FLAME PROPAGATION RESEARCH IDENTIFIES VAPOUR HANDLING HAZARDS

Abstract

Flame propagation research has identified hazards in vapour handling systems. Flame propagation is adversely affected in vapour handling piping by variables such as vapour pressure, gas type, length of pipe, pipe fittings, larger line sizes, protected side restrictions and additional vapour volume containers. Flame suppression equipment (Flame arresters being the product of choice) is used to isolate the explosion hazards. Flame arresters are classified according to tests conducted in laboratory equipment without the field piping variables. Research proves these variables accelerate flame propagation beyond the tests used to establish the classification resulting in test standards worldwide not being able to guarantee safe vapour handling systems.

Additional hazards are created by the inconsistency of classification methods. There are several standards organisations that specify classifications and test conditions for flame arresters. These test methods and application parameters are not consistent. A flame arrester may pass one standard and fail another.

Understanding the piping conditions that create hazardous situations requires general knowledge of flame propagation confined in piping, the types of flame fronts and the classification applied to suppression equipment.

Each hazard is outlined and supported with research documentation. A "Field Appraisal" can identify adverse conditions in a vapour handling system and suggest a safe alternative.

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FLAME PROPAGATION RESEARCH
IDENTIFIES
VAPOUR HANDLING HAZARDS

Introduction

AN ENGINEERING AND USER VIEW OF RESEARCH ON EXPLOSION ISOLATION IN VAPOUR HANDLING SYSTEMS

When combustible vapours are recovered and/or transported, plant safety, environmental concerns, corporate explosion isolation policy and best engineering practice are applied. How can compliance with safety and equipment performance be evaluated? Corporate explosion isolation points set the parameters for application of flame suppression equipment. Since flame arresters are the products of choice, the reference will apply to them. Flame arrester performance can be evaluated when the difference between performance testing and field application is understood.

Three facts control flame arrester safety and isolation capability:

Fact 1: Standards organization set - flame arrester performance testing criteria in straight run test pipe

Fact 2: Field pipe configuration set – flame arrester performance demands using piping hazards

Fact 3: Flame front propagating strength is:
- set by field piping
- challenged by laboratory straight test pipe quenching capability

The field piping and straight run test piping are not the same!

Flame fronts propagate in a most aggressive manner aided by the pipe configuration available. Aggressive flame propagation can be a hazard to flame arrester performance. Listed are variables that enhance flame propagation and challenge flame arrester performance. Methods of identifying arrester performance hazards and removing them are offered.

FLAME ARRESTER RESEARCH
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A. FLAME FRONT PROPAGATION AND INDUSTRY CLASSIFICATION

1. Definitions

Deflagration:

- A flame front propagating at subsonic velocity.
- Overpressures can reach up to 20 times the initial absolute operating pressure. In vapour handling systems, this overpressure could reach values above 2,067 kPa (300 psig).

Example: The gauge operating pressure of the system is 14 kPa (2 psig). Therefore the absolute operating pressure is 115 kPa (16.7 psia). 115 kPa (16.7 psia) x 20 = 2,300 kPa (334 psia). The measured explosion pressure is 2,200 kPa (320 psig).

Overdriven Detonation (unstable):

- A flame front that propagates by shock wave ignition.
- The condition exists during the transition phase from a deflagration to a stable detonation characterized by very high pressures in a short time frame.
- Flame speeds are supersonic, measured at over Mach 5.2 (2,500 m/s) (8,200 f/s).
- The overpressures can be far in excess of 100 times the initial absolute operating pressure. Example: In a system with 35 kPa (5 psig) operating pressure, the overdriven pressure was measured at 30,000 kPa (4,300 psig), which is about 860 times the initial operating pressure or 218 times the absolute operating pressure.

Stable Detonation:

- A flame front propagating by shock wave compression ignition
- Flame speeds are at sonic velocity
- The overpressure ranges from 20 to 25 times the initial absolute operating pressure. Example: Operating pressure operating in gauge at 14 kPa (2 psig). Therefore the absolute operating pressure is 115 kPa (16.7 psia).
  115 kPa (16.7 psia) x 25 = 2,875 kPa (417 psia)
  The measured explosion pressure is 2,774 kPa (403 psig).

TYPICAL INDUSTRY APPLICATIONS EXPLOSION PRESSURES			
Flame Front	**Speed**	**Gauge Pressure**	**Absolute Pressure**
Deflagration	Up to 1,800 m/s (5,900 f/s)	Up to 2,070 kPa (300 psig)	2,170 kPa (315 psia)
Overdriven	Variable, up to 2,500 m/s (8,200 f/s)	Variable, up to 29,650 kPa (4,300 psig)	Variable, up to 29,750 kPa (4,315 psia)
Stable	Typically 1,900 m/s (6,200 f/s)	Typically 2,500 kPa (360 psig)	Typically 2,585 kPa (375 psia)

2. Flame Arresters

Flame arresters protect storage, distribution and chemical processing facilities containing flammable gases from fire and explosions. When correctly applied, flame arresters are effective devices that isolate sources of ignition and allow vapour to flow freely in venting and collection systems. Flame arresters have different capabilities and designs. The equipment is classified by its ability to stop a stationary or travelling flame confined in a pipe. Flame arresters are tested and categorised by test standard organisations as one of the following:

- End-of-Line Flame Arrester
- In-Line Deflagration Flame Arrester
- In-Line Detonation Flame Arrester (Stable and Overdriven)

Awareness of the piping effects and application of the basic flame arrestment technology will identify areas of explosion protection that may require change to obtain a safe vapour handling system.

3. Flame Front Technology as Applied to Piping Systems

An unconfined atmospheric ignition of a gallon of gasoline on the ground produces a startling flame, strong pressure waves and a loud sound. When this same rapidly expanding combusted vapour is confined in a pipe, the flame front and pressure wave start travelling in the direction of the unburned gas. The combusted vapour expands to nine times its original volume, causing a jet effect and driving the deflagration to higher speeds and pressures. The flame front transitions through an explosion, from deflagration to overdriven detonation reaching the peak pressure and speed. It then stabilizes and continues to travel through the piping system as a stable detonation.

Thus, a small, low energy ignition can be transformed within a very short distance and in fractions of a second into an enormous destructive force.

All confined explosions can be plotted comparing pressure of the flame with the distance travelled. Every flame front that is not quenched will follow this flame profile with variations only to height and length, depending on several variables. Refer to the graphs in Figures 1 and 2 showing run up distance and flame profile curve.

Deflagration

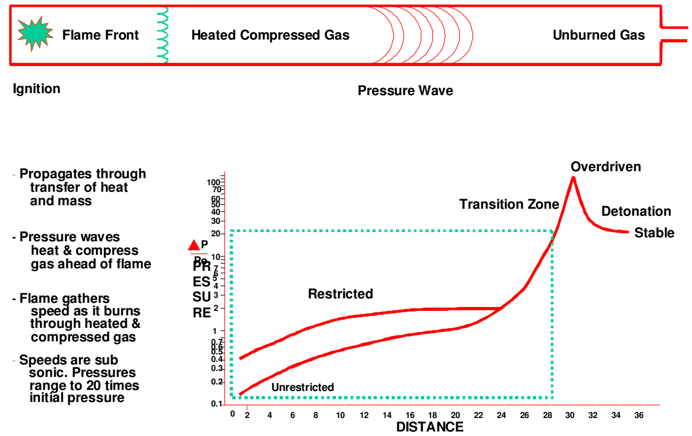


Figure 1

Stable & Overdriven Detonations

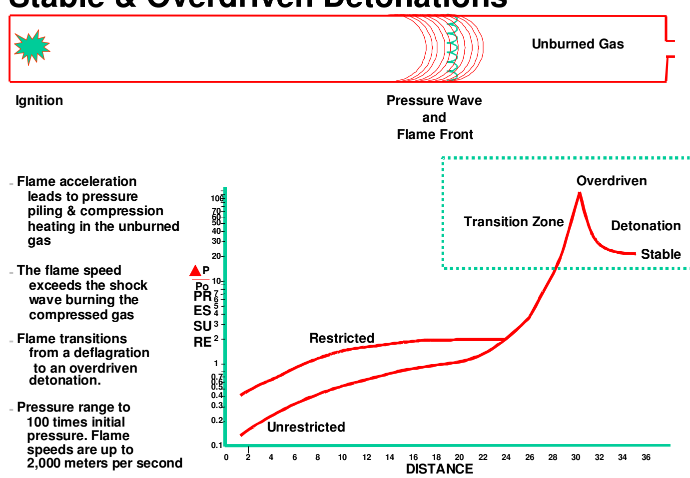


Figure 2

4. Standards Organizations and Flame Arrester Standards

In the last 15 years, the areas of vapour emission control, flame propagation knowledge and flame arrester technology have gone through massive change. Industry and government safety departments have asked standards-writing organizations working in the field of fire safety to establish standards with qualifying parameters to classify flame arresters. A number of organizations have been involved.

BSI: British Standards Institute
CEN: European Committee for Standardization
CSA: Canadian Standards Association
FM: Factory Mutual
IMO: International Maritime Organization
PTB: Physikalisch-Technische Bundesanstalt (German Technical Institute)
UL: Underwriters Laboratory
USCG: United States Coast Guard

Individually these organizations have set guidelines on how flame arresters are to be tested. They are not in agreement with each other. Test parameters, test repeatability, and differences in test facilities are a problem for industry, standards organizations and manufacturers. (See Reference 1: Standards Development and Flame Propagation, a partial listing of technical and research papers describing areas of difficulty in determining flame arrester testing procedure and criteria.)

- Environmental regulations are changing how industry handles emissions. Free venting of vapour is restricted. For example, Canadian oil producers were required to collect and destroy H_2S (sour gas) vapours at production sites and batteries. In the United States, the Environmental Protection Agency (EPA) introduced the Clean Air Act in the 1980s and major changes in operating procedures became necessary.
- Applications are different. The required tests are different. The explosion and fire protection for a process application is different from that of a vent application on gasoline storage tanks, requiring different tests.
- Some standards writers have under estimated flame propagation phenomena and their standards do not address new flame front technology developed through research. As a result, current flame front technology and its effects are not utilized by all standards.
- Manufacturers lobby for standards in their favour. New regulations mean product redesign, stricter requirements and potential loss of market share.
- The industry has concerns that new standards may change their processes. They are uncertain as to the magnitude, reasons and cost for such changes.
- Test standards, flame arrester manufacturers and field installations have an incorrect match of the explosion protection equipment to flame front propagation phenomena.

STANDARDS COMPARISON CHARTS

Note: Only major test parameters are listed.

End-of-Line and In-line Deflagration Arresters:

Standard	Test Rig	Test Gas	Deflagrations	Test Pressure	Endurance Burn Test
End-of-Line Deflagration Arrester					
USCG	Tank and plastic bag	Propane or Specific Gas	3	Atmospheric	Yes
BSI	Tank and plastic bag	Propane, Ethylene, Hydrogen	9	Atmospheric	Yes, if specified
UL 525	Pipe, at least 1.5 m long	Propane	10 at various gas concentrations	As specified	Yes, plus continuous burn
IMO	Tank and plastic bag	Propane	3	Atmospheric	Yes
CSA	NO TEST				
FM	1.2 m vertical pipe	Propane or specific gas	0	Atmospheric	Yes
CEN	Tank	Propane, Ethylene, Hydrogen	3	Atmospheric	Yes, if required
PTB	NO INFORMATION AVAILABLE				
In-line Deflagration Arrester					
USCG	Tank, including all piping & fittings	Propane or specific gas	3	Atmospheric	Yes
BSI	Straight pipe for flame quench.	Propane, Ethylene, Hydrogen	15	Atmospheric	Yes, if specified
UL 525	NO TEST				
IMO	NO TEST				
CSA	NO TEST				
FM	NO TEST				
CEN	Straight pipe, closed, <50 L/D, at least 3 m	Propane, Ethylene, Hydrogen	6	As specified	Yes, if required
PTB	NO INFORMATION AVAILABLE				

In-line Detonation Arresters:

Standard	Test Pipe	Test Gas	Stable Detonation	Overdriven Detonation	Deflagrations	Test Pressure	Endurance Burn Test
In-line Detonation Flame Arrester							
USCG	Straight pipe for stable det.	Propane Ethylene or specific gas	5 unrestr.	5 unrestr.	10 unrestr. 10 restr.	As specified	Yes
BSI	Straight pipe for stable det.	Propane Ethylene Hydrogen	0 unrestr.	11 unrestr.	3 unrestr.	Atmospheric	Yes, if required
UL 525	Straight pipe for stable det.	Propane Ethylene	5 unrestr.	5 unrestr.	10 unrestr. 10 restr.	As specified	Yes
IMO	Straight pipe for stable det.	Propane	3 unrestr.	0	0	Atmospheric	No
CSA	Straight pipe for stable det.	Propane Ethylene	5 restr.	5 restr.	15 restr.	As specified	Yes
FM	Straight pipe for stable det.	Propane Ethylene or specific gas	5 unrestr.	5 unrestr.	10 restr. 10 unrestr.	As specified	Yes
CEN	Straight pipe, closed for stable det.	Propane Ethylene Hydrogen	3 closed	0 closed	0 closed	As specified for stable and unstable detonations	Yes, if required
PTB	Straight pipe, closed for stable det.	Propane Ethylene Hydrogen	3 closed	0	0	As specified	No

5. Classifications of Flame Arresters and Their Specifications

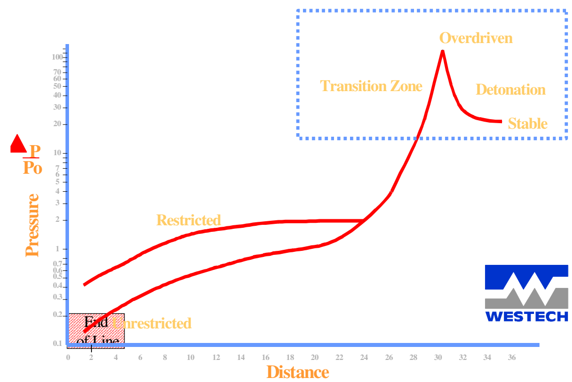
Three application classifications of arresters in North America are: End-of-Line Flame Arresters, In-Line Deflagration Arresters and In-Line Detonation Arresters. The certified flame arrester product is designed to meet one or all of the three specific classifications.

a. End-of-Line Flame Arrester

An End-of-Line Flame Arrester is designed to prevent flame transmission from an open-air ignition source located close to the vent side of the arrester. It is not designed to arrest flames and maintain structural integrity when subjected to travelling flame fronts and detonations in closed piping systems.

Application Parameters:

An end-of-line arrester prevents unconfined (open air) ignitions from entering a vessel or vapour handling system. It is typically located on top of storage tanks, vessels or lines venting vapour directly to the atmosphere. The maximum length of pipe separating an end-of-line arrester from the external ignition source is 1.5 m (5 feet) unless specifically tested at further lengths. End-of-line arresters operate at atmospheric pressure.



Acceptance Standards Test Rigs (End-of-Line):

The test rigs used by the standards organizations for approval testing of End- of-Line arresters are not consistent. An example of a test rig used by the USCG, BSI, IMO and CEN, is a tank and plastic bag configuration. (Figure 3)

UL 525 (Edition No. 6) uses two test rigs, one of which has a straight pipe configuration of 1.5 m (60 inches) long in a horizontal position. (Figure 4a and 4b)

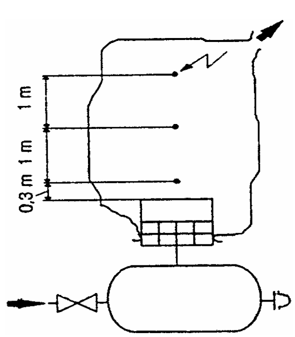


Figure 3

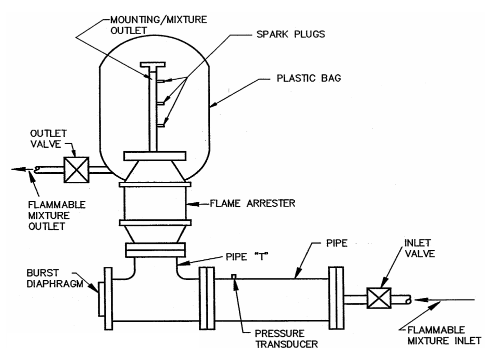


Figure 4a

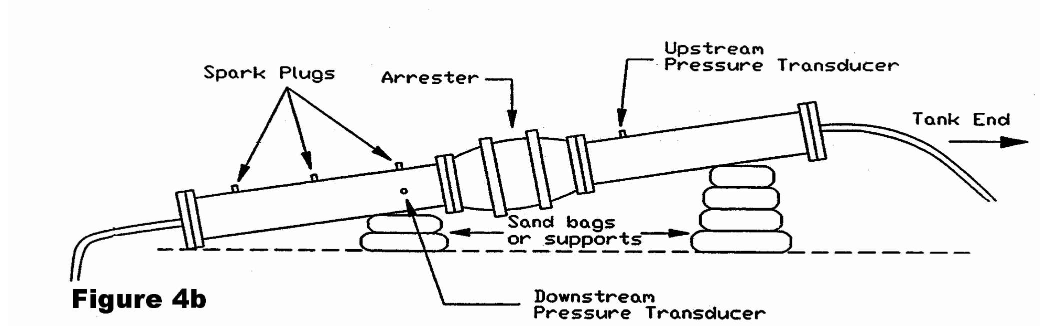


Figure 4b

The test rig used by FM is a straight pipe configuration of 1.2 m (48 inches) long in a vertical position. (Figure 5) The procedure used is a burn test with no deflagration explosions.

Capability Specifications Published by the Standards Organizations (End-of-Line arrester):

The typical statement of the flame arrester standards organization is "No passage of flame or spark through the arrester." No guarantee or guidance is provided by the standards organization when used in applications varying from that of the test rig.

Manufacturer's Specification (End-of-Line arrester):

The manufacturer specifies the following about its product: 1) the standards organization that has performed the tests, 2) the deflagration arrestment capability, 3). the gas type, 4) the distance of allowable straight pipe and 5) a liability limit statement. Seldom is the deflagration arrestment capability distinguished between End-of-Line and In-line arresters.

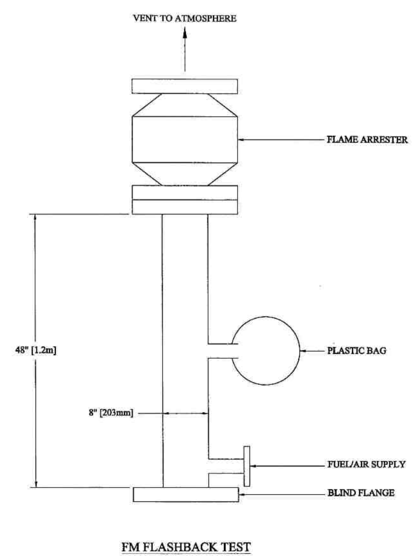


Figure 5

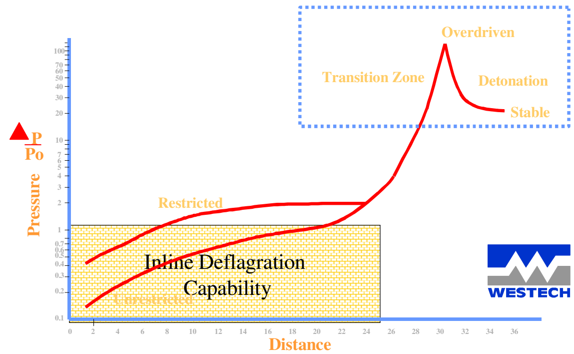
The end user's engineer must evaluate the field application with its many variations and determine the appropriate flame arrester category. Then he makes a product selection.

b. In-Line Deflagration Flame Arrester

An In-Line Deflagration Flame Arrester is designed to quench an in-line deflagration flame front with a short, unrestricted run up distance to any of the following standards: 1.5 m (5 ft.) to <50 L/D or actual straight length of test rig. It is not designed to arrest flames and maintain structural integrity when subjected to high speed travelling flame fronts and detonations in closed piping systems.

Application Parameters:

An In-Line Deflagration Flame Arrester is used to quench flames generated inside a pipe close to the arrester. It is positioned close to the ignition source, isolating the flame from the process. These arresters are suited for straight pipe connections unless specifically tested with fittings. There are great differences between the arrestment capabilities of an in-line deflagration arrester and an end-of-line arrester.



Test Rigs Specified by Standards (In-Line Deflagration Arrester):

An example of a USCG and IMO test rig: A tank and plastic bag configuration with all applicable connected piping. (Figure 6)

BSI uses a test rig with a straight pipe at least 1.5 M (60 inches) long or at arrester capability limit. (Figure 7)

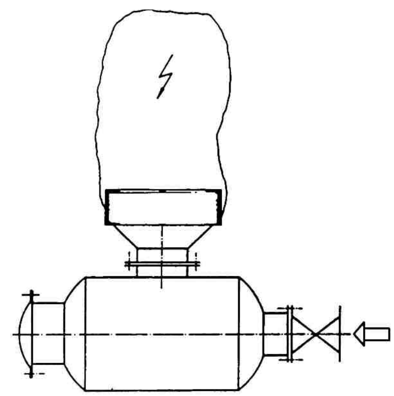
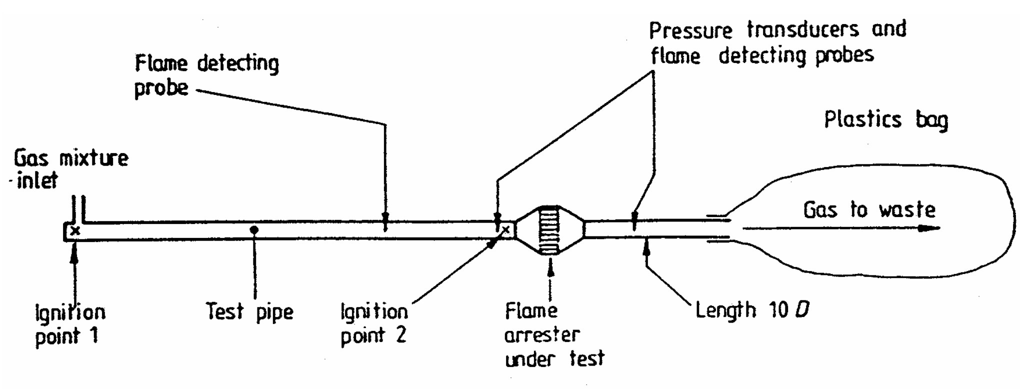


Figure 6



D is the pipe diameter.

Figure 7

Capability Specifications Published by the Standards Organizations (In-Line Deflagration Arrester):

The typical statement of the flame arrester standards organization is "No passage of flame or spark through the arrester." No guarantee or guidance is provided by the standards organization when used in applications varying from that of the test rig.

Manufacturer' s Specification (In-Line Deflagration Arrester):

The manufacturer specifies the following about his product: 1. the standards organization that has performed the tests, 2. deflagration arrestment capability, 3. the gas type, 4. the distance of allowable straight pipe and 5. a liability limit statement.

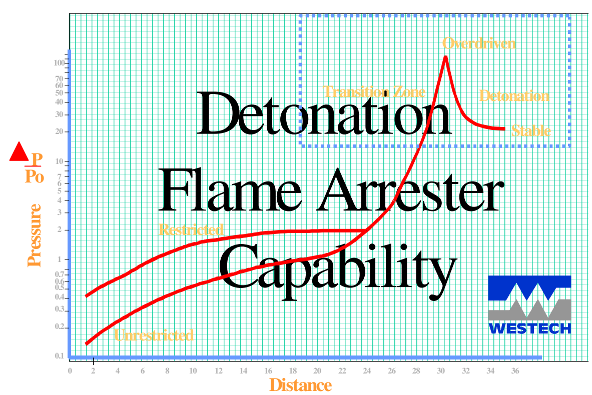
The end user's engineer must evaluate the field application with its many variations and determine the appropriate flame arrester category, and then make a product selection.

c. In-Line Detonation Arrester

The in-line detonation flame arrester is designed and tested to stop travelling flame fronts under the conditions of low, medium and high pressure deflagration, overdriven and stable detonations, and stabilized (long term) burning on the arrester element. It can be installed anywhere in the piping system, regardless of distance from the source of ignition and the configuration of the same size piping system. (There are some limitations that are described later.)

Application Parameters:

In-line detonation flame arresters are suitable for installation at any distance from the ignition source and are unaffected by elbows, bends, pipe fittings and protected-side restrictions. They are suited for elevated operating line pressures and various types of gases as accepted by test agency. These arresters are to be installed in piping equal to or less than the piping diameter used in testing.



Test Rigs Specified by Standards (Detonation):

USCG, BSI, UL 525 (6th edition), IMO, CSA, FM and CEN all use test rigs with a straight pipe capable of generating deflagrations, stable and unstable detonations. (Figure 8)

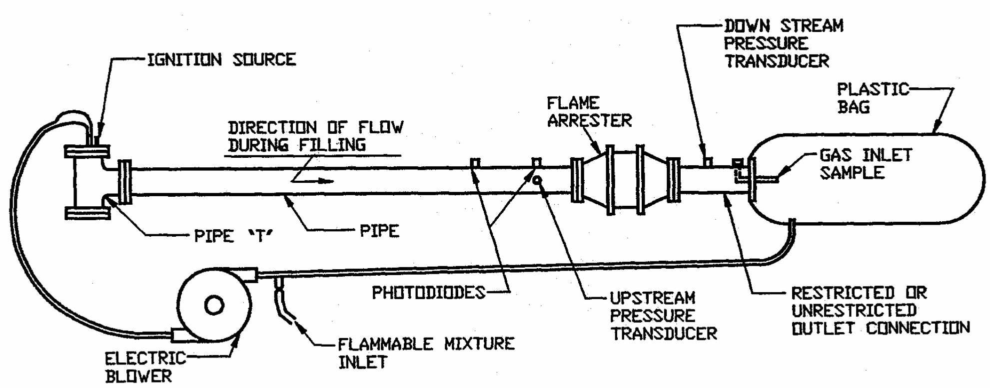


Figure 8

Capability Specifications Published by the Standards Organizations (Detonation Arrester):

The typical statement of the flame arrester standards organization is "No passage of flame or spark through the arrester."

Manufacturer' s Specification (Detonation arrester):

The manufacturer specifies the following about his product: 1. the standards organization that has performed the tests, 2. the gas type, 3. the maximum operating pressure, 4. the line size, 5. the endurance burn capability and, 6. a liability limit statement.

B. NEW FLAME PROPAGATION TECHNOLOGY IDENTIFIES HAZARDS TO FLAME ARRESTERS

Flame arresters can become ineffective thereby allowing hazardous conditions when current flame propagation technology and piping configuration are not addressed in the testing standards.

Standards organisations set the performance criteria for flame arresters using straight run test pipes. Field piping configurations set the performance demands for flame arresters in the field. The criteria and the demands are not the same! Flame fronts propagate in the most aggressive manner possible based on the field piping and are challenged by the arrester' s quenching capability as established in straight run test pipe. Field piping differs from test pipes. For example, a 15 ft. process piping run may have valve housings or weld joints that increase the speed and pressure of the flame front. The effect of field piping is critical on the performance of end-of-line and in-line deflagration arresters. Flame speed and pressure that exceeds those occurring in the test pipes during acceptance tests will result in flame arrester failure in operating systems.

Hazards (Misapplications) That Occur in Field Piping

- Unapproved flame arresters and “grandfathered’ installations
- Approved flame arresters placed in the wrong category
- Operating vapour pressure above proven capability
- More volatile gas type than acceptance test
- Longer pipe run than tested
- Elbows and fittings in the piping configuration
- Larger line size than the flame arrester
- Restrictions on the protected side of the arrester
- Pre-volume or vessel in the vapour
- Flow restrictions

Analyzing line piping and applying the latest findings in flame front technology will achieve operational safety. Conversely, by ignoring this technology, inevitable losses will occur due to misapplication of flame arresters.

1. <u>Hazard: Unapproved Flame Arresters and “Grandfathered’ Installations</u>

Old technology and “grandfathered” flame arrester installations are significant hazards when viewed against the new flame front technology. For example: the test procedure, UL525 (First Edition – December 1936), originally developed for storage tank flame arresters, required an atmospheric gasoline test having only 1.5 m (5 ft.) of pipe on each side of the arrester. This test method was used for years in every application and currently are installed in lines with greater pressure and more volatile gases. Since then, other UL525 editions have been issued, up to the Sixth Edition in December 1994. The others were issued in July 1946, September 1973, June 1979 and December 1984. The scope of the Sixth Edition includes tank vent deflagration arresters and in-line detonation flame arresters. Which approval edition does your equipment have, as every edition is considered UL525 listed? The flame arrester with the current listing has major capability over the earlier editions.

<u>Solution:</u> Confirm the basic parameters of line configuration, gas type and operating pressure. If these applications are End-of-Line or In-line Deflagration, be cautious of anything other than straight pipe and accepted run up distance. The flame is driven by pipe configuration. Even though the equipment can have the physical appearance and be called a "flame arrester" it may not have the capability to stop a flame. Update the installation as required.

2. **<u>Hazard: Misapplication - An Arrester Accepted by Current Standards Placed in the Wrong Category (The wrong tool for the job!)</u>**

<u>End-of-Line Flame Arrester:</u>

An End-of-Line flame arrester will fail when installed "in line" on a piping system because of the run up distance. Flame speed and pressure waves can exceed an End-of-Line arrester' s capability in as little as 2 feet (0.6 meters) of excess run up.

<u>In-Line Deflagration Flame Arrester:</u>

In-Line Deflagration Flame Arrester misapplications are the most common. The installation criteria are vague because of ambiguity and variation in testing standards. Due to the absence of clear guidelines, the arrester is then purchased based on cost savings rather than capability. The flame arrester capability is limited to a maximum flame pressure and speed before flame passage as determined during test tube explosions. Should this arrester be placed in a longer line, the flame speed and pressure will be higher and the arrester will fail. This run up distance is substantially reduced by field piping factors such as bends, weld seams, pipe deposits, valve bodies and fittings.

Hazard No. 2. Typical misapplication

<u>Detonation Flame Arresters:</u>

Detonation Flame arresters will prevent flame passage when installed in any category. They can be installed anywhere in the piping system.

<u>Solution:</u> Install flame arresters that meet the category, ensure that the gas type, line size and pressure match those used during acceptance testing. Ensure that none of the following hazardous conditions listed below are present.

3. **<u>Hazard: Operating Vapour Pressure Above Proven Capability</u>**

<u>Significance:</u> The initial operating pressure has a direct effect on the ultimate pressures reached during deflagrations and detonations. If the operating vapour pressure is higher than the flame arrester approval pressure, the arrester will allow flame passage. Reference Figure 9 showing how a small increase (2/10 psi) in the initial operating pressure will cause a flame arrester to fail.

Applicable classification: In-Line Deflagration and Detonation Arresters.

Manufacturers:
Manufacturers receive acceptance for the maximum allowable operating pressure for a specific gas.

Solution: Maintain the operating pressure at or below the approval pressure of the flame arrester or replace existing equipment with a flame arrester with greater capabilities.

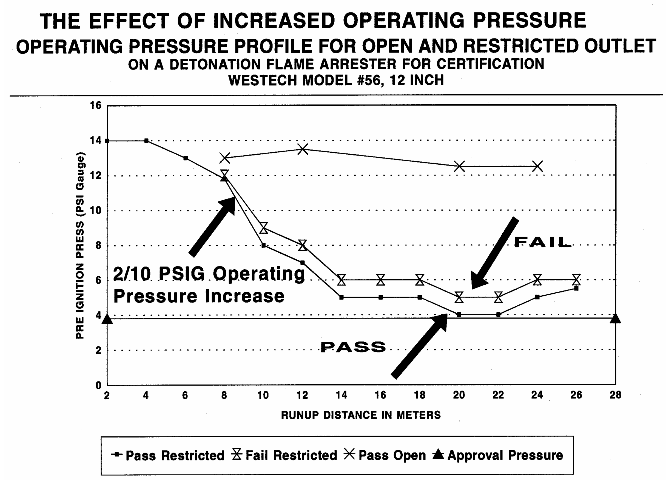


Figure 9

REFLECTED PRESS ZONE PORTION ENLARGED
LOW PRESSURE CAPABILITY REGION (20-22 M) REPRESENTS REFLECTED PRESSURE ZONE
DIFFERENCE BETWEEN DFA CAPABILITY AND FAILURE SEPARATED BY ONLY 0.014 BAR (2/10 PSIG)

4. Hazard: More Volatile Gas Type

Gas types are: Propane, Ethylene and Hydrogen

Significance: A gas type more volatile than the approval test gas type will allow a flame front to pass through the arrester. A reference criterion used to relate the flame arrester performance is the Maximum Experimental Safe Gap (MESG). The MESG number identifies the largest gap between two metal plates that will just prevent flame passage through the gap. The MESG is stated in mm or thousandths of an inch.

Type of Gas	American Code - NEC Group	European Code - EN 50014	MESG	Most Easily Ignited Mixture in Air
Propane	Class D	IIA	0.965 mm (0.038")	4.2%
Ethylene	Class C	IIB3	0.71 mm (0.028")	6.5%
Hydrogen	Class B	IIC	0.310 mm (0.012")	28.5%

Applicable classification: All flame arresters.

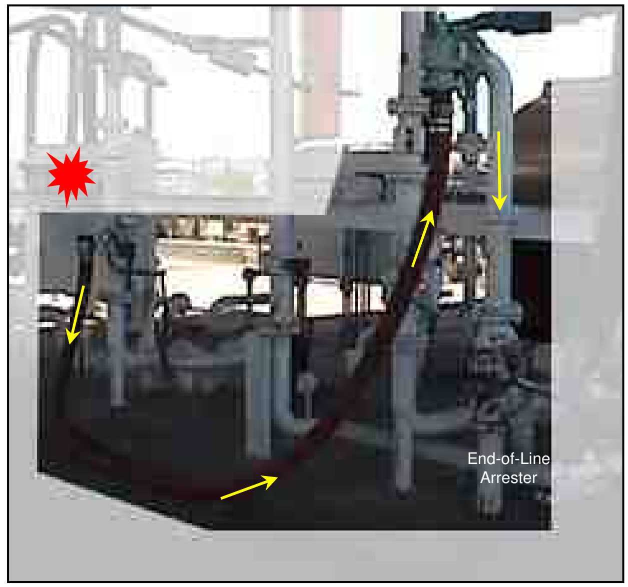
Manufacturers: Specify accepted gas type.

Solution: Install flame arresters that are tested and accepted to meet the process gas type. Mixtures can be tested for MESG to establish the gas type.
For mid range mixtures, refer to NEC Group Classification of Mixtures by Edward Briesch Reference No. 3. Flame arresters installed with a higher gas group than required are subject to fowling and higher pressure drop due to the smaller flame channels.

5. Hazard: Longer Pipe Runs

Significance: The length of the installed pipe between the ignition source and the arrester is critical to End-of-Line and In-Line Deflagration Arresters. Line lengths greater than test lengths allow higher flame speeds and pressures to develop causing the arrester to fail.

For detonation arresters, lengthening the pipe between the ignition source and the detonation arrester will not create any higher peak flame speed or pressures. The flame quenching ability of the arrester will not be affected.



Hazard No. 5. Typical long run piping.

Applicable classification: Applies only to End-of-Line and In-Line Deflagration Arresters.

Manufacturers: Some specify maximum lengths suitable for their model.

Solution: Install End-of-Line and In-Line flame arresters only according to actual proven test capabilities. If any hazardous conditions exist as listed in this paper, the arrester will fail. Change the condition or install Detonation Flame Arresters.

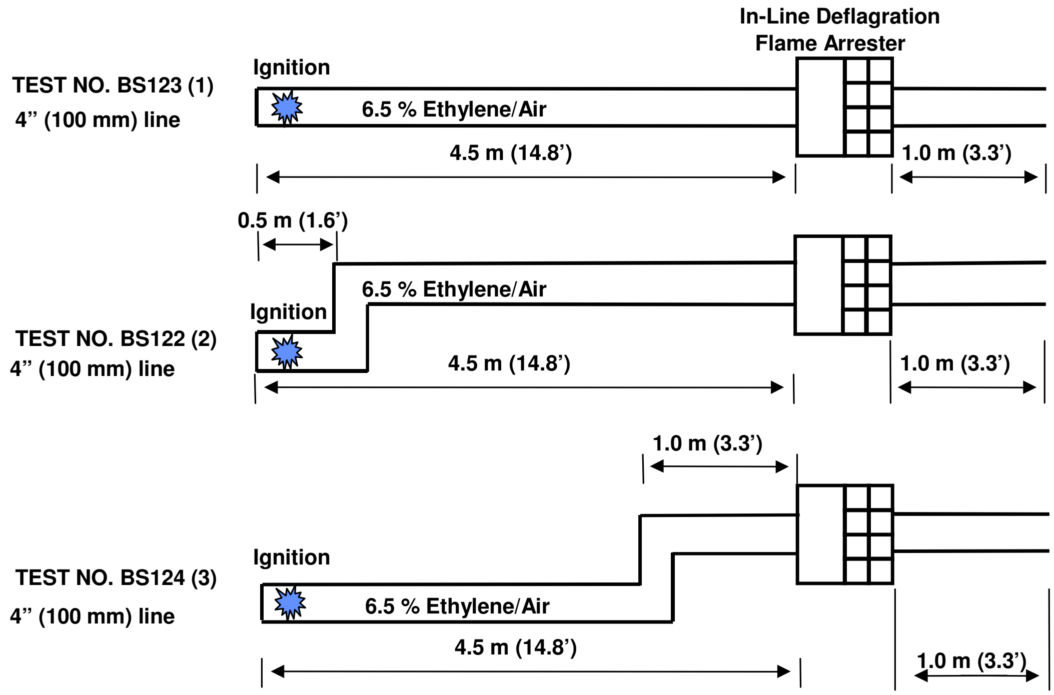
6. Hazard - Elbows and Fittings in the Piping System

Significance:

a. Pipe fittings (elbows, tees, Y' s) and valves create turbulence causing a confined flame front to accelerate in a shorter distance than in a straight run of pipe. In this short distance a flame front can reach speeds and pressure beyond the capability of End-of-Line and In-Line Deflagration arresters. The arrester will fail.

b. The number of elbows and fittings in a piping system will not affect the performance of a detonation arrester. The detonation arrester has successfully arrested peak pressure and flame speed conditions in acceptance tests.

c. “Effect of Tube Bends on Explosion Pressure”, Risk Analysis Laboratory Test Report, March 1999.



“Effect of Tube Bends on Explosion Pressure”
Risk Analysis Laboratory Test Report - March 1999

Figure 10

Test conditions: Deflagration arrester, ethylene gas/air mixture, 4-inch line, two 90° elbows. The separation between the arrester and the ignition source was 4.5 M (14.76 ft.). (Figure 10)

Elbow Location	Initial Pressure	Explosion Pressure	Test Number
No elbows (1*)	34 kPa (5 psig)	593 kPa (86 psig)	BS123
Outer end (2*)	35 kPa (5.1 psig)	1,186 kPa (172 psig)	BS122
Inner end (3*)	21 kPa (3 psig)	2,834 kPa (411 psig)	BS124
**See Figure 10*			

Results:

- Elbows have a significant effect on the flame speed and pressure of a deflagration.
- The location of the elbows in the line also has a significant effect.
- Contrary to expectations, elbows located close to the arrester are significantly more hazardous than elbows located close to the ignition point.

<u>Approval Standards</u>

No guarantee or guidance is provided by the standards organization when used in applications varying from that of the test rig. Some standards provide a "Best

Practice Annex" in which they warn of fittings and other considerations. (Reference No. 2, CEN prEN 12874 Annex D)

Applicable classification: Applies only to End-of-Line and In-Line Deflagration arresters.

Manufacturers: Some may test actual straight pipe distance with a single elbow and have limited capability. A major hazard is probable if the exact elbow location is not matched in the field application to compare with the acceptance test.

Solution:

a. Flame front acceleration is extremely sensitive to any internal pipe disturbance that enhances turbulent flow characteristics. The risk of predicting an acceptable amount of flame speed and pressure increase generated by any given change to a straight pipe, will be highly unsuccessful.

b. Locate low performance arresters (End-of-Line and In-Line Deflagration) in piping systems without elbows, bends and fittings. Locate these arresters only within the distance from the ignition source that has been proven by its specific acceptance tests.

Hazard No. 6. Typical elbow and fitting.

c. Replace the arrester with a higher capability arrester.

7. **Hazard - Larger Line Sizes than the Flame Arrester**

Significance: Flame arresters are designed, tested and accepted to stop flame propagation in a specific line size. Installing an arrester in a larger line size than the unit' s acceptance can result in failure. Actual testing has shown that when a USCG-accepted Detonation flame arrester is connected to a larger line size, it failed to stop low pressure and low speed flame fronts in operating conditions far less severe than original test conditions. All deflagration capability was also lost and the arrester failed. (Reference Figure 11 which shows run up distance.)


Hazard No. 7. Typical larger line size.

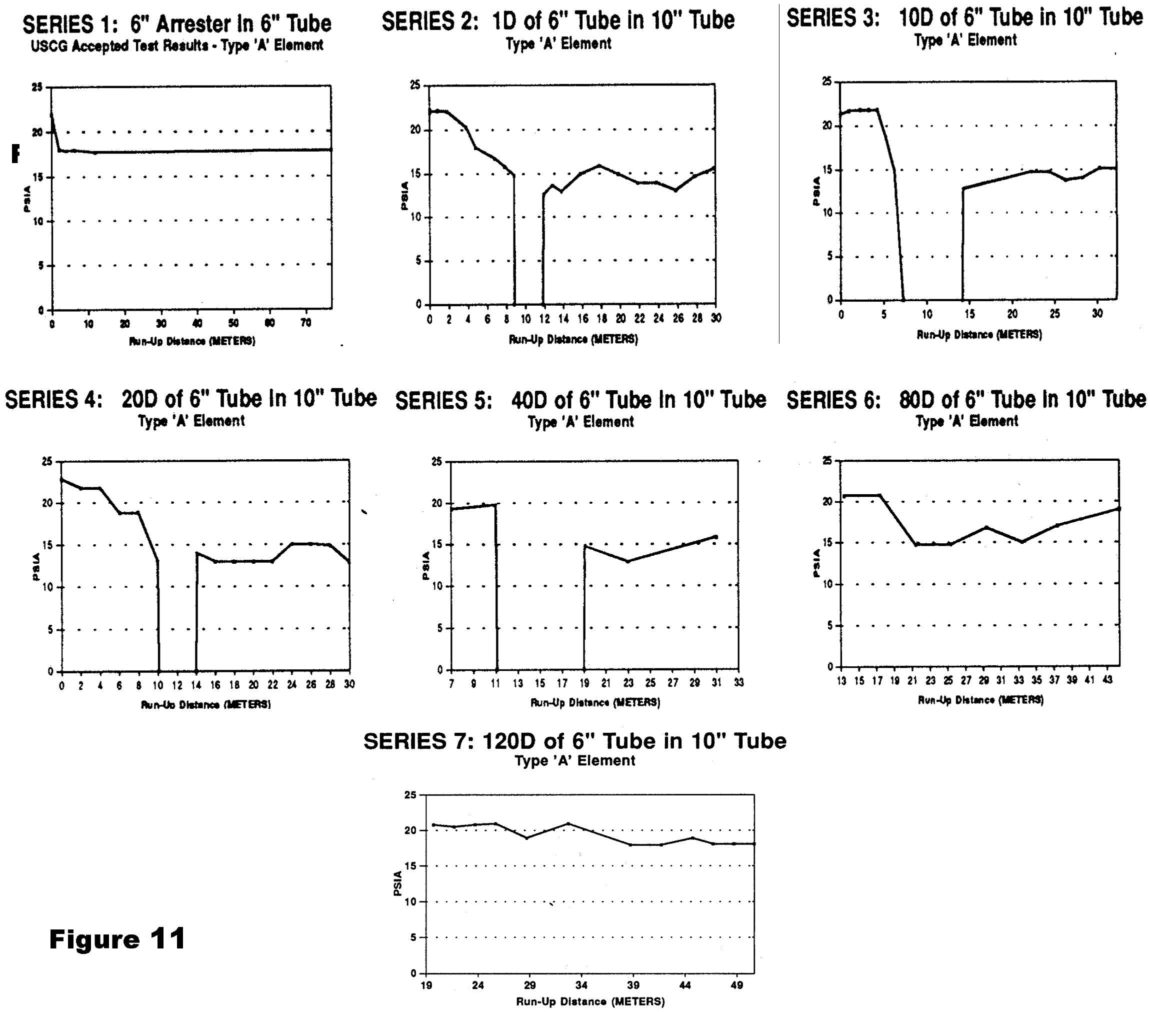


Figure 11

<u>Applicable classification:</u> All Flame Arresters

<u>Approval standard:</u> Some test standards clearly identify this parameter.

<u>Solution:</u> Install accepted flame arresters into the corresponding line size. Install a pipe at least 120 pipe diameters long of nominal arrester size between the larger line size and the flame arrester.

Note: New research   *A Westech research and development project is to identify the 120 diameter separation between larger line sizes and smaller arresters when elbows are inserted in the smaller line size area.*

8. Hazard - Restrictions on the Protected Side of the Arrester

Significance: A protected-side restriction, such as a valve, has a significant effect on a flame arrester' s capabilities due to reflected initial pressure in the arrester element. The reflected pressure decreases the performance capability of an In-Line Arrester. If the reflected pressure waves from a downstream restriction meet the advancing flame front in the flame quenching element, a temporary rise in operating pressure is created inside the arrester. As the flame quenching capability of any arrester is linked directly to the operating pressure in the system, any rise in this operating pressure, even if only temporary, will allow the flame front to pass through. Refer to Hazard No. 3: "Operating Vapour Pressure Above Proven Capability."


Hazard No. 8. Typical protected side restriction.

Applicable Classification: All In-Line Flame Arresters and those detonation arresters that have not been tested with a protected-side restriction.

Approval Standard: Some standards do not ask for protected-side restrictions and are not documented in the approval information.

Solution: Use flame arresters proven to quench flame fronts with protected-side restriction. Do not install an arrester near a restriction.

(Reference No. 1, "A Comprehensive Test Method for In-line Flame Arresters".)

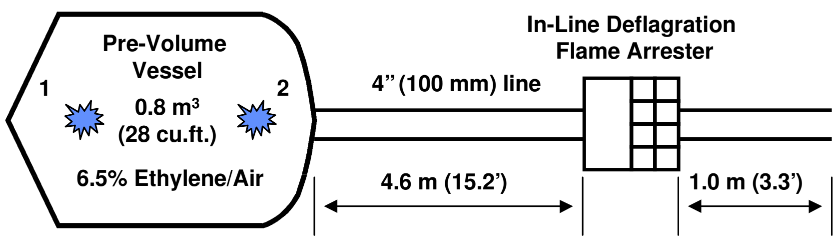
9. Hazard - Pre-volume or Vessels in the Vapour Line

Significance: Ignitions originating in tanks or vessels connected to piping systems propagate as high-pressure deflagration and detonation flame fronts. End-of-Line and In-Line deflagration flame arresters will fail! The pre-volume and run up distance will duplicate the "larger line size" phenomenon at some relation and cause detonation arresters to fail.

> ***Note: New research***
> *A Westech research and development project is to determine the critical pre-volume to pipe size and length ratio which causes the detonation arrester to fail.*

Risk Analysis Laboratory "Pre-Volume" Test Report March, 1999:

Test conditions: In-line Deflagration Arrester, ethylene gas/air mixture, unrestricted protected side piping, 4-inch line, a pre-volume container approximately 0.85 cu. m (30 cu. ft.) in volume. The separation between the



Risk Analysis Laboratory Pre-Volume Test - March 1999

*1. Outer end, 2. Inner end

Figure 12

arrester and the pre-volume was 4.64 m (15.22 ft.).

THE EFFECT OF PRE-VOLUME CONTAINER ON FLAME ARRESTER CAPABILITY			
Pre-volume Ignition Point	**Initial Pressure**	**Explosion Pressure**	**Performance**
No Pre-Volume	34 kPa (5 psig)	1,516 kPa (220 psig)	Stopped flame
Outer End (1*)	34 kPa (5 psig)	1,579 kPa (229 psig)	Failed
Outer End (1*)	21 kPa (3.1 psig)	3,102 kPa (450 psig)	Failed
Inner End (2*)	20 kPa (3 psig)	Read Error	Failed
Outer End (1*)	20 kPa (3 psig)	6,895+ kPa (1000+ psig)	Failed
**See Figure 12*			

Results: Explosions originating in a pre-volume container and travelling 4.64 M (15.22 ft.) to the arrester, passed though the arrester. This same arrester stopped all flame fronts in a similar straight pipe test without a pre-volume attached, and at an initial pressure of 34 kPa (5 psig). Some lower ignition pressure explosions were arrested. Some higher initial pressure explosions were arrested.

Applicable Classification: All arresters.

Solution: When pre-volume vessels are present use only Detonation Flame arresters. Arrester location must be 120 pipe diameters from the vessel unless pre-volume/pipe ratio evaluations are done or the actual vessel/pipe configuration is tested.

Hazard No. 9. Typical Pre-volume or Vessel.

10. Hazard: Flow Performance of a Flame Arrester

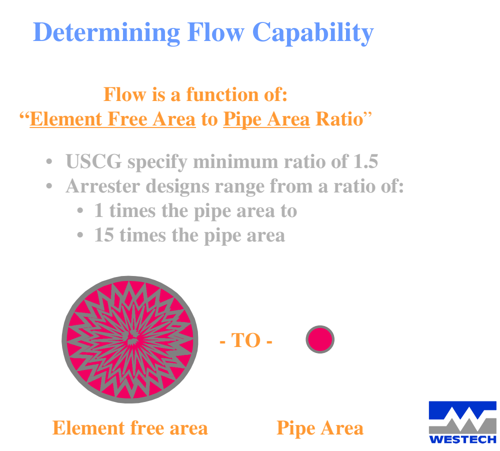
The flow performance of a flame arrester affects the process transfer time and volume, system maintenance and facility operating cost.

Significance:

Flow is the every day job of the flame arrester! When pressure drop climbs, so does the transfer time, maintenance cost, system operating cost and operating risk. The most common upset to system performance is obstruction to normal flow. Overpressure relief of vapour, due to stoppage of flow through the arrester, creates the potential for an explosion, personnel hazard and defeats the purpose of emissions reduction. Emergency shutdown situations can lead to mistakes in assembly and personnel safety.

a. Flow performance and clogging of a flame arrester:

"Element free area to pipe area ratio" is an accurate way to rate flow capability without performing actual flow tests. The free area to pipe ratios range up to 18 to 1. An arrester is designed with or without good flow characteristics. The loss of flow is due to a progressive build up of particulate. Clogging prevents the normal flow of condensed liquids from passing through the arrester. Arresters with poor flow characteristics cause liquid build up, further increasing differential pressure.



b. System maintenance:

Flame arrester cleaning is a major interruption in the vapour handling process requiring purging of the system, heavy lifting equipment (in some cases), time and labour for cleaning and replacement of the element and leak testing after assembly.

Flow history indicates major flame arrester product variations to "Time Between Maintenance" (TBM). One product' s TBM can be one tenth that of another. Specifically, some designs allow for yearly inspection and cleaning whereas others require continuous maintenance - worst case 50 times per year! Element cleaning processes range from simple on site cleaning to extensive chemical cleaning and drying. Some elements must be returned to the manufacturer for cleaning.

Spare elements can add a major operating cost to an arrester.

c. Cost burden for your facility:

Costs for a flame arrester are both a one time capital purchase and operating costs related to arrester performance. A major cost is the shutdown of a facility. Flame arresters are a significant consideration. For example, if the arrester does not stop a flame front, or if the arrester clogs, operation stops.

Costs that may be incurred due to poor flame arrester performance include: longer transfer times, vapour mover power consumption, emergency shut down, process interruptions, demurrage, labour and equipment required for replacement and cleaning, and spare element.

Consequential costs can be high. For example, an unscheduled shutdown due to arrester clogging could cause demurrage charges of $24,000 U.S. per day on a plant with the following operating specifications: crude loading facility averaging 800,000 barrels per week at a loading rate of 16,000 barrels per hour on a 10-inch line. One such incident would have offset the cost of an arrester product with the lowest TBM rating. These incidents are unpredictable and recurring. They are a major consequential cost.

Applicable classification: All flame arrester products.

Test Standard:

Flow curves are required. Not all standards require independent flow curve certification. A minimum element free area to pipe size ratio of 1.5 to 1 is required by some standards. Standards do not address the significance of flow because variations in flow do not reduce the flame quenching capability of a flame arrester.

Manufacturers: Pressure drop and flow curves are standard information. Most provide certified flow curves witnessed by a third party. The element free area to pipe area ratio is seldom available. The cleaning procedure and costs are not popular topics.

Solution:

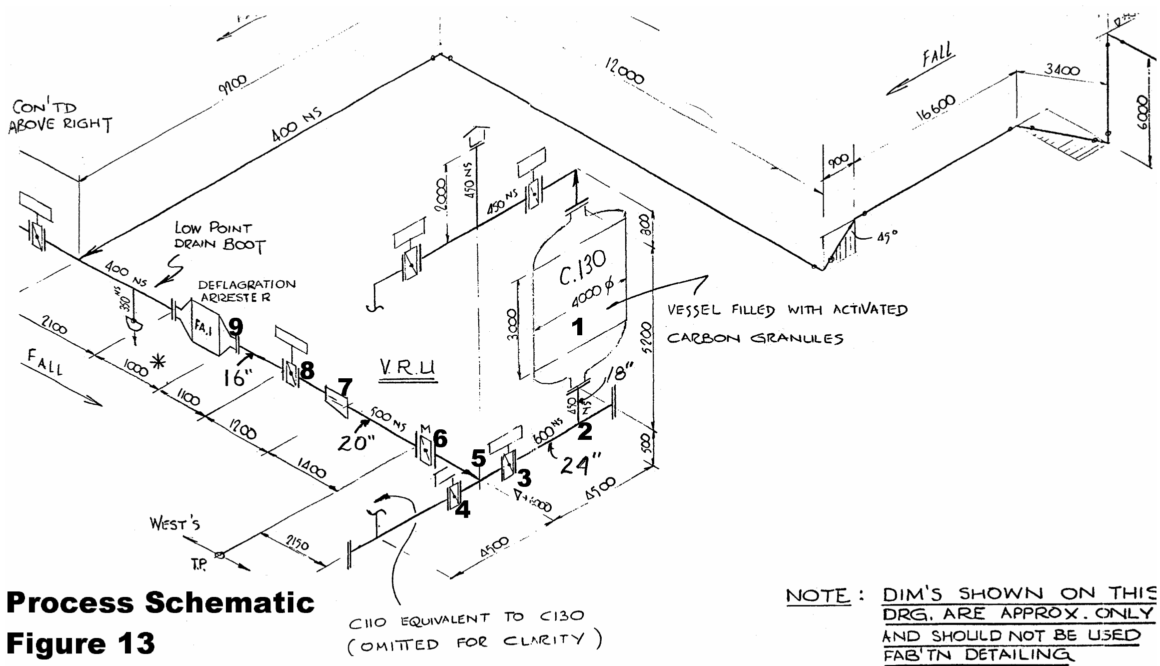
- Product flow information can be acquired at purchase time.
- Obtain certified third party witnessed flow curves.
- Evaluate the element free area to pipe area ratio.
- Evaluate flow, maintenance costs and consequential cost.
- Obtain field references from loading facilities with long operating histories.
- Additional equipment such as filter housings can be installed to reduce flame arrester clogging; however, they have associated capital and maintenance costs.

Hazard No. 10. Typical flow and maintenance hazards.

C. FIELD APPRAISALS FOR VAPOUR HANDLING AND TRANSPORT SYSTEMS

How is the potential hazard identified? How complicated is a field appraisal? In that context, refer to the two examples that follow: an actual vapour recovery unit (refer to process schematic, Figure 13) and a loading rack vapour return system (Figure 14). Focus on the piping between the ignition source vessel and the flame arrester. Listed is the pipe configuration starting from the ignition source to the arrester.

Example One: VAPOUR RECOVERY UNIT



Process Schematic
Figure 13

1. Hazard No. 9 - Ignition source is in the vessel. The pre-volume hazard applies.
2. Hazard No. 6 - Exit line is 18 inch to a 24-inch tee. The elbows and fitting hazard applies.
3. Hazard No. 6 - The 24-inch line passes through a valve body. The elbows and fitting hazard applies.
4. Hazard No. 6 - The flow turns in a 90° tee. The elbows and fitting hazard applies.
5. Hazard No. 7 – The line size changes from 24 inches to 20 inches. The larger line size hazard applies.
6. Hazard No. 6 - The flow is through a flow meter. The elbows and fitting hazard applies.
7. Hazard No. 7 - The flow passes a 20-inch to 16-inch reducer. The larger line size hazard applies.
8. Hazard No. 6 - The flow passes through a valve body. The elbows and fitting hazard applies.
9. Hazard No. 2 - The flow enters arrester FA1, a deflagration arrester.

Summary of Vapour Recovery Unit Appraisal

1. The deflagration arrester will fail.

2. The run up distance from ignition to arrester is 5.8 m (19 ft.) more than most In-Line Deflagration Arresters are accepted with.

3. A single hazard would disqualify a deflagration flame arrester.

4. There are seven hazards in this pipe run all enhancing flame speed and pressure.

5. A Detonation flame arrester will fail in this application.

6. A change is required to provide explosion safety.

Pipe changes necessary:

Many options are available. Consider these two:

a. Relocate the Detonation flame arrester farther away from the vessel and pipe reducer by a distance of 120 pipe diameters.

b. Maintain the 18-inch line size from the vessel through to the arrester if possible and increase the arrester size from 16-inch to 18-inch. Relocate valves and meters where possible on the protected side of the arrester.

Example Two: **LOADING RACK** (Refer to Figure 14)

1. Hazard No. 9 - Ignition source is in the road tanker to vapour return line connection. The pre-volume hazard applies.
2. Hazard No. 5 - The vapour return hose is approximately 25 ft. of 4-inch line. The line length from the open end to the arrester is specified as 10 ft. by Factory Mutual. The longer pipe runs hazard applies.
3. Hazard No. 2 - The arrester is an end-of-line approved unit and is misapplied for this application.
4. Hazard No. 8 - A pressure relief and backpressure valve is located directly on the protected side of the arrester. This is a restriction on the protected side of the arrester.
5. Hazard No. 8 - An additional elbow restriction is located on the protected side of the flame arrester.

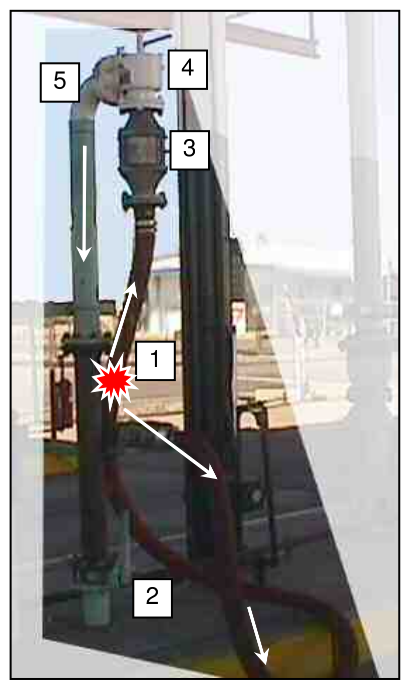


Figure 14 Loading Rack Vapour Return Application

Summary of Loading Rack Appraisal

1. The deflagration arrester will fail.

2. The run up distance from ignition to arrester is approximately 5.8 m (19 ft.). The distance exceeds the acceptance test distance for end-of-line arresters.

3. A single hazard would disqualify a deflagration flame arrester.

4. There are five hazards in this pipe run all enhancing flame speed and pressure.

5. The pipe run between the vapour return coupling and the arrester cannot be shortened.
6. A detonation flame arrester will quench flame originating at the coupling within the road tanker and also protect the road tanker from a flame front propagating in the main vapour return manifold.

CONCLUSION

HOW FLAME ARRESTER INSTALLATIONS CAN BE CHANGED FROM HAZARDOUS TO SAFE

Awareness is a major part of explosion prevention. Be aware of the field piping conditions between the potential ignition source and the flame arrester and look for the hazardous field conditions.

HAZARDS ADVERSELY AFFECTING FLAME ARRESTER CAPABILITIES			
Hazards	Flame Arrester Categories		
	End-of-Line	In-Line Deflagration	Detonation
Grandfather	Fail	Fail	Fail
Wrong Category	Fail	Fail	Pass
Extra Operating Pressure	Pass	Fail	Fail
Wrong Gas Group	Fail	Fail	Fail
Longer Pipe Runs	Fail	Fail	Pass
Elbows & Fittings	Fail	Fail	Pass
Larger Line Sizes	Fail	Fail	Fail
Protected Side Restrictions	Pass	Fail	Fail*
Pre-volume Containers	Fail	Fail	Fail
Flow Performance	Fail	Fail	Fail
Unless incorporated in the standards test.			

A number of simple steps will provide a good safety evaluation:

1. Train your personnel in basic flame propagation technology.

2. Perform field flame arrester application appraisals. They are quick and easy.

3. Accept flame arrester standards as a guide to equipment capability. Flame propagation is unpredictable and not yet fully understood.

4. When evaluating arrester capital cost versus arrester performance, refer to the "Hazards" chart above for guidance in determining the amount of reduced arrester capability and explosion protection.

5. If there is no explosion risk, remove the flame arrester equipment to reduce operational hazards and consequential operating cost. If there is hazard, both flow and flame arrestment are required for a safe operation.

Awareness of flame propagation technology and equipment will provide excellent explosion protection and trouble-free operation.

REFERENCES

Reference No. 1

“Standards Development and Flame Propagation”

The following is a listing of papers describing flame propagation effects on flame arrester test methods. Some excerpts are also listed. These papers show the difficulty in predicting results.

- Capp, B., and Seebolt. *Detonation Experiments in an 18-inch Pipe.* 1991.
- Frobese, D.H., and H. Foerster. *Propagation of Detonations Through Pipe Work Junctions.*
- Knystautas, R., and J. H. Lee. *Transmission of a Flame From a Rough to a Smooth Walled Tube.* 1986.
- Lapp, K., and P. Thibault. *The Effect of Momentum and Thermal Flux in Long Lines on the Westech Second Generation Detonation Flame Arrester.* June 1993.
- Lapp, K. *Detonation Flame Arresters and Protected Side Explosion Venting.* June 1992.
- Lapp, K., and K. Vickers. *Detonation Flame Arresters and Larger Line Sizes*, October 1992.
- Roussakis, N., and K. Lapp. *A Comprehensive Test Method for In-Line Flame Arresters*. April 1989.
- Thomas, G., and Oakley. *On Practical Difficulties Encountered When Testing Flame and Detonation Arresters to BS 7244.* 1992.
- Werneburg, H. *Test Instrumentation and Standardization of Data Collection Methods.* October 1992.

Excerpts from "On Practical Difficulties Encountered When Testing Flame and Detonation Arresters to BS 7244", by Thomas/Oakley, 1992:

"Difficulty in developing ten repeat tests with high flame velocities. There is a significant variation in the magnitude of the velocities obtained under nominally identical initial conditions."

"The arrester still exerted an influence, presumably by restricting the gas flow along the tube ahead of the flame."

"Downstream obstructions influenced flame behaviour."

"A major problem arises from the lack of guidance for quantifying any parameter other than flame tube length. Lack of any quantifiable parameter that can be used to compare the performance of different test facilities."

"For flames, the origin of such differences is the results of the flame acceleration process, which is sensitively dependent on the nature of the tube wall roughness and on the presence of obstacles."

"The BS standard was found insufficient to develop a system whose test parameters could easily be compared to other facilities. Future revisions should address pressure and velocity in arrester performance, define an accelerating section geometry for run up, identify the greatest potential hazard aspect of detonation phenomenon, test the worst case conditions in a repeatable manner."

Excerpts from "A Comprehensive Test Method for In-Line Flame Arresters" by Roussakis, Nick, and Lapp, Ken, 1991:

"The experiments show that the capability of an arrester can be very inconsistent when exposed to the full range of deflagration and detonation tests."

"Flow restrictions on the protected-side of the flame arrester can have a very significant effect on arrester performance."

Reference No. 2

CEN – FLAME ARRESTERS
Specifications, Operational Requirements and Test Procedures
Annex D, Best Practice (Informative)

Manufacturers and users shall be aware of the following:

1. Flame speeds and pressures of flammable mixtures can be enhanced by upstream turbulence that can be caused by bends, valves or any change of section in the pipe. Pipe lines shall be as straight as possible without obstructions. High Velocity Vent Valves are also sensitive to turbulence that may cause "hammering" or undamped oscillations.

2. In-line deflagration flame arresters shall be fitted as near as possible to the source of ignition and no further than the tested length, otherwise detonation units shall be installed.

3. It is important to note there are two types of detonation. Stable detonation (3.7.1) and unstable detonation (3.7.2). Unstable detonations occur during the transition of a flame front from deflagration to stable detonation and are more violent with higher flame speeds and pressures. Unstable detonation conditions require flame arresters of a higher performance than stable detonation conditions. The pipe length at which unstable detonations occur varies with pipe size and other conditions.

4. Continuous monitoring of pressure drop is advised if the process is known to contain particulate or substances which may block the element and over-pressurize the system. Any monitoring system shall have its own flame arrester if it connects the protected and unprotected sides.

5. Flame arresters covered in this standard are not suitable for gas and vapour mixtures containing more than the atmosphere oxygen concentration.

6. Always reconsider the specifications of a flame arrester if the process conditions or pipe layouts have been altered.

Reference No. 3

NEC Group Classification of Mixtures, Edward Briesch, AICHE, 34 Loss Prevention Symposium Atlanta, Georgia, March 5, 2000.

October 2001
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