Flame Arrestor Technology

A Flame Arrestor is a device which allows gas to pass through it but stops a flame in order to prevent a larger fire or explosion. There is an enormous variety of situations in which flame arrestors are applied. Anyone involved in selecting flame arrestors needs to understand how these products work and their performance limitations. For that purpose, this paper provides an introduction to the technology and terminology of flame arrestors and the types of products available.

Figure 1. The earliest flame arrestors: Davy safety lamps for coal miners.

Blocking flame with narrow passages

The operating principle of flame arrestors was discovered in 1815 by Sir Humphry Davy, a famous chemist and professor at the Royal Institution in England. A safety committee of the English coal mining industry had approached Davy for technical assistance. They needed a way to prevent miners' oil lamps from causing explosions when flammable gas called firedamp seeped into the mine shafts. Sir Humphry studied the gas, which consisted mostly of methane. The investigation centered on how methane burns under various conditions and with various proportions of air. Davy's solution was to enclose the lamp flame securely with a tall cylinder of finely woven wire screen called metal gauze. Three of the earliest Davy safety lamps are shown in Figure 1.

Enough lamplight passes out through the screen to be useful. Air for the oil flame around the lamp wick enters through the lower part of the screen. Hot exhaust gas escapes through the upper part. When a combustible mixture of methane flows in with the air, a methane flame burns against the inside of the screen. However, neither the methane flame nor the lamp flame passes through the narrow openings of the screen. The metal wire absorbs heat from the flame and then radiates it away at a much lower temperature.

Modern flame arrestors

Since Sir Humphry's time, flame arrestors of numerous varieties have been applied in many industries. All of them operate on the same principle: removing heat from the flame as it attempts to travel through narrow passages with walls of metal or other heat-conductive material. For instance, flame arrestors made by Enardo employ layers of metal ribbons with crimped corrugations as shown in Figure 2.
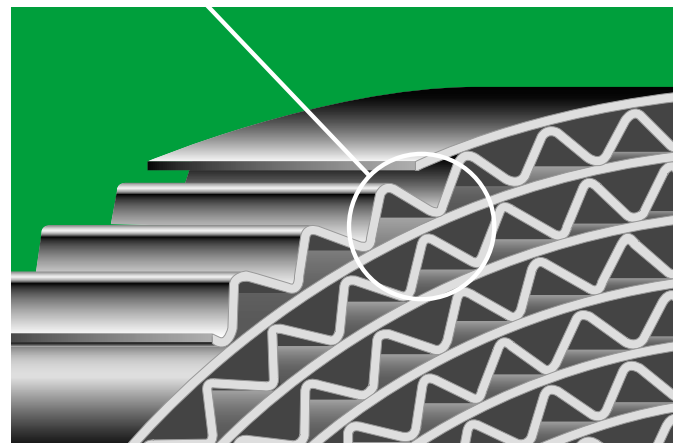
Flame Cell Channel

Figure 2. Concept of flame arrestor element used in Enardo products, featuring a crimped wound metal ribbon element

Flame arrestors are used in approximately 22 industries, including refining, pharmaceutical, chemical, petrochemical, pulp and paper, oil exploration and production, sewage treatment, landfills, mining, power generation, and bulk liquids transportation. In some cases, the flames involve exothermic (heat-producing) reactions other than oxidation. Processes which generate the combustible or reactive gases include blending, reacting, separation, mixing, drilling, and digesting. These processes involve numerous equipment configurations and gas mixtures.

End-of-line, vent-to-atmosphere type

Most flame arrestor applications and designs fall into two major categories. One group consists of *end-of-line* flame arrestors, also known as the *vent-to-atmosphere* type (Figure 3).

Figure 3. End-of-line flame arrestors are used in applications such as petroleum storage tank vents.

The classic application is in preventing fire in the atmosphere from entering an enclosure. Around 1920, for instance, flame arrestors began to be installed on vents on oilfield storage tanks. They keep the tanks from exploding when gas flowing from the vents is struck by lightning (Figure 4).
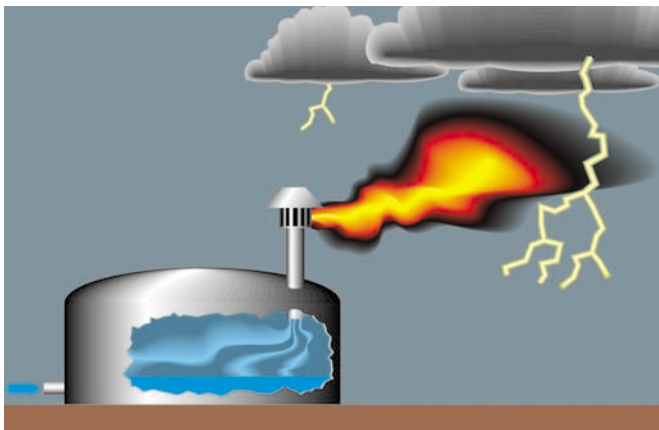

Figure 4. Oilfield storage tank vents were an early application of industrial flame arrestors.

Conversely, some end-of-line flame arrestors prevent fire in an enclosure from igniting an explosive atmosphere such as in a refinery. For instance, flame arrestors may be installed in furnace air inlets and exhaust stacks. The Davy lamp might be considered another example of that sort.

In-line, deflagration or detonation type

The other major category consists of in-line flame arrestors, also known as *deflagration* and *detonation* flame arrestors. (Speaking non-technically, deflagration means rapid burning, and detonation means explosion.) These units are installed in pipes to prevent flames from passing, as shown in Figure 5.
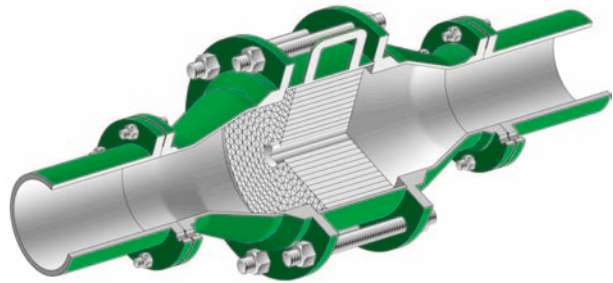

Figure 5. A typical Enardo in-line flame arrestor.

Most in-line flame arrestor applications are in systems which collect gases emitted by liquids and solids. These systems, commonly used in many industries, may be called vapor control systems. The gases which are vented to atmosphere or controlled via vapor control systems are typically flammable. If the conditions are such that ignition occurs, a flame inside or outside of the system could result, with the potential to do catastrophic damage.

One variety of vapor control systems is called vapor destruction systems. Included are elevated flare systems (Figure 6), enclosed flare systems, burner and catalytic incineration systems, and waste gas boilers.
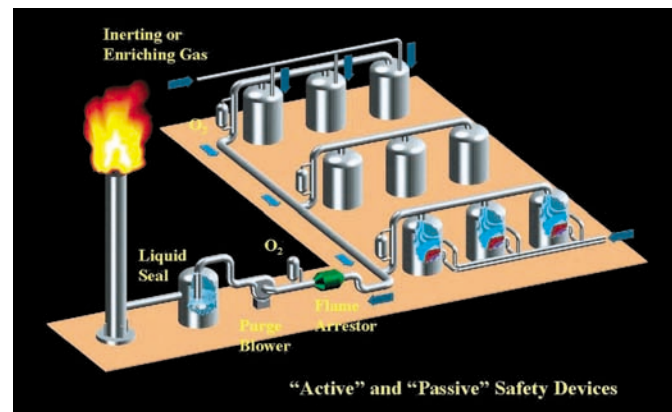

Figure 6. An in-line flame arrestor in a flare system.

Another type of vapor control system using in-line flame arrestors is vapor recovery systems. Included here are vapor balancing, refrigeration, adsorption, absorption, and compression systems.

However, in-line flame arrestors are sometimes used in end-of-line applications. For instance, an in-line unit may be mounted below a tank vent valve on a liquid storage tank (Figure 7). The valve reduces emissions and product loss, while the flame arrestor protects the tank from flames in the atmosphere during venting of flammable gases.

As technology throughout the world has become more complicated, safety products have also evolved to meet new requirements. Flame arrestors, in particular, changed immensely during the last decade of the twentieth century. As will be explained later, flames in pipes can reach much higher speeds and pressures than in the open atmosphere. Therefore in-line flame arrestors are now subdivided into three categories on that basis. Furthermore, special provisions are made for each of the three major groups of gases according to degree of flame hazard (also explained later)—NEC Groups B, C, and D. Thus, there are now as many as twelve different types of flame arrestors, as follows:

1. End-of-line, Group B
2. End-of-line, Group C
3. End-of-line, Group D
4. In-line, low/medium-press. deflagration, Group B
5. In-line, low/medium-press. deflagration, Group C
6. In-line, low/medium-press. deflagration, Group D
7. In-line, high-pressure deflagration, Group B
9. In-line, high-pressure deflagration, Group C
9. In-line, high-pressure deflagration, Group D
10. In-line, detonation, Group B
11. In-line, detonation, Group C
12. In-line, detonation, Group D

In applying flame arrestors, it should be remembered that these safety devices are passive ones, and they are often used together with active safety devices. Active devices used in flame safety include hydraulic (liquid) seals, isolation valves, blankets of inert gas or enriching (fuel) gas, gas analyzers, and oxygen analyzers. Unlike active devices, passive devices such as flame arrestors do not depend on a power source, have no moving parts, and do not require human attention except to be cleaned periodically.
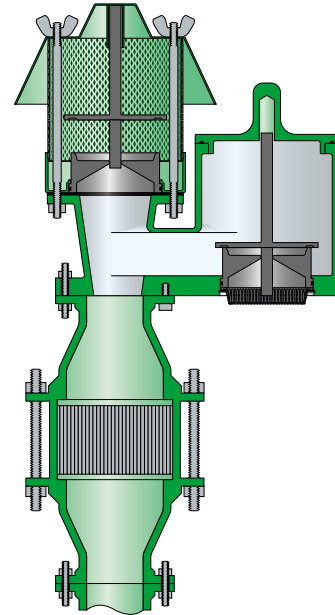

Figure 7. An in-line flame arrestor used in an end-of-line application (below a pressure and vacuum relief valve for a liquid storage tank).

For example, the primary flame safety devices in a vapor control system are usually active ones such as liquid seals and oxygen analyzers as shown before in Figure 6. However, active devices can be rendered ineffective by loss of power, failure of mechanical components, failure of electronic communication, or human error. Flame arrestors, in turn, are the system's secondary or fail-safe provision. In other words, if the active, primary method malfunctions, the passive, secondary method will be the last defense against an explosion.

Flame propagation

The differences between the various types of flame arrestors are based mainly on the nature of the flame which is expected (especially how fast it moves) and on the expected intensity of the pressure pulse created by the flame. A flame is a volume of gas in which a self-sustaining exothermic (heat-producing) chemical reaction is occurring. The reaction is presumed to be oxidation, also known as combustion.

To have a flame, three things must be present; oxygen (supplied by air), very high temperature (initially supplied by an ignition source) and a flammable gas

mixed with the air in suitable proportions called a combustible mixture. So long as these requirements remain available, a flame can burn indefinitely. Flame arrestors operate by removing one of these requirements: high temperature.

In a stationary flammable mixture, a flame seems to move toward the unburned gas, leaving combustion products behind. That apparent motion is called *flame propagation*. The flame exists only within a relatively narrow volume at the boundary between the unburned gas and the combustion products.

The speed at which the flame propagates is measured at the front edge of the flame. This speed depends on several variables, including the speed of the chemical reaction, the air-to-gas mixture ratio, and whether the flame is confined or unconfined.

Chemical reaction kinetics

The speed of a chemical reaction, such as that between fuel gas and oxygen, is called its kinetics. This is determined mainly by the amount of energy released by each molecule of flammable gas when it combines with oxygen. For instance, hydrogen burns much faster than propane. Thus, given ideal air mixtures at room conditions, an open (unconfined) hydrogen flame propagates at 3 meters per second, compared to only 0.4 meters per second for propane. However, reaction speed also depends strongly on the temperature and pressure: the hotter a flame, and the higher its pressure, the faster the reaction that sustains it.

Air-to-gas mixture ratio

Another determinant of flame propagation speed and pressure generation is the air-to-gas mixture ratio. A given flammable gas will sustain a flame only within a certain mixture range at a given pressure and temperature.

If there is too little gas for a lasting flame at that condition, the mixture is said to be too "lean" to burn. In that case, the concentration (volumetric percentage) of gas in the air is below the *lower explosion limit* (LEL) for that particular gas. This is the concentration below which a flame will not last at that pressure and temperature. For example, the LEL at room conditions is 2.1% for propane and 4.0% for hydrogen.

Conversely, if there is too little air, the mixture is too "rich" to burn. The *upper explosion limit* (UEL) for a particular gas is the concentration of gas *above* which a flame will die out at a given pressure and temperature. At room conditions, propane's UEL is 9.5%, and hydrogen's is 75.0%.

The *flammable range* of a gas is the difference between its lower and upper explosion limits. Hydrogen has a much wider flammable range than propane.

A mixture with exactly the right amount of oxygen for complete combustion—no more, no less, producing the maximum energy per volume of gas—is called *stoichiometric*. Air-to-gas ratios at or near stoichiometric provide the highest flame propagation velocities and thus the most intense pressure impulse waves. However, as long as the mixture is well within the flammable range, the flame velocity ordinarily does not vary a great deal.

Unconfined propagation of flame

Flames generally propagate much faster in pipes than in the open atmosphere. Flames which are not restricted by physical barriers such as pipes are called unconfined. An unconfined flame is free to expand by consumption of unburned gas into an ever-widening volume. This expansion provides quick dissipation of the heat and pressure energy generated by the flame.

The most common example of unconfined propagation occurs when gas venting from a process system or liquid storage tank contacts an ignition source (Figure 8). From that point, flame propagates outward and towards the unburned gas until it comes to the gas source.
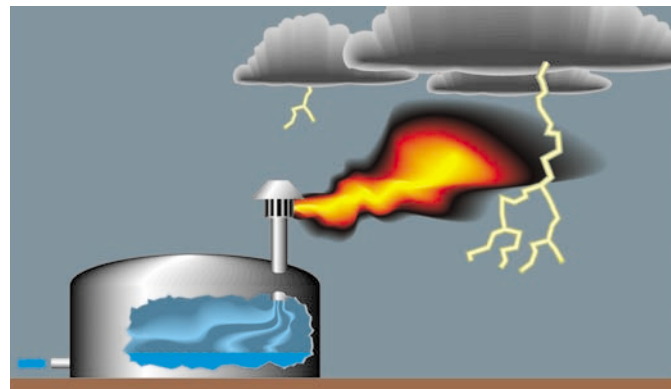

Figure 8. Concept of an unconfined deflagration

When the unconfined flame first begins to consume the unburned gas, the flame front travels below sonic velocity (the speed of sound in the atmosphere). If the velocity remains subsonic, the event is called a *deflagration*; the gas is said to deflagrate, meaning burn rapidly. By contrast, flame propagation at or above the speed of sound is called a *detonation*, which is an explosion strong enough to cause shock waves in the gas. Some gases can detonate without being confined, but it is not a common occurrence.

As the subsonic flame moves in the direction of the unburned gas, it produces heat. The heat, in turn, expands the unburned gas in a layer in front of the flame, called the boundary layer. The rapid expansion of the boundary layer along with the fast-moving flame is commonly called an atmospheric explosion and percussion wave. The pulse of elevated temperature and pressure quickly spreads out and dissipates into the atmosphere in a relatively simple manner.

Confined propagation of flame

The most common example of *confined* flame is propagation inside a pipe or explosion inside a process vessel or liquid storage tank. The flame is usually a *flashback*, meaning that it propagates upstream, against the flow of gas and towards its source. The heat and pressure energy of a confined flame is not relieved as readily as that of an unconfined flame. This restriction of energy dissipation makes a tremendous difference in how the flame propagates and thus what kind of flame arrestor is required to stop it.

In a readily combustible mixture, the velocity of an *unconfined* flame depends primarily on the kinetics of the combustion reaction. Most of the combustion heat and resulting pressure are dissipated in the surrounding atmosphere, without influencing propagation speed very much.

Confined flames also rely on the kinetics of burning for flame propagation velocity. However, since the flame is confined, the heat energy and pressure remain concentrated, causing a much stronger effect on the kinetics of burning and therefore the flame propagation velocity.

More particularly, imagine a very long, straight pipe about six inches in diameter, closed by a cap at one end and filled with combustible mixture at room temperature and pressure. Suppose the gas is ignited

by a spark plug at the closed end as suggested in Figure 9. A flame propagates in the unburned gas along the pipe. As described before for an unconfined flame, the heat of the flame expands the gas boundary layer directly in front, causing a pulse of pressure. However, the energy is not allowed to dissipate by spreading into an ever-widening region of atmosphere. Instead, as the flame propagates down the pipe, it encounters gas with higher temperature and pressure, speeding the combustion reaction. This process feeds on itself, producing flame velocities, temperatures, and pressures much higher than those seen in unconfined conditions.
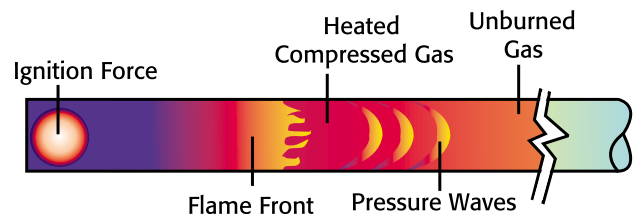

Figure 9. Elements of flame propagation from the closed end of a pipe of indefinite length.

To be more precise, suppose a pressure gauge capable of extremely quick response is placed 10 meters away from the ignited end. As the flame moves towards the gage, the reading increases. When the flame reaches the gage, it causes a pressure spike as high as 100 psig (7 bars) or higher.

While propagating down a pipe, the flame functions not only as a chemical reaction, but also as a mechanical reaction—like a piston in a cylinder—compressing the gas before consuming it and imparting more energy and velocity. If the pipe is long enough, in some cases the flame can reach hypersonic (much faster than sound) velocities as high as 6,500 miles per hour (2,900 meters per second). The pressure may approach 4,900 pounds per square inch (34,000 kilopascals).

Development stages of confined flame

Selection of an appropriate in-line flame arrestor depends on how intense any flame in the pipe is expected to be, in terms of velocity and pressure. Studies of flame propagation in pipes reveal seven distinct stages or phases which a flame may reach if the pipe is long enough and the combustion is fast enough and energetic enough.
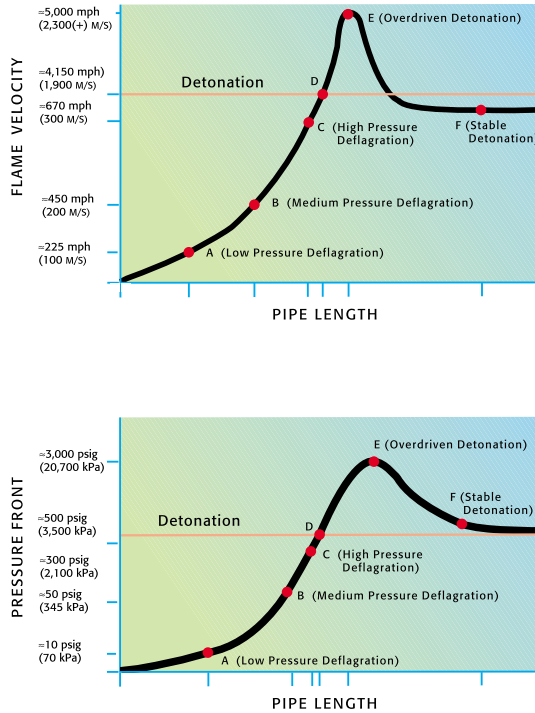
Figure 10. Conceptual graphs showing velocity and pressure of a flame front at points along a long pipe, beginning with ignition at a closed end. All scales are logarithmic.

These stages are illustrated in Figure 10 by imaginary graphs of the speed and pressure of a flame at each point as it travels along a pipe of indefinite length. Note that the pressure is the transient peak that would be indicated by a very quick-response gauge at each point along the pipe. The flame reaches stages labeled A through F, one after another, at increasing distances from the ignition point.
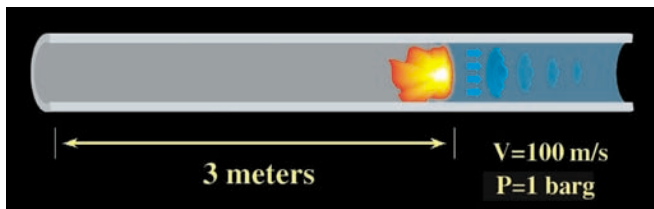

Figure 11. Concept of low-pressure deflagration confined in a pipe, showing typical distance from ignition point.

Low-pressure deflagration

So long as the flame front travels well below the speed of sound with minimal pressure increase

caused by the expanding boundary layer, its condition is considered to be *low-pressure deflagration* (Figure 11). That stage is generally associated with velocities up to about 112 meters per second and relative increases of absolute pressure (DP/P_O) up to 1. (Assuming initial atmospheric pressure, the gage pressure is less than about 100 kPag). This initial flame propagation state develops in a short length of pipe— for example, approximately 3 meters for a propane-air mixture. Hydrogen is in its low-pressure deflagration state only to about 1.0 meter from the point of ignition.

(DP/P_O is the dimensionless ratio for deflagration and detonation testing as measured in the piping system on the side of the arrestor where ignition begins. P_O is the system initial absolute pressure. DP is the measured absolute pressure, minus P_O.)
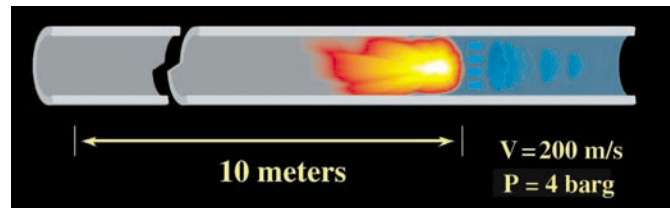

Figure 12. Concept of medium-pressure deflagration confined in a pipe, showing typical distance from ignition point.

Medium-pressure deflagration

As the flame propagates farther down the pipe, its intensity increases to the dynamic state of *medium-pressure deflagration*. Flame speed is higher but still subsonic—up to 200 m/s. The pressure impulse at the flame reaches levels considered to be medium, with DP/P_O up to 10. For a propane/air mixture beginning at room conditions, the flame is in this state when passing from about 3 to about 10 meters from the ignition point. Hydrogen, by comparison, is in its medium pressure deflagration state between 1.0 and 2.5 meters from ignition.
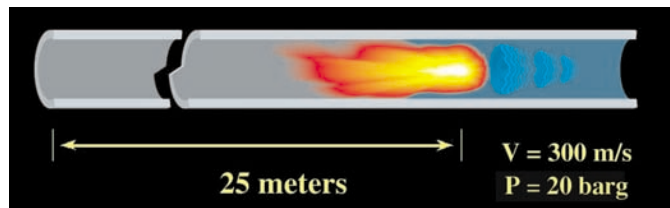

Figure 13. Concept of high-pressure deflagration confined in a pipe, showing typical distance from ignition point.

High-pressure deflagration

Beyond the limit of medium-pressure deflagration, the propagating flame reaches the condition of *high-pressure deflagration*. The flame front velocity—still subsonic—is up to 300 m/s, and the pressure increase caused by the expanding boundary layer reaches a DP/DP_O as high as 20. The distance from the ignition point is between 20 and 30 meters for a propane/air mixture and between 2.5 and 6 meters for hydrogen and air.
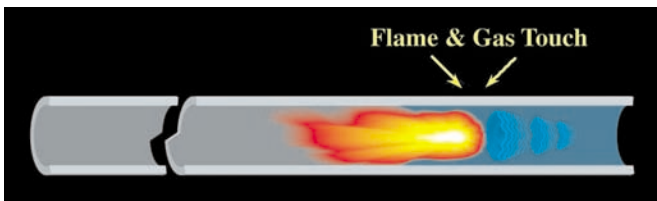

Figure 14. Concept of deflagration-to-detonation transformation in a pipe.

Deflagration-to-detonation transformation

When the propagating flame front passes sonic velocity, what occurs is called *transformation from deflagration to detonation*, abbreviated DDT. The pressure impulse in front of the flame becomes a shock wave. The compressed gas immediately in front of the expanding boundary layer of gas just in front of the flame, which can reach pressures around 700 kPa(g), comes in contact with the flame. The result is an explosion. The energy of that explosion, which includes heat, velocity, and pressure, has nowhere to go but down the pipe. The explosion generates tremendous shock-wave compression of the gases both upstream and downstream of the initial point of transformation.
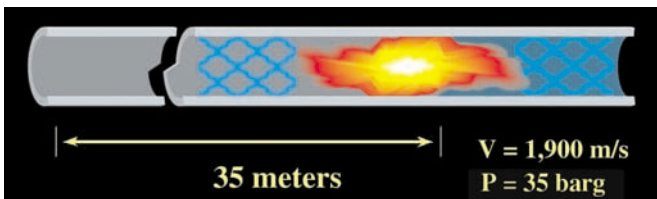

Figure 15. Concept of detonation confined in a pipe, showing typical distance from ignition point.

Detonation

A *detonation* is defined as a flame front moving at or above the speed of sound. It entails increased compression of the gases by shock waves in front of the flame. A detonation may have a velocity in the range of

300 m/s and a maximum impulse pressure of 3,500 kPa(g), with DP/P_O as high as 20. This flame propagation state develops in a pipe length from slightly beyond the high-pressure deflagration up to approximately 30 meters beyond the ignition point for a propane/air mixture and approximately 10 meters for hydrogen in air.
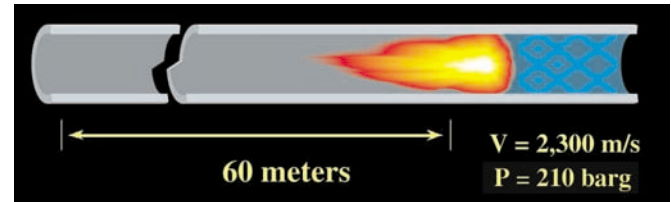

Figure 16. Concept of overdriven detonation confined in a pipe, showing typical distance from ignition point.

Overdriven (unstable) detonation

As the flame propagates even farther down the pipe, it goes into the dynamic state of *overdriven or unstable detonation*. This is defined as a flame front moving at supersonic velocity and in some instances at hypersonic velocity, attended by tremendous compression of gas by multiple shock waves. It is an unstable and transient condition. As the flame goes through DDT, it continues to pile shock waves into a dense concentration. Gas in front of the flame is compressed and heated above the ignition point like the fuel mixture in a diesel engine cylinder. When the compressed gas self ignites, the explosion releases an extremely large amount of energy, much like the earlier DDT. Again, the energy is restrained by the piping and only allowed to move straight ahead. Since the flame velocity is already supersonic, the flame accelerates to hypersonic velocities.

The reason this condition is temporary is that the flame velocity and pressure are dependent on numerous shock waves providing gas compression in front of the flame. These shock waves dissipate soon after the initial explosion, and the velocity and pressure of the flame stabilize. An overdriven detonation has a typical peak velocity in the range of 2,300 m/s and a maximum impulse pressure of about 20,995 kPa(g)— equivalent to a DP/P_O of 130. This flame propagation state develops in a pipe length beginning just beyond the DDT and ending approximately 60 meters from the ignition source for a propane/air mixture and 20 meters for hydrogen and air.

Stable detonation

Beyond the transient overdriven detonation, the propagating flame finally reaches the dynamic state of stable detonation. The flame front moves at or above the speed of sound with shock-wave compression in front. The flame will not go through any more transitions but will remain in this stable condition to the other end of the pipe. A stable detonation has a velocity in the range of 300 m/s and a peak impulse pressure of 3,500 kPa(g), equivalent to a DP/P_O of 20.

80 meters
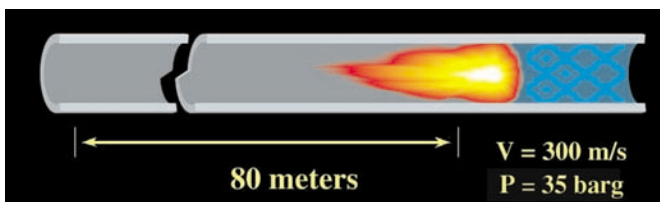
V = 300 m/s
P = 35 barg

Figure 17. Concept of stable detonation confined in a pipe, showing typical distance from ignition point.

Galloping detonation

A detonation that periodically fails and reinitiates during propagation is known as a galloping detonation. *"This type of detonation is typically observed in near-limit mixtures (they have been observed near the lean and possibly near the rich limit). Since it reinitiates via DDT, a galloping detonation is periodically overdriven and results in large overpressures at periodic distances along a pipe. Over these periodic cycles the wave oscillates between a fast deflagration and a leading shock, transition to an overdriven detonation, and a short lived apparently steady detonation phase."*[1]

Selection considerations for in-line flame arrestors

Selecting an appropriate in-line flame arrestor for a given application requires understanding several considerations. These considerations are based on the foregoing general understanding of how an accidental gas flame behaves in pipes.

Burn-back gas velocity

When a flammable mixture is flowing in a pipe, one especially important condition is the *burn-back gas velocity*. It is the gas velocity at which a flame is stationary when propagating upstream in a condition of

[1]*Grossel, Stanley, Deflagration and Detonation Flame Arresters (AIChe, 2002), 66.*

low-pressure deflagration. This refers to the "superficial" average gas velocity across the pipe—the volumetric flow rate divided by the crosssectional flow area. If the gas flows slower than the burn-back velocity, a flame can propagate upstream. The burn-back velocity depends on the type of gas and its air-to-gas mixture ratio as well as the temperature and pressure. At stoichiometric mixture and standard room conditions, propane's burn-back velocity is approximately 3.2 m/s, whereas hydrogen's is approximately 20 m/s.

If the gas feeding a flare or waste gas burner slows down below the burn-back velocity at the flare tip or burner, then the flame moves upstream toward the process source. If the gas velocity is only slightly lower than the burn-back velocity, the flame will creep slowly upstream. However, at zero gas velocity in a long pipe, the flame will accelerate as explained before and flash back at high speed. Zero flow allows the most severe flame propagation conditions. All flame arrestor products should be tested by the manufacturer at static (zero) flow so that they will work in the most severe flame propagation conditions (flashback).

Initial operating pressure (IOP)

The *initial operating pressure* (IOP) is the absolute pressure of a flammable gas mixture in a given piping system when the velocity falls below the burn-back velocity. The IOP is usually less than the normal operating pressure of that system. For example, when a vapor control system is operating properly, so that the flow stream velocity is above the burn-back velocity of the process gas, then the system pressure is within some normal operating range above atmospheric pressure. But when the system is shut down during normal or emergency conditions and the process stream slows down, the pressure also falls. At some point before the velocity reaches zero, a flashback can occur. The pressure in the system in this shutdown situation or static flow condition is the IOP for that particular system.

Remember that pressure affects flame: the higher the pressure, the more energy the flame releases per unit volume. That equates to higher flame intensity and energy exchange per unit volume and faster flame acceleration. The explosive pressure of a given gas is roughly proportional to the initial absolute pressure. For instance, doubling the absolute pressure approximately doubles the explosive pressure.

Therefore, the IOP in a given system determines two things pertaining to selection of a flame arrestor product. The first is flame velocity and pressure relative to the distance the flame has traveled down the pipe. For example, when a flame has propagated 10 meters in a stoichiometric propane-to-air mixture at atmospheric pressure (101.3 kPa absolute), the flame velocity is approximately 200 m/s, and the pressure front is at about 800 kPa absolute. If instead the IOP is increased to 150.0 kPa, the flame velocity and pressure at 10 meters will be approximately 300 m/s and 1,200 kPa. Thus, in this example, increasing the static pressure 50% causes an increase of 50% in the velocity of the flame front and 50% in its pressure. This consideration can affect how close to the ignition source the arrestor must be placed. It can also require the use of one arrestor device rather than another.

The second selection consideration affected by IOP pertains to the energy which an arrestor must absorb per unit volume of gas in order to quench a flame. When pressure increases in a process system, the energy released by flame per unit volume also increases. Thus the arrestor must absorb more heat to lower the flame's temperature sufficiently. However, that task can be difficult for the arrestor, since it was designed with a certain heat transfer capacity. If an arrestor is placed in an application for which the IOP is higher than it has been tested or designed for, the arrestor could fail to stop the flame. Therefore, to enable proper selection and system design, manufacturers must indicate the maximum IOP which their flame arrestors can handle for various flammable gas mixtures. Every flame arrestor product should be tested at a series of increasing pressures to determine its IOP performance threshold for commonly encountered gas mixtures. For example, a standard low-pressure deflagration arrestor typically has a maximum allowed IOP of around 5% above atmospheric condition, or 106.0 kPa (15.4 psig), while that for detonation flame arrestors ranges up to 160 kPa (23 psig).

Transient momentum pressure

Piping can withstand a propagating flame driving a pressure pulse which may be thousands of times greater than the maximum pressure for which the pipe is rated. This pressure caused by flame propagation is not a static pressure, because the pressure wave is moving so fast it exerts its force on the piping walls for only a fraction of a second. Instead, flame pressure is considered a dynamic impulse pressure, called

transient momentum pressure or TMP. Because the transient motion of gas in the forward direction is so rapid when a pressure wave passes, the wave carries a tremendous amount of momentum (mass multiplied by velocity) and resulting energy (one-half of mass multiplied by the square of velocity). Anything which changes the direction of that momentum, such as pipe bends, shut-off valves, blower housings, or an arrestor device, experiences transfer of energy via momentum. This momentum energy can have a catastrophic effect on equipment.

Standard flame arrestors are designed for low transient momentum pressures (TMPs) and can fail mechanically when exposed to very high TMPs. Enardo detonation arrestors are designed to withstand TMPs of any magnitude.

Flame stabilization

There are two types of flame stabilization: open and confined. An *open stabilized flame* occurs when a flammable mixture emerges from confinement at a velocity such that an open flame fed by the gas is stationary. For example, when a flare is burning, the stationary flame at the tip experiences open flame stabilization. If for some reason the process stream slows down below the burn-back velocity of the gas, the flame begins moving down the flare stack. It may then stabilize at the arrestor device or somewhere else down the pipe. This condition is referred to as *confined flame stabilization*. (See Figure 18.) If the process stream velocity were to go to zero, the flame would not creep down the flare but would accelerate in a flashback and possibly detonate. The possibility for a stabilized flame in the system during flashback is very slight, but it sometimes happens.

Each flame arrestor design performs differently when exposed to flame stabilization, depending on the mass and type of material of the flame-arrestor element. Users should contact the manufacturer of a given arrestor for information on how its products perform when exposed to flame stabilization. A good way to safeguard against flashback due to flame stabilization is to install a temperature sensing device on the exposed side of the arrestor. The heat of a stabilized flame triggers automatic controls designed to extinguish the flame.
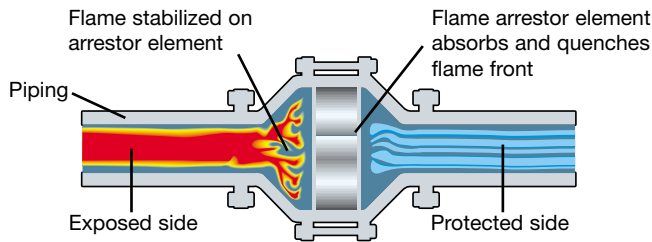
Figure 18. Concept of flame stabilization at aflame arrestor. Flow is from right to left.

Air-to-fuel mixture ratios

The ratio of combustible gas to air, described earlier, has a profound effect on how a flame burns. It influences not only flame speed as mentioned before, but also heat intensity, ignition energy, auto-ignition temperature, pressure piling, and others.

Grouping of Gases

Hundreds of different flammable gases are generated as products or by-products of industrial processes. One gas may vary widely from another in its characteristics pertaining to flame propagation. It is necessary to have means for describing those characteristics in order to design safety equipment, instrumentation, etc. Several testing and regulatory bodies, including the NEC, IEC, NFPA, and NTIS, classify flammable gases based on the following criteria, some of which are explained later:

MESG (maximum experimental safe gap)
Flame temperature
Flame velocity
AIT (auto-ignition temperature)
LEL-to-UEL range
Ignition energy

NEC	IEC	MESG	Test Gas List
Group A		0.25	Acetylene
Group B	Group IIC	0.28	Hydrogen
	Group IIB	0.50	Enriched H_2
Group C	Group IIB3	0.65	Ethylene
Group D	Group IIA	0.90	Propane
G.M		1.15	Methane

Table 1. Hazardous gas groups according to NEC and IEC

Each testing or regulatory authority has its own system for classifying gases according to combustion hazard groups. Classifications are based on severity of explosion hazard as indicated by low AIT, broad LEL-to-UEL range, higher flame temperature, faster flame velocity, or a combination of any of these characteristics. Most of them relate directly to the MESG of the combustible gas. (See Table 1.)

Maximum experimental safe gap (MESG)

Maximum experimental safe gap is a standard measurement of how easily a gas flame will pass through a narrow gap bordered by heat-absorbing metal. MESG was developed to classify gases for design and selection of electrical instrumentation, electrical enclosures, and flame arrestor devices. The measurement is conducted with a standard apparatus consisting of a small, hollow metal sphere of a certain diameter which is split into two halves. The circular edge of each hemisphere is provided with a smooth metal flange of a certain width. The hemispheres are held close together in the apparatus with the flanges parallel and separated by a narrow gap. This apparatus is immersed in a stoichiometric mixture of the test gas and air at standard room conditions, and the mixture inside the sphere is ignited with an electric spark. The experiment is repeated with a wider and wider gap between the two flanges, until the mixture outside the sphere is ignited. The MESG is the greatest distance between flanges at which the flame fails to pass through. The more hazardous the gas, the narrower the MESG. An arrestor must be designed for the MESG value of the process gas.

Multiple gas mixtures

Some vapor collection systems deal with a single, relatively pure combustible gas—for instance methane or acetylene—mixed with air. However, most processes requiring flame arrestors involve mixtures of several combustible gases, each having its own set of hazard characteristics. Some gases consume air more efficiently than others in a mixture, thus making the mixture behave much like a single constituent gas. One gas component may act as a catalyst to another, making the mixture more dangerous than the single most hazardous gas by itself. Not much experimental data is available on the hazardous characteristics of combustible gas mixtures.

The MESG of mixed gases is not normally known and it is impractical to test all gas mixtures for their MESG. The industry standard has been to select an arrestor design based on the worst case gas component in the mixture. This method is in most cases, overly conservative. NFPA 497 provides a new method to estimate the group classification based on knowing the

MESG of each flammable gas component and calculating the effective MESG by applying a form of Le Chatelier's relationship. Enardo can assist you with this calculation if provided the gas mixture composition.

Auto-ignition temperature (AIT)

AIT is the temperature at which a stoichiometric mixture of a combustible gas at standard atmospheric pressure will ignite. Propane's AIT is 493°C, Hydrogen's is 560°C, and ethylene's is 425°C. An arrestor works by cooling the gas below its AIT. Therefore, if the process is operating close to the AIT of the gas, this initial heat may affect the performance of the arrestor. It is very important that the process temperature be stated to the manufacturer when selecting an arrestor.

Length to diameter (L over D) ratio

In explaining the various stages of flame propagation earlier, each stage was said to occur within a certain range of distances from the ignition source. Those distances were specified for a certain inside pipe diameter of 12 inches. It turns out that the distances are directly proportional to the diameter. What matters is not the actual distance from the ignition point, but the distance relative to the diameter—the distance divided by the diameter. That relative distance is called the *length-to-diameter ratio*, or the L/D ratio (L over D ratio). For example, for a stoichiometric air-propane mixture at room conditions, a low-pressure deflagration will occur within an L/D ratio less than 10, and a stable detonation will usually occur at L/D ratios greater than 60. All arrestors except the unstable detonation types have L/D performance limitations. Information on these limitations must be obtained from the manufacturer.

Pipe configuration and restrictions

How a flame burns and propagates is affected not only by the length of a pipe, but also by bends, instrumentation (metering runs, restrictive orifices, thermowells, etc.), pipe contractions and expansions, valves, etc. Anything which increases turbulence of the gas gives the flame a more uniform air-to-gas mixture, thus enhancing combustion.

In addition, as mentioned before, transient momentum acts on piping irregularities. Gas expansion caused by burning acts as thrust propulsion when given a surface on which to apply the force of expansion. The flame cannot exert a thrust force on smooth, straight pipe. However, when it travels past a bend or restriction, it can exert a force on this surface area, giving it a forward velocity and pressure boost.

Each arrestor design has been tested to protocols which may or may not include bends and restrictions. The manufacturer should be consulted before installing any arrestor in a system with bends or restrictions.

Ignition source and energy

Accidental gas ignition can be caused by such things as static discharge, sparks from a blower impeller hitting the blower housing, instrumentation, pilot flame for a flare or burner, main flame on the flare tip or in the burner chamber, hot work within a plant, external fire, and many other origins. These ignition sources can cause a flame inside or outside a process system.

The ignition energy is defined as the amount of energy required to ignite a flammable gas mixture. That amount depends on the type of gas and the air-to-gas mixture ratio. The closer the air-to-gas ratio is to stoichiometric, the lower the ignition energy. This is illustrated in Figure 19. In that diagram, note that the energy required to ignite methane at stoichiometric is 0.2 joules, compared to the energy required at its UEL, which is 3.5 joules. Different gases require different amounts of energy to ignite them; some require little, while others are almost impossible to ignite. The lower the ignition energy, the more dangerous the gas is to the system and its surroundings.

The ignition source is the starting point for measuring the most important variable for flame arrestor selection, which is the distance to the arrestor. Therefore the user must know the locations of all potential ignition sources relative to the arrestor.

High-energy ignition

Typical ignition sources have energy levels which are considered to be low, meaning just enough energy to ignite the combustible gas mixture. A *high-energy ignition source*, on the other hand, can cause the flame to be in a more severe state of propagation within a given length or L/D ratio than a low-energy source. The flame can actually skip the low, medium, and high-pressure deflagration states and jump directly into detonation. Such behavior represents an exception to the conventional theory of flame propagation which was outlined earlier here. There are no established standards to differentiate between normal ignition
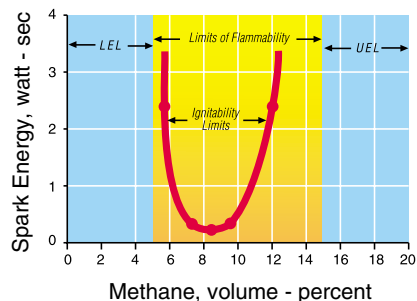
Figure 19.

energy and high-energy ignition. However, lightning strike, vessel explosion, and burner chamber explosion are all considered to be high-energy ignitions.

Since a high-energy ignition changes the way a flame propagates, the rules for selecting a flame arrestor product also change. For example, consider a deflagration flame arrestor in a typical flare application for which it is designed—a 20-foot stack for a group "D" gas with flame arrestor near the base of the flare. If the process stream velocity falls below the burn-back velocity of the gas at the tip, a flashback could occur. Since the length of pipe from the tip of the flare (ignition source) to the arrestor is relatively short, the flame dynamics will probably be no more severe than a medium-pressure deflagration, and thus the deflagration flame arrestor will quench the flame. However, if the flare is struck by lightning (high energy ignition) while the flow is below burn-back velocity, the flame could be in a more severe state when it reaches the flame arrestor, such as high-pressure deflagration or overdriven detonation. In that case, the flame arrestor will probably fail, because it is not designed for a high-pressure deflagration or detonation. If there is a chance for high-energy ignition, an unstable detonation flame arrestor should be used instead of a standard deflagration flame arrestor.

Enriched oxygen

In most vapor control systems, the source of oxygen in the combustible mixture is ambient air. However, some processes have a larger content of oxygen than standard air-gas mixture. Passive flame arrestor products discussed here are not designed for the more dangerous and severe condition of enriched oxygen.

Dust versus gas

When pulverized into dust suspended in air, combustible solids burn, propagate in piping, and explode much like combustible gases. Passive flame arrestor products discussed here are not designed for use with flammable dust suspensions because of special concerns such as plugging.

Selecting end-of-line flame arrestors

As explained before, end-of-line deflagration flame arrestors are designed for unconfined flame propagation, also referred to as atmospheric explosion or unconfined deflagration. They simply bolt or screw onto the process or tank connection. These designs incorporate well-established but simple technology. Most use a single element of crimped wound metal ribbon that provides the heat transfer needed to quench the flame before it gets through the arrestor element.

The main points of concern when selecting an arrestor for end-of-line applications are as follows:

1. Hazardous group designation or MESG value of the gas
2. Flame stabilization performance characteristics of the arrestor compared to the system potential for flame stabilization for sustained periods of time
3. Process gas temperature
4. Pressure drop across the arrestor during venting flow conditions, relative to the system's maximum allowable pressure and vacuum
5. Materials of construction that meet the ambient and process conditions – for example, extremely cold climate, salt spray, chemically aggressive gas, etc.
6. Connection type and size
7. Instrumentation requirements

Selecting in-line flame arrestors

The various dynamic states explained earlier for confined flames can be very dangerous for a process system due to the tremendous energies associated with detonation pressure and flame velocity. Things happen fast and can turn catastrophic. These multiple dynamic states increase the challenge of providing a flame arrestor product or products which stop the flame and withstand the enormous pressures caused by explosions within the confined piping.

The very wide range of possible behavior for a confined flame causes two particular problems for flame arrestor products. First, the high-pressure deflagration and

stable detonation states have very stable kinetics of burning, and the flame is moving very fast. Therefore the arrestor must be able to absorb the flame's heat much faster than is required by standard low-to-medium-pressure deflagration conditions. Second, the instantaneous impulse pressures caused by the shock waves of overdriven detonation subject the arrestor to forces of up to 20995 kPa(g) (3000 psig). Thus, the arrestor must be structurally superior to standard low-pressure deflagration arrestors.

Confined deflagration flame arrestors

In-line deflagration flame arrestors are designed for confined flame propagation, also referred to as flashback or confined deflagrations. Like the end-of-line variety, flame arrestors of this type have been used in numerous applications for many decades. They resemble end-of-line flame arrestors in many ways. However, things are much different for these arrestors,
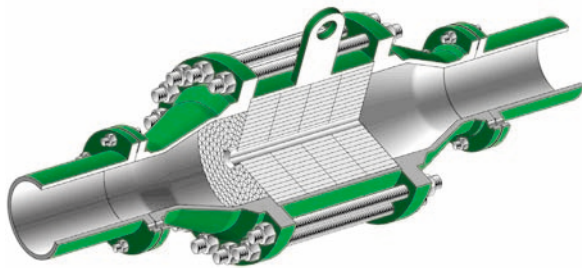

Figure 20. An Enardo detonation flame arrestor

because they are subject to more severe flame states. For almost every state of flame, there is a special type of arrestor. For example, *a standard in-line deflagration flame arrestor* is designed to stop flame propagation in short lengths of pipe, involving low-pressure and medium-pressure deflagrations. The *high-pressure deflagration flame arrestor* is an enhanced version of the standard deflagration flame arrestor, designed to stop flames in the low, medium, and high pressure deflagration states.

Detonation flame arrestors

Enardo has offered a line of detonation flame arrestors since the early 1990's. These detonation arrestors were developed and tested in accordance with the requirements of Appendix-A to Part 154 of 33 CFR, commonly called the "U.S. Coast Guard Standard"(USCG). These arrestors received USCG

approval in 2" through 20" sizes, concentric and eccentric designs, with models for Group-D (IIA) and models for Group-C (IIB3) flammable vapors. Detonation arrestors approved to this standard must pass both stable and unstable detonations in addition to meeting other requirements, in other words, the most severe flame stage. There is no provision in this standard for detonation arrestors that are approved for stable detonations only.

Enardo used the "U.S. Coast Guard Standard" as a guideline, when developing a detonation flame arrestor for the European market. EN 12874 does allow detonation arrestors to be classified for stable detonations only, however, Enardo believes that determining the location where the flame propagation transitions to a stable detonation is unpredictable. During testing in a controlled system all phases of flame propagation can be mapped. But in real life there are many variables,(fuel mixtures, temperature, pressure, pipe layout etc) which may lead to a situation where a galloping detonation may occur.
Our belief is that the state of a detonation is unpredictable and therefore only those DFA's approved for unstable detonations should be specified.

None of the deflagration arrestor designs can withstand a detonation. Therefore the detonation flame arrestor was designed. (See Figure 20.) It has the heat transfer capacity and structural design to withstand all the dynamic conditions of flame propagation and still stop the flame. The detonation flame arrestor is the ultimate flame-stopping product and is used when the flame can be in any of the detonation states.

These capabilities do not come without some trade-offs. Detonation flame arrestors impose higher pressure drops than deflagration flame arrestors due to heat-transfer requirements, they are heavier because of structural requirements, and they are typically more expensive. Therefore in-line deflagration flame arrestors will always have a place in industry.
The main points of concern when selecting an arrestor device for in-line applications are the same as listed before for end-of-line applications, except for one additional consideration: the L/D ratio and piping configuration between the arrestor and the potential ignition source.