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Pennsylvania Technical Advisory Committee
Diesel Powered Equipment

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June 22, 2004

Joseph Sbaffoni, Director
Bureau of Deep Mine Safety
Fayette County Health Center
100 New Salem Road, Room 167
Uniontown, Pa 15402

Re: Flame Arrestor Investigation

Dear Mr. Sbaffoni:

Article II-A of the Pennsylvania Bituminous Coal Mine Act of 1961 provides for the use of diesel-powered equipment in underground bituminous coal mines. Section 224-A created a Technical Advisory Committee for the purpose of advising the Secretary regarding implementation of Article II A.

On March 4, 2004, a “fire” occurred at the RAG Cumberland Resources, LP Cumberland Mine on a 5402 Diesel Mantrip which is fitted with a 100 HP Caterpillar 3304 PCNA diesel Engine and a Dry Systems Technologies Exhaust Conditioning System. This Diesel engine and exhaust conditioning system consists of a heat insulated exhaust manifold, heat insulated exhaust pipes and elbows, a heat insulated oxidation catalyst, a water cooled tube and shell heat exchanger, a disposable DST paper filter, and a crimped ribbon flame arrestor in that order which was recommended for approval by the TAC and approved by the Department.

On March 17, 2004, Cumberland Mine requested that the TAC attend a meeting at the Cumberland Mine together with the BDMS and Dry Systems Technologies representatives as part of their investigation into the “fire” incident. The BDMS and Cumberland Mine officials presented to the group(Attachment 1) the results of their investigation as of that date. Based upon the information presented at that time, the group was in agreement that the diesel units could continue to operate safely in the interim provided that operational corrective actions were taken and that the flame arrestor was tested by the manufacturer to determine if it was defective and a new flame arrestor was installed on the unit. It should be noted that the incident was labeled a “fire” by the

Cumberland Mine due to the fact that a flame was reported by mine personnel as exiting the flame arrestor and burn spots were found on the DST paper filter.

On March 18, 2004, Cumberland Mine distributed to the group, operational corrective actions which were being implemented (Attachment 2).

Since the TAC was conducting an audit of the underground fleet at the Cumberland Mine at the time, we included the "fire" incident in our audit investigation. The purpose of this report is to present to the Department the results of our investigation into the technical aspects of the flame arrestor and its relationship to the "fire" incident. The actual investigation of the "fire" incident, the investigations of the facts surrounding the incident, and any reports required by the Department regarding the fire are under the purview of the Department and are not a part of our investigation and this report.

Technical Investigation of the TAC

During the diesel audit of the Cumberland Mine, the TAC performed emissions testing on the 5402 diesel mantrip- which experienced the "fire"- and also examined the approved exhaust conditioning system and the implementation of the corrective actions proposed by Cumberland on March 18, 2004. The diesel emissions were found to be in compliance with the Act, the corrective actions were well implemented, and the exhaust conditioning system which had a new flame arrestor installed was in compliance with it's approval.

We noticed that there was a 5' exhaust pipe with two significant elbows installed on the outby end of the flame arrestor that was necessary to divert the exhaust flow away from the occupants of the mantrip. Closer examination found this pipe to be "saturated" with an oily film which appeared to be a combination of unspent fuel and hydrocarbon byproducts. It was obvious that the statement that a flame exited the flame arrestor was not quite accurate since the flame arrestor can not be seen directly and evidently the flame exited the end of the exhaust pipe.

We contacted Enardo Manufacturing Company which we believed produced the flame arrestor that was sent out for testing. Enardo sent us literature (Attachment 3) which expanded our limited knowledge of flame arrestors. We also arranged a telephone conference call with Enardo and other members of the investigating group which took place on June 3, 2004. This meeting greatly expanded our knowledge of flame arrestor technology.

On June 7, 2004, we received a report from DST on the flame arrestor which was involved in the "fire" incident (Attachment 4).

Results of our Investigation

The Caterpillar 3304 diesel engine is not a state-of-the-art diesel engine and although it can meet the emission standards of the Act, one must realize that it is common for small quantities of unspent fuel and hydrocarbon byproducts to be deposited both on the dry paper filter and on the components outby the dry paper filter such as the heat exchanger, flame arrestor, and any exhaust piping.

Dry Paper Filter: There have been verified reports by RAG officials of small burn spots on the dry paper filter although this is quite uncommon. The TAC believes this poses no significant hazard since this filter is approved by MSHA as a spark arrestor- which is required by PA Law- and the low oxygen content in the exhaust does not readily support combustion. Under certain conditions, a spark can be deposited on the paper filter and if enough oxygen is present, a burn spot can occur. During our investigation, we checked many used filters at the mines and could find no burn spots on the paper filters.

Flame Arrestor: Our investigation revealed that the crimped ribbon component of the flame arrestor is manufactured by Enardo and they perform final assembly of the flame cell in a DST supplied housing. The flame arrestor approved for use in Pa is required to have .064" triangular openings. We found the flame arrestor installed at the time of the fire had .038" triangular openings, which is not approved although the .038" openings would not reduce safety versus the .064" opening. For Group D hydrocarbon mixtures such as diesel fuel, .064" openings are acceptable. There are no markings on the flame arrestor to denote the size of openings.

The flame arrestor approved for this application is an end-of-line vent to atmosphere type. The preferred arrangement is to have no piping on the outby side of the flame arrestor. The protected side of the flame arrestor is the outby side and preferably there should be no piping and/ or elbows on the protected side of the flame arrestor. Bends in the piping cause the flame to intensify, pressure to build, and velocity to increase exponentially. If a flame is propagated through the flame arrestor, it is greatly intensified by the bends in piping.

The examination of the flame arrestor showed burns/heat discoloration on the outby (protected) side of the flame arrestor. This indicates that a burn/ignition occurred on the protected side and was stabilized on the outby side of the flame arrestor. The flame cell was found to be defective with signs of mechanical damage and openings exceeding the approved specifications. However, there was no burn/heat discoloration on the filter side of the flame arrestor indicating a fire did not start on the inby side of the flame arrestor.

Exhaust Piping Outby the flame arrestor: On all the units we examined with the exhaust piping, unspent fuel and hydrocarbon byproducts were present in the piping. It is not uncommon on these units with the piping to have smoke billow out of the exhaust piping for brief periods of time when the engine is superheated such as in the alternate testing procedure. Our investigation showed this to be due to light duty cycles causing the buildup of unspent fuel and hydrocarbon by-products in the exhaust piping and the resultant smoking of the material in the pipe once the engine is superheated.

SUMMARY AND RECOMMENDATIONS

We concur with the June 7, 2004 report of DST that the flame observed coming out of the exhaust pipe outby the flame arrestor was probably due to the ignition of the unspent fuels and hydrocarbon mixture in the exhaust piping outby the flame arrestor. Since the flame arrestor was found to be defective, it is also a contributing factor to the incident.

Exhaust piping and bends outby the flame arrestor are to be avoided which in the case of the configuration of this system is not possible without exposing workers to the exhaust stream. To move the flame arrestor to the outby end of the exhaust piping would only worsen the situation since an end of line flame arrestor could not be used in that application and a detonation type flame arrestor would be required.

The TAC recommends that exhaust piping should not be installed outby an end of line flame arrestor if its length either exceeds 18" or contains more than one elbow which shall not exceed 45 degrees. In order to prevent a reoccurrence of this incident, we recommend the following for all systems **where exhaust piping exceeding the above specifications is required to be installed outby an end-of-line flame arrestor:**

. An additional temperature sensor must be installed as close as possible to the outby side of the flame cell that will shut the engine down at a maximum temperature of 350 degrees Fahrenheit. Since diesel auto ignition temperature is 450-500 degrees Fahrenheit, this will prevent any ignition of the material in the exhaust pipe should the heat exchanger fail or temperatures increase due to the exhaust pipe configuration.

. The exhaust piping must be cleaned as part of the 100 hr maintenance procedure and more often if excessive smoking of the material in the exhaust pipe is experienced.

. The flame arrestor should be cleaned in a solvent or soapy water and rinse. High pressure detergent wash or corrosive cleaners are not recommended.

. All flame arrestors on all equipment must be checked at least every 500 hours for signs of failure and a pin gauge, of the approved size of the triangular openings, must be used to check random openings, generally near the edges of the arrestor, for openings that visually appear inconsistent with the others. Any separations of the flame cell from its housings or any openings exceeding its approved size will require the flame arrestor to be replaced.

. Unless approved otherwise, all flame arrestors must be as approved with .064" triangular openings. We recommend all flame arrestors must be permanently marked with the opening size of the triangular openings.

. If a "fire" or flame should be observed, the equipment should be shut down and the canister for the dry paper filter should not be opened until the equipment has cooled down. Opening of the canister will introduce oxygen to the paper filter which may ignite if not allowed to cool. This should be included in the annual training program at the Mine.

. If substantial burning of the paper filter is observed or flames are observed exiting the flame arrestor or piping on any diesel unit, the TAC and BDMS should be immediately contacted and the equipment idled until an investigation can take place.

Robert Du Breucq, TAC.

Gene Davis, TAC

[illegible]7-04 Diesel Filter First Meeting

JOE MAZUR	RAG CUMB.
BOB DUBREUCQ	TJR
Gene Davis	TAC
A.J. PACIGA	D.E.P.
Alan L. Martin	DEP-BDMS
JOSEPH A. SBAFFONI	DEP-BDMS
Randy Bedilion	UMWA 2300 mechanic
Tim Hroblak	UMWA LU.2300 Safety Comm.
Chris Rhoades	Brookville Equipment Corp.
RON RUSSO	RAG Emerald
JOHN GALLICK	RAG Emerald
Chuck Burggraf	RACH
Harry Kitz	Brookville Equipment Corp
Larry Conrad	Brookville Equipment Corp
GRANT COLBERT	CUMBERLAND
PAUL S. KERUSKIN	DMS
LOU KODAVICH	MAINTENANCE MGR CUMBERLAND MINE
BOB BOHACH	MANAGER OF SAFETY CUMBERLAND
SAM Cario	G.M. Cumberland
TERRY MC DONALD	DRY Systems Technologies
Ron Eberhart	Dry Systems Technologies

ATTACHMENT 1

Memorandum

RAG CUMBERLAND RESOURCES, LP

TO: Distribution

FROM: Bob Bohach

DATE: March 18, 2004

SUBJECT: **5402 Diesel Mantrip Corrective Actions**

The following are a list of maintenance and operational issues that were addressed as a result of the fire that occurred on 5402 diesel mantrip on March 4, 2004. A final investigative report will be forthcoming.

Maintenance inspection and testing as of 3/18/04:

Inspected machine after fire.
Added coolant (5gallons).
Replaced thermostat
Found leak on coolant system and repaired.
Replaced two broken breeze bands on coolant hose
Added 5 more gallons of coolant
Tested exhaust gases
Replaced exhaust filter
Tested exhaust temperature probe for machine shut down
Removed flame arrestor from machine and sent out for OEM testing
 And will replace with new.
In the process of cleaning heat exchanger
Checked manual brake releases on all diesel mantrips and jitneys

Operational corrective actions:

Re-enforced the importance of preoperational checks
Re-enforced the importance of not allowing equipment idle unnecessarily.
Re-enforced policy of not leaving equipment unattended.
Established policy of routinely changing motors out from section tail tracks.
Re-instructed work force on proper procedures for releasing park brakes.
Reviewed incident with all employees.

ATTACHMENT 2

ATTACHMENT 3

ENARDO

TECHNICAL BULLETIN

Flame Arrestor Technology

Michael Wittman, Senior Applications Engineer • Enardo International, Ltd. • Tulsa, Oklahoma

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.

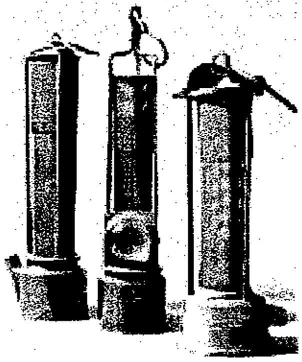

Figure 1. The earliest flame arrestors: Davy safety lamps for coal miners

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 in-side 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 International employ layers of metal ribbons with crimped corrugations as shown in Figure 2.

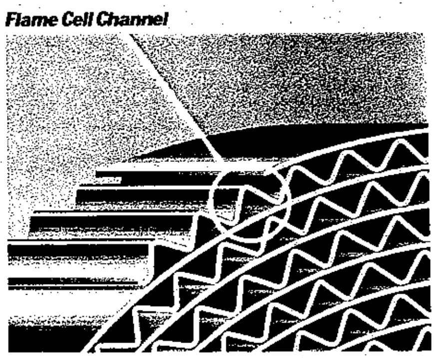

Figure 2. Concept of flame arrestor element used in Enardo products, featuring a crimped wound metal ribbon element

Flame arrestors are used in many industries, primarily 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).

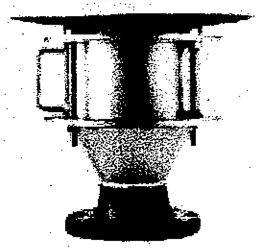

Figure 3. End-of-line flame arrestors are used in applications such as petroleum storage tank vents.

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 vapors flowing from the vents are struck by lightning (Figure 4).

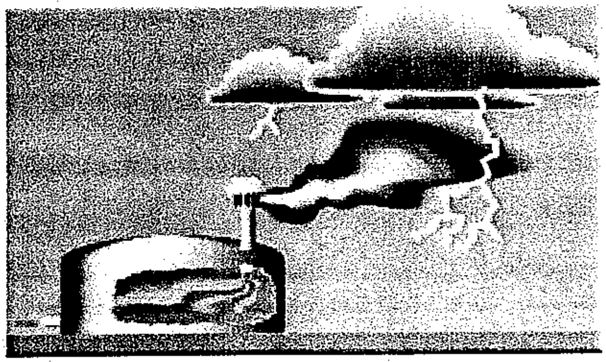

Figure 4. Oilfield storage tank vents were an early application of industrial flame arrestors

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 nontechnically, deflagration means rapid burning, and detonation means explosion.) These units are installed in pipes to prevent flames from passing, as shown in Figure 5.

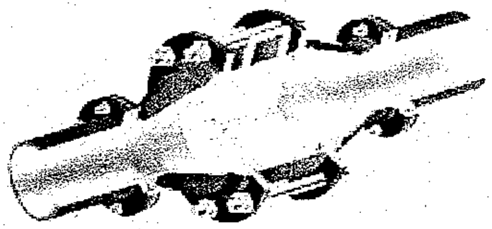

Figure 5. A typical Enardo in-line flame arrestor

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.

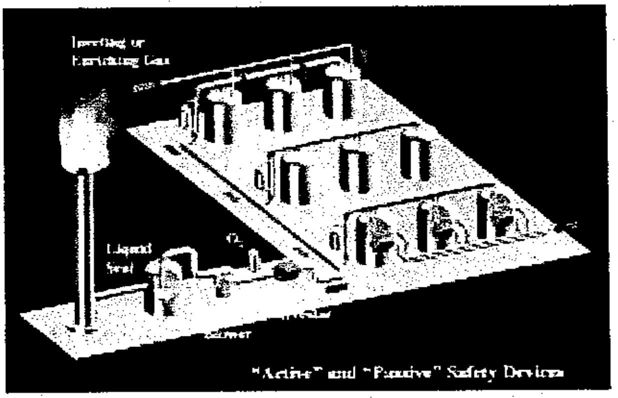

Figure 6. An in-line flame arrestor in a flare system

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.

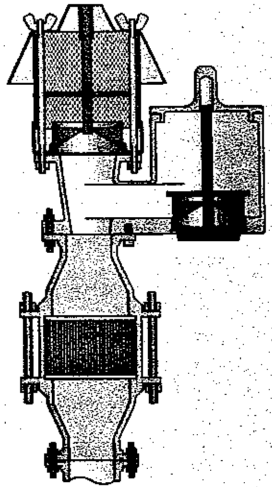

Figure 7. An in-line flame arrestor used in an end-of-line application (below a pressure and vacuum relief valve for a liquid storage tank)

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 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, so 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.

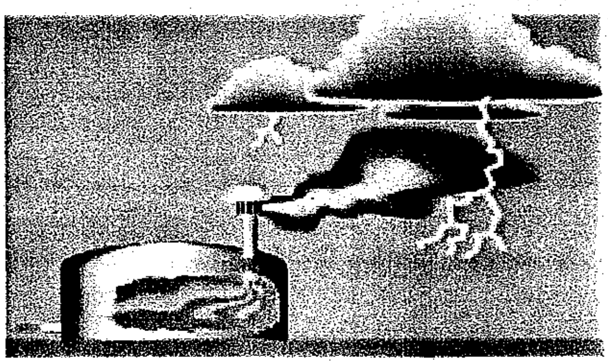

Figure 8. Concept of an unconfined deflagration

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 up-stream, against the flow of gas and towards its source. The heat and pressure energy of a confined flame is not relieved so 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 everwidening 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.

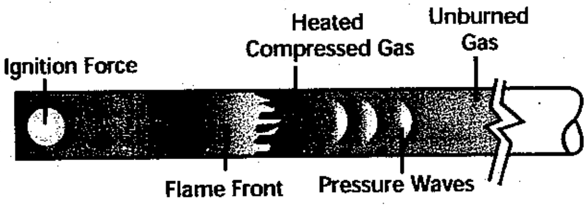

Figure 9. Elements of flame propagation from the closed end of a pipe of indefinite length

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 gauge, the reading increases. When the flame reaches the gauge, it causes a pressure spike as high as 100 psig 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 six

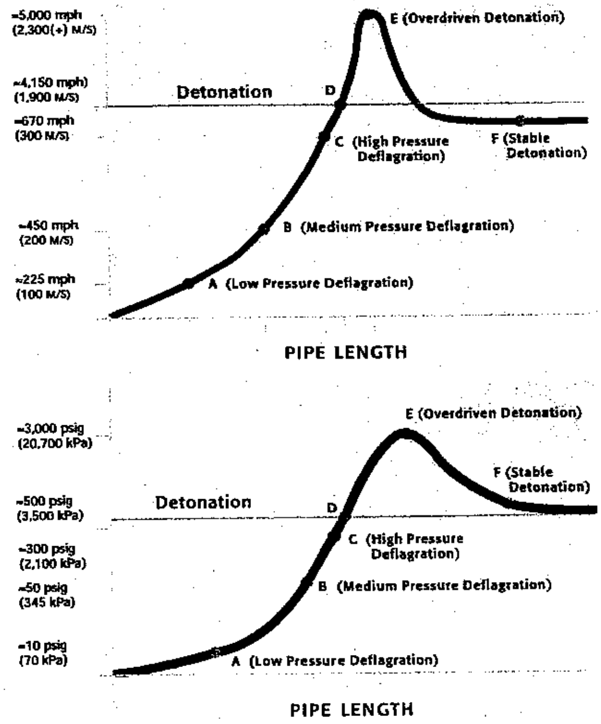

Figure 10. Conceptual graphs showing velocity and pressure of a flame front at points along a long pipe, beginning with ignition at a closed end. All scales are logarithmic.

distinct stages or phases which a flame may reach if the pipe is long enough and the combustion is fast enough and energetic enough.

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.

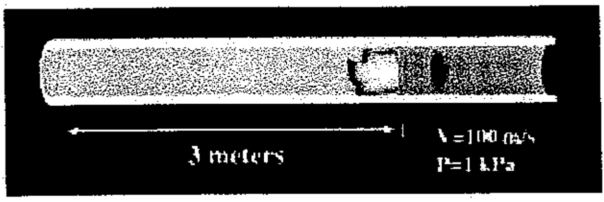

Figure 11. Concept of low-pressure deflagration confined in a pipe, showing typical distance from ignition point

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/Po) 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 0.5 meter from the point of ignition.

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

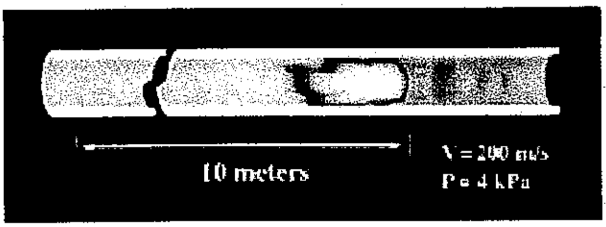

Figure 12. Concept of medium-pressure deflagration confined in a pipe, showing typical distance from ignition point

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/Po 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 0.5 and 2 meters from ignition.

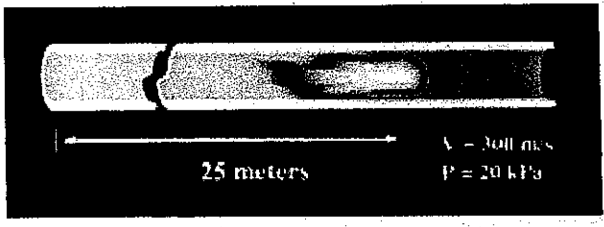

Figure 13. Concept of high-pressure deflagration confined in a pipe, showing typical distance from ignition point

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/DPo as high as 20. The distance from the ignition point is between 20 and 30 meters for a propane/air mixture and between 2 and 6 meters for hydrogen and air.

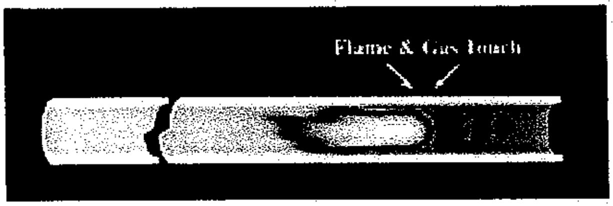

Figure 14. Concept of deflagration-to-detonation transformation in a pipe

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 shockwave compression of the gases both upstream and downstream of the initial point of transformation.

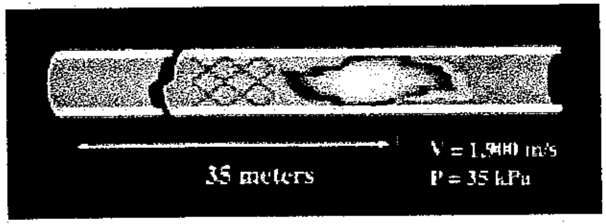

Figure 15. Concept of detonation confined in a pipe, showing typical distance from ignition point

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 270 m/s and a maximum impulse pressure of 3,500 kPa(g), with DP/Po 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 (10 meters for hydrogen in air).

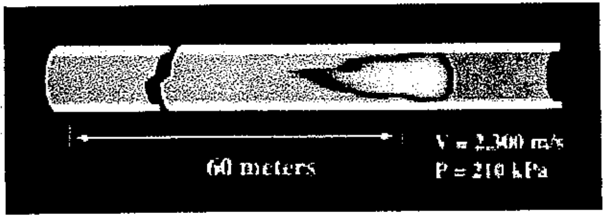

Figure 16.Concept of overdriven detonation confined in a pipe, showing typical distance from ignition point

Overdriven detonation

As the flame propagates even farther down the pipe, it goes into the dynamic state of *overdriven 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 selfignites, 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/Po 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 (from DDT to 20 meters for hydrogen and air).

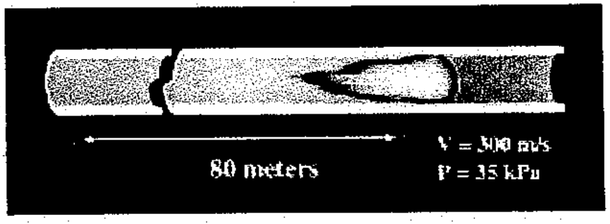

Figure 17.Concept of stable detonation confined in a pipe, showing typical distance from ignition point

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/Po of 20.

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 low-pressure deflagration. This refers to the "superficial" average gas velocity across the pipe – the volumetric flow rate divided by the cross-sectional 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, while that for detonation flame arrestors ranges up to 160 kPa.

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, shutoff 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. 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.

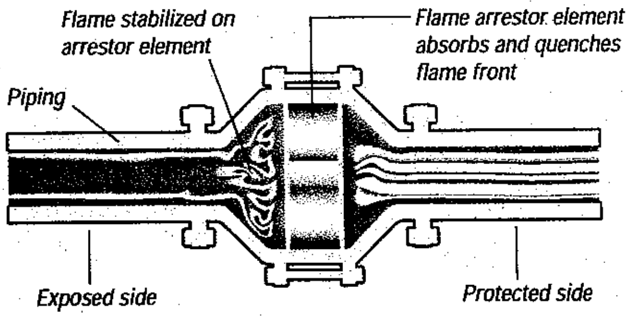

Figure 18. Concept of flame stabilization at a flame arrestor. Flow is from right to left.

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

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.)

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

Table 1. Hazardous gas groups according to NEC and IEC

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.

When selecting an arrestor device for multiple gases in a process, the industry standard is to choose the arrestor design which matches the most severe gas constituent – the one with the lowest MESG value. The flame arrestor manufacturer must always be provided with the gas composition when requested to recommend an arrestor for a given application.

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 occur at L/D ratios greater than 60. All arrestors except the 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.

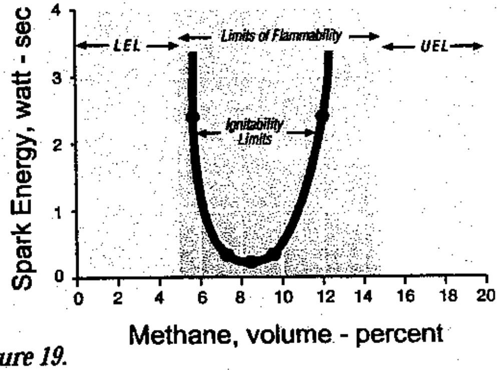

Figure 19.

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 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, a 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 34,000 kPa(g). 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, 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.

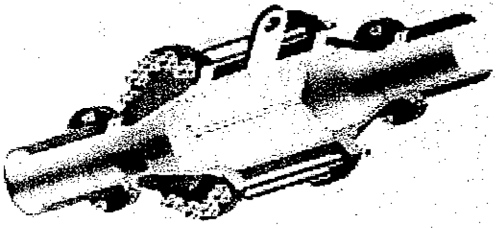

Figure 20. An Enardo detonation flame arrestor

Detonation flame arrestors

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 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.

ATTACHMENT 4

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7 June 2004

Flame Arrestor Inspection Report Cumberland Mine Mantrip #5402

As a part of the investigation of the fire incident on a Brookville 9-ton Diesel Mantrip # 5402 that occurred at the Cumberland Mine on March 4, 2004, a request was made to Dry Systems Technologies to determine what role the flame arrestor may have played in the incident. The actual incident and what led up to it is based on statements by various people that had either seen the incident or investigated it. The information is not always consistent, but the focus of our investigation is to determine if there was a failure of the crimped ribbon exhaust flame arrestor.

The background information on the system arrangement in this paragraph is provided for reference. The 9-ton Diesel Mantrip is fitted with a 100 Hp Caterpillar 3304 PCNA Diesel Engine and a Dry Systems Technologies Exhaust Conditioning System. The diesel engine is approved by MSHA under 30 CFR, Part 7E-B for use in Outby areas of coal mines. The Dry Systems Technologies exhaust conditioning system consists of a heat insulated exhaust manifold, heat insulated exhaust pipes and elbows, a heat insulated oxidation catalyst, a water-cooled tube-and-shell heat exchanger, a disposable filter and a crimped ribbon flame arrestor arranged in that order. This component arrangement is used on all Dry Systems Technologies fitted diesel equipment operating in Pennsylvania coal mines and meets all requirements stated in the State Regulations. After delivery of the machine, the Mantrip was fitted with a pipe of about six (6) feet in length and two 90° turns to divert the exhaust gases away from the personnel riding on the Mantrip. This pipe was added to the outlet of the flame arrestor.

The crimped ribbon exhaust flame arrestor that is commonly used in mining and other industries for methane/air mixtures is a Class D flame cell. A Class D flame cell that is made from 0.006" – 0.008" thick and 4.00" wide crimped and uncrimped stainless steel ribbons that are wrapped around a center arbor. They form triangular openings through which a 0.064" diameter pin gage can not pass. This flame cell is then inserted tightly into a housing made from a retaining pipe and two retaining flanges that are permanently welded together.

The flame arrestor functions as a heat sink that will stop a methane/air based ignition from escaping out of the exhaust system. A flame will not propagate through a flame arrestor as long as the cell temperature and the operating conditions are within the design limits. Under a failure condition, significant discoloration and burning of the housing would be noticed; neither of these conditions was observed. Because a crimped ribbon flame arrestor has no movable part or wear components, it can be expected to remain functional as long as it is installed and maintained. To detect damage, typically from external sources, a periodic visual inspection is performed.

There has been significant testing and years of use that provided the industry standard which the manufacturers and regulators of flame arrestors have adapted. The flame arrestor that was in use at the time of this incident was sent to Dry Systems Technologies for inspection. It was a Class C flame arrestor with 0.038" opening. All flame arrestors used by Dry Systems Technologies are manufactured exclusively by Enardo, a leading manufacturer of flame arrestors for all industries.

The flame cell was inspected with a 0.038" pin gage and there were several areas where a 0.038" pin passed through openings. The flame cell also failed our visual inspection. The triangular openings did not appear consistent in size and shape. There were signs of mechanical damage (distortion) and discoloration visible on the downstream (outlet) side of the flame arrestor. Separation between the housing and the flame cell was noticed on the upstream (filter) side of the flame arrestor. There was soot deposit on the face of the upstream (filter) side of the flame arrestor, while the downstream (outlet) side appeared clean, but discolored from heat. Enardo was consulted concerning the physical condition of this unit.

This raises the question if there was indeed a flame present upstream (on the filter side) of the flame arrestor. Although the flame arrestor was found to have some mechanical damage, the probability that the flame arrestor failed and caused the fire is highly unlikely. A possible scenario would be that the oil/fuel deposits downstream of the flame arrestor may have ignited. Deposits may have been inside the additional pipe downstream to the exhaust end of the flame arrestor. We recommend that a periodic inspection and/or cleaning of the pipe be added to the maintenance schedule to minimize the risk of a similar incident.

If you have any further questions or need additional information, please feel free to contact me.

Sincerely

Norbert Paas
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