Overview of Deflagration and Detonation Prevention and Protection Practices

3.1. Introduction

This chapter presents an overview of the various practices used in the chemical process industries to prevent and protect against deflagrations and detonations. It includes an introduction to deflagration and detonation flame arresters and also other methods that can be used when flame arresters are not practical or are too expensive.

3.2. Deflagration and Detonation Flame Arresters

Flame arresters are broadly divided into two major types: deflagration and detonation flame arresters. Another parameter for selecting a flame arrester is directionality, which refers to the direction of flame approach for which an arrester is designed to operate in a pipeline. The pipeline connecting a flame arrester with an identified ignition source is the “unprotected side” of the arrester. The pipeline connecting the arrester with at-risk equipment (equipment that must be protected from the temperature or pressure associated with flame penetration) is the “protected side.” If a flame arrester may encounter a flame arriving from only one direction, a “unidirectional” arrester can be used. If a flame may arrive
from either direction, a “bidirectional” flame arrester is needed. The latter
arrester is either symmetrically constructed or has been tested and certi-
fied for deflagrations and detonations approaching from either direction.
Back-to-back use of unidirectional flame arresters will not usually be cost-
effective unless testing reveals a specific advantage such as increased allow-
able operating pressure during restricted-end deflagration testing where
the test pipeline has one end closed.

A number of essential points about flame arresters are as follows (CCPS
1993):

1. A flame arrester is a device permeable to gas flow but impermeable
to any flame it may encounter under anticipated service conditions.
   It must both quench the flame and cool products sufficiently to pre-
   vent reignition at the arrester outlet.
2. Proper application of a flame arrester can help avoid catastrophic
   fire and explosion losses by providing a flame barrier between at-
   risk equipment and anticipated ignition sources.
3. Flame arresters have often failed in practice. There have been sig-
   nificant advances in flame arrester technology over the last decade
   that explain many “failures” as due to misapplication. Plant inspec-
   tions have shown that misapplication of flame arresters continues to
   be common.
4. Flame arresters cannot be designed from first principles and can
   only be proven by tests simulating the conditions of use. The user
   should ensure that a flame arrester has been properly tested to
   meet the intended purpose, and should be prepared to stipulate the
   required performance standard or test protocol to be followed.
5. In almost all cases, if a flame arrester is placed in-line rather than at
   (or close to) the open end of a vent pipe, a detonation flame arrester
   is needed. Detonation flame arresters must be able to stop both def-
   lagrations and detonations. They require extensive testing and
   mandatory testing protocols may apply.
6. Unless flame arresters meet all the necessary requirements dis-
   cussed in this book, they should be replaced, relocated, or elimi-
   nated in favor of an alternative means of protection.

Flame arresters are classified according to certain characteristics and
operational principles, as follows:

- location in process
- combustion conditions (deflagration or detonation, operating tem-
  perature and pressure)
- arrester element (matrix) construction for dry type arresters
other types (hydraulic liquid seal, high velocity vent valves and velocity flame stoppers)

These are briefly discussed below.

Location in Process
Flame arresters are classified according to their location with respect to the equipment they are protecting. When a flame arrester is located directly on a vessel/tank vent nozzle, or on the end of a vent line from the vent nozzle, it is called an end-of-line arrester, and is usually a deflagration flame arrester. These are commonly installed on atmospheric pressure storage tanks, process vessels, and transport containers. If the vented vapors are ignited, perhaps by lightning, the flame arrester will prevent the flame from spreading from the atmosphere to the inside of the vessel. Such flame arresters are neither designed for nor suitable for stopping detonations. Figure 3-1 shows the installation of end-of-line flame arresters on vessels located inside of buildings and outdoors.

If the arrester is not placed at the end of a line, it is known as an in-line arrester. In-line arresters can be of the deflagration or detonation type,
depending on the length of piping and pipe configuration on the unprotected side of the arrester and the restrictions on the protected side of the arrester. A detonation flame arrester is used in all cases where sufficient “run-up” distance exists for a detonation to develop. Some types of in-line deflagration flame arresters are called “pipe-away” or vent-line arresters. These are also installed on the vent nozzles of atmospheric pressure tanks and vessels, and have a short length of pipe attached to them to direct the vapors, and possibly flame, away from the tank or vessel roof. Figure 3-2 shows the installation of an in-line deflagration flame arrester. The maxi-

![Diagram of in-line deflagration flame arrester location.](image-url)

FIGURE 3.2. In line deflagration flame arrester location.
mum length of pipe from the discharge side of an in-line flame arrester to
the atmosphere is usually no more than 20 feet for Group D gases, and is a
function of the pipe size and the manufacturer’s design. For other gases
(Group B or Group C), the maximum allowed distance must be established
by proper testing with the appropriate gas mixture and the pipe diameter
involved. Turbulence-promoting devices in the flow path (bends, elbows,
tees, valves, etc.) cannot be used unless testing has addressed the exact
geometry in the installation. It is essential to ensure that run-up to detona-
tion cannot occur in the actual piping system. For some fast-burning gases
such as hydrogen–air and ethylene oxide–air, the run-up distance (maxi-
mum attached pipe length) can be appreciably less. In all cases the manu-
facturer should be consulted for their recommended maximum “run-up”
length for in-line deflagration flame arresters.

An in-line detonation flame arrester must be used whenever there is a
possibility of a detonation occurring. This is always a strong possibility in
vent manifold (vapor collection) systems, where long pipe runs provide
sufficient “run-up” distances for a deflagration-to-detonation transition to
occur. Figure 3-3 shows the installation of in-line arresters of the detonation
type in a vent manifold system.

Combustion Conditions
As mentioned earlier, flame arresters can be classified as either deflagra-
tion or detonation type. Deflagration flame arresters on tanks are designed
to stop a flame from propagating into a tank from an unconfined atmo-

![FIGURE 3.3. In-line detonation flame arrester locations.](image)
spheric deflagration, or to prevent a flame generated from a confined volume deflagration in a vessel from escaping to the outside of the vessel (Halstrick 1995). They normally cannot withstand significant internal pressure and cannot stop detonations. Typical flame speeds in a deflagration occurring in piping range from 10 to 200 ft/s. Deflagrations of fuel–air mixtures typically generate pressures 8 to 12 times the initial pressure in closed process vessels and equipment. Figure 3-4 shows several types of deflagration arresters.

Detonation flame arresters are devices designed to withstand and extinguish the high speed and high pressure flame front that characterizes a detonation propagating through a piping system. Therefore, a detonation arrester must be able to withstand the mechanical effects of a detonation shock wave while quenching the flame. Some designs have a “shock absorber” in front of the flame arresting element to reduce both the high pressure shock wave and the dynamic energy and to split the flame front before it reaches the flame arrester element (Halstrick 1995). Figure 3-5 shows details of a “shock absorber” as designed by Protego™. Another design variation has what is called a “detonation momentum attenuator” (DMA) (Westech 1989). Details of such a DMA as designed by Westech is shown in Figure 3-6. Detonations occurring in piping have velocities of about 6000 ft/s, or greater, and in closed process vessels and equipment can generate pressures from 20 to 100+ times the initial pressure. Detonation flame arresters are available as both unidirectional or bidirectional types. When installed in a vent manifold system the flame arresters on the tanks may be unidirectional or bidirectional, depending on the manufacturer’s recommendations. They should preferably be installed in a vertical orientation, so that if liquid is present, the arrester will drain. If they must be installed in a horizontal orientation, they should be provided with drain connections. Most detonation arresters have crimped metal ribbon arrester elements, although expanded metal cartridges are also used. Arrester elements for detonation arresters are usually longer than for deflagration arresters. Figure 3-7 shows several designs of detonation arresters.

It has been reported that there have been some cases where a detonation arrester failed to stop a deflagration (Howard 1982). This occurs when a restriction (e.g., a valve) exists on the protected side of the arrester. Roussakis and Lapp (1991) present data from tests on three types of in-line flame arresters that corroborates this seemingly anomalous behavior. The causes for this phenomenon are complex and depend on such factors as run-up length effect on relative overpressure (ratio of pressure rise caused by the flame front to the absolute operating pressure at the time of ignition), flow restriction on the protected side, and the absolute operating pressure. Flame quenching capability of a flame arrester is determined by
FIGURE 3-4. Types of deflagration flame arresters.

(a) End-of-line parallel plate flame arresters
(b) End-of-line crimped metal ribbon flame arrester
(c) In-line parallel plate flame arrester
(d) In-line crimped metal flame arrester

FIGURE 3-4. Types of deflagration flame arresters.
the initial operating pressure. The following explanation is given in Canadian standard CSA-Z343 (1998). In the low and medium pressure deflagration zone, a “reflected pressure” effect may take place, which reduces the maximum operating pressure in the flame arrester (the pressure at which the flame arrester would have successfully quenched a flame if there was no reflected pressure effect) when ignitions occur in that zone. In essence, what happens is that the reflected pressure has the effect of allowing a flame to pass through a flame arrester at a lower operating pressure. Consider the case of a given hypothetical flame arrester that is able to successfully stop detonations when the initial pressure (the pressure in the pipe just before the explosion) is less than 20.3 psia. If a low or medium pressure deflagration was involved rather than a detonation, the flame arrester could fail at an initial pressure of less than 20.3 psia.
During a deflagration, unburned gas ahead of the flame is precompressed, leading to an increase of pressure in the arrester before the flame arrives. This increased pressure may facilitate passage of the flame through the arrester element if it significantly exceeds the pressures that were developed during certification testing. The buildup of pressure in the flame arrester is influenced by downstream obstructions that are addressed by restricted-end deflagration testing as described in Chapter 8. The following is one possible scenario for reflected pressure effects. When the gas is ignited, two flame fronts propagate from the ignition point—one front moves down the pipe toward the flame arrester, and one moves up the pipe away from the flame arrester. The flame front moving away from the flame arrester may have sufficient distance available along the pipe to accelerate and develop into a detonation. The detonation will produce the usual fast-rising pressure wave, which will eventually reach some obstruction as it continues to travel away from the flame arrester. When it does reach the obstruction, a wave of lesser pressure will be reflected back (as in an echo) toward the flame arrester. Traveling back toward the flame arrester, the reflected pressure wave will travel through burnt gas. During this period the other flame front, the one involving the relatively slow-moving deflagration, continues to progress toward the flame arrester. For
certain adverse geometries, the coincident arrivals of the deflagration pressure wave and the reflected pressure wave at the flame arrester element in the unburned gas will have the effect of momentarily increasing the initial pressure at the element just prior to the arrival of the deflagration flame front. This transitory pressure increase may be sufficient to allow the flame front to pass through the flame arrester element. Another similar scenario involves the reflection coming from the protected side of the flame arrester. Because of this, before the flame

FIGURE 3-7. Various types of detonation flame arresters. (Sources: Protectoseal Company, NAO, Inc., and Westech Industrial, Ltd.)
arrester is specified and installed, realistic tests should be run using an approved test method (see Chapter 8) to verify that the flame arrester will stop both deflagrations and detonations.

**Arrester Element (Matrix) Construction for Dry Type Arresters**

Dry type deflagration and detonation flame arresters have an internal arrester element (sometimes called a matrix) that quenches the flame and cools the products of combustion. A great number of arrester elements have been developed and used. The most common types currently available are as follows:

- crimped metal ribbon
- parallel plate
- expanded metal cartridge
- perforated plate
- wire gauze and wire gauze in packs
- sintered metal
- metal shot in small housings
- ceramic balls

Other types that have been used but are not currently commercially available in the United States are compressed wire wool and metal foam. However, compressed wire wool flame arresters are available in the United Kingdom.

Currently available flame arrester elements will be discussed in detail in Chapter 5.

**Other Types**

Other types of deflagration and detonation flame arresters that do not contain an arrester element (matrix) have been used successfully in various applications where conventional dry type arresters were not suitable or were very expensive. Among these are:

- hydraulic (liquid seal)
- packed bed
- velocity flame stoppers
- high velocity vent valves
- conservation vent valves

These will be discussed in detail in Chapter 5.
3.3. Deflagration Venting

Venting of deflagrations is often used for overpressure protection for process equipment, pipes and ducts.

Procedures for the sizing and design of deflagration vents for pipes and ducts operating at or near atmospheric pressure (up to 3 psig) are presented in Chapter 8 of NFPA 68 (NFPA 1998).

The following guidelines are provided in Chapter 8 of NFPA 68:

1. Multiple vent locations can be provided along the length of a pipe or duct to reduce the maximum pressure generated during a deflagration.

2. Deflagration vents should be located close as possible to ignition sources where these sources can be identified.

3. Pipes or ducts connected to a vessel in which a deflagration can occur also need deflagration protection. Such protection can be accomplished by installing a vent on the pipe with an area equal to the cross-sectional area of the pipe or duct. It should be located on the pipe or duct no more than two pipe or duct diameters from the point of connection to the process vessel or equipment.

4. For systems that handle gases, vents should be provided on each side of turbulence-producing devices (e.g., elbows) at a distance of no more than three diameters of the pipe or duct.

5. In order to use the correlations presented later in the guide, the weight of the deflagration vent closures should not exceed 2.5 lb/ft² (12.2 kg/m²) of free vent area.

6. The static burst pressure of the vent closures should be as far below $P_{\text{red}}$ (the maximum pressure generated in the pipe or duct by the deflagration that one wishes to allow during venting) as practical and should be consistent with operating pressures.

7. Deflagration vents should discharge to a location that cannot endanger personnel.

8. Consideration should be given to reaction forces that develop during venting.

Guidelines are also given in NFPA 68 for vent placement to prevent deflagration-to-detonation transition. Methods are also presented for calculating the maximum pressure generated by a deflagration for a single deflagration vent and multiple deflagration vents on a pipe or duct, based on system flow velocities and gas fundamental burning velocities.

When deflagration venting is used, a major hazard of concern is the fireball (flame cloud consisting of burning gases and/or dust) discharged from the vent. This can cause harm to personnel or process equipment and
buildings if it impacts on them. If the process equipment is inside of a building then a vent discharge duct is attached to the vent to direct the fireball outside of the building. An alternate solution to the fireball problem is the use of a combination flame-arresting and particulate retention vent system (see Figure 3-8, which shows details of such a device). As a deflagration is vented through the device, any burned and unburned dust is retained within the device, and the flame is quenched, so that no flame emerges from the equipment. In addition, near-field blast effects (overpressure) are greatly reduced outside the vented equipment. Its main advantage is that it can be installed on indoor equipment. This obviates the need for a vent duct that would otherwise be needed to direct the flame, combustion products, and particulate matter outside of the building.

Two types of such a device are currently commercially available, the Q-Rohr™ and the FlamQuench™. The Q-Rohr™ is manufactured by Rembe in Germany (available in the United States from Cv Technology, Inc.) and
the FlamQuench II™ by Fike Corporation in the U.S. and Europe. The Q-Rohr™ and the FlamQuench II™ are designed to achieve the same thing, but have different mechanical designs. The Q-Rohr™ consists of a cylinder with a rupture disk at the inlet and a cylindrical internal dust filter (which retains the particles) of special ceramic-fiber mat and a second cylindrical internal flame arrester element of high-grade stainless steel mesh. On the other hand, the FlamQuench II™ consists of a cylinder with a rupture disk at the inlet and an internal cylinder consisting of particle-retaining and flame extinguishing stainless steel mesh layers. The Q-Rohr™ has been tested on a number of dust and dust-air-flammable gas hybrid mixtures (Stevenson 1998) and also for some specific gases (e.g., carbon monoxide, methane, propane, and alcohols), and these tests were all successful (Stevenson 2000). For gases with significantly different flame characteristics than the ones tested, further testing would be required. The FlamQuench II™ has been tested in vessels having volumes from 0.5 m³ to 10 m³ and with propane and dusts with $K_s$ values up to 318 bar-m/s (Chatrathi 2001).

The Q-Rohr™ is approved by Factory Mutual. The FlamQuench II™ has been tested for CEN and ATEX approval in Europe at the Laboratorio Oficial Madariaga in Spain, and is being tested by Factory Mutual Global.

The deflagration venting approach can also be applied to the protection of vent manifold systems if desired. Venting products of combustion gases upstream of a flame arrester has been found to be effective in reducing the temperature measured on the run-up (unprotected) side of flame arresters for tests conducted with noncommercial flame arresters (White and Oswald 1992). Although venting appeared to have a small effect on peak overpressure and more effect on impulse, the benefit appears to be largely in a vent’s ability to reduce the thermal impact on the flame arrester. Venting, however, presents environmental problems around the vent opening, which can include hot gas emissions, noise, and discharge of fragments (e.g., vent cover segments, hot particles). Properly located vents are designed to prevent a detonation from developing.

3.4. Oxidant Concentration Reduction

One of the most widely used methods of preventing deflagrations and detonations is oxidant concentration reduction. This method can be applied to process equipment and vent manifold systems. The prevention of deflagrations or detonations can be accomplished by either inerting or fuel enrichment.

In the case of inerting, the oxidant (usually oxygen) concentration is reduced by the addition of inert gas to a value below the limiting oxidant
concentration (LOC). Values of the LOC for many gases and dusts can be found in NFPA 69 (NFPA 1997). Some commonly used inert gases used in industry are nitrogen, steam, carbon dioxide, and rare gases. Figure 3-9 shows the effect of various inert gases on the limits of flammability of methane–inert-gas–air mixtures at 25°C (77°F) and atmospheric pressure.

In the design of inerting systems one must provide sufficient inerting gas to assure not only that the normal process conditions are rendered nonflammable, but also that any credible alteration of the process environment remains outside the combustible limits. Figure 3-10 is adapted from the flammability triangular diagram presented by Zabetakis (1965) for the system methane–oxygen–nitrogen under atmospheric conditions. On this type of diagram, the sum of the three gas components is 100% at every
point. On the “methane” leg of the diagram the nitrogen concentration is zero, and the flammable limits of methane in oxygen are read as 60% (UFL) and 5% (LFL). As air is added to pure methane, mixture compositions follow line “A,” since this line represents all compositions that contain a 79:21 ratio of nitrogen to oxygen. The intersections of line “A” with the flammable envelope show that the flammable limits in air are 15% (UFL) and 5% (LFL). Now consider point “M,” comprising 50% methane, 30% oxygen, and 20% nitrogen. This composition lies above the flammable envelope in the “methane rich” region and normally represents a safe operating condition. However, should air leak into the system, the resulting compositions follow line “B,” which passes through the flammable envelope. Given the possibility of an air leak, available strategies are (1) operate below the LFL in air, or (2) operate so that there is insufficient oxygen to support a flame at the given concentration of fuel. In this section option (2) or “oxidant concentration reduction” is considered. There are two variants of this method:
3.4. Oxidant Concentration Reduction

**Operation below LOC**

The minimum concentration of oxygen that can support a flame is known as the “limiting oxidant concentration” or LOC, which is a singularity appearing at a fuel concentration marginally above the LFL. As shown in Figure 3-10, the LOC is identified as the line of constant oxygen concentration that is tangential to the “nose” of the flammable envelope. For methane the LOC is 12% oxygen at standard conditions. Provided the oxygen concentration is kept below the LOC, mixtures are nonflammable at all possible fuel concentrations. Therefore, where the fuel concentration is not controlled, it is common practice to control flammability by operating below the LOC.

A safety margin between the LOC and the normal oxidant concentration in the process equipment or piping system is mandated by NFPA 69 (NFPA 1997) as follows:

1. Where the oxidant concentration is continually monitored, a safety margin of at least 2 volume percent below the measured worst credible case LOC shall be maintained, unless the LOC is less than 5 volume percent, in which case, the equipment or piping shall be operated at no more than 60% of the LOC.
2. Where the oxidant concentration is not continually monitored, the oxidant concentration shall be maintained at no more than 60% of the LOC or 40% of the LOC if the LOC is below 5 volume percent. If the oxidant concentration is not continually monitored the oxidant concentration shall be checked on a regularly scheduled basis.

When inerting is used, it is prudent practice to monitor the oxidant concentration in the system by means of oxygen analyzers. The analyzers may be permanently installed, or portable ones can be used on a regularly scheduled basis. The three most commonly used oxygen analyzers are the electrochemical cell, the paramagnetic resonance type, and the zirconium catalytic cell (used for boiler and heater firing control). The zirconium catalytic cell type mounts directly in the process stream in a thermowell and does not require a sampling system. All work equally well if properly installed and maintained. Quite often a gas sample must be pretreated to remove harmful components such as water, acids, and dust to prevent damage to the analyzer cell. Also, gas sample lines should not be oversized as a long time lag can result, which would be detrimental to using the analyzer to trigger an alarm or shutdown.

A problem common to electrochemical cells is the analyzer can fail (degradation of the anode material and electrolyte or loss of sensor sensitivity), but still indicate a safe oxidant level when in reality it may not be so. Adherence to the manufacturer’s recommendation as to how...
frequently the cell should be replaced will minimize the problem. It is possible to purchase an electrochemical cell oxygen analyzer with two cells in tandem, and an alarm to indicate when the first cell is failing. To keep oxygen analyzers operating properly, they should be calibrated and maintained on a regular schedule. In a highly hazardous system, two different types of oxygen analyzers (e.g., electrochemical cell and paramagnetic resonance), with one acting as a backup and check for the other one, can be considered. The paramagnetic resonance type exhibits the best stability and reliability for most applications. It is extremely important that a representative and timely sample be obtained for analysis. If a sample system is employed, it must be responsive and reliable. The IChemE (1983) has published guide notes on the safe application of oxygen analyzers.

It is very important that the inert gas be available from a reliable source and that the proper pressure and flow rate are always provided. A low-pressure switch and alarm are sometimes installed in the inert gas supply line to the equipment and piping. The alarm will warn the operator that a problem may be occurring with the inert gas supply. The switch is also sometimes interlocked to open up a valve in piping from a backup inert gas cylinder bank.

Following maintenance on or vessel entry into an inerted system, oxygen may be introduced via air into a single vessel or multiple vessels in a manifoldded system. This may place oxygen into the manifold and create a potential for a deflagration or detonation to occur. The vessels that are opened and allow air ingress must be purged to the atmosphere so that they are below the LOC before they are reconnected to the manifold. This can be accomplished by proper valving.


**Gas Enrichment**

For nondecomposable gases the concentration of oxygen required to support a flame increases as the fuel concentration increases. For example, Figure 3-10 shows that it requires about 40% oxygen to support a methane flame in oxygen compared with only 12% oxygen at the LOC composition, which contains approximately 9% methane and 79% nitrogen. For mixtures containing increasing concentrations of methane, the oxygen concentrations required to support a flame increase along the upper bound of the flammable envelope (UFL) curve. Provided the fuel concentration is maintained sufficiently high, it is possible to operate safely
at oxygen concentrations greater than the LOC. For systems in which the fuel concentration is not inherently maintained at a safe level, such as high vapor pressure liquids in closed tanks, an option is to use “gas enrichment” with a suitable fuel gas such as methane. This approach is recognized in NFPA 69.

As discussed by Britton (1996) there are sometimes advantages in operating at high concentrations of fuel rather than at low concentrations of oxygen, especially in flowing systems. The principal case considered was a methane-enriched, marine tank vent collection header as regulated by the US Coast Guard in 33 CFR 154; in certain cases the regulations require operation at less than the LOC (alarm at 8% oxygen). It was shown that designing to maintain ≥25% methane via flow control yields a larger oxygen safety factor than designing to maintain oxygen 2% volume percent below the LOC. The former approach could in some cases result in enrichment gas savings up to 50%, with attendant environmental benefits. The maintenance of at least 25% methane enrichment gas via flow control was shown to preserve nonflammability of any gas mixture not containing decomposable gases or more oxygen than could be obtained from the air. This included cases where cargo tanks were initially ballasted (inerted) with nitrogen, and cases where the UFL of the flammable cargo vapor greatly exceeded that of methane.

While the approach suggested by Britton (1996) can be applied to general in-plant vent header systems, it should be noted that marine vent collection headers continue to be regulated under 33 CFR 154. These regulations provide for the use of detonation flame arresters and other mitigating strategies for start-up, operation, and shutdown. Comparable safety systems should be considered for nonregulated systems employing gas enrichment methods.

3.5. Combustible Concentration Reduction

Combustible concentration reduction can also be used to prevent deflagrations and detonations in process equipment and piping. The combustible concentration is reduced below the lower flammable limit (LFL) by means of ventilation (air dilution).

NFPA 69 (NFPA 1997) contains information on basic design considerations, design and operating requirements, and instrumentation requirements. Appendix D presents methods for ventilation calculations, including the time required for ventilation to reduce the concentration to a safe limit, the number of air changes required for reaching a desired
combustible concentration, and the time required to reach a buildup of combustible concentration in an enclosed volume.

NFPA 69 stipulates that the combustible concentration be maintained at or below 25% of the LFL with the following exceptions:

1. When automatic instrumentation with safety interlocks is provided, the combustible concentration may be maintained at or below 60% of the LFL.
2. In aluminum powder production systems, the combustible concentration is permitted to be maintained at or below 50% of the LFL.

Under certain situations, for specific equipment configurations, it may be possible to safely operate above the NFPA limit of 60% of the LFL. If this method of operation is to be considered, system-specific test data should be generated which demonstrates that the combustible concentration can be controlled in a safe manner, and only then in consultation with appropriate company and (where required) regulatory authorities.

3.6. Deflagration Suppression

In many cases, deflagration flames can be extinguished before unacceptable pressures occur within process equipment and piping if the onset of combustion can be detected early and an appropriate extinguishing agent can be delivered to the proper location within equipment or piping. The technique of deflagration suppression is applicable to most flammable gases and vapors, combustible mists, or combustible dusts that are subject to deflagration in a gas phase oxidant. Suppression systems are active systems that include components for detection, suppressant delivery, electrical supervision to assure readiness to operate, and interlock functions to shut off or isolate other process equipment connected to the equipment to be protected.

Deflagration suppression systems can be applied to a large number of types of process equipment, rooms, and piping systems (including vent manifolded systems) (NFPA 69 1997). Deflagration suppression is a competitive process between a rising rate of combustion heat release and a delayed, but rapid, delivery of extinguishing agent. The deflagration will be suppressed when the unburned fuel-air mixture has been rendered noncombustible due to the addition of an extinguishing agent, or the combustion zone has been cooled to the point of extinguishment, or the reaction kinetics are impeded. The time required for a suppression system to stop a flame front from propagating is dependent on the equipment or piping volume (time increases with increasing volume) and the flame
speed of the material being handled (time decreases with increasing flame speed). For example, the time to suppress a deflagration in a 1.9 cubic meter vessel takes about 100 milliseconds, while it takes 250 milliseconds for the same event in a 25 cubic meter vessel (CCPS 1993). Each application requires experimental validation of suppression system design.

The sequence of events that occurs in a suppressed explosion is shown in Figure 3-11 for a pressure-threshold-type detector. For rate of pressure rise and optical flame detectors the sequence differs slightly. Figure 3-11 is for a dust explosion, but the sequence is similar for a gas explosion. Referring to Figure 3-11, after ignition the pressure in the equipment or piping rapidly increases. After a time $t_d$, the explosion pressure somewhere in the equipment reaches the pressure $P_a$ (at which the pressure detector is set), commonly about 0.05 bar. The explosion pressure wave propagates through the vessel at the speed of sound so that it takes a finite time $t_e$ before the pressure threshold is attained at the explosion detector. This equalization time depends on the relative positions of the detector and the ignition source. In the case of a cubical vessel with 3-meter sides, and the detector in the center of one side and the ignition source in the opposite corner, the equalization time is about 12 milliseconds. The time actually taken to fire the suppressor actuator is usually quite small (in the order of a few milliseconds). The suppressant is then injected across the vessel initially at the discharge velocity of the suppressor (about 40 m/s) and thus it takes a finite time for the suppressant to reach all parts of the vessel. The time required for the suppressant to reach the furthest part of the vessel can be considerably reduced by the use of more than one suppressor. In Figure 3-11, this time is labeled $t_s$.

![Figure 3-11. Sequence of events during a suppressed deflagration.](image)
As mentioned earlier, a suppression system consists of three subsystems for (a) detection, (b) extinguishment, and (c) control and supervision. Incipient deflagrations are detected using either pressure detectors, rate of pressure rise (or “rate”) detectors, or optical flame detectors. Pressure detectors are employed in closed process equipment or piping, and particularly where dusty atmospheres are present. Rate detectors are used in processes that operate at pressures significantly above or below atmospheric pressure. Optical detectors may be infrared (IR), ultraviolet (UV) or hybrid (i.e., both IR and UV) depending on the flame to be detected and the absorbent properties of the operating environment.

The extinguishment subsystem consists of one or more high rate discharge (HRD) suppressant containers charged with suppressing agent and propellant. Normally, dry nitrogen is used to propel the agent out of the container into the equipment or piping. The propellant pressure is normally in the range of 300 to 900 psig, depending on the supplier of the suppression system. An explosive charge is electrically detonated and opens valves providing rapid agent delivery to the equipment or piping being protected.

Common extinguishing agents are water, Halon substitutes, and dry chemical formulations typically based on sodium bicarbonate or ammonium dihydrogen phosphate. The extinguishing mechanism of each agent is often a combination of thermal quenching and chemical inhibition. The selection of the appropriate agent is usually based on several considerations such as effectiveness, toxicity, cost, product compatibility, and volatility. Water is often a very effective suppressant, and should be used whenever possible since it is not toxic and is easier to clean up in comparison to the other types of suppressants. Dry chemical agents have been used for many years in Europe and are being used now more often in the United States. Halons were used for many years as they were very effective suppressants, but they have been outlawed in many countries because of their adverse effect on stratospheric ozone (the “ozone layer”). Numerous substitutes are now available, but none have been found to be as effective as Halon 1301 and other Halons. One new substitute that is being widely used is FM 200™ (a hydrofluorocarbon).

The control and supervision of a suppression system is achieved using an electrical power/control unit with 24-hour (minimum) standby battery backup power. The unit supplies sufficient energy to accomplish the following (NFPA 69 1997):

- power all detection devices
- energize all electrically fired initiators
- energize visual and audible alarms
3.6. Deflagration Suppression

- transfer all auxiliary control and alarm contacts
- control system disabling interlock and process shutdown circuits

Control and supervision systems should be designed with circuit monitoring and self-diagnostic testing to verify that the field sensors and devices are electrically active and connected. The system should alarm when an electrical fault is detected.

It should be recognized that deflagration suppression systems have a number of shortcomings, such as:

- spurious activation (false trips)
- servicing problems (testing, bypassing for maintenance)
- clean-up after activation for a real event
- good for only one event and then they have to be refilled
- potential for overpressure of the protected equipment upon discharge which needs to be considered in design

Figure 3-12 is a schematic of a deflagration suppressant system for process equipment. Each application requires experimental validation of the suppression system design.

Suppressant systems for piping are called suppressant or chemical barriers and are discussed in Section 3.8.


FIGURE 3-12. Schematic of a deflagration suppression system for process equipment.
3. Overview of Deflagration and Detonation Prevention and Protection Practices

3.7. Deflagration Pressure Containment

Deflagration pressure containment is an approach for selecting the design pressure of a vessel so that it is capable of withstanding the maximum pressure resulting from an internal deflagration. Vessels or process equipment can be designed to either

- prevent rupture, but allow deformation (known as “shock-resistant” design in Europe), or
- prevent rupture and deformation (requires a thicker vessel wall).

NFPA 69 (1997) provides equations for calculating the required design pressures for both types of containment design. It also discusses the limitations of deflagration pressure containment design.

In Europe process equipment such as spray dryers, fluid-bed dryers, and mills are available in “shock-resistant” designs for pressures up to 10 barg (145 psig).

Pressure containment can also be provided by using piping systems with a pressure rating above the anticipated maximum pressure generated during a deflagration.

More information about pressure containment design is available in NFPA 69 and the books by Bartknecht (1981, 1989) and Eckhoff (1997).

3.8. Equipment and Piping Isolation

It is common practice in the chemical process industries to provide isolation devices for stopping flame fronts, deflagration pressures, pressure piling, and flame-jet ignition between process equipment interconnected by pipes or ducts. There are several devices for providing this isolation as follows:

- suppressant barriers
- fast-acting valves
- material chokes
- flame front diverters

These are discussed below.

Suppressant Barriers

This type of isolation device (also called a chemical barrier) is similar to deflagration suppression systems used on process equipment. This barrier system consists of an optical sensor, installed in the pipeline or duct between two items of equipment, that detects an oncoming deflagration
3.8. Equipment and Piping Isolation

flame and emits a signal to a control unit. The amplified signal triggers the detonator-activated valve in a suppressant bottle, which injects an extinguishing agent into the pipeline through suitable nozzles. Pressure sensors are not normally used for pipeline barriers since there is no clear correlation between the front of the pressure wave and the flame front, and pressure sensor response times often are too slow for use in this application.

Suppressant barrier systems have the same shortcomings as cited in Section 3.6. In addition, the location of the sensor is critical to the successful isolation of a deflagration flame in a piping system. Bartknecht (1981) states that the flame sensor is installed at a distance of 1 meter from the ignition source, and the extinguisher nozzles at a distance of 10 meters from the ignition source.

Figure 3-13 is a schematic of a deflagration suppressant barrier system for pipelines.

Further information on suppressant barriers can be found in NFPA 69 (1997), and the books by Bartknecht (1981 and 1989) and Eckhoff (1997).

Fast-Acting Valves

A variety of fast-acting valves are available, including slide gate, flap (butterfly), and float (poppet) valves. Slide gate and flap type valves are actuated (closed) upon a signal from a detector (sensor) in the pipeline between two items of interconnected process equipment. The detector sends a
signal to a compressed air cylinder which then discharges the compressed air to a mechanism at the top of the valve, thereby closing the valve. A typical closing time for a fast-acting valve is about 25 milliseconds. The deflagration detector is located about 1 meter away from the source of ignition (equipment), and the fast-acting valve is usually installed 5 to 10 meters along the connecting pipeline, so that by the time the flame front reaches it, the valve is fully closed. A fast-acting slide gate isolation valve is shown in Figure 3-14 and a fast-acting flap (butterfly) valve is shown in Figure 3-15.
Another type of fast-acting valve is the Ventex™ valve (a float type valve), which is activated by the deflagration pressure wave advancing through the pipeline. This valve must be installed horizontally, and its minimum activation pressure is in the order of 0.1 barg (1.45 psig). In normal operation, the gas or dust being conveyed in the pipeline flows around the valve poppet without causing any significant off-set as long as the flow velocity is less than about 20 m/s. However, in the case of a deflagration in the pipeline, the advancing pressure wave pushes the valve poppet in the axial direction until it hits a neoprene gasket, where it is held in position by a mechanical catch lock, which can be released from the outside. However, the neoprene gasket may be adversely affected in high temperature environments. Figure 3-16 shows a schematic drawing of a Ventex™ valve.
Another, more recent, type of fast-acting valve is the Exkop™ valve. The valve trim (internals) is actually a rubber bladder surrounded by an air chamber. In the event of a deflagration, an electrical signal is sent from a sensor, typically mounted on a deflagration relief device, to the Exkop™ valve air tank mounted integral to the valve. The air tank discharges air to the chamber surrounding the rubber bladder and compresses it, which pinches off flow in the pipeline. Because the rubber bladder has relatively little mass, it is both very fast acting and imparts low shock to the piping. The rubber bladder, however, may be adversely affected by high temperatures. One advantage of the Exkop™ valve is that it can be mounted fairly close to the equipment in which the deflagration occurs, usually 15 to 18 feet away from the equipment. It also immediately rearms itself with ordinary plant air and is automatically placed back in service. Figure 3-17 shows details of an Exkop™ valve installation. Exkop™ valves are only used for isolation of piping carrying a dust–air mixture. They are not recommended for stopping gas deflagrations as tests have shown that in a gas/vapor deflagration, the flame propagation is too fast for the valve to work effectively (Stevenson 2000).

**Material Chokes**

Flame propagation can also be stopped between process equipment handling bulk solids and powders by judicious selection and design of bulk solids/powders conveying equipment such as rotary valves (rotary airlocks) and screw conveyors. The mass of bulk solids/powders contained in these items of equipment provide a tortuous path through which the gas and flame have to pass, and so can act as a “material choke” when certain design features are implemented.

Rotary valves will generally prevent flame propagation if the following criteria are followed (Bartknecht 1989, NFPA 69 1997):

- two vanes per side are always in contact with the housing
- the vanes or tips are made out of metal (no plastic vanes) and
- the gap between the rotor and housing is ≤0.2 mm

In screw conveyors the removal of part of the screw will ensure that a plug of bulk solids/powder will always remain as a choke (Eckhoff 1997).

Several considerations have to be taken into account when using a rotary valve as a material choke. When a deflagration occurs in the equipment upstream of the rotary valve, the rotary valve has to be stopped immediately by a suitable detector in order not to pass burning or glowing solids into downstream equipment, which could then cause a second fire or...
3.8. Equipment and Piping Isolation

FIGURE 3-17. Exkop™ fast-acting isolation valve (quench valve). (Source: Cv Technology, Inc.)

(a) Photo of Exkop fast-acting isolation valve

(b) Schematic of Exkop valve before and after activation

FIGURE 3-17. Exkop™ fast-acting isolation valve (quench valve). (Source: Cv Technology, Inc.)
deflagration. Rotary valves must be tested for their suitability as flame arresters as well as for their pressure rating with appropriate explosion tests (Bartknecht 1989). These devices must be properly maintained to ensure that normal wear and tear does not result in a loss of seal between the rotor blades and the housing.

**Flame Front Diverters**

Flames can also be prevented from propagating from one piece of equipment to another through interconnecting piping by means of a flame front diverter. The basic principle of operation of this device is that the deflagration is vented at a point where the flow direction is changed by 180 degrees. Due to the inertia of the fast flow caused by the deflagration, the flow will tend to maintain its direction upward rather than making a 180 degree turn when the velocity is low (at normal conditions). When the high-speed deflagration flame continues upward, it pushes open either a hinged cover or bursts a rupture disk located at the top of the diverter, allowing the flame to be released to the atmosphere. The location of a flame front diverter must be chosen so that the release of the flame does pose a hazard to people or equipment.

Some flame front diverters have demonstrated the ability to successfully divert deflagration flames by directing them to the atmosphere. However, in some cases, tests have indicated that some diverters have been ineffective in completely diverting a deflagration; but where this has occurred, the deflagration severity has been reduced (NFPA 69 1997). Therefore, before they are used, it is recommended that they be tested for the desired application. Figure 3-18 shows several flame front diverter designs.


**3.9. References**

**3.9.1. Regulations, Codes of Practice, and Industry Standards**


(a) Types of flame front diverters

(b) Schematic of flame front diverter installation

3.9.2. Specific References


