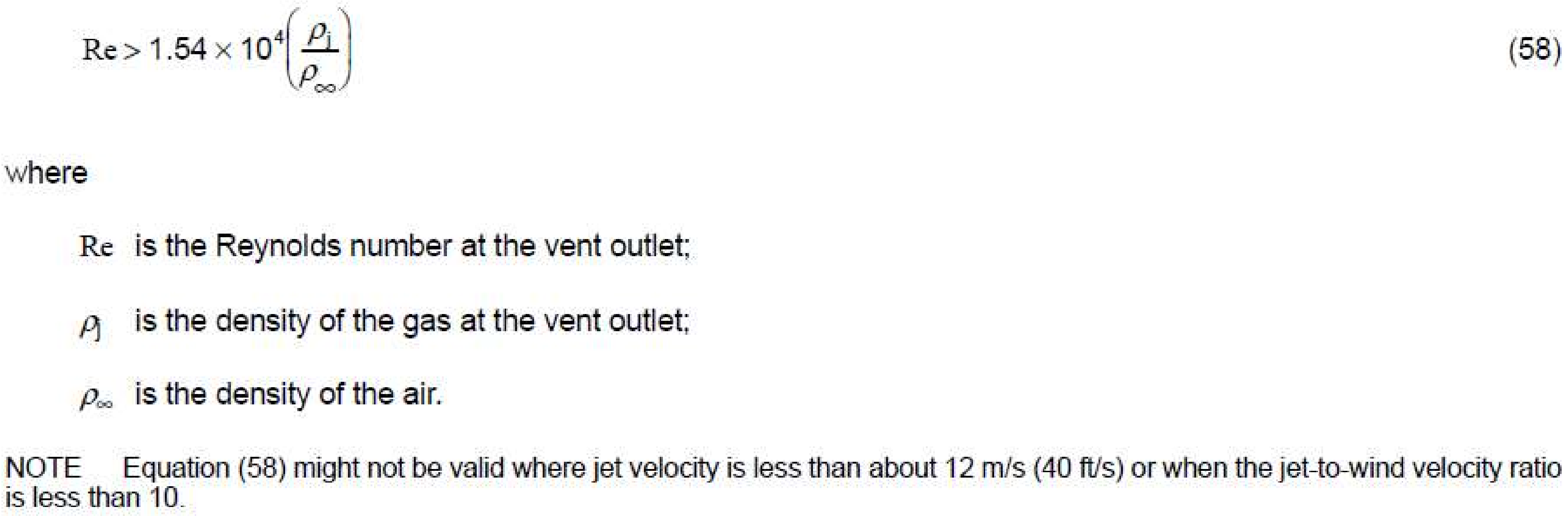
- The minimum recommended design pressure for piping is 50 psig (3.5 barg) to correspond to the K.O. drum design pressure.
- This minimum is to be raised, if necessary, to provide a margin of 10% over the maximum pressure calculated for the design relieving case.
- Due to the significant pressure drop associated with relief valve discharge laterals, a design pressure for the main relief header lower than the lateral is acceptable where significant cost savings are anticipated.
- Flare header systems are generally proven by weld x-rays and/or by air/nitrogen testing. Hydrotesting is rarely used and is not recommended for large header systems.

# Selection of Disposal System

## Design Criteria for Atmospheric Releases

- The release point must be located such that nearby personnel and equipment are not endangered. This generally means that the release must be at least **3 meters** above any platform or ladder within a **8 meter radius** of the release point. Pressure-relief-valve stacks that discharge to the atmosphere at least **15 m (50 ft) horizontally** from any structures or equipment running to a higher elevation than the discharge point should be considered.

- The release outlet piping must be sized for adequate dispersion. API RP 521 provides some guidelines which are based upon the exit Reynolds' number :



$$\mathrm{Re} > 1.54 \times 10^4 \left( \frac{\rho_j}{\rho_\infty} \right) \tag{58}$$

where

$\mathrm{Re}$ is the Reynolds number at the vent outlet;

$\rho_j$ is the density of the gas at the vent outlet;

$\rho_\infty$ is the density of the air.

NOTE Equation (58) might not be valid where jet velocity is less than about 12 m/s (40 ft/s) or when the jet-to-wind velocity ratio is less than 10.

This evaluation should be performed at the minimum stable relief device flow. For spring opposed pressure relief valves, this is 25% of capacity.

# Flare Network

## Design of Flare System

- Design of flare systems consists of the following major activities :

  1-Identification and quantification of the simultaneous flow rates which may enter the system.

  2-Sizing of flare headers and design of required supports.

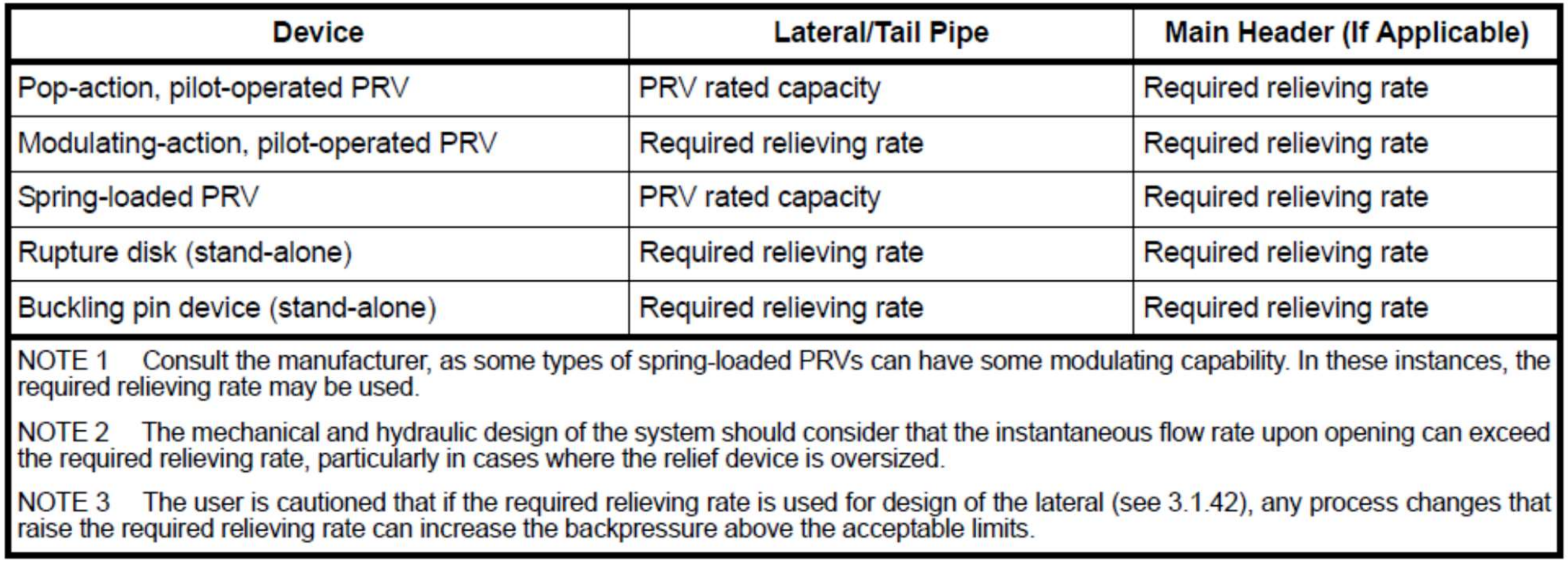
  3-Sizing of liquid knock-out drums and pump-out capacity.

  4-Sizing and selection of the flare.

# Flare Network

## Design Criteria for Relief Headers

1. Common header systems and manifolds in multiple device installations are generally sized based on the worst-case cumulative required capacities of all devices that may reasonably be expected to discharge simultaneously in a single overpressure event.



| Device | Lateral/Tail Pipe | Main Header (If Applicable) |
|---|---|---|
| Pop-action, pilot-operated PRV | PRV rated capacity | Required relieving rate |
| Modulating-action, pilot-operated PRV | Required relieving rate | Required relieving rate |
| Spring-loaded PRV | PRV rated capacity | Required relieving rate |
| Rupture disk (stand-alone) | Required relieving rate | Required relieving rate |
| Buckling pin device (stand-alone) | Required relieving rate | Required relieving rate |

NOTE 1 Consult the manufacturer, as some types of spring-loaded PRVs can have some modulating capability. In these instances, the required relieving rate may be used.

NOTE 2 The mechanical and hydraulic design of the system should consider that the instantaneous flow rate upon opening can exceed the required relieving rate, particularly in cases where the relief device is oversized.

NOTE 3 The user is cautioned that if the required relieving rate is used for design of the lateral (see 3.1.42), any process changes that raise the required relieving rate can increase the backpressure above the acceptable limits.

# Flare Network

## Design Criteria for Relief Headers

2. The maximum superimposed back pressure for non-discharging PR valves during a maximum system release (from either single or multiple valve releases under a design contingency) shall not exceed backpressure limits for any PRV in the system.

3. Where the ratios of pressure relief valve set pressures in a system are in the order of 5 to 1 or higher, the feasibility and economy of separate high and low pressure collection headers should be investigated.

4. There is no definite velocity limitations which should be used for sizing flare main and sub headers. A general value of 0.5 Mach is usually selected as sizing basis.

# Flare Network

## Design Criteria for Flare Headers

5. The basic criteria for sizing the relief header is that the back pressure, which may exist or be developed at any point in the system, does not reduce the relieving capacity of any of the pressure-relieving devices below the amount required to protect the corresponding vessels from overpressure.

6. The Following criteria for Mach no. should be followed:

*Intermittent Gas flow :*

lines downstream relieving devices, sub-headers and headers: 0.5-0.7 Mach
Velocity of 0.8 Mach could be accepted for a long straight line without elbows and connections ( e.g. stack, line on bridge ).

*Continuous flow :*

Velocity < 0.35 Mach

*Two-Phase Flow ( 2 phase flow at the inlet of relieving device)*

Velocity < 0.25 Mach

# Flare Network

## **Design Criteria for Flare Headers**

7. The Following criteria for Rho-V2 should be followed:

   *Intermittent Gas flow* : Rho.V2 <150000 Kg/m/s2

   *Continuous Gas Flow* : Rho.V2<50000 Kg/m/s2 ,

   *Two-Phase Flow* : Rho.V2<50000 Kg/m/s2 , Velocity < 0.25 Mach

8. The noise from safety/relief valves and high-rate depressuring valves (and their piping) which blow ***under emergency conditions only***, shall not exceed the **absolute limit** in any work area. (IPS-G-SF-900)
   The sound pressure level anywhere in the work area shall not exceed 115 dB(A) in any situation (absolute limit ), including emergencies such as blowing of safety/relief valves.

# Flare Network

## Design Criteria for Flare Headers

8. The following guidelines apply to relief valves which discharge to a collection header system:

- Top entry into the header is preferred over side or angle entry. Entering at a **45° angle** in the direction of main flow is common for the relief valve discharge pipes, however, it is not mandatory.
- Pressure relief valves are normally located at a higher elevation than the header to provide drainage.
- Discharge piping from relief devices which are located below the header is to be arranged to rise continuously to the header entry point. A drain discharging to a safe location is required at the piping low point.
- Relief system headers that may be in contact with liquid are to be sloped to knockout drums. The minimum slope is **8.3 in/330 ft (21 cm/100 m)** of piping length taking into account piping deflections between supports. Traps or other devices with operating mechanisms cannot be used for liquid knockout service.

# Flare Network

## Design Criteria for Flare Headers

- If the outlet configuration results in a calculated back pressure in excess of allowable values, then the following options can be considered as a next step. The order of consideration will depend upon the nature of the job. Design of new piping will be approached differently from a review of existing piping.

1. Increase outlet line size.
2. Change valve selection for lower orifice/outlet area ratio valve(s) which still meet relief load requirements.
3. Work with Piping to reduce outlet line length and/or number of fittings.
4. Work with the Instrument Engineer to determine if back pressure can be increased for balanced bellows or pilot operated PSVs.
5. Change valve selection to a type more tolerant of back pressure.
6. Obtain client and vendor agreement to exceed allowable back pressure (conventional valves).

# Flare Network

## Design of Flare Headers – Calculation Details

- Several methods can be used to calculate the size of discharge piping when the flow conditions are known. These range from treating the flow as ***isothermal*****,** with appropriate allowances for kinetic energy effects, to the more rigorous solutions afforded by the ***adiabatic*** approach.

- The isothermal equations are generally used for flare system evaluation, since this approach gives the most conservative results. Actual flow conditions in relief systems are normally somewhere between isothermal and adiabatic conditions.

- The adiabatic flow equations can be preferable for some less-common applications (e.g. cryogenic conditions).

- For two phase flow conditions, typically a two-phase pressure-drop method, such as Beggs and Brill or the homogeneous equilibrium method (HEM) may be used.

# Flare Network

## Design of Flare Headers – Calculation Details

- The sizing of relief-discharge piping can usually be simplified by starting at the system outlet, where the pressure is known, and working back through the system to verify, acceptable back pressure at each pressure relief device.
- Calculations are performed in a stepwise manner for each pipe segment of constant diameter.

ISOTHERMAL (Pressure Drop):

$$\frac{f \cdot l}{d} = \frac{1}{Ma_2^2}\left[\left(\frac{p_1}{p_2}\right)^2\right]\left[1-\left(\frac{p_2}{p_1}\right)^2\right] - \ln\left(\frac{p_1}{p_2}\right)^2$$

| | |
|---|---|
| $f$ | is the Moody friction factor, dimensionless; |
| $l$ | is the equivalent length of pipe, expressed in metres (feet); |
| $d$ | is the pipe inside diameter, expressed in metres (feet); |
| $Ma_1$ | is the Mach number at pipe inlet; |
| $Ma_2$ | is the Mach number at pipe outlet; |
| $p_1$ | is the pipe inlet absolute pressure, expressed in kilopascals (pounds per square inch); |
| $p_2$ | is the pipe outlet absolute pressure, expressed in kilopascals (pounds per square inch). |

# Flare Network

## Design of Flare Headers – Calculation Details

ISOTHERMAL (Mach. No):

In SI units:

$$Ma_2 = 3{,}23 \times 10^{-5} \left( \frac{q_m}{p_2 \cdot d^2} \right) \left( \frac{Z \cdot T}{M} \right)^{0{,}5}$$

In USC units:

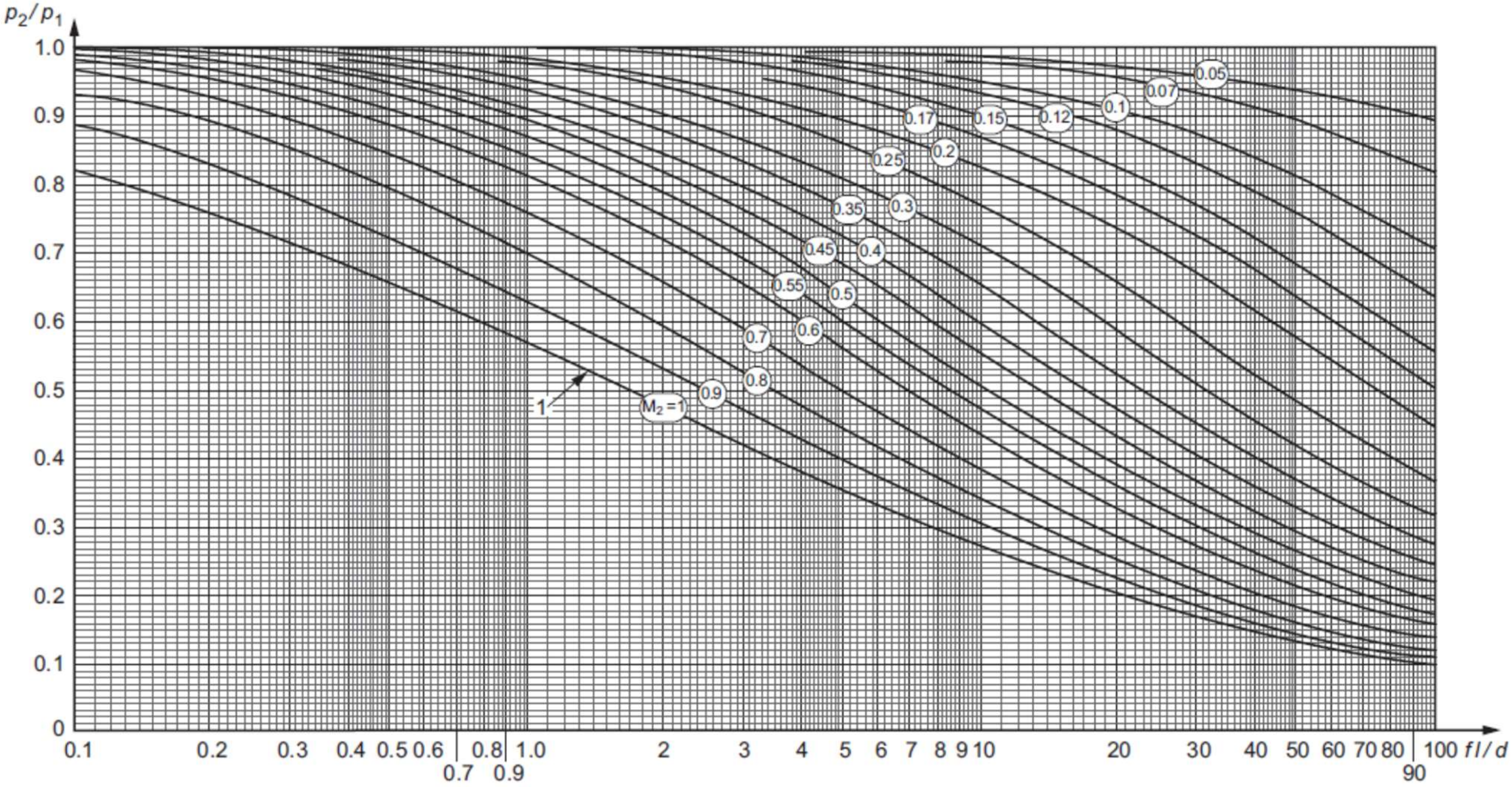
$$Ma_2 = 1{,}702 \times 10^{-5} \left( \frac{q_m}{p_2 \cdot d^2} \right) \left( \frac{Z \cdot T}{M} \right)^{0{,}5}$$

where

| | |
|---|---|
| $q_m$ | is the gas mass flow rate, expressed in kilograms per hour (pounds per hour); |
| $Z$ | is the gas compressibility factor; |
| $T$ | is the absolute temperature, expressed in kelvin (degrees Rankin); |
| $M$ | is the gas relative molecular mass. |
| $d$ | is the pipe inside diameter, expressed in metres (feet); |
| $p_2$ | is the pipe outlet absolute pressure, expressed in kilopascals (pounds per square inch). |

# Flare Network

## Design of Flare Headers – Calculation Details



**Key**

1 critical flow line

# Flare Network

## **Design of Flare Headers – Calculation Details**

- Procedure :

1-Gather flare system data such as UFDs, P&IDs, plot plans, isometric drawings, and a PSV summary list.

2- Prepare a flare system sketch.

3- Use the flare system data to develop the required input data to the program.

4- Build and debug the model (Using spreadsheet or commercial softwares like FLARENET or VISUALFLOW).

5- Review and document model results. Indicate flow and backpressure at each PSV and other critical locations.

6- Identify any system deficiencies. Verify that the backpressure at the outlet of each relieving PSV is acceptable. Also check velocity, Rho-V2 and Noise.

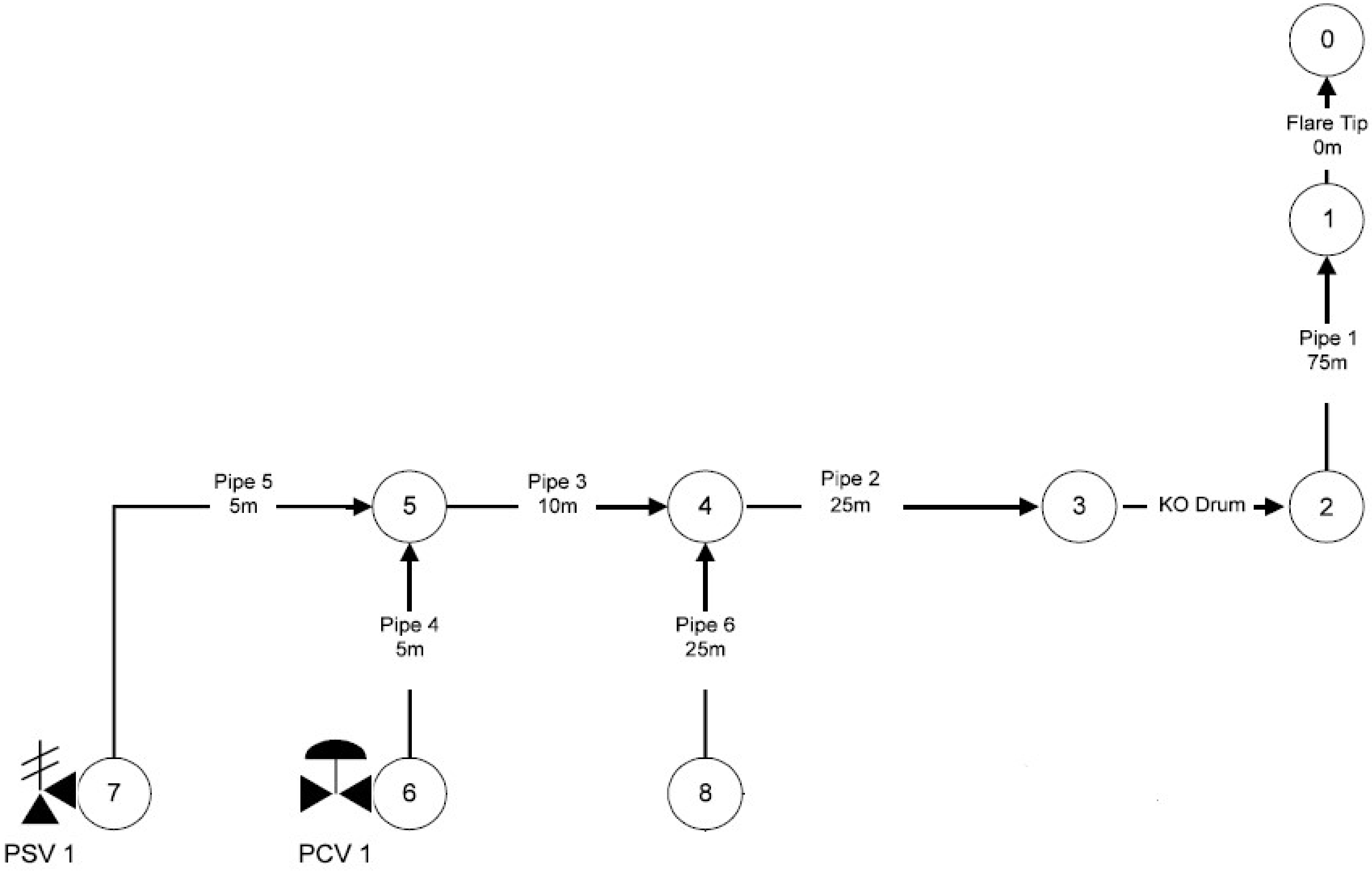
# Flare Network

## Introduction to FlareNet

- FLARENET has been designed to facilitate the design and rating of flare and vent system piping throughout the entire design process.
- The program interface uses a flow diagram for direct visualisation of the piping network supported by detailed tables of all pertinent data and calculated results.
- FLARENET allows the ability to design a grass roots flare system, rate an existing design or to debottleneck existing systems with a view to plant expansion.

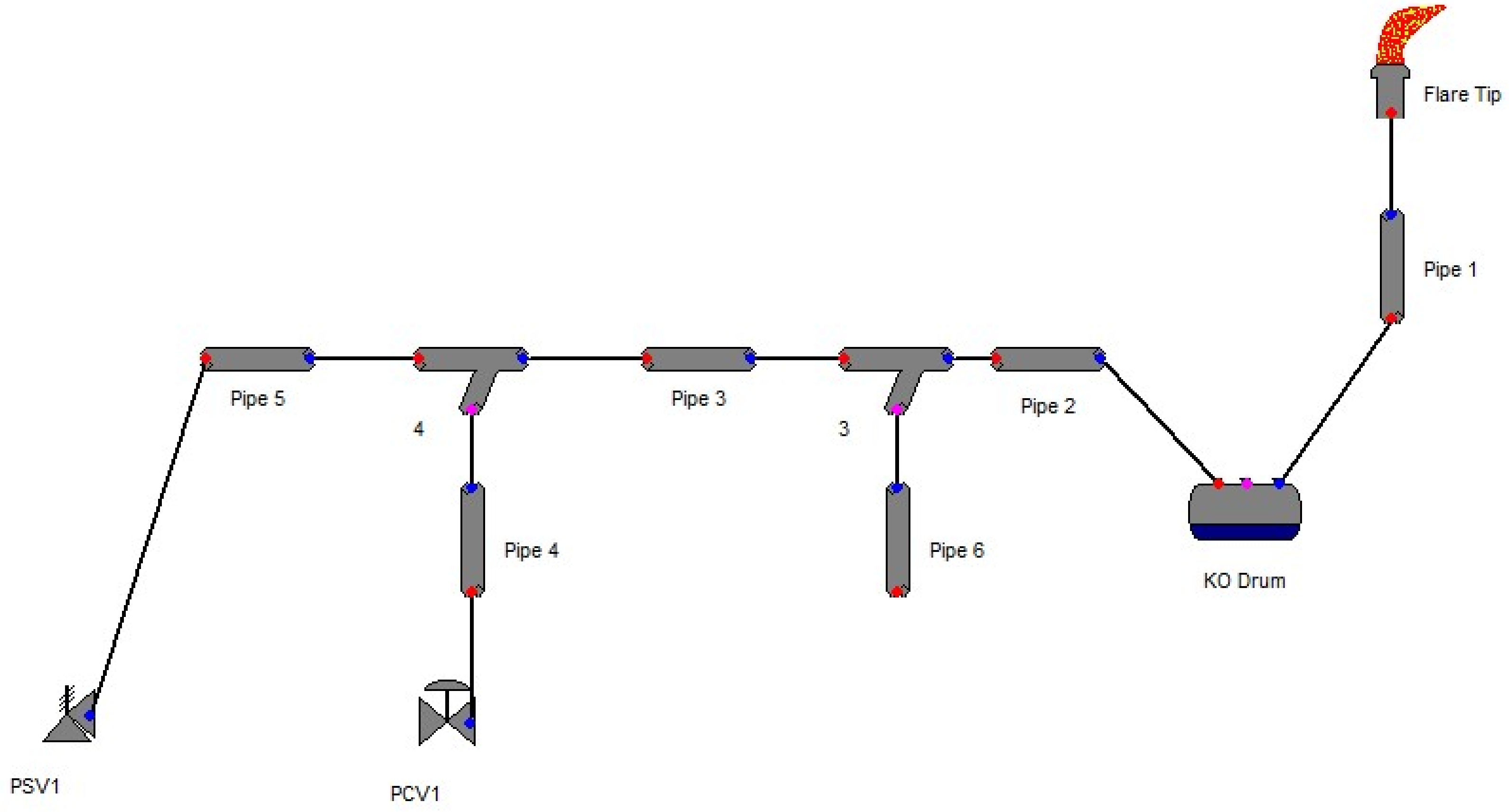
# Flare Network

## Schematic of a Typical Flare System



# Flare Network

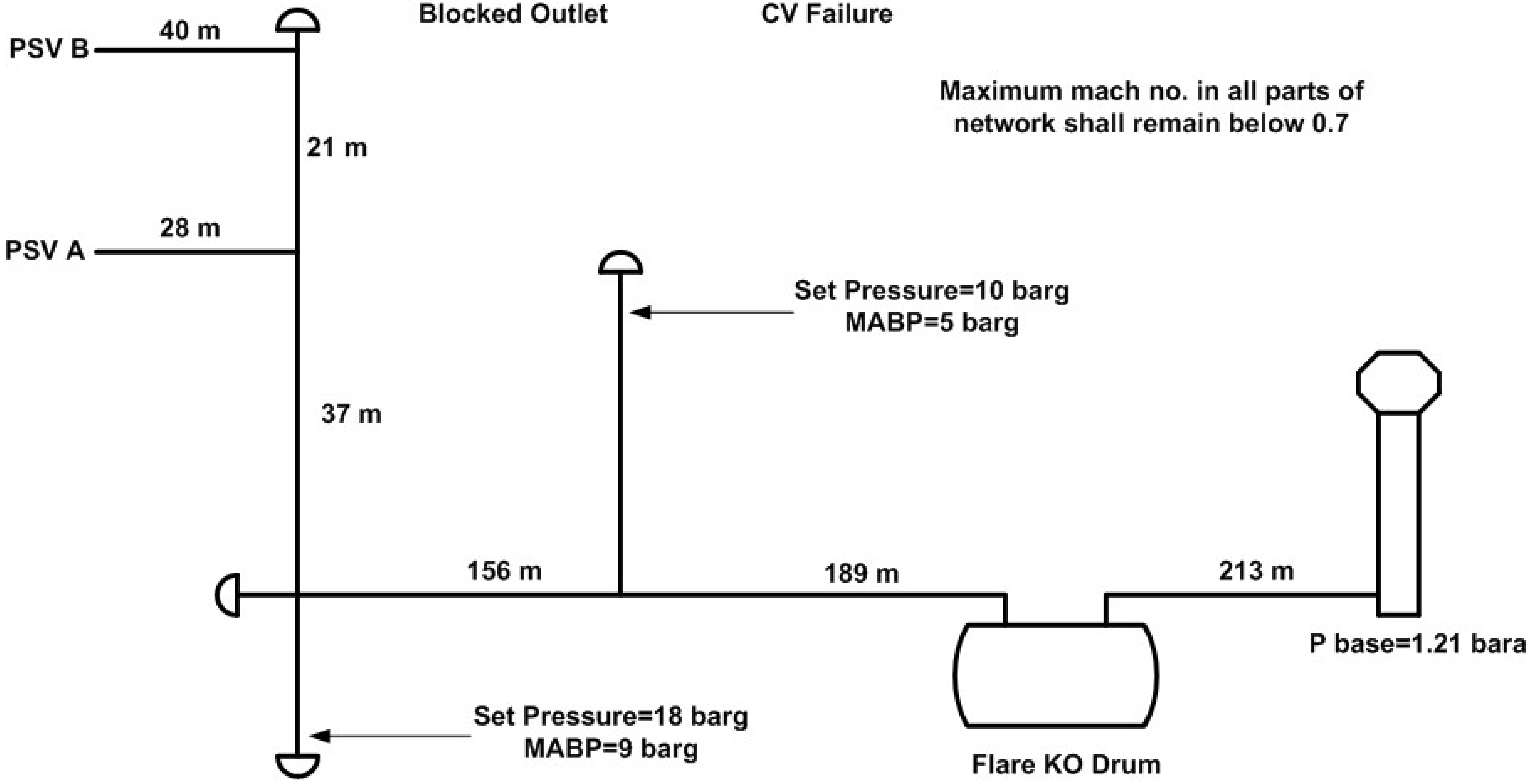
## FLARENET Schematic Example



# Flare Network

**PSV B**
W=168676 kg/h
Set P=107 barg
T=136°C
Cp/Cv=1.34
MW=22
Blocked Outlet

**PSV A**
W=200423 kg/h
Set P=107 barg
T=60°C
Cp/Cv=1.55
MW=21.28
CV Failure



Maximum mach no. in all parts of network shall remain below 0.7

Set Pressure=10 barg
MABP=5 barg

Set Pressure=18 barg
MABP=9 barg

# Design of Flare Drums and Seals

- Four types of vessels or drums are typically used in the design of flare systems for specific reasons:

  - Knockout drum (Liquid/Gas Separator)
  - Blowdown drum (Liquid holdup)
  - Seal drum (To prevent the air ingression into the flare system to avoid explosion)
  - Quench drum (Condenser/Cooler)

## Knockout drum :

- Flare systems generally require a flare knockout drum to separate liquid from gas in the flare system and to hold the maximum amount of liquid that can be relieved during an emergency situation.

- Knockout drums are typically located on the main flare line upstream of the flare stack or any liquid seal.

- If there are particular pieces of equipment or process units within a plant that release large amounts of liquid to the flare header, it is desirable to have knockout drums inside the battery limits to collect these liquids (on-plot).

# Design of Flare Drums and Seals

**Knockout drum :**

- The location of the flare knockout drum should consider the following:
    a) condensation of vapor or agglomeration of liquid droplets if there is a long line between the flare knockout drum and the flare stack resulting in increased liquid droplet size,
    b) personnel access for maintenance on the knockout drum during normal and emergency flaring,
    c) thermal radiation effects on flare knockout drum instrumentation and necessity for thermal shielding.

- The economics of drum design can influence the choice between a horizontal and a vertical drum. If a large liquid storage capacity is desired and the vapor flow is high, a horizontal drum is often more economical. Also, the pressure drop across horizontal drums is generally the lowest of all the designs.

- Vertical knockout drums are typically used if the liquid load is low or limited plot space is available. They are well suited for incorporating into the base of the flare stack

# Design of Flare Drums and Seals

**Knockout Drum :**

- A split-entry or -exit configuration can be used to reduce the drum diameter (but increase the length) for large flow rates and should be considered if the vessel diameter exceeds 3,66 m (12 ft).
- Careful consideration should be given to the hydraulics of split-entry configurations to ensure the flow is indeed split in the desired proportion.
- Inlet nozzles should include means such as baffles or long sweep elbows to prevent re-entrainment of liquid. Long sweep elbows are typically used up to DN 300 (NPS 12) inlet diameter. Baffles are typically used for larger inlet diameters.
- There is no restriction on inlet or outlet velocity, except that the back pressure developed in the relief system discharge should not adversely affect the capacity or operation of the pressure relief device. Lower velocity tends to reduce the break-up of liquid into smaller droplets.
- For segregated cold and warm flare headers, separate dry and wet flare knockout drums are provided due to different piping material’s requirement.

# Design of Flare Drums and Seals

## Knockout Drum :

- The function of the knockout drum is to provide residence time for liquid discharges and to limit the size of droplets directed to the liquid seal drum (if present) or the flare burner.
- Large liquid droplets and liquid loading can cause smoke, liquid droplets (burning or not burning) to be released from the flare, or mechanical damage.
- The phenomenon generally referred to as “burning rain” occurs when a liquid hydrocarbon droplet does not burn completely within the flare flame envelope and the rate of burning is lower than the rate of settling of the liquid droplet.
- Liquid can accumulate along the pipe walls and low points in flare piping due in part to condensation as well as where flare gas velocities are too low to overcome drag forces of any liquid mist or droplets in the system.
- Liquid droplets 300 µm and larger may drop out of the gas stream at less than 2 m/s. If liquids are not drained from the system, flare flows with gas velocities exceeding about 3 m/s or 4 m/s can entrain liquid droplets up to 1000 µm in size.
- Liquid droplets exceeding 1000 µm can readily lead to burning rain regardless of flare type. Burning rain can occur at smaller droplet sizes for some flare types.

# Design of Flare Drums and Seals

## Knockout Drum :

- Flare burners with smoke suppression technology or those operating at high discharge velocity (i.e. ≥ 0.5 Mach) promote complete combustion of liquid droplets.
- Flare burners that operate at lower discharge velocity, handle high relative molecular mass liquid components, and/or contain high viscosity liquid droplets will be far less effective at burning liquid droplets.
- The following is general guidance on droplet size and liquid loadings for several types of flare burners.

a) Unassisted Flare Burners—Large liquid droplets cannot be handled smokelessly without smoke-suppression equipment. Burning rain is generally considered possible in an unassisted pipe flare for liquid droplets with a diameter of 600 μm or larger.

b) Steam-assisted and Air-assisted Flare Burners—Flare gases containing less than 1 % by mass of liquids up to a liquid droplet size of 600 μm can be handled smokelessly and without burning rain. Some air assisted burners with small ports and operated at significant pressures can handle larger amounts, and with larger droplet size, without smoke.

c) High-pressure (i.e. Sonic Type) Flare Burners—If operated at gauge pressures of at least 200 kPa (30 psi), these flare burners can handle flare gases containing 1 % by mass of liquids up to a liquid droplet size of 1000 μm, without smoke.

# Design of Flare Drums and Seals

## Knockout Drum :

- Knockout drum design parameters & procedure:
- The flare vendor should be consulted to specify the maximum allowable liquid droplet size and loading specific to their equipment and flaring conditions.
- Sizing a knockout drum is generally a trial-and-error process. The first step is to determine the drum size required for liquid entrainment separation. Liquid particles separate :

  (a) when the residence time of the vapor or gas is equal to or greater than the time required to travel the available vertical height at the dropout velocity of the liquid articles and

  (b) when the gas velocity is sufficiently low to permit the liquid dropout to fall. This vertical height is usually taken as the distance from the maximum liquid level.

# Design of Flare Drums and Seals

**Knockout Drum**

- The dropout velocity expressed in meters per second (feet per second) of a particle in a stream is calculated from :

$$u_c = 1.15\sqrt{\frac{g \cdot D(\rho_l - \rho_v)}{\rho_v \cdot C}}$$

where

$g$ is the acceleration due to gravity [= 9.8 m/$s^2$ (32 ft/$s^2$)];

$D$ is the particle diameter, expressed in m (ft);

$\rho_l$ is the density of the liquid at operating conditions, expressed in kg/$m^3$ (lb/$ft^3$);

$\rho_v$ is the density of the vapor at operating conditions, expressed in kg/$m^3$ (lb/$ft^3$);

$C$ is the drag coefficient (see Figure 12).

# Design of Flare Drums and Seals

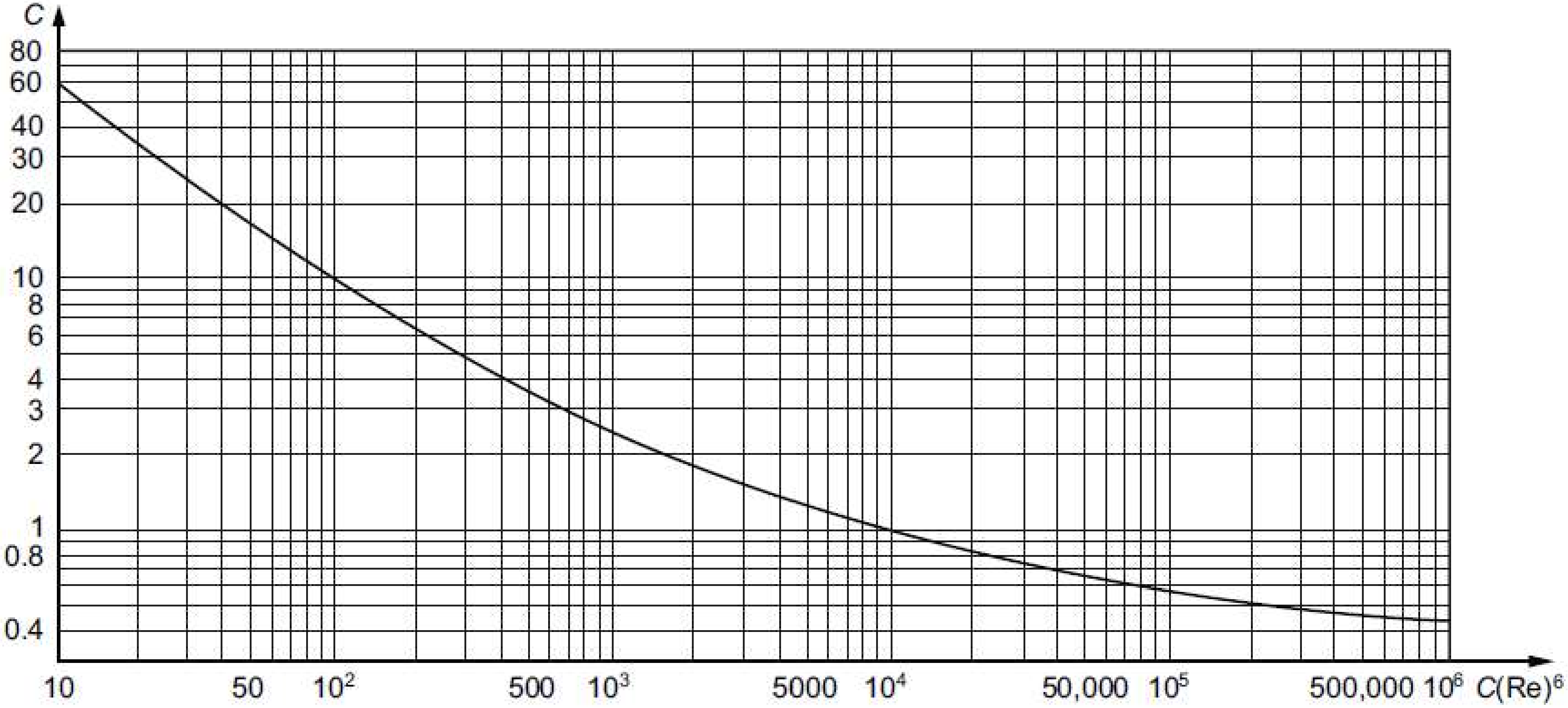


**Figure 12—Determination of Drag Coefficient**

$$C(\mathrm{Re})^2 = \frac{0.13 \times 10^8 \rho_v D^3 (\rho_l - \rho_v)}{\mu^2}$$

$\mu$ is the viscosity of the gas, expressed in millipascal-seconds (centipoise)

$\rho_v$ is the density of the gas, expressed in kg/m$^3$

$\rho_l$ is the density of the liquid, expressed in kg/m$^3$

$D$ is the particle diameter, expressed in m

# Design of Flare Drums and Seals

## Knockout Drum

- The second step in sizing a knockout drum is to consider the effect any liquid contained in the drum can have on reducing the volume available for vapor liquid disengagement. This liquid may result from

  a) condensate that separates during a vapor release, or
  b) Liquid streams that accompany a vapor release.

- The volume occupied by the liquid should be based on a release that lasts 20 min to 30 min. Longer hold-up times can be required if it takes longer to stop the flow.

- It is important to realize as part of the sizing considerations that the maximum vapor release case might not necessarily coincide with the maximum liquid. Therefore, the knockout drum size should be determined through consideration of both the maximum vapor release case as well as the release case with the maximum amount of liquid.

- If no valid liquid case exists and the vapor is either condensable or has a condensable component, then the design liquid case should be a minimum of 2 wt % of the maximum gas rate to the flare knockout drum.

# Design of Flare Drums and Seals

## Knockout Drum Sizing

- The sizing case for an on-plot knock-out drum will generally (but not always) be the provision of liquid hold-up.
- The sizing case for a flare knock-out drum may be:

a) the provision of liquid hold-up (if there is no on—plot knock-out drum)

b) the provision of vapor/liquid separation capacity (if there is no significant vapor condensation).

c) the provision of both liquid hold-up and vapor/liquid separation capacity if the governing case comprises a two-phase flow (two-phase relief or the result of vapor condensation)

- The maximum design liquid level shall be 50 percent. The maximum design liquid level will typically be tower unless the flare gas contains significant condensable components.

- Where a flare knock-out drum is provided downstream and there is a strong incentive to minimize the drum diameter, the maximum liquid level for an on-plot knock-out drum may be relaxed to 80 percent, consistent with the provision of any necessary vapor/liquid separation capacity.

# Design of Flare Drums and Seals

## Knockout Drum Sizing

- It shall be possible to pump out the maximum anticipated liquid inventory to the specified low level within two hours.
- For the purpose of sizing the pump:
    - the minimum liquid level (LAL) shall normally be assumed to be 300 mm (12 inches);
    - the maximum anticipated liquid level shall be assumed to be a minimum of 50 percent of the drum diameter.
- Where a flare KO drum is provided downstream and there is a strong incentive to minimize the drum diameter, the maximum liquid level for an on-plot KO drum may be relaxed to 80%, consistent with the provision of any necessary vapor / liquid separation capacity.
- An independent high level alarm shall be provided as an ultimate warning of the drum overfilling and the possible need to consider a process unit shutdown.
- The alarm setting shall typically be between 80 and 90 percent of drum diameter, consistent with providing a free path allowing unrestricted flare gas flow through the drum.

# Design of Flare Drums and Seals

## Knockout Drum Sizing

- IA Client may require pump operation to be manual. However, unless otherwise instructed, automatic pump operation on the following basis should be used.

1. LAH — service pump cuts in

   LAH should be set to give a pump-out time of around 30 minutes to LAL (time period is not critical).

2. LAHH — stand-by pump cuts in

   This should be ~5 minutes after LAH at pump-out capacity.

3. LAL — pump trips

   LAL should be a minimum distance above the heating coil (if provided) to ensure that the coil is always totally immersed.

4. LALL — pump has not tripped and manual shutdown is required to prevent damage on loss of suction

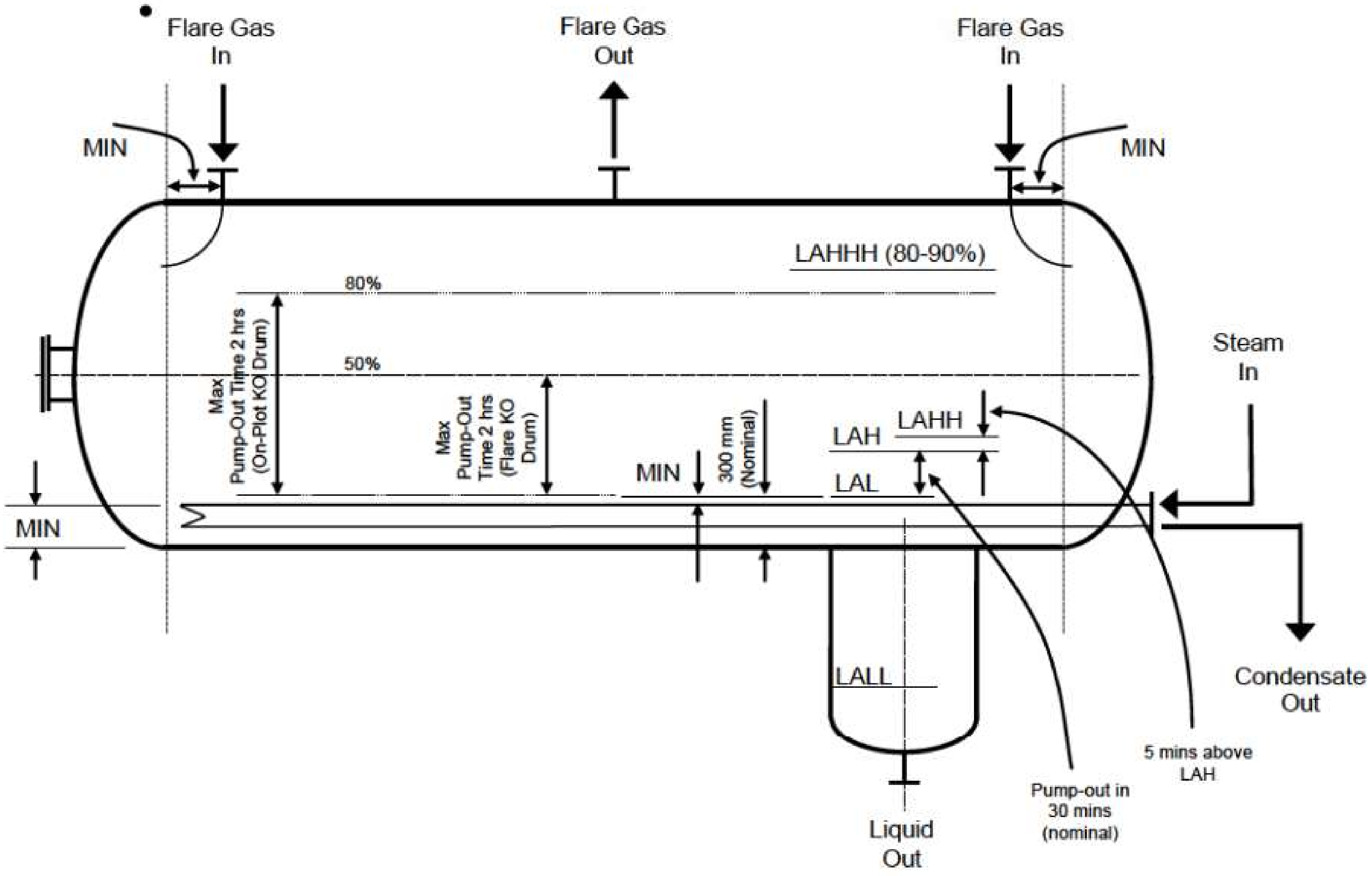
5. LAHHH — independent high level alarm warning that drum is about to overfill LAHHH should be set at 80-90 percent level.

6. TAH — locks out pump

7. TAL — indicates that steam coil should be commissioned.

# Design of Flare Drums and Seals

## Knockout Drum Sizing



# Design of Flare Drums and Seals

**Knockout Drum**

- Procedure of sizing Flare KO Drum :

  - Assume Drum diameter and length of drum, L=2.5D or L=3D
  - $A_L = Q_L \times t / (L.N)$ t: Liquid Holdup Time
  - $A_T = \pi D^2/4$
  -Calculate $A_L/A_T$ and obtain $h_L/D$ from tables or below equation:
  $A_L/A_T=(\theta - \sin\theta)/(2\pi)$ and $\theta = 2 \arccos(1-2 h_L/D)$, θ in radians

  - $h_V = D - h_L$
  - $\varphi = h_V / U_c$
  - $A_V = A_T - A_L$
  - $U_V = Q_V / (A_V.N)$ N: number of inlet or outlet nozzles
  - $L_{Req} = U_V.\varphi.N$

- If $L_{Req}$ is greater than L, increase the drum diameter and repeat the $L_{Req}$ calculations again until $L_{Req}$ is less than L.

# Design of Flare Drums and Seals

## Knockout Drum

- Example for sizing Flare KO Drum :

The following conditions are assumed.

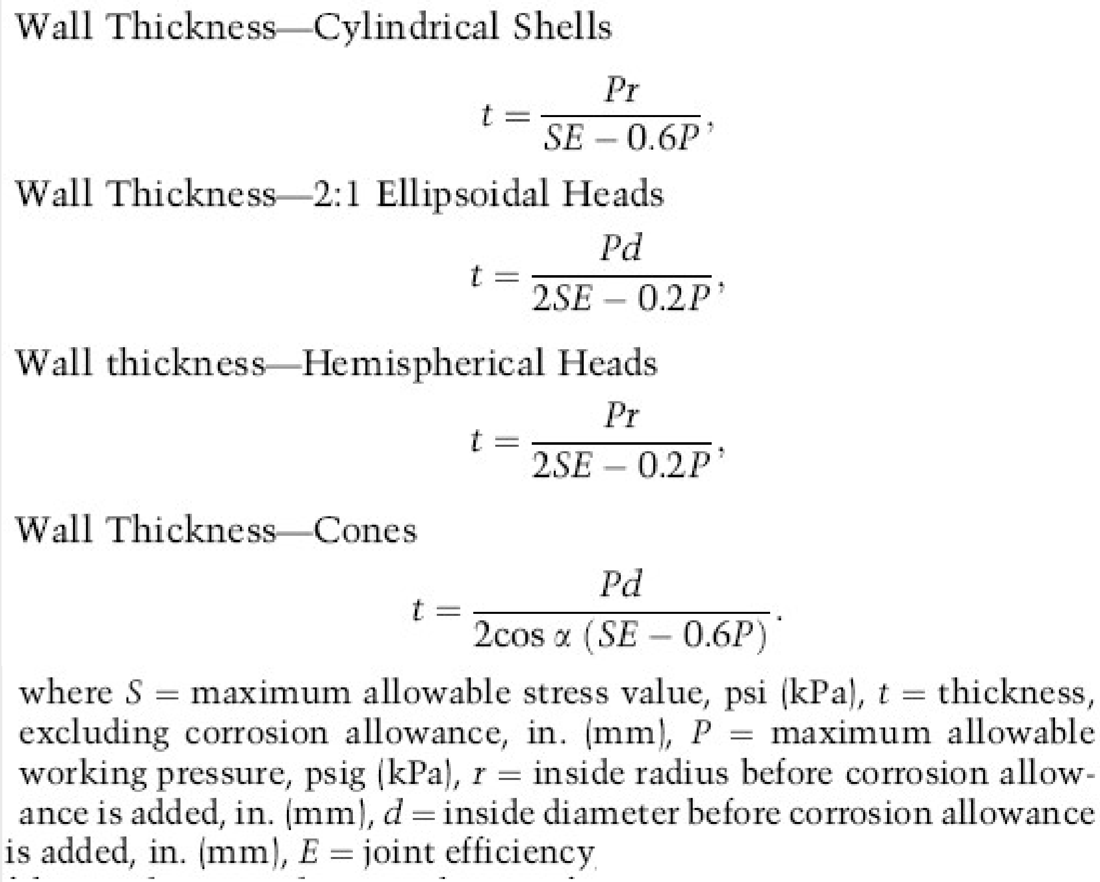
- A single contingency results in the flow of 25,2 kg/s (200 000 lb/h) of a fluid with a liquid density of 496,6 kg/m$^3$ (31 lb/ft$^3$) and a vapour density of 2,9 kg/m$^3$ (0,18 lb/ft$^3$), both at flowing conditions.
- The gauge pressure is 13,8 kPa (2 psi), and the temperature is 149 °C (300 °F).
- The viscosity of the vapour is 0,01 mPa·s (0,01 cP).
- The fluid equilibrium results in 3,9 kg/s (31 000 lb/h) of liquid and 21,3 kg/s (169 000 lb/h) of vapour.

In addition, 1,89 m$^3$ (500 US gal) of storage for miscellaneous drainings from the units is desired. The schematic in Figure 17 applies. The droplet size selected as allowable is 300 µm (0,012 in) in diameter.

# Design of Flare Drums and Seals

## Knockout Drum

- Calculation of Drum Weight (1-Thickness):



Wall Thickness—Cylindrical Shells

$$t = \frac{Pr}{SE - 0.6P},$$

Wall Thickness—2:1 Ellipsoidal Heads

$$t = \frac{Pd}{2SE - 0.2P},$$

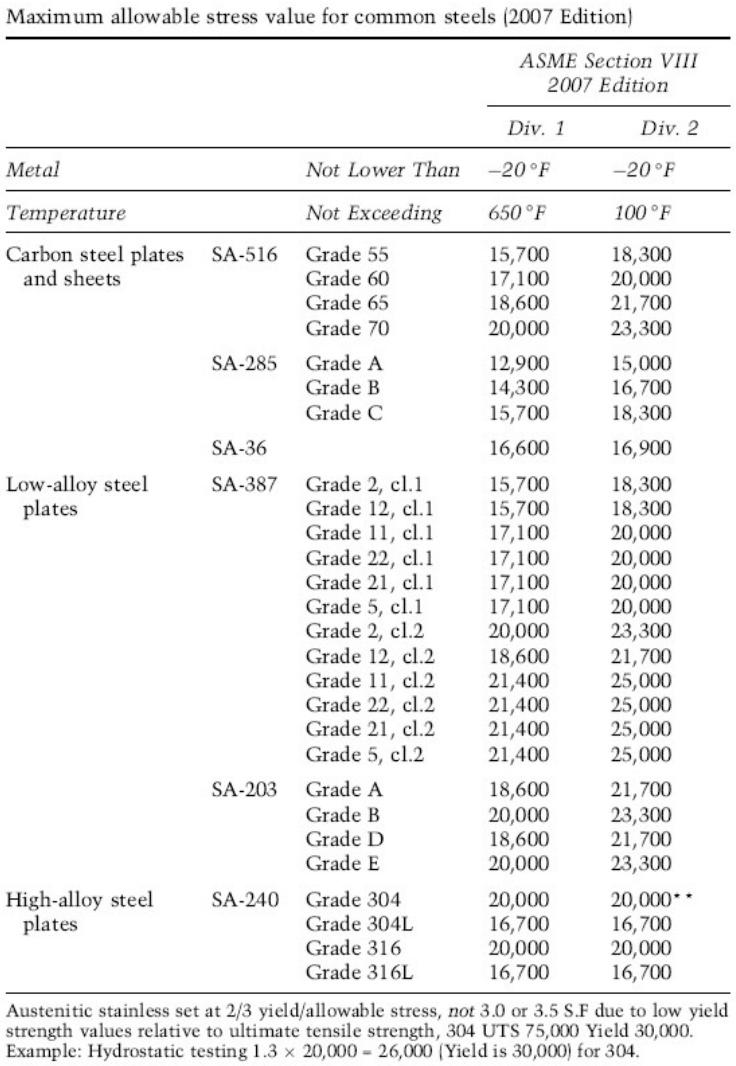
Wall thickness—Hemispherical Heads

$$t = \frac{Pr}{2SE - 0.2P},$$

Wall Thickness—Cones

$$t = \frac{Pd}{2\cos\alpha\,(SE - 0.6P)}.$$

where $S$ = maximum allowable stress value, psi (kPa), $t$ = thickness, excluding corrosion allowance, in. (mm), $P$ = maximum allowable working pressure, psig (kPa), $r$ = inside radius before corrosion allowance is added, in. (mm), $d$ = inside diameter before corrosion allowance is added, in. (mm), $E$ = joint efficiency



Maximum allowable stress value for common steels (2007 Edition)

| | | | *ASME Section VIII 2007 Edition* | |
|---|---|---|---|---|
| | | | *Div. 1* | *Div. 2* |
| *Metal* | | *Not Lower Than* | *–20 °F* | *–20 °F* |
| *Temperature* | | *Not Exceeding* | *650 °F* | *100 °F* |
| Carbon steel plates and sheets | SA-516 | Grade 55 | 15,700 | 18,300 |
| | | Grade 60 | 17,100 | 20,000 |
| | | Grade 65 | 18,600 | 21,700 |
| | | Grade 70 | 20,000 | 23,300 |
| | SA-285 | Grade A | 12,900 | 15,000 |
| | | Grade B | 14,300 | 16,700 |
| | | Grade C | 15,700 | 18,300 |
| | SA-36 | | 16,600 | 16,900 |
| Low-alloy steel plates | SA-387 | Grade 2, cl.1 | 15,700 | 18,300 |
| | | Grade 12, cl.1 | 15,700 | 18,300 |
| | | Grade 11, cl.1 | 17,100 | 20,000 |
| | | Grade 22, cl.1 | 17,100 | 20,000 |
| | | Grade 21, cl.1 | 17,100 | 20,000 |
| | | Grade 5, cl.1 | 17,100 | 20,000 |
| | | Grade 2, cl.2 | 20,000 | 23,300 |
| | | Grade 12, cl.2 | 18,600 | 21,700 |
| | | Grade 11, cl.2 | 21,400 | 25,000 |
| | | Grade 22, cl.2 | 21,400 | 25,000 |
| | | Grade 21, cl.2 | 21,400 | 25,000 |
| | | Grade 5, cl.2 | 21,400 | 25,000 |
| | SA-203 | Grade A | 18,600 | 21,700 |
| | | Grade B | 20,000 | 23,300 |
| | | Grade D | 18,600 | 21,700 |
| | | Grade E | 20,000 | 23,300 |
| High-alloy steel plates | SA-240 | Grade 304 | 20,000 | 20,000** |
| | | Grade 304L | 16,700 | 16,700 |
| | | Grade 316 | 20,000 | 20,000 |
| | | Grade 316L | 16,700 | 16,700 |

Austenitic stainless set at 2/3 yield/allowable stress, *not* 3.0 or 3.5 S.F due to low yield strength values relative to ultimate tensile strength, 304 UTS 75,000 Yield 30,000. Example: Hydrostatic testing 1.3 × 20,000 = 26,000 (Yield is 30,000) for 304.

# Design of Flare Drums and Seals

**Knockout Drum**

- Calculation of Drum Weight (2-weight):

The shell weight can be estimated from (SI) :

$$W = 0.0254\, d t L \qquad (5.5b)$$

where $W$ = weight, lb (kg), $d$ = internal diameter, in. (mm), $t$ = wall thickness, in. (mm), $L$ = shell length, ft (m).

The weight of one 2:1 ellipsoidal head is approximately (SI):

$$W \approx 9.42 \times 10^{-6} t d^2 + 1.34 \times 10^{-3} t d$$

The weight of nozzles and internals can be estimated at 5–10% of the sum of the shell and head weights.

The weight of pedestals for a horizontal vessel can be estimated as 10% of the total weight of the vessel.

# Design of Flare Drums and Seals

## Seal Drum

- The purpose of a liquid seal in a flare system includes the following:

a) To prevent any flashback originating from the flare tip from propagating back through the flare system.

b) To maintain a positive system pressure to ensure no air leakage into the flare system and permit use of a flare gas recovery system.

c) To prevent an ingress of air into the flare system during sudden temperature changes or condensation of flare gas, such as can occur following a major release of flare gas or following a steaming operation.

- Liquid seals are located between the main knockout drum and the flare stack and are quite often incorporated into the base of the stack.

- They are sized for the maximum vapor-release case. When equipment, piping elevations, and other factors permit, liquid seal volume and seal leg height should be sufficient to prevent the seal from being broken as a result of the vacuum formed in the flare header following a major release of flare gas or steaming operation.

# Design of Flare Drums and Seals

## Seal Drum

- For facilities that have cryogenic products in the flare header, consideration should be given to the effect of the cold material on the seal liquid medium.
- Alternate sealing fluids such as glycol-water mixture may be considered. Alternatively, methods such as heating the seal fluid or draining the seal when cold temperature is detected have been used.
- To prevent air entry, it is necessary that the seal dip-leg height and the density and amount of seal liquid within the drum be sufficient to prevent the seal from being broken as a result of the vacuum formed in the flare header.
- The physical dip-leg height is measured from the top opening of the seal head or end piece (e.g. the top of the V-notches on the end of the pipe) to the bottom of the horizontal section of the flare header piping immediately upstream of the inlet leg.
- The relative elevations of the flare header and other equipment and other factors can limit the vacuum sealing capability.
- If it is necessary to have the liquid seal inlet some height above the flare header elevation, then the flare header shall be sloped to avoid low points.

# Design of Flare Drums and Seals

## Seal Drum

- The seal drum should be designed to provide the volume of liquid (without credit for makeup liquid) to fill the vertical seal leg up to the specified vacuum. It is important that the purchaser states this performance requirement on the datasheet.

- Experience has shown that a minimum dip-leg height of 3 m (10 ft) above the liquid level [i.e. ~34.5 kPa (5 psi) vacuum if water is used as the seal liquid] is effective in minimizing the ingress of air into the flare header from flare stacks for typical refining applications.

- A tank-blanketing regulator, pressure regulator, and/or pressure switch/transmitter that dumps extra purge gas into the flare header system in the event of vacuum can also be considered in addition to, or in place of, the water seal.

- In some situations, special considerations can affect the size of a seal drum. One such occurrence is a large flow of hot vapor into the vent header. The vacuum created when this vapor cools can pull sufficient liquid into the header to break the seal, thus allowing air to be drawn into the flare system.

- To prevent this occurrence, the inlet line should be constructed to form a vacuum leg. The total vertical height of the inlet leg at the seal drum is determined by the maximum vacuum expected. The volume of liquid in the inlet line at the maximum vacuum should be obtained from the seal drum. This requirement can necessitate an increase in the size of the drum.

# Design of Flare Drums and Seals

## Seal Drum

- The flare header pressure at which gas begins passing through the seal can vary depending upon the purpose of the water seal (i.e. prevent air infiltration, act as a flame arrester, act as a staging device or provide backpressure to a flare gas recovery system).

- The gas pressure at the start of flow through the liquid seal can vary from 50 mm (2 in. H2O) to 3050 mm (120 in. H2O) or more. Typical seal depths are equivalent to a gauge pressure of 13.8 kPa to 34.5 kPa (2 psi to 5 psi) for staged flares or 6.9 kPa to 13.8 kPa (1 psi to 2 psi) where a flare gas recovery system is used.

- For general applications, a seal depth of 150 mm (6 in.) is common.

## Seal Drum Design

- A baffle maintains the normal water level, and the vapor inlet is submerged 75 mm to 100 mm.

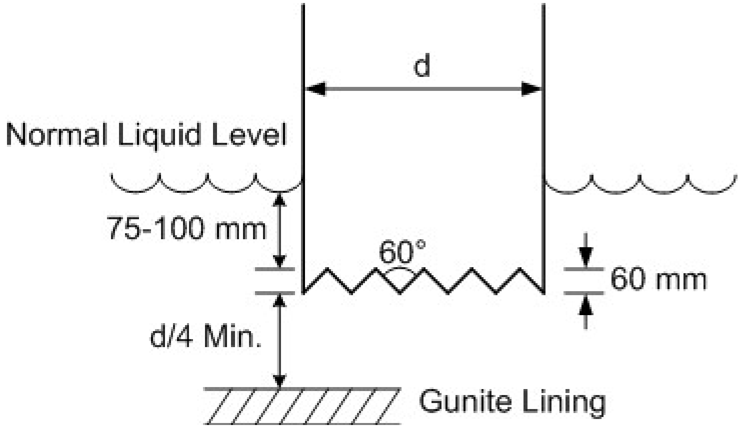
- Drum dimensions are designed such that a 3 m slug of water is pressured back into the vertical inlet piping in the event of flashback, thus preventing the explosion from propagating further upstream.

- The vapor space is sized to avoid water entrainment in the flare gas. As a rule, vapor velocities in the drum should not exceed 150 % of critical. This however can be increased to 230 % V, (Vc, critical velocity) when considering a remote contingency.

# Design of Flare Drums and Seals

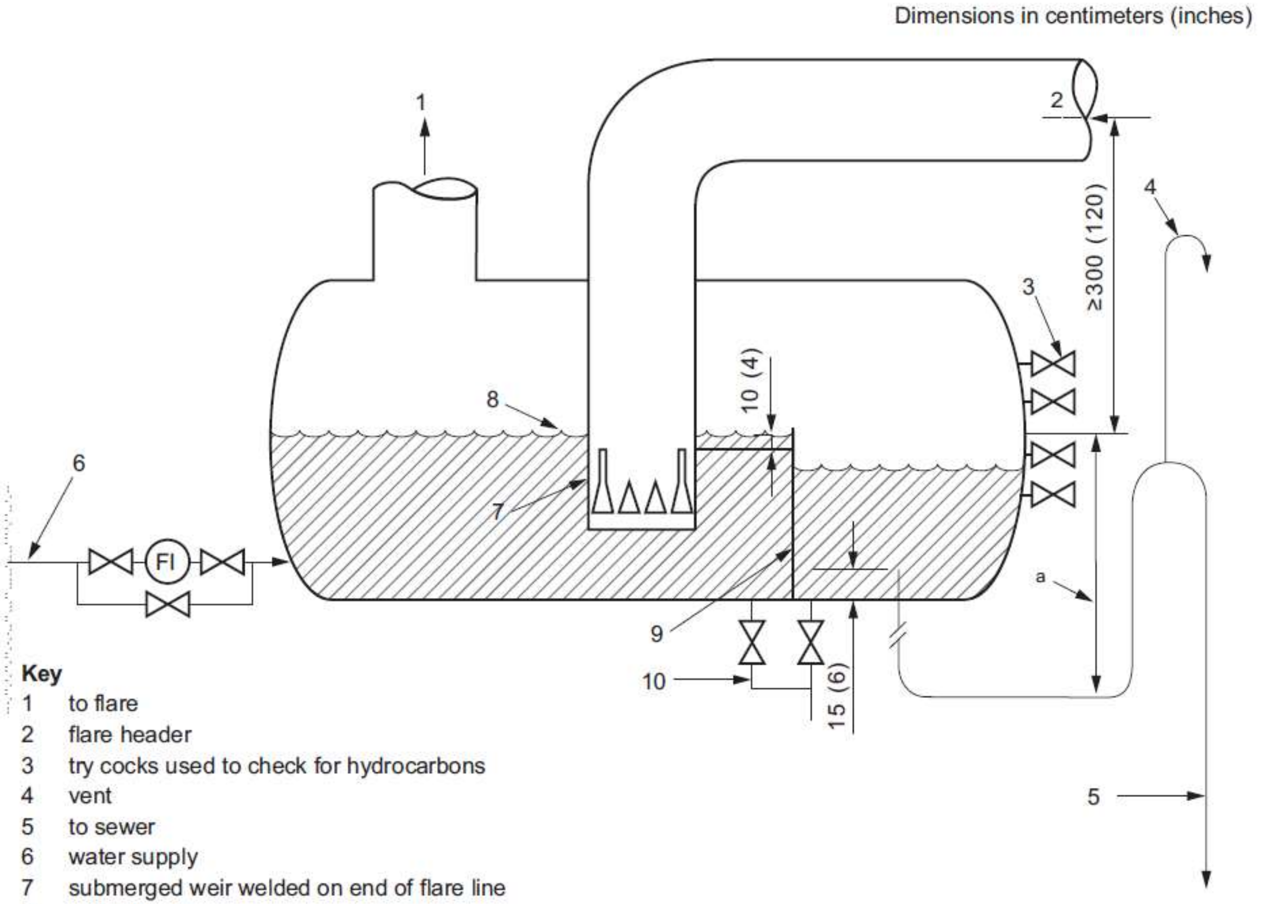
## Seal Drum Design

- The seal drum designs described include a serrated edge at the base of the dip leg,



# Design of Flare Drums and Seals

## *Typical Horizontal Flare Seal Drum*



**Key**

| | |
|---|---|
| 1 | to flare |
| 2 | flare header |
| 3 | try cocks used to check for hydrocarbons |
| 4 | vent |
| 5 | to sewer |
| 6 | water supply |
| 7 | submerged weir welded on end of flare line |
| 8 | water level |
| 9 | baffle |
| 10 | drain |

[a] The sewer seal should be designed for a minimum of 175 % of the drum's maximum operating pressure.

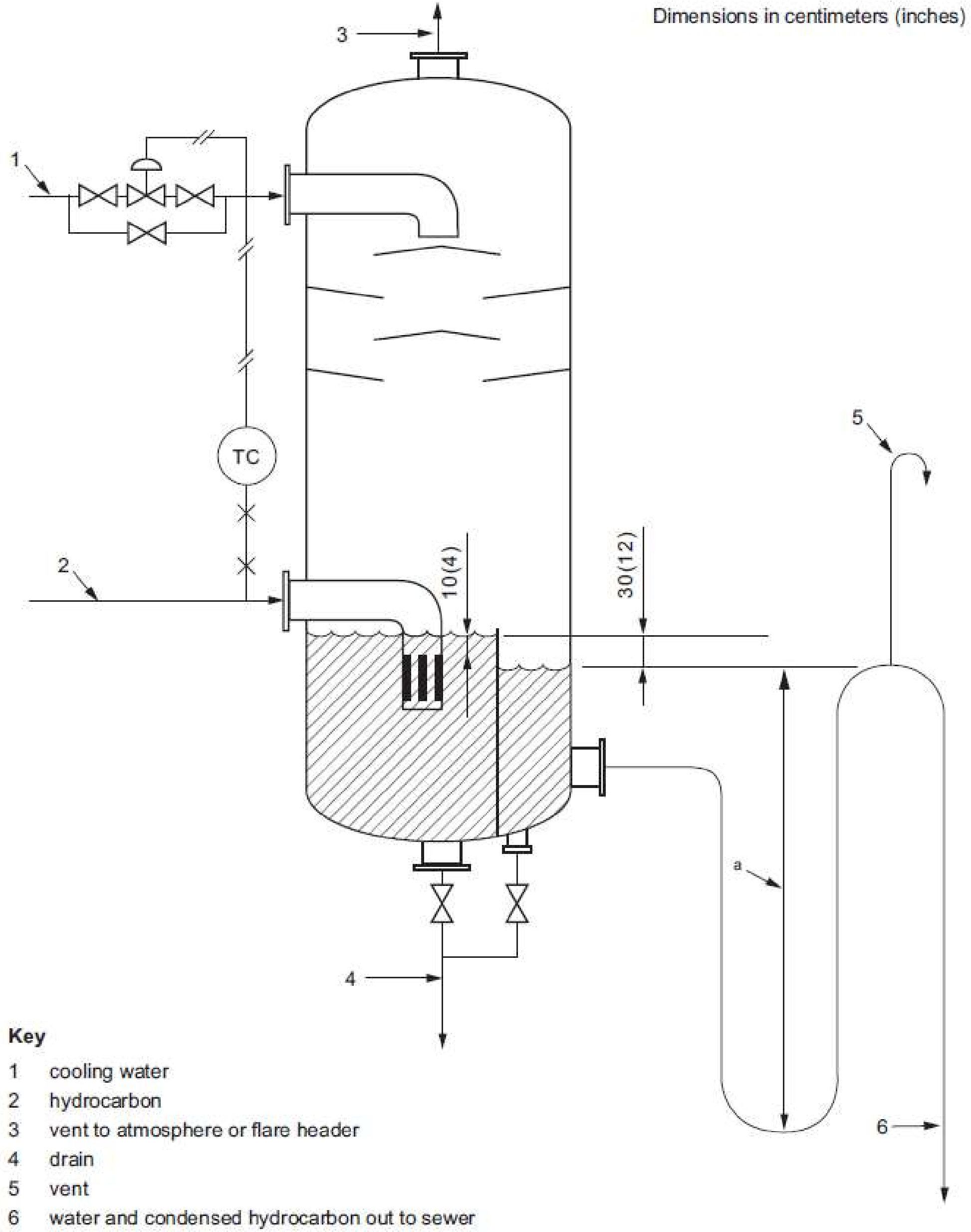
# Design of Quench Drums

**Quench Drum**

- Relief streams that are above the auto-ignition temperature on the upstream side of the valve can ignite spontaneously on contact with air unless sufficient cooling occurs before a flammable vapor-air mixture is formed.
- For this reason, these hot streams should usually be routed to a closed system, cooler, or quench tower.
- A quench drum can be used to condense the vapor discharge from a relief device for either later return back into the process after the relieving condition has passed or for disposal to the sewer.
- Generally, a quench drum is provided whenever the material being relieved is too valuable to be burned in a flare or too toxic to be relieved to atmosphere in a vent stack.
- A quench drum can be used to cool hot material so that the entire relief system does not need to be designed for the higher temperature.

# Design of Quench Drums

**Quench Drum**



**Key**

| | |
|---|---|
| 1 | cooling water |
| 2 | hydrocarbon |
| 3 | vent to atmosphere or flare header |
| 4 | drain |
| 5 | vent |
| 6 | water and condensed hydrocarbon out to sewer |

# Design of Flare K.O. Drum Pump

**Design of Flare K.O. Drum Pump**

- Pump sizing is based on to pump out the maximum anticipated liquid inventory to the specified low level.
- Due to the wide range of fluids handled, the pump should be specified for 7 ft (2 m) NPSH requirement at the suction flange and spacing between pump and K.O. drum should be minimized.
- The pump design temperature should be the same as that of the K.O drum, and design pressure is set according to the disposal routing downstream.
- Disposal of pump-out material from the K.O drum is normally to pressure slop storage, light atmospheric slop storage, or other atmospheric tankage.
- A spare pump is normally provided for this service which can be used in case the liquid level rises too fast in the drum due to unforeseen circumstances or if the operating pump is out of service.

# Design of Flare K.O. Drum Pump

**Design of Flare K.O. Drum Pump**

- Horizontal centrifugal pumps are commonly selected for flare knockout drum service. Centrifugal pumps are usually less costly and more reliable as well as being simpler to maintain than positive displacement pumps.

- The motor driven knockout drum pumps should be connected to the emergency power system or powered from two separate feeders. Where this is not possible, a steam turbine driver should be provided to the spare pump to assure its operation during partial or total power failure.

- A steam-driver manually started and automatically shut off on low level is often preferred for the pump out service because it is not always known where the material will be disposed.

# Vent Stack

**Vent Stack**

- Where the atmospheric vent handles combustible vapors, the outlet from the vent should be elevated approximately 3 m (10 ft) above any adjacent equipment, building, chimney or other structure.
- The size of a vent stack is determined by the available pressure drop and by any minimum velocity required to prevent hazardous conditions due to combustible or toxic material at grade or working levels.
- Normally, a size is selected that results in a high discharge velocity; for example, a velocity of 150 m/s (500 ft/s) provides excellent dispersion.
- The siting of vent stacks discharging to atmosphere should consider personnel health and safety, noise, potential odor, potential ground level concentrations, potential liquid carryover, ignition sources, and thermal radiation.

# Vent Stack

**Vent Stack**

- The height and location of the vent stack shall be selected so that the concentration of vapor at a point of interest is below the lower flammable limit of the vapor.

- The lower threshold for flammability concerns can be satisfied by ensuring the concentration at potential sources of ignition, personnel location, or other vulnerable areas does not exceed 0.1 times to 0.5 times the lower flammable limit.

- Toxic thresholds are generally much lower than the flammability thresholds in certain applications and can become the governing factor.

- The potential for flashback shall be considered. An example of a method to mitigate flashback is to install an appropriate and reliable continuous purge gas at a rate determined by the Husa correlation to prevent air intrusion.

- Steam is not an effective purge fluid for preventing air infiltration because it can condense.

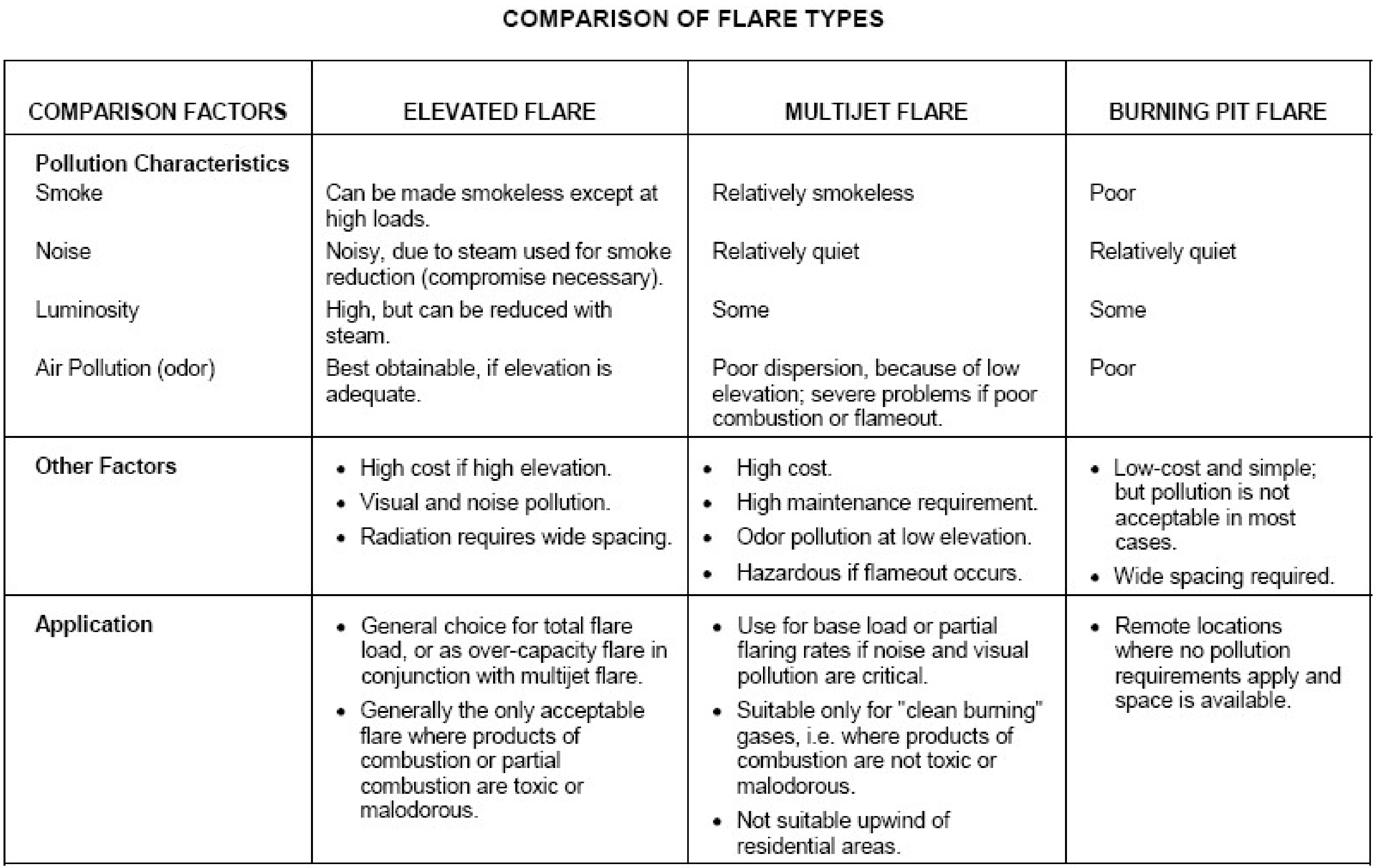
# Flare System

- The flare provides a means of safe disposal of the vapor streams from disposal system, by burning them under controlled conditions such that adjacent equipment or personnel are not exposed to hazard, and at the same time meeting pollution control and public relations requirements.

- Three types of flare are available:
    - Elevated flare
    - Ground flare
    - Burning-pit flare.

- Selection is based primarily on pollution/public relations considerations; i.e., smoke, luminosity, air pollution, noise and spacing factors.

# Flare



COMPARISON OF FLARE TYPES

| COMPARISON FACTORS | ELEVATED FLARE | MULTIJET FLARE | BURNING PIT FLARE |
|---|---|---|---|
| **Pollution Characteristics** | | | |
| Smoke | Can be made smokeless except at high loads. | Relatively smokeless | Poor |
| Noise | Noisy, due to steam used for smoke reduction (compromise necessary). | Relatively quiet | Relatively quiet |
| Luminosity | High, but can be reduced with steam. | Some | Some |
| Air Pollution (odor) | Best obtainable, if elevation is adequate. | Poor dispersion, because of low elevation; severe problems if poor combustion or flameout. | Poor |
| **Other Factors** | • High cost if high elevation.<br>• Visual and noise pollution.<br>• Radiation requires wide spacing. | • High cost.<br>• High maintenance requirement.<br>• Odor pollution at low elevation.<br>• Hazardous if flameout occurs. | • Low-cost and simple; but pollution is not acceptable in most cases.<br>• Wide spacing required. |
| **Application** | • General choice for total flare load, or as over-capacity flare in conjunction with multijet flare.<br>• Generally the only acceptable flare where products of combustion or partial combustion are toxic or malodorous. | • Use for base load or partial flaring rates if noise and visual pollution are critical.<br>• Suitable only for "clean burning" gases, i.e. where products of combustion are not toxic or malodorous.<br>• Not suitable upwind of residential areas. | • Remote locations where no pollution requirements apply and space is available. |

# Flare

## Elevated Flare

- The elevated flare is by far the most commonly used type of flare used in refineries and chemical plants.
- If adequately elevated, this type of flare has the best dispersion characteristics for malodorous and toxic combustion products, but visual and noise pollution can present public relations problems.
- Elevated flares shall not exceed the work area limit (80 dB(A)) at the perimeter of the sterile area (of at least 60 m from the flare base) when operating at flow rates up to 15% of maximum flaring capacity. (IPS-G-SF-900)
- If the plant to which the flare is allocated is subject to environmental noise requirements, the application of low noise flares shall be evaluated even if the flare is to be used for emergency conditions only.

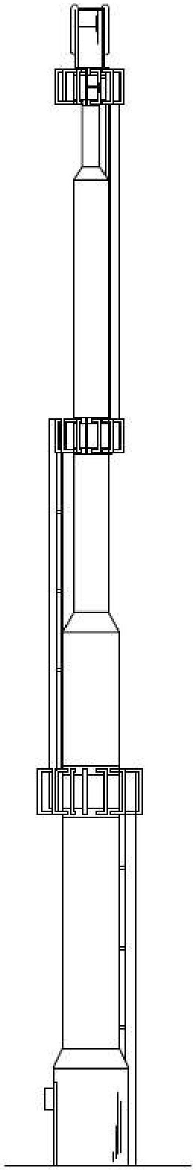
# Flare

**Elevated Flare**

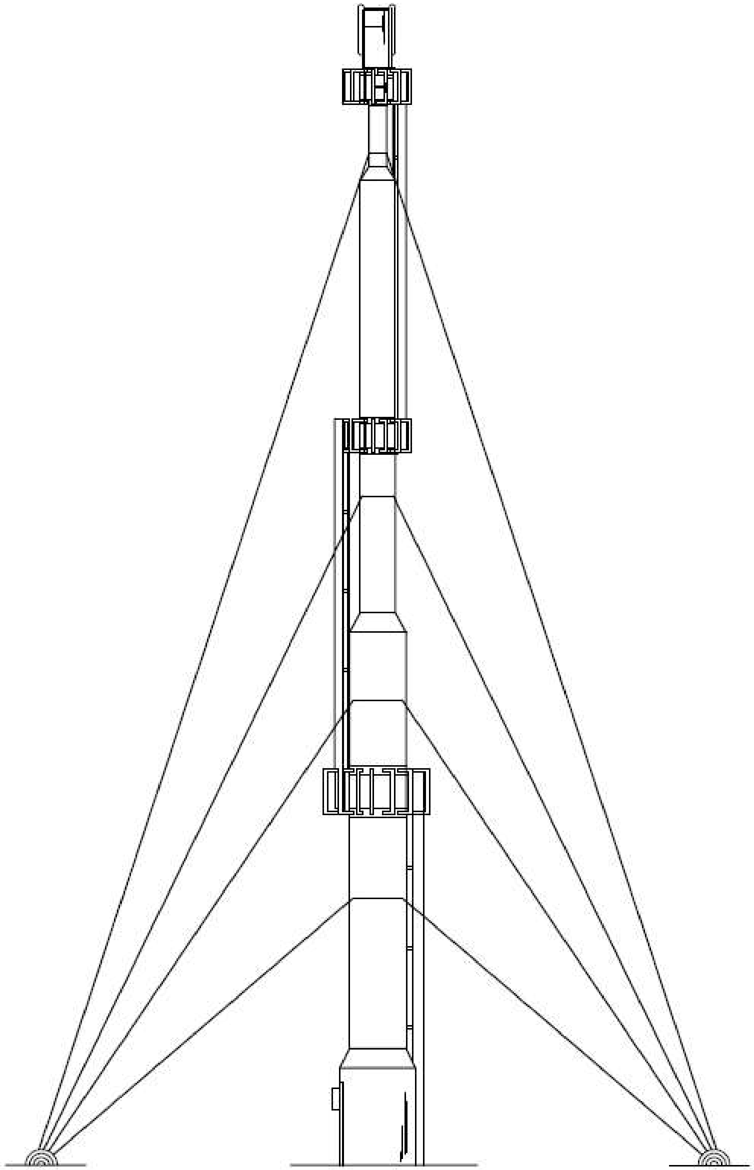
- Capital costs are relatively high, and an appreciable plant area may be rendered unavailable for plant equipment, because of radiant heat considerations.
- Despite some of its disadvantages, the elevated flare is the general choice either for total flare loads, or for handling overcapacity releases in conjunction with a multijet ground flare.
- For most applications, the elevated type is the only acceptable means of flaring "dirty gases," i.e., gases high in unsaturates or hydrogen sulfide, or which have highly toxic combustion products.

# Flare

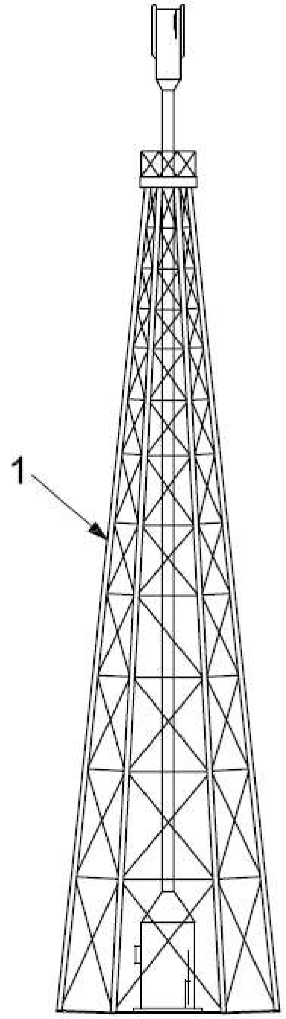
## Elevated Flare



a) Self-supporting



b) Guy-supported



c) Derrick-supported

# Flare

## Elevated Flare

- Self-Supported :

  are normally the most desirable. However, they are also the most expensive because of greater material requirements needed to ensure structural integrity over the anticipated conditions (wind, seismic and the like). They require only enough land area for the foundation and the ability to meet safe ground-level thermal-radiation levels, but are normally limited (economically versus alternatives) to a stack height 100 m (330 ft).

- Guy-Wire-Supported :
  These are the least expensive but require the largest land area due to the guywire radius requirements. The typical guy-wire radius is equal to one-half the overall stack height. Guyed stack height is normally limited to a stack height of 250 m (800 ft).

- Derrick-Supported :

  These are used only on larger stacks where self-supported design is not practical, or available land area excludes a guy-wire design.

# Flare

## Ground Flare

- Various designs of ground flare are available. The type, which has been used almost exclusively, is the multijet flare.
- Smokeless operation can generally be achieved, with essentially no noise or luminosity problems, provided that the design gas rate to the flare is not exceeded.
- Since the flame is near ground level, dispersion of stack releases is poor and this may result in severe air pollution or hazard if the combustion products are toxic or in the event of flame-out.
- Capital and operating cost and maintenance requirements are high.
- The multijet flare is suitable for "clean burning" gases (i.e., where toxic or malodorous concentrations are unlikely to be released through incomplete combustion or as combustion products)

# Flare

## Ground Flare

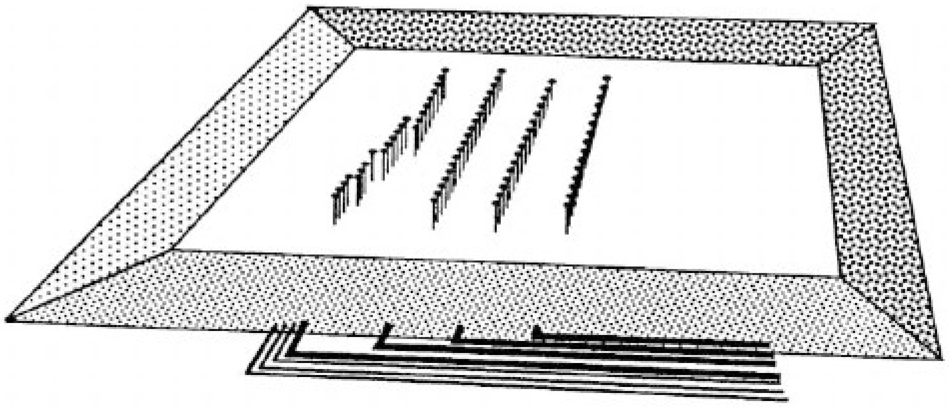


Figure 6—Multi-Burner Staged Flare

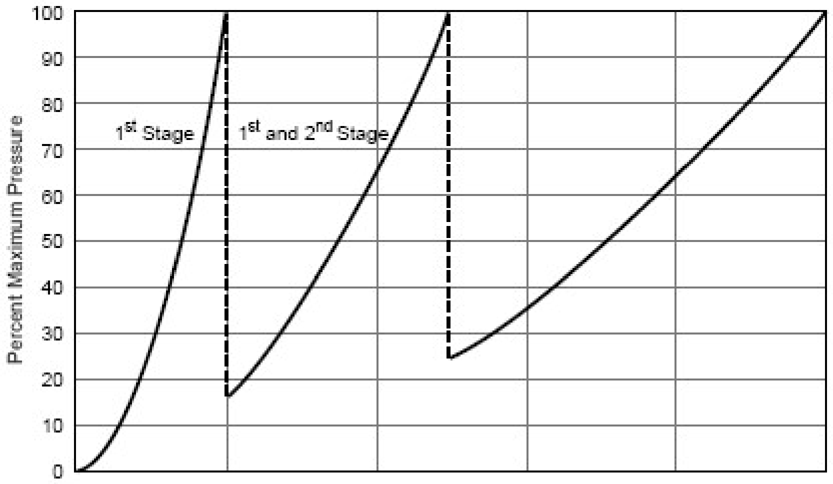


Figure 7—Multi-Burner Flare Staging Curve

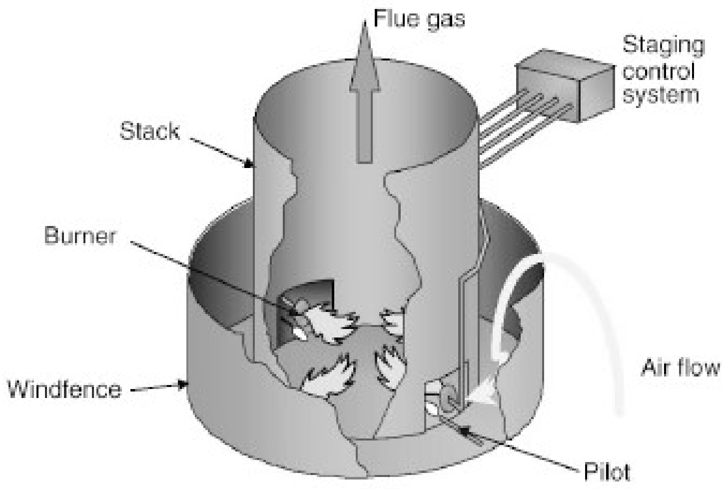


Figure 5—Enclosed Flare

# Flare

## Ground Flare – Multi Burner Flares

- Multi-burner flare systems utilize the available pressure energy of the gas to entrain additional air. This improves combustion as flare gas is better mixed with the air.
- Multiburner flares are usually designed to achieve smokeless combustion if adequate pressure and space are available. The multiple burning points may be arranged in arrays located near grade or at an elevated position.
- MultiJet Flare Systems are designed to handle a proportion of the maximum flow, typically 20%, so that releases up to this level will be relatively smokeless and non-luminous.
- An over-capacity line to an elevated flare is provided to handle the excess flow when the flaring rate exceeds the capacity of the multijet flare. The over-capacity flare is normally not provided with steam injection, and smoke formation is accepted during the infrequent occasions when it discharges.

# Selection of Flare Stack Location

**New Units**

- Location of the flare stack for a new relief system is dependent on the total relief load (Btu/h, kJ/h, kcal/h), height of the flare stack, and acceptable ground level radiation.

- The selection of the new flare stack location is based on two primary criteria:

1-Available pressure drop from the relief sources to the flare tip:

For low relief valve set pressures, the available pressure drop may be low enough to limit the distance between the source of relief and the flare tip. However, this is usually not the case. Sufficient pressure drop is normally available to site the flare stack at any location within the refinery plant limits.

2- Available plot space for the flare stack and safety circle:

The first choice would be an open area at the extreme end of the refinery where future expansion could be performed without impact on any adjacent facilities, including tankage areas.

# Selection of Flare Stack Location

**Revamp Projects**

- A new flare should not be selected for revamp of an existing relief system without first exploring the possibility of continued use of the unmodified existing flares :

1-Check if the existing capacity is sufficient

2-Reduce the new design case to fit the existing system

3-Where flare header hydraulics are limiting, several solutions may be available:

-Provide a new relief header parallel to the existing relief header(s).

-Replace conventional relief valves with balanced bellows or pilot operated relief valves in order to increase the allowable pressure at the discharge of the relief valves.

-Review the equipment with the lowest allowable relief valve outlet pressure to determine if the equipment MAWP can be increased. This is a specialized review that should include vessel designers. Also, consider the existing condition of the protected equipment with respect to corrosion.

- Dynamic analysis

# Selection of Flare Stack Location

- Spacing, location and height of flares are determined by consideration of the following factors:

  -Radiant Heat : Acceptable levels of radiant heat density for equipment and in areas where personnel may be present.

  -Pollution Limitations (i.e., smoke formation, malodorous or toxic combustion products, noise) : May be based on statutory and/or public relations requirements.

- The sizing of the flare stack requires that the following items be calculated or estimated:

  1. Flare stack diameter (set by velocity and available $\Delta P$)
  2. Wind tilt (set by wind velocity and stack exit velocity)
  3. Dispersion (set by stack height and wind speed)
  4. Height (set by radiation intensity and ground level concentration of emissions)

# Elevated Flare Design

## Flare Tip Diameter

- The flare tip diameter is generally sized on a velocity basis, but the pressure drop must also be checked. Pressure drops as large as 14 kPa (2 psi) have been satisfactorily used at the flare tip
- API 521 recommends a maximum tip velocity corresponding to a Mach Number of up to 0.5 for peak, short-term, infrequent flow emergency discharges and 0.2 for continuous, more frequent releases.
- The Mach Number for a given tip diameter and flow rate may be calculated from :

(English) :

$$Ma_2 = 1{,}702 \times 10^{-5} \left( \frac{q_m}{p_2 \cdot d^2} \right) \left( \frac{Z \cdot T}{M} \right)^{0{,}5}$$

(SI):

$$Ma_2 = 3{,}23 \times 10^{-5} \left( \frac{q_m}{p_2 \cdot d^2} \right) \left( \frac{Z \cdot T}{M} \right)^{0{,}5}$$

$q_m$ is the gas mass flow rate, expressed in kilograms per hour (pounds per hour);

$Z$ is the gas compressibility factor;

$T$ is the absolute temperature, expressed in kelvin (degrees Rankin);

$M$ is the gas relative molecular mass.

$d$ is the pipe inside diameter, expressed in metres (feet);

$p_2$ is the pipe outlet absolute pressure, expressed in kilopascals (pounds per square inch).

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Protecting personnel and facilities from excess thermal radiation is one of the major factors in setting the height of an elevated flare.

- The thermal radiation at any point (e.g., grade) depends on the total heat release, the luminosity of the flame, the length of the flame, the tilting of the flame from vertical (caused by wind), etc.

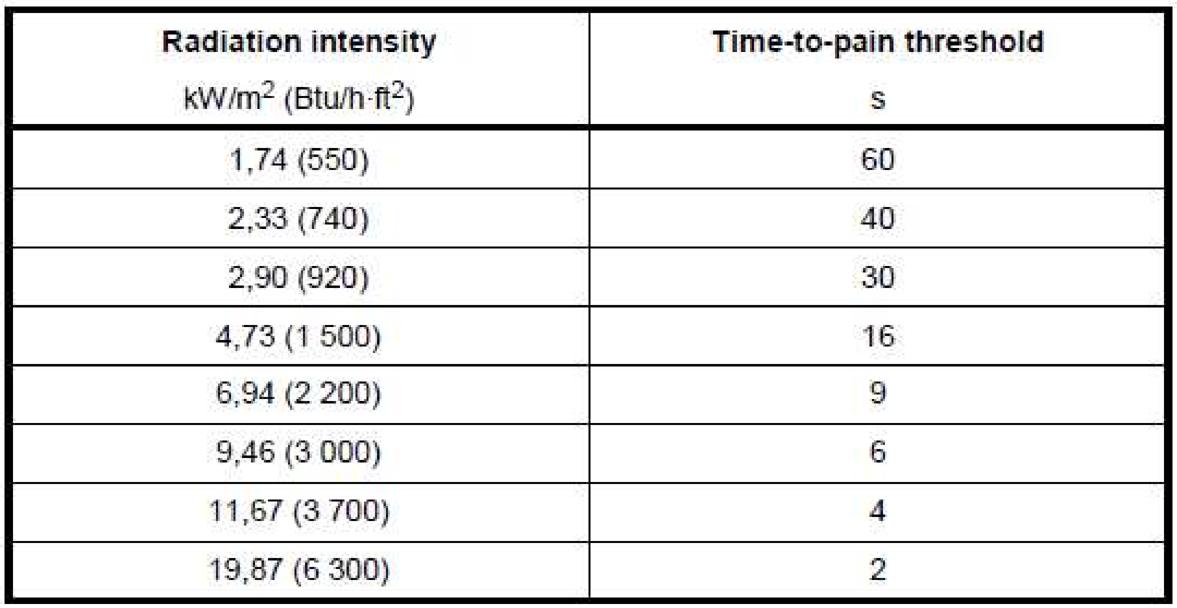


**Table 8 — Exposure times necessary to reach the pain threshold**

| Radiation intensity kW/m$^2$ (Btu/h·ft$^2$) | Time-to-pain threshold s |
|---|---|
| 1,74 (550) | 60 |
| 2,33 (740) | 40 |
| 2,90 (920) | 30 |
| 4,73 (1 500) | 16 |
| 6,94 (2 200) | 9 |
| 9,46 (3 000) | 6 |
| 11,67 (3 700) | 4 |
| 19,87 (6 300) | 2 |

# Elevated Flare Design

## Flare Height and Thermal Radiation

| **Permissible design level**<br>$K$<br>kW/m$^2$ (Btu/h·ft$^2$) | **Conditions** |
|---|---|
| 9,46 (3 000) | Maximum radiant heat intensity at any location where urgent emergency action by personnel is required. When personnel enter or work in an area with the potential for radiant heat intensity greater than 6,31 kW/m$^2$ (2 000 Btu/h·ft$^2$), then radiation shielding and/or special protective apparel (e.g. a fire approach suit) should be considered.<br>**SAFETY PRECAUTION — It is important to recognize that personnel with appropriate clothing [a] cannot tolerate thermal radiation at 6,31 kW/m$^2$ (2 000 Btu/h·ft$^2$) for more than a few seconds.** |
| 6,31 (2 000) | Maximum radiant heat intensity in areas where emergency actions lasting up to 30 s can be required by personnel without shielding but with appropriate clothing [a] |
| 4,73 (1 500) | Maximum radiant heat intensity in areas where emergency actions lasting 2 min to 3 min can be required by personnel without shielding but with appropriate clothing [a] |
| 1,58 (500) | Maximum radiant heat intensity at any location where personnel with appropriate clothing [a] can be continuously exposed |

[a] Appropriate clothing consists of hard hat, long-sleeved shirts with cuffs buttoned, work gloves, long-legged pants and work shoes. Appropriate clothing minimizes direct skin exposure to thermal radiation.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Industrial flares are normally designed so that personnel in the vicinity are not exposed to a heat intensity greater than 1500-2000 Btu/(h-ft2) when flaring at their maximum design rates.

- Personnel are commonly protected from high thermal radiation intensity by restricting access to any area where the thermal radiation can exceed 6,31 kW/m2 (2 000 Btu/(h.ft2)). (API 521 – 2007)

- The boundary of a restricted access area can be marked with signage warning of the potential thermal radiation exposure hazard. Personnel admittance to, and work within, the restricted access area should be controlled administratively.

- It is essential that personnel within the restricted area have immediate access to thermal radiation shielding or protective apparel suitable for escape to a safe location.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- The flare owner/operator shall determine the need for a solar-radiation-contribution adjustment to the values given in Table 9.

- While an adjustment of 0,79 kW/m2 to 1,04 kW/m2 (250 Btu/(h.ft2) to 330 Btu/(h.ft2)) to a 6,31 kW/m2 (2 000 Btu/(h.ft2)) level has a relatively small impact on flare cost, the same adjustment to a 1,58 kW/m2 (500 Btu/(h.ft2)) level results in a significant increase in cost.

- A design wind velocity of 9 m/s (20 mph) is a common assumption for most radiation calculations. The normal wind velocity of 10 ft/s (3 m/s) is also considered in relevant calculations.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- A common approach to determining the flame radiation to a point of interest is to consider the flame to have a single radiant epicenter and to use the following empirical equation by Hajek and Ludwig :

$$D = \sqrt{\frac{\tau \cdot F \cdot Q}{4\pi \cdot K}}$$

| | |
|---|---|
| $D$ | is the minimum distance from the epicentre of the flame to the object being considered, expressed in metres (feet); |
| $\tau$ | is the fraction of the radiated heat transmitted through the atmosphere; |
| $F$ | is the fraction of heat radiated; |
| $Q$ | is the heat release (lower heating value), expressed in kW (Btu/h); |
| $K$ | is the radiant heat intensity, expressed in kW/m$^2$ (Btu/h·ft$^2$). |

# Elevated Flare Design

## Flare Height and Thermal Radiation

- The fraction of heat intensity transmitted, τ, is used to correct the radiation impact. It can be estimated by the following equations:

$$\tau = 0{,}79\left(\frac{100}{R_{\mathrm{H}}}\right)^{1/16}\left(\frac{30}{D}\right)^{1/16} \qquad \text{SI units}$$

$$\tau = 0{,}79\left(\frac{100}{R_{\mathrm{H}}}\right)^{1/16}\left(\frac{100}{D}\right)^{1/16} \qquad \text{USC units}$$

$\tau$ is the fraction of $K$ transmitted through the atmosphere;

$R_{\mathrm{H}}$ is the relative humidity, expressed as a percentage;

$D$ is the distance from the flame to the illuminated area, expressed in metres (feet).

- The above empirical equations are applicable only under the following conditions: hydrocarbon flame radiating at 1227°C, dry bulb ambient temperature is 27°C, relative humidity is more than 10%, and distance from the flame is between 30m and 150m. However, these equations should prove adequate for most flare gases, except for those such as H2 or H2S, which burn with little or no luminous radiation.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- The fraction of heat radiated, F, is a function of the gas flared. The F factor allows for the fact that not all the heat released in a flame can be transferred by radiation.

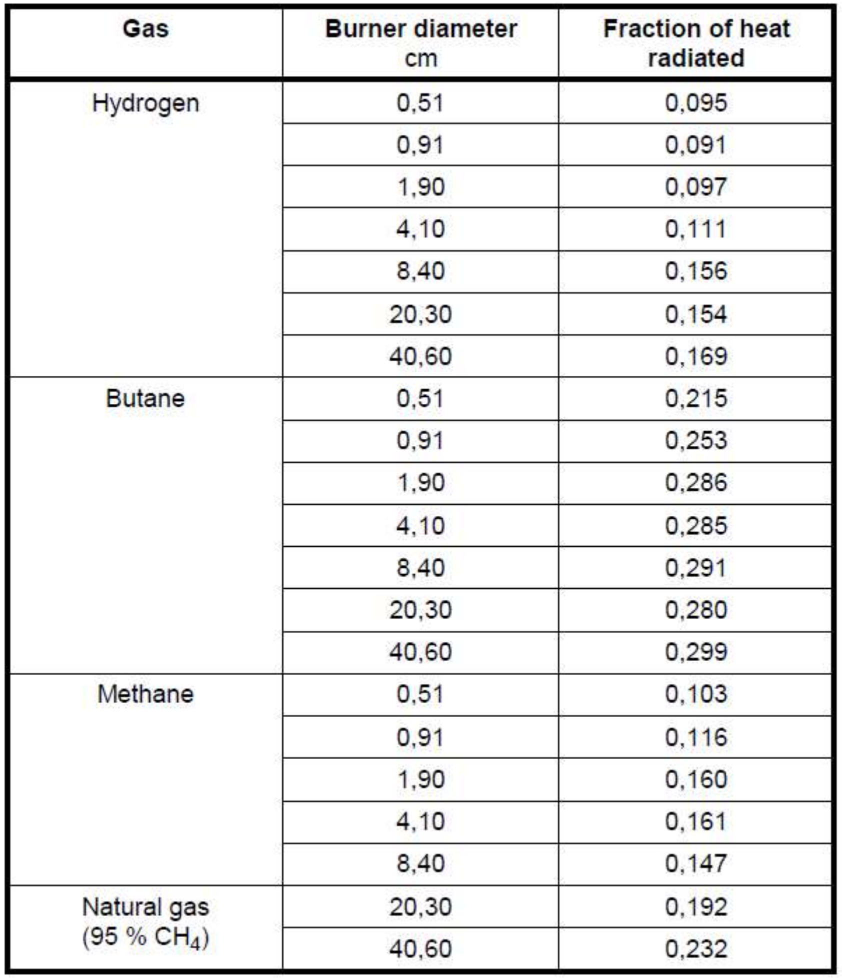
- If stream-specific data are not available, a design basis of F=0.2 can be used, which normally will give conservative results for most hydrocarbons and organics.

- Where steam injection is used at a rate of about 0,3 kg (0,7 lb) of steam per kilogram (pound) of flare gas, then the fraction of heat radiated, F, is decreased by 20 %.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- The data in below table apply only to the radiation from a flame from subsonic flares. If liquid droplets of hydrocarbon larger than 150 µm in size are present in the flame, the values in following table should be somewhat increased. If the flame is not entirely smokeless, the effective overall *F-factor can be less than the values in* this table. Exit velocity and flare-tip design can also influence the *F-factor.*



| Gas | Burner diameter cm | Fraction of heat radiated |
|---|---|---|
| Hydrogen | 0,51 | 0,095 |
| | 0,91 | 0,091 |
| | 1,90 | 0,097 |
| | 4,10 | 0,111 |
| | 8,40 | 0,156 |
| | 20,30 | 0,154 |
| | 40,60 | 0,169 |
| Butane | 0,51 | 0,215 |
| | 0,91 | 0,253 |
| | 1,90 | 0,286 |
| | 4,10 | 0,285 |
| | 8,40 | 0,291 |
| | 20,30 | 0,280 |
| | 40,60 | 0,299 |
| Methane | 0,51 | 0,103 |
| | 0,91 | 0,116 |
| | 1,90 | 0,160 |
| | 4,10 | 0,161 |
| | 8,40 | 0,147 |
| Natural gas (95 % $CH_4$) | 20,30 | 0,192 |
| | 40,60 | 0,232 |

# Elevated Flare Design

**Flare Height and Thermal Radiation**

- For pipe flare recommended emissivity coefficient is:

| | |
|---|---|
| natural gas molecular weight of 18 | : 0.21 |
| natural gas molecular weight of 21 | : 0.23 |
| ethane | : 0.25 |
| propane | : 0.30 |

- For molecular weights above approximately 30, flares have an increasing tendency to smoke unless diluted with stream or air. Smoky flames absorb much of the radiation in the outer layers and consequently the emissivity coefficients are unpredictable. For propane (flare from NGL plant, say) a value of less than 0.30 should not even be considered.
- For sonic flare recommended emissivity coefficient is 0.13 for all gases without liquid carry-over and 0.15 with liquid carry-over not exceeding 5% weight.
- When a radiation calculation is performed by a flare vendor it is necessary to check carefully the emissivity coefficient used because some vendors take a too low value for this emissivity coefficient. Many time, the emissivity coefficient used by the manufacturers does not take into account the liquid carry over, they consider an ideal gas/liquid separation. The droplets size used for the flare drum sizing shall be clearly indicated in the flare tip Process data sheet.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Flares should be at least as high as any platform or building within 500 ft (150 m) horizontally, and in no case less than 50 ft (15 m) high.
- Any source of ignitable hydrocarbons, such as separators or floating roof tanks, should be at least 200 ft (60 m) from the base of the flare stack, assuming the potential for liquid fall-out from the flare is minimal.
- Flares should be located to limit the maximum ground level heat density to 500 Btu/hr/ft2 (1.6 kW/m2) at any property line. The minimum distance from the base of the flare stack to the property line should be 200 ft (60 m).

- The general steps to be followed for calculating the flare stack height :

1- Establish a flare area (circle) with piping design group, where personal access shall be limited. This circle shall not include process plot areas, combustible material storage tanks, utility areas and any other facilities where personal access is required for daily activities. Flare K.O. drum and seal drums may be located inside this circle, if proper shelter is provided near the K.O. drums and/or seal drums.

# Elevated Flare Design

## Flare Height and Thermal Radiation

2- Calculate the stack height so that the maximum ground level radiant heat intensity does not exceed 1,500 – 2000 Btu/ft2/h at the edge of the flare area circle, based upon the maximum instantaneous relief flow to the flare and the design wind velocity.

If free personal access is required at any flare area, the stack height shall be sized not to exceed 1,500 Btu/ft2/h (4.73 kW/m2, 4,069 kcal/m2/h) at any ground level.

3- Using the height and radius calculated in the first step and the normal wind velocity, check that the radiant heat intensity does not exceed 500 Btu/ft2/h at a distance from the base of the stack equal to this radius when the maximum continuous relief flow to the flare occurs.

4- Check that the surface temperatures of process equipment and storage tanks do not exceed 302 to 392 °F (150 to 200 °C) when the maximum relief flow occurs.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Equipment Surface Temperature

The surface temperatures of process equipment and storage tanks, when the maximum relief flow to the flare occurs, can be estimated using the following equations:

$$K = \sigma ( T_s^4 - T_a^4 ) + (h / \varepsilon_s)( T_s - T_a )$$

$T_a$ = absolute ambient air temperature, °R (°K).

$\varepsilon_s$ = surface emissivity

$T_s$ = hot spot temperature on equipment surface, °R (°K)

$\sigma$ = Stefan-Boltzman constant, $1.712 \times 10^{-9}$ Btu/ft$^2$/h/°R$^4$ ($2.05 \times 10^{-7}$ kJ/m$^2$/h/°K$^4$, $4.89 \times 10^{-8}$ kcal/m$^2$/h/°K$^4$)

$h$ = convective heat transfer coefficient over equipment surface, Btu/ft$^2$/h/°F (kJ/m$^2$/h/°C, kcal/m$^2$/h/°C).

For surfaces sheltered from the wind:

$h = 0.214 (T_s - T_a)^{1/3}$ Btu/ft$^2$/h/°F

$h = 5.32 (T_s - T_a)^{1/3}$ kJ/m$^2$/h/°C

$h = 1.27 (T_s - T_a)^{1/3}$ kcal/m$^2$/h/°C

For surfaces exposed to the wind:

$h = 4.1$ Btu/ft$^2$/h/°F

$h = 84$ kJ/m$^2$/h/°C

$h = 20$ kcal/m$^2$/h/°C

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Equipment Surface Temperature

  For surfaces exposed to the wind:

h = 2.05 Btu/ft$^2$/h/°F

h = 42 kJ/m$^2$/h/°C

h = 10 kcal/m$^2$/h/°C

for wind velocity up to 7 ft/s (2 m/s)

h = 4.1 Btu/ft$^2$/h/°F

h = 84 kJ/m$^2$/h/°C

h = 20 kcal/m$^2$/h/°C

for wind velocity between 7 ft/s and 30 ft/s (2 m/s and 9 m/s)

h = 6.2 Btul/ft$^2$/h/°F

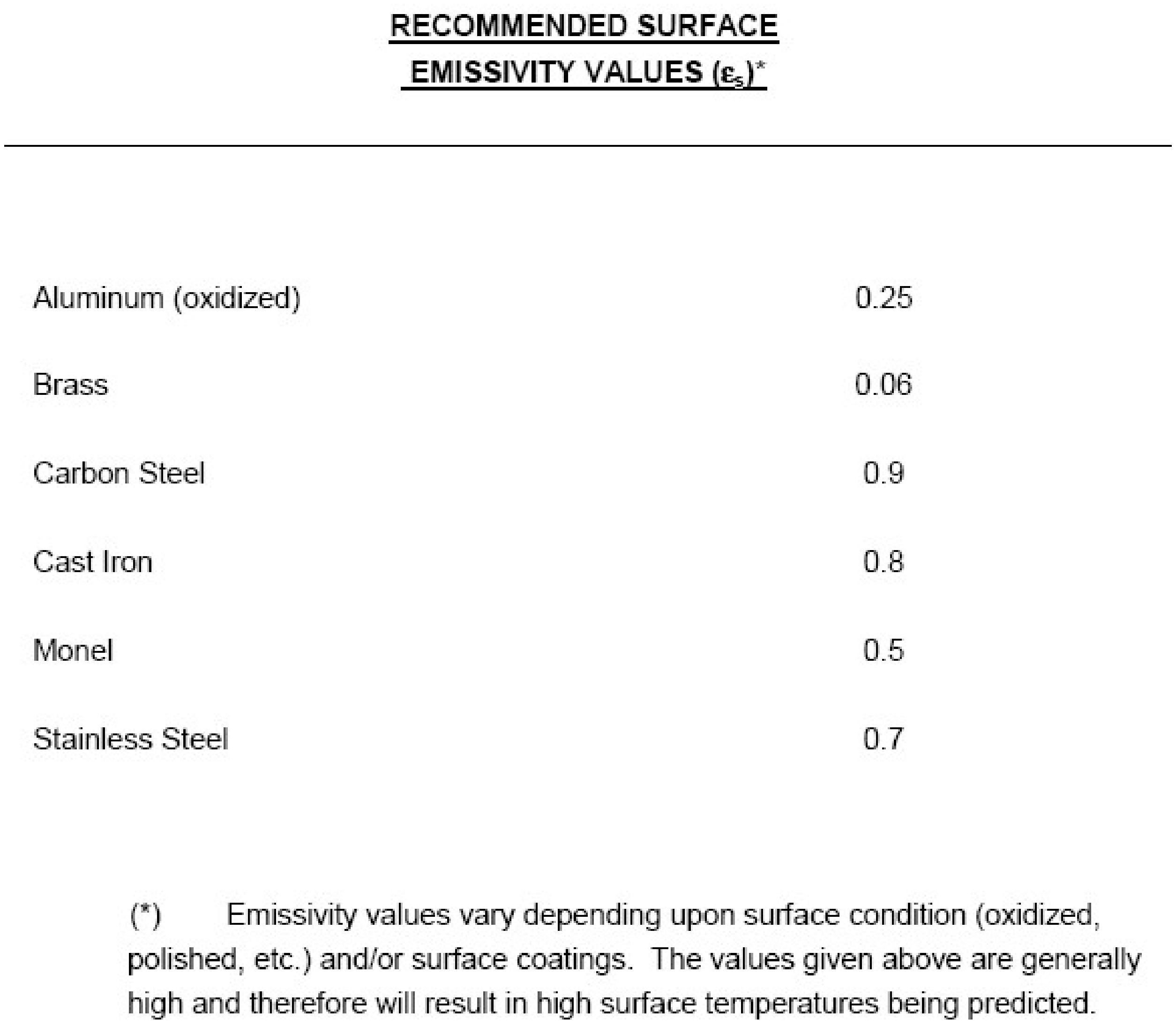
h = 126 kJ/m$^2$/h/°C

h = 30 kcal/m$^2$/h/°C

for wind velocity greater than 30 ft/s (9 m/s)

# Elevated Flare Design

## Flare Height and Thermal Radiation



**RECOMMENDED SURFACE**
**EMISSIVITY VALUES ($\varepsilon_s$)***

| | |
|---|---|
| Aluminum (oxidized) | 0.25 |
| Brass | 0.06 |
| Carbon Steel | 0.9 |
| Cast Iron | 0.8 |
| Monel | 0.5 |
| Stainless Steel | 0.7 |

(*) Emissivity values vary depending upon surface condition (oxidized, polished, etc.) and/or surface coatings. The values given above are generally high and therefore will result in high surface temperatures being predicted.

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Equipment Surface Temperature

  Example: Estimate the surface temperature on cast iron equipment which is receiving radiation from the flare at 498 Btu/ft2/h. The air temperature is 61°F and wind velocity is 19 ft/s.

- Data Required for Radiation Calculation :

  -Gas flow rate; maximum instantaneous (peak) relief flow rate, and maximum continuous (normal) flow rate.

  -Approximate composition of the gas to be flared. If there is a substantial difference between the composition of the gas during the maximum instantaneous relief and that of the maximum continuous relief, both compositions are needed. If composition is not available, approximation can be done based on molecular weight.

  -Temperature of the gas to be flared.

  -Low (net) heating value (LHV) of the gas to be flared. If composition unknown, A simplifying assumption can be made that most hydrocarbon gases have a lower heating value of approximately 19,980 Btu/lb (46,500 kJ/kg, 11,100 kcal/kg).

  -Wind velocity

  -Stack Diameter

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Procedure for Stack Height Calculation (Simple Approach – API521):

1) Calculate Flare Stack Diameter based on Mach No. Criteria

2) Calculate the heat liberated from : $Q = W \times LHV$

3) Calculate the gas density by:

$\rho g = (Mg\ P) / (Rg\ Tg)$

4) Calculate the volumetric gas flow rate by:

$V = W / \rho g$

5) The flame distortion caused by wind velocity (see Figure 9) can be represented by Equation

$$u_{\infty}/u_{\mathrm{j}}$$

$u_{\infty}$ is the lateral wind speed

$u_{\mathrm{j}}$ is the jet exit velocity

$Uj = 4 \times V / \pi \times d^2$

Read from Fig.9 the $\sum \Delta y/L$ and $\sum \Delta x/L$

# Elevated Flare Design

## Flare Height and Thermal Radiation

- Procedure for Stack Height Calculation (Simple Approach – API521):

6) Read flame length ,L , from figure 7

7) Calculate the distance from the flame center to the grade-level boundary (that is, the object being considered), *D* :

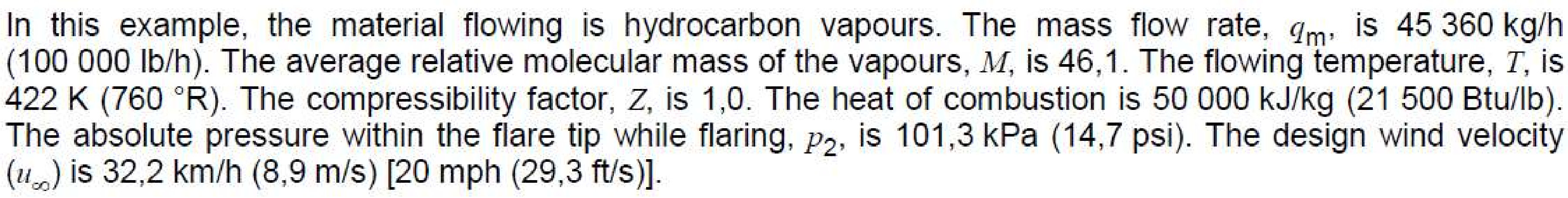
8) $$D = \sqrt{\frac{\tau \cdot F \cdot Q}{4\pi \cdot K}}$$

$$h' = h + (0{,}5 \sum \Delta y)$$

$$r' = r - (0{,}5 \sum \Delta x)$$

$$D^2 = r'^2 + h'^2$$

Example :



In this example, the material flowing is hydrocarbon vapours. The mass flow rate, $q_m$, is 45 360 kg/h (100 000 lb/h). The average relative molecular mass of the vapours, $M$, is 46,1. The flowing temperature, $T$, is 422 K (760 °R). The compressibility factor, $Z$, is 1,0. The heat of combustion is 50 000 kJ/kg (21 500 Btu/lb). The absolute pressure within the flare tip while flaring, $p_2$, is 101,3 kPa (14,7 psi). The design wind velocity ($u_\infty$) is 32,2 km/h (8,9 m/s) [20 mph (29,3 ft/s)].

Circle area radius = 45.7 m.

# Elevated Flare Design

## Flare Height and Thermal Radiation

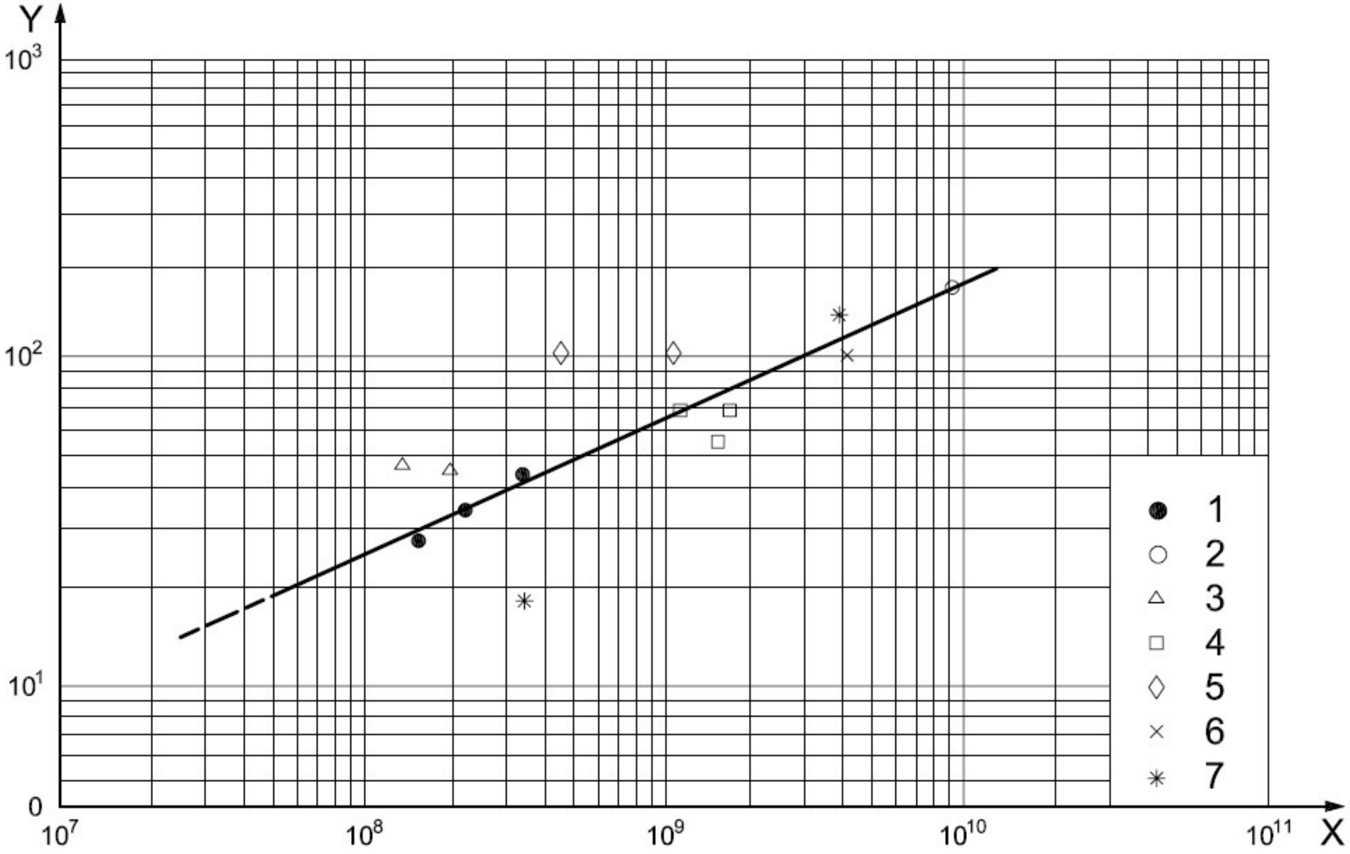


Figure 7 — Flame length versus heat release — Industrial sizes and releases (SI units)

**Key**

X heat release, expressed in watts

Y flame length (including any lift-off), expressed in metres

# Elevated Flare Design

## Flare Height and Thermal Radiation

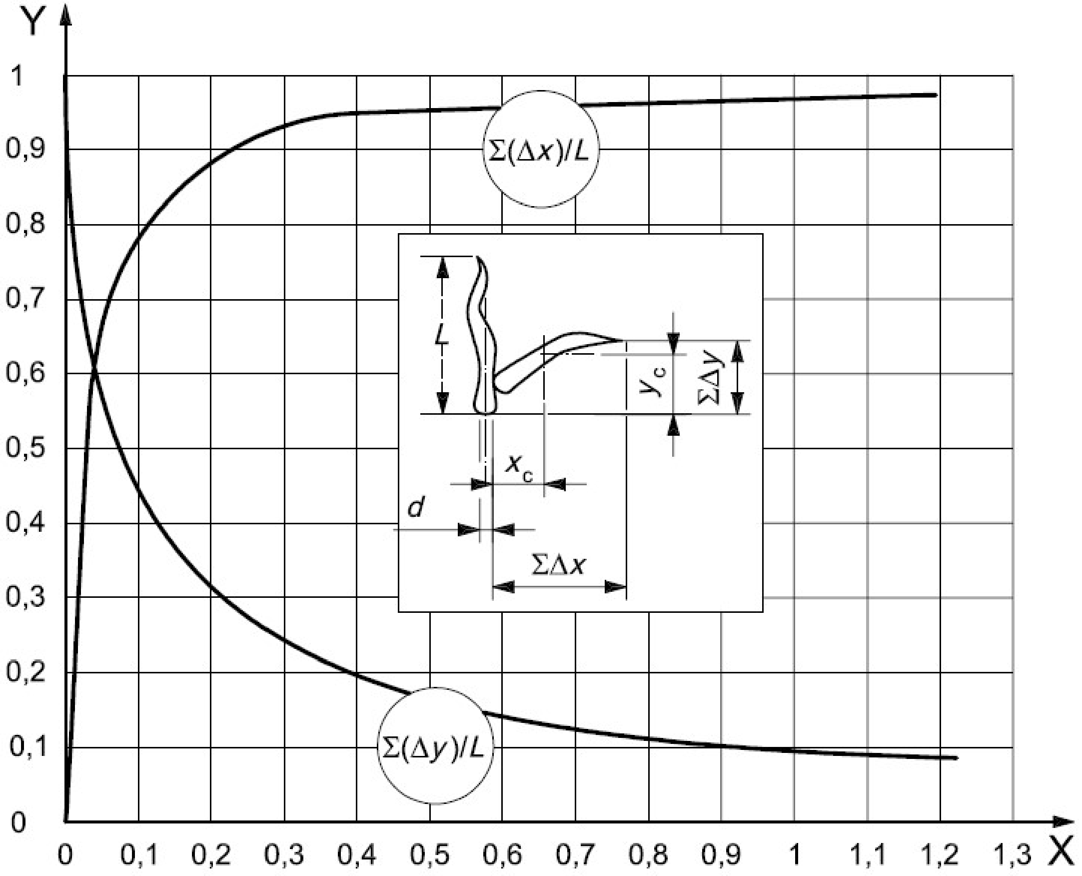


Figure 9 — Approximate flame distortion due to lateral wind on jet velocity from flare stack

X $\sum\left(u_\infty/u_j\right)$

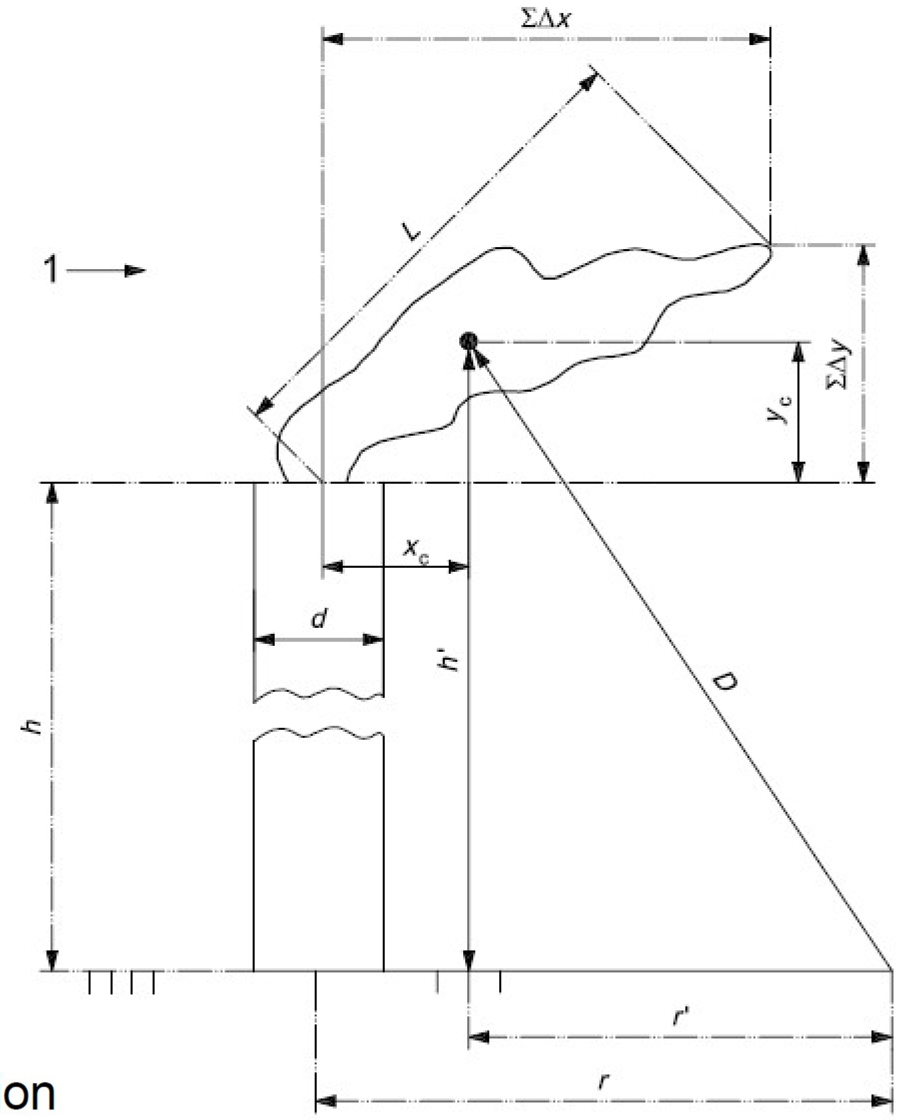
Y $\sum\Delta y/L$ or $\sum\Delta x/L$

$u_\infty$ is the lateral wind speed

$u_j$ is the jet exit velocity

# Elevated Flare Design

## Flare Height and Thermal Radiation



1 wind direction

# Elevated Flare Design

**Flaresim Example:**

1) The objective is to design a flare stack for an offshore platform. It is assumed that an inclined flare (60°) boom will be used mounted on the side of the platform which faces the prevailing wind. The design is to be based on thermal radiation limits as follows:

- 600 btu/hr/ft2 at the helideck located 150 ft from the side of the platform and 30 ft above the base of the flare stack.
- 1,500 btu/hr/ft2 at the base of the flare stack.

The following design data is available

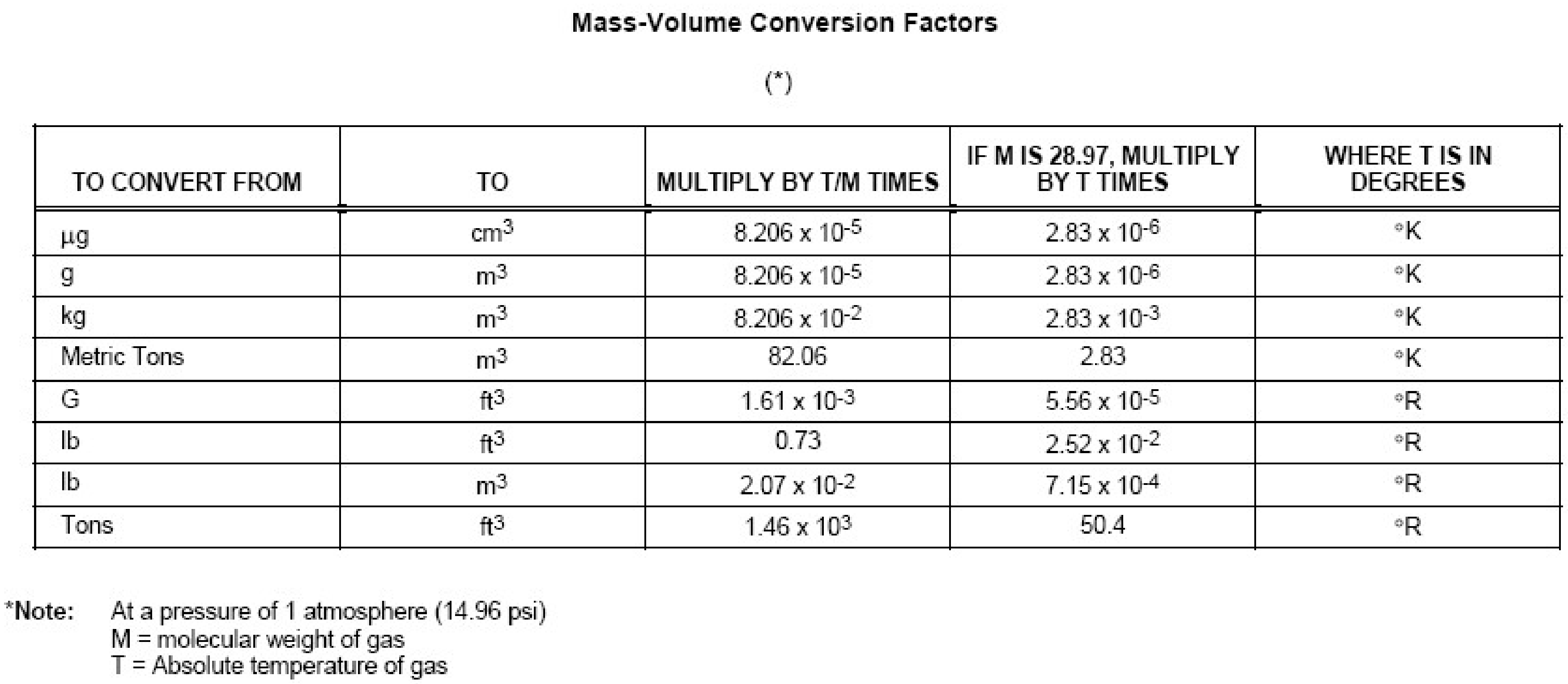
| | |
|---|---|
| Fluid Material | Hydrocarbon Vapour |
| Flow | 100,000 lb/hr |
| Mol Wt. | 46.1 |
| Vapour Temp. | 300 ˚F |
| Heat of combustion | 21,500 btu/lb |
| Heat Capacity ratio | 1.1 |
| Tip Diameter | 18 in |
| Tip Length | 3 ft |
| Wind Velocity | 20 mph |

Calculate stack height based on subsonic and sonic flare tip.

# Dispersion

- Air pollution concentrations are usually expressed in units of mass of pollutant per volume of contaminated air, e.g., µg/m3

- If the contaminant is a gas, the concentrations may also be expressed in units of volume of pollutant per volume of contaminated air, e.g., cm3/m3 or the equivalent volume parts per million (ppmv).



**Mass-Volume Conversion Factors**

(*)

| TO CONVERT FROM | TO | MULTIPLY BY T/M TIMES | IF M IS 28.97, MULTIPLY BY T TIMES | WHERE T IS IN DEGREES |
|---|---|---|---|---|
| µg | cm$^3$ | $8.206 \times 10^{-5}$ | $2.83 \times 10^{-6}$ | °K |
| g | m$^3$ | $8.206 \times 10^{-5}$ | $2.83 \times 10^{-6}$ | °K |
| kg | m$^3$ | $8.206 \times 10^{-2}$ | $2.83 \times 10^{-3}$ | °K |
| Metric Tons | m$^3$ | 82.06 | 2.83 | °K |
| G | ft$^3$ | $1.61 \times 10^{-3}$ | $5.56 \times 10^{-5}$ | °R |
| lb | ft$^3$ | 0.73 | $2.52 \times 10^{-2}$ | °R |
| lb | m$^3$ | $2.07 \times 10^{-2}$ | $7.15 \times 10^{-4}$ | °R |
| Tons | ft$^3$ | $1.46 \times 10^{3}$ | 50.4 | °R |

*Note: At a pressure of 1 atmosphere (14.96 psi)
M = molecular weight of gas
T = Absolute temperature of gas

# Dispersion

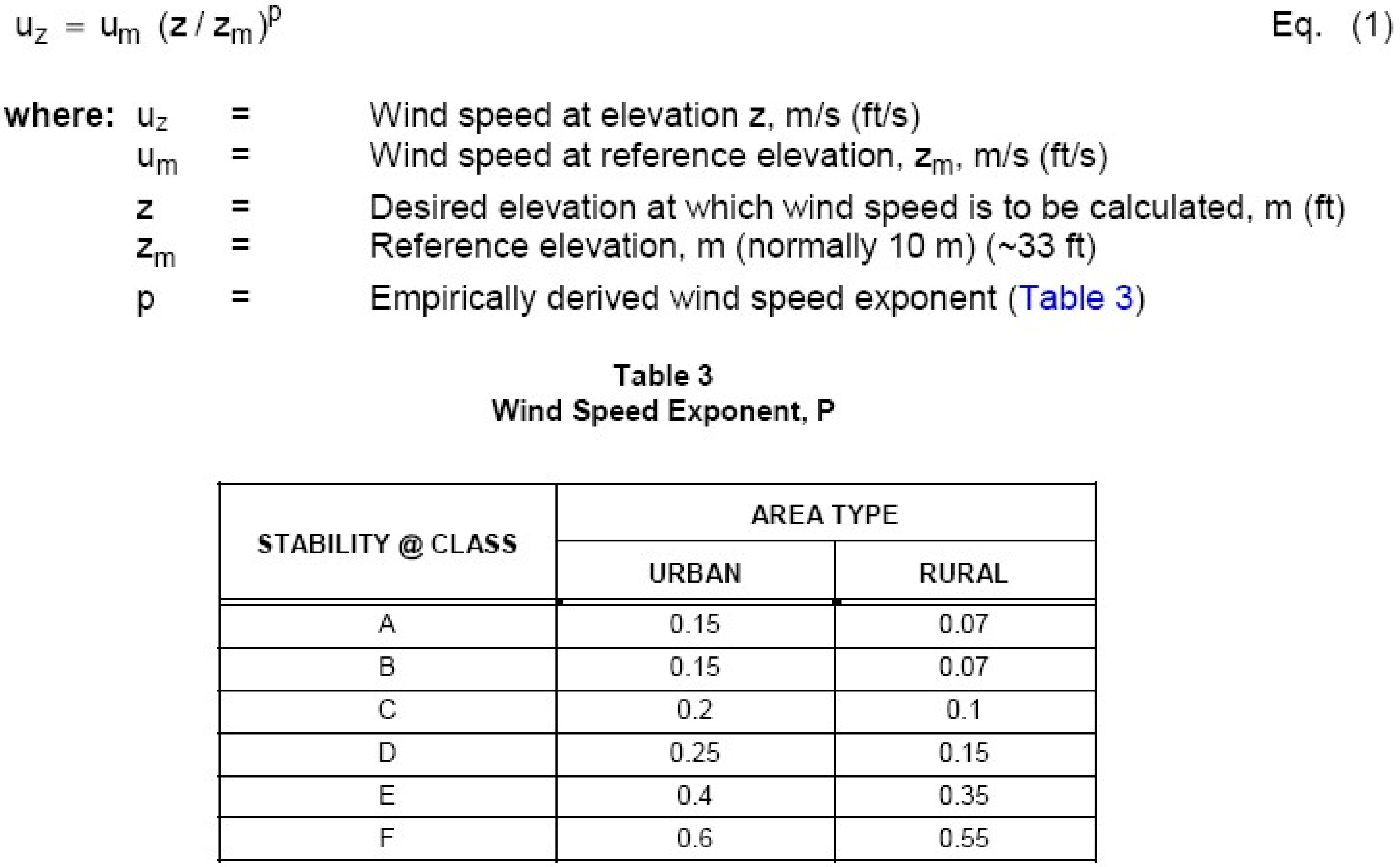
- Two specific concentrations of interest are the ambient concentration and the ground level concentration (glc).
- An ambient concentration is the concentration at any point of interest in the atmosphere. Ambient concentrations at points on or close to the ground due to all sources are glcs.
- Any substance discharged into the atmosphere from an air pollution source is an **emission.**
- A **point source is one from which** emissions of waste gas are discharged into the atmosphere through a well-defined conduit, and for which the downwind distance of concern is much larger than the conduit diameter.
- An **area source,** unlike a point source, does not emit pollutants through a well-defined conduit nor does the downwind distance of concern have to be larger than the area of the source.

# Dispersion

- A **volume source** is generally a combination of numerous point sources of different height.
- **Fugitive emissions**, usually treated as either an area or volume source, result from leaks in pollution control devices and other mechanical equipment.
- **Air dispersion,** or **atmospheric diffusion,** is the dilution of an air pollutant due to natural atmospheric movement and to the interaction between the momentum and buoyancy (if any) of the pollutant and natural convective mixing of the atmosphere.
- the average of the larger-scale slowly changing component is termed the **mean wind speed, u,** while the rapidly changing smaller-scale components are called **turbulence** and is treated statistically.
- **Surface roughness length** is a measure of the mechanical turbulence.
- the wind (speed and direction) changes with elevation. This is called **wind shear.**

# Dispersion

- The often-used method is the logarithmic wind speed power law as follows:



$$u_z = u_m \, (z / z_m)^p \qquad \text{Eq. (1)}$$

**where:** $u_z$ = Wind speed at elevation z, m/s (ft/s)
$u_m$ = Wind speed at reference elevation, $z_m$, m/s (ft/s)
$z$ = Desired elevation at which wind speed is to be calculated, m (ft)
$z_m$ = Reference elevation, m (normally 10 m) (~33 ft)
$p$ = Empirically derived wind speed exponent (Table 3)

**Table 3**
**Wind Speed Exponent, P**

| STABILITY @ CLASS | AREA TYPE | |
|---|---|---|
| | URBAN | RURAL |
| A | 0.15 | 0.07 |
| B | 0.15 | 0.07 |
| C | 0.2 | 0.1 |
| D | 0.25 | 0.15 |
| E | 0.4 | 0.35 |
| F | 0.6 | 0.55 |

# Dispersion

- Calculated maximum concentrations may be converted from one averaging time to another (up to 24-hour averages) using this equation :

$$(\chi_1 / \chi_2) = (t_1 / t_2)^{-\alpha}$$

**where:** $\chi_1$ = Highest glc over averaging time $t_1$

$\chi_2$ = Highest glc over averaging time $t_2$

$\alpha$ = Conversion exponent = 0.2

- For approximate estimates of annual average concentrations, a reasonable rule of thumb for the annual concentration value is about 10% of 1-hour maximum concentrations.
- Throughout the day, the dispersive capacity of the atmosphere changes as solar radiation and wind speed change.
- Atmospheric stability describes the dispersive capacity of the atmosphere in terms of convective and mechanical turbulence.

# Dispersion

- What is done in practice is to define atmospheric stability by empirical or semi-empirical means based on easily observed phenomena, and then to use the stability so defined as an indicator of dispersive capability.

- Most schemes consider 4 or 6 discrete stability categories (more rarely 7 or some other number) with the designation “A” (or “1”) going to the most unstable atmosphere and subsequent letters (or numbers) indicating progressively more stable atmospheres.

- Neutral atmospheres are usually indicated by “C” or “D” (“3” or “4”).

**Pasquill-Turner Stability Categories**

| SURFACE WIND SPEED (at 10 m) in m/s | INSOLATION(1)(3) | | | NIGHT(2)(3) | |
|---|---|---|---|---|---|
| | STRONG | MODERATE | SLIGHT | THINLY OVERCAST OR > 4/8 LOW CLOUD | < 3/8 CLOUD |
| < 2 | A | A – B | B | — | — |
| 2–3 | A – B | B | C | E | F |
| 3–5 | B | B – C | C | D | E |
| 5–6 | C | C – D | D | D | D |
| > 6 | C | D | D | D | D |

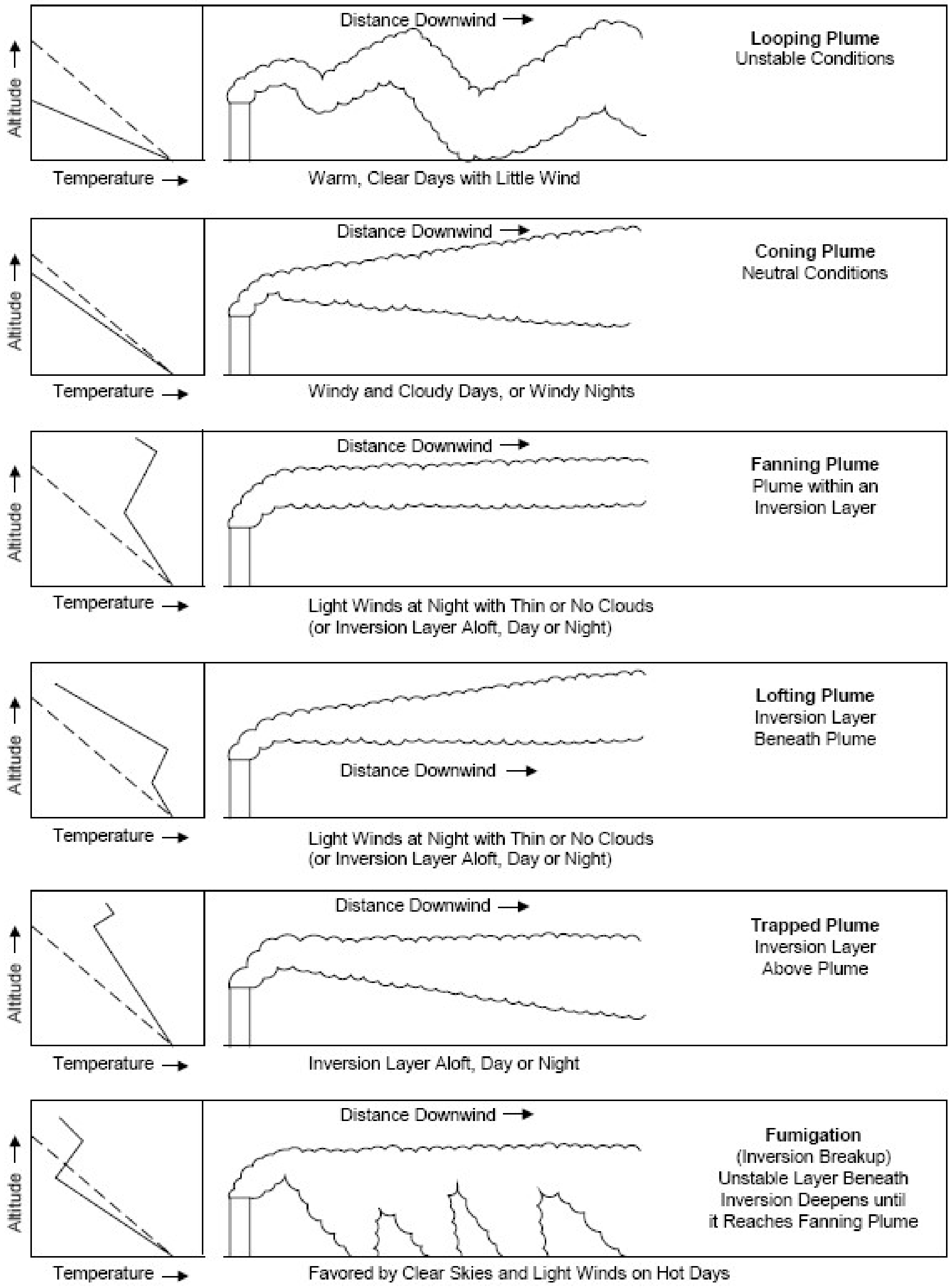
Notes:

(1) Strong insolation corresponds to sunny midday in midsummer in England; slight insolation to similar conditions in midwinter.

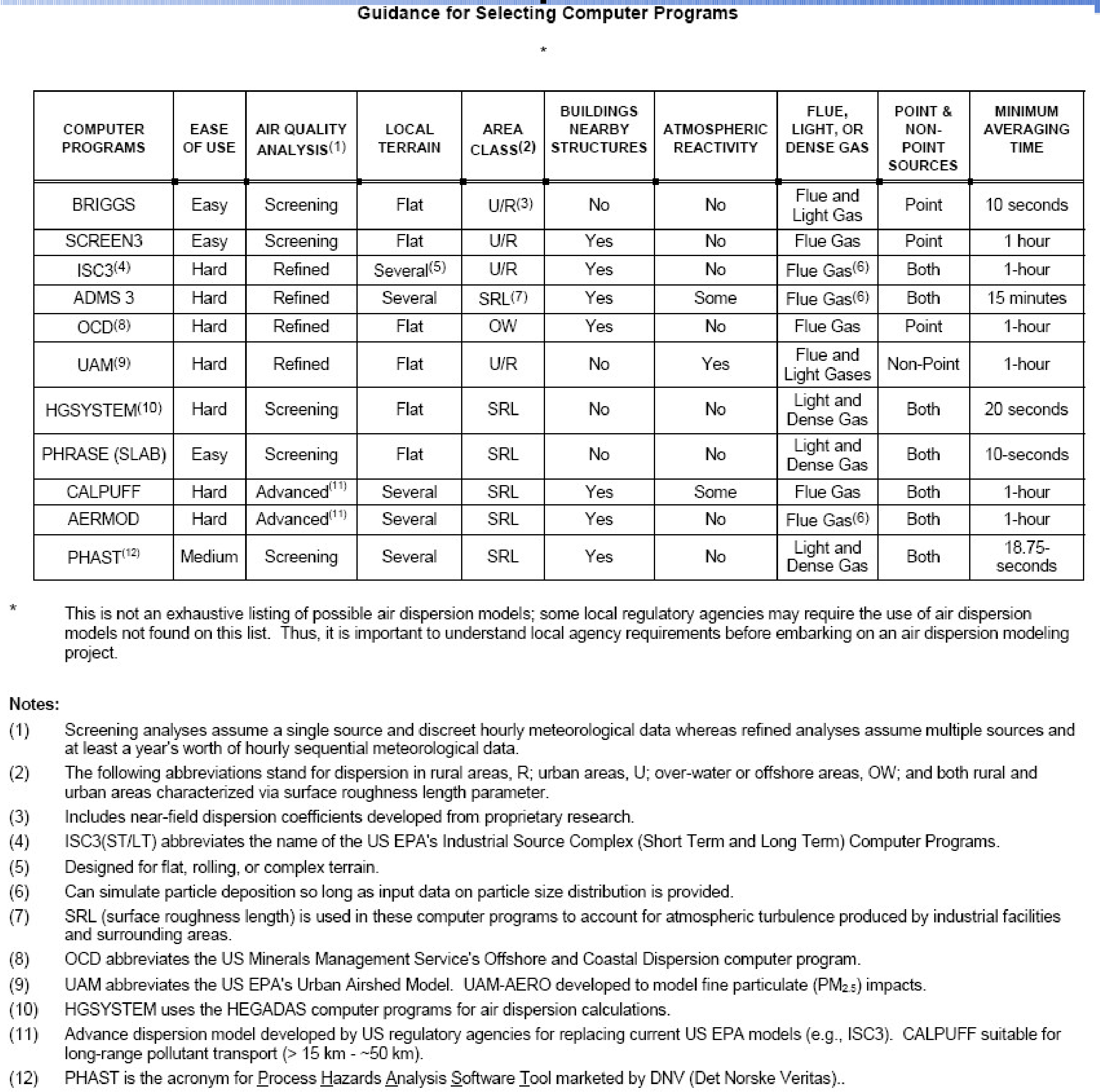
(2) Night refers to the period from 1 hour before sunset to 1 hour after sunrise.

(3) The neutral Category D should also be used, regardless of wind speed, for overcast conditions during day or night and for any sky conditions during the hour preceding or following night as defined above.

# Dispersion


Altitude
Temperature
Distance Downwind
Looping Plume
Unstable Conditions
Warm, Clear Days with Little Wind
Coning Plume
Neutral Conditions
Windy and Cloudy Days, or Windy Nights
Fanning Plume
Plume within an Inversion Layer
Light Winds at Night with Thin or No Clouds (or Inversion Layer Aloft, Day or Night)
Lofting Plume
Inversion Layer Beneath Plume
Light Winds at Night with Thin or No Clouds (or Inversion Layer Aloft, Day or Night)
Trapped Plume
Inversion Layer Above Plume
Inversion Layer Aloft, Day or Night
Fumigation
(Inversion Breakup)
Unstable Layer Beneath Inversion Deepens until it Reaches Fanning Plume
Favored by Clear Skies and Light Winds on Hot Days

# Dispersion



**Guidance for Selecting Computer Programs**

*

| COMPUTER PROGRAMS | EASE OF USE | AIR QUALITY ANALYSIS(1) | LOCAL TERRAIN | AREA CLASS(2) | BUILDINGS NEARBY STRUCTURES | ATMOSPHERIC REACTIVITY | FLUE, LIGHT, OR DENSE GAS | POINT & NON-POINT SOURCES | MINIMUM AVERAGING TIME |
|---|---|---|---|---|---|---|---|---|---|
| BRIGGS | Easy | Screening | Flat | U/R(3) | No | No | Flue and Light Gas | Point | 10 seconds |
| SCREEN3 | Easy | Screening | Flat | U/R | Yes | No | Flue Gas | Point | 1 hour |
| ISC3(4) | Hard | Refined | Several(5) | U/R | Yes | No | Flue Gas(6) | Both | 1-hour |
| ADMS 3 | Hard | Refined | Several | SRL(7) | Yes | Some | Flue Gas(6) | Both | 15 minutes |
| OCD(8) | Hard | Refined | Flat | OW | Yes | No | Flue Gas | Point | 1-hour |
| UAM(9) | Hard | Refined | Flat | U/R | No | Yes | Flue and Light Gases | Non-Point | 1-hour |
| HGSYSTEM(10) | Hard | Screening | Flat | SRL | No | No | Light and Dense Gas | Both | 20 seconds |
| PHRASE (SLAB) | Easy | Screening | Flat | SRL | No | No | Light and Dense Gas | Both | 10-seconds |
| CALPUFF | Hard | Advanced(11) | Several | SRL | Yes | Some | Flue Gas | Both | 1-hour |
| AERMOD | Hard | Advanced(11) | Several | SRL | Yes | No | Flue Gas(6) | Both | 1-hour |
| PHAST(12) | Medium | Screening | Several | SRL | Yes | No | Light and Dense Gas | Both | 18.75-seconds |

* This is not an exhaustive listing of possible air dispersion models; some local regulatory agencies may require the use of air dispersion models not found on this list. Thus, it is important to understand local agency requirements before embarking on an air dispersion modeling project.

**Notes:**

(1) Screening analyses assume a single source and discreet hourly meteorological data whereas refined analyses assume multiple sources and at least a year's worth of hourly sequential meteorological data.

(2) The following abbreviations stand for dispersion in rural areas, R; urban areas, U; over-water or offshore areas, OW; and both rural and urban areas characterized via surface roughness length parameter.

(3) Includes near-field dispersion coefficients developed from proprietary research.

(4) ISC3(ST/LT) abbreviates the name of the US EPA's Industrial Source Complex (Short Term and Long Term) Computer Programs.

(5) Designed for flat, rolling, or complex terrain.

(6) Can simulate particle deposition so long as input data on particle size distribution is provided.

(7) SRL (surface roughness length) is used in these computer programs to account for atmospheric turbulence produced by industrial facilities and surrounding areas.

(8) OCD abbreviates the US Minerals Management Service's Offshore and Coastal Dispersion computer program.

(9) UAM abbreviates the US EPA's Urban Airshed Model. UAM-AERO developed to model fine particulate ($PM_{2.5}$) impacts.

(10) HGSYSTEM uses the HEGADAS computer programs for air dispersion calculations.

(11) Advance dispersion model developed by US regulatory agencies for replacing current US EPA models (e.g., ISC3). CALPUFF suitable for long-range pollutant transport (> 15 km - ~50 km).

(12) PHAST is the acronym for Process Hazards Analysis Software Tool marketed by DNV (Det Norske Veritas)..

# Dispersion

- **THRESHOLD LIMIT VALUES (TLVs),** Refer to air borne concentration of substances and represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse health effects.
- TLVs for gases and vapors are usually established in terms of parts per million of substances in air by volume (ppm). For convenience to the user, these TLVs are listed with molecular weights.

  TLV in mg/m3= (TLV in ppm) x (molecular weight of substance) / 24.45

  where 24.45 is molar volume of air (m3/kmol) at normal temperature and pressure conditions (25°C and 1 atm).

- Two categories of Threshold Limit Values (TLVs) are specified herein, as follows:

  Short Time Exposure Limit (STEL): used to quantify short term exposure of personnel to toxic gas (maximum of 4 exposures per day of less than 15 min each).

  Time Weighted Average (TWA): used to quantify continuous exposure of personnel to toxic gas (8 hours a day or 40 hours per week).

# Elevated Flare

- **Assist Gas:** Combustible gas that is added to relief gas prior to the flare burner or at the point of combustion in order to raise the heating value.
- **Blow-Off:** Loss of a stable flame where the flame is lifted above the burner, occurring if the fuel velocity exceeds the flame velocity.
- **Combustion Air:** Air required to combust the flare gases.
- **Burnback:** Internal burning within the flare tip. Burnback can result from air backing down the flare burner at purge or low flaring rates.
- **Burning Velocity (Flame velocity):** speed at which a flame front travels into an unburned combustible mixture.

# Elevated Flare

- **Deflagration:** Explosion in which the flame-front of a combustible medium is advancing at less than the speed of sound.
- **Detonation:** Explosion in which the flame-front of a combustible medium is advancing at or above the speed of sound.
- **Destruction Efficiency:** Mass fraction of the fluid vapor that can be oxidized or partially oxidized. For a hydrocarbon, this is the mass fraction of carbon in the fluid vapour that oxidizes to CO or $CO_2$.
- **Enrichment:** Process of adding assist gas to the relief gas.
- **Flame-Retention Device:** Device used to prevent flame blow off from a flare burner.
- **Flare Burner (Flare Tip):** Part of the flare where fuel and air are mixed at the velocities, turbulence and concentration required to establish and maintain proper ignition and stable combustion.

# Elevated Flare

- **Flashback:** Phenomenon occurring in a flammable mixture of air and gas when the local velocity of the combustible mixture becomes less than the flame velocity, causing the flame to travel back to the point of mixture.

- **Purge Gas:** Fuel gas or non-condensable inert gas added to the flare header to mitigate air ingress and burnback.

- **Windshield:** Device used to protect the outside of a flare burner from direct flame impingement. The windshield is so named because external flame impingement occurs on the downwind side of an elevated flare burner.

- **Flame Dip:** When the slow upward flow of a lighter than air gas permits air to flow downward along the stack wall.

# Elevated Flare

**Flare Tip**

- The flare tip is the last device of the flare system. It is used to burn the gas without liquid, except the small quantity due to the carryover from the associated drum. Different types can be used and they are: pipe flare and sonic flare.
- Incoloy 800 and stainless 310 are the recommended materials for flare .
- The length of the flare tip is normally 3 m.
- The pipe flare tip may have a mechanical device (e.g. flame retention ring) or other means of establishing and maintaining a stable flame.
- The ignition fire from the gas discharge is initially ignited by interaction with the pilot(s) flames. Once the pilot lights and the flame stabilizes, the flare should maintain flame stability over the operating design range.

# Elevated Flare

**Flare Tip**

- The allowable flare burner exit velocity is a function of relief gas composition, flare burner design, and the gas pressure available. These parameters are interrelated.
- Some flare tips incorporate a flame-retention device or other means that provides a stable burning flame either attached or detached relative to the flare tip.
- Experience has shown that a properly designed and applied flare burner can have an exit velocity of more than Mach 0.5, if pressure drop, noise, and other factors permit. Many pipe flares, assisted or unassisted, and air-assisted flares have been in service for many years with maximum Mach numbers of Mach 0.8 and higher.

# Elevated Flare

## Sonic Flare Tip

- The exit gas velocity is at least 1 Mach. Fluid jets discharging into the atmosphere induce air and tend to mix the induced air with the fluid. Air when premixed with gas in a gas burner improves combustion and gives a clean efficient flame which reduces the emissivity and radiation.
- The sonic flare back pressure for the design flow rate could reach 4 to 10 bars (normal 4 to 5 bars), when properly designed, however the downstream equipment have smaller sizes due to the lowest gas volume but an highest design pressure. Each manufacturer has its own design.

*Advantages and Drawnbacks*

The advantages and drawbacks of the sonic flare with the conventional pipe flare are:

# Elevated Flare

## Sonic Flare Tip

*Advantages*

- Lower emissivity coefficient due to a better combustion (good mixing with air) and consequently lower radiations and lower flare height.
- Higher back pressure and consequently smaller headers, sub-headers and flare drum.
- Could be installed inclined but not recommended and not accepted by all manufacturers due to the possible tip damage at low flow rate.

*Drawnbacks*

- More maintenance (replacement every to 2 or 3 years, depending of manufacturer).
- More weight of flare tip.
- More noise.
- Cost ( more expensive ).
- Low pressure flare system could not be connected to sonic flare due to back-pressure. In this case a separated low pressure flare system is required or combined with the sonic tip, the LP flare tip being installed in the center of the sonic tip.

# Elevated Flare

**Flame Properties**

- A flame is a rapid, self-sustaining chemical reaction that occurs in a distinct reaction zone.

- The two basic types of flames are

  (a) the diffusion flame, which is found in conventional flares and occurs on ignition of a fuel jet issuing into air, and

  (b) the aerated flame, which occurs when fuel and air are premixed before ignition. The burning velocity, or flame velocity, is the speed at which a flame front travels through the unburned combustible mixture.

- In the case of a flare, the flame front is normally at the top of the stack.
- At low gas velocities, back mixing of air occurs in the top of the stack.
- Experiments have shown that if a sufficient flow of combustible gas is maintained to produce a flame visible from ground level, there is usually no significant back mixing of air into the stack.
- At lower gas flows, there is the possibility of combustion at a flame front located part of the way down the flare tip with a resultant high tip temperature. Or there can be flame extinguishment with subsequent formation of an explosive mixture in the stack and ignition from the pilot light.

# Elevated Flare

## Flame Properties

- In an aerated flame from a premixing device, such as a flare pilot, a phenomenon known as flashback can occur.
- This results from the linear velocity of the combustible mixture becoming less than the flame velocity, causing the flame to travel back to the point of mixture.
- In the case of diffusion flames, if the fuel flow rate is increased until it exceeds the flame velocity at every point, the resultant turbulent mixing and dilution with air can cause the flame to be lifted above the burner until a new stable position in the gas stream above the burner is reached.
- This phenomenon is called a detached, stable flame. (Extinguishment of the flame is referred to as blow off).
- Both blow off and flashback velocities are greater for fuels that have high burning velocities. Small amounts of hydrogen in a hydrocarbon fuel widen the stability range because blow-off velocity increases much faster than flashback velocity.

# Smoke

## Smoke

- Many hydrocarbon flames are luminous because of incandescent carbon particles formed in the flames.
- The smoking tendency is a function of the gas calorific value and of the bonding structure of the hydrocarbons. The paraffinic series of hydrocarbons has the lowest tendency to produce smoke, whereas olefinic, diolefinic and aromatic series of hydrocarbons have a much higher tendency to produce smoke.
- Smoke is formed during the combustion of hydrocarbons only when the system is fuel-rich, either overall or locally.
- Observation has revealed that suppression of the hydrogen-atom concentration in the flames accompanies the suppression of smoke formation.

# Smoke

## Smoke

- There are many possible causes for a smoking flare such as liquid carryover, flare gas flow rate change, change in flare gas composition, or incorrect flow of smoke suppression fluid.

- Smoking is a visual signal to check operation (e. g. adjust the flow of smoke suppression fluid).

- Smoke formation can possibly be reduced by reactions that consume hydrogen atoms or render them ineffective.

Steam Effects on Smokeless Operation

- One theory suggests that steam separates the hydrocarbon molecules, thereby minimizing polymerization, and forms oxygen compounds that burn at a reduced rate and temperature and that are not conducive to cracking and polymerization.

- Another theory claims that water vapor reacts with the carbon particles to form carbon monoxide, carbon dioxide and hydrogen, thereby removing the carbon before it cools and forms smoke.

# Smokeless Flaring

## Smokeless Flaring

- To promote even air distribution throughout the flames (and thus prevent smoke formation), energy is required to create turbulence and mixing of the combustion air within the flare gas as it is being ignited.
- This energy can be present in the gases, in the form of pressure, or it can be exerted on the system through another medium, such as injecting high-pressure steam, compressed air or low-pressure blower air and water into the gases as they exit the flare tip.
- The flare is usually required to be smokeless for the gas flows that are expected to occur from normal day-to-day operations. This is usually a fraction of the maximum gas flow, but some environmentally sensitive areas require 100 % smokeless or even a fully enclosed flare.

# Smokeless Flaring

## Degree of Smokelessness

- The flare may be designed for various degrees of smokelessness. Many state and federal regulations state the smokeless requirement in the form “No operator shall allow the flare emissions to exceed 20 % opacity for more than 5 min in any consecutive 2-h period.” This type of regulation is usually the basis for designing flares to achieve Ringelmann 1 (20 % opacity) performance.

- Other applications can require Ringelmann 0 (zero opacity) for regulatory or community relations reasons. It is necessary for the user to understand the local regulatory requirements that govern smokeless requirements.

## Steam Injection:

- Flare tips that use steam to control smoking are a common form of smokeless flare tip.

- The steam can be injected through a single pipe nozzle located in the centre of the flare, through a series of steam/air injectors in the flare, through a manifold located around the periphery of the flare tip or a combination of all three, as appropriate for a particular application.

# Smokeless Flaring

**Steam Requirements**

- The amount of steam required for smokeless burning depends on the vapor flow rate to be burned and the detailed composition of the mixture.

- Key parameters involving smokeless combustion include percentage of unsaturates, percentage of inerts, and the mixture relative molecular mass.

- Certain specific compounds require special consideration by the vendor. Examples include ethylene, butadiene, acetylene, and ethylene oxide.

$$\text{Suggested Steam-to-flare-Gas Ratio} = \sum_{i=1}^{n} w(i) \cdot \mathrm{API}(i)$$

where

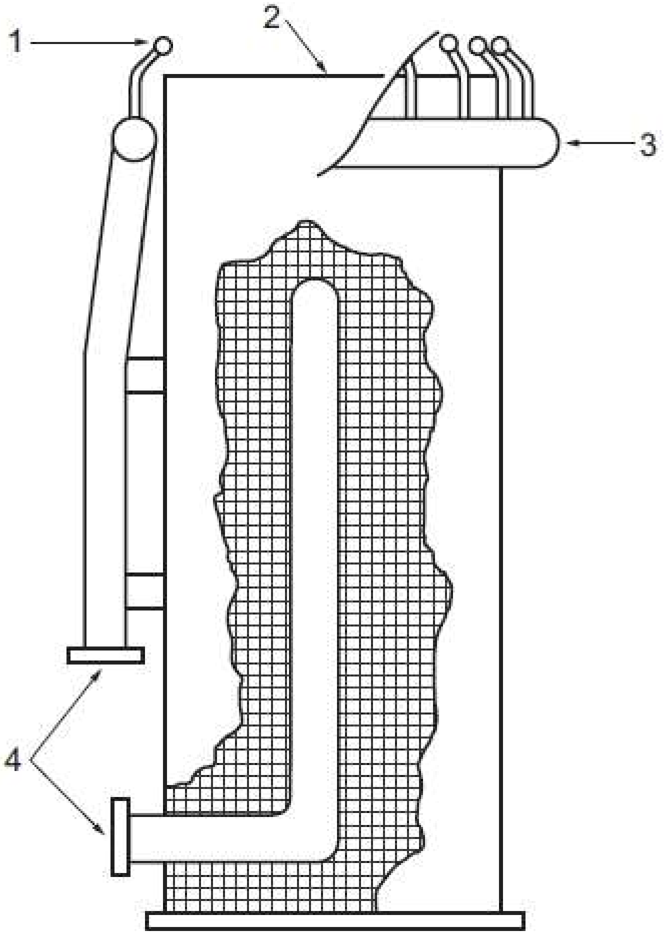
| | |
|---|---|
| n | is the number of components in flare gas mixture. Both hydrocarbon and nonhydrocarbons are included in this count; |
| $w(i)$ | is the weight fraction of component $(i)$ in the flare gas mixture; |
| $\mathrm{API}(i)$ | is the steam-to-hydrocarbon mass ratio for hydrocarbon $(i)$ from this table. Note that nonhydrocarbons such as hydrogen, hydrogen sulfide, carbon monoxide, ammonia, nitrogen, carbon dioxide, etc. would have a steam ratio value of zero. |

# Smokeless Flaring

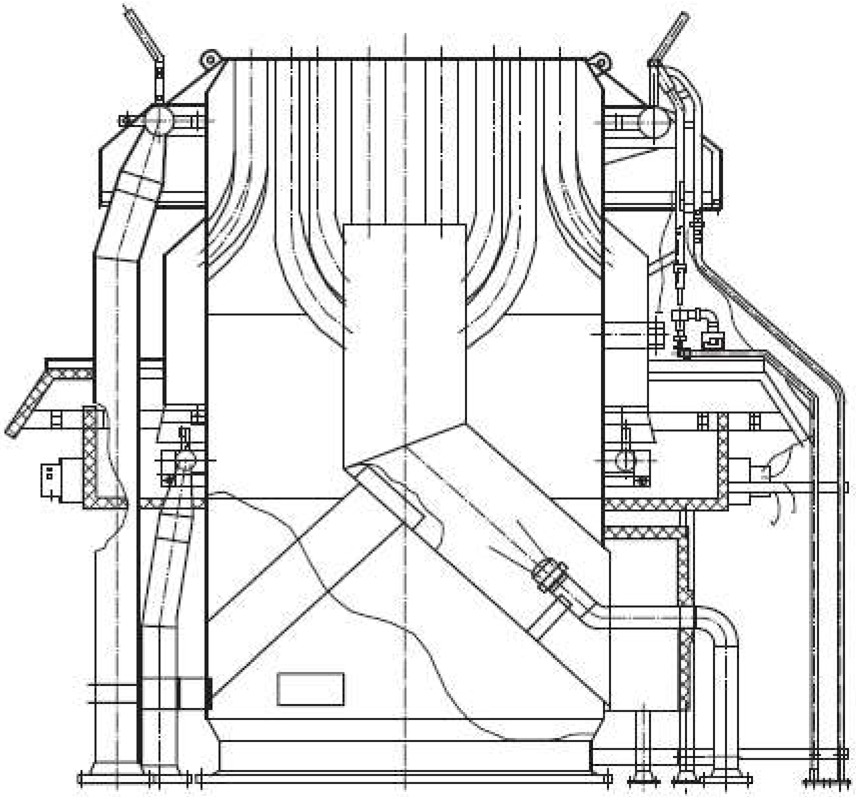
| **Gases Being Flared** | **Approximate Steam Rate** [a b]<br>kg (lb) of steam per kg (lb) of hydrocarbon gas |
|---|---|
| **Paraffins** | |
| Ethane | 0.10 to 0.15 |
| Propane | 0.25 to 0.30 |
| Butane | 0.30 to 0.35 |
| Pentane plus | 0.40 to 0.45 |
| **Olefins** | |
| Ethylene | 0.40 to 0.50 |
| Propylene | 0.50 to 0.60 |
| Butene | 0.60 to 0.70 |
| **Diolefins** | |
| Propadiene | 0.70 to 0.80 |
| Butadiene | 0.90 to 1.00 |
| Pentadiene | 1.10 to 1.20 |
| **Acetylenes** | |
| Acetylene | 0.50 to 0.60 |
| **Aromatics** | |
| Benzene | 0.80 to 0.90 |
| Toluene | 0.85 to 0.95 |
| Xylene | 0.90 to 1.00 |

# Elevated Flare

## Steam-injected Smokeless Flare Tips



a) Normal



b) Low noise

**Key**

1 steam tips
2 flame holder
3 steam manifold
4 steam connections

# Smokeless Flaring

## Steam Injection

- Although steam is normally provided from a supply header at a gauge pressure of 700 kPa to 1 000 kPa (approx. 100 psi to 150 psi), special designs are available for utilizing steam-gauge pressure as low as 200 kPa (approx. 30 psi).

- The major impact of lower steam pressure is a reduction in steam efficiency during smokeless turndown conditions.

- In cold climates, an internal steam nozzle can cause condensate to enter the flare stack and header, collect, and freeze. In some instances, this has resulted in complete blockage of the flare stack or flare header. Therefore, consideration should be given to supplying steam to an internal steam nozzle through a separately controlled steam line so that it can be turned off in cold conditions.

# Smokeless Flaring

**High-Pressure Air:**

- High-pressure air can also be used to prevent smoke formation. This approach is less common because compressed air is usually more expensive than steam.
- In some situations with low smokeless capacities, it can be preferable, for example, in arctic or low-temperature applications where steam can freeze and plug the flare tip/stack.
- Other applications include desert or island installations where there is a shortage of water for steam, or where the waste-flare gas stream reacts with water.
- The air is usually provided at a gauge pressure of 689 kPa (100 psi) and the mass of air required is approximately 1.2 times the steam mass, because the compressed air does not produce the water-gas shift reaction that occurs with steam.

# Smokeless Flaring

**High-Pressure Water:**

- High-pressure water, while quite uncommon, is also used to control smoking, especially for horizontal flare applications and when it is necessary to eliminate large quantities of waste water or brine.

- One lb (0,45 kg) of water at a gauge pressure 350 kPa to 700 kPa (approx. 50 psi to 100 psi) is usually required for each 0,45 kg (1 lb) of gas flared. Freeze protection is required in cold climates.

**High-pressure Fuel Gas Injection**

- High-pressure fuel gas can also be used to prevent smoke formation by entraining outside air into the flare flame and generating turbulence to assist overall combustion.

- Special high-performance tips are used to reduce the amount of assist gas. If natural gas is used as the assist gas, typically 0.5 lb to 0.75 lb of assist gas per lb of flare gas is required, based on a flare gas consisting of normal paraffinics such as propane and butane.

- The gauge supply pressure for natural gas assist is typically 500 kPa (~75 psi) (minimum) with 1000 kPa (~150 psi) preferred.

# Smokeless Flaring

**Low-Pressure Air:**

- A low-pressure forced-air system is usually the first alternative evaluated if insufficient on-site utilities are available to aid in producing a smokeless operation.

- The system creates turbulence in the flame zone by injecting low-pressure air supplied from a blower across the flare tip as the gases are being ignited, thus promoting even air distribution throughout the flames.

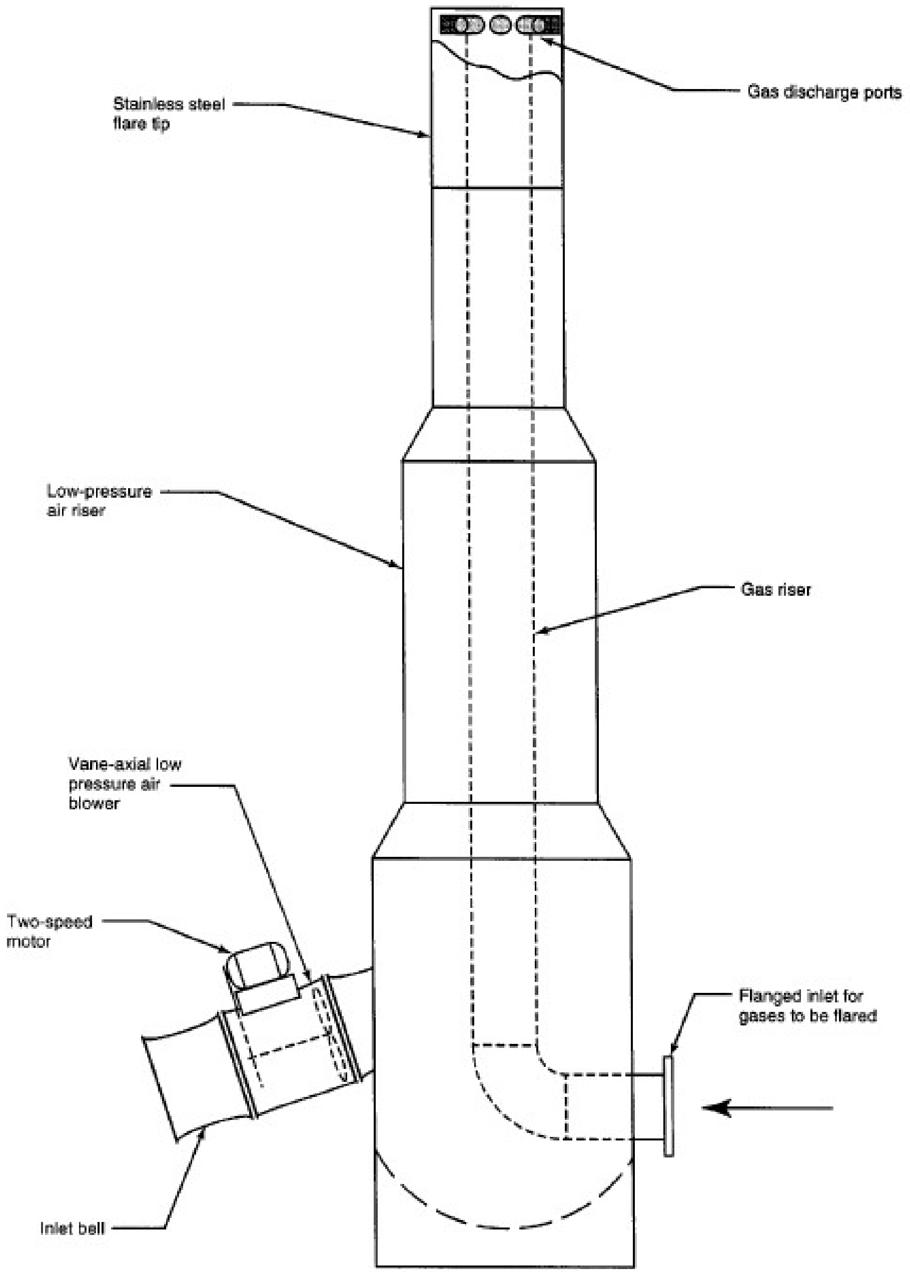
- Usually, air at a gauge pressure of 0,5 kPa to 5,0 kPa (2 in $H_2O$ to 20 in $H_2O$) flows coaxially with the flare gas to the flare tip where the two are mixed.

- This system has a higher initial cost due to the requirement for a dual stack and an air blower. However, this system has much lower operating costs than a steam-assisted design (requiring only power for a blower). The additional quantity of air supplied by the blower for smokeless operation is normally 10 % to 30 % of the stoichiometric air required for saturated hydrocarbons and 30 % to 40 % of the stoichiometric air required for unsaturated hydrocarbons.

# Smokeless Flaring

**Low-Pressure Air:**

**(Dual Stack)**



# Smokeless Flaring

**A high-pressure system:**

- A high-pressure system does not require any utilities such as steam or air to promote smokeless flaring.
- These systems utilize pressure energy available within the flare gas itself (typically a gauge pressure of 35 kPa to 140 kPa (5 psi to 20 psi) minimum at the flare tip) to eliminate fuel-rich conditions and resulting smoke within the flames.
- Since no external utilities are required, these systems are normally advantageous for disposing of very large gas releases, both from the economics of smokeless operation and the control of flame shape. The individual tips used have relatively small capacities, and larger system designs can require that many tips be manifolded together.

# Smokeless Flaring

**Control of Fluid Injection for Smoke Suppression:**

- The following methods of controlling steam (or compressed air, water and so on) for smokeless flare control are common (many other strategies are possible).

a) *Manual Operation*
This method is satisfactory if short-term smoking can be tolerated when a sudden increase in flaring occurs.

a) *Video Monitoring with Manual Control*

b) *Feed Forward Control System for Pressure, Mass Flow, or Velocity*
This system might not be desirable if the composition of the gas being flared varies widely over time (in other words, paraffins to olefins or aromatics, hydrogen, or various mixtures thereof).

a) *Feedback System Using an Infrared Sensor*
A disadvantage of this system is that infrared waves are absorbed by moisture and the resultant feedback signal is reduced in rainy or foggy conditions.

# Smokeless Flaring

**Flares Without Smoke Suppression**

- The simplest flare-tip design is commonly referred to as a utility or pipe-flare tip and can consist of little more than a piece of pipe fitted with a flame retention device for flame stability at higher exit velocities (the upper portion is typically stainless steel to endure the high flame temperatures) and a pilot for gas ignition.
- This plain design has no special features to prevent smoke formation, and consequently should not be used in applications whereas methane or hydrogen smokeless operation is required, unless the gases being flared, such, are not prone to smoking.
- Flare tips of this style should include a flame-retention device (to increase flame stability at high flow rates) and one or more pilots (depending upon the diameter of the tip). Windshields or heat shields are usually added on flare tips to reduce flame lick on the outside of the tip.

# Elevated Flare

**Flaring of Gases with Low Heating Value**

- Gases that have a high enough heating value (usually greater than 7.5 MJ/m3 (200 Btu/Scf) for unassisted flares and 11.2 MJ/m3 (300 Btu/Scf) for assisted flares) to sustain combustion on their own without any auxiliary fuel additions.

- Endothermic gases can be disposed of in thermal incineration systems; however, there are situations where the preferred approach is to use a special flare design. These flares utilize auxiliary fuel gas to burn the flare gases. With small gas flow rates, simple enrichment of the flare gases by adding fuel gas in the flare header to raise the net heating value of the mixture can be sufficient.

- In other situations, it can be necessary to add a fuel-gas injection manifold around the flare tip (similar to a steam manifold) and build a fire around the exit end of the flare tip through which it is necessary for the gases to flow. Dilute ammonia or high $CO_2$ composition flare gases with small amounts of $H_2S$ are common applications where the addition of fuel gas is required.

- Gases with low heating value shall have low exit velocities to avoid creation of high excess air conditions that could over aerate a combustible mixture causing incomplete combustion and flame instability

# Elevated Flare

## Unassisted Pipe Flare

- An unassisted pipe flare is used where smokeless burning assist is not required.

- Unassisted flares require the gas to have a minimum net heating value of 200 Btu/SCF.

- The pipe-flare tip may have a mechanical device or other means of establishing and maintaining a stable flame. The ignition fire from the gas discharge is initially ignited by interaction with the pilot(s) flames. Once the pilot lights and the flame stabilizes, the flare should maintain flame stability over the operating design range. Flame stability for a pipe flare is primarily dependent upon the selection of the gas exit velocity.

- Low gas-exit velocities and buoyancy-dominated flames are preferred for successful combustion of low heating-value relief gas.

- High gas-exit velocities are preferred for higher-heating-value hydrocarbon relief gases or for relief gases rich in hydrogen.

# Elevated Flare

**Purge Gas Requirement**

- Flare system purging has traditionally been used to prevent the formation of explosive mixtures in flare and vent systems by preventing the admission of air into the flare system through leaks, back-flow of air at the flare tip at very low flows and back-diffusion of air into the flare tip.

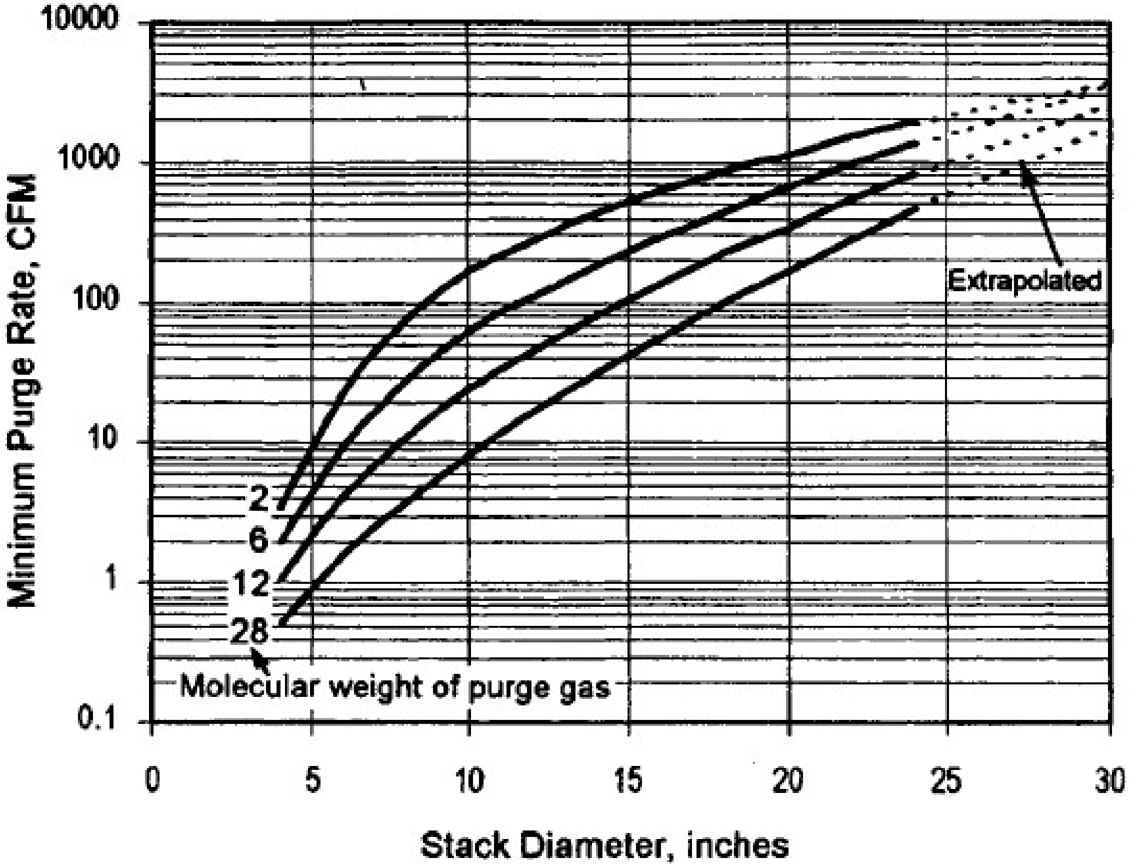
- The requirements for a continuous purge can be eliminated if a liquid seal is located near the base of the stack. This requires special precautions in the design of the stack to assure viability in the event of an internal explosion.

- Combustible gases such as methane or natural gas, or inert gases such as nitrogen or carbon dioxide, are frequently used for purging flare systems.

- The quantity of purge gas (flow rate) required depends on whether other air sealing methods are used; e.g., diffusion or velocity seals. By using diffusion or velocity seals, the purge gas requirements can be reduced by 90% or more.

# Elevated Flare

## Purge Gas Requirement



- Husa (1964) presented an empirical correlation to estimate the purge gas flow rates required to prevent explosive mixtures within a flare stack with no seal.

# Elevated Flare

## Purge Gas Requirement

- These purge rates are based on limiting the oxygen concentration in the flare system below 6% by volume, a so-called "safe purge gas rate."

- Husa‘s method are not directly applicable to stacks with length-to-diameter ratios less than 50 or to stacks shorter than 50 feet. For short stacks, the level of safe oxygen concentration is probably closer than 25 feet to the top of the stack. The purge requirements for short stacks can be estimated by multiplying the value from Husa‘s Figure by a correction factor of 25/a, where “a” is the desired distance (ft) from the top of the stack to the level of safe oxygen concentration.

- Required purge gas flow based on “Total” procedure (2005):
  Purge gas flow = $2.4\text{x}10^4\ Ø^3\ MW^{-0.565}$ (without molecular or velocity seal)
  Purge gas flow = $1.2\text{x}10^4\ Ø^3\ MW^{-0.565}$ (with molecular or velocity seal)
  - Purge gas flow ($Sm^3/h$)
  - tip Ø (m), or equivalent Ø of all openings for sonic flares
  - MW purge gas (kg/kmole).

# Elevated Flare

## Purge Gas Requirement

- Required purge gas flow based on “API 521”:
- For lighter-than-air purge gases, below equation can be used to determine Q, the purge gas rate, expressed in Nm3/h for continuous purge requirements in open flares without the effect of buoyancy seal or velocity seal.

$$Q = 190.8 D^{3.46} \frac{1}{y} \ln\left(\frac{20.9}{O_2}\right)\left(\sum_{i}^{n} C_i^{0.65} \cdot K_i\right)$$

In SI units

$D$ is the flare stack diameter, expressed in m

$y$ is the column depth at which the oxygen concentration ($O_2$) is predicted, expressed in meters

$O_2$ is the oxygen volume fraction, expressed as a percentage

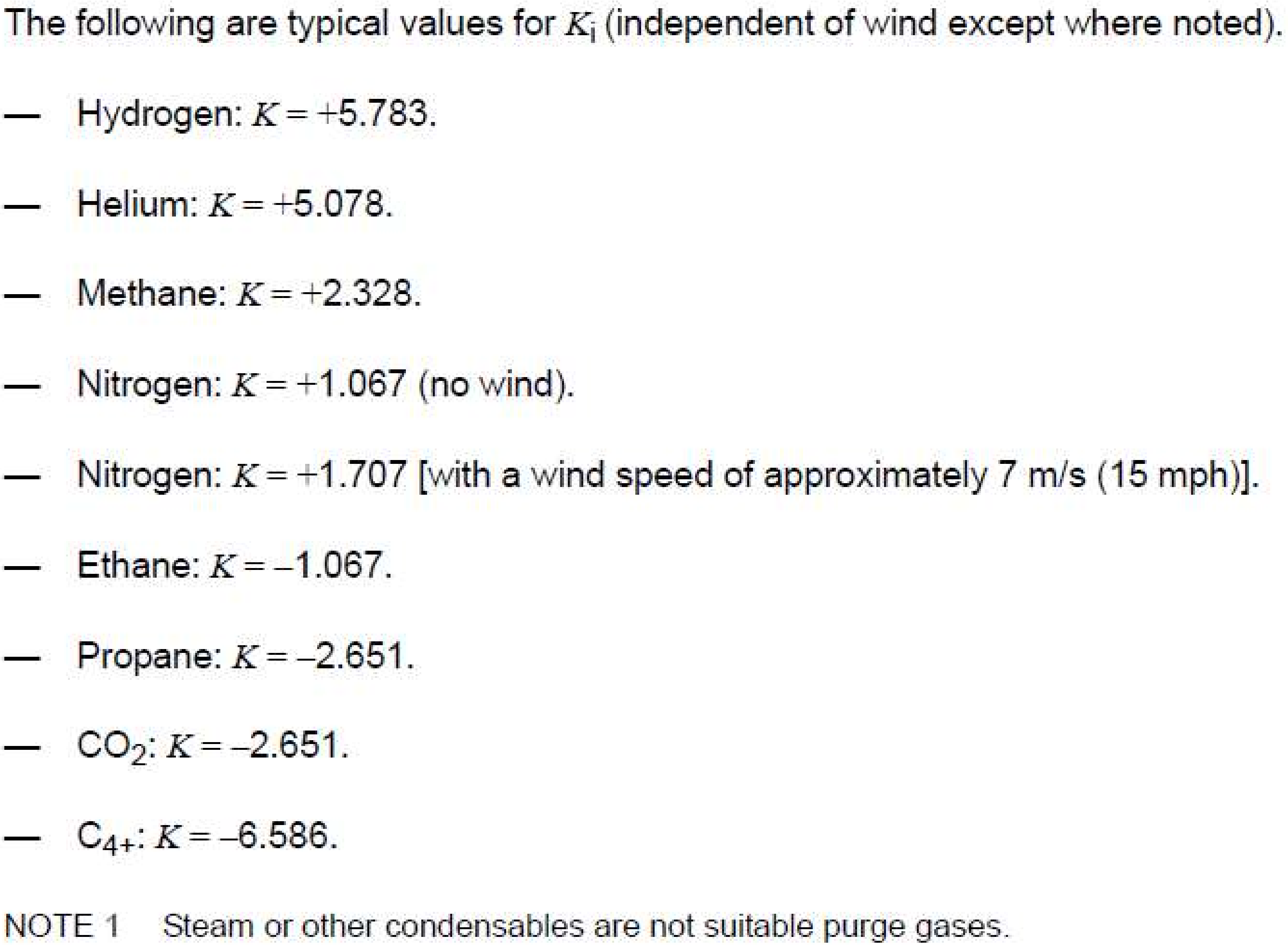
$C_i$ is the volume fraction of component $i$, a number between 0 and 1

$K_i$ is a constant for component $i$.

# Elevated Flare

## Purge Gas Requirement

- Required purge gas flow based on “API 521”:



The following are typical values for $K_i$ (independent of wind except where noted).

— Hydrogen: $K = +5.783$.

— Helium: $K = +5.078$.

— Methane: $K = +2.328$.

— Nitrogen: $K = +1.067$ (no wind).

— Nitrogen: $K = +1.707$ [with a wind speed of approximately 7 m/s (15 mph)].

— Ethane: $K = -1.067$.

— Propane: $K = -2.651$.

— $CO_2$: $K = -2.651$.

— $C_{4+}$: $K = -6.586$.

NOTE 1 Steam or other condensables are not suitable purge gases.

# Elevated Flare

## Purge Gas Requirement

- Required purge gas flow based on “API 521”:

- API equation can be simplified using the typical criteria of limiting the oxygen volume fraction to 6 % at a distance of 7.62 m (25 ft) down the flare stack (except that lower oxygen concentrations should be used for certain compounds such as hydrogen):

$$Q = 31.25D^{3.46} \cdot K$$ In SI units

$Q$ is the purge gas rate, expressed in normal m$^3$/h

$D$ is the flare stack diameter, expressed in meters

## Control of Purge Rate

- Once the required quantity of purge gas has been established, the injection rate should be controlled by a fixed orifice, rotameter or other device that ensures the supply remains constant and is not subject to instrument malfunction or maladjustment

# Elevated Flare

## Air Seals

- Air seals (also called purge reduction or gas seals) prevent air from entering the stack, and are often recommended to prevent flashbacks and explosions in a flare system.
- Purge-reduction seals are not flame arrestors; that is, they will not stop a flashback. They are designed as energy-conservation devices to reduce purge-gas flows required to mitigate air infiltration into the stack.
- Air present in the stack can create a potentially explosive mixture with incoming flare gas during low-flare gas flow rate conditions.
- There are two common types of mechanical seals, usually located at/or below the flare tip that are used to reduce the amount of continuous purge gas required to prevent air infiltration into the flare stack : molecular seals (sometimes called diffusion, buoyancy or labyrinth seals), and velocity (fluidic) types.

# Elevated Flare

## Air Seals

- In the event of loss of purge-gas flow (and assuming that there is no other waste-gas flow) the oxygen level below the velocity type seal will almost immediately begin to increase. In the case of the buoyancy seal there is a time delay between the moment the purge gas flow stops and the time the oxygen level below the seal begins to increase.
- Molecular seals are acceptable only for LP flares where gas velocity in the stack does not exceed, say, 60 m/s. They are strictly prohibited for sonic flares.
- Velocity seals have none of these limitations and are the preferred solution but they become immediately inefficient in case of loss of purge gas. Where a kinetic seal is used, and where practical, two independent sources of purge gas should be used in parallel to improve reliability.
- The molecular seal consists of a baffled concentric cylinder arrangement, which uses the difference in molecular weight of the flare gas and the ambient air to prevent air from entering the flare stack. This seal normally reduces the purge-gas velocity required through the tip to 0,003 m/s (0,01 ft/s).

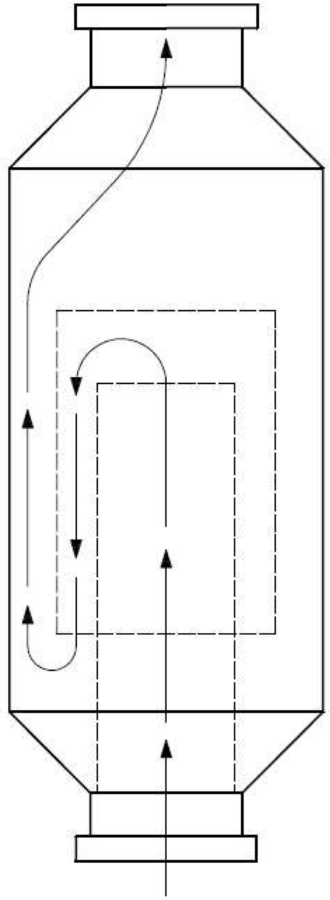
# Elevated Flare

**Air Seals**

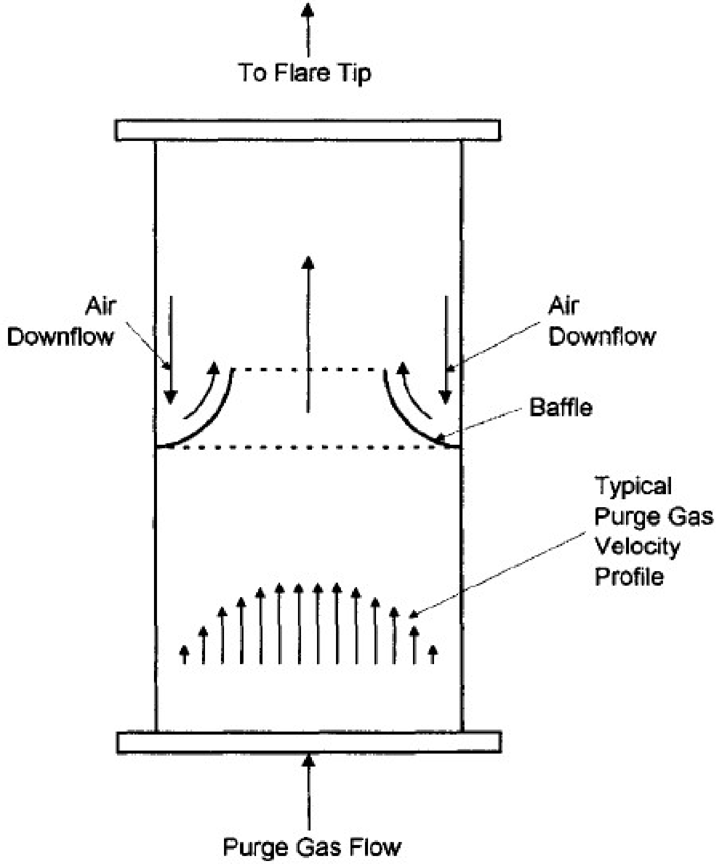
- This rate limits oxygen levels below the device to less than 0,1 %. Higher purge-gas velocities can be required to avoid burnback within the flare tip.
- Velocity seals are more recent developments in seal design to prevent air entry into the flare stack.
- Velocity seals use conical baffles to redirect and focus the purge gas flow field just below the flare tip to sweep air from the flare stack. This seal normally reduces the purge gas velocity through the tip to between 0,006 m/s to 0,012 m/s (0,02 ft/s and 0,04 ft/s).
- This rate limits oxygen concentrations below the seal to 4 % to 8 % (approximately 50 % of the limiting oxygen concentration required to create a flammable mixture).
- Higher purge gas velocities can be required to avoid burn-back within the flare tip. Caution should be exercised when the waste-gas stream can contain hydrogen, ethylene or other gases with wide explosive limits. In such cases, a higher purge rate can be required to avoid an explosive mixture with air.
- Pressure drops as large as 14 kPa (2 psi) have been satisfactorily used at the flare tip. (Flare tip + Air Seal).

# Elevated Flare

## Air Seals



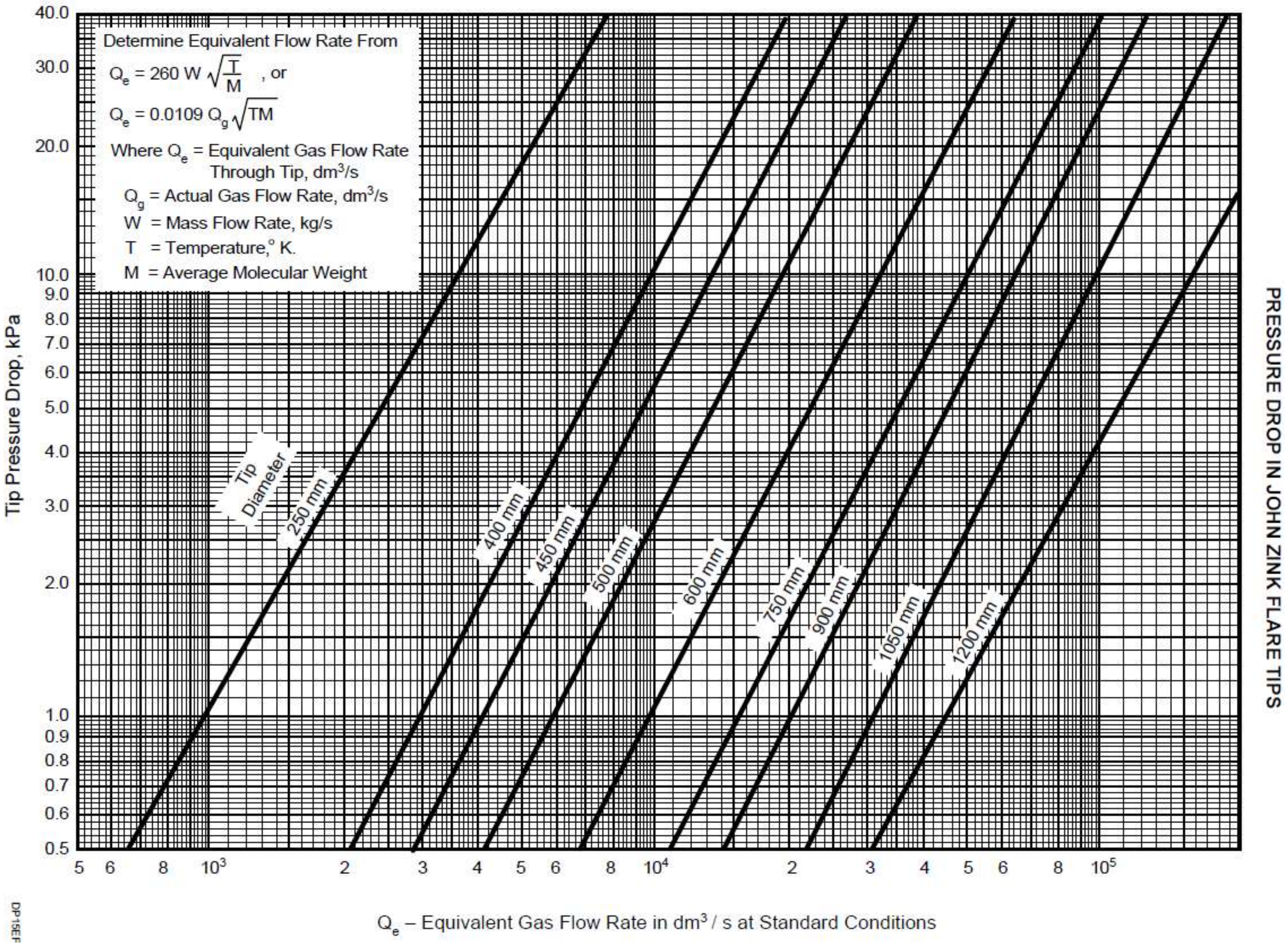
Purge-reduction seal — Buoyancy seal



**Purge Reduction Seal—Velocity Type.** (Adapted from API RP-521)

# Elevated Flare

## Flare Tip Pressure Drop



Determine Equivalent Flow Rate From

$Q_e = 260\, W \sqrt{\frac{T}{M}}$ , or

$Q_e = 0.0109\, Q_g \sqrt{TM}$

Where $Q_e$ = Equivalent Gas Flow Rate Through Tip, $dm^3/s$

$Q_g$ = Actual Gas Flow Rate, $dm^3/s$

W = Mass Flow Rate, kg/s

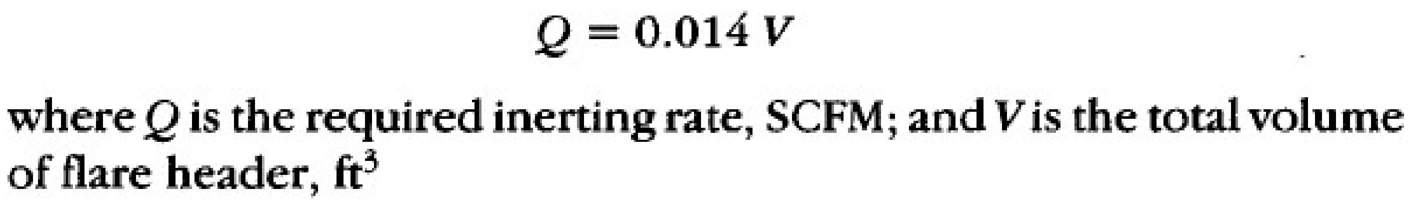
T = Temperature, ° K.

M = Average Molecular Weight

# Elevated Flare

## Purge Gas Requirement

- Purge gas (inert) should also be introduced into the flare header during sudden ambient cooling (e.g., rain storm or sudden temperature drop) to offset the pressure reduction in the header caused by the cooling, which can draw in air.
- API 2000 uses a rate of internal temperature change of 100°F/hr or 1.7 °F/min for atmospheric tanks. This corresponds to a rate of 2 SCFH of air per square foot of total roof and shell area.
- Simpson (1995b) recommends a design cooling rate of 8°F/min. This may be conservative, but not unduly so for flare headers. With an initial temperature of 100°F, the required inert gas rate is approximately:



$$Q = 0.014\,V$$

where $Q$ is the required inerting rate, SCFM; and $V$ is the total volume of flare header, $\text{ft}^3$

- It is recommended that Simpson's equation be used for estimating the purge rate needed to compensate for air ingress due to sudden ambient cooling.

# Elevated Flare

## Ignition of Flare Gases

- To ensure ignition of flare gases, continuous pilots with means for remote ignition are recommended for all flares.
- Some regulations can require the presence of a continuous pilot flame to be proven by thermocouple or equivalent means.
- The most commonly used type of igniter is the flame-front propagation type, which uses a spark from a remote location to ignite a flammable mixture.
- Pilot-igniter controls are located near the base of elevated flares and at least 30 m (100 ft) from ground flares.

## Pilot Fuel Gas Supply

- The fuel gas supply to the pilots and igniters should be highly reliable. Since normal plant fuel sources can be upset or lost, it is desirable to provide a backup system connected to the most reliable alternative fuel source, with a provision for automatic cut-in on low pressure.
- Parallel instrumentation for pressure reduction is frequently justifiable. The flare fuel system should be carefully checked to ensure that hydrates cannot present a problem.

# Elevated Flare

## Pilot Burners and Ignition System

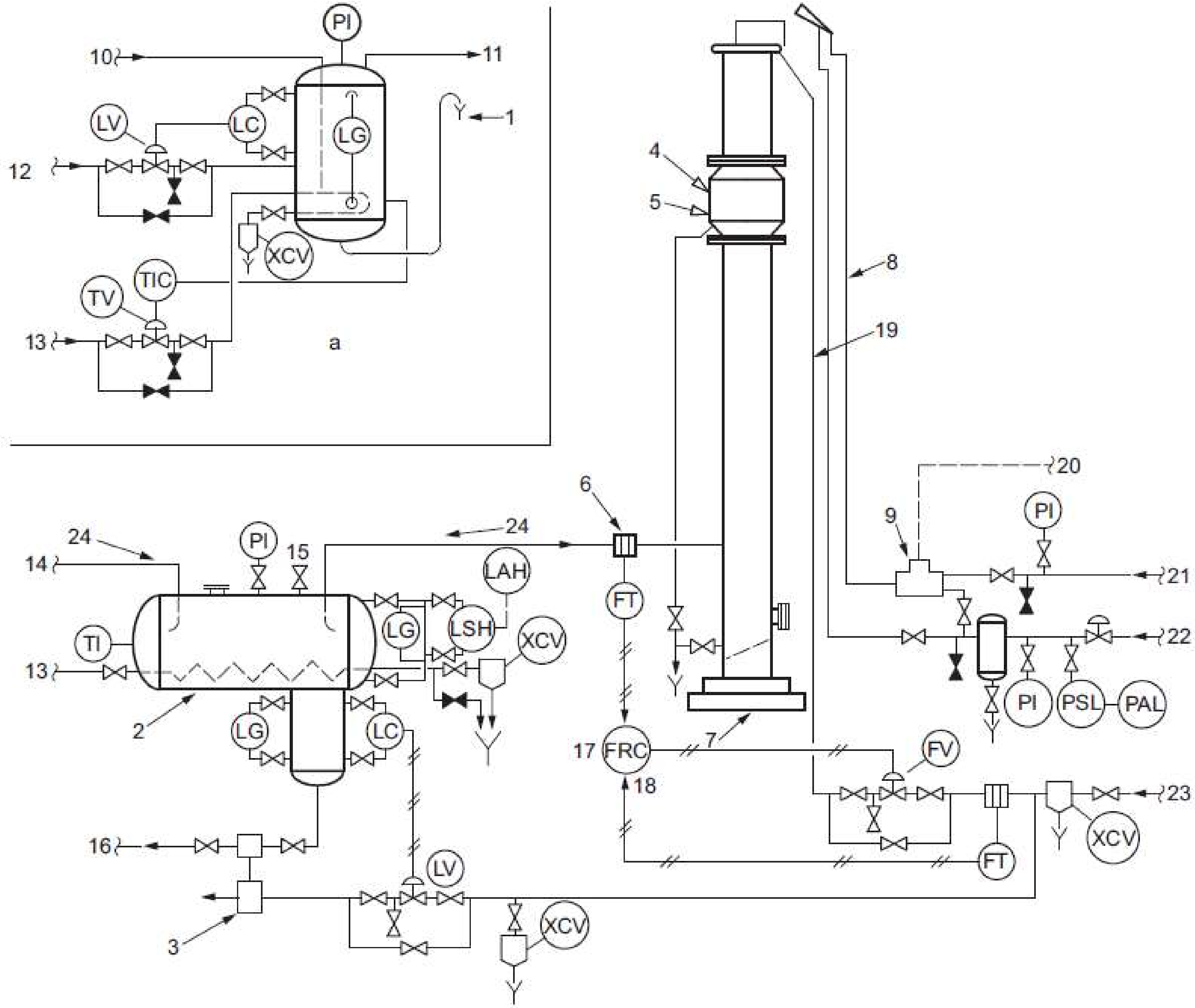
- The ignition mechanism for a flare installation usually consists of pilot burners and pilot burner igniters.
- The pilot burners serve to ignite the out-flowing gases and to keep the gas burning. These pilots must provide a stable flame to ignite the flare gases, and in many cases, to keep them burning.
- To accomplish this, more than one—and usually three or four—pilot burners are always used.
- Pilot burner gas requirements are about 200 SCFH *per pilot* for wind speeds above 50 mph; for wind speeds below 50 mph, the pilot burner gas requirement can be reduced to about 100 SCFH
- A separate system must be provided for the ignition of the pilot burner to safeguard against flame failure. The usual method is to ignite a gas/air mixture in an ignition chamber by a spark.

# Elevated Flare

## Pilot Burners and Ignition System

- The flame front travels through an igniter tube to the pilot burner at the top of the flare. This system permits the igniter to be set up at a safe distance from the flare (up to 100 ft) and still ignite the pilots satisfactorily.
- The fuel gas supply to the pilots and igniters must be clean, dry, and reliable. Backup natural gas (or LPG) fuel should feed automatically when the normal supply is lost.
- Moisture is the biggest single problem when designing ignition systems. The air for pilots must be dry, since wet air will flood the ignition lines, short out the spark plug, and prevent ignition of the pilots. Use of -40°F dew point (or drier) instrument air is recommended.

# Elevated Flare



# Elevated Flare

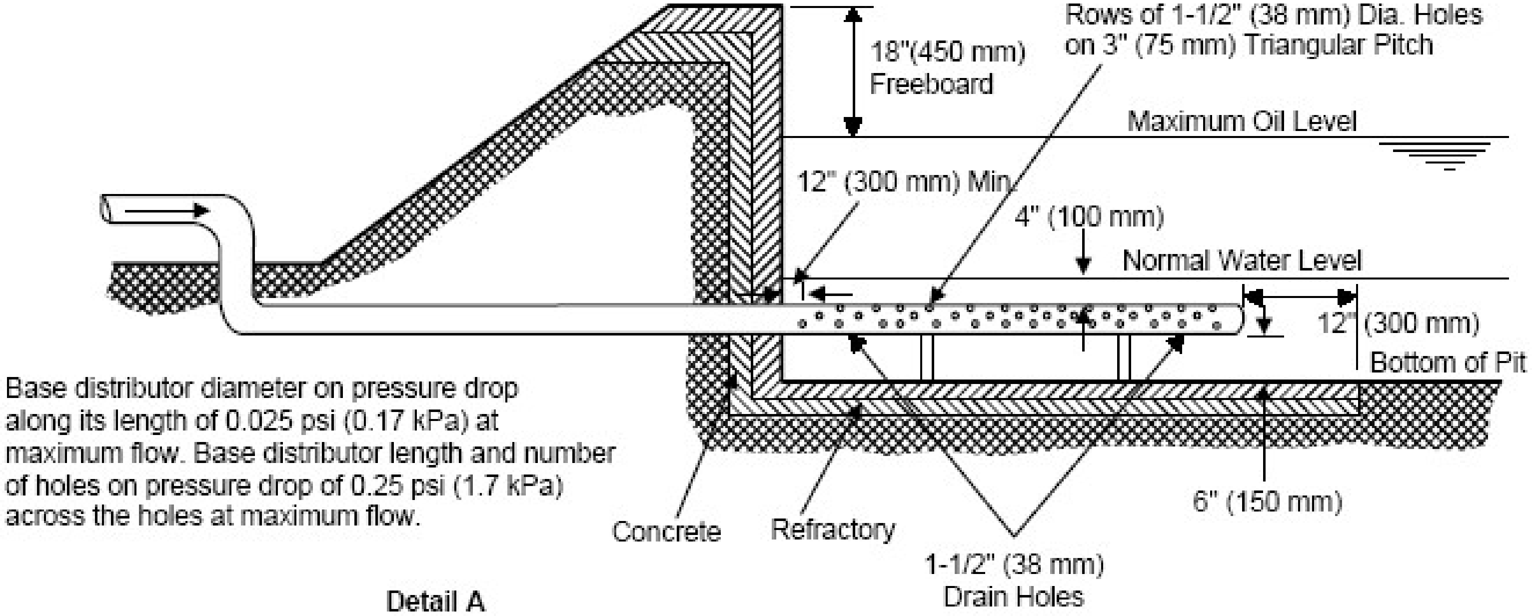
**Key**

| | |
|---|---|
| 1 | oily water sewer (to sour water system if large quantities of $H_2S$ are flared continuously) |
| 2 | knockout drum |
| 3 | steam-driven pump and electrically-driven spare |
| 4 | molecular seal |
| 5 | purge gas |
| 6 | flow-measuring element |
| 7 | flare stack |
| 8 | igniter line |
| 9 | flame-front generator |
| 10 | from knockout drum |
| 11 | to flare stack |
| 12 | water |
| 13 | steam |
| 14 | from relief or vent header system |
| 15 | vent |
| 16 | to oil recovery facilities or slop |
| 17 | panel-mounted |
| 18 | ratio |
| 19 | steam to nozzle manifold for smokeless burning |
| 20 | power supply for spark ignition |
| 21 | air supply |
| 22 | fuel gas to pilots and ignition |
| 23 | steam for smokeless burning |
| 24 | slope towards drum |

[a] Insert shows alternative sealing method (water seal).

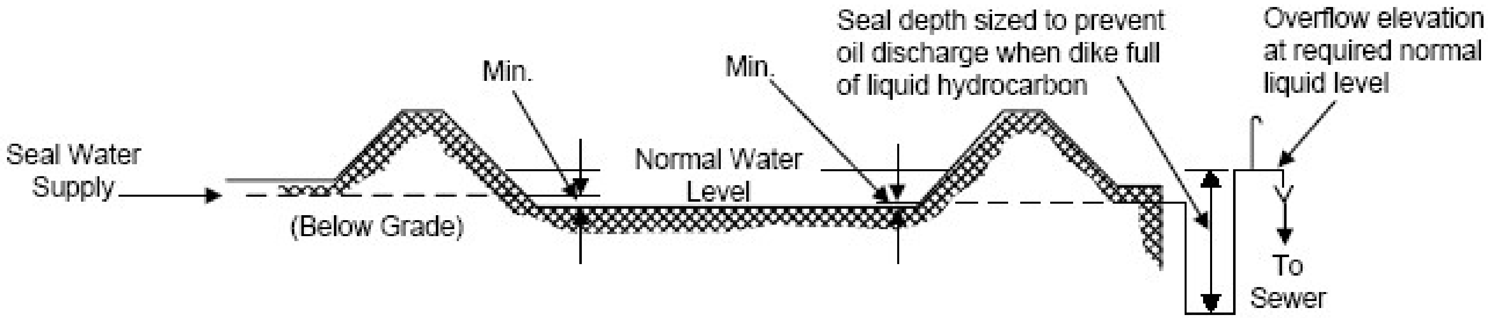
# Burn Pit

- Burning-pit flares can handle flammable liquids or gases or mixtures of the two.



Base distributor diameter on pressure drop along its length of 0.025 psi (0.17 kPa) at maximum flow. Base distributor length and number of holes on pressure drop of 0.25 psi (1.7 kPa) across the holes at maximum flow.

**Detail A**
**Liquid and Vapor Distributor**



**Detail B**
**Seal Water Inlet and Overflow Seal**

# Burn Pit

## Sizing Procedure

- The burning-pit area is sized to provide sufficient surface to vaporize and burn liquid at a rate equal to the maximum incoming liquid rate.

1. Determine the linear regression rate of the liquid surface (i.e., the rate at which the liquid level would fall as a result of vaporization by radiant heat from the burning vapor above it, assuming no addition of incoming liquid):

$$R = 0.003\frac{LHV}{H_v} \qquad \text{(Customary)}$$

$$R = 0.00127\frac{LHV}{H_v} \qquad \text{(Metric)}$$

2. Determine the pit area necessary to vaporize and burn liquid at a rate equal to the liquid input rate:

$$A = \frac{0.2\,m}{R\,\rho_L}; \qquad \text{(Customary)}$$

$$A = \frac{1001\,m}{R\,\rho_L} \qquad \text{(Metric)}$$

# Burn Pit

## Sizing Procedure

LHV = Lower Heating Value of incoming vapor and vaporized liquid, Btu/lb (kW/kg).

A = Pit area required to vaporize and burn liquid, $ft^2$ ($m^2$).

m = Rate of vaporization and burning of liquid, lb/hr (kg/s) (selected as equal to the rate of flashed liquid entering the pit).

R = Linear regression rate of liquid surface, in./min (mm/s).

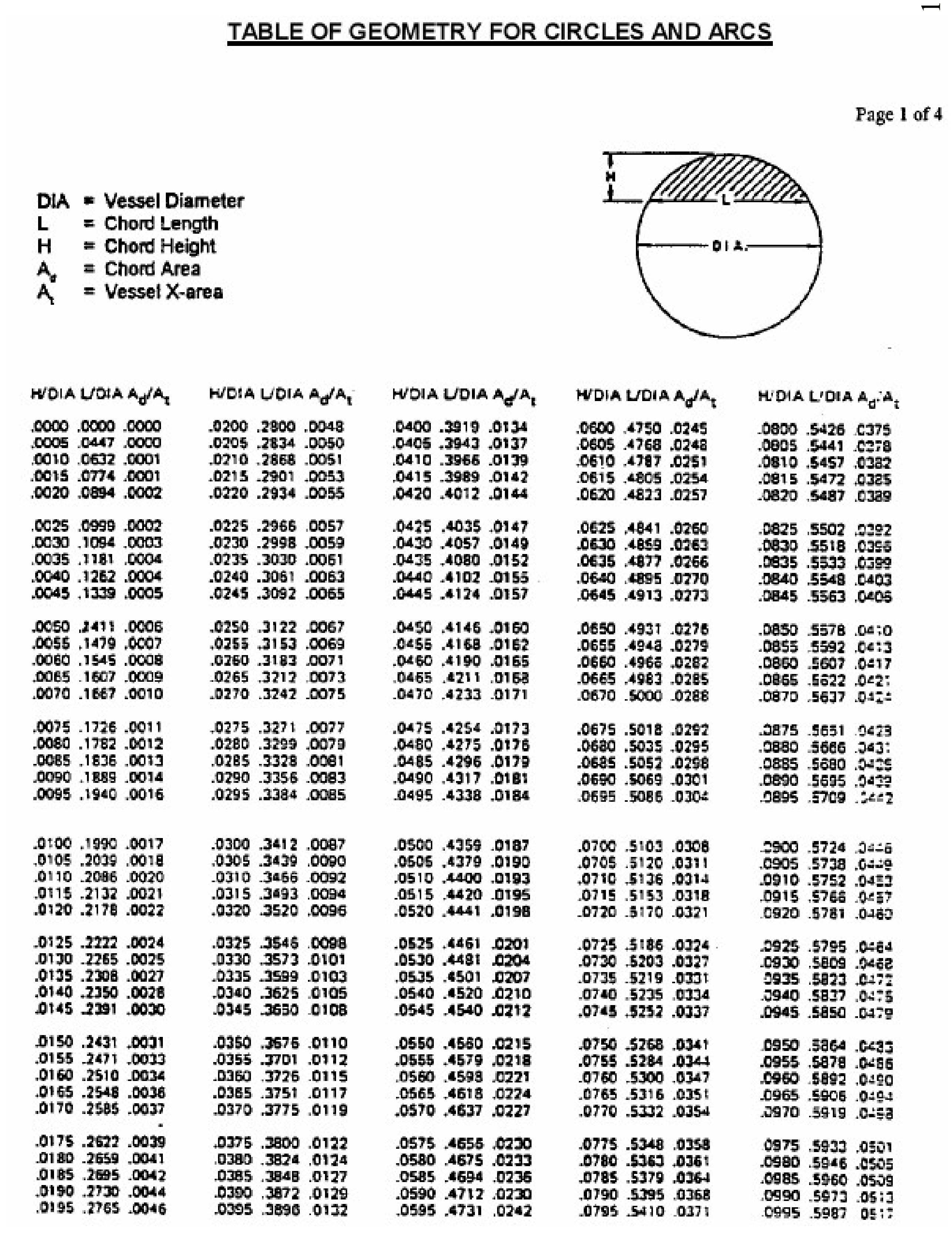
$\rho_L$ = Liquid density, $lb/ft^3$ ($kg/m^3$).

$H_v$ = Liquid latent heat of vaporization, Btu/lb (kJ/kg).

3. The dike wall height above the water level is selected to provide holdup capacity for the largest liquid release resulting from a single contingency during 30 minutes, plus 18 in. (450 mm) freeboard.

The liquid rate is based on the actual flashed liquid entering the pit, assuming no burning or further vaporization in the pit. The height of the dike wall above the water level should not, however, be less than 4 ft (1.2 m).

# Flare Network



## TABLE OF GEOMETRY FOR CIRCLES AND ARCS

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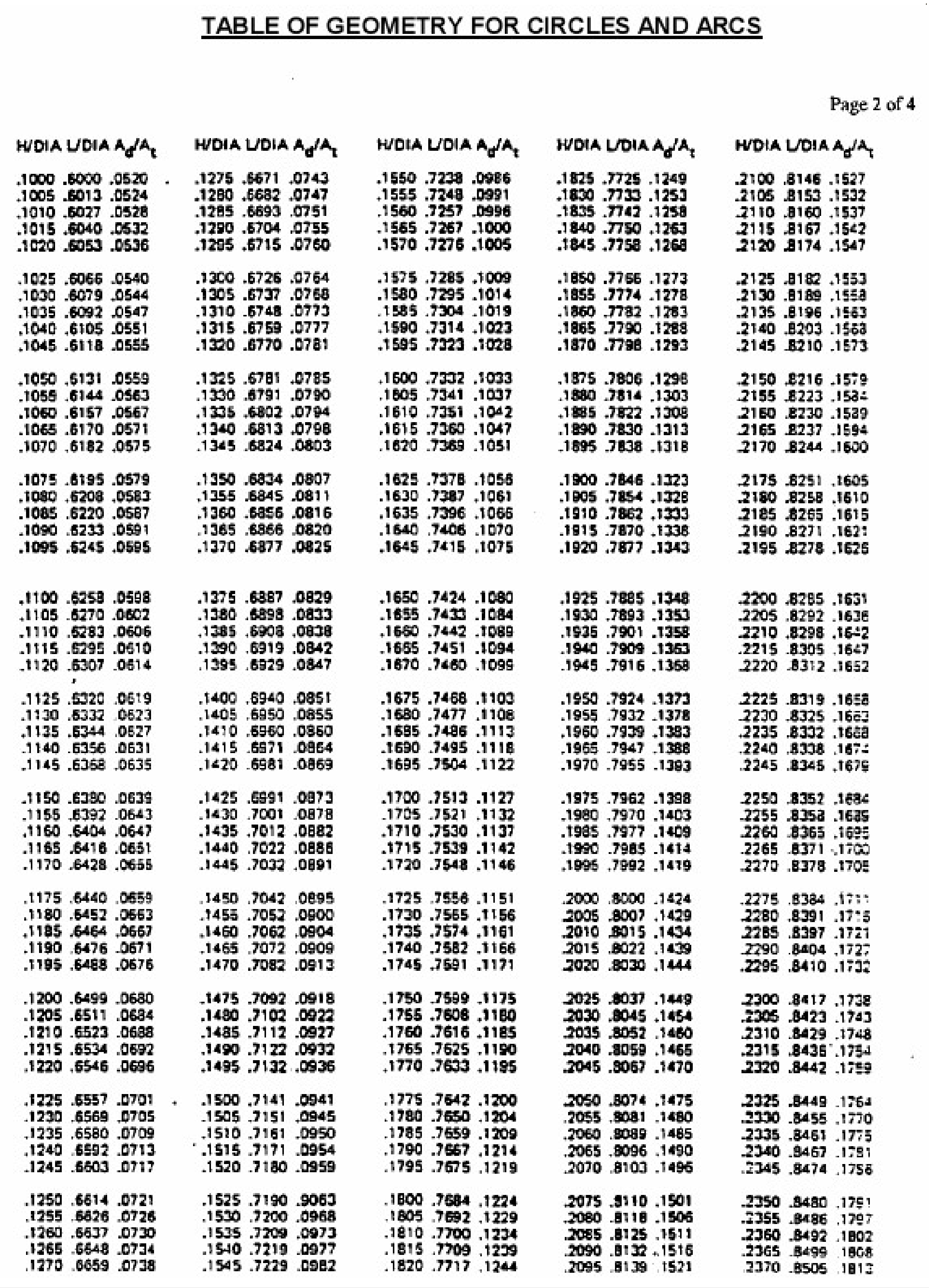
DIA = Vessel Diameter
L = Chord Length
H = Chord Height
$A_d$ = Chord Area
$A_t$ = Vessel X-area

| H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .0000 | .0000 | .0000 | .0200 | .2800 | .0048 | .0400 | .3919 | .0134 | .0600 | .4750 | .0245 | .0800 | .5426 | .0375 |
| .0005 | .0447 | .0000 | .0205 | .2834 | .0050 | .0405 | .3943 | .0137 | .0605 | .4768 | .0248 | .0805 | .5441 | .0378 |
| .0010 | .0632 | .0001 | .0210 | .2868 | .0051 | .0410 | .3966 | .0139 | .0610 | .4787 | .0251 | .0810 | .5457 | .0382 |
| .0015 | .0774 | .0001 | .0215 | .2901 | .0053 | .0415 | .3989 | .0142 | .0615 | .4805 | .0254 | .0815 | .5472 | .0385 |
| .0020 | .0894 | .0002 | .0220 | .2934 | .0055 | .0420 | .4012 | .0144 | .0620 | .4823 | .0257 | .0820 | .5487 | .0389 |
| .0025 | .0999 | .0002 | .0225 | .2966 | .0057 | .0425 | .4035 | .0147 | .0625 | .4841 | .0260 | .0825 | .5502 | .0392 |
| .0030 | .1094 | .0003 | .0230 | .2998 | .0059 | .0430 | .4057 | .0149 | .0630 | .4859 | .0263 | .0830 | .5518 | .0396 |
| .0035 | .1181 | .0004 | .0235 | .3030 | .0061 | .0435 | .4080 | .0152 | .0635 | .4877 | .0266 | .0835 | .5533 | .0399 |
| .0040 | .1262 | .0004 | .0240 | .3061 | .0063 | .0440 | .4102 | .0155 | .0640 | .4895 | .0270 | .0840 | .5548 | .0403 |
| .0045 | .1339 | .0005 | .0245 | .3092 | .0065 | .0445 | .4124 | .0157 | .0645 | .4913 | .0273 | .0845 | .5563 | .0406 |
| .0050 | .1411 | .0006 | .0250 | .3122 | .0067 | .0450 | .4146 | .0160 | .0650 | .4931 | .0276 | .0850 | .5578 | .0410 |
| .0055 | .1479 | .0007 | .0255 | .3153 | .0069 | .0455 | .4168 | .0162 | .0655 | .4948 | .0279 | .0855 | .5592 | .0413 |
| .0060 | .1545 | .0008 | .0260 | .3183 | .0071 | .0460 | .4190 | .0165 | .0660 | .4966 | .0282 | .0860 | .5607 | .0417 |
| .0065 | .1607 | .0009 | .0265 | .3212 | .0073 | .0465 | .4211 | .0168 | .0665 | .4983 | .0285 | .0865 | .5622 | .0421 |
| .0070 | .1667 | .0010 | .0270 | .3242 | .0075 | .0470 | .4233 | .0171 | .0670 | .5000 | .0288 | .0870 | .5637 | .0424 |
| .0075 | .1726 | .0011 | .0275 | .3271 | .0077 | .0475 | .4254 | .0173 | .0675 | .5018 | .0292 | .0875 | .5651 | .0428 |
| .0080 | .1782 | .0012 | .0280 | .3299 | .0079 | .0480 | .4275 | .0176 | .0680 | .5035 | .0295 | .0880 | .5666 | .0431 |
| .0085 | .1836 | .0013 | .0285 | .3328 | .0081 | .0485 | .4296 | .0179 | .0685 | .5052 | .0298 | .0885 | .5680 | .0435 |
| .0090 | .1889 | .0014 | .0290 | .3356 | .0083 | .0490 | .4317 | .0181 | .0690 | .5069 | .0301 | .0890 | .5695 | .0439 |
| .0095 | .1940 | .0016 | .0295 | .3384 | .0085 | .0495 | .4338 | .0184 | .0695 | .5086 | .0304 | .0895 | .5709 | .0442 |
| .0100 | .1990 | .0017 | .0300 | .3412 | .0087 | .0500 | .4359 | .0187 | .0700 | .5103 | .0308 | .0900 | .5724 | .0446 |
| .0105 | .2039 | .0018 | .0305 | .3439 | .0090 | .0505 | .4379 | .0190 | .0705 | .5120 | .0311 | .0905 | .5738 | .0449 |
| .0110 | .2086 | .0020 | .0310 | .3466 | .0092 | .0510 | .4400 | .0193 | .0710 | .5136 | .0314 | .0910 | .5752 | .0453 |
| .0115 | .2132 | .0021 | .0315 | .3493 | .0094 | .0515 | .4420 | .0195 | .0715 | .5153 | .0318 | .0915 | .5766 | .0457 |
| .0120 | .2178 | .0022 | .0320 | .3520 | .0096 | .0520 | .4441 | .0198 | .0720 | .5170 | .0321 | .0920 | .5781 | .0460 |
| .0125 | .2222 | .0024 | .0325 | .3546 | .0098 | .0525 | .4461 | .0201 | .0725 | .5186 | .0324 | .0925 | .5795 | .0464 |
| .0130 | .2265 | .0025 | .0330 | .3573 | .0101 | .0530 | .4481 | .0204 | .0730 | .5203 | .0327 | .0930 | .5809 | .0468 |
| .0135 | .2308 | .0027 | .0335 | .3599 | .0103 | .0535 | .4501 | .0207 | .0735 | .5219 | .0331 | .0935 | .5823 | .0472 |
| .0140 | .2350 | .0028 | .0340 | .3625 | .0105 | .0540 | .4520 | .0210 | .0740 | .5235 | .0334 | .0940 | .5837 | .0475 |
| .0145 | .2391 | .0030 | .0345 | .3650 | .0108 | .0545 | .4540 | .0212 | .0745 | .5252 | .0337 | .0945 | .5850 | .0479 |
| .0150 | .2431 | .0031 | .0350 | .3676 | .0110 | .0550 | .4560 | .0215 | .0750 | .5268 | .0341 | .0950 | .5864 | .0483 |
| .0155 | .2471 | .0033 | .0355 | .3701 | .0112 | .0555 | .4579 | .0218 | .0755 | .5284 | .0344 | .0955 | .5878 | .0486 |
| .0160 | .2510 | .0034 | .0360 | .3726 | .0115 | .0560 | .4598 | .0221 | .0760 | .5300 | .0347 | .0960 | .5892 | .0490 |
| .0165 | .2548 | .0036 | .0365 | .3751 | .0117 | .0565 | .4618 | .0224 | .0765 | .5316 | .0351 | .0965 | .5906 | .0494 |
| .0170 | .2585 | .0037 | .0370 | .3775 | .0119 | .0570 | .4637 | .0227 | .0770 | .5332 | .0354 | .0970 | .5919 | .0498 |
| .0175 | .2622 | .0039 | .0375 | .3800 | .0122 | .0575 | .4656 | .0230 | .0775 | .5348 | .0358 | .0975 | .5933 | .0501 |
| .0180 | .2659 | .0041 | .0380 | .3824 | .0124 | .0580 | .4675 | .0233 | .0780 | .5363 | .0361 | .0980 | .5946 | .0505 |
| .0185 | .2695 | .0042 | .0385 | .3848 | .0127 | .0585 | .4694 | .0236 | .0785 | .5379 | .0364 | .0985 | .5960 | .0509 |
| .0190 | .2730 | .0044 | .0390 | .3872 | .0129 | .0590 | .4712 | .0230 | .0790 | .5395 | .0368 | .0990 | .5973 | .0513 |
| .0195 | .2765 | .0046 | .0395 | .3896 | .0132 | .0595 | .4731 | .0242 | .0795 | .5410 | .0371 | .0995 | .5987 | .0517 |

# Flare Network



## TABLE OF GEOMETRY FOR CIRCLES AND ARCS

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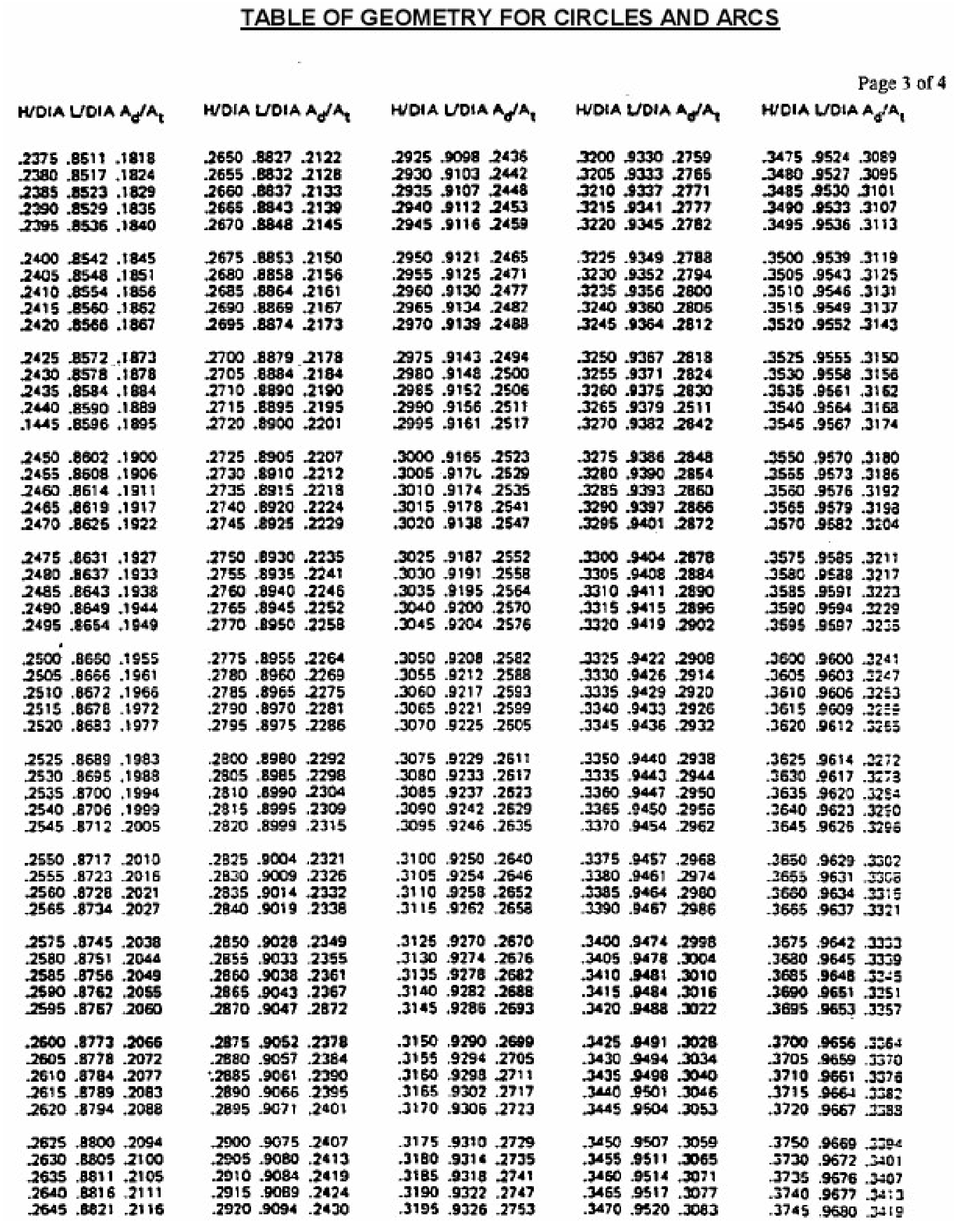
| H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .1000 | .6000 | .0520 | .1275 | .6671 | .0743 | .1550 | .7238 | .0986 | .1825 | .7725 | .1249 | .2100 | .8146 | .1527 |
| .1005 | .6013 | .0524 | .1280 | .6682 | .0747 | .1555 | .7248 | .0991 | .1830 | .7733 | .1253 | .2105 | .8153 | .1532 |
| .1010 | .6027 | .0528 | .1285 | .6693 | .0751 | .1560 | .7257 | .0996 | .1835 | .7742 | .1258 | .2110 | .8160 | .1537 |
| .1015 | .6040 | .0532 | .1290 | .6704 | .0755 | .1565 | .7267 | .1000 | .1840 | .7750 | .1263 | .2115 | .8167 | .1542 |
| .1020 | .6053 | .0536 | .1295 | .6715 | .0760 | .1570 | .7276 | .1005 | .1845 | .7758 | .1268 | .2120 | .8174 | .1547 |
| .1025 | .6066 | .0540 | .1300 | .6726 | .0764 | .1575 | .7285 | .1009 | .1850 | .7766 | .1273 | .2125 | .8182 | .1553 |
| .1030 | .6079 | .0544 | .1305 | .6737 | .0768 | .1580 | .7295 | .1014 | .1855 | .7774 | .1278 | .2130 | .8189 | .1558 |
| .1035 | .6092 | .0547 | .1310 | .6748 | .0773 | .1585 | .7304 | .1019 | .1860 | .7782 | .1283 | .2135 | .8196 | .1563 |
| .1040 | .6105 | .0551 | .1315 | .6759 | .0777 | .1590 | .7314 | .1023 | .1865 | .7790 | .1288 | .2140 | .8203 | .1568 |
| .1045 | .6118 | .0555 | .1320 | .6770 | .0781 | .1595 | .7323 | .1028 | .1870 | .7798 | .1293 | .2145 | .8210 | .1573 |
| .1050 | .6131 | .0559 | .1325 | .6781 | .0785 | .1600 | .7332 | .1033 | .1875 | .7806 | .1298 | .2150 | .8216 | .1579 |
| .1055 | .6144 | .0563 | .1330 | .6791 | .0790 | .1605 | .7341 | .1037 | .1880 | .7814 | .1303 | .2155 | .8223 | .1584 |
| .1060 | .6157 | .0567 | .1335 | .6802 | .0794 | .1610 | .7351 | .1042 | .1885 | .7822 | .1308 | .2160 | .8230 | .1589 |
| .1065 | .6170 | .0571 | .1340 | .6813 | .0798 | .1615 | .7360 | .1047 | .1890 | .7830 | .1313 | .2165 | .8237 | .1594 |
| .1070 | .6182 | .0575 | .1345 | .6824 | .0803 | .1620 | .7369 | .1051 | .1895 | .7838 | .1318 | .2170 | .8244 | .1600 |
| .1075 | .6195 | .0579 | .1350 | .6834 | .0807 | .1625 | .7378 | .1056 | .1900 | .7846 | .1323 | .2175 | .8251 | .1605 |
| .1080 | .6208 | .0583 | .1355 | .6845 | .0811 | .1630 | .7387 | .1061 | .1905 | .7854 | .1328 | .2180 | .8258 | .1610 |
| .1085 | .6220 | .0587 | .1360 | .6856 | .0816 | .1635 | .7396 | .1066 | .1910 | .7862 | .1333 | .2185 | .8265 | .1615 |
| .1090 | .6233 | .0591 | .1365 | .6866 | .0820 | .1640 | .7406 | .1070 | .1915 | .7870 | .1338 | .2190 | .8271 | .1621 |
| .1095 | .6245 | .0595 | .1370 | .6877 | .0825 | .1645 | .7415 | .1075 | .1920 | .7877 | .1343 | .2195 | .8278 | .1626 |
| .1100 | .6258 | .0598 | .1375 | .6887 | .0829 | .1650 | .7424 | .1080 | .1925 | .7885 | .1348 | .2200 | .8285 | .1631 |
| .1105 | .6270 | .0602 | .1380 | .6898 | .0833 | .1655 | .7433 | .1084 | .1930 | .7893 | .1353 | .2205 | .8292 | .1636 |
| .1110 | .6283 | .0606 | .1385 | .6908 | .0838 | .1660 | .7442 | .1089 | .1935 | .7901 | .1358 | .2210 | .8298 | .1642 |
| .1115 | .6295 | .0610 | .1390 | .6919 | .0842 | .1655 | .7451 | .1094 | .1940 | .7909 | .1363 | .2215 | .8305 | .1647 |
| .1120 | .6307 | .0614 | .1395 | .6929 | .0847 | .1670 | .7460 | .1099 | .1945 | .7916 | .1368 | .2220 | .8312 | .1652 |
| .1125 | .6320 | .0619 | .1400 | .6940 | .0851 | .1675 | .7468 | .1103 | .1950 | .7924 | .1373 | .2225 | .8319 | .1658 |
| .1130 | .6332 | .0623 | .1405 | .6950 | .0855 | .1680 | .7477 | .1108 | .1955 | .7932 | .1378 | .2230 | .8325 | .1663 |
| .1135 | .6344 | .0627 | .1410 | .6960 | .0860 | .1685 | .7486 | .1113 | .1960 | .7939 | .1383 | .2235 | .8332 | .1668 |
| .1140 | .6356 | .0631 | .1415 | .6971 | .0864 | .1690 | .7495 | .1118 | .1965 | .7947 | .1388 | .2240 | .8338 | .1674 |
| .1145 | .6368 | .0635 | .1420 | .6981 | .0869 | .1695 | .7504 | .1122 | .1970 | .7955 | .1383 | .2245 | .8345 | .1679 |
| .1150 | .6380 | .0639 | .1425 | .6991 | .0873 | .1700 | .7513 | .1127 | .1975 | .7962 | .1398 | .2250 | .8352 | .1684 |
| .1155 | .6392 | .0643 | .1430 | .7001 | .0878 | .1705 | .7521 | .1132 | .1980 | .7970 | .1403 | .2255 | .8358 | .1685 |
| .1160 | .6404 | .0647 | .1435 | .7012 | .0882 | .1710 | .7530 | .1137 | .1985 | .7977 | .1409 | .2260 | .8365 | .1695 |
| .1165 | .6416 | .0651 | .1440 | .7022 | .0886 | .1715 | .7539 | .1142 | .1990 | .7985 | .1414 | .2265 | .8371 | .1700 |
| .1170 | .6428 | .0655 | .1445 | .7032 | .0891 | .1720 | .7548 | .1146 | .1995 | .7992 | .1419 | .2270 | .8378 | .1705 |
| .1175 | .6440 | .0659 | .1450 | .7042 | .0895 | .1725 | .7556 | .1151 | .2000 | .8000 | .1424 | .2275 | .8384 | .1711 |
| .1180 | .6452 | .0663 | .1455 | .7052 | .0900 | .1730 | .7565 | .1156 | .2005 | .8007 | .1429 | .2280 | .8391 | .1715 |
| .1185 | .6464 | .0667 | .1460 | .7062 | .0904 | .1735 | .7574 | .1161 | .2010 | .8015 | .1434 | .2285 | .8397 | .1721 |
| .1190 | .6476 | .0671 | .1465 | .7072 | .0909 | .1740 | .7582 | .1166 | .2015 | .8022 | .1439 | .2290 | .8404 | .1727 |
| .1195 | .6488 | .0676 | .1470 | .7082 | .0913 | .1745 | .7591 | .1171 | .2020 | .8030 | .1444 | .2295 | .8410 | .1732 |
| .1200 | .6499 | .0680 | .1475 | .7092 | .0918 | .1750 | .7599 | .1175 | .2025 | .8037 | .1449 | .2300 | .8417 | .1738 |
| .1205 | .6511 | .0684 | .1480 | .7102 | .0922 | .1755 | .7608 | .1180 | .2030 | .8045 | .1454 | .2305 | .8423 | .1743 |
| .1210 | .6523 | .0688 | .1485 | .7112 | .0927 | .1760 | .7616 | .1185 | .2035 | .8052 | .1460 | .2310 | .8429 | .1748 |
| .1215 | .6534 | .0692 | .1490 | .7122 | .0932 | .1765 | .7625 | .1190 | .2040 | .8059 | .1465 | .2315 | .8436 | .1754 |
| .1220 | .6546 | .0696 | .1495 | .7132 | .0936 | .1770 | .7633 | .1195 | .2045 | .8067 | .1470 | .2320 | .8442 | .1759 |
| .1225 | .6557 | .0701 | .1500 | .7141 | .0941 | .1775 | .7642 | .1200 | .2050 | .8074 | .1475 | .2325 | .8449 | .1764 |
| .1230 | .6569 | .0705 | .1505 | .7151 | .0945 | .1780 | .7650 | .1204 | .2055 | .8081 | .1480 | .2330 | .8455 | .1770 |
| .1235 | .6580 | .0709 | .1510 | .7161 | .0950 | .1785 | .7659 | .1209 | .2060 | .8089 | .1485 | .2335 | .8461 | .1775 |
| .1240 | .6592 | .0713 | .1515 | .7171 | .0954 | .1790 | .7667 | .1214 | .2065 | .8096 | .1490 | .2340 | .8467 | .1781 |
| .1245 | .6603 | .0717 | .1520 | .7180 | .0959 | .1795 | .7675 | .1219 | .2070 | .8103 | .1496 | .2345 | .8474 | .1756 |
| .1250 | .6614 | .0721 | .1525 | .7190 | .9063 | .1800 | .7684 | .1224 | .2075 | .8110 | .1501 | .2350 | .8480 | .1791 |
| .1255 | .6626 | .0726 | .1530 | .7200 | .0968 | .1805 | .7692 | .1229 | .2080 | .8118 | .1506 | .2355 | .8486 | .1797 |
| .1260 | .6637 | .0730 | .1535 | .7209 | .0973 | .1810 | .7700 | .1234 | .2085 | .8125 | .1511 | .2360 | .8492 | .1802 |
| .1265 | .6648 | .0734 | .1540 | .7219 | .0977 | .1815 | .7709 | .1239 | .2090 | .8132 | .1516 | .2365 | .8499 | .1808 |
| .1270 | .6659 | .0738 | .1545 | .7229 | .0982 | .1820 | .7717 | .1244 | .2095 | .8139 | .1521 | .2370 | .8505 | .1813 |

# Flare Network



## TABLE OF GEOMETRY FOR CIRCLES AND ARCS

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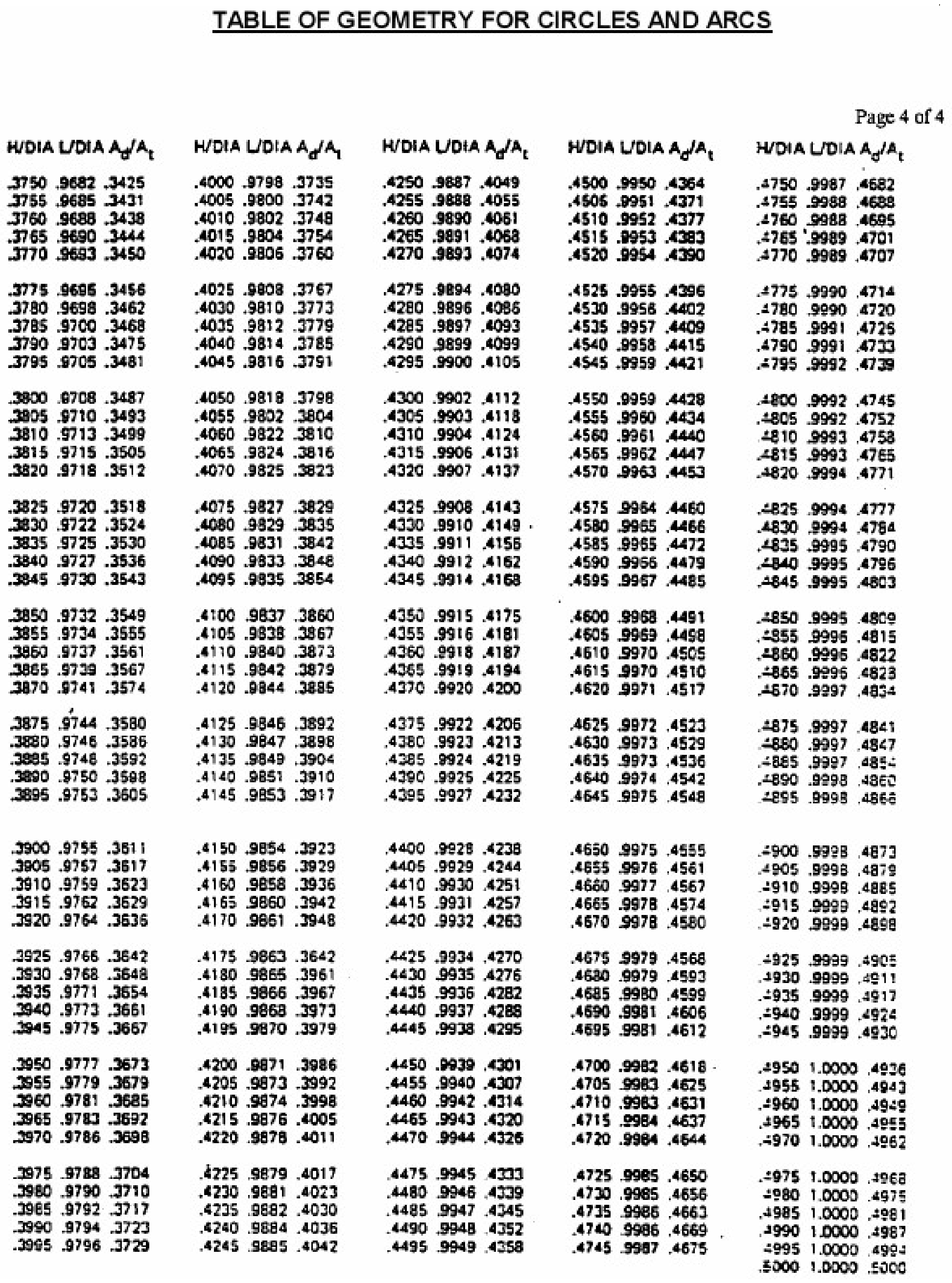
| H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .2375 | .8511 | .1818 | .2650 | .8827 | .2122 | .2925 | .9098 | .2436 | .3200 | .9330 | .2759 | .3475 | .9524 | .3089 |
| .2380 | .8517 | .1824 | .2655 | .8832 | .2128 | .2930 | .9103 | .2442 | .3205 | .9333 | .2765 | .3480 | .9527 | .3095 |
| .2385 | .8523 | .1829 | .2660 | .8837 | .2133 | .2935 | .9107 | .2448 | .3210 | .9337 | .2771 | .3485 | .9530 | .3101 |
| .2390 | .8529 | .1835 | .2665 | .8843 | .2139 | .2940 | .9112 | .2453 | .3215 | .9341 | .2777 | .3490 | .9533 | .3107 |
| .2395 | .8536 | .1840 | .2670 | .8848 | .2145 | .2945 | .9116 | .2459 | .3220 | .9345 | .2782 | .3495 | .9536 | .3113 |
| .2400 | .8542 | .1845 | .2675 | .8853 | .2150 | .2950 | .9121 | .2465 | .3225 | .9349 | .2788 | .3500 | .9539 | .3119 |
| .2405 | .8548 | .1851 | .2680 | .8858 | .2156 | .2955 | .9125 | .2471 | .3230 | .9352 | .2794 | .3505 | .9543 | .3125 |
| .2410 | .8554 | .1856 | .2685 | .8864 | .2161 | .2960 | .9130 | .2477 | .3235 | .9356 | .2800 | .3510 | .9546 | .3131 |
| .2415 | .8560 | .1862 | .2690 | .8869 | .2167 | .2965 | .9134 | .2482 | .3240 | .9360 | .2806 | .3515 | .9549 | .3137 |
| .2420 | .8566 | .1867 | .2695 | .8874 | .2173 | .2970 | .9139 | .2488 | .3245 | .9364 | .2812 | .3520 | .9552 | .3143 |
| .2425 | .8572 | .1873 | .2700 | .8879 | .2178 | .2975 | .9143 | .2494 | .3250 | .9367 | .2818 | .3525 | .9555 | .3150 |
| .2430 | .8578 | .1878 | .2705 | .8884 | .2184 | .2980 | .9148 | .2500 | .3255 | .9371 | .2824 | .3530 | .9558 | .3156 |
| .2435 | .8584 | .1884 | .2710 | .8890 | .2190 | .2985 | .9152 | .2506 | .3260 | .9375 | .2830 | .3535 | .9561 | .3162 |
| .2440 | .8590 | .1889 | .2715 | .8895 | .2195 | .2990 | .9156 | .2511 | .3265 | .9379 | .2511 | .3540 | .9564 | .3168 |
| .1445 | .8596 | .1895 | .2720 | .8900 | .2201 | .2995 | .9161 | .2517 | .3270 | .9382 | .2842 | .3545 | .9567 | .3174 |
| .2450 | .8602 | .1900 | .2725 | .8905 | .2207 | .3000 | .9165 | .2523 | .3275 | .9386 | .2848 | .3550 | .9570 | .3180 |
| .2455 | .8608 | .1906 | .2730 | .8910 | .2212 | .3005 | .9170 | .2529 | .3280 | .9390 | .2854 | .3555 | .9573 | .3186 |
| .2460 | .8614 | .1911 | .2735 | .8915 | .2218 | .3010 | .9174 | .2535 | .3285 | .9393 | .2860 | .3560 | .9576 | .3192 |
| .2465 | .8619 | .1917 | .2740 | .8920 | .2224 | .3015 | .9178 | .2541 | .3290 | .9397 | .2866 | .3565 | .9579 | .3198 |
| .2470 | .8625 | .1922 | .2745 | .8925 | .2229 | .3020 | .9138 | .2547 | .3295 | .9401 | .2872 | .3570 | .9582 | .3204 |
| .2475 | .8631 | .1927 | .2750 | .8930 | .2235 | .3025 | .9187 | .2552 | .3300 | .9404 | .2878 | .3575 | .9585 | .3211 |
| .2480 | .8637 | .1933 | .2755 | .8935 | .2241 | .3030 | .9191 | .2558 | .3305 | .9408 | .2884 | .3580 | .9588 | .3217 |
| .2485 | .8643 | .1938 | .2760 | .8940 | .2246 | .3035 | .9195 | .2564 | .3310 | .9411 | .2890 | .3585 | .9591 | .3223 |
| .2490 | .8649 | .1944 | .2765 | .8945 | .2252 | .3040 | .9200 | .2570 | .3315 | .9415 | .2896 | .3590 | .9594 | .3229 |
| .2495 | .8654 | .1949 | .2770 | .8950 | .2258 | .3045 | .9204 | .2576 | .3320 | .9419 | .2902 | .3595 | .9597 | .3235 |
| .2500 | .8660 | .1955 | .2775 | .8955 | .2264 | .3050 | .9208 | .2582 | .3325 | .9422 | .2908 | .3600 | .9600 | .3241 |
| .2505 | .8666 | .1961 | .2780 | .8960 | .2269 | .3055 | .9212 | .2588 | .3330 | .9426 | .2914 | .3605 | .9603 | .3247 |
| .2510 | .8672 | .1966 | .2785 | .8965 | .2275 | .3060 | .9217 | .2593 | .3335 | .9429 | .2920 | .3610 | .9606 | .3253 |
| .2515 | .8678 | .1972 | .2790 | .8970 | .2281 | .3065 | .9221 | .2599 | .3340 | .9433 | .2926 | .3615 | .9609 | .3259 |
| .2520 | .8683 | .1977 | .2795 | .8975 | .2286 | .3070 | .9225 | .2605 | .3345 | .9436 | .2932 | .3620 | .9612 | .3265 |
| .2525 | .8689 | .1983 | .2800 | .8980 | .2292 | .3075 | .9229 | .2611 | .3350 | .9440 | .2938 | .3625 | .9614 | .3272 |
| .2530 | .8695 | .1988 | .2805 | .8985 | .2298 | .3080 | .9233 | .2617 | .3335 | .9443 | .2944 | .3630 | .9617 | .3278 |
| .2535 | .8700 | .1994 | .2810 | .8990 | .2304 | .3085 | .9237 | .2623 | .3360 | .9447 | .2950 | .3635 | .9620 | .3284 |
| .2540 | .8706 | .1999 | .2815 | .8995 | .2309 | .3090 | .9242 | .2629 | .3365 | .9450 | .2956 | .3640 | .9623 | .3290 |
| .2545 | .8712 | .2005 | .2820 | .8999 | .2315 | .3095 | .9246 | .2635 | .3370 | .9454 | .2962 | .3645 | .9626 | .3296 |
| .2550 | .8717 | .2010 | .2825 | .9004 | .2321 | .3100 | .9250 | .2640 | .3375 | .9457 | .2968 | .3650 | .9629 | .3302 |
| .2555 | .8723 | .2016 | .2830 | .9009 | .2326 | .3105 | .9254 | .2646 | .3380 | .9461 | .2974 | .3655 | .9631 | .3308 |
| .2560 | .8728 | .2021 | .2835 | .9014 | .2332 | .3110 | .9258 | .2652 | .3385 | .9464 | .2980 | .3660 | .9634 | .3315 |
| .2565 | .8734 | .2027 | .2840 | .9019 | .2338 | .3115 | .9262 | .2658 | .3390 | .9467 | .2986 | .3665 | .9637 | .3321 |
| .2575 | .8745 | .2038 | .2850 | .9028 | .2349 | .3125 | .9270 | .2670 | .3400 | .9474 | .2998 | .3675 | .9642 | .3333 |
| .2580 | .8751 | .2044 | .2855 | .9033 | .2355 | .3130 | .9274 | .2676 | .3405 | .9478 | .3004 | .3680 | .9645 | .3339 |
| .2585 | .8756 | .2049 | .2860 | .9038 | .2361 | .3135 | .9278 | .2682 | .3410 | .9481 | .3010 | .3685 | .9648 | .3345 |
| .2590 | .8762 | .2055 | .2865 | .9043 | .2367 | .3140 | .9282 | .2688 | .3415 | .9484 | .3016 | .3690 | .9651 | .3351 |
| .2595 | .8767 | .2060 | .2870 | .9047 | .2872 | .3145 | .9286 | .2693 | .3420 | .9488 | .3022 | .3695 | .9653 | .3357 |
| .2600 | .8773 | .2066 | .2875 | .9052 | .2378 | .3150 | .9290 | .2699 | .3425 | .9491 | .3028 | .3700 | .9656 | .3364 |
| .2605 | .8778 | .2072 | .2880 | .9057 | .2384 | .3155 | .9294 | .2705 | .3430 | .9494 | .3034 | .3705 | .9659 | .3370 |
| .2610 | .8784 | .2077 | .2885 | .9061 | .2390 | .3160 | .9298 | .2711 | .3435 | .9498 | .3040 | .3710 | .9661 | .3376 |
| .2615 | .8789 | .2083 | .2890 | .9066 | .2395 | .3165 | .9302 | .2717 | .3440 | .9501 | .3046 | .3715 | .9664 | .3382 |
| .2620 | .8794 | .2088 | .2895 | .9071 | .2401 | .3170 | .9306 | .2723 | .3445 | .9504 | .3053 | .3720 | .9667 | .3388 |
| .2625 | .8800 | .2094 | .2900 | .9075 | .2407 | .3175 | .9310 | .2729 | .3450 | .9507 | .3059 | .3750 | .9669 | .3394 |
| .2630 | .8805 | .2100 | .2905 | .9080 | .2413 | .3180 | .9314 | .2735 | .3455 | .9511 | .3065 | .3730 | .9672 | .3401 |
| .2635 | .8811 | .2105 | .2910 | .9084 | .2419 | .3185 | .9318 | .2741 | .3460 | .9514 | .3071 | .3735 | .9676 | .3407 |
| .2640 | .8816 | .2111 | .2915 | .9089 | .2424 | .3190 | .9322 | .2747 | .3465 | .9517 | .3077 | .3740 | .9677 | .3413 |
| .2645 | .8821 | .2116 | .2920 | .9094 | .2430 | .3195 | .9326 | .2753 | .3470 | .9520 | .3083 | .3745 | .9680 | .3419 |

# Flare Network



## TABLE OF GEOMETRY FOR CIRCLES AND ARCS

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| H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ | H/DIA | L/DIA | $A_d/A_t$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .3750 | .9682 | .3425 | .4000 | .9798 | .3735 | .4250 | .9887 | .4049 | .4500 | .9950 | .4364 | .4750 | .9987 | .4682 |
| .3755 | .9685 | .3431 | .4005 | .9800 | .3742 | .4255 | .9888 | .4055 | .4506 | .9951 | .4371 | .4755 | .9988 | .4688 |
| .3760 | .9688 | .3438 | .4010 | .9802 | .3748 | .4260 | .9890 | .4061 | .4510 | .9952 | .4377 | .4760 | .9988 | .4695 |
| .3765 | .9690 | .3444 | .4015 | .9804 | .3754 | .4265 | .9891 | .4068 | .4515 | .9953 | .4383 | .4765 | .9989 | .4701 |
| .3770 | .9683 | .3450 | .4020 | .9806 | .3760 | .4270 | .9893 | .4074 | .4520 | .9954 | .4390 | .4770 | .9989 | .4707 |
| .3775 | .9696 | .3456 | .4025 | .9808 | .3767 | .4275 | .9894 | .4080 | .4525 | .9955 | .4396 | .4775 | .9990 | .4714 |
| .3780 | .9698 | .3462 | .4030 | .9810 | .3773 | .4280 | .9896 | .4086 | .4530 | .9956 | .4402 | .4780 | .9990 | .4720 |
| .3785 | .9700 | .3468 | .4035 | .9812 | .3779 | .4285 | .9897 | .4093 | .4535 | .9957 | .4409 | .4785 | .9991 | .4726 |
| .3790 | .9703 | .3475 | .4040 | .9814 | .3785 | .4290 | .9899 | .4099 | .4540 | .9958 | .4415 | .4790 | .9991 | .4733 |
| .3795 | .9705 | .3481 | .4045 | .9816 | .3791 | .4295 | .9900 | .4105 | .4545 | .9959 | .4421 | .4795 | .9992 | .4739 |
| .3800 | .8708 | .3487 | .4050 | .9818 | .3798 | .4300 | .9902 | .4112 | .4550 | .9959 | .4428 | .4800 | .9992 | .4745 |
| .3805 | .9710 | .3493 | .4055 | .9802 | .3804 | .4305 | .9903 | .4118 | .4555 | .9960 | .4434 | .4805 | .9992 | .4752 |
| .3810 | .9713 | .3499 | .4060 | .9822 | .3810 | .4310 | .9904 | .4124 | .4560 | .9961 | .4440 | .4810 | .9993 | .4758 |
| .3815 | .9715 | .3505 | .4065 | .9824 | .3816 | .4315 | .9906 | .4131 | .4565 | .9962 | .4447 | .4815 | .9993 | .4765 |
| .3820 | .9718 | .3512 | .4070 | .9825 | .3823 | .4320 | .9907 | .4137 | .4570 | .9963 | .4453 | .4820 | .9994 | .4771 |
| .3825 | .9720 | .3518 | .4075 | .9827 | .3829 | .4325 | .9908 | .4143 | .4575 | .9964 | .4460 | .4825 | .9994 | .4777 |
| .3830 | .9722 | .3524 | .4080 | .9829 | .3835 | .4330 | .9910 | .4149 | .4580 | .9965 | .4466 | .4830 | .9994 | .4784 |
| .3835 | .9725 | .3530 | .4085 | .9831 | .3842 | .4335 | .9911 | .4156 | .4585 | .9965 | .4472 | .4835 | .9995 | .4790 |
| .3840 | .9727 | .3536 | .4090 | .9833 | .3848 | .4340 | .9912 | .4162 | .4590 | .9956 | .4479 | .4840 | .9995 | .4796 |
| .3845 | .9730 | .3543 | .4095 | .9835 | .3854 | .4345 | .9914 | .4168 | .4595 | .9967 | .4485 | .4845 | .9995 | .4803 |
| .3850 | .9732 | .3549 | .4100 | .9837 | .3860 | .4350 | .9915 | .4175 | .4600 | .9968 | .4491 | .4850 | .9995 | .4809 |
| .3855 | .9734 | .3555 | .4105 | .9838 | .3867 | .4355 | .9916 | .4181 | .4605 | .9969 | .4498 | .4855 | .9996 | .4815 |
| .3860 | .9737 | .3561 | .4110 | .9840 | .3873 | .4360 | .9918 | .4187 | .4610 | .9970 | .4505 | .4860 | .9996 | .4822 |
| .3865 | .9739 | .3567 | .4115 | .9842 | .3879 | .4365 | .9919 | .4194 | .4615 | .9970 | .4510 | .4865 | .9996 | .4823 |
| .3870 | .9741 | .3574 | .4120 | .9844 | .3885 | .4370 | .9920 | .4200 | .4620 | .9971 | .4517 | .4670 | .9997 | .4834 |
| .3875 | .9744 | .3580 | .4125 | .9846 | .3892 | .4375 | .9922 | .4206 | .4625 | .9972 | .4523 | .4875 | .9997 | .4841 |
| .3880 | .9746 | .3586 | .4130 | .9847 | .3898 | .4380 | .9923 | .4213 | .4630 | .9973 | .4529 | .4880 | .9997 | .4847 |
| .3885 | .9748 | .3592 | .4135 | .9849 | .3904 | .4385 | .9924 | .4219 | .4635 | .9973 | .4536 | .4885 | .9997 | .4854 |
| .3890 | .9750 | .3588 | .4140 | .9851 | .3910 | .4390 | .9925 | .4225 | .4640 | .9974 | .4542 | .4890 | .9998 | .4860 |
| .3895 | .9753 | .3605 | .4145 | .9853 | .3917 | .4395 | .9927 | .4232 | .4645 | .9975 | .4548 | .4895 | .9998 | .4866 |
| .3900 | .9755 | .3611 | .4150 | .9854 | .3923 | .4400 | .9928 | .4238 | .4650 | .9975 | .4555 | .4900 | .9998 | .4873 |
| .3905 | .9757 | .3617 | .4155 | .9856 | .3929 | .4405 | .9929 | .4244 | .4655 | .9976 | .4561 | .4905 | .9998 | .4879 |
| .3910 | .9759 | .3623 | .4160 | .9858 | .3936 | .4410 | .9930 | .4251 | .4660 | .9977 | .4567 | .4910 | .9999 | .4885 |
| .3915 | .9762 | .3629 | .4165 | .9860 | .3942 | .4415 | .9931 | .4257 | .4665 | .9978 | .4574 | .4915 | .9999 | .4892 |
| .3920 | .9764 | .3636 | .4170 | .9861 | .3948 | .4420 | .9932 | .4263 | .4670 | .9978 | .4580 | .4920 | .9999 | .4898 |
| .3925 | .9766 | .3642 | .4175 | .9863 | .3642 | .4425 | .9934 | .4270 | .4675 | .9979 | .4568 | .4925 | .9999 | .4905 |
| .3930 | .9768 | .3648 | .4180 | .9865 | .3961 | .4430 | .9935 | .4276 | .4680 | .9979 | .4593 | .4930 | .9999 | .4911 |
| .3935 | .9771 | .3654 | .4185 | .9866 | .3967 | .4435 | .9936 | .4282 | .4685 | .9980 | .4599 | .4935 | .9999 | .4917 |
| .3940 | .9773 | .3661 | .4190 | .9868 | .3973 | .4440 | .9937 | .4288 | .4690 | .9981 | .4606 | .4940 | .9999 | .4924 |
| .3945 | .9775 | .3667 | .4195 | .9870 | .3979 | .4445 | .9938 | .4295 | .4695 | .9981 | .4612 | .4945 | .9999 | .4930 |
| .3950 | .9777 | .3673 | .4200 | .9871 | .3986 | .4450 | .9939 | .4301 | .4700 | .9982 | .4618 | .4950 | 1.0000 | .4936 |
| .3955 | .9779 | .3679 | .4205 | .9873 | .3992 | .4455 | .9940 | .4307 | .4705 | .9983 | .4625 | .4955 | 1.0000 | .4943 |
| .3960 | .9781 | .3685 | .4210 | .9874 | .3998 | .4460 | .9942 | .4314 | .4710 | .9983 | .4631 | .4960 | 1.0000 | .4949 |
| .3965 | .9783 | .3692 | .4215 | .9876 | .4005 | .4465 | .9943 | .4320 | .4715 | .9984 | .4637 | .4965 | 1.0000 | .4955 |
| .3970 | .9786 | .3698 | .4220 | .9878 | .4011 | .4470 | .9944 | .4326 | .4720 | .9984 | .4644 | .4970 | 1.0000 | .4962 |
| .3975 | .9788 | .3704 | .4225 | .9879 | .4017 | .4475 | .9945 | .4333 | .4725 | .9985 | .4650 | .4975 | 1.0000 | .4968 |
| .3980 | .9790 | .3710 | .4230 | .9881 | .4023 | .4480 | .9946 | .4339 | .4730 | .9985 | .4656 | .4980 | 1.0000 | .4975 |
| .3985 | .9792 | .3717 | .4235 | .9882 | .4030 | .4485 | .9947 | .4345 | .4735 | .9986 | .4663 | .4985 | 1.0000 | .4981 |
| .3990 | .9794 | .3723 | .4240 | .9884 | .4036 | .4490 | .9948 | .4352 | .4740 | .9986 | .4669 | .4990 | 1.0000 | .4987 |
| .3995 | .9796 | .3729 | .4245 | .9885 | .4042 | .4495 | .9949 | .4358 | .4745 | .9987 | .4675 | .4995 | 1.0000 | .4994 |
|  |  |  |  |  |  |  |  |  |  |  |  | .5000 | 1.0000 | .5000 |