NFPA® 67

Recommended Practice on Explosion Protection for Gaseous Mixtures in Piping Systems

2024 Edition

NFPA, 1 Batterymarch Park, Quincy, MA 02169-7471
An International Codes and Standards Organization

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Recommended Practice on

Explosion Protection for Gaseous Mixtures in Piping Systems

2024 Edition

This edition of NFPA 67, *Recommended Practice on Explosion Protection for Gaseous Mixtures in Piping Systems*, was prepared by the Technical Committee on Explosion Protection Systems. It was issued by the Standards Council on December 1, 2023, with an effective date of December 21, 2023, and supersedes all previous editions.

This edition of NFPA 67 was approved as an American National Standard on December 21, 2023.

Origin and Development of NFPA 67

In 1965, an NFPA committee was appointed to develop standards for explosion protection systems. The standards were to include information on explosion prevention and mitigation in vessels, ducts, and buildings, focusing primarily on deflagrations. During a meeting in 1997, the committee first considered the subject of protection against detonations in manifold pipe networks out of concern for the proliferation of vapor recovery systems at flammable liquid transfer stations. In 1999, the Standards Council approved the creation of a new document to address this issue, and the first draft of NFPA 67 was presented in 2011. Following a period of public review and comment, NFPA 67, *Guide on Explosion Protection for Gaseous Mixtures in Pipe Systems*, was issued in 2013.

The 2016 edition expanded the section on detonation forces on pipes, provided additional guidance on the proper application of detonation arresters, and provided references to address the design of piping systems that are outside the scope of this document.

The 2019 edition included three additional applications to which NFPA 67 can be applied where there is potential for flammable gas formation. A new annex was added to provide examples of applying the equations for suitable pipe wall thickness for pipe wall elastic response to stable detonations. Additional clarifications were made throughout the document to assist the user.

For the 2024 edition, the entire document was rewritten as a Recommended Practice rather than a Guide to improve the ease of use and applicability. Recommendations were reorganized into different chapters, and informational material was moved to the annexes.

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Committee Scope: This Committee shall have primary responsibility for documents on explosion protection systems for all types of equipment and for buildings, except pressure venting devices designed to protect against overpressure of vessels such as those containing flammable liquids, liquefied gases, and compressed gases under fire exposure conditions, as now covered in existing NFPA standards.

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NOTICE: An asterisk (*) following the number or letter designating a paragraph indicates that explanatory material on the paragraph can be found in Annex A.

A reference in brackets [ ] following a section or paragraph indicates material that has been extracted from another NFPA document. Extracted text may be edited for consistency and style and may include the revision of internal paragraph references and other references as appropriate. Requests for interpretations or revisions of extracted text shall be sent to the technical committee responsible for the source document.

Information on referenced and extracted publications can be found in Chapter 2 and Annex F.

Chapter 1 Administration

1.1 Scope.

Δ **1.1.1** The intent of this recommended practice is to provide recommendations for the design, installation, and operation of piping systems where there is potential for the formation and ignition of a flammable gas mixture.

Δ **1.1.2** This recommended practice addresses protection methods for use where there is an explosion risk due to either a deflagration or detonation.

1.1.3 This document does not apply to runaway reactions, decompositions, or oxidants other than oxygen.

Δ **1.2 Purpose.**

N **1.2.1** The purpose of this document is to provide the user with criteria for designing piping systems to protect against damage from deflagration or detonation due to combustion of flammable atmospheres therein.

N **1.2.2** Piping systems can be protected using explosion prevention methods *(see NFPA 69)*, deflagration venting *(see NFPA 68)*, passive or active detonation isolation methods, or containment.

N **1.2.3** Deflagration containment or deflagration venting should include designs that minimize the probability of deflagration-to-detonation transition (DDT), unless the nonventing components of the system are designed to contain detonation.

1.3 Piping Installation and Maintenance. The design and installation of the piping systems addressed in this document should be performed in accordance with the applicable standards, such as NFPA 54, ASME B31.1, ASME B31.3, or ASME B31.12.

Δ **1.3.1** Additional standards, such as NFPA 2, NFPA 55, and NFPA 58, also include requirements for specific gases and applications.

1.3.2 Inadvertent formation of flammable gas mixtures during pipe cleaning and purging can be prevented by following the planning and procedures described in NFPA 56.

1.4 Applications. This document can be applied to the following:

(1) Process piping for which a hazard analysis has identified the potential for flammable mixtures
(2) Vapor recovery system piping
(3) Gas venting piping and manifolds
(4) Gas piping for water electrolysis and fuel cell systems
(5) Flare systems
(6) Fuel gas piping for which a hazard analysis has identified the potential for flammable mixtures
(7) Oxygen piping for which there is a potential for flammable gas or vapor entry
(8) Piping cleaned by flammable liquid solvents that can develop flammable mixtures

Chapter 2 Referenced Publications

2.1 General. The documents or portions thereof listed in this chapter are referenced within this recommended practice and should be considered part of the recommendations of this document.

2.2 NFPA Publications. National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169-7471.

NFPA 2, *Hydrogen Technologies Code,* 2023 edition.

NFPA 54, *National Fuel Gas Code,* 2024 edition.

NFPA 55, *Compressed Gases and Cryogenic Fluids Code,* 2023 edition.

NFPA 56, *Standard for Fire and Explosion Prevention During Cleaning and Purging of Flammable Gas Piping Systems,* 2023 edition.

NFPA 58, *Liquefied Petroleum Gas Code,* 2024 edition.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* 2023 edition.

NFPA 69, *Standard on Explosion Prevention Systems,* 2024 edition.

2.3 Other Publications.

Δ **2.3.1 ASME Publications.** American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990.

ASME B31.1, *Power Piping*, 2022.

ASME B31.3, *Process Piping*, 2022.

ASME B31.12, *Hydrogen Piping and Pipelines*, 2019.

2.3.2 US Government Publications. US Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401-0001.

Title 29, Code of Federal Regulations, Part 1910.146, "Permit-Required Confined Spaces."

Title 29, Code of Federal Regulations, Part 1910.147, "The Control of Hazardous Energy (Lockout/Tagout)."

Δ **2.3.3 Other Publications.**

Cooper, W. E., "The Significance of Tensile Test to Pressure Vessel Design," *Welding Journal*, 1957.

Karnesky, J., J. Damazo, J. E. Shepherd, and A. Rusinek, "Plastic Response of Thin-Walled Tubes to Detonation," Proceedings of the ASME Pressure Vessel and Piping Conference, 2010.

Merriam-Webster's Collegiate Dictionary, 11th edition, Merriam-Webster, Inc., Springfield, MA, 2020.

Shepherd, J. E., "Structural Response of Piping to Internal Gas Detonation," *Journal of Pressure Vessel Technology* 131, no. 3, 2009.

TRGS 509, Lagern von flüssigen und festen Gefahrstoffen in ortsfesten Behältern sowie Füll- und Entleerstellen für ortsbewegliche Behälter, Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2014.

2.4 References for Extracts in Recommended Sections.

NFPA 53, *Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres,* 2021 edition.
NFPA 68, *Standard on Explosion Protection by Deflagration Venting,* 2023 edition.
NFPA 69, *Standard on Explosion Prevention Systems,* 2024 edition.

Chapter 3 Definitions

Δ **3.1 General.**

N **3.1.1** The definitions contained in this chapter apply to the terms used in this recommended practice.

N **3.1.2** Where terms are not defined in this chapter or within another chapter, they should be defined using their ordinarily accepted meanings within the context in which they are used.

N **3.1.3** *Merriam-Webster's Collegiate Dictionary,* 11th edition, is the source for the ordinarily accepted meaning.

3.2 NFPA Official Definitions.

3.2.1* Approved. Acceptable to the authority having jurisdiction.

3.2.2* Authority Having Jurisdiction (AHJ). An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

3.2.3 Labeled. Equipment or materials to which has been attached a label, symbol, or other identifying mark of an organization that is acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of production of labeled equipment or materials, and by whose labeling the manufacturer indicates compliance with appropriate standards or performance in a specified manner.

3.2.4* Listed. Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of products or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that either the equipment, material, or service meets appropriate designated standards or has been tested and found suitable for a specified purpose.

N **3.2.5 Recommended Practice.** An NFPA standard similar in content and structure to a code or standard but that contains only nonmandatory provisions using the word "should" to indicate recommendations in the body of the text.

3.2.6 Should. Indicates a recommendation or that which is advised but not required.

3.3 General Definitions.

Δ **3.3.1 Burning Velocity.** The rate of flame propagation relative to the velocity of the unburned gas that is ahead of it. [**68,** 2023]

Δ **3.3.1.1** ***Fundamental Burning Velocity.*** The burning velocity of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas. [**68,** 2023]

N **3.3.2* Chapman-Jouguet (CJ) Detonation Velocity.** A unique detonation velocity for a flammable gas mixture at a given temperature and pressure for which the corresponding velocity of the burned gases is equal to the speed of sound in the burned gases.

Δ **3.3.3 Combustion.** A chemical process of oxidation that occurs at a rate fast enough to produce heat and usually light in the form of either a glow or flame. [**68,** 2023]

3.3.4 Deflagration. Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium. [**68,** 2023]

3.3.5 Deflagration-to-Detonation Transition (DDT). The transition point to an unstable detonation.

Δ **3.3.6* Detonation.** Propagation of a combustion zone at a velocity greater than the speed of sound in the unreacted medium. [**68,** 2023]

3.3.7 Detonation Cell Size. (Reserved)

Δ **3.3.8 Dynamic Load Factor (DLF).** The ratio of the deformation in a detonation to the deformation expected for a static load based on the Chapman-Jouguet detonation pressure *(see 6.6.1.2).*

3.3.9 Equivalence Ratio. For a particular fuel-oxidant mixture, the fuel oxidant ratio of a particular mixture divided by the fuel oxidant ratio of the stoichiometric mixture.

Δ **3.3.10* Flame Arrester.** A device that prevents the transmission of a flame through a flammable gas/air mixture by quenching the flame on the surfaces of an array of small passages through which the flame must pass. [**69,** 2024]

3.3.11 Flame Speed (S_F). The speed of a flame front relative to a fixed reference point. [**68,** 2023]

3.3.12 Flammable Limits. The minimum and maximum concentrations of a combustible material, in a homogeneous mixture with a gaseous oxidizer, that will propagate a flame. [**68,** 2023]

3.3.13 Flammable Mixture. A mixture of fuel, oxygen (or other oxidant), and inert gases that has a composition in the flammable range.

3.3.14 Flammable Range. The range of concentrations between the lower and upper flammable limits. [**68,** 2023]

3.3.15 Flash Point. The minimum temperature at which a liquid or a solid emits vapor sufficient to form an ignitible mixture with air near the surface of the liquid or the solid. [**68,** 2023]

3.3.16 Fuel. A material that will maintain combustion under specified environmental conditions.

3.3.17 Gas. The state of matter characterized by complete molecular mobility and unlimited expansion; used synonymously with the term *vapor*. [**68,** 2023]

3.3.18 Limiting Oxidant Concentration (LOC). The concentration of oxidant in a fuel-oxidant-diluent mixture below which a deflagration cannot occur under specified conditions.

3.3.19 Lower Flammable Limit (LFL). The lowest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame, under defined test conditions. [**68,** 2023]

Δ **3.3.20* Mach Number (*M*).** The velocity divided by the local speed of sound.

3.3.21 Maximum Pressure (P_{max}). The maximum pressure developed in a contained deflagration of an optimum mixture. [**68,** 2023]

3.3.22 Maximum Rate of Pressure Rise (dP/dt_{max}). The slope of the steepest part of the pressure-versus-time curve recorded during deflagration in a closed vessel. [**68,** 2023]

3.3.23 Minimum Ignition Energy (MIE). The minimum amount of energy released at a point in a combustible mixture that causes flame propagation away from the point, under specified test conditions. [**68,** 2023]

3.3.24 Mist. A dispersion of fine liquid droplets in a gaseous medium. [**68,** 2023]

3.3.25* Optimum Mixture. A specific mixture of fuel and oxidant that yields the most rapid combustion at a specific measured quantity or that yields the lowest value of the minimum ignition energy or that produces the maximum deflagration pressure. [**68,** 2023]

3.3.26 Oxidant. Any gaseous material that can react with a fuel (either gas, dust, or mist) to produce combustion. [**68,** 2023]

N **3.3.27 Piping System.** Pipe, tubing, hose, flexible rubber hose, or metallic hose and connectors with valves and fittings made into a complete system for conveying gas from one point to another.

3.3.28 Pressure Piling. A condition during deflagration in which pressure increases in the unreacted medium ahead of the propagating combustion zone.

3.3.29 Rate of Pressure Rise (*dP/dt*). The increase in pressure divided by the time interval necessary for that increase to occur. [**68,** 2023]

3.3.30 Reduced Pressure (P_{red}). The maximum pressure developed in a vented enclosure during a vented deflagration. [**68,** 2023]

3.3.31 Static Activation Pressure (P_{stat}). Pressure that activates a vent closure when the pressure is increased slowly [with a rate of pressure rise less than 0.1 bar/min (1.5 psi/min)]. [**68,** 2023]

3.3.32 Stoichiometric Mixture. A balanced mixture of fuel and oxidizer such that no excess of either remains after combustion. [**53,** 2021]

3.3.33 Ultimate Strength. The pressure that results in the failure of the weakest structural component of an enclosure. [**68,** 2023]

3.3.34 Upper Flammable Limit (UFL). The highest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame. [**68,** 2023]

3.3.35 Vapor. See 3.3.17, Gas.

3.3.36 Vent. An opening in an enclosure to relieve the developing pressure from a deflagration. [**68,** 2023]

N **3.3.37 Yield Strength.** The maximum stress for which there is no permanent deformation and where a 0.2 percent offset yield stress is commonly used.

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N Chapter 4 General Detonation Protection Recommendations

N 4.1* Detonation Protection Methods Based on the Prevention of Combustion.

N **4.1.1** Detonation protection methods based on the prevention of combustion can be used.

N **4.1.2** Detonation protection methods based on the prevention of combustion should be the same methods used for deflagration prevention listed in NFPA 69.

N **4.1.3** The following detonation protection methods based on preventing combustion should be considered:

(1)* Oxidant concentration reduction in accordance with NFPA 69
(2) Combustible concentration reduction in accordance with NFPA 69
(3)* Application of end-of-line deflagration arresters in accordance with NFPA 69

N **4.1.4** NFPA 69 should be referenced for installation and maintenance requirements for these methods.

N **4.2* Detonation Protection Methods Based on the Prevention or Limitation of Damage.** Detonation protection methods based on the prevention or limitation of damage can be used to protect equipment.

N **4.2.1** The following detonation protection methods based on the prevention or limitation of damage should be considered:

(1) Suppression
(2) Isolation
(3) Pressure/shock containment

N **4.2.2*** NFPA 69 should be referenced for installation and maintenance requirements for suppression and isolation systems.

N **4.2.3** Chapter 6 should be referenced for additional information on detonation isolation and the installation and maintenance recommendations for pressure/shock containment.

N **4.3 Limitations.** The limitations specific to each detonation protection method should be considered.

N **4.4 Factors to be Considered.** The following factors should be considered in the selection of one or more of the detonation protection methods and the design of the system:

(1) Effectiveness of each method
(2) Reliability of the system
(3) Personnel hazards inherent in each method

N **4.4.1** The reliability of the system chosen should be assessed using the following factors:

(1) System design basis
(2) Possibility of electrical and mechanical malfunction (see NFPA 69 for safety system controls and instrumentation reliability requirements)
(3) Dependence on sophisticated activation systems
(4) Need for special installation, training, operation, testing, and maintenance procedures
(5) Further limitations as presented in each chapter

N **4.4.2** In general, detonation prevention systems should be used to protect processing, storage, and materials-handling equipment.

N **4.4.3** When a detonation is possible within rooms, buildings, or other enclosures in which personnel are present, consideration should be given to the safety of the personnel.

N **4.5 Plans.**

N **4.5.1** Plans, system specifications, and manufacturer's recommendations for testing and maintenance should contain information that enables the authority having jurisdiction to evaluate the detonation hazard and effectiveness of the system.

N **4.5.2** Details of the plans should include the following information:

(1) Pertinent chemical and physical characteristics of the materials involved
(2) Locations of hazards
(3) Enclosures or limits and isolation of the hazards
(4) Exposure to the hazards

N **4.6 System Acceptance.** All new protection installations and modifications should be tested or otherwise evaluated to confirm operational integrity.

N **4.6.1** Tests should be in accordance with the manufacturer's recommendations.

N **4.6.2** A written report of the tests should be provided to the users.

N **4.7 Inspection and Maintenance.**

N **4.7.1** All systems should be inspected for operability in accordance with the manufacturer's recommendations.

N **4.7.2** An inspection and preventive maintenance schedule should be established in accordance with the manufacturer's recommendations.

Chapter 5 Detonation Prevention and Mitigation

5.1 Detonation Prevention by Prevention of Combustion. NFPA 69 should be referenced for design, installation, and maintenance requirements for these systems.

N **5.2* Preventing Deflagration-to-Detonation Transition.** In-line deflagration arresters can be used to prevent deflagration-to-detonation transition when installed within the run-up distance to DDT, as described in D.4.4, from any potential ignition source.

N **5.3* Detonation Isolation.** Detonation isolation can be used to protect equipment interconnected by pipelines.

N **5.3.1* Where Recommended.** The use of detonation isolation devices is recommended in the following cases:

(1) Where plant components are connected to systems or equipment in which effective ignition sources could meet explosive atmospheres, thus causing explosions.
(2) Where vessels are connected by long pipelines [L > 6 m (20 ft)] to locations where flame jet ignition or points of high pressure can occur.

N **5.3.2* Passive Isolation Methods.** Passive isolation methods should be designed to isolate vulnerable equipment from a potential detonation wave.

N **5.3.2.1 Detonation Arrester.**

N **5.3.2.1.1*** A detonation arrester should be certified as suitable for the anticipated process stream composition and operating conditions by the manufacturer.

N **5.3.2.1.2*** A detonation arrester should also be certified for deflagration in the anticipated process stream composition and operating conditions by the manufacturer.

N **5.3.2.1.3** Installation of a detonation arrester should conform with the manufacturer's certification and follow the manufacturer's recommendations for installation and maintenance.

N **5.3.2.1.4*** Where deflagration-to-detonation transition could occur at the arrester location, the arrester should be designed for unstable detonation.

N **5.3.2.1.5** The operability of an installed detonation arrester should be evaluated prior to any changes in the process stream composition or operating conditions to ensure continued effectiveness.

N **5.3.2.1.6** Annex B should be referenced for additional guidance on detonation propagation across boundaries.

N **5.3.2.1.7*** The mounting system used for the detonation flame arrester and piping should be designed to account for the stresses imparted on the system by detonation on the unprotected side.

N **5.3.2.1.8** Detonation arresters should be installed close to either the component that is being protected or the ignition source, if known (e.g., an incinerator).

N **5.3.2.1.9** The nominal size of the detonation arrestor should not be less than the nominal piping size on the side of the ignition source (i.e., the unprotected side).

N **5.3.2.1.10** The pipe diameter on the protected side of the detonation arrester should be greater than or equal to the pipe diameter on the unprotected side.

N **5.3.2.1.11*** Shutoff valves installed in a piping system should not reduce the free flow area.

N **5.3.2.1.12** Shutoff valves should be secured in a fully open position during operation.

N **5.3.2.2 Other Passive Devices. (Reserved)**

N **5.3.3* Active Isolation Systems.** Active systems, consisting of detector(s), a control unit, and acting device(s), can be used to protect equipment interconnected by pipelines.

N **5.3.3.1* Detectors.** Detectors should be classified as either static or dynamic and designed to function accordingly.

N **5.3.3.1.1** A variety of detector types can be used, including the following:

(1)* Optical — Ultraviolet radiation (UV), infrared radiation (IR), UV/IR, IR/IR (detection of two narrow bands)
(2)* Multiband IR
(3)* Pressure based, such as piezoelectric or piezoresistive
(4)* Thermal-based, such as thermoelectric

N **5.3.3.2* Control Unit.** The control unit should be designed to reliably activate the isolation device.

N **5.3.3.2.1** The control unit should provide the following:

(1) Supervision and analysis of the electronic circuits so operational signals can be transmitted and processed
(2) Provision of the necessary power for operation of the required device(s)

N **5.3.3.2.2*** The following recommendations for the control unit should also be considered:

(1) It should be in accordance with electrical safety classifications.
(2) It should initiate process shutdown in a safe manner if explosion or failure occurs.
(3) It should provide emergency power backup in the event of main power failure.
(4) A coded access key should be used to prevent unauthorized system access.
(5) A data log should be maintained.

N **5.3.3.3* Active Devices for Explosion Isolation.** Active device(s) can be used to prevent, protect, or contain a deflagration.

N **5.3.3.3.1* Chemical Isolation Barriers.** NFPA 69 should be consulted for a description of the operation of a chemical isolation barrier.

N **5.3.3.3.2* Fast-Acting Valves.** NFPA 69 should be consulted for a description of the operation of fast-acting valves.

N **5.3.3.3.3* System Design Certification.** The system design methodology and application range should be supported by appropriate testing and certified by a recognized testing organization acceptable to the authority having jurisdiction.

Chapter 6 Detonation Containment

6.1* General. When detonation containment is employed, the elements of the piping system should be designed to accommodate the expected transient detonation load.

Δ **6.1.1*** The piping system can be designed with dynamic response to the pressure load in mind and allow for slight permanent deformation of the system provided the piping itself does not rupture.

N **6.2* Chapman-Jouguet Detonation Properties.**

N **6.2.1** The estimated pressure loads generated by a detonation should be evaluated with the CJ pressure and velocity of the fuel in mind.

N **6.2.2*** Table 6.2.2 can be used to estimate CJ parameters of common fuels.

N **Table 6.2.2 Chapman-Jouguet Pressure and Velocity Values of Typical Fuels**

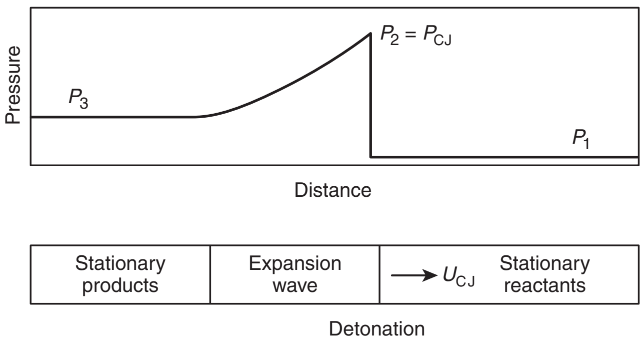
Property	Hydrogen	Ethylene	Propane	Methane
CJ pressure (bar)	15.8	18.6	18.6	17.4
CJ velocity (m/s)	1968	1822	1804	1802

N **6.2.3*** Values of the CJ properties of different fuels and conditions can be evaluated using computer tools such as CalTech's Shock and Detonation Toolbox.

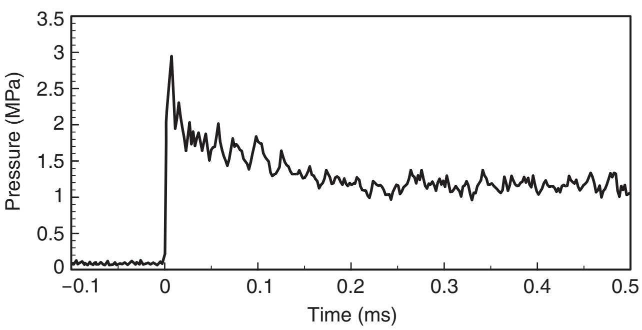
N **6.3 Detonation Forces on Piping and Piping Supports.**

N **6.3.1*** A spatially non-uniform pressure distribution should be assumed for detonation loads in piping systems, as shown in Figure 6.3.1 for propagation in a pipe with a closed end, where P_1 is the pressure upstream of the detonation, P_2 is the CJ detonation pressure, and P_3 is approximately 0.4 P_{CJ}.

N **6.3.2*** The pressure load transient generated by detonation at a given location within a pipe can be assumed to have a characteristic shape similar to that shown in Figure 6.3.2, where the peak pressure can be approximated as the CJ detonation pressure, which decays to approximately 0.4 P_{CJ}.



N **FIGURE 6.3.1 Detonation Pressure Load on Pipe Wall. (Source: Shepherd, 2009)**



N **FIGURE 6.3.2 Transient Pressure Load Due to CJ Detonation in Pipe. (Source: Shepherd, 2009)**

N **6.3.3** The spatial pressure distribution shown in Figure 6.3.1 and its transient variation shown in Figure 6.3.2 can be approximated using Equation 6.3.3:

Δ **[6.3.3]**

$$P(x,t)=\begin{cases} P_1 & \text{if } x/t > U_{CJ} \\ P_3\left[1-\frac{\gamma-1}{\gamma+1}\left(1-\frac{x}{c_3 t}\right)\right]^{\frac{2\gamma}{\gamma-1}} & \text{if } c_3 < x/t < U_{CJ} \\ P_3 & \text{if } 0 < x/t < c_3 \end{cases}$$

where:
$P_{(x,t)}$ = spatial pressure distribution
P_1 = pressure upstream of the detonation
P_3 = pressure of the products downstream of the detonation (after expansion)
γ = effective ratio of specific heats in the products computed on the basis of chemical equilibrium
c_3 = speed of sound in the products downstream of the detonation (after expansion)
U_{CJ} = CJ detonation velocity

N **6.3.4** Equation 6.3.4a and Equation 6.3.4b should be used to estimate the Taylor wave parameters in Equation 6.3.3:

Δ

[6.3.4a]

$$c_3=\frac{\gamma+1}{2}c_{CJ}-\frac{\gamma-1}{2}U_{CJ}$$

Δ **[6.3.4b]**

$$P_3=P_{CJ}\left(\frac{c_3}{c_{CJ}}\right)^{\frac{2\gamma}{\gamma-1}}$$

where:
c_3 = speed of sound in the products downstream of the detonation (after expansion)
γ = effective ratio of specific heats in the products computed on the basis of chemical equilibrium
c_{CJ} = speed of sound in the CJ state
U_{CJ} = CJ detonation velocity
P_3 = pressure of the products downstream of the detonation (after expansion)
P_{CJ} = CJ pressure

N **6.3.5** Equations 6.3.3, 6.3.4a, and 6.3.4b can be used as input in a finite element analysis to evaluate a pipe's structural response, but the reflected pressures and DDT should also be taken into account.

N **6.4 Reflected Pressure Waves and Deflagration-to-Detonation Transition (DDT).**

N **6.4.1*** The design of detonation containment should account for the potential for increased pressure due to shock reflections at pipe end walls, bends, reducers, or other connections.

N **6.4.2** The pressure decay behind the leading edge of the reflected detonation wave can be represented as shown in Equation 6.4.2:

[6.4.2]

$$P_R(t)=P_{CJref}\exp\left(-[t-t_0]/\tau\right)+P_3$$

where:
P_R = pressure decay behind the leading edge of the reflected detonation wave
t = time
P_{CJref} = reflected CJ pressure (about 2.5 P_{CJ})
t_0 = L/U_{CJ}, the arrival time of the reflected wave at a distance, L, from the end wall
τ = empirical decay time with the approximate value of 300 μs for stoichiometric ethylene-oxygen detonations (Karnesky, et al., 2010)
P_3 = pressure of the products downstream of the detonation (after expansion)

N **6.4.3*** In piping sections where a DDT is likely to occur, the piping design should account for short-duration pressure loads that can significantly exceed P_{CJ}.

N **6.5* Detonation Containment in Pipes.**

N **6.5.1* Practical Guidance for Piping Design.**

N **6.5.1.1** Piping and fittings between detonation flame arresters and a possible ignition location should be designed to resist the expected explosion pressure without bursting.

N **6.5.1.2** Pipes and fittings at ambient initial pressure up to 1.1 bar absolute with nominal diameters up to and including 200 mm (7.9 in.) should be designed with a pressure rating of at least 10 barg.

N **6.5.1.3** Pipes and fittings of a nominal diameter above 200 mm (7.9 in.) should be designed to withstand a pressure of at least 16 barg.

N **6.5.1.4** Piping with nominal diameters up to and including 200 mm (7.9 in.) can include bends with a variable curvature radius, *r*, as well as T-fittings and other fittings.

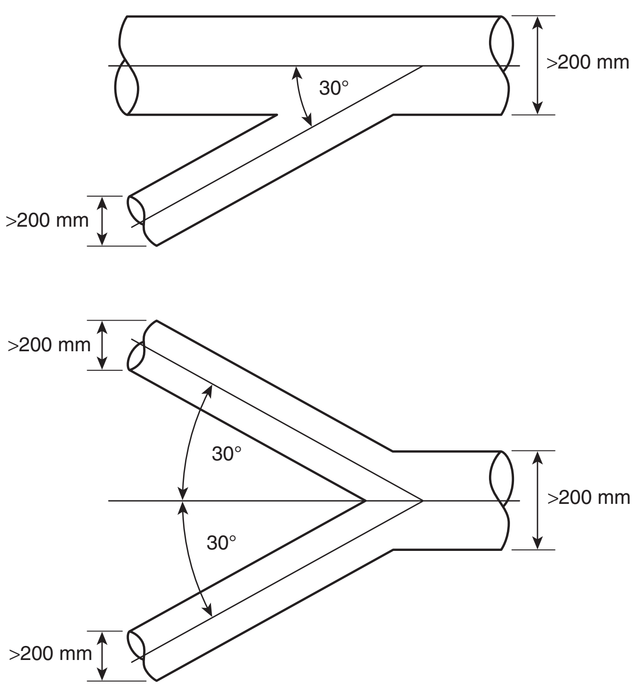
N **6.5.1.5** Bends in piping with nominal diameters above 200 mm (7.9 in.) should have a ratio of curvature radius *r* to pipe diameter *d* of at least 1.5.

N **6.5.1.6** T-fittings with a nominal diameter greater than 200 mm (7.9 in.) within the diverging branch should not be used.

N **6.5.1.7** The configurations shown in Figure 6.5.1.7 should be used.

N **6.5.2** Cross-section reductions in piping should be located at a distance greater than 120 pipe diameters from the detonation flame arrester.

N **6.5.3** Installation of flame arresters at or near pipe branches should follow the manufacturer's specific installation instructions.



N **FIGURE 6.5.1.7 Design of Piping for Detonation Containment in Combination with Detonation Arresters. (Source: TRGS 509)**

N **6.5.3.1** At pipe branches, stable detonation flame arresters should be placed in a configuration where any instability caused by the propagation of a detonation through the pipe does not cause any unsafe stress.

N **6.5.3.2** The distance between a branch and any sudden reduction in cross-sectional area in straight pipe sections, or a pipe end which has a length at least 20 times the diameter of this straight pipe section, should be greater than 3 m (9.8 ft).

N **6.5.3.3** In addition, the following criteria should be maintained:

(1) At pipe branches that are not right-angled or sharp-edged, flame arresters for stable detonations should be located in the branch pipe at a distance of at least 120 pipe diameters from the branch connection [*see Figure 6.5.3.3(a)*].
(2) At right-angled and sharp-edged pipe branches, flame arresters for stable detonations should be placed in the branch pipe at a distance between five pipe diameters of this pipe [minimum of 0.5 m (1.6 ft)] and 50 pipe diameters from the branch connection, or at a distance greater than 120 pipe diameters [*see Figure 6.5.3.3(b)*].

N **6.6* Pipe Structural Response to Detonation Loads.**

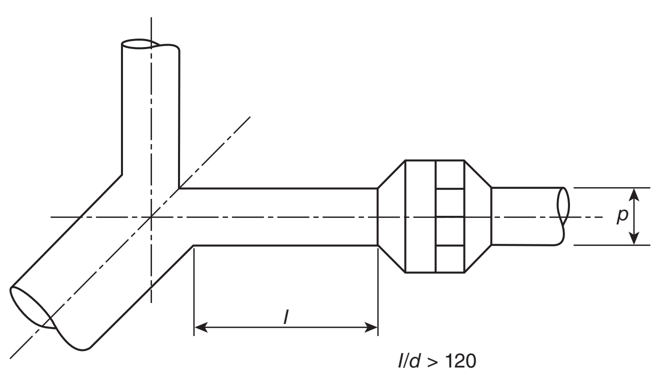
N **6.6.1 Elastic Regime Response.** Pipe wall elastic deformations in response to detonation wave propagation can be characterized in terms of the dynamic load factors associated with various vibration modes.

N **6.6.1.1*** For short, thin-walled pipes, the critical wave speed, $V_{c0,}$ for this vibration mode can be approximated with the following:

Δ **[6.6.1.1]**

$$V_{c0} = \left[\frac{E^2 h^2}{3\rho^2 R^2 \left(1-\nu^2\right)}\right]^{1/4}$$

where:
E = Young's modulus of elasticity of pipe material in N/m^2
h = pipe wall thickness in m
ρ = material mass density in kg/m^3
R = outer pipe radius in m
ν = material Poisson ratio; dimensionless



N **FIGURE 6.5.3.3(a) Design of Branch for Non-Rectangular and Non-Sharp-Edged Branch Pipes. (Source: TRGS 509)**

N **6.6.1.2*** The dynamic load factor, or DLF, for the defined yield point associated with piping vibrations can be estimated as follows:

[6.6.1.2a]

$$DLF = \frac{\sigma_d}{\sigma_s}$$

The *DLF* for a linear elastic material can be estimated as follows:

[6.6.1.2b]

$$DLF = \frac{\epsilon_d}{\epsilon_s}$$

where:
σ_d = maximum stress caused by a dynamically applied force or pressure, pascals
σ_s = stress caused by a slowly applied force or pressure, pascals
ε_d = maximum strain caused by a dynamically applied force or pressure, dimensionless
ε_s = strain caused by a slowly applied force or pressure, dimensionless

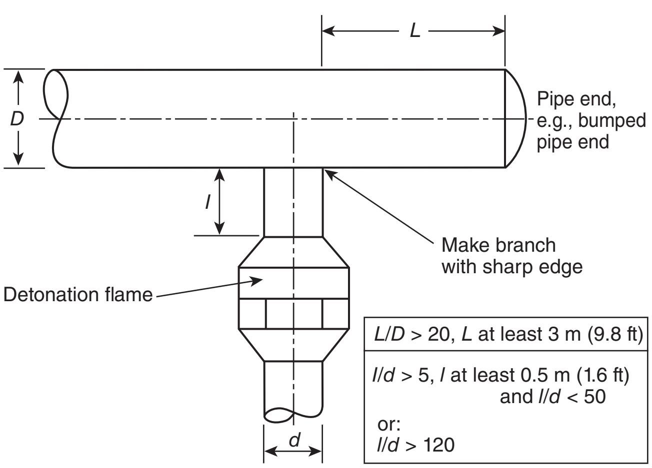
N **6.6.1.3*** Where the CJ detonation velocity, U_{CJ}, is less than 90 percent of the critical velocity of the thin-walled piping, Vc_0, a value of DLF = 1 should be assumed.

N **6.6.1.4** Where the CJ detonation velocity, U_{CJ}, is between 90 and 110 percent of the critical velocity of the thin-walled piping, V_{c0}, a value of DLF = 4 should be assumed.

N **6.6.1.5** Where the CJ detonation velocity, U_{CJ}, is greater than 110 percent of the critical velocity of thin-walled piping, V_{c0}, a value of DLF = 2 should be assumed.

N **6.6.1.6** For pipes, the dynamic load factor should be assumed to be less than 4.

N **6.6.1.7** Equation 6.6.1.7 can be used to estimate the minimum pipe thickness needed to avoid permanent deformation due to a detonation load associated with a particular gas-oxidant mixture.



N **FIGURE 6.5.3.3(b) Design of Branch for Rectangular and Sharp-Edged Branch Pipes. (Source: TRGS 509)**

Δ **[6.6.1.7]**

$$h \geq DLF\frac{R\Delta P_{CJ}(1-\nu^2)}{E\varepsilon_y}$$

where:
h = pipe wall thickness in m
DLF = dynamic load factor, dimensionless
R = outer pipe radius in m
ΔP_{CJ} = CJ pressure difference in pascals
ν = pipe material Poisson ratio, dimensionless
E = pipe material, Young's modulus of elasticity in N/m^2
ε_y = assumed maximum material strain that will prevent permanent deformation, dimensionless

N **6.6.2 Plastic Regime Response.**

N **6.6.2.1*** In general, it can be assumed that pipe wall deformations and strains can be 10 or more times the elastic limit in typical ductile materials, such as copper and some steel alloys, without a pipe rupture occurring.

N **6.6.2.2*** The pressure to rupture piping can be estimated using the equation and strain hardening exponents found in Cooper (1957).

N **6.6.2.3*** Calculations of dynamic loading-induced transient plastic deformations can be performed using finite element model (FEM) computer models considering the expected detonation pressure load.

N **6.6.2.3.1** The calculated pressures might vary from the experimental results, as shown in Karnesky, et al.(2010).

N **6.6.2.4*** Routine inspection of visible surfaces for flaws, such as surface scratches, as well as periodic nondestructive testing of pipe wall thickness should be performed on pipes subject to detonation loads.

N **6.6.2.4.1** With insulated piping, the insulation should be inspected to ensure the underlying piping has not been damaged.

N **6.6.2.4.2** Corrosion evaluation of piping subjected to explosive loads should be performed.

•

Chapter 7 Applications of Passive Detonation Protection Strategies

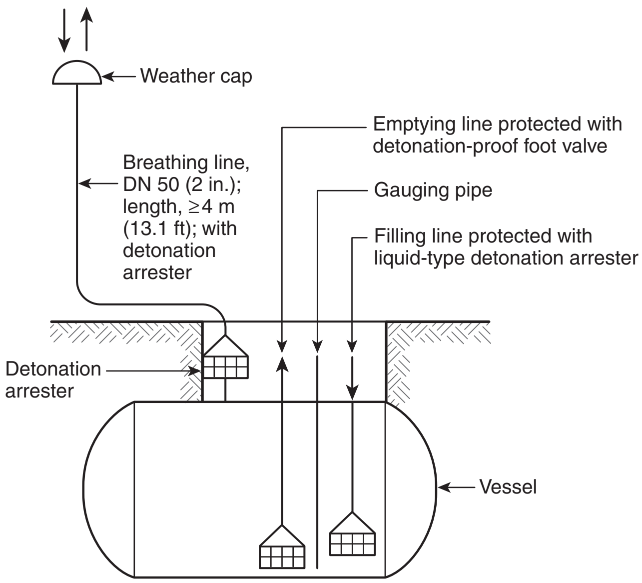
Δ **7.1 Underground Storage Vessels.**

N **7.1.1*** In-line detonation flame arresters should be installed within the filling and emptying lines of underground storage vessels if flammable atmospheres can form in these systems.

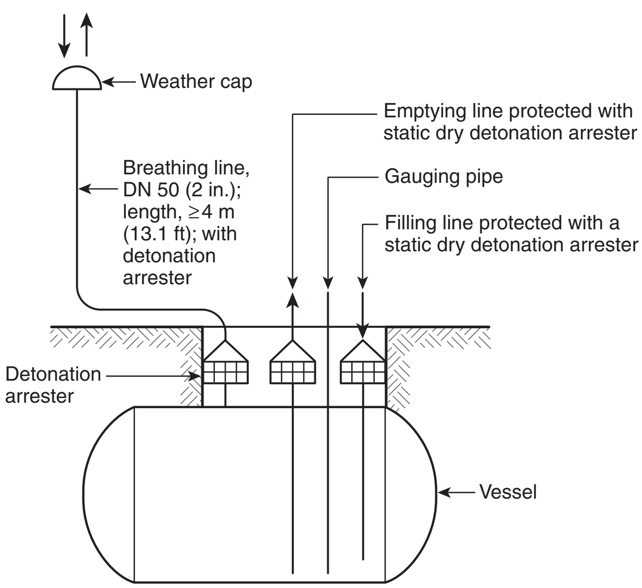
N **7.1.2*** When detonation flame arresters are installed, a process hazard assessment should be performed to ensure proper use of the device.

Δ **7.1.3*** When liquid product detonation flame arresters are used, they should be located within the underground vessel, as shown in Figure 7.1.3.

7.1.4 When static dry detonation flame arresters are used, they should be installed outside of the vessel, as shown in Figure 7.1.4.



Δ **FIGURE 7.1.3 Application of Liquid Product Detonation Flame Arresters in an Underground Vessel.**



Δ **FIGURE 7.1.4 Application of Static Dry Detonation Flame Arresters in an Underground Vessel.**

N **7.1.4.1** Static dry detonation flame arresters in liquid lines should only be used in applications where the products are clean and cannot create residue that can interfere with the operation of the flame arrester.

N **7.1.5*** Atmospheric vent pipes in which flammable atmospheres might be present should be equipped with one of the following:

(1) A detonation arrester
(2) An end-of-line deflagration arrester
(3) An in-line deflagration arrester rated for the L/D of the vent pipe

N **7.2 Aboveground Storage Vessels.**

N **7.2.1 Aboveground Storage Vessels Filled from Above the Liquid Level.**

N **7.2.1.1*** Detonation arresters should be installed in any fill line in which flammable atmospheres can form.

N **7.2.1.2** Static dry detonation flame arresters should be installed outside aboveground storage vessels, as shown in Figure 7.2.1.2.

N **7.2.1.3** Liquid product detonation flame arresters should be installed at the end of the filling line inside the vessel, as shown in Figure 7.2.1.3.

N **7.2.2* Aboveground Storage Vessels Filled from Below the Liquid Level.**

N **7.2.2.1** When filled from below the liquid level, aboveground storage vessels should include flame arresters and detonation arresters anywhere a flammable atmosphere can form, as shown in Figure 7.2.2.1.

N **7.2.2.2** The capacity of end-of-line pressure vacuum valves with integrated flame arresters used for thermal venting should be matched to the filling and emptying capacity plus the thermal venting capacity.

N **7.2.2.2.1*** Any end-of-line flame arrester-vent combination device used should be approved for endurance burning by an independent third party.

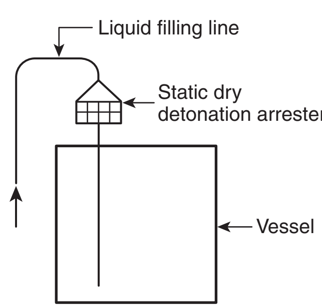
N **7.2.2.3** A detonation flame arrester for liquid products (liquid seal) should be installed on the liquid filling line.

N **7.2.2.4*** Vapor balance lines where flammable atmospheres can form should be protected by detonation arresters that can accommodate the filling and emptying capacity of the system plus 25 percent of the thermal outbreathing capacity.

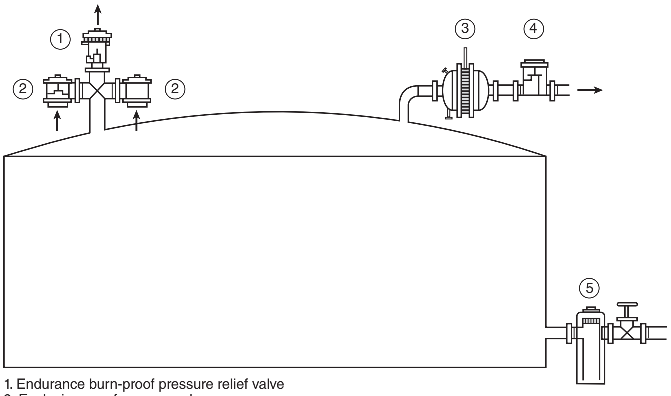
N **7.2.2.4.1** In the vapor balance line, a pressure relief valve should be installed downstream of the detonation flame arrester.

N **7.3* Protection of Process Units and Tank Farms from Waste Gas Systems (Incinerators, Flares, Thermal Oxidizers).**

N **7.3.1** In sections of the piping system in which a flammable atmosphere is present continuously, for long periods, or frequently (zone 0), three independent measures should be present to protect the process plant and storage area from flashback of the flame.



N **FIGURE 7.2.1.2 Storage Vessel with In-Line Dry Detonation Flame Arrester.**



N **FIGURE 7.2.2.1 Safeguarding a Tank for Flammable Liquids Against Flame Transmission from the Outside or Connected Parts of a Plant.**

N **7.3.1.1*** A feeding system should be installed at the burner inlet, which is designed to account for flashback.

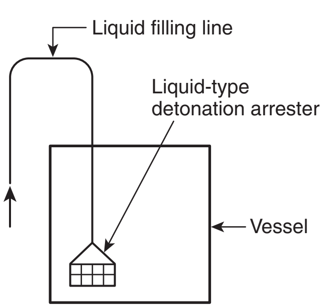
N **7.3.1.2*** An in-line deflagration flame arrester with temperature monitoring should be installed immediately upstream of a burner inlet.

N **7.3.2*** A detonation flame arrester should be installed in the waste gas line for each storage tank.

N **7.3.3*** The outlet of waste air to the atmosphere should be equipped with a device resistant to endurance burning.

N **7.3.4** If suitable endurance burning flame arresters cannot be used, detonation flame arresters can be used in ventilation ducts if the minimum pipe lengths in Table 7.3.4 are maintained between the detonation flame arrester and the opening of the ventilation duct leading into the open air *(see Table 7.3.4)*.

N **7.4* Protection Strategy for Carbon Adsorption Units.** Strategies to control explosion hazards in carbon absorption units are application-specific and should include a combination of concentration control, flame and detonation flame arresters, instrumented interlocks, and equipment that can contain explosion overpressures.



N **FIGURE 7.2.1.3 Storage Vessel with End-of-Line Liquid Detonation Flame Arrester.**

N **7.4.1* Thermally Regenerated Carbon Adsorption Units.**

N **7.4.1.1*** To avoid hot-spotting resulting from adsorption heat release, the vapor concentration should be brought down below 50 percent of the LFL.

N **7.4.1.2*** The inlet line to the carbon adsorption unit should be equipped with a detonation flame arrester.

N **7.4.1.3** The bypass line should be equipped with end-of-line endurance burning flame arresters for process upset conditions.

N **7.4.1.4** Either end-of-line flame arresters or in-line flame arresters should be installed at the discharge side of the adsorption vessel.

N **7.4.1.5*** The inlet side of the adsorption vessel should be equipped with in-line detonation flame arresters or explosion volume-proof flame arresters.

N **7.4.2 Vacuum-Regenerated Carbon Bed Adsorption Systems.**

N **7.4.2.1*** Explosion protection considerations for the pertinent piping in these systems should include an analysis of the piping's strength and the potential closed vessel deflagration pressures associated with pertinent hydrocarbon vapor-air mixtures.

N **7.4.2.2** The potential for deflagration-to-detonation transition in piping should be evaluated to determine whether deflagration flame arresters or detonation flame arresters are appropriate for the application.

N **7.4.2.2.1** Special requirements for the operating temperature and pressure of the system should be included in the design requirements if dry running vacuum pumps are equipped with in-line flame or detonation flame arresters.

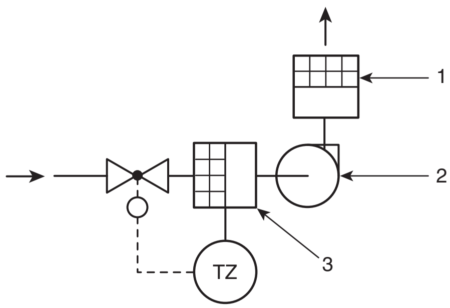
N **7.4.2.3** The decision-making analysis and conclusions should be documented and reviewed as part of any management of change analysis.

N **7.5* Protection Strategy for Equipment (Blowers, Vacuum Pumps, etc.).** If flame transmission cannot be prevented based on the design of equipment, a flame arrester should be installed between the equipment and the target that needs protection, as shown in Figure 7.5.

N **7.5.1** All safety devices should be tested for the process temperature and pressure on the discharge side of equipment.

N **Table 7.3.4 Minimum Pipe Length to Prevent Stabilized Burn on a Detonation Flame Arrester**

Pipe diameter (mm)	Pipe length (m)
15	0.5
20	1
25	1.5
32	2
40	3
50	4
65	6
80	8
100–200	10



1 Deflagration arrester
2 Blower or vacuum pump
3 Deflagration arrester
TZ Temperature switch

N **FIGURE 7.5 Specially Tested Flame Arresters for Zone 0 Blowers and Vacuum Pumps.**

N **7.5.2** All safety devices should have a temperature sensor installed on the flame arrester at the suction side to detect any potential stabilized flames.

N **7.6 Selecting Flame Arresters for Actual Process Conditions.** The following steps should be taken to avoid misapplication of flame arresters *(see Section F.4 of NFPA 69 for further details)*:

(1) Determine the hazards from propagating flames.
(2) Determine the flame arrester classifications.
(3) Determine the location of flame arresters.
(4) Determine the process conditions.
(5) Verify approval.
(6) Evaluate the process plant's classification of hazardous areas.

Chapter 8 Management of Change

8.1 Procedures for Management of Change.

Δ **8.1.1** Management of change is necessary for detonation control systems.

N **8.1.2** Management of change procedures should be followed for changes to processes, materials, technology, equipment, process flow, exposure, and procedures affecting equipment protected by the guidelines of this recommended practice.

8.1.3 Management of change should include review by all life and process safety system suppliers and relevant authorities having jurisdiction.

8.1.4 Changes in piping configurations and gas compositions in piping should be reviewed by a person knowledgeable in the material encompassed in this recommended practice.

Δ **8.1.5** Management of change procedures should ensure that the following issues are addressed prior to any change:

(1) Technical basis for the proposed change
(2) Safety and health implications
(3) Fire and explosion prevention systems review
(4) Whether the change is permanent or temporary
(5) Personnel exposure changes
(6) Modifications to operating maintenance procedures
(7) Human element changes involving members of loss prevention programs
(8) Employee training requirements
(9) Authorization for the proposed change

N **8.1.6** Implementation of the management of change procedures is not applicable for replacements-in-kind.

8.1.7 Design documentation as required by Section 9.2 should be updated to incorporate the process changes made by management of change.

Chapter 9 Installation, Inspection, and Maintenance of Piping Explosion Protection Systems

9.1 General.

9.1.1 This chapter covers the installation, inspection, and maintenance procedures necessary for proper function and operation of explosion protection system(s) of all types.

Δ **9.1.2** Maintenance should be performed with strict observation of the relevant safety instructions.

N **9.1.3** Maintenance should be performed by personnel trained by the manufacturer.

N **9.1.4** Generally, maintenance of explosion protection systems should be performed only while the process or part of a plant is not under pressure and is neither filled nor emptied.

Δ **9.1.5** Plant lockout/tagout procedures should be strictly followed.

N **9.1.6** Before the maintenance activity begins, it should be verified that measured gas-air mixtures or product vapor-air mixtures are not health hazards; otherwise, protective measures are to be taken (e.g., breathing apparatus should be used).

9.1.7* To ensure proper function, regular inspection and maintenance of devices should be performed.

Δ **9.1.8** In case the operator does not have experience with the process, regular inspections should be conducted during plant start-up to determine the time intervals at which to check for contamination and clogging of the protection device.

N **9.1.9** Future maintenance intervals, which are necessary to ensure safe operation, should be determined and documented accordingly within plant/process operating instructions.

9.2 Design Parameters and Documentation. Data sheets, installation details, and design calculations should be developed for each explosion protection system suitable for review by an authority having jurisdiction, including the following:

(1) Data sheets
(2) Design calculations
(3) NFPA 67 design chapter referenced and edition year
(4) General specifications
(5) Manufacturer's specific specifications
(6) End user inspection and maintenance forms
(7) Third-party review of suitability
(8) Product identification
(9) Material test report
(10) Copy of product identification label
(11) Process plan view
(12) Process elevation view
(13) Pressure relief path
(14) Proximity of personnel to relief path

(15) Mechanical installation details
(16) Electrical supervision (if provided) installation details

9.3 Installation.

9.3.1 Explosion protection system (s) should be installed in accordance with the manufacturer's instructions.

Δ **9.3.2*** An explosion prevention system should not be located near hot equipment unless it is certified for elevated temperatures.

9.3.3 Acceptance inspections and applicable tests should be conducted after installation to establish that systems have been installed according to the manufacturers' specifications and accepted industry practices.

Δ **9.3.3.1** Protection equipment should be clearly marked as explosion protection systems or devices.

Δ **9.3.3.2** The relief path should be unobstructed and should not lead to areas where personnel can be harmed by relief pressure.

9.4 Inspection.

Δ **9.4.1*** Explosion protection system(s) should be inspected according to the manufacturer's requirements on a regular basis, with intervals of no more than 365 days.

Δ **9.4.1.1** Systems should initially be inspected at 3-month intervals.

9.4.1.2 The frequency of inspection can be increased or decreased based on documented operating experience or a documented hazard analysis.

9.4.2 The owner or operator of the property in which an explosion protection system is located is responsible for inspecting and maintaining the system after it is installed.

9.4.2.1 Disarming and lockout/tagout procedures (29 CFR 1910.147) and confined space entry procedures (29 CFR 1910.146) or a local country equivalent should be followed prior to entering or performing maintenance on explosion protection systems.

Δ **9.4.3** After the process has been made and verified safe for inspection, the inspector should verify the explosion protection system as follows:

(1) Pressure relief pathway is free and clear of any obstructions.
(2) Pressure relief pathway does not extend into an area that could cause injury to personnel.
(3) The system is properly installed according to the manufacturer's instructions.
(4) No parts of the system are corroded.
(5) Construction material is compatible with the environment to which it is exposed.
(6) Equipment and devices are clearly and properly identified.
(7) An explosion protection system or device is clearly labeled as such.
(8) Relief pathway is located in a safe outside location.
(9) The system has no damage and is protected from the accumulation of water, snow, ice, or debris.
(10) No equipment or devices have been painted or coated.
(11) There is no buildup of deposits on inside surfaces.
(12) The system has not been tampered with.
(13) The system shows no signs of fatigue.
(14) Hinges (if provided) are lubricated and operate freely.
(15) Restraints (if provided) are in place and operational.
(16) The manufacturer's required housekeeping requirements have been followed.
(17) There are no existing conditions that will hinder the system's operation.
(18) Sealing gaskets are intact and show no leakage indications.

Δ **9.4.4** It should be verified that there have been no process changes since the last inspection.

N **9.4.5** The verification recommended in 9.4.4 should be included on the inspection form.

9.5 Availability of Explosion Protection System Documentation.

9.5.1 The explosion protection system design submittal parameters should be readily available for inspection, maintenance, and replacement reordering, including the following:

(1) Manufacturer and model number
(2) Size
(3) Type
(4) Spare parts list
(5) Manufacturer or supplier contact information

9.6 Maintenance.

9.6.1 A full inspection should be conducted after a process maintenance turnaround.

9.6.2 Inspections should be conducted following any activity that can adversely affect the operation or relief path of an explosion protection system device (e.g., after process changes, hurricanes, and snow and ice accumulations).

9.6.3 Inspection procedures and their necessary frequency should be maintained in writing and include provisions for periodic testing.

Δ **9.6.4** To facilitate inspection, access to and visibility of the explosion protection system should not be obstructed.

9.6.5 Any broken seals or tampering indicators, any obvious physical damage or corrosion, and any other defects found during inspection should be corrected immediately.

9.6.6 Any structural changes or additions that could compromise the effectiveness of the explosion protection system or create a hazard to personnel or equipment should be reported and corrected immediately.

9.6.7 Deficiencies found during inspections should be reported and corrected before the process is restarted.

9.7* Cleaning. Elements should be thoroughly cleaned and inspected prior to being returned to service.

9.8 Procedures After an Explosion Protection System Event.

9.8.1 In the event of an explosion protection system event, inspection and testing as specified in Section 9.4 should be performed before the system is placed back into service.

Δ **9.8.2** An investigation and review of the cause of the explosion protection system event should be performed, including but not limited to the following:

(1) Recording process operating data at the time of the actuation and noting any process upsets that recently occurred
(2) Recording the status of the explosion prevention control systems
(3) Recording the status and condition of the process safety interlocks
(4) Capturing history data from the explosion prevention control system, if available
(5) Recording statements and observations from personnel in the area of the event
(6) Photographing the area in and around the event location
(7) Collecting samples of the material in process at the time of actuation
(8) Recording weather conditions at the time of actuation

Δ **9.8.3** Corrective process and protection system actions should be completed and refurbishment of the explosion protection system should be performed by personnel authorized by the manufacturer.

N **9.8.4** Corrective actions should be implemented before the process is returned to service.

9.9 Recordkeeping.

Δ **9.9.1** A record should be maintained that indicates the date and results of each inspection and the date and description of each maintenance activity.

Δ **9.9.2** System inspection reports should be retained on-site for at least 3 years.

N **9.9.3** The report referenced in 9.9.2 should include the test and calibration data of all system components.

9.9.4 The records of inspection should be retained by the owner/operator for the life of the protected process.

9.10 Personnel Safety and Training.

Δ **9.10.1** Operating and maintenance procedures and emergency plans should be developed.

N **9.10.2** The plans and procedures should be revalidated regularly and as required by management of change procedures.

N **9.10.3** Initial and refresher training should be provided to personnel who operate, maintain, supervise, or are exposed to equipment and processes protected by explosion protection systems.

Δ **9.10.4** Training should include the following:

(1) Hazards of their respective workplaces
(2) General orientation, including plant safety rules
(3) Process description
(4) Equipment operation, safe start-up, shutdown, and response to upset conditions
(5) The necessity for proper functioning of related fire and explosion protection systems
(6) Maintenance requirements and practices
(7) Explosion protection system procedures
(8) Process lockout/tagout procedures
(9) Housekeeping requirements
(10) Emergency response and egress plans
(11) Management of change procedures
(12) System impairment reporting procedures

Annex A Explanatory Material

Annex A is not a part of the recommendations of this NFPA document but is included for informational purposes only. This annex contains explanatory material, numbered to correspond with the applicable text paragraphs.

Δ **A.3.2.1 Approved.** The National Fire Protection Association does not approve, inspect, or certify any installations, procedures, equipment, or materials nor does it approve or evaluate testing laboratories. In determining the acceptability of installations or procedures, equipment, or materials, the "authority having jurisdiction" may base acceptance on compliance with NFPA or other appropriate standards. In the absence of such standards, said authority may require evidence of proper installation, procedure, or use. The "authority having jurisdiction" may also refer to the listings or labeling practices of an organization that is concerned with product evaluations and is thus in a position to determine compliance with appropriate standards for the current production of listed items.

A.3.2.2 Authority Having Jurisdiction (AHJ). The phrase "authority having jurisdiction," or its acronym AHJ, is used in NFPA standards in a broad manner because jurisdictions and approval agencies vary, as do their responsibilities. Where public safety is primary, the authority having jurisdiction may be a federal, state, local, or other regional department or individual such as a fire chief; fire marshal; chief of a fire prevention bureau, labor department, or health department; building official; electrical inspector; or others having statutory authority. For insurance purposes, an insurance inspection department, rating bureau, or other insurance company representative may be the authority having jurisdiction. In many circumstances, the property owner or his or her designated agent assumes the role of the authority having jurisdiction; at government installations, the commanding officer or departmental official may be the authority having jurisdiction.

A.3.2.4 Listed. The means for identifying listed equipment may vary for each organization concerned with product evaluation; some organizations do not recognize equipment as listed unless it is also labeled. The authority having jurisdiction should utilize the system employed by the listing organization to identify a listed product.

N **A.3.3.2 Chapman-Jouguet (CJ) Detonation Velocity.** The CJ detonation velocity and the associated detonation pressure and temperature can be calculated from a combination of thermochemical equilibrium constraints and shock wave discontinuity conservation equations. Several computer codes are available to do those calculations.

One readily available thermochemical equilibrium computer code that can calculate CJ detonation conditions is called GASEQ and can be downloaded for free from the following website: www.gaseq.co.uk. Another commonly used computer code for CJ detonation calculations is CET89, developed at the NASA Lewis Research Center (now known as the NASA Glenn Research Center). Both codes calculate and show burned gas composition as part of their output.

A.3.3.6 Detonation. A detonation is a coupled combustion–shock wave complex that moves with a wave speed that is supersonic, between 5 and 10 times the speed of sound in the unburned gas ahead of the flame. Unlike a propagating flame (deflagration), the ideal detonation wave speed has a definite value that can be determined from thermodynamic considerations alone. An ideal detonation, often called a Chapman-Jouguet (CJ) detonation, is defined as a wave in which the burned gas moves at the speed of sound relative to the wave. This model defines a precise wave speed that can be computed by assuming complete chemical equilibrium in the combustion products and conservation of mass, momentum, and energy across the wave front. Real detonations travel slower than the ideal value due to energy and momentum losses. The wave speeds can be up to 30 percent lower than the ideal value in some cases but are usually within 5 to 10 percent of the ideal value for detonations in highly reactive mixtures.

A.3.3.10 Flame Arrester. The emerging gases are sufficiently cooled to prevent ignition on the protected side. [**69,** 2024]

N **A.3.3.20 Mach Number (*M*).** The Mach number of a propagating flame front is the flame speed divided by the speed of sound in the unburned mixture.

A.3.3.25 Optimum Mixture. The optimum mixture is not always the same for each combustion property that is measured.

N **A.4.1** The prevention of ignition of a deflagration can also prevent the formation of a detonation. The advantages of using methods based on the prevention of combustion include the following:

(1) The possibility of explosion and fire can be eliminated.
(2) These methods can be used for different enclosure shapes.
(3) High-strength enclosures are not necessary.

N **A.4.1.3(1)** Disadvantages of oxidant concentration reduction include the following:

(1) Process equipment must be airtight.
(2) It can be ineffective for combustible agents that decompose without an external oxidizer (e.g., ethylene oxide, acetylene).
(3) Costs are relatively high, especially for large systems that require large amounts of inerting agents.
(4) It can create an asphyxiation hazard for workers.

Oxidant concentration reduction introduces the serious safety risk of asphyxiation or suffocation of personnel due to reduced oxygen concentrations in the air. In the chemical industry during 1960–1978, at least seven people were killed by nitrogen (Kletz, 1980). Inerting gases are typically odorless, and people exposed to too low concentrations of oxygen might not experience any warning signals; they can simply lose consciousness and die. Eckhoff (1991) cites 17 to 18 vol. percent of oxygen as the value below which humans suffer serious respiratory problems.

N **A.4.1.3(3)** End-of-line deflagration arresters can prevent combustion in piping by blocking external deflagration from entering the piping.

N **A.4.2** Detonation protection methods based on the prevention or limitation of damage are similar concepts to those used for deflagration prevention; however, the speed of response and system robustness can be significantly different.

N **A.4.2.2** NFPA 69 does not strictly apply to devices or systems designed to protect against detonations; it also offers a framework for their minimum requirements. Detonations are much more severe events than deflagrations, and this fact should be considered during the design of detonation protection systems.

N **A.5.2** A flame arrester that is capable of stopping and extinguishing a deflagration in pipes is called an in-line deflagration arrester. Depending on the mode of installation and the objective of protection, a deflagration arrester can be used in the following situations:

(1) When a deflagration in an enclosure threatens to enter a connected apparatus via a piping system that is necessary for operation *[see Figure A.5.2(a)]*. Flame arresters for this application are called pre-volume flame arresters. Pre-volume flame arresters must be used, for example, at connections between fans and vapor pumps that carry mixtures because, after ignition, unintended ignition and propagation of combustion into a connected apparatus should be prevented.
(2) When a deflagration can propagate in pipes *[see Figure A.5.2(b)]*. Flame arresters that stop a flame that propagates within a pipe are called in-line deflagration arresters. In-line deflagration arresters can be used when the connection between potential ignition sources and safety devices consists only of pipes.

Additional information and application criteria for flame and detonation arresters can be found in Annex F of NFPA 69.

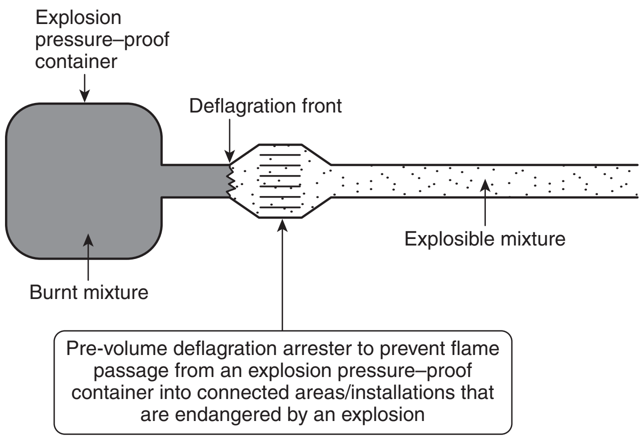
N **A.5.3** In cases where vessels and equipment in plants are connected by pipelines and exposed to explosion hazards, there is a danger that an explosion occurring at a particular location in the plant can be transmitted to other sites by the pipelines. If such explosion propagation occurs, displacement, turbulence, and pre-compression effects can result in excessive explosion pressures or even detonation. A practical solution for the prevention of such a transmission is the provision of suitable appliances to shut certain parts of the plant off from other parts; that is, to isolate the plant from the explosion.

N **A.5.3.1** Particular problems could arise in locations where large vessels are discharged into small vessels or vessels of relatively high strength are connected to vessels of low strength.

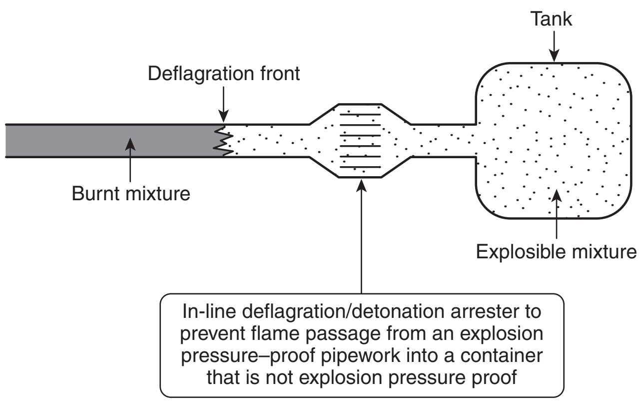
Because deflagrations are always propagated by flames and not by pressure waves, it is especially important to detect, extinguish, or hinder the flame front at an early stage; that is, to isolate or decouple the flame front.

N **A.5.3.2** Isolation systems are generally classified according to their mode of operation as either passive or active systems. Passive isolation systems operate without additional control units; that is, their function (activation) is determined by the physical effect of an explosion.

N **A.5.3.2.1.1** A deflagration arrester is not suitable for isolation of a detonation. See NFPA 69 for design, installation, and maintenance requirements for a deflagration arrester.



N **FIGURE A.5.2(a) Pre-Volume Situation.**



N **FIGURE A.5.2(b) In-Line Situation.**

N **A.5.3.2.1.2** See NFPA 69 for static flame arrester system design considerations. Concerning the pressure and safety against flame transmission, the high-pressure, transient forces generated by detonations are significantly higher than those generated by deflagrations. Nevertheless, detonation arresters should also be rated to prevent the transmission of deflagrations. Most modern test standards fulfill this requirement, so most detonation arresters provide safety against both detonations and deflagrations.

NFPA 69 does not strictly apply to devices or systems designed to protect against detonations; it also offers a framework for their minimum requirements. Detonations are much more severe events than deflagrations, and this fact should be taken into consideration during the design of detonation protection.

N **A.5.3.2.1.4** Pressures experienced during the transition from a deflagration to a detonation can exceed that of a stable detonation wave, and a more robust design is recommended when it could occur at the location of the arrester.

Extraordinarily high-pressure transient forces can occur in the immediate vicinity of a transition from deflagration to detonation. If this transition takes place within a detonation arrester, even flame arresters designed for unstable detonations cannot ensure 100 percent safety. For that reason, multiple layers of protection could be needed to adequately safeguard the system.

N **A.5.3.2.1.7** The design should consider how stresses from adjoining piping can be limited to acceptable levels through the appropriate installation, construction, and selection of materials.

N **A.5.3.2.1.11** Flame pressures and velocities can be enhanced by upstream turbulence, which can be caused by valves, bends, or any change of cross-section in the pipe.

N **A.5.3.3** The detector(s), or sensors, continuously measure certain process parameters and the signals are analyzed by the control unit. If a given threshold value is exceeded—due to, for example, an incipient explosion—the active system intervenes to restrict the effects of the initial explosion. This is achieved by initiating a particular action in an installed device specific to the given situation.

For example, in the case of explosion isolation, a fast-acting valve is closed. The control unit might activate more than one device. These actions are possible only through activation of the device by a signal coming from the control unit. The action of the control unit is initiated by a signal coming from the detector(s), indicating that a process parameter is above a certain threshold value (e.g., pressure).

A single detector or a set of detectors can be installed in equipment. Using a set of detectors improves the reliability of the system and can help prevent false alarms and spurious trips. More detectors are necessary when the equipment is larger than the detection size range of a single detector (especially applicable for optical detectors).

N **A.5.3.3.1** A static detector works in binary mode: activation occurs if a set threshold value is exceeded. If oscillations in the process are possible, a static detector can cause false alarms.

A dynamic detector acquires and analyzes incoming process condition data. The detector might initially run in a learn mode through which process data (e.g., maximum measured static and dynamic pressures and their duration times, light intensities during normal process) can be measured and incorporated into its memory. Through evaluation of this gathered information, threshold values can be automatically tuned to the process conditions with the highest accuracy for proper and error-free operation. Activation takes place after an adjusted set sequence is exceeded; for example, when three adjacent points have sequentially higher values than the triggering value and the increase rate is too high for normal process operation.

This type of detector is recommended for processes that will be subjected to significant variations in pressure or operating at sub-ambient pressures. To minimize false alarms and spurious trips, it is common practice to use two or more static pressure detectors positioned in different places and operated in "and" mode. The selected sensor type must be able to withstand and properly operate in the process environment (corrosion, dust deposition, variation in temperature), meet electrical safety classifications, and distinguish the early combustion reaction of an incipient explosion from normal oscillations in process conditions.

N **A.5.3.3.1.1(1)** Electromagnetic bands emitted by a flame should be considered when choosing a proper optical detector, as flame radiation spectral patterns are characteristic of the burning substance. For instance, a hydrogen flame generates a large amount of UV with very little IR, while a coal fire generates little UV and a large amount of IR.

UV detectors respond to wavelengths between 0.185 mm and 0.245 mm; they have a very fast response time and detect flames within 3–4 ms. UV detectors are not greatly affected by deposits of ice on the lens but can be affected by deposits of grease and oil. Welding operations, lightning, X-rays, high solar radiation, and hot refractory surfaces well above 1600°C (2912°F) can cause false alarms. Smoke and some compounds' vapors, typically those with unsaturated bonds, can also cause signal attenuation.

N **A.5.3.3.1.1(2)** IR detectors respond to wavelengths between 4.1 and 4.6 mm (0.16 in. and 0.18 in.) and their response time is very short (milliseconds). Smoke, lightning, and electrical welding do not cause false alarms in IR detectors, but hot surfaces such as ovens, furnaces, incandescent lamps, and halogen lamps can cause false alarms. Ice formation on the lenses of IR detectors reduces their sensitivity. UV/IR, IR/IR, and multiband IR detectors are triggered if radiation is detected in multiple wavelength regions. Owing to this feature, multiwavelength detectors are much more reliable than single-band detectors and are used in outdoor operations where the atmosphere does not absorb radiation. Multiwavelength detectors can be set to not respond to ambient radiation.

N **A.5.3.3.1.1(3)** Piezoelectric and piezoresistive pressure sensors are triggered by a rate of pressure rise or pressure increase above a threshold value. Because the flame front and pressure wave are separated from one another for deflagrations (the pressure wave moves ahead of the flame front), pressure-based detectors are very successful at detecting explosions in closed units in the early stages.

In the case of deflagrations in a pipeline, flame speed and pressure generation are strongly dependent on fuel composition. A flame can propagate close to the flammability limit without the generation of significant overpressure. Hence, in such cases, using a pressure sensor as an explosion indicator might not work (Chatrathi, et al., 2001).

N **A.5.3.3.1.1(4)** Thermoelectric detectors are triggered by heat coming from hot combustion regions. These detectors are not recommended for explosion applications, as they only work effectively if they are located close to the heat source. Thus, they are far too slow to respond in case of an explosion. Owing to their low price, thermoelectric detectors are commonly used in fire detection systems.

N **A.5.3.3.2** The role of the control unit is to analyze signals (determine whether an explosion hazard exists) and initiate proper action(s) if required.

N **A.5.3.3.2.2** In most cases, multiple detectors and action devices can be controlled by one centralized control system. An audible or visual alarm is usually connected to the control unit to alarm nearby personnel.

N **A.5.3.3.3** The design and characteristic action of the active device(s) depend on the system used.

N **A.5.3.3.3.1** NFPA 69 does not strictly apply to devices or systems designed to protect against detonations but offers a framework for their minimum requirements. Detonations are much more severe events than deflagrations, and this fact should be considered during the design of detonation protection.

N **A.5.3.3.3.2** NFPA 69 does not strictly apply to devices or systems designed to protect against detonations but offers a framework for their minimum requirements. Detonations are much more severe events than deflagrations, and this fact should be considered during the design of detonation protection.

N **A.5.3.3.3.3** See NFPA 69 for system testing considerations for active isolation systems.

N **A.6.1** The philosophy of the detonation containment method is to design a sufficiently strong vessel that can withstand maximum explosion pressure. Donat (1978) introduced two distinctions in designing pressure-resistant equipment: explosion pressure-resistant equipment and pressure shock-resistant equipment. Explosion pressure-resistant equipment applies to a pressure vessel that is capable of withstanding explosion pressures (Section VIII-3 of the *Boiler and Pressure Vessel Code*).

There are certain applications for which detonations can occur, but a detonation containment strategy might not be feasible, such as in lightweight ductwork far from occupied spaces or critical pieces of equipment.

N **A.6.1.1** The pressure shock-resistant equipment approach assumes that an explosion is permitted to cause slight permanent deformation of the process unit as long as the unit does not rupture. This means that, for a given expected maximum explosion pressure, a considerably less heavy and less expensive construction is designed than would be required for explosion pressure-resistant equipment. Pasman and van Wingerden (1988) discussed the influence of the dynamic characteristics of explosion loads on structural response and pointed out that typical dust explosion pressure pulses in industrial equipment have a duration time in the range of 0.1 second to 1 second. Pritchard (1983) obtained similar results.

Owing to the short duration of the maximum explosion pressure (heat loss to the walls, overpressure spreading to other unit elements), another type of design has been envisaged: explosion pressure shock-resistant design. A vessel of this design should be able to withstand the maximum explosion pressure for a short period of time without any deformation.

N **A.6.2** The Chapman-Jouguet (CJ) detonation theory was proposed in the early 1900s and is based on pure gas dynamic and thermodynamic arguments that assume infinitely fast chemistry.

N **A.6.2.2** This theory combines analysis based on the conservation of mass, energy, and momentum with basic thermodynamics. It is a one-dimensional model and assumes that the reaction rate is infinitely fast. The model's representation of a detonation, with an infinitely thin reaction zone, is known as an ideal detonation. The model neglects the high momentary pressure in the von Neumann spike at the leading edge of the detonation wave. A CJ analysis can be used to calculate detonation properties such as velocity and pressure. The predicted values compare reasonably well with experimental data (Lee, 1984; Nettleton, 1987), and the model is still widely used.

N **A.6.2.3** The CJ model cannot be used to calculate parameters that require knowledge of the structure of the detonation wave, such as the detonation limits, initiation energy, critical pipe diameter, or thickness of the reaction zone.

N **A.6.3.1** Detonation propagation in a straight pipe produces a spatially non-uniform pressure load, as shown in Figure 6.3.1. For a pipe with a closed end, the situation can be characterized as three separate regions. First, there is the unreacted gas mixture, which is at the initial pressure, P_1, ahead of the propagating detonation front. The pressure at a fixed location jumps up suddenly to pressure P_2 when the detonation front arrives there. The peak pressure, P_2, which is just behind the front, can be approximated by the CJ value and computed with various thermochemical equilibrium codes, such as those in McBride and Gordon (1992). The detonation front is followed by an expansion wave, called the Taylor wave, that extends to approximately midway between the wave front and the initiation end of the pipe. Behind the expansion wave, the gas is stationary, and the pressure P_3 in this region is approximately 0.4 P_{CJ}.

N **A.6.3.2** The transient pressure load at a given position in a pipe should have the characteristic shape shown in Figure 6.3.2 prior to any reflections from closed valves or tube end walls. The peak pressure is effectively the CJ pressure, and the residual pressure far behind the detonation front is the same pressure, $P_3 \approx 0.4\ P_{CJ}$, shown in Figure 6.3.2. The fluctuations behind the detonation front are produced by transverse waves propagating in a radial direction in the pipe.

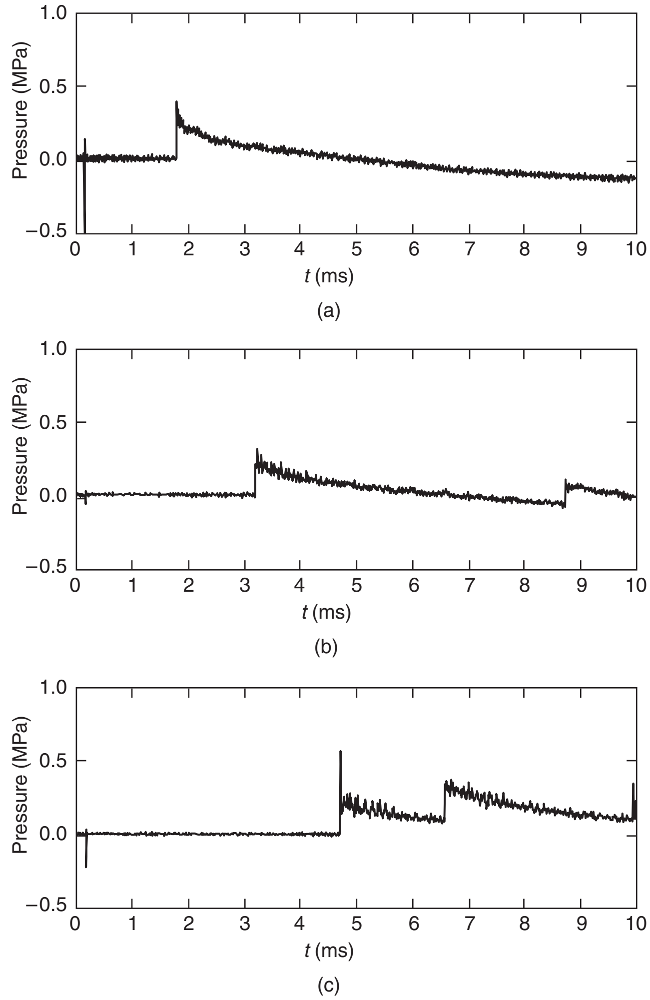
N **A.6.4.1** At later times, when a reflected detonation wave arrives at the same pipe location, there is a second distinct shock wave and expansion wave, as seen in Figure A.6.4.1(a). The corresponding transducer locations from the reference test are shown in Figure A.6.4.1(b). The reflected detonation wave peak pressure is often about 2 times the incident pressure at the end wall and decays as it propagates back down the pipe.

N **A.6.4.3** Peak pressures shortly after a DDT are often significantly higher than the CJ detonation pressure. The increased peak pressure is caused by the pre-compression of the gas mixture ahead of the flame front as the flame accelerates. Large flame accelerations can produce shock waves that cause the local pressure to be a multiple of the initial pressure when the flame front arrives at that location. These so-called overdriven detonations associated with pressure piling have detonation front pressures 1.5 to 4.5 times the CJ pressure and usually occur in only a small length of pipe surrounding the location of the DDT.

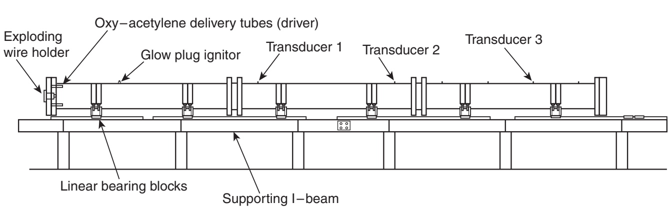
The worst-case situation occurs when a DDT occurs near a closed valve or the closed end of a pipe so that the reflected pressure increase compounds the pressure piling effect. In that case, peak pressures can be 10 times the CJ pressure (Kuznetsov, et al., 2009; Ligon, Gross, and Minichiello, 2017). Since DDT run-up distance is longer for less reactive gas mixtures than for stoichiometric mixtures (and can therefore occur closer to the closed end of the pipe), a less reactive gas mixture can sometimes produce a more severe detonation load on a closed pipe.

N **A.6.5** This section provides practical guidance based on experience and testing.

Experiments have shown that pipelines designed for a nominal pressure of 10 bar tend to rupture at the points where DDTs occur but can withstand steady-state detonation pressure



N **FIGURE A.6.4.1(a) Measured Pressure Signals for a Detonation Propagating at 1267 m/s in the GALCIT Large Detonation Tube. A) transducer 1. B) transducer 2. C) transducer 3. (Source: Shepherd, 2009)**



N **FIGURE A.6.4.1(b) The GALCIT Large Detonation Tube Facility. (Source: Shepherd, 2009)**

without rupturing (Bartknecht, 1981; Bjerketvedt, et al., 1997). This is due to the short duration of the transient overpressure.

Failure of a pipeline can occur at fairly regular intervals due to galloping detonation. Such failure is caused by the acceleration of the flame up to detonation, followed by the quenching of the unstable overdriven wave as the pipe fails. This process is repeated as the flame re-accelerates (Munday, 1971).

Failure occurs in regions such as bends and junctions due to the high pressures generated by the partial reflection of an incident wave (Williams, 1998). Damage is less severe for more gradually sweeping bends and junctions (a ratio of the radius of the curvature to the bore radius of at least 5), as a large bend radius helps to preserve the planar nature of the front as it propagates around the bend. The bend configuration has a critical effect on the point at which the maximum pressure is generated (Thomas and Williams, 2002).

A detonation exerts tremendous stress on pipe mountings as well as on pipes themselves, and pipes typically bounce off their supports (Williams, 1998). Failure usually occurs because the supports are designed to carry the static pipe load, not severe internal transient pressures (Thomas, 2002).

N **A.6.5.1** The guidance provided in this section is based on German TRGS 509, which provides guidance on how to design piping in combination with flame arresters.

Analytical equations for calculating pipe wall strain due to detonations are included in Section 6.6. Criteria to determine whether the calculated wall strain will produce permanent pipe deformation or pipe rupture are included in 6.6.1.7 and 6.6.2, respectively.

N **A.6.6** Depending on the magnitude and duration of the transient detonation wave pressure and the pipe wall dimensions, yield strength, and ductility, the pipe structural response will be in either the elastic or plastic regime. The current understanding of detonation load-induced plastic deformation and pipe rupture is less developed than it is for elastic deformation.

N **A.6.6.1.1** Equation 6.6.1.1 is based on the simultaneous fourth order differential equations of motion for the hoop strains in thin-walled piping based on shell theory and Newton's Law. Thick-walled pipe that is typical in piping designs has been shown to have a maximum dynamic load factor of 4.

Material properties can be determined with small-scale tensile tests. A typical stress-strain curve for a ductile material is shown in Marin (1926). The magnitude of strain at a given stress can be significantly different for different materials [see Marin (1926)].

Tensile tests establish several material properties, including the yield strength, ultimate strength, and elastic modulus, E (Young's modulus of elasticity). The yield strength is also referred to as the yield stress, which is frequently specified at ε_y of 0.002 = 0.2 percent to overcome initial material instabilities in some ductile materials. The ultimate strength is also referred to as the ultimate stress and the tensile strength. One type of tensile test uses a 50.8 mm (2-in.) long, 12.7 mm (½-in.) diameter test section of a bar that is elongated at a maximum strain rate of 1.6 mm to 12.7 mm per mm (1⁄16 to ½ in. per in.) per minute for the determination of the yield and tensile strengths. The bar is strained until it snaps. Alternatively, standards permit smaller diameter bars or flat or curved plate specimens to be tested as required.

Note that these standard tensile tests provide ultimate strength values that are lower than the failure strengths during explosions. That is, strain rates affect the material properties as shown. As mentioned, tensile test strain rates are controlled to provide tensile test data comparable to the codes (ASTM A370).

However, explosions subject piping to different strain rates, and strain rate effects are pertinent during dynamic loading. Additionally, the strain rate significantly affects both the yield strength and ultimate tensile strength [see Manjoine (1944)]. Note that as the strain rate increases, both the yield and ultimate strength increase and the yield strength approaches the value of the ultimate strength. One implication of this is that at very high strain rates, the material might respond to sudden loads elastically rather than plastically. This effect is not as pronounced as material temperature increases (Leishear, 2013).

N **A.6.6.1.2** At this time, Equation 6.6.1.1 has only proven to be valid for thin-walled piping; it is not applicable for thick-walled piping (Leishear, 2013 and 2015). This work showed that the DLF was less than 4 for a 50 mm (2 in.), Schedule 40 pipe where Equation 6.6.1.1 found that the DLF equaled 1.1. More research is required to clearly understand piping strains due to explosions.

Bitter and Shepherd (2015) showed that Equation 6.6.1.1 is applicable to short, thin-walled piping.

Leishear demonstrated that DLFs were less than 4 for pipes, but further research is required to understand DLFs for different piping lengths and diameters. Even so, that work concluded that 6.6.1.1 is inapplicable to thick-walled piping. Again, more research is required to clearly understand piping strains due to explosions.

Bitter and Shepherd (2015) also found that shell theory and the experiment disagreed, but they concluded that shell theory was not disproven.

N **A.6.6.1.3** Because the higher peak pressures associated with overdriven DDT effects, elbows, reducers, and end-wall reflections described in Section 6.4 can produce correspondingly larger pipe wall deformations, the DLF values in 6.6.1.3 through 6.6.1.5 are not necessarily upper bounds.

N **A.6.6.2.1** Pipe wall deformations in the plastic regime are more complex and difficult to characterize than elastic deformations. Material strain hardening and strain rate effects, as well as detonation development history, need to be accounted for in plastic regime characterization.

N **A.6.6.2.2** During explosions, the equation from Cooper (1957) can significantly under-predict ductile material catastrophic failures because dynamic yield stresses and dynamic ultimate strengths (S_u) increase during sudden force or pressure loads.

Shepherd (2009) reported that deflagration-to-detonation transitions triggered the pipe ruptures shown in Figure A.6.6.2.2. As the photographs indicate, these pipes showed fragmentation and multiple fractures.

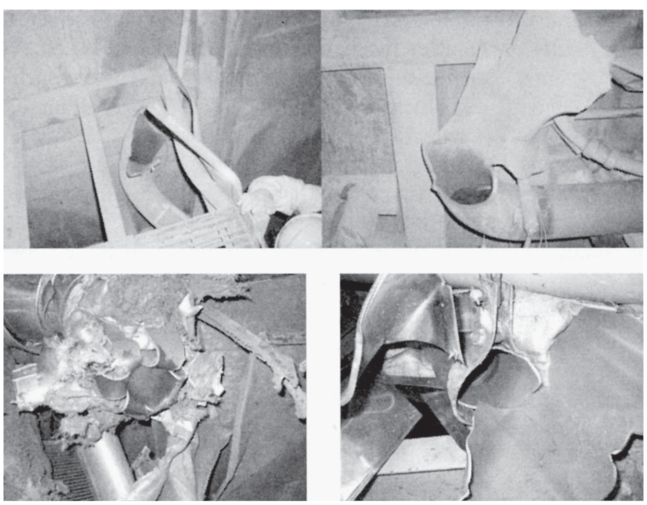
N **A.6.6.2.3** Calculations of dynamic loading-induced transient plastic deformations usually entail using finite element model (FEM) computer models. However, under certain conditions, as described by Shepherd (2009) and Karnesky (2010), single degree-of-freedom, radial-deformation-only analytical modeling can be used as an approximation away from pipe end walls and valves. According to Karnesky (2010), this analytical modeling produced reasonably accurate computations of the residual plastic strain resulting from a reflecting detonation for axial locations several bending lengths away from the reflecting boundary. The measured maximum strains for a mild steel tube with an inner diameter of 127 mm (5 in.), a wall thickness of 1.5 mm (0.06 in.), and a length of 1.2 m (3.9 ft) subjected to reflected detonation loads were about 0.05 for a 2 bar initial pressure and about 0.19 for a 3 bar initial pressure. These measured maximum strains, which occurred at distances of 3 cm to 6 cm (1.2 in. to 2.4 in.) from the pipe rigid end wall, are 17 to 63 times the static yield strain. See Cooper (1957).

N **A.6.6.2.4** When a pipe wall contains a flaw, such as a surface scratch, crack propagation and pipe rupture can occur at much lower strains and detonation pressures and without the fragmentation shown in Figure A.6.6.2.2. For example, a predetonation, 1.27 cm (0.5 in.) scratch in an aluminum tube produced the rupture pattern shown in Figure A.6.6.2.4.

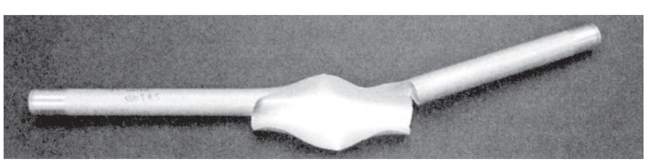
The maximum strains measured prior to the rupture of the flawed, thin-wall piping were approximately 0.007 (Chao and Shepherd, 2003). Such an explosion depends on the elastic deformation of the pipe wall where fracture mechanics theory describes such failures (API 579-1/ASME FFS-1).

The increased propensity of flawed pipes to rupture under detonation loads demonstrates the importance of frequent visual inspections and periodic nondestructive testing of pipe wall thicknesses. The frequency of inspection will depend on the specific scenario, as factors like corrosive environments and the presence of higher reactivity fuels might necessitate more frequent inspections (API 579-1/ASME FFS-1).

N **A.7.1.1** In-line detonation flame arresters are recommended because the ignition source is likely to be remote from the protected vessel. For systems that contain flammable atmospheres during nonroutine operations, such as commissioning and decommissioning, the selection of mitigation strategies should be commensurate with the risk.



N **FIGURE A.6.6.2.2 Pipe Ruptures Due to Detonations. (Source: Shepherd, 2009; credit: Linda Hall Library of Science, Engineering, and Technology)**



N **FIGURE A.6.6.2.4 Detonation-Induced Rupture in a Flawed Aluminum Tube. (Source: Shepherd, 2009; credit: Linda Hall Library of Science, Engineering, and Technology)**

N **A.7.1.2** When detonation flame arresters are added, it is important that the use of the devices does not introduce a new risk (e.g., plugged vent or process lines, which could result in equipment overpressure).

N **A.7.1.3** The best technology for the suction line is a foot valve *(see NFPA 69)*. For the filling line, a liquid seal should be used. These devices have the advantage of being almost maintenance free.

N **A.7.1.5** To avoid exceeding a vessel's maximum allowable working pressure (MAWP) and maximum allowable working vacuum (MAWV), a vent pipe to the atmosphere is typically installed.

N **A.7.2.1.1** Some aboveground storage vessels are filled from the top due to certain operational conditions. If the likelihood exists that the filling or emptying line could be drained and a flammable atmosphere could be created from the stored liquid and air, a liquid product or static detonation flame arrester should be installed to protect against possible detonations.

N **A.7.2.2** Other options for protecting aboveground tanks using inerting with or without flame arresting devices are provided in Annex F of ISO 28300 and API 2000.

N **A.7.2.2.2.1** In case of failure of the vapor-balancing system, a flammable mixture can escape through the flame arrester if the temperature in the tank rises or if the tank is filled. This can create a situation in which a flame is stabilized at the flame arrester itself.

N **A.7.2.2.4** Additional venting requirements might be necessary due to the presence of an inerting system on the tank.

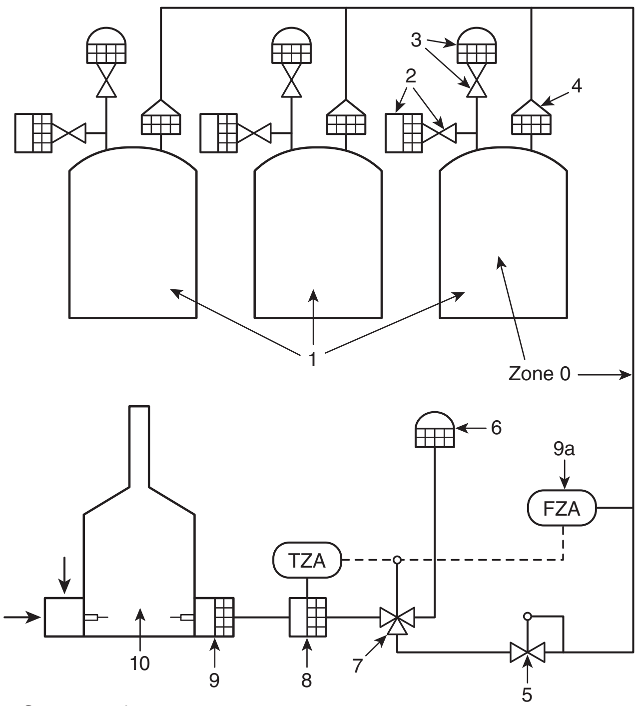
N **A.7.3** An example of a properly protected waste gas system is shown in Figure A.7.3.

N **A.7.3.1.1** This can be achieved by monitoring and controlling the velocity of the feed flow. Depending on the explosion group of the expected mixture and the diameter and maximum operating temperature of the feeding pipe, minimum values of the flow velocity should be obtained. In this example, the minimum flow velocity at the burner is produced with the aid of a jet of auxiliary gas.

N **A.7.3.1.2** Temperature monitoring is necessary because flammable mixtures flow through these systems for a long time, allowing for the formation of stabilized flames at the arrester itself. In the case of a drop in the flow velocity or a response from the temperature monitor, inert gas is fed in immediately (7 in Figure A.7.3) and, at the same time, the waste gas flow is diverted to the atmosphere as quickly as possible.

N **A.7.3.2** Temperature monitoring is not necessary for flame arresters installed in waste gas lines near storage tanks, as studies have shown that the formation of a permanent flame is extremely improbable if the pipe between the static detonation arrester and the ignition source has a certain minimum length (Thomas, 2002). In that case, the flame is pushed into the quenching channels of the arrester by the pressure of the burnt fumes and is immediately extinguished.

N **A.7.3.3** The rationale for this is further explained in Thomas, et al. (2000).



N **FIGURE A.7.3 Protection of Process Unit and Tank Farm from Thermal Oxidizer.**

N **A.7.4** In this section, it is assumed that flammable liquids are stored and processed and the vapors are recovered by a carbon adsorption unit. The internal area of the storage vessels, process vessels, and piping is defined as zone 0. Carbon adsorption units can be thermally regenerated, typically operating below the lower flammable limit (LFL), or vacuum regenerated, typically operating within and above the flammable range.

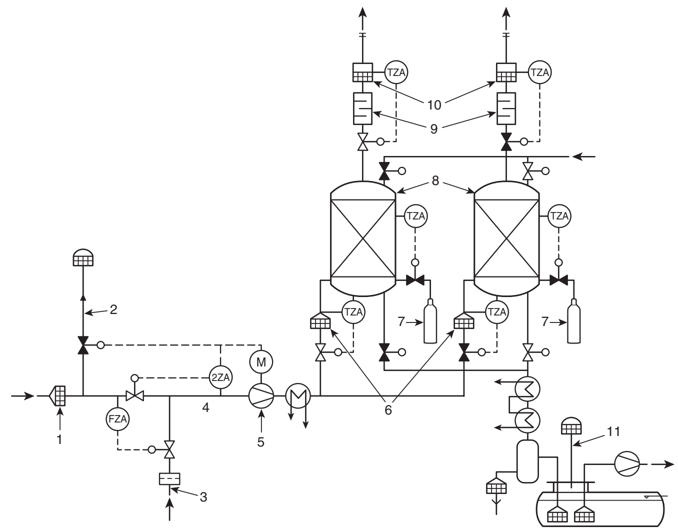
N **A.7.4.1** An example of the recommended protection strategy for a typical thermally regenerated carbon adsorption unit is shown in Figure A.7.4.1.

N **A.7.4.1.1** This measure, if controlled properly, is the primary measure for explosion prevention. Additional explosion isolation measures are needed, however, as carbon adsorption vessels are not designed to be explosion-pressure proof; during the regenerative cycles, it cannot be ensured that the vapor-air mixture will remain below 50 percent of the LFL.

N **A.7.4.1.2** A detonation arrester is necessary because the ignition source might be far away.

N **A.7.4.1.5** See Schampel(1988).

N **A.7.4.2.1** Carbon bed flammable vapor adsorption systems often use vacuum regeneration of the carbon bed after it has



N **FIGURE A.7.4.1 Protection Strategy for a Typical Thermally Regenerated Carbon Adsorption Unit for Solvent Recovery.**

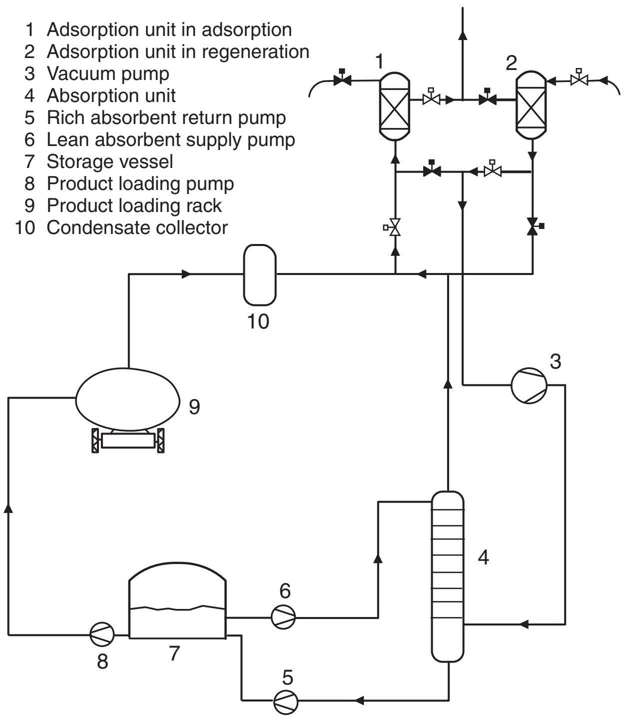
been highly saturated with hydrocarbons. Flammable vapor-air mixtures can form in the piping leading to the adsorbing mode carbon bed and in the piping between the vacuum pump and the twin carbon bed unit operating in the vacuum generation mode. *(See Figure A.7.4.2.1.)*

Although many of these systems have operated safely for a long time, the potential for an ignition source in the equipment or instrumentation connected to this flammable mixture piping cannot be ruled out. During the desorbing process, the dry running vacuum pump can potentially act as an ignition source. High temperatures in the active carbon bed due to high inlet vapor loads can also represent a potential ignition source. The result would be flame propagation and explosion development in the piping.

N **A.7.5** Figure 7.5 shows the protection strategy for a vacuum pump. A vacuum pump should be protected with either an arrester specifically tested for the vacuum pump or a detonation arrester.

N **A.9.1.7** The suitable time intervals depend mainly on the consistency of the products in the plant and on the mixtures that flow through the devices. In general, "clean products" (e.g., solvents, alcohols, fuels) need only one check per year. Product contamination, possible polymerization, or other types of deposits could lead to much shorter maintenance intervals to prevent hazardous blocking of elements that are important for proper function.

N **A.9.3.2** Heat transfer can reduce performance and even cause the system to fail.



N **FIGURE A.7.4.2.1 Typical Simplified Diagram of a Vacuum-Regenerated Carbon Adsorption Unit.**

N **A.9.4.1** The frequency should depend on the environmental and service conditions to which the devices will be exposed. Process or occupancy changes that can introduce significant changes in condition, such as changes in the severity of corrosive conditions or increases in the accumulation of deposits or debris, might necessitate more frequent inspection.

N **A.9.7** The cleaning methods used will depend on the nature of the process material that is fouling the element and the manufacturer's specific instructions.

Cleaning methods include brushing, caustic wash, drainage (in the event of liquid entrainment), solvent wash, steam cleaning, ultrasonics, water wash, and compressed air.

Annex B Examples of Calculations of Suitable Pipe Wall Thickness for Pipe Wall Elastic Response to Stable Detonations

This annex is not a part of the recommendations of this NFPA document but is included for informational purposes only.

B.1 General. Four calculation examples are given in Sections B.2 through B.5 for the elastic regime response of a pipe for the case of a stable detonation. The calculation procedure follows the equations given in 6.6.1. The Chapman and Jouguet pressure and velocity values from Table 6.2.2 for the following gases are used as a basis:

(1) Hydrogen
(2) Ethylene
(3) Propane
(4) Methane

The examples in Sections B.2 through B.5 determine the minimum pipe thickness to prevent permanent deformation of the pipe subject to a stable detonation scenario. Deflagration-to-detonation transition (DDT) and other phenomena, such as pressure piling or pressure wave reflections, may increase the required pipe wall thickness significantly as discussed in Sections 6.4 and 6.5, and in 6.6.2. A comprehensive overview of detonation scenarios is given by Schildberg, 2016. [1,2]

The calculation examples are based on the characteristic data for a stable detonation from Table 6.2.2, which are valid for the following:

(1) Ambient initial conditions of the gas in the pipe—approximately a pressure of 1 bar absolute and a temperature of 15°C
(2) Maximum stoichiometric concentration of the reactive gas in air

A significant input is the elastic strain limit for the pipe material of construction. For some materials the elastic strain limit can be clearly determined from the stress-strain curve. However, for numerous alloy steels the stress-strain curve does not exhibit a clear elastic limit and instead the limit is typically set in design codes at 0.2 percent or a strain fraction of 0.002.

The examples are all at near-ambient temperature. The Young's modulus and yield stress decrease with increased temperature and this has significant effect on the minimum thickness. The user should reference design codes for the appropriate values, depending on normal operating temperature.

B.2 Example 1 — Stable Detonation of a Hydrogen-Air Mixture.

Δ **B.2.1 Input Data.** A hydrogen-air mixture is flowing through a 4 in. stainless steel pipe with schedule 10S according to ASTM A312/A312M, Grade 316 (1.4401). The mixture is assumed to have the maximum stoichiometric concentration for hydrogen in air. (*See Table B.2.1.*)

Δ **Table B.2.1 Example 1 Equation Data**

R = 57.15 mm	outer pipe radius (0.5·114.30 mm)
h = 3.05 mm	pipe wall thickness
E = 193,000 N/mm²	pipe material Young's modulus of elasticity
ρ = 8000 kg/m³	pipe material mass density
ν = 0.27	pipe material Poisson ratio
ε_y = 0.2%	maximum material strain that will prevent permanent deformation
U_{CJ} = 1968 m/s	Chapman and Jouguet velocity from Table 6.2.2
ΔP_{CJ} = 15.8 bar	Chapman and Jouguet pressure difference from Table 6.2.2
p_1 = 1 bar a	initial pressure of the unburned gas
T_1 = 15°C	initial temperature of the unburned gas

Δ **B.2.2 Required Wall Thickness.** First, based on Equation 6.6.1.1, the critical wave speed V_{r0} of the pipe's radial bending mode is calculated as shown in Equation B.2.2a:

[B.2.2a]

$$V_{r0} = \left[\frac{E^2h^2}{3\rho^2R^2(1-v^2)}\right]^{1/4}$$
$$V_{r0} = \left[\frac{\left(1.93\cdot10^{11}\frac{N}{m^2}\cdot3.05\cdot10^{-3}m\right)^2}{3\left(8\cdot10^3\frac{kg}{m^3}\cdot3.05\cdot10^{-3}m\right)^2\cdot(1-0.27^2)}\right]^{1/4}$$
$$V_{r0} = 878.6\frac{m}{s}$$

The Chapman and Jouguet velocity is larger than the critical wave speed.

[B.2.2b]

$$U_{CJ}\left(=1968\frac{m}{s}\right) > V_{r0}\left(=878.6\frac{m}{s}\right)$$

According to 6.6.1.5 the dynamic load factor DLF=2.

The Chapman and Jouguet detonation properties according to Table 6.2.2 are valid because the unburned gas is at ambient conditions (p_1=1 bar a, T_1=15°C).

Based on Equation 6.6.1.7, the minimum required pipe wall thickness is determined as shown in Equation B.2.2c:

[B.2.2c]

$$h \geq DLF\frac{R\Delta P_{CJ}(1-\nu^2)}{E\varepsilon_y}$$
$$h \geq \frac{2\cdot3.05\cdot10^{-3}m\cdot1.58\cdot10^6\frac{N}{m^2}(1-0.27^2)}{1.93\cdot10^{11}\frac{N}{m^2}\cdot0.002}$$
$$h \geq 4.34\cdot10^{-4}m$$
$$0.434\text{ mm} \leq h = 3.05\text{ mm}$$

The 4 in. pipe, schedule 10S is expected to withstand a stable detonation without permanent deformation.

Detailed experimental data specifically for hydrogen-air mixtures on the pipe response induced by detonation phenomena is given by Schildberg, 2015. [3]

B.3 Example 2 — Stable Detonation of an Ethylene-Air Mixture.

Δ **B.3.1 Input Data.** An ethylene-air mixture is flowing through a 2 in. stainless steel pipe with schedule 40S, according to ASTM A312/A312M, Grade 316 (1.4401). The mixture is assumed to have the maximum stoichiometric concentration for ethylene in air. (*See Table B.3.1.*)

Δ **B.3.2 Required Wall Thickness.** Based on Equation 6.6.1.1, the critical wave speed V_{r0} of the pipe's radial bending mode is calculated as shown in Equation B.3.2a:

Δ **Table B.3.1 Example 2 Equation Data**

R = 30.17 mm	outer pipe radius (0.5·60.33 mm)
h = 3.91 mm	pipe wall thickness
E = 193,000 N/mm²	pipe material Young's modulus of elasticity
ρ = 8000 kg/m³	pipe material mass density
ν = 0.27	pipe material Poisson ratio
ε_y = 0.2%	maximum material strain that will prevent permanent deformation
U_{CJ} = 1822 m/s	Chapman and Jouguet velocity from Table 6.2.2
ΔP_{CJ} = 18.6 bar	Chapman and Jouguet pressure difference from Table 6.2.2
p_1 = 10 bar a	initial pressure of the unburned gas
T_1 = 15°C	initial temperature of the unburned gas

[B.3.2a]

$$V_{r0} = \left[\frac{E^2h^2}{3\rho^2R^2(1-v^2)}\right]^{1/4}$$
$$V_{r0} = \left[\frac{\left(1.93\cdot10^{11}\frac{N}{m^2}\cdot3.91\cdot10^{-3}m\right)^2}{3\left(8\cdot10^3\frac{kg}{m^3}\cdot3.91\cdot10^{-3}m\right)^2\cdot(1-0.27^2)}\right]^{1/4}$$
$$V_{r0} = 1369.2\frac{m}{s}$$

The Chapman and Jouguet velocity is larger than the critical wave speed.

[B.3.2b]

$$U_{CJ}\left(=1822\frac{m}{s}\right) > V_{r0}\left(=1369.2\frac{m}{s}\right)$$

According to 6.6.1.5 the dynamic load factor DLF=2.

Note: The Chapman and Jouguet detonation properties taken from Table 6.2.2 are *NOT valid* because the unburned gas is at an increased pressure (p_1=10 bar a, T_1=15°C). Instead of using a thermodynamic equilibrium program, the pressure difference at an increased initial pressure $\Delta P_{CJ,1}$ may be approximated within a few percent by:

[B.3.2c]

$$\Delta P_{CJ,1} = \left(\frac{\Delta P_{CJ}+1\text{ bar}}{1\text{ bar}}\right)\cdot p_1 - 1\text{ bar}$$
$$\Delta P_{CJ,1} = \left(\frac{18.6+1\text{ bar}}{1\text{ bar}}\right)\cdot p_1 - 1\text{ bar}$$
$$\Delta P_{CJ,1} = 195.0\text{ bar}$$

Based on Equation 6.6.1.7, the minimum required pipe wall thickness is determined by using the Chapman and Jouguet pressure difference at an increased initial pressure $\Delta P_{CJ,1}$ as shown in Equation B.3.2d:

[B.3.2d]

$$h \geq DLF\frac{R\Delta P_{CJ,1}\left(1-\nu^2\right)}{E\varepsilon_y}$$

$\Delta P_{CJ,1}$ for an increased initial pressure:

$$h \geq \frac{2\cdot 3.91\cdot 10^{-3}\text{m}\cdot 1.95\cdot 10^{7}\,\frac{\text{N}}{\text{m}^2}\left(1-0.27^2\right)}{1.93\cdot 10^{11}\,\frac{\text{N}}{\text{m}^2}\cdot 0.002}$$

$$h \geq 2.83\cdot 10^{-3}\text{m}$$

$$2.83\text{ mm} \leq h = 3.91\text{ mm}$$

The given 2 in. pipe, schedule 40S, is expected to withstand a stable detonation without permanent deformation.

B.4 Example 3 — Stable Detonation of a Propane-Air Mixture.

Δ **B.4.1 Input Data.** A propane-air mixture is flowing through a 2 in. stainless steel pipe with schedule 5S according to ASTM A312/A312M, Grade 316 (1.4401). The mixture is assumed to have the maximum stoichiometric concentration for propane in air. (*See Table B.4.1.*)

Δ **B.4.2 Required Wall Thickness.** Based on Equation 6.6.1.1, the critical wave speed V_{r0} of the pipe's radial bending mode is calculated as shown in Equation B.4.2a:

Δ **Table B.4.1 Example 3 Equation Data**

R = 30.17 mm	outer pipe radius (0.5·60.33 mm)
h = 1.65 mm	pipe wall thickness
E = 193,000 N/mm²	pipe material Young's modulus of elasticity
ρ = 8000 kg/m³	pipe material mass density
ν = 0.27	pipe material Poisson ratio
ε_y = 0.2%	maximum material strain that will prevent permanent deformation
U_{CJ} = 1804 m/s	Chapman and Jouguet velocity from Table 6.2.2
ΔP_{CJ} = 18.6 bar	Chapman and Jouguet pressure difference from Table 6.2.2
p_1 = 1 bar a	initial pressure of the unburned gas
T_1 = 15°C	initial temperature of the unburned gas

[B.4.2a]

$$V_{r0} = \left[\frac{E^2h^2}{3\rho^2R^2\left(1-\upsilon^2\right)}\right]^{1/4}$$

$$V_{r0} = \left[\frac{\left(1.93\cdot 10^{11}\,\frac{\text{N}}{\text{m}^2}\cdot 1.65\cdot 10^{-3}\text{m}\right)^2}{3\left(8\cdot 10^{3}\,\frac{\text{kg}}{\text{m}^3}\cdot 1.65\cdot 10^{-3}\text{m}\right)^2\cdot\left(1-0.27^2\right)}\right]^{1/4}$$

$$V_{r0} = 889.5\,\frac{\text{m}}{s}$$

The Chapman and Jouguet velocity is larger than the critical wave speed.

[B.4.2b]

$$U_{CJ}\left(=1804\,\frac{\text{m}}{\text{s}}\right) > V_{r0}\left(=889.5\,\frac{\text{m}}{\text{s}}\right)$$

According to 6.6.1.5, the dynamic load factor DLF=2.

The Chapman and Jouguet detonation properties according to Table 6.2.2 are valid because the unburned gas is at ambient conditions (p_1=1 bar a, T_1=15°C).

Based on Equation 6.6.1.7, the minimum required pipe wall thickness is determined as shown in Equation B.4.2c:

[B.4.2c]

$$h \geq DLF\frac{R\Delta P_{CJ}\left(1-\nu^2\right)}{E\varepsilon_y}$$

$$h \geq \frac{2\cdot 1.65\cdot 10^{-3}\text{m}\cdot 1.86\cdot 10^{6}\,\frac{\text{N}}{\text{m}^2}\left(1-0.27^2\right)}{1.93\cdot 10^{11}\,\frac{\text{N}}{\text{m}^2}\cdot 0.002}$$

$$h \geq 2.70\cdot 10^{-4}\text{m}$$

$$0.270\text{ mm} \leq h = 3.65\text{ mm}$$

The given 2 in. pipe, schedule 5S is expected to withstand a stable detonation without permanent deformation.

B.5 Example 4 — Stable Detonation of a Methane-Air Mixture.

Δ **B.5.1 Input Data.** A methane-air mixture is flowing through a 3 in. stainless steel pipe with schedule 40S, according to ASTM A312/A312M, Grade 316 (1.4401). The mixture is assumed to have the maximum stoichiometric concentration for methane in air. Subsection D.2.3 indicates that methane-air mixtures cannot sustain stable C-J detonations in pipe diameters smaller than 4 in. However, stable detonations can occur at higher initial pressures because the cell size decreases. There are other types of detonations or high-speed deflagrations that have been observed in smaller pipe diameters with methane. [4] (*See Table B.5.1.*)

Δ **Table B.5.1 Example 4 Equation Data**

R = 44.45 mm	outer pipe radius (0.5·88.90 mm)
h = 5.49 mm	pipe wall thickness
E = 193,000 N/mm²	pipe material Young's modulus of elasticity
ρ = 8000 kg/m³	pipe material mass density
ν= 0.27	pipe material Poisson ratio
ε_y = 0.2%	maximum material strain that will prevent permanent deformation
U_{CJ} = 1802 m/s	Chapman and Jouguet velocity from Table 6.2.2
ΔP_{CJ} = 17.4 bar	Chapman and Jouguet pressure difference from Table 6.2.2
p_1 = 12 bar a	initial pressure of the unburned gas
T_1 = 15°C	initial temperature of the unburned gas

Δ **B.5.2 Required Wall Thickness.** Based on Equation 6.6.1.1, the critical wave speed V_{r0} of the pipe's radial bending mode is calculated as shown in Equation B.5.2a:

[B.5.2a]

$$V_{r0} = \left[\frac{E^2h^2}{3\rho^2R^2\left(1-v^2\right)}\right]^{1/4}$$
$$V_{r0} = \left[\frac{\left(1.93\cdot10^{11}\,\frac{\text{N}}{\text{m}^2}\cdot5.49\cdot10^{-3}\,\text{m}\right)^2}{3\left(8\cdot10^3\,\frac{\text{kg}}{\text{m}^3}\cdot5.49\cdot10^{-3}\,\text{m}\right)^2\cdot\left(1-0.27^2\right)}\right]^{1/4}$$
$$V_{r0} = 1336.7\,\frac{\text{m}}{\text{s}}$$

The Chapman and Jouguet velocity is larger than the critical wave speed.

[B.5.2b]

$$U_{CJ}\left(=1802\,\frac{\text{m}}{\text{s}}\right) > V_{r0}\left(=1336.7\,\frac{\text{m}}{\text{s}}\right)$$

According to 6.6.1.5, the dynamic load factor DLF=2.

Note: The Chapman and Jouguet detonation properties according to Table 6.2.2 are *NOT valid* because the unburned gas is at an increased pressure (p_1=12 *bar a*, T_1=15°C).

The required pressure difference at an increased initial pressure $\Delta P_{CJ,1}$ may be approximated by:

[B.5.2c]

$$\Delta P_{CJ,1} = \left(\frac{\Delta P_{CJ}+1\text{ bar}}{1\text{ bar}}\right)\cdot p_1 - 1\text{ bar}$$
$$\Delta P_{CJ,1} = \left(\frac{17.4+1\text{ bar}}{1\text{ bar}}\right)\cdot p_1 - 1\text{ bar}$$
$$\Delta P_{CJ,1} = 219.8\text{ bar}$$

Based on Equation 6.6.1.7, now the minimum required pipe wall thickness is determined by using the Chapman and Jouguet pressure difference at an increased initial pressure $\Delta P_{CJ,1}$ as shown in Equation B.5.2d:

[B.5.2d]

$$h \geq DLF\,\frac{R\Delta P_{CJ,1}\left(1-\nu^2\right)}{E\varepsilon_y}$$
$\Delta P_{CJ,1}$ for an increased initial pressure:
$$\text{h} \geq \frac{2\cdot5.49\cdot10^{-3}\text{m}\cdot2.198\cdot10^{7}\,\frac{\text{N}}{\text{m}^2}\left(1-0.27^2\right)}{1.93\cdot10^{11}\,\frac{\text{N}}{\text{m}^2}\cdot0.002}$$
$$h \geq 4.70\cdot10^{-3}\text{m}$$
$$4.70\text{ mm} \leq h = 5.49\text{ mm}$$

The given 3 in. pipe, schedule 40S is expected to withstand a stable detonation without permanent deformation.

B.6 Accounting for DDT Location. The examples in Sections B.2 through B.5 of elastic regime response pipe wall thickness need to be adjusted in practice to account for the increased detonation pressures at the pipe location where DDT occurs. Data from Kuznetsov, 2010 [5] (*see Figure B.6*) show that the peak pressure at the DDT location (i.e., 110 bar for hydrogen-oxygen mixture) is 2.3 times the stable C-J detonation pressure (i.e., 48 bar). The end-wall reflected detonation pressure is 162 bar (i.e., 3.4 times the stable C-J detonation pressure). In the "perfect storm" situation where DDT occurs at the end wall, Kuznetsov reports a 10-factor increase in the peak pressure compared to the C-J detonation pressure.

As stated in Figure 6.5.1, the nominal design pressure for detonation containment, depending on pipe diameter, is 10 bar or 16 bar, which have significantly thicker walls than the minimum thickness calculated by these examples.

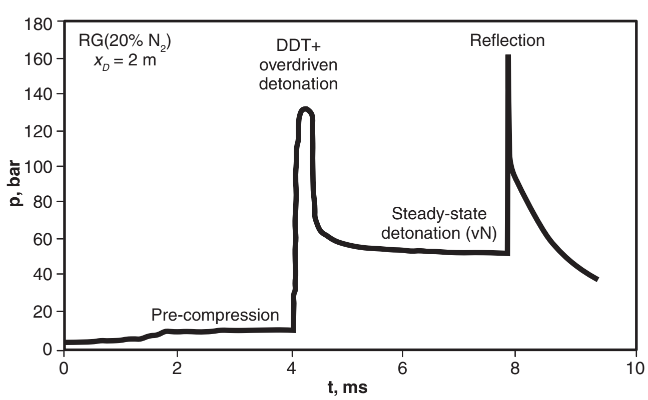


FIGURE B.6 Computed Peak Pressure in the Pipe for Radiolysis Gas with 20% Nitrogen and a DDT Point at x_D=2 m.

B.7 Bibliography.

[1] Schildberg H., 2016, "Gas phase detonations in pipes: the 8 possible different pressure scenarios and their static equivalent pressures determined by the pipe wall deformation method, (part 1)." *Chemical Engineering Transactions*, 48, 241–246; DOI:10.3303/CET1648041.

[2] Schildberg H., 2016, "Gas phase detonations in pipes: the 8 possible different pressure scenarios and their static equivalent pressures determined by the pipe wall deformation method, (part 2)." *Chemical Engineering Transactions*, 48, 247–252; DOI:10.3303/CET1648042.

[3] Schildberg H., 2015, Experimental Determination of the Static Equivalent Pressures of Detonative Explosions of Stoichiometric H2/O2/N2-Mixtures in Long and Short Pipes, PVP2015-45286 in Proceedings of the 2015 Pressure Vessels & Piping Conference, July 19–23, 2015, Boston, Massachusetts, USA.

[4] Heidermann, T. and Davies, M., In-Line Flame Arrester Application Limits And Matrix Concept For Process Plant Safety From Flash Back Of Thermal Combustion Units, Proceedings of GCPS, 2005.

[5] Kuznetsov, Mike, Alexander Lelyakin and Wolfgang Breitung, 2010, "Numerical Simulation of Radiolysis Gas Detonations in a BWR Exhaust Pipe and Mechanical Response of the Piping to the Detonation Pressure Loads, Numerical Simulations - Examples and Applications in Computational Fluid Dynamics," Prof. Lutz Angermann (Ed.), InTech, DOI: 10.5772/12839.

N Annex C Fundamentals of Deflagrations

This annex is not a part of the recommendations of this NFPA document but is included for informational purposes only.

N **C.1 General.** A deflagration is the propagation of a combustion flame front through a flammable atmosphere at a velocity that is less than the speed of sound in the unreacted medium. The rate of propagation of a deflagration is controlled by diffusion of heat and reactive species from the reaction zone (flame front) to the unburned material. In practice, the flame propagation velocity depends on the degree of confinement and the size and shape of the flammable mixture. Assuming that the unburned gas is stationary, the flame will propagate into the unburned gas at a characteristic laminar burning velocity. This is a fundamental parameter whose value reflects the reactivity of the mixture. If the unburned gas is turbulent, the burning velocity can increase and is then called the turbulent burning velocity. If the unburned gas is moving, a stationary observercan measure the flame velocity that is the sum of the unburned gas velocity and the burning velocity. This observed flame speed is called the deflagration velocity. Typical deflagration speeds range from a few meters per second in an unconfined cloud to several hundred meters per second in a pipe or other volume containing repeated obstacles. In an enclosed vessel containing a fuel-air mixture, the deflagration pressure rise is typically seven to nine times the initial pressure.

The work of Helen James, "Detonations," HSE Report TD5/039, is used extensively in this section.

N **C.1.1 Example and Explanation of Limitations. (Reserved)**

N **C.2 Flammable Limits.** A flammable gas mixture is one consisting of fuel, oxygen, and inert gases that can propagate a flame. The term *flammable limits* usually refers to the lowest and highest concentrations of fuel vapor in atmospheric air that will propagate a flame. The range between the lower flammable limit (LFL) and upper flammable limit (UFL) will depend on the temperature of the unburned gas. If the temperature of the unburned gas increases, the range will be wider. Flammable limits can be determined by tests such as those in ASTM E681 or ASTM E2079. Examples of flammable limits for several gases are given in Table C.2.

In this recommended practice, it is assumed that the source of oxygen for combustion is air. As used here, the term *inert gases* refers to any other nonreacting gases that can be included in a fuel-air mixture. Such gases can arise from process steps or be combustion-inhibiting additives.

N **Table C.2 Flammable Limits in Air**

Fuel	LFL (Vol. %)	UFL (Vol. %)
Methane	5.3	15
Ethane	3.0	12.5
Propane	2.2	9.5
Butane	1.8	8.4
Ethylene	3.1	32
Methyl alcohol	7.3	36
Hydrogen	4.0	75
Acetone	3.0	13
Methyl acetate	3.1	16

N **C.3 Burning Velocity.**

N **C.3.1 General.** Burning velocity (also called fundamental burning velocity) is the rate of flame propagation relative to the velocity of the unburned gas that is ahead of the reaction zone or flame front. A flame front propagates by heat transfer, conduction, and radiation from the reaction zone to adjacent unburned gas. Many different elementary reactions result in the global chemical process called combustion. The rates of these reactions in a volume of heated gas increase with temperature (approximately exponentially), eventually reaching the point of becoming self-sustaining. The self-sustaining point of combustion is that at which a volume of flammable mixture generates more thermal energy than it loses, with the effect that the local temperature rises rapidly to the final flame temperature. Burning velocity is a reactivity characteristic of a flammable gas that depends on fuel type, viscosity, conductivity, fuel composition (χ) in the fuel-air (or other oxidant) mixture, initial temperature, and pressure. The burning velocity is designated S_v.

N **C.3.2 Maximum Burning Velocity.** The burning velocity of a given fuel in air will have a maximum value in the composition domain, typically in a region that is somewhat fuel rich. Values of the maximum burning velocity for a number of flammable gases are given in Table C.3.2.

N **C.3.3 Determination of Burning Velocity.** Burning velocity can be determined by test, and several methods have been used, including those based on the size measurement of Bunsen flames and pressure development in closed vessels.

N **Table C.3.2 Maximum Burning Velocity of Selected Flammable Gases in Air**

Fuel	Maximum S_U (cm/s)
Acetone	54
Acetylene	166
Acrylonitrile	50
Butane	45
Carbon disulfide	58
Carbon monoxide	46
Decane	43
Dimethyl ether	54
Ethane	47
Ethylene	80
Ethylene oxide	108
Hydrogen	312
Isopropyl alcohol	41
HFC-152a	23.6
HFC-143a	7.1
HFC-32	6.7
HFC-143	13.1
Methane	40
Methyl alcohol	56
Propane	46
Propylene oxide	82
Toluene	41

HFC-32: difluoromethane; HFC-143: 1,1,2-trifluoroethane; HFC-143a: 1,1,1-trifluoroethane; HFC-152a: 1,1-difluoroethane.
Note: Abstracted from NFPA 68, Table D.1.

N **C.4 Flame Speed.** The speed of a flame front, S_F, measured in relation to a fixed special reference frame is the sum of the burning velocity, S_U, and the flow velocity induced in the unburned gas by the rate of production of combustion products, S_P, as follows:

N **[C.4]**

$$S_F = S_U + S_P$$

N **C.4.1** In the simplest case, the volumetric rate of production of combustion products is equal to the total area of the flame front times the burning velocity at the conditions (temperature and pressure) of the unburned gas, as follows, where Q_P is the integral of the composition-dependent burning velocity, $S_U(\chi)$, over the flame surface, s_{FF}.

N **[C.4.1]**

$$Q_P = \oint S_U(\chi) \cdot ds_{FF}$$

N **C.4.2** The component of flow velocity induced by the production of combustion products is as follows, where A is the cross-sectional area of flow:

N **[C.4.2]**

$$S_P = \frac{Q_P}{A}$$

N **C.4.3** In a closed system, such as a duct, the flame speed is time, space, and composition dependent. Flame speed increases with passage in a smooth duct due to flame stretch from wall friction. Any feature in a duct, such as an obstacle in the flow path, that causes the flame surface area to become extended will lead to acceleration of the flame front.

N **C.5 Mixtures.**

N **C.5.1 General.** Mixtures of fuel gases can result in deflagration properties that are different from those of the original individual fuel gas species. The combination of fuel gas species can also result in unforeseen chemical or molecular transport interaction between fuels. Experimental determination of deflagration parameters of fuel mixtures is recommended. Properties of fuel mixtures can be approximated using simplified mixing formulas based on the mixture composition and properties of the component fuel gases.

N **C.5.2 Lower Flammable Limits of Mixtures.** The LFL of a mixture of fuels can be approximated using Le Chatelier's mixing rule based on the molar or volumetric fraction (x) of all fuel components. The following formula does not account for the effect of added inerts:

N **[C.5.2]**

$$(LFL)_{mixture} = \frac{1}{\sum \frac{x_i}{(LFL)_i}}$$

N **C.5.3 Burning Velocities of Mixtures.** The fundamental burning velocity of gas mixtures can be approximated using a Le Chatelier–type mixing rule based on the molar or volumetric fraction (x) of all fuel components. The following formula does not account for the effect of added inerts:

N **[C.5.3]**

$$(S_U)_{mixture} = \frac{1}{\sum \frac{x_i}{(S_U)_i}}$$

N **C.5.4 Maximum Adiabatic Flame Temperature and Pressure of Mixtures.** The maximum adiabatic flame temperature and pressure achieved by a fuel mixture in a closed vessel or at atmospheric pressure can be calculated using an equilibrium composition software program, such as NASA's Chemical Equilibrium with Applications (CEA) program, or a similar thermodynamic model. Using this software, the final pressure and temperature of the gas mixture can be obtained for a known initial composition, temperature, and pressure, assuming a constant internal energy and density. The maximum temperature and pressure calculated in this manner will be greater than the values obtained in closed vessel experiments due to heat losses at the vessel boundary during experiments.

N Annex D Principles of Detonations

This annex is not a part of the recommendations of this NFPA document but is included for informational purposes only.

N D.1 Properties.

N **D.1.1** Detonations require fuel-oxidant mixtures that are sufficiently reactive for the combustion zone to propagate at supersonic speeds; that is, to keep pace with the leading shock wave. The shock wave heats the reactive mixture and triggers a rapid combustion reaction with its associated exothermic energy release. The maximum pressure and temperature exist at the reaction front, and there is a continuous decrease of pressure and temperature behind the flame. Pressure loads produced by detonations are described in Chapter 5.

N **D.1.2** Because the maximum pressure in a detonation occurs as a shock wave, there is no opportunity to detect the rising pressure and take post-ignition mitigating action, as in a deflagration. The primary detonation protection measures are prevention, as discussed in this chapter, and containment, as discussed in Annex E. There are also a few possible mitigation measures to arrest or weaken the propagating detonation, as described in Chapter 8, but those measures must be in place before the detonation occurs.

N **D.1.3** An inherent property of propagating detonations is the occurrence of transverse waves with complicated three-dimensional structures. These transverse waves produce geometric cellular patterns that can be captured optically or by impressions on smoke foils lining the inner surface of detonation tubes. The size of the detonation cells is related to the combustion kinetics such that faster-burning gas mixtures have smaller detonation cells than slow-burning mixtures. The detonation cell size is also a key parameter in the criteria for detonation composition limits in a particular piping configuration.

N **D.1.4** Detonation cell size data for a variety of gas-air mixtures are plotted in Figure D.1.4 as a function of mixture equivalence ratio. The solid curves in Figure D.1.4 are based on chemical reactivity calculations that produce a reaction scale length, *l*, which is multiplied by an empirical coefficient, *A*.

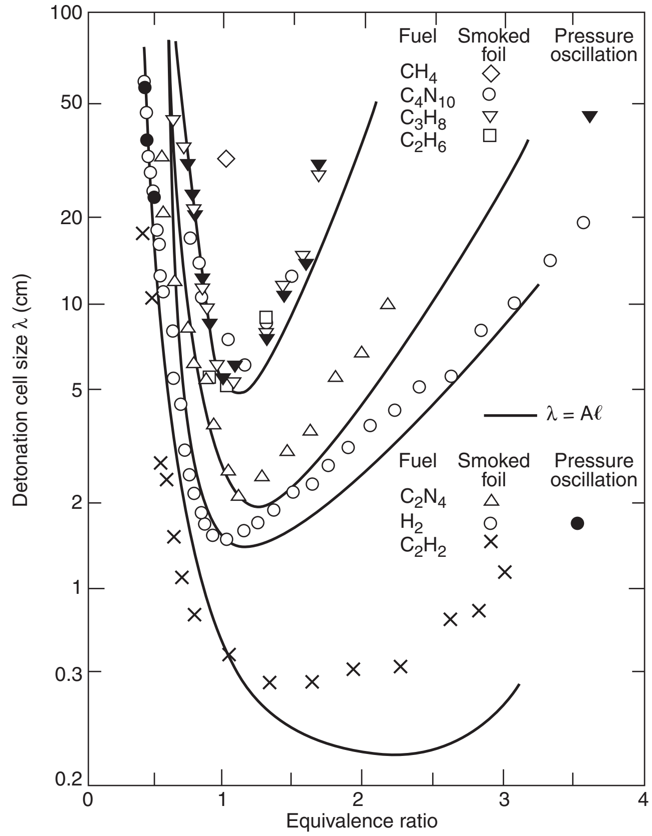


FIGURE D.1.4 Detonation Cell Size Versus Fuel-Oxygen Equivalence Ratio.

N D.2 Detonation Cells and Mixture Composition Limits.

N **D.2.1** Extensive research has demonstrated that composition limits for detonation propagation are scale dependent, with the governing parameter being the ratio of the pipe diameter (or other characteristic equipment dimension) to the detonation cell size.

N **D.2.2** The minimum tube or pipe diameter in which a detonation can propagate, also termed the *critical diameter*, is equal to λ/π, where λ is the detonation cell size for a particular gas mixture at a specified temperature and pressure.

N **D.2.3** Gas-air lower and upper composition limits for detonations in piping with diameters of 25 mm (1 in.), 50 mm (2 in.), and 100 mm (4 in.) are shown in Table D.2.3 for acetylene-air, ethylene-air, hydrogen-air, methane-air, and propane-air mixtures initially at 1 atmosphere and 300 K. Except for methane (which cannot detonate in pipe diameters smaller than 100 mm), the detonation limits for the gases widen as the pipe diameter increases. If gas composition is outside the range of the upper and lower detonation limits, the mixture would not be expected to detonate in internally smooth piping of the indicated or smaller diameter.

N **D.2.4** Detonation limits for the gases listed in Table D.2.3 in piping with other diameters in the range 25 mm to 100 mm (1 in. to 4 in.) can be determined via linear interpolation of the data in Table D.2.3.

N **D.2.5** Detonation limits for other alkane-air gas mixtures can be estimated from the cell size data in Figure D.1.4 for ethane, propane, and butane.

N **D.2.6** In channels or ducts with small height/width ratios, the minimum channel height that can support a detonation of a particular gas mixture is equal to one detonation cell size and can be estimated using the detonation cell size data in Figure D.1.4.

N **D.2.7** In an external cloud of a heavier-than-air flammable mixture, the minimum cloud height that can support a detonation is equal to 1.5 times the detonation cell size shown in Figure D.1.4.

N D.3 Chapman-Jouguet (CJ) Detonations.

N **D.3.1** Extensive experiments have shown that detonations in pipes and tubes tend toward CJ velocities and pressures and will eventually propagate as CJ detonations if the pipe or tube lengths and diameters are sufficiently large.

N **Table D.2.3 Detonation Limits for Gas-Air Mixtures at 300 K and 1 Atmosphere**

Pipe Inner Diameter (mm)	Gas	Lower Limit for Detonation (vol. %)	Upper Limit for Detonation (vol. %)
25	Acetylene	4	No data
	Ethylene	4.7	12.3
	Hydrogen	19	58
	Methane	NA	NA
	Propane	3.3	5.4
50	Acetylene	3.4	No data
	Ethylene	4	14.9
	Hydrogen	17	59
	Methane	NA	NA
	Propane	3.1	6.3
100	Acetylene	3.1	No data
	Ethylene	3.4	17.4
	Hydrogen	15	61
	Methane	9.5	9.5
	Propane	2.9	7.5

NA: Stable detonations are not possible for methane in this diameter pipe.
Note: Entries for acetylene, ethylene, methane, and propane were calculated from the data in Figure D.1.4. Data for hydrogen were obtained from Appendix D of the OECD Nuclear Energy Agency's "Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety: State of the Art Report."

N **D.3.2** CJ detonation pressures for an assortment of flammable gas–air mixtures are shown in Figure D.3.2. Near-stoichiometric mixtures have CJ detonation pressures in the range of 16 to 20 bar. These values are approximately twice the corresponding values of P_{max} for deflagrations of those gas mixtures.

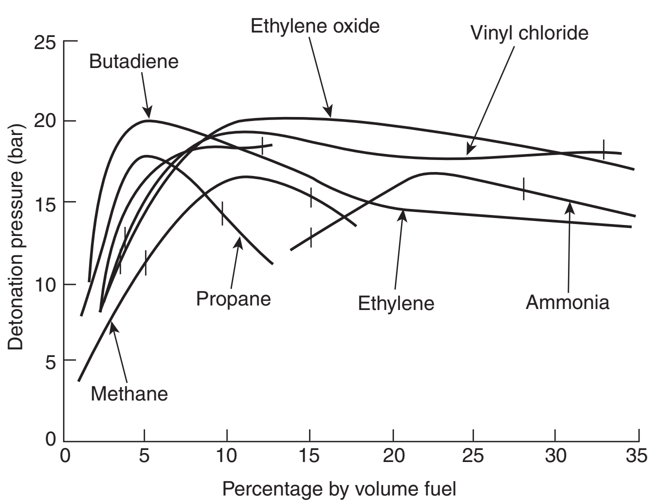


FIGURE D.3.2 Chapman-Jouguet Detonation Pressures as a Function of Fuel Concentration for Various Flammable Gas–Air Mixtures.

N **D.3.3** Chapman-Jouguet detonation velocities and pressures for ethylene-air mixtures are shown in Figure D.3.3. The near-limit mixture detonation velocities are about 1500 m/s (4921 ft/s), while the near-stoichiometric mixture detonation velocities are about 1900 m/s (6234 ft/s).

N **D.4 Detonation Development from Deflagration.**

N **D.4.1 Flame Acceleration in a One-Dimensional System.** The initiation of a detonation in a tube closed at one end can be explained with a simplified one-dimensional model as shown in Figure D.4.1. This model does not consider that local explosions can generate oblique pressure waves. After ignition, the flame propagates. The unburned gas is driven to the open tube end and the processes described above start growth of the flame front, beginning of the turbulence, and increasing compression of the unburned and burned gas, which can lead to shock waves. With increasing compression, the location at which self-ignition is possible after heating the fresh gas with shock waves moves closer to the flame, into the flame, and, finally, ahead of the flame. Hence, after self-ignition, the gas reacts before the flame reaches it. This generally leads to an increase in the shock-wave's intensity and forms a backward-running pressure wave (retonation wave). The propagation mechanism of the combustion process changes once a shock wave forms. While transport processes in a flame co-determine the flame velocity and its propagation velocity, they play practically no role in ignition by shock waves. The pressure that is reached at the point of transition to a detonation is generally much higher—sometimes several times higher—than the CJ pressure of the corresponding detonation. In Figure D.4.1, several simplifications have been made. For example, it was assumed that the process is strictly one-dimensional and that no oblique shock waves or reactive centers form that can accelerate the initiation of a detonation. Also, the formation of shock waves is often not as simple as shown in Figure D.4.1.

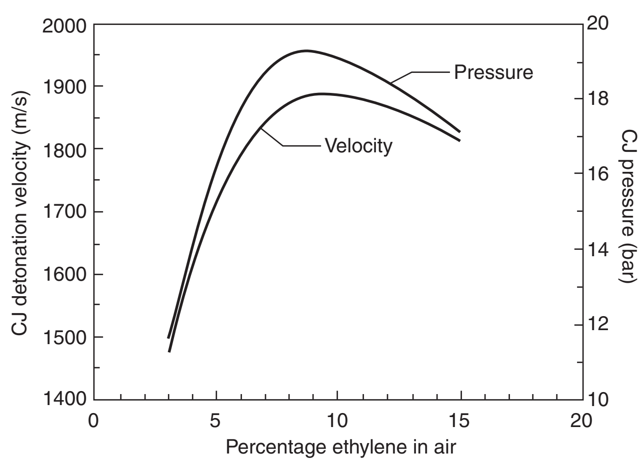


FIGURE D.3.3 Chapman-Jouguet Detonation Velocities and Pressures for Ethylene-Air Mixtures.