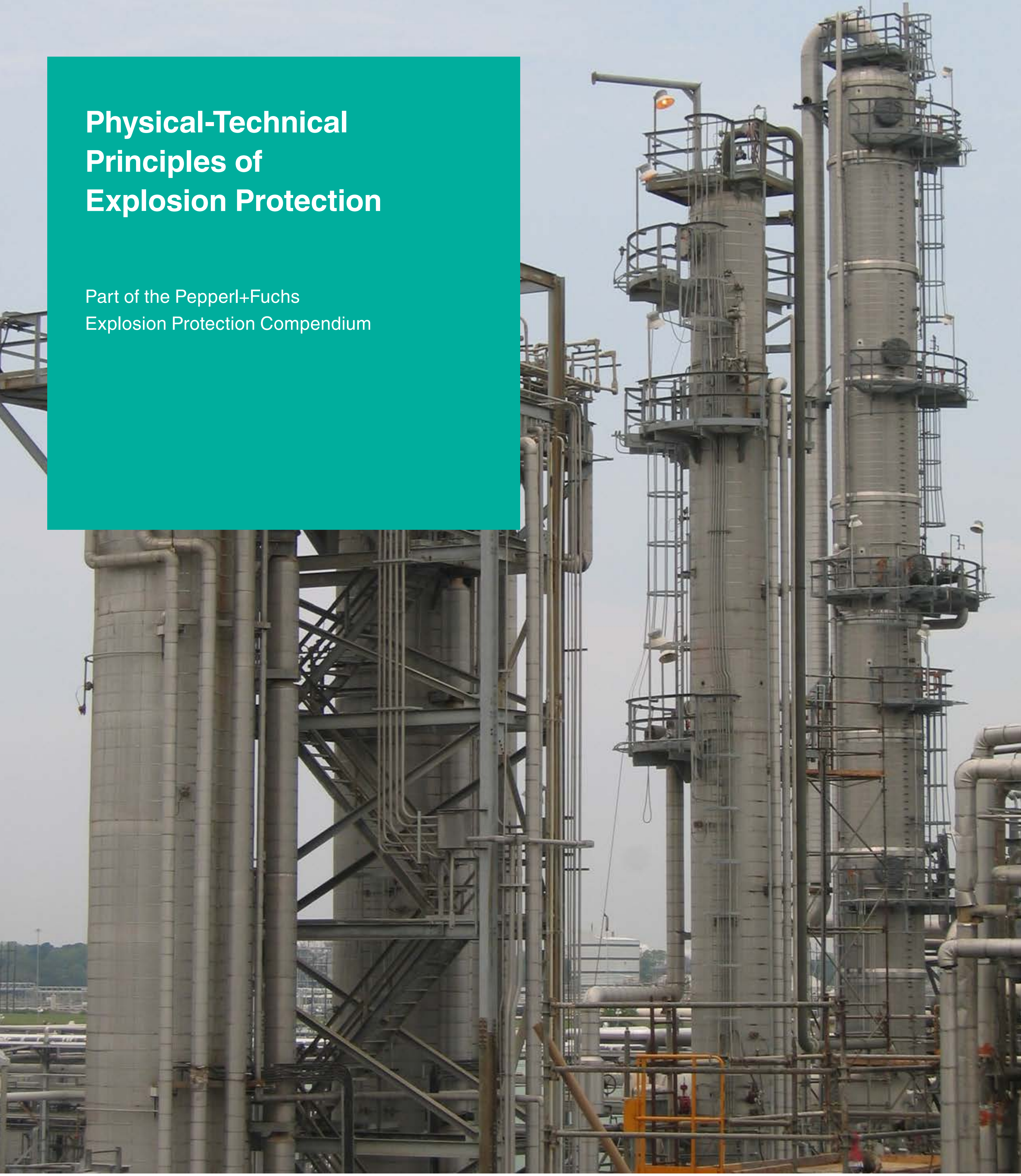
Physical-Technical Principles of Explosion Protection

Part of the Pepperl+Fuchs
Explosion Protection Compendium



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Disclaimer

The contents of this publication have been compiled by the editor with due and thorough regard for the legal regulations valid at the date of publication and of established technical measures. Nevertheless, incomplete, inaccurate, or ambiguous assertions cannot be excluded. The publication consists of several individual volumes that contain general information on explosion protection.

Adherence to local, national, and international explosion protection laws and standards is a fundamental obligation of plant designers and operators. The contents of this publication are not intended for and are not suitable for assessing the hazard situation of a specific plant.

Explosion protection regulations are subject to legal guidelines and can vary by country. Further, industrial plants can differ greatly from one another in their design, materials used, and methods of operation. The individual volumes of this compendium provide an overview of topics relating to explosion protection. With this in mind, the technical and organizational measures for explosion protection can only be detailed generally and thus incompletely. In a given specific case, each plant operator must determine the requirements and approach based on an individual hazard assessment, and implement and document these in a fashion verifiable in accordance with the national regulations.

International and European IEC/EN standards are generally referenced in this publication. In the United States and Canada, most IEC/EN standards have UL or CSA national harmonizations. The national harmonizations are based on the IEC/EN standards but are not exactly the same.

With regard to the supply of products, the current issue of the following document is applicable: The General Terms of Delivery for Products and Services of the Electrical Industry, published by the Central Association of the Electrical Industry (Zentralverband Elektrotechnik und Elektroindustrie (ZVEI) e.V.) in its most recent version as well as the supplementary clause: “Expanded reservation of proprietorship.”

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About the Explosion Protection Compendium

This booklet is one part of the Pepperl+Fuchs Explosion Protection Compendium. The goal of these volumes is to give plant operators a general overview of explosion protection.

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Introduction

Explosions can cause catastrophic damage. To prevent this, special protective measures must be taken in plants that are at risk of explosion. These measures are based on knowledge about the substances in use and their safety-relevant properties.

Historical Development

Steam engines, coal mining, and steel production were the cornerstones for industrialization in the middle of the 19th century. The wood available from European forests was no longer sufficient to feed the ever-increasing number of steam engines. Bituminous coal was the ideal “new” energy source and was mined at the surface at first. Later, deeper shafts became necessary to find deposits.

Explosion hazards due to ignitable methane/air mixtures (firedamp) were unheard of in surface mining at that time. However, in the underground coal shafts, the methane concentration of the air could reach dangerous explosion limits. Underground explosions, triggered by tools or light sources—and often fueled by the subsequent ignition of dispersed coal dust—claimed countless lives. The coal mining industry was therefore forced to address these explosion hazards. Initially, safety lamps were developed that could no longer ignite atmospheres rich in methane.

Around 1880, the electrification of the mines led to another massive increase in explosion accidents. Further technical advances were only possible after the introduction of functioning protective measures for avoiding electrically generated ignition sources. The “flameproof enclosure,” “increased safety,” and “intrinsic safety” types of protection emerged at this time.

Over time, steel became ever more important. Previously, furnaces could only be operated using charcoal, as bituminous coal is not suitable for steel production. Steel only became available as a mass-produced product through transforming coal into coke. A combustible gas was produced as a side product of coke oven plants. This mixture of hydrogen, methane, and carbon monoxide was originally used for illumination and heating steam boilers.

But soon enough, the first explosions due to coke oven gases occurred. The types of protection, which at that time were focused on methane, now needed to be adapted to the properties of hydrogen and carbon monoxide. Many more combustible substances have gradually been added due to the use of petroleum components and the ever-developing chemical industry.

Current Practices

To assess possible explosion risks, the chemical-physical behavior and the safety-relevant properties of each substance are taken into account. These properties are described in safety parameters (SP) of combustible gases and liquids or in SPs for combustible dusts.

Combustion Processes

From a physical viewpoint, combustion and explosion are exothermic reactions with different reaction rates. Unstable substances exist that can spontaneously combust without external energy input. These substances will not be dealt with here. Moreover, explosive substances exist, where the oxidizing agent is bound to the combustible substance. These substances fall under the Explosive Substances Ordinances and will not be dealt with here. This booklet deals with combustible substances that, when mixed with air under atmospheric conditions, can cause an explosion when ignited.

Subdivision into Groups

In the European Union, the explosion hazards for underground mining and the explosion hazards outside of mining (surface mining) are considered separately (Directive 2014/34/EU; ATEX Directive). To differentiate, the European Directive uses group classifications "I" (mining) and "II" (other areas outside of the mining industry).

The Directive 2014/34/EU subdivides Group II further into Group IIG (gases) and Group IID (dusts). The scope of the Directive also determines "atmospheric conditions." This concerns the situation in which combustible substances are released into the air and therefore endanger employees.

International device standardization is technically implemented by the International Electrotechnical Commission (IEC) for electrical equipment and the International Organization for Standardization (ISO) for nonelectrical equipment. This results in discrepancies in the labeling of dusts, as the IEC has differentiated the identification system for electrical equipment for explosive atmospheres even further. Now the technical identification for Group II is only used for devices that are used with gases. For Group III, devices that can be used with dusts are identified. This branching allows further subdivision of Group III into fibers and lint (IIIA), nonconductive dust (IIIB), and conductive dust (IIIC).

For the purposes of simplification, this compendium refers to regulations according to IEC when referring to the worldwide standard, even if an ISO standard should be used as the basis in individual cases.

Categories for North American Classification

In brief, we can differentiate between the IEC and the North American procedure for Class/Division. The differences lie in the categorization of explosion hazardous areas, the design of equipment, and the installation technology of electrical systems. The installation for these areas is carried out in North America in accordance with the National Electrical Code® (NEC®) NFPA 70®, Article 500-506 for the US and the Canadian Electrical Code CSA 22.1 for Canada. The installation takes place according to the following material groups:

- Class I: gases, vapors, and mist
- Class II: dust
- Class III: ignitable fibers/flyings not suspended

The areas are then further subcategorized according to the probability of occurrence of these materials being present in a potentially hazardous quantity:

- Division 1: probability of explosion hazardous materials being present in a potentially hazardous quantity during normal activities
- Division 2: probability of explosion hazardous materials being present in a potentially hazardous quantity during abnormal conditions

The Prerequisites of an Explosion

For an explosion to occur, three components must be present at the same time:

- A combustible substance, for example:
    - Flammable gases
    - Mists and vapors of combustible liquids
    - Combustible dusts, fibers, and suspended particles

- An oxidizing agent:
    - Oxygen, normally from the air

- Ignition energy:
    - An energy input that triggers the combustion process, usually electrical or thermal. For this, a minimum ignition energy is required. The amount of energy needed depends on the exact physical conditions.

The combination of these components is referred to as the “ignition triangle.”

Ignition Triangle

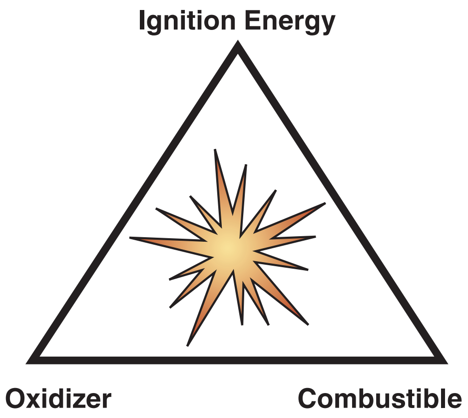


Figure 1. The ignition triangle

For an explosion to occur, additional prerequisites must be fulfilled, such as the following:

- The mixing ratio of the fuel and the oxidant is within defined limits.
- A potentially hazardous amount is present.
- The input of energy is higher than the minimum ignition energy, or the temperature is higher than the minimum ignition temperature.

All methods of explosion protection aim to eliminate at least one component of the ignition triangle and therefore eliminate the risk of explosion.

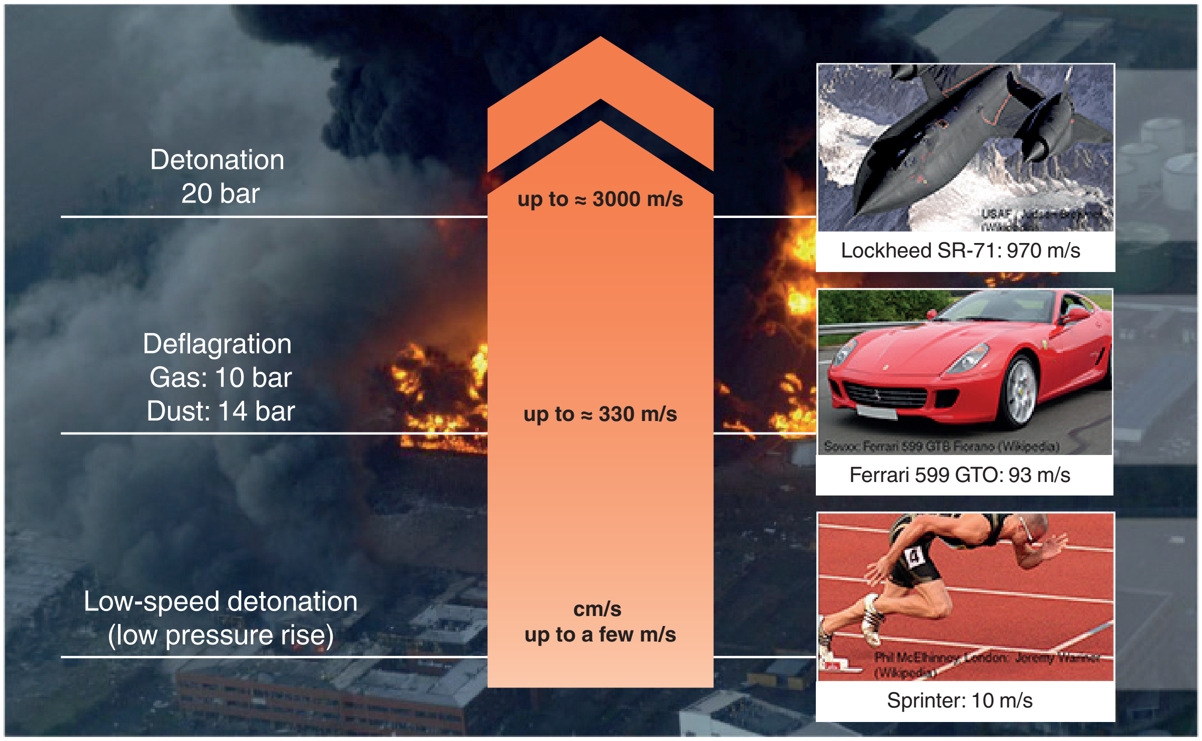
Rate of Combustion—Flame Velocity (v)

After ignition, combustion is perpetuated through the unburned mixture at a specific rate of combustion. This process depends on the mixing ratio of fuel to air and the degree of dispersion. The dispersing combustion gas propels a flame, which can reach a speed of up to several kilometers per second.

Depending on the rate of combustion, one of the following phenomena is applicable:

- Low-speed detonation: fewer m/s, pressure increase up to 1 bar (14.5 psi)
- Deflagration: up to 330 m/s, pressure increase up to 10 bar (145 psi); v < the speed of sound
- Detonation: up to several km/s, shock waves equal to or greater than 20 bar (290 psi)

Explosion Speed and Consequences



USAF

Soxxx: Ferrari 599 GTB Fiorano (Wikipedia)

Phil McElhinney London: Jeremy Wanner (Wikipedia)

Figure 2. Explosion pressure and propagation speed of pressure waves

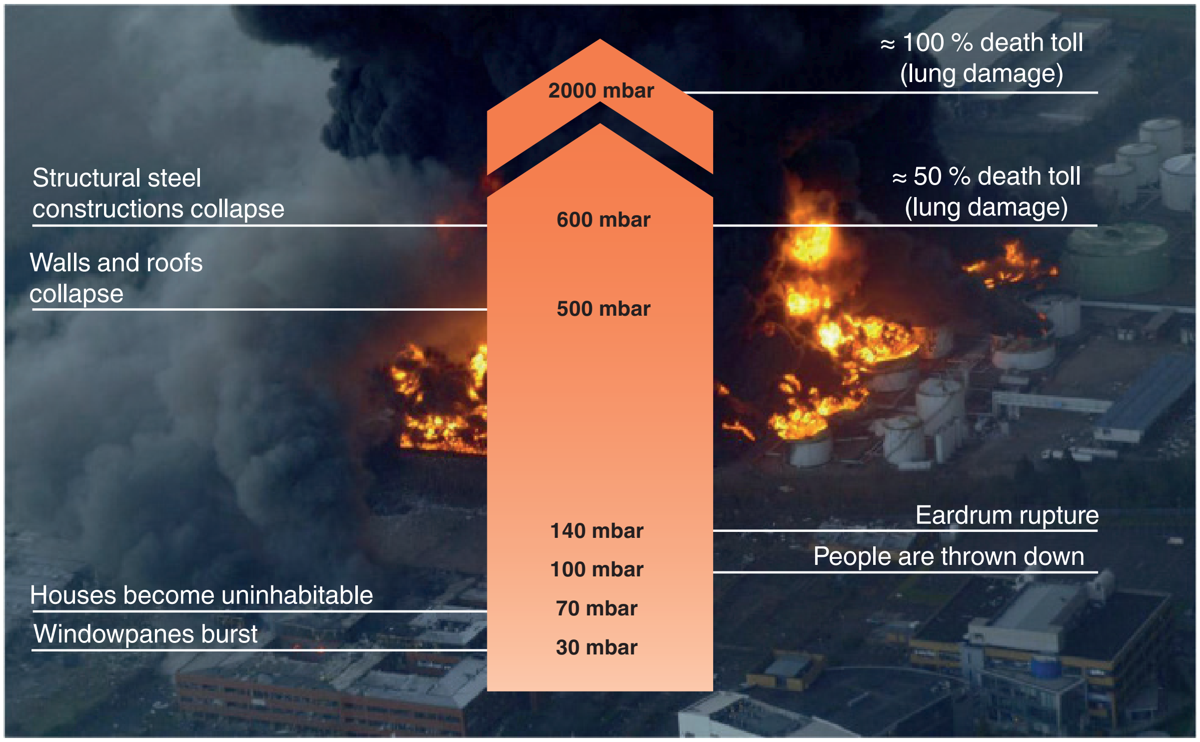


Figure 3. Effects of explosion pressure on buildings and humans

Atmospheric Conditions

The main aim of explosion protection is to ensure occupational safety. Employees usually work under normal atmospheric conditions. These are defined according to IEC/EN 60079-0 as follows:

- Temperature -20 °C ... +60 °C
- Pressure 80 kPa (0.8 bar) ... 110 kPa (1.1 bar)
- Air with a normal oxygen content, usually 21 vol.-%

Degree of Dispersion

Ignition can only occur if the combustible substance is mixed with oxygen to a sufficient level.

First, the combustible substance must be sufficiently distributed—i. e., the degree of dispersion must be sufficiently high

Range of Concentration

A combustible mixture is only explosive within substance-specific limits. The lowest concentration at which an explosion is possible is referred to as the “lower flammable limit” (LFL). The highest concentration at which an explosion is possible is referred to as the “upper flammable limit” (UFL). A combustible mixture within these explosion limits is referred to as an explosive mixture. As long as the atmospheric conditions are fulfilled, the mixture is then referred to as a “potentially explosive atmosphere.”

Flash Point

Vaporized liquids can only be ignited if enough vapor is emitted from the liquid. If the temperature of the liquid is so high that the vapor phase can be ignited above an enclosed liquid surface, then the flash point is reached or already exceeded. Liquids are difficult to ignite directly. In practice, the vapors above a liquid surface are ignited, which can subsequently lead to the liquid itself also being ignited.

Oxygen Content

A potentially explosive atmosphere can be prevented by removing the oxygen in the atmosphere. The explosion limits (see “Range of Concentration” above) are applicable to an oxygen concentration of 21 vol.-% in the air. The oxygen concentration at which the most flammable mixture begins to ignite can be determined experimentally for each substance. This concentration is the limiting oxygen concentration (LOC).

Protective Measures

The STOP principle is used in some countries to protect workers:

- **S**ubstitution
- **T**echnical measures
- **O**rganizational measures
- **P**ersonal measures

In the introduction of the IEC/EN 60079-14:2013 standard regarding “Selecting and erecting electrical installations,“ the IEC specifies which preventative measures must be used to reduce the risk of explosion:

- Replacing a combustible substance with another substance that is not ignitable, or difficult to ignite (S)
- Monitoring (T, O)
- Diluting (T, O, P)

According to European ATEX regulations (Directive 1999/92/EG), the principles of integrated explosion protection must be used to protect employees.

- Primary explosion protection: Preventing the occurrence of a hazardous, potentially explosive atmosphere (S or T)
- Secondary explosion protection: Preventing possible ignition sources (T, O)
- Tertiary or structural explosion protection: Suppressing the explosion or reducing the possible effects of an explosion (T, O, P)

Primary Explosion Protection

Typical measures for observing primary explosion protection are using noncombustible substances, preventing releases and displacing the atmospheric oxygen, i. e., inerting the plant interiors. Additional measures include extracting emissions and diluting an existing gas concentration using mechanical or natural ventilation measures. The latter measures are often combined with monitoring the fuel concentration in operational areas.

Precautions for Preventing a Potentially Explosive Atmosphere

To prevent a potentially explosive atmosphere, the following aspects must be considered:

- The substances selected
- Using noncombustible substances
- Using solvents with a flash point above the processing temperature
- Avoiding powdered products or products that may form dust, e. g., using sugar syrup in recipes instead of powdered sugar

Monitoring the Concentration of Combustible Substances

The concentration of combustible substances can be influenced by the flash point, ventilation measures, and dust elimination.

- Reducing the concentration so that it is below the lower flammable limit (LFL) using ventilation measures, e. g., suction at the exit point, interior ventilation
- Using liquids with high flash points or increasing their flash points by adding noncombustible liquids
- Disposing of deposited dusts regularly without dispersing the dusts, e. g., by wet cleaning or using suction, before the quantity deposited can become dangerous
- Decreasing or eliminating dust layers in difficult-to-reach locations using structural measures, e. g., by avoiding horizontal surfaces

A mixture is nonincendive when it is under the LFL as it is too “lean.” If the amount of fuel released is restricted, the concentration of the gas/air mixture remains under the LFL. The risk of a combustion reaction that can continue independently is eliminated.

If the concentration is to be decreased using ventilation, mechanical ventilation systems are subject to particular requirements:

- An active and specific ventilation duct must be available.
- The extracted air may not come into contact with ignition sources.
- Ventilators must be explosion-protected if a potentially explosive atmosphere is to be facilitated. Observe the Zone or Division classification!
- Transported air may not contain combustible substances.
- The effectiveness of the exhaust fan must be continually monitored, e. g., using gas leak detectors or excess flow valves.
    - Before the first commissioning, and regularly thereafter, the ventilation system and its associated monitoring systems must be checked for effectiveness and to ensure they are in perfect condition.

Inertization or Displacement of Atmospheric Oxygen

The reactivity of fuel/air mixtures is decreased by reducing the concentration of the oxygen. This can be achieved by inertization, which is based on the addition of inert gases, generally nitrogen. This enables the oxygen concentration in the mixture to be reduced to the point that the fuel/air mixture is no longer explosive. The decisive limit value is defined by the limiting oxygen concentration. To ensure that inertization is effective, the oxygen concentration or the flow rate of the inert gas must be constantly monitored.

If the approved threshold range is not upheld, appropriate protective measures are triggered. To achieve this, the maximum oxygen concentration in the plant must remain significantly lower than the limiting oxygen concentration. This allows sufficient reaction time to be given for activating designated protective measures in the event of a failure, e. g., making ignition sources inactive.

Adapting the Operating Conditions

- For liquids: avoid heating to or above the flash point
- Prevent the release of substances, e. g., by providing a vacuum in equipment

Processes in which the operating temperature remains below the flash point must be secure enough to ensure that no temperature excesses can occur. To ensure that a potentially explosive atmosphere does not occur due to a fault, warning devices must be provided if temperature excesses still cannot be excluded.

Structural Precautions in the Plant

- Prevent the release of substances: Mechanically sound plants and fasteners are used for this purpose—e. g., dual end face mechanical seals, tongue-and-groove flanges, welded connections, and magnetically coupled unsealed pumps
- Use enclosed cycles of substances, e. g., double valve systems when filling containers, product feeders when removing probes, etc.
- Use vapor return devices when decanting combustible liquids
- If substances escape: ensure rapid dilution, e. g., by relocating the operations outdoors.
- The natural air exchange in outdoor plants is significantly better than that of work stations inside buildings.

Monitoring with Gas Leak Detectors

Gas leak detectors are used to monitor the effectiveness of ventilation systems in areas where potentially explosive gas atmospheres would not usually occur.

If the defined fuel concentration, e. g., 10 % of the LFL, is reached, the ventilation system is stepped up, or an additional ventilation unit is switched on to counteract a potentially explosive atmosphere. At the same time, the employees are warned that there is an increasingly hazardous situation by audible and visual signals.

If the fuel concentration continues to increase, the ignition of the potentially explosive atmosphere is prevented by promptly shutting down all potential ignition sources. Example: automatic shutdown at 25 % of the LFL.

Such gas leak detectors take over control of safety functions and must therefore correspond to the requirements of Directive 2014/34/EU regarding their functional safety and reliability

The Specifics of Handling Dusts

The overriding aim of primary explosion protection is to prevent a potentially explosive atmosphere from arising. If the prevention of the potentially explosive atmosphere cannot be guaranteed, measures must be taken to limit the potentially explosive atmosphere, both in terms of time and space. Although only the dispersed dust cloud can explode, the deposited dust also poses a risk. There are several reasons for this:

- Deposited dust has a smolder temperature
- Deposited dust can be dispersed at any time
- The amount of deposited dust can accumulate
- The smolder temperature of the dust reduces when the layer thickness increases
- Apparatus dissipate less heat when the layer thickness is increased and become hotter

Removing deposited dusts is therefore an important measure for primary explosion protection. If deposited dust with a layer thickness of 1 mm is dispersed, this creates a cloud that fills the space above it.

Deposited dust layers must therefore be regularly removed. This requires the site of the deposit to be readily accessible.

Cleaning processes must be used that do not cause dispersions. Common methods include:

- Wet cleaning methods
- Removal using vacuum cleaners

To ensure that the vacuum cleaner does not become an ignition source, these devices must have an explosion-protected design. Personnel must find structural and design-based measures that make the cleaning process easier. Horizontal surfaces on which dust can deposit are to be avoided. For cable trays, angled covers help, which systematically channel the dust onto the floor or into areas that are easily and safely accessible. Walls must have a smooth and jointless design. Floor markings and cleaning schedules can ensure that a dangerous layer thickness does not accumulate.

Secondary Explosion Protection

If the risk of potentially explosive atmosphere formation cannot be eliminated despite the use of primary measures, secondary explosion protection measures must be used. Their aim is to prevent the ignition of the hazardous atmospheres. If the release of various substances is possible, the measures must be oriented toward the SPs of the most ignition-capable substance.

Determination of Explosion Hazardous Areas

Hazardous areas are differentiated based on the frequency and duration of the occurrence of an explosive atmosphere. Using Zone classification, different areas are determined depending on the type of combustible substances, gases, vapors, mists, and dusts. Release conditions are also part of the classification: frequent, occasional during normal operation, never during normal operation, for a short time during faults.

Potentially Explosive Atmosphere, Zone Classification (IEC-Based)

Zone	Type of Fuel	Potentially Explosive Atmosphere: Duration of Occurrence
0	Gases, vapors, mists	Permanent, frequent, over long periods of time
20	Dust clouds	
1	Gases, vapors, mists	Occasional during normal operation
21	Dust clouds	
2	Gases, vapors, mists	Not to be expected during normal operation. Possible short-term occurrences when deviating from standard operation
22	Dust clouds	

Table 1. Classification of Zones according to types of fuel and the duration of occurrence.

Example for Zone Classification of a Fuel Tank

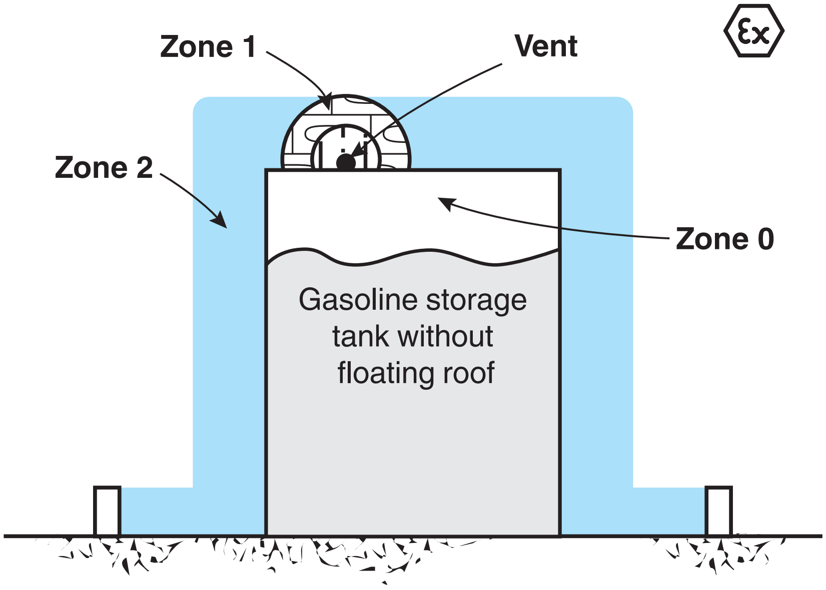


Figure 4. Illustration of Zone classification around a fuel tank

Determination of Explosion Hazardous Areas (Class/Division)

Hazardous areas are dependent on the type of flammable materials present and are divided into the following three categories:

- Class I: Locations containing flammable gases, flammable liquid-produced vapors, or combustible liquid produced vapors
- Class II: Locations containing combustible dusts
- Class III: Locations containing ignitable fibers and flyings

The probability of occurrence of these materials is taken into consideration through the classification into Divisions:

The Two–Division Model

	Class I (Gases and Vapors) in Accordance with NEC 500 and CE Code J18	Class II (Combustible Dust or Powder) in Accordance with NEC 500 and CE Code J18	Class III (Ignitable Fibers or Flyings) in Accordance with NEC 500 and CE Code J18
Division 1	Areas containing dangerous concentrations of flammable gases, vapors, or mist continuously or occasionally under normal operating conditions.	Areas containing dangerous concentrations of combustible dusts continuously or occasionally under normal operating conditions.	Areas containing dangerous concentrations of ignitable fibers or flyings continuously or occasionally under normal operating conditions.
Division 2	Areas probably not containing dangerous concentrations of flammable gases, vapors, or mist under normal operating conditions.	Areas probably not containing dangerous concentrations of combustible dusts under normal operating conditions.	Areas probably not containing dangerous concentrations of ignitable fibers or flyings under normal operating conditions.

Table 2. Classification into Divisions

Classes of hazardous areas are divided into subgroups depending on the type of flammable gas or vapor present. The subgroups and the gases contained within each subgroup are based on the maximum experimental safe gap (MESG) or the minimum ignition current (MIC).

Class I, Flammable Gases and Vapors: Groups

Group A	Atmospheres containing acetylene.
Group B	Atmospheres containing hydrogen and flammable process gases with more than 30 % hydrogen by volume, or gases or vapors posing a similar risk level such as butadiene and ethylene oxide.
Group C	Atmospheres such as ethylene, or gases or vapors posing a similar risk level.
Group D	Atmospheres such as acetone, ammonia, benzene, butane, cyclopropane, ethanol, gasoline, methane, naphtha, propane, or gases or vapors posing a similar risk level.

Table 3. Groups A … D subdivision of Class I. Source: NFPA 497 (2017)

Class II, Combustible Dusts: Groups

Group E	Combustible metal dusts, such as aluminum and magnesium
Group F	Combustible carbonaceous dusts, such as coal coke
Group G	Combustible dusts not in E or F, such as grain and wood.

Table 4. Groups E … G subdivision of Class II. Source: NFPA 499 (2017)

Class III, Fibers and Flyings: Divisions

Class III locations are hazardous locations where easily ignitable fibers or flyings are present. However, these fibers or flyings are not likely to be in suspension in the air in quantities sufficient to produce ignitable mixtures.

Easily ignitable fibers and flyings include rayon, cotton, sisal, hemp, cocoa fiber, kapok, Spanish moss, excelsior, etc. Locations belonging in Class III usually include parts of textile mills, cotton gins, flax-processing plants, clothing manufacturing plants, woodworking plants, etc.

Class III locations are subdivided into the following Divisions:

- Class III, Division 1: Locations in which easily ignitable fibers or flyings are handled, manufactured, or used.
- Class III, Division 2: Locations in which easily ignitable fibers or flyings are stored or handled.

Class III locations are not further subdivided into groups.

Example of a Division-Based Area Classification

The following figure shows a gasoline tank with a fixed roof and vent as a typical example of a Class I hazardous area applicable anywhere that uses the Class/Division method.

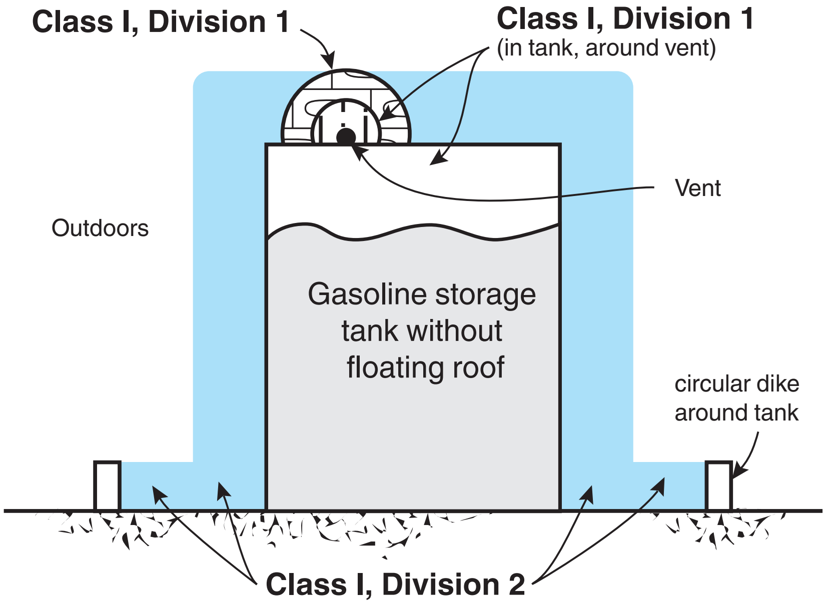


Figure 5. Illustration of Class/Division classification around a fuel storage tank

The Three-Zone Model in North America

In Canada, plants for Class I applications were transferred to the three-Zone model of the IEC in 1988. For plants built after 1988, the three-Zone model is mandatory (CE Code, 1988 edition). In the US, the NEC 505 section was introduced for Class I applications in 1996. Since the time of this addition to the NEC, area classification according to the IEC zones has been an option for companies. However, in the US, the traditional Division practice dominates, and the opportunity for Zone classification is still seen as secondary.

Zone Classification

Zone 0	Areas containing dangerous concentrations of flammable gases, vapors, or mist continuously or for long periods under normal operating conditions.
Zone 1	Areas containing dangerous concentrations of flammable gases, vapors, or mist during normal operating conditions, during repair or maintenance operations, or because of leakage.
Zone 2	Areas likely to contain not containing dangerous concentrations of flammable gases, vapors, or mist under normal operating conditions.

Table 5. Zones in accordance with NEC 505.5 and CE Code 18-006

Determination of Ignition Sources

All ignition sources must be eliminated or reduced to the appropriate level within the Zones or Divisions. The hazard assessment must identify ignition sources and determine circumstances in which the ignition sources could become active. Ignition hazards may potentially first arise through operations and activities of employees in the plant, for example, during cleaning processes or maintenance work. These fundamental operations must be considered during a hazard assessment.

Examples of typical ignition sources from EN 1127-1 include the following:

- Hot surfaces
- Flames
- Electrical sparks
- Electrostatic spark discharges
- Mechanical sparks
- Electrical equalization currents
- Ionizing radiation
- Electromagnetic fields (radio waves)
- Visible light, UV and infrared radiation
- Ultrasound
- Lightning
- Adiabatic compression and shock waves
- Exothermic reactions and the spontaneous ignition of dusts

Equipment Without Explosion Protection

Equipment without explosion protection must be located outside of the Zones or Divisions. This prevents a potentially explosive atmosphere and an active ignition source being in the same space.

Explosion-Protected Equipment

If neither spatial separation nor the shutdown of the equipment is possible, explosion-protected equipment must be used. If used as intended, such equipment poses no ignition source for the relevant Zones/Divisions and therefore does not need to be shut down. The one prerequisite is that the equipment conforms to defined equipment categories that are specified in the relevant Zones/Divisions

IEC and NEC/CE Code Zone/Equipment Category Class/Division Correlation

IEC		NEC/CE Code		
Zone	Equipment Category	Class	Division	Requirements
0	II 1G	I	1	Safety must be guaranteed, even in the case of rare device malfunctions
20	II 1D	II, III		
1	II 2G	I		Safety must be guaranteed if frequent device malfunctions or fault states are expected
21	II 2D	II, III		
2	II 3G	I	2	Work equipment may not operate as an ignition source during normal operation.
22	II 3D	II, III		

Table 6. Correlation between IEC and NEC/CE Code classification

The level of effort that must be made by the manufacturer regarding protection for this equipment depends on the probability that a potentially explosive atmosphere is expected. Consequently, it is considerably easier to provide equipment for Zones 2 or 22/Division 2 than for Zones 0 or 20/Division 1. Generally, equipment category 1G or 1D/Division 1 devices offer a high level of safety and can also be used in the less critical Zones 1 and 2, or Zones 21 and 22/Division 2.

Selection of Equipment According to Temperature Classes (IEC Zones)

The maximum acceptable surface temperature of the equipment is restricted by the various ignition temperatures of the gases and vapors. During the process of determining a temperature class, the manufacturer adds a safety margin for the highest measured surface temperature (during normal operation or in the case of a fault) for all equipment categories. This is 5 K for temperature classes T6 ... T3; for temperature classes T2 and T1, it is 10 K.

Temperature Classes

Temperature Class of the Equipment	Ignition Temperature of the Gases	Maximum Surface Temperature of the Equipment
T1	> 450 ˚C	< 450 ˚C
T2	> 300 ˚C	< 300 ˚C
T3	> 200 ˚C	< 200 ˚C
T4	> 135 ˚C	< 135 ˚C
T5	> 100 ˚C	< 100 ˚C
T6	> 85 ˚C	< 85 ˚C

Table 7. Correlating temperature classes, ignition temperature of the gases, and the maximum surface temperature

Classification of Surface Temperature for Divisions (NEC/CE Code)

Apparatus installed directly in a hazardous area must be classified for the maximum surface temperature that the device produces under intended operation or in the event of a fault. The maximum surface temperature must be below the minimum ignition temperature of the gas present.

In the US and Canada, as in Europe, six temperature classes exist: T1 ... T6. The classes T2, T3, and T4 are divided into further subclasses, as indicated in the following table.

Temperature Classes for Divisions

Maximum Temperature		Temperature Class in North America
°C	**°F**	
450	**842**	**T1**
300	**572**	**T2**
280	536	T2A
260	500	T2B
230	446	T2C
215	419	T2D
200	**392**	**T3**
180	356	T3A
165	329	T3B
160	320	T3C
135	**275**	**T4**
120	248	T4A
100	**212**	**T5**
85	**185**	**T6**

Table 8. Classification of surface temperature

Each gas is allocated to a temperature class according to its ignition temperature. Note that for all specific mixtures there is no connection between ignition energy and ignition temperature. Example: Hydrogen has a minimum ignition energy of 20 µJ and an ignition temperature of 560 °C (1040 °F). By contrast, acetaldehyde has an ignition energy of more than 180 µJ and an ignition temperature of 140 °C (284 °F).

An apparatus classified for a particular temperature class can be used in the presence of all gases if its ignition temperature is above the temperature class rating of the apparatus. For example, a T5 classified apparatus can be used with all gases with an ignition temperature above 100 °C (212 °F).

For all explosion protection methods, a temperature classification is required for all surfaces that may be exposed to a potentially explosive atmosphere.

Selection According to Surface Temperature for Dusts

The device manufacturer determines the highest measured surface temperature (in normal operation and in cases of a fault) of their equipment and specifies this.

The device operator must ensure that the dust cloud only reaches 2/3 of its ignition temperature and that a safety distance of 75 K is upheld from the smolder temperature of the dust layer. If the deposits exceed a layer thickness of 5 mm, the acceptable temperature limit value must be reduced accordingly.

Selection of Equipment According to Explosion Groups

Gases and vapors in Group II/Class I used on surface areas are divided into the following explosion subgroups according to their minimum ignition energy:

IEC	NEC/CE Code	Minimum Ignition Energy
Subgroup IIA	Group D	high ignition energy
Subgroup IIB	Group C	medium ignition energy
Subgroup IIC	Groups A and B	low ignition energy

Table 9. IEC and NEC/CE Code surface area grouping concepts based on the minimum ignition energy

The ignition probability increases from Subgroups IIA ... IIC / Groups D ... A and B. Substances in the IIC / A and B explosion groups require the lowest amount of ignition energy, and can therefore be ignited relatively easily. Because energy may be released when using some types of protection and during possible electrostatic discharges, equipment is labeled with the applicable subgroup or group and selected according to this.

Types of protection that release energy include intrinsic safety (energy release via sparks) and flameproof/explosion-proof enclosures (energy release through enclosure joints). For flameproof/explosion-proof enclosures, each subgroup specifies the substance-specific maximum experimental safe gap (MESG) for the apparatus needed to prevent flashback: the maximum size of a gap without ignitable flashback.

Tertiary Explosion Protection

Tertiary or structural explosion protection must be provided if it cannot be avoided that potentially explosive atmospheres and active ignition sources may meet in the same space. However, by designing containers and equipment in accordance with the maximum explosion pressure possible, the effects of the explosion can be controlled. Also, the propagation of the explosion to other sections of the plant must be prevented using explosion decoupling. The options are presented in brief below.

Designs That Are Resistant to Explosion Pressure

Containers of this kind are able to withstand explosion pressure without lasting deformation or damage. They are dimensioned using the calculation and building regulations for pressure containers.

Designs That Are Resistant to Explosion Pressure Shock

Devices, protective systems, and Ex components must be able to withstand the maximum explosion pressure without rupturing-deformation. The required strength can be established by experimenting with prototypes. It is necessary to test the affected devices, protective systems, and Ex components after an explosion to determine whether this equipment can continue to be operated safely.

Explosion Pressure Relief

Relief is achieved using a specific derivative of the combustion products and the unburned mixture components via a sufficiently large relief joint. This relief enables the maximum explosion pressure to be reduced to the maximum reduced explosion pressure. Each section of the plant is designed according to the maximum reduced explosion pressure. The size of the relief joint complies with the maximum rate of pressure rise. All products of combustion, whether burned, unburned, or burning, must be discharged in a way in which they are not dangerous.

Explosion Suppression

If an explosion occurs, systems for explosion suppression prevent the maximum explosion pressure from being reached. For this, appropriate extinguishing agents are injected into the ongoing explosion. This process is triggered by a combined system that detects rapid explosion pressure rise using simultaneous infrared radiation. This stops the explosion, and the reduced explosion pressure does not exceed the maximum acceptable overpressure for the plant. The devices and plants to be protected can also be designed for a reduced explosion pressure. The advantages of explosion suppression include the following:

- No flame emergence and no pressure effects in the space
- Not dependent on installation location and can be used with toxic products
- No product release

Preventing Explosion Propagation for Gases

Deflagration Flame Arresters

Deflagration flame arresters are used to avoid explosion propagation via pipelines (e.g., filling or exhaust lines) or vents into neighboring sections of the plant. They prevent the explosion from being propagated through flames and can resist the explosion pressure and the thermal stress of a deflagration.

Detonation Flame Arresters

If high speeds are expected during flame propagation or detonation, detonation flame arresters are required. These arresters withstand the mechanical and thermal stress of a detonation and prevent propagation.

Extinguishing Barriers

These solutions prevent explosion propagation in pipelines by extinguishing the flames of the explosion through injecting a suitable extinguishing agent. They are activated by detectors.

Flashback Arrestors for Flames

A flashback can be structurally prevented. If, for example, the temperature of a flame arrester increases, this is usually caused by a continuous flame on one side of the flame arrestor. In this case, measures are triggered that completely interrupt the flame path using sliders.

Preventing Explosion Propagation for Dusts

Due to the risk of blockage by dust particles, not all above-noted procedures are suitable for preventing the propagation of dust explosions. The following procedures are suitable for dusts:

- Extinguishing barriers: see “Extinguishing Barriers” above.
- Quick closing slide valves, quick closing flaps

These appliances take a short time to close in order to prevent flame and pressure propagation in pipelines. The closing process can be carried out using mechanical parts, which are driven by the pressure wave, or using a detector that controls the drive unit.

Rotary Feeders

Rotary feeders are specially constructed components that prevent flame and pressure transfers. If an explosion occurs, the rotor is automatically shut down to preempt the discharge of smoldering or burning dust.

Double Valve Systems

For this, two valves are connected in a way that only allows one to be open at a time. Explosion propagation in the product stream can be prevented by using this effect, which is similar to that of a canal lock.

Assessing Explosion Hazards

Possible explosion hazards can be assessed in the following ways. The substances involved are considered based on their ignition and explosion behavior, manner of release, and safety-relevant properties. In practice, safety parameters (SP) are used as a basis for the safe operation of processing plants. SPs define the dangerous properties of combustible substances and delineate operation and design parameters for fire and explosion protection.

In addition to the SPs, process parameters must be included in the assessment. Explosion hazards can exist during the vaporization of a liquid or during the atomization of liquids under high pressure (clouding). Knowing whether atmospheric conditions or deviations thereof (pressure, temperature, oxygen content) are present is also important for the assessment of an explosion hazard.

SPs are not constants, but are instead assessment criteria based on experimental measuring techniques. The investigation of the substances is based on the historical development of explosion protection. The first SPs related to methane and coal dust. Subsequent parameters were scaled in relation to those that were already known.

Safety Parameters of Combustible Gases and Liquids

To enable figures to be compared, standardized measuring techniques are used that are based on various boundary conditions. Therefore, the figures from one technique may deviate from those from another technique.

Example: Determining the maximum rate of explosion pressure rise: Depending on the selected technique, the measurement of the explosion pressure rise rate delivers speeds of pressure rise that deviate from each other but are always reproducible. The reason for these deviations is the fact that the maximum rate of explosion pressure rise depends on volume, and the containers used are either 20-liter spheres or 1 m^3 containers, depending on the method. See also EN 14034-2 2011-04 for dusts and EN 15967 2011-10 for gases.

Figure 6. Equipment for determining the rate of explosion pressure rise
Source: Kühne AG

The formation of explosive gas/air mixtures can be prevented by using one of the following measures:
- Not reaching the lower flammable limit (LFL)
- Not reaching the limiting oxygen concentration
- Exceeding the upper flammable limit (UFL)

The ignition of explosive gas/air mixtures can be prevented by using one of the following measures:
- Not reaching the ignition temperature and minimum ignition energy

The effects of an explosion can be controlled in the following ways:
- Adjustment of the corresponding protective measures to the maximum explosion pressure and the maximum rate of explosion pressure rise

Typically, a sufficient safety distance to each limit value is determined and monitored. Therefore, the following safety parameters should be evaluated in order to assess the hazards of combustion gas, vapors, and mists:
- Flash point in liquids
- The LFL and UFL
- Limiting oxygen concentration
- Ignition temperature
- Minimum ignition energy or explosion group
- Maximum explosion pressure
- Maximum rate of explosion pressure rise

For information regarding dusts, see “Safety Parameters of Combustible Dusts,” page 39.

Distinctive Properties of Gases

All substances with a temperature above their boiling point are considered gases. Under atmospheric conditions between -20 °C ... +60 °C, substances are gaseous if their boiling point is below the ambient temperature.

If a combustible gas is released in a room that is filled with air, spontaneous and continual mixing occurs, due to the random movements of gas particles. Through this process, the combustible gas distributes itself throughout the room. The combustible gas can no longer be separated from the air. The warmer and lighter the gases are, the quicker they mix and the quicker the differences in concentration within the room balance.

Distinctive Properties of Liquids

At temperatures below a substance's boiling point, the liquid can create vapor instead. The vapor phase can coexist with the liquid phase. Depending on the temperature, an equilibrium can occur between these phases.

The vapors over a liquid surface are liquid molecules that could overcome the surface tension due to their kinetic energy and now move among air molecules. Every liquid has a characteristic vapor pressure that only depends on the temperature. After a specific temperature, this vapor pressure corresponds to the pressure of the surrounding atmosphere. The result of this is that the liquid boils when above this temperature.

Flash Points of Combustible Liquids

The flash point is used to assess the fire and explosion hazards of a liquid. It specifies the lowest temperature at which the liquid gives off enough combustible vapors to immediately ignite with an effective ignition source under normal ambient conditions.

Because the boiling point has been exceeded, combustible gases are already in a gaseous state and do not have a flash point.

Flash Point and Auto Ignition Temperature (AIT) of Selected Liquids

Substance	Flash point [˚C]	AIT [˚C]
Gasoline	-46	+280
Acetone	-20	+465
n-Hexane	-23	+225
Carbon disulfide	-30	+90
Acetaldehyde	-38	+175
Methanol	+12	+385
Ethanol	+13	+363
Acetic acid	+39	+426
Methyl ethyl ketone	-6	+404
Kerosene	+72	+210

Table 10. Flash point and ignition temperature of common liquids. Source: NFPA 497 (2017)

Spraying Combustible Liquids

If a liquid is finely distributed, sprayed in the air or released in the form of aerosols (spray painting, use of aerosol cans, mists forming due to leaking pressurized cable conduits, etc.), it can be ignited in temperatures below its flash point. This depends on the mixing ratio of liquid droplets and atmospheric oxygen.

Explosive Limits

If combustible gases and vapors mix with air, combustion and therefore an explosion after ignition can only occur if the components are within a substance-specific range of concentrations. The concentration limits at which this is no longer possible are designated as the LFL and UFL.

Example of a Minimum Ignition Curve

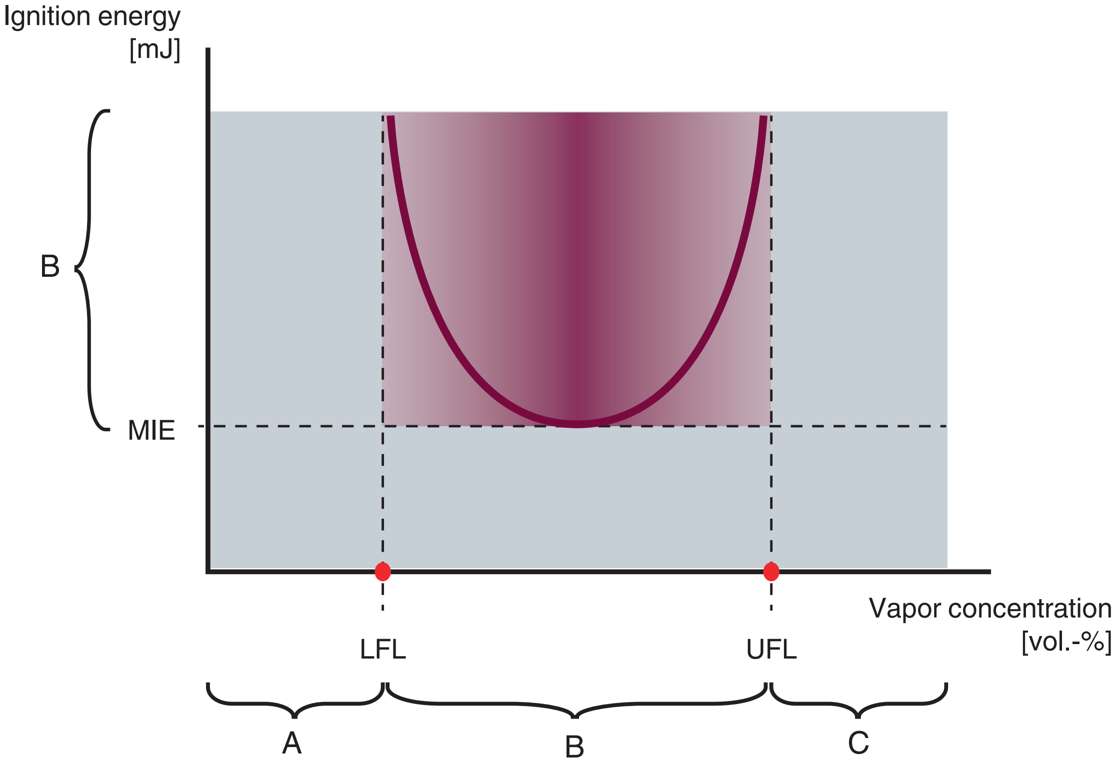


Figure 7. Typical minimum ignition curve under atmospheric conditions. Ignition energy as a function of the concentration of a substance in air (O_2 with 21 vol.-%).

- Section A: Below the LFL, the mixture is not ignitable, because it is too lean. The mixture is noncombustible and non-explosive but could promote a fire.
- Section B: Above the minimum ignition energy (MIE), the mixture is explosible in an explosive atmosphere between the two explosion limits. That means, the mixture can cause a combustion with flame propagation.
- Section C: Above the UFL, the mixture is not ignitable, because it is too rich. The oxygen content is too small to cause an explosion. The mixture is combustible.

The explosion hazard is assessed using the flash point as an SP. The flash point is defined as the temperature at which an ignitable vapor/air mixture forms above the closed surface of a liquid. It is important to note that the flash point has differing values depending on whether it is determined in a closed or an open cup.

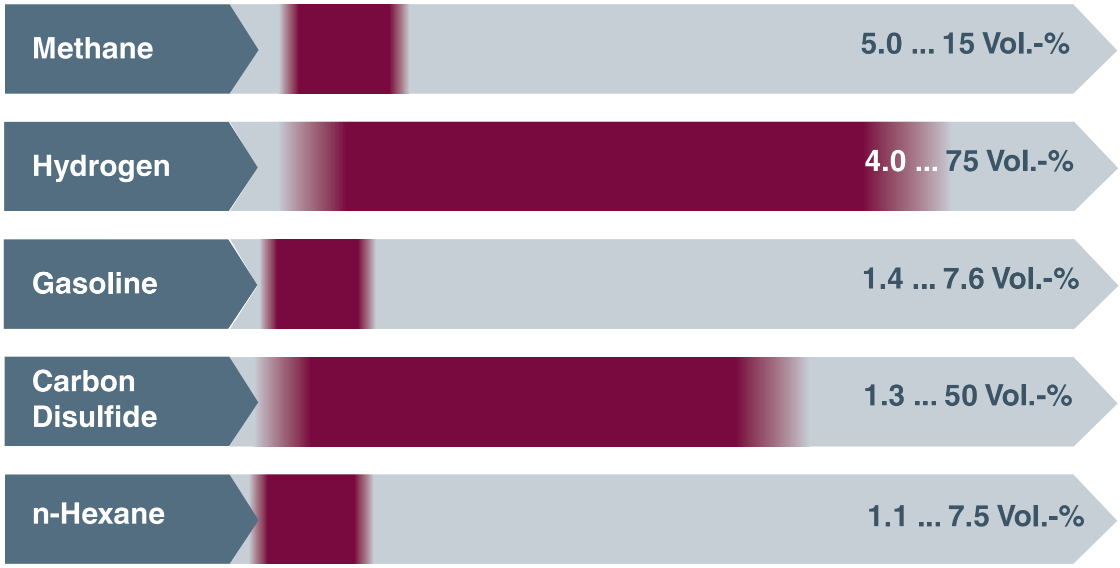


Figure 8. LFL and UFL of selected gases and vapors. Source: NFPA 497 (2017)

Limiting Oxygen Concentration

Flammability and reaction to fire depend on the oxygen content. Explosions can no longer occur below a specific limit value or a limiting oxygen concentration (LOC). The limit value is determined by introducing an inert gas, often nitrogen, into the mixture. This causes the natural oxygen fraction of the air to be reduced by diluting from 20.8 vol.-%, the point where an explosion is no longer possible under the defined test conditions.

If you consider that carbon monoxide can explode with an oxygen content of only 4 %, knowledge regarding the LOC is essential if an environment is to be created that is assuredly free from explosion hazards due to existing oxygen.

For example, the inside of a container can be rendered inert so the oxygen can be displaced from it. This can be achieved by purging the container with an inert gas, by filling the container with quartz sand, oil, etc. Nitrogen, carbon dioxide, noble gases, exhaust gases, and water vapor are the most commonly used gases for inertization processes.

Minimum Ignition Temperature and Temperature Classes

The ignition temperature of a combustible substance is the lowest temperature at which the most flammable mixture of a substance—in the form of gas, vapor, mist, or dispersed dust—and air can still be brought to explosion under defined conditions. Based on their ignitability, combustible gases and vapors are subdivided into temperature classes that are assigned to their defined range of ignition temperatures. The maximum surface temperature of a potential ignition source, e.g., of an electrical apparatus, must always be lower than the ignition temperature of the gas or vapor/air mixture in which it is used.

Temperature Classes of Various Chemical Substances

T1 (> 450˚C)	T2 (> 300˚C)	T3 (> 200˚C)	T4 (> 135˚C)	T5 (> 100˚C)	T6 (> 85˚C)
Acetone	Ethanol	Hexane	Acetaldehyde		Carbon disulfide
Acetic acid	Gasoline	Diesel fuel			
Methane	Methanol	No. 2 fuel oil			
Propane	Ethene	Hydrogen sulfide			
Ammonia	Butane				
Benzene					
Toluene					
Hydrogen cyanide					
Hydrogen					

Table 11. Classification of various gases and vapors into the respective temperature class. Source: GESTIS

Combustible dusts are not classified according to temperature classes. Instead, the minimum ignition temperature of the dispersed dust/air cloud is compared to the maximum surface temperature of a potential ignition source. Specified safety distances must be observed for this process. For additional information, see “Safety Parameters of Combustible Dusts,” page 34.

Minimum Ignition Energy and Explosion Group

The minimum ignition energy (MIE) is the smallest amount of electric energy, determined under predefined test conditions, that is sufficient to ignite the flammable mixture in an explosive atmosphere when discharged.

Minimum Ignition Energy of Various Chemical Substances

Substance	MIE [mJ]
Methane	0.29
Butane	0.25
Propane	0.24
Benzene	0.20
Ammonia	0.14
Ethene	0.082
Hydrogen	0.019
Carbon disulfide	0.009

Table 12. MIE of various gases and vapors. Source: GESTIS

Gases and vapors in Group II/Class I are divided into the following explosions subgroups according to their minimum ignition energy:

IEC	NEC/CE Code	MIE
Subgroup IIA	Group D	high ignition energy
Subgroup IIB	Group C	medium ignition energy
Subgroup IIC	Groups A and B	low ignition energy

Table 13. IEC and NEC/CE Code surface area grouping concepts based on the minimum ignition energy

The hazard potential increases from IIA ... IIC / Groups D ... A and B. Substances in the IIC/A and B explosion groups require the lowest amount of ignition energy, and can therefore be ignited relatively easily. Since energy may be released when using some types of protection and during possible electrostatic discharges, apparatus is labeled with the applicable subdivision. Types of protection that release energy include “intrinsic safety” and “flameproof/explosion-proof enclosures.” The type of protection “intrinsic safety” allows for energy to be released in the form of sparks. The type of protection “flameproof/explosion-proof enclosure” provides a suitable enclosure design that allows energy to escape via an interstice. In the latter case, each subdivision specifies the substance-specific safe gap needed to prevent flashback for each apparatus.

Ignition Energy according to Explosion Group and Temperature Class

	Explosion Group		Temperature Class					
	IEC	NEC/ CE Code	T1 (> 450 °C)	T2 (> 300 °C)	T3 (> 200 °C)	T4 (> 145 °C)	T5 (> 100 °C)	T6 (> 85 °C)
Ignition Energy	IIA	D	Acetone	Gasoline	Hexane	Acetaldehyde		
			Acetic acid	Methanol	No. 2 diesel fuel			
			Methane	Butane	No. 2 fuel oil			
			Propane					
			Ammonia					
			Benzene					
			Toluene					
	IIB	C	Hydrogen cyanide	Ethanol Ethen	Hydrogen sulfide			
	IIC	B	Hydrogen					Carbon disulfide

Table 14. Examples of ignition energies of various explosion groups in connection with temperature classes.
Source: GESTIS

Maximum Explosion Overpressure

The maximum occurring explosion overpressure p_{max} of most organic gases and vapors when mixed with air in atmospheric initial conditions is approximately 8 bar ... 10 bar. In contrast to the maximum rate of explosion pressure rise, the maximum explosion overpressure is not dependent on volume.

Maximum Rate of Explosion Pressure Rise

The maximum rate of explosion pressure rise of a substance indicates how rapidly the explosion overpressure can build up in a reference container. Because this value is volume-dependent, the cubic law applies. According to this law, the product of the maximum rate of explosion and the cubic root of the volume is a constant (CL).

$(dp/dt)_{max} \times V^{1/3} = C_L$

The C_L value is the maximum rate of explosion pressure rise based on volume (e. g., 1 cubic meter, or 20 liters). Transferring a C_L value to other containers is, strictly speaking, only possible if it has the same dimensions as the original.

The maximum explosion overpressure and the maximum rate of explosion pressure rise are required as limit values in order to implement structural protective measures of “explosion-proof design,” “explosion pressure relief,” and “explosion suppression.”

Safety Parameters of Combustible Dusts

The following applies to combustible solid substances: The larger the surface area of the fuel per unit of weight, the quicker the substance reacts with atmospheric oxygen. Approximately 80 % of all industrially processed dusts are combustible and can—depending on the grain size—form explosive mixtures in the air. For a dust explosion to be possible, the dust must be distributed finely in the atmosphere, i.e., be dispersed, and exist within defined concentration limits.

Deviating Explosion Behaviors of Dust and Gas

If a gas cloud is ignited, the resulting explosion pressure causes rapid propagation of the combustion gases and therefore causes a dilution of the gas/air mixture that has not yet burned. If the LFL is not reached because of this dilution, the explosion comes to a standstill. If a dust cloud is ignited, the resulting explosion pressure causes the dispersion of further dust layers that had previously been inactive. These new dust clouds can extend to neighboring buildings and sections of the plant. At the same time, the first explosion generates burning dust, which represents a “long-lasting” ignition source and triggers subsequent explosions. In unfavorable circumstances, this process can repeat itself multiple times.

- The formation of explosive dust/air mixtures can be prevented if the LFL and the LOC are not reached.
- The ignition of explosive dust/air mixtures can be prevented if the ignition temperature and the minimum ignition energy of the dispersed dust cloud are not reached. At the same time, it must be ensured that the smolder temperature of the deposited dusts is not reached.
- The effects of an explosion are influenced by adjusting the corresponding protective measures to the maximum explosion pressure and the maximum rate of pressure rise.

Especially regarding dusts, the plant operator must ensure that a sufficiently safe distance is observed for every limit value. Only the plant operator knows the individual situation, which is determined by the grain size and possible layer thickness of the dust deposits, and can determine and observe the limit values while taking these conditions into account.

Due to these variables and in contrast to gases, no fixed temperature classes can be used for dusts. To assess the hazards regarding dusts, the following safety parameters for deposited dusts or dispersed dusts are examples of those used as a basis:

- Grain size
- Smolder temperature
- Minimum ignition temperature

These are described in detail in the following sections.

Grain Size

The grain size is often specified using the median value, which corresponds to the average grain size. This means that 50 % of the dust is coarser by weight, and 50 % is finer by weight than the given median value. During the processing and transportation of coarse solids, dusts can be released. In general, dust with a grain size of over 400 μ is classified as non-incendive. However, they have still caused explosions, e.g., when filling silos. The reason for this is a fraction of the dust that has smaller particle sizes, which can be attributed to abrasion caused by transportation, among other causes. Because the coarse content settles rapidly, and fine content remains in the air for longer, an explosive dust cloud can separate from the dust when filling a silo.

Smolder Temperature

The smolder temperature of dust layers is the lowest temperature of a heated exposed surface, on which a 5-mm thick layer of deposited dust ignites. The smolder temperature is lower for thicker layers.

Minimum Ignition Temperature

The minimum ignition temperature relates to a dust cloud. It is the lowest temperature of a hot surface determined under specified test conditions, at which the flammable mixture of dust and air is ignited in an oven. For combustible dust, the minimum ignition temperature of the dispersed dust/air cloud is compared to the maximum surface temperature of a potential ignition source. Specified safety factors must be taken into account during this process.

Dust Ignition Temperatures

Substance	Layer or Cloud Ignition Temperature [˚C]
Malt barley	250
Activated charcoal	180
Wood flour	260
Carboxymethyl cellulose	290

Table 15. Layer or cloud ignition temperature of various dusts. Source: NFPA 499 (2017)

Auto-Ignition Temperature

The auto-ignition temperature relates to a deposited dust layer, which ignites itself when subjected to a thermal effect on all sides in the presence of air, without any other ignition sources. Spontaneous ignition is caused if the rate of heat production of the oxidation reaction or decomposition reaction is higher than the rate of heat loss from the dust layer. The heat resulting from the reaction can also cause a low-temperature carbonization gas that is able to form an explosive gas/air mixture.

Explosive Limits

As with gases, dusts are only explosive within defined concentration limits. Depending on material and grain size, the amount of dust needed for the LFL is approximately 20 g/m^3 ... 60 g/m^3 air and for the UFL is approximately 2 kg/m^3 ... 6 kg/m^3 air. Exceeding the UFL for a prolonged period of time would prevent a dust explosion, but only if the dispersed dust is not disturbed or displaced. However, this is not practical, as the dust concentration within a cloud is not homogeneous. The upper dust flammable limit is therefore of lesser importance with regard to safety-related considerations.

Limiting Oxygen Concentration

As well as the addition of inert gases such as nitrogen, powdered inert materials such as calcium sulfate, ammonium phosphate, sodium bicarbonate, powdered rock, or other noncombustible substances can be used to reduce the risk of explosion. It is important that the inert material(s) cannot react with the fuel.

For more information, see “Safety Parameters of Combustible Gases and Liquids,” page 26.

Minimum Ignition Energy

The MIE of combustible dusts is typically much higher than those of gases and vapors. The MIE of the dust depends on the grain size, the surface texture, and the material moisture.

Maximum Explosion Overpressure

For dusts, the maximum explosion overpressure p_{max} can be up to 14 bar in enclosed containers. For additional information see "Safety Parameters of Combustible Gases and Liquids," page 26.

Maximum Rate of Explosion Pressure Rise

For dusts, the constant for the maximum rate of rise is represented by K_{St} (rate of explosion pressure rise and the cubed root of the volume.) Combustible dusts are assigned three graduated dust explosion classes according to their K_{St} value: St 1, St 2, and St 3.

K_{St} Value [bar·m·s-1]	Dust Explosion Class
...< 200	St 1
200 ≤ ... < 300	St 2
300 ≤ ...	St 3

Table 16. Maximum rate of pressure rise for each dust explosion class

The dust explosion classes provide advice for selecting suitable protection concepts regarding dust explosions and how protective measures for structural explosion protection should be designed. Typical protective measures for structural explosion protection are explosion-proof designs, explosion pressure relief, and explosion suppression.

For additional information, see "Safety Parameters of Combustible Gases and Liquids," page 26.

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