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EXPLOSION VENTING 1974

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Guide for

Explosion Venting

NFPA No. 68 — 1974

Origin and Development of No. 68

The Guide for Explosion Venting was first adopted as a Temporary Standard in 1945. In 1954 the Temporary Standard was replaced by a Guide. At that time, all of the best available information was brought together on the fundamentals and parameters of explosions, the data developed by small scale tests, the interpretation of the results of such tests, and the use of the vents and vent closures in use at the time. This was then related to "rules of thumb" vent ratio recommendations which have been used for many years. Some of these vents have functioned well. Perhaps it is well that some were never put to the test.

Since 1954, there has not been extensive experimentation in the United States done to add to the information already known. However, work done in Great Britain and Germany has opened the way to a method for designing vents. The U. S. Dept. of Interior, Bureau of Mines, has also done some work in this direction which was not completed because the group involved has been assigned to different programs.

The present committee has reviewed the work done in Great Britain and Germany and finds it has merit in design of vent recommendations. This guide, therefore, has been revised with the hope of providing a means for calculating vent ratios with a greater degree of accuracy than that provided by the "rules of thumb".

Committee on Explosion Venting

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Introduction

Object and Scope of This Guide

The object of this Guide is to provide useful information for the design and utilization of vents to limit pressures developed by explosions (deflagrations) of dusts, or gases (vapors) in buildings, rooms, bins and equipment in order to prevent or reduce structural or mechanical damage.

Vents are not generally intended to serve as a means of preventing explosions, although in some cases, they may be used to retard the development of an explosion, or prevent propagation from one section of a plant to another.

This Guide is not intended to be used for calculating venting or emergency relief for exothermic runaway reactions.

For the purposes of this Guide, a vapor is considered a gas. Also, the term "explosion" shall mean the bursting of a building or container as a result of internal pressure developed by a "deflagration," beyond the confinement capacity of the building or container.

Materials, Processes and Equipment Covered

Materials

The following materials considered in this guide are combustible substances which when mixed with air or other supporter of combustion are capable of exploding:

a. Finely divided combustible solids, including certain metals, in the form of dusts or powders.

b. Vapors of flammable liquids.

c. Flammable gases.

This guide is not intended to cover explosives.

Processes

This guide covers equipment, housings, rooms and buildings associated with:

a. The manufacture, handling, processing and storage of finely divided solid combustible materials.

b. Combustible materials which may produce finely divided particles in processing, handling or storage.

c. Flammable liquids, vapors and gases.

Equipment

Typical equipment to which this guide applies includes:

a. Crushers, grinders, pulverizers, etc.
b. Sieves, screens, bolters, dust collectors and arrestors, etc.
c. Conveyors, screw feed conveyors, bucket elevators, etc.
d. Dryers, ovens, furnaces, spray driers, etc.
e. Blenders, mixers, etc.
f. Ducts, pipes, etc.
g. Bins, silos, etc.
h. Spreaders.
i. Coating machines.
j. Packaging equipment.

This guide is not intended to cover the following equipment:

a. Oil-insulated transformers and switchgear.
b. Pressure vessels, such as reactors and autoclaves.
c. Excess pressure relief devices on tanks or pressure vessels, or equipment designed solely for ventilating purposes.

Guidance for Explosion Prevention

There are two distinct phases involved in a study of any explosion problem as follows:

a. *Prevention,* which deals with the elimination of the conditions which permit the formation of an explosive mixture and the elimination of all possible sources of ignition; and
b. *Protection,* which deals with reducing the effects of an explosion, the basic purpose of this guide.

Information relating to explosion prevention measures and required fire protection for many specific industries are covered in NFPA codes and reports.* Briefly these codes deal with the following:

a. Prevention of the formation of an explosive mixture of dust, vapor, or gas with air, particularly in rooms or buildings containing hazardous operations. This may be accomplished by good housekeeping, by preventing the escape of dusts, vapors or gases, by good mechanical ventilation, by dilution of the mixture, by effective dust collection systems, by addition of some inert material such as rock dust or inert gas.
b. Eliminating all sources of ignition where an explosive atmosphere might exist: Open flames, lights, and smoking should be prohibited. All electrical equipment should con-

* Complete list available from NFPA on request.

form with Article 500 of the National Electrical Code, NFPA No. 70, 1974. All sources of heat such as friction, hot plates, hot surfaces, sparks, exothermic reactions, spontaneous ignition, etc., should be guarded against; and all equipment should be properly bonded and grounded according to the Recommended Practice on Static Electricity, NFPA No. 77, 1972, to prevent the accumulation of static electricity.

It is understood that even though explosion prevention measures have been adopted, it is equally necessary to apply proper protection measures.

Definitions

Deflagration

Burning which takes place at a flame speed below the velocity of sound in the unburned medium.

Detonation

Burning which takes place at a flame speed above the velocity of sound in the unburned medium.

Dust

In this Guide dust or powder refers to any finely divided solid material whether product or waste.

Explosion

The bursting of a building or container as a result of development of internal pressure beyond the confinement capacity of the building or container.

Explosive Limits (Flammable Limits)

In the case of most flammable or combustible liquids, gases and dusts, there is a minimum concentration of vapor, gas or dust in air or oxygen below which propagation of flame does not occur on contact with a source of ignition. There is also a maximum concentration of vapor, gas or dust in air above which propagation of flame does not occur. These limit mixtures of vapor, gas or dust with air, which if ignited will just propagate flame, are known as "lower and upper explosive or flammable limits." In the case of vapors and gases limits are usually expressed in terms of percentage by volume of gas or vapor in air. In the case of dusts, limits are usually expressed in terms of ounces of dust per cubic foot of volume. (The upper limit for a dust usually cannot be well defined.)

Explosive Range

The concentration lying between lower and upper explosive or flammable limits, expressed in terms of percentage of vapor or gas in air by volume, comprises the "explosive range," also often referred to as the "flammable range."

Fire Point

The fire point is the lowest temperature of liquid in an open container at which vapors are evolved fast enough to support continuous combustion. (Methods for determining fire point are the Tag Open Cup ASTM-D1310 and, for high temperature, the Cleveland Open Cup ASTM-D92.)

Flash Point

The flash point of the liquid or solid is the minimum temperature at which it gives off sufficient vapor to form an ignitible mixture with air near the surface of the liquid or within the vessel used. By "ignitible mixture" is meant a mixture within the explosive range (between upper and lower limits) that is capable of the propagation of flame away from the source of ignition when ignited. (By "propagation of flame" is here meant the spread of flame from layer to layer independently of the source of ignition.) This is not to be confused with "Fire Point." (Methods for determining flash point are the Tag Closed Cup ASTM-D56, and for viscous liquids, the Pensky-Martin ASTM-D93.)

Ignition Temperature

The ignition temperature of a substance, whether solid, liquid or gaseous, is the minimum temperature required to initiate or cause self-sustained combustion independently of the heating or heated element. The ignition temperature of a solid is influenced by its physical condition and the rate of heating. Figures on ignition temperatures may vary, depending upon the test method, since the ignition temperature varies with the size, shape and material of the testing container and other factors.

Open Vent Pressure

Open vent pressure may be defined as the pressure developed by an explosion in a container having an unobstructed vent.

Optimum Mixture

Optimum mixture is one in which the combustible material and air are in the proper proportion to give the most violent explosion. Generally this occurs at approximately the stoichiometric proportions.

Rate of Pressure Rise

Rate of pressure rise during a particular interval of an explosion may be expressed as the ratio of the increase in explosion pressure to the time interval (ΔP/sec.) required to attain that increase of pressure. The "average rate of pressure rise" is the ratio of the maximum pressure to the time interval from the initiation of the explosion until the maximum pressure is reached, and the "maximum rate of pressure rise " (ΔP_{max}/sec.) is computed from the slope of the steepest portion of the pressure-time curve during the development of the explosion. The rate of pressure rise depends somewhat on the volume of the container.

Vapor

As specified herein is a gas.

Vent Ratio

Vent ratio is the relationship of the area of the rupture diaphragms or explosion panels to the volume of the equipment or room subject to internal explosions. Vent ratio may be expressed in terms of "square feet per 100 cubic feet" or as the reciprocal of the cubic feet of vented volume per square foot of vent.

NOTE

Reference herein to the 1974 National Electrical Code, NFPA No. 70, is to that code adopted by the National Fire Protection Association on May 22, 1974 at its Annual Meeting. This code is also known as the 1975 National Electrical Code.

Chapter 1. Fundamentals of Explosion Venting

Conditions that Influence the Explosion Hazard

What Will Explode

Any flammable dust, vapor or gas mixed with air or other supporter of combustion, under the proper conditions, will explode when ignited. The three prerequisites for an explosion are:

a. A combustible material.

b. Air, or other supporter of combustion.

c. A source of ignition, or temperature above the ignition temperature.

Conditions Affecting Violence of Explosions

The principal factors influencing the violence of an explosion are:

a. The nature of the material, *i.e.*, chemical structure.

b. The concentration of the material in air.

c. Particle size, in the case of dusts.

d. Source of ignition, external spark, flame or hot surface.

e. Effect of moisture or diluting substances.

f. The oxygen concentration.

g. Point of origin of the explosion with respect to position of vents.

h. Material of construction and shape of the container.

i. Condition of the container surface.

j. Turbulence of the mixture.

k. Vent area.

l. Nature of the vent closure, *i.e.*, the material and its physical construction.

Important Basic Considerations for Venting Explosions

In considering the suggestions made in this pamphlet, the following principles established by test and experience should be kept in mind:

a. Many substances not ordinarily considered combustible will burn and explode under proper conditions of particle size, increased temperature, or increased oxygen concentration.

b. An ordinary building wall will not withstand a sustained internal pressure as great as 1 psi (144 lbs. per square foot.)

c. There is a pressure rise during an explosion within an enclosure even with open, unobstructed vents and any delay in opening venting devices increases the pressure.

d. Delay in opening vents may be due to the pressure required to open the vent or to the inertia of the vent closure. Therefore, it is essential that various relieving devices should start to open at as low a pressure as can be tolerated and also that the construction be light so that full opening can be quickly attained.

e. The present knowledge of the mechanism of large scale explosions and the resistance of buildings to internal forces does not permit precise recommendations. However, it is known from experience and testing that generally it may not be practical to provide sufficient vent area to prevent serious damage from an optimum-mixture explosion, which involves a large volume in a building. Experience has shown that most explosions of dusts, vapors and gases do not involve a large part of the total volume of the enclosure and that explosions of vapors and gases frequently occur near the limits of the explosive range. Consequently, such explosions are rather weak. Venting as recommended in this guide will prevent major damage in nearly all incidents. Since explosion venting is a complex subject on which much essential information is lacking, this is only a general guide for best current practice. Appendix III contains some illustrations of various methods of providing explosion vents.

Important Basic Recommendations

Basic recommendations of importance in reducing explosion damage:

a. Vents are generally required in buildings containing operations or departments where combustible dusts can accumulate, or where flammable gases, vapors or mists, including aerosols in fumigation, may be present in sufficient amounts to create explosive concentrations in air. These buildings are more specifically defined in Article 500 of the National Electrical Code NFPA No. 70, 1974, as Class I and Class II areas.

b. Structural damage can be minimized by locating hazardous operations or equipment outside of buildings and cut off from other operations by a pressure resisting wall. This is particularly true of dust collectors, arrestors and bucket elevators. In cases of multiple installations of dust collectors serving one building, there should be no physical interconnections between the duct work systems of each collector. Furthermore, such equipment should be properly vented and a device should be provided at the inlet of the collector which will prevent an explosion from blowing back through the ductwork and into the building.

c. When it is impractical to locate hazardous operations or equipment outdoors, they should be located, where practical, in a single-story building or on the top floor of a multi-story building, or in a lightly constructed penthouse and vented directly to the outside through ducts of adequate cross-sectional area.

d. Highly hazardous operating equipment should be separated into individual units by pressure resisting walls, and each unit so formed should be vented outdoors. Exterior walls may be made of heavy construction if equipped with suitable vents or adequate light-weight panels which blow out easily. Locating hazardous operations or equipment in basements or areas partially below grade should be avoided due to the difficulty of providing adequate venting.

e. Vents which are properly designed and located will usually limit pressures resulting from an explosion of a dust, vapor or gas sufficiently to prevent damage. Wherever possible, venting should be directed to the outside of the building. (See Chapter 3 for a description of vents and vent closures.)

f. The required area of explosion vents depends upon the intensity of an explosion, the strength of the structure, the type of vent closure, and other factors.

g. When venting a room, building, or piece of equipment, consideration must be given to the location into which an explosion is to be vented, in order to prevent damage to exposures and injury to personnel. In congested locations, substantial ducts or diverters should be provided to direct the blast.

h. Ice crystals may form between explosion venting sash and the frame during cold weather due to high humidity in the area producing a cementing action on the vent and thereby allowing greater pressures to be built up before the vent will open A coating of grease on the adjacent surfaces may prevent the bridging of the ice crystals between the members of the vent.

i. Corrosion and paint may also increase friction in opening this type of vent. Precautionary measures should be taken to prevent the moving and sliding parts from being affected.

Basic Considerations for Enclosure Design

Design of Structures

No data are available on actual forces or loads applied to the walls of full-size structures by different types of explosions. Design must be based upon the specific equipment, the building and its material of construction, its shock resisting ability, and the effect of vent openings on the pressure developed and its duration. Pressures produced by explosions of common vapors and gases in air in laboratory test bombs at atmospheric pressure, are of the order of 100 psi. To withstand an explosion of a dust, vapor or gaseous mixture, a building need not be constructed to withstand the pressure such as can be produced in a closed laboratory test bomb provided the volume is adequately vented. It is impractical to construct a building to withstand 100 psi; an ordinary brick wall 12 inches thick may be destroyed by less than 1 psi internal pressure.

Rate of Pressure Rise

The rate of pressure rise is an important factor in explosion venting as it determines the time interval available for some of the combustion products of an explosion to escape. A rapid rate of rise means that only a short time is available for venting and conversely a slower rate allows a longer time. Consequently, the slower the rate of pressure rise, the more easily an explosion can be vented. (See Appendix II, Tables 3, 4 and 5 for rates of pressure rise for some common naterials.)

The maximum pressure developed in a laboratory test bomb does not fully define the true explosion load imposed on the walls. This is because a given force applied to a wall panel for a long period may be more destructive than the same or an even greater force applied for a short period. Moreover, the explosion pressure is not constant. The area under the pressure-time curve determines the total impulse exerted and hence the dynamic effect of the explosion on the structure. Concisely, the effects of an explosion depend upon the maximum explosion pressure developed, the rate of pressure rise and the duration of the excess pressure.

Empirical Formulas

There have been a number of empirical formulas employed for computing size of vent openings for a specific vessel or structure, but unfortunately none of these can be considered as entirely satisfactory.

Theoretical calculations have been made by several research organizations to determine and evaluate the ability of various structures to withstand the shock of an external explosion and some actual tests were made by the Corps of Engineers, U. S. Army, which dealt with the ability of various structures and shelters to resist bomb explosions from without. Most enclosed structures, by reason of tie-ins and bracing, can usually withstand more pressure from without than from within. At times, this may be in the ratio of 2 to 3 times greater.

Protection of Piping for Sprinklers, Standpipes

Fire can be expected to follow an explosion in most occupancies so that any fixed fire extinguishing equipment should be so installed as to minimize damage to it. Piping for automatic sprinklers should be supported by main framing members of the building whenever practicable. Inside fire hose lines should be fed by a source other than the sprinkler line or riser serving that building, since damage to them may render the hose line inoperable.

Fundamentals of Piping and Duct System Design

When ductwork is used to conduct the explosion products outdoors, it should be constructed, as far as practicable, of sufficient strength to withstand maximum explosion pressure. (Insufficient data are available concerning vented explosions in ductwork to predict the maximum explosion pressure which will be developed by the explosion products within the duct. Therefore, small scale experiments should be conducted when designing such systems and the results applied within limits to larger installations.)

Explosions within duct and piping systems may be vented by the use of suitable diaphragms which will blow out at some predetermined pressure.

There should be no physical connection between ductwork systems for more than one collector.

Under certain restricted conditions in piping or duct systems mixtures of vapors or gases may detonate upon ignition. When this occurs, a high pressure shock wave traveling at a speed of several thousand feet per second precompresses and preheats the combustible mixture ahead of the flame to a high pressure and temperature, so that effective venting cannot be accomplished.

Conditions which affect detonations are not well understood, but experimental results have shown that:

a. The (minimum) length of pipe required for detonation to take place is a function of the diameter;

b. the nature of the surface of the vessel is a contributing factor;

c. the nature of the combustible material influences the ability for detonation to occur;

d. turbulence of the mixture increases the possibility of detonation, and

e. the detonation range of a flammable mixture is usually narrower than the explosive range.

Chapter 2. Intepretation of Test Data

Classification of Explosive Materials

The rates of pressure rise developed by gas-air mixtures are usually higher than those of dust-air mixtures. The average rate of pressure rise is the governing factor to be taken into consideration in any venting problem; therefore, it is desirable to classify materials according to this characteristic, as in Table 1. (See also Appendix II, Tables 3, 4 and 5.)

Comparison of Dust, Vapor and Gas Explosions

In certain respects, dust explosions are similar to vapor and gas explosions. The similarity is more pronounced as the particle size of the dust decreases. (Figures 1, 2 and 3 illustrate the effect of particle size on explosion pressures, minimum explosive concentrations and minimum igniting energies of dust clouds.) A

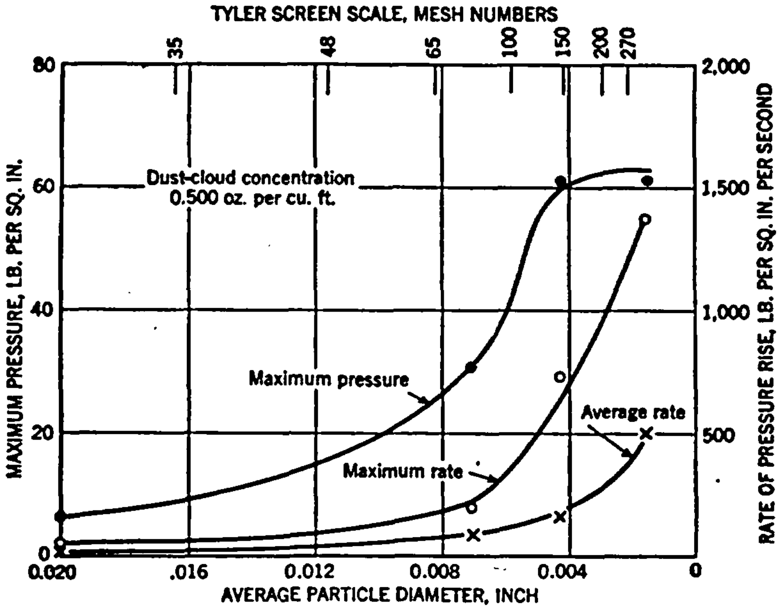

Figure 1. Variation of maximum explosion pressure and rate of pressure rise with fineness of cellulose acetate molding powder. (Reprinted from U. S. Bureau of Mines Report of Investigation 3751.)

Table 1. Classification of Explosive Material According to Rates of Pressure Rise

Class A Materials (Slow rates of pressure rise)

Metal Dusts
- Antimony
- Cadmium
- Chromium
- Copper
- Iron (impure)
- Lead
- Tungsten

Vapors
- Ethylene Dichloride

Miscellaneous Dusts
- Anthracite
- Carbon Black
- Coffee
- Coke, low volatile
- Graphite
- Leather
- Tea

Class B Materials (Medium rates of pressure rise)

Metal Dusts, or Powders
- Iron (carbonyl, electrolytic or H_2 reduced)
- Manganese
- Tin
- Zinc

Vapors
- Propylene Dichloride

Grains, Spices, etc. — Dusts
- Alfalfa
- Cocoa
- Grain dust and flour
- Mixed grains
- Rice
- Soy Bean
- Spices
- Starch
- Yeast

Plastic Dusts
- Cellulose Acetate
- Methyl Methacrylate
- Phenolformaldehyde
- Phthalic Anhydride and its resins
- Polethylene
- Polystyrene
- Urea Resins
- Urea — Melamine
- Vinyl Butryal

Miscellaneous Dusts
- Bituminous Coal
- Cork
- Calcium Lignosulfonic Acid
- Coumarone Indene
- Dextrin
- Lignin
- Lignite
- Peat
- Powdered Drugs
- Pyrethrum
- Shellac
- Silicon
- Sulfur
- Tung
- Woodflour

Class C Materials (Fast rates of pressure rise)

Metal Dusts
- Aluminum
- *Stamped Aluminum
- Magnesium
- Magnesium — aluminum alloys
- *Sorbic Acid
- *Titanium
- *Zirconium
- Some Metal Hydrides

Vapors and Gases
- Acetone
- Methyl-ethyl Ketone
- Ethers
- Alcohols (methyl, ethyl, isopropyl and butyl)
- Hydrocarbons (see App. II, Table 3)
- Gasoline
- *Acetylene
- *Ethylene
- *Carbon Disulfide
- *Hydrogen

* These are exceptionally fast.

dust, like a gas, must be mixed with air or other supporter of combustion to produce an explosion, and a source of ignition generally is necessary to initiate the explosive reaction. Only in rare instances have explosions been produced by spontaneous rapid oxidation and heating of dusts. The explosions of lower and upper limit mixtures are weak, and the strongest explosions are produced by optimum concentrations of the combustible material. (See Figure 4.) During the initial stages of most dust and vapor explosions, there is an induction or ignition-leg period sometimes attributed to the initiation of a chain reaction.

The reaction rate and the rate of pressure rise in vapor and gas explosions are generally higher than in dust explosions, while the energy and pressures developed by complete combustion of dust in a given volume of air are frequently greater than by combustion of gas. The combustion of dust is a surface reaction, at least in the initial stages, and therefore diffusion of oxygen toward the reacting surface is necessarily slower and less complete than in gas explosions. Turbulent mixing of the dust with air enhances diffusion of oxygen to the reacting surfaces and promotes stronger explosions; the effect of turbulence is similar in the combustion of gas-air mixtures.

Dust explosions are sometimes more disastrous in their effects than gas explosions. This is partly due to the slower rate of their development and therefore longer duration, which results in a greater total impulse, and partly because combustible dust is often widely distributed through lack of attention in many industrial plants.

The nature and intensity of the ignition source have important effects on the character of the resulting explosions. With dusts, the ignition source frequently produces the dust cloud.

Characteristics of Materials Which Affect Explosion Pressures

Under similar test conditions, some materials produce stronger explosion than other. Experimentally, stamped aluminum powder produced the most violent dust explosions, followed by stamped and milled magnesium, atomized aluminum, phenol formaldehyde resin, cornstarch, soybean protein, wood flour and coal dust, while in gas and vapor explosions, hydrogen, ethylene, carbon disulfide, and acetylene were most violent, followed by methyl alcohol, acetone, hydrocarbons, and then chlorinated hydrocarbons. (Refer to Appendix II, Tables 3, 4 and 5.)

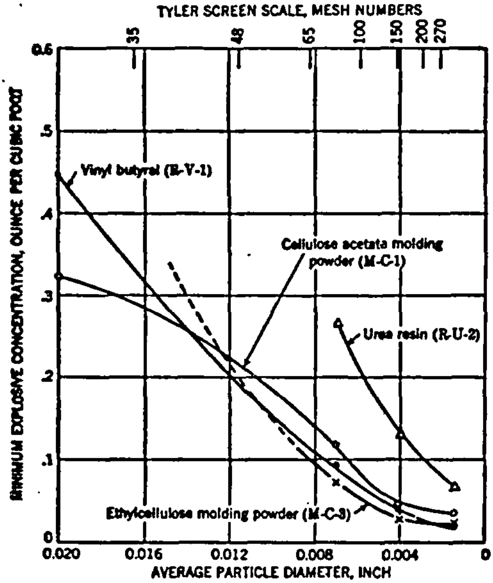

Figure 2. Effect of fineness on minimum explosive concentration of dust clouds. (Reprinted from U. S. Bureau of Mines Report of Investigation 3751.)

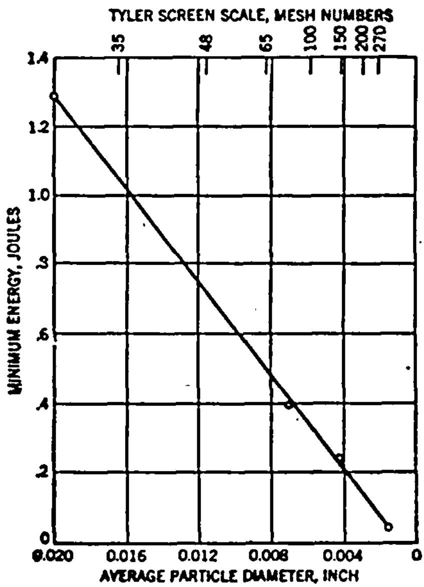

Figure 3. Effect of fineness on minimum energy required for ignition of dust clouds. Graph shows results of tests with cellulose acetate molding powder. (Reprinted from U. S. Bureau of Mines Report of Investigation 3751.)

For a given material, the finer the particle size the more violent is the explosion, the less energy is required to ignite it, and the more likely it will remain in suspension for a longer time.

Some materials, such as stamped aluminum powder, hydrogen and acetylene, are difficult to vent effectively due to the rapid rate of pressure rise.

Some slow burning materials, such as coal dust, in a confined space may do much damage because of the longer duration of the pressure against the walls of the building.

As the concentration of the dust increased in air above its lower explosive limit, there is a progressive increase in explosion pressure until the optimum concentration is reached, beyond which a considerable increase in concentration of dust may be necessary before the reaction is retarded.

Some dusts, such as magnesium, titanium and zirocnium, and several metal hydrides, may react with and ignite in some common inert gases, such as nitrogen and carbon dioxide.

Reducing Destructive Effects of an Explosion

Effect of Vent Size

The maximum explosion pressure (as well as the total impulse) in a vented structure decreases as the size of the vent increases (see Figure 5).

Several small unrestricted vents will relieve the pressure of an explosion in a small room as effectively as one large vent whose area equals the combined area of the small vents. However, this may not be true in large structures; here the position of vents relative to the explosion is important.

Effect of Vent Closures

When vents are sealed by paper, plastic, or metal diaphragms, hinged panels or other closures, etc., the maximum explosion pressures are higher than when the vent is unrestricted. Therefore, the vent areas must necessarily be larger. (See Table 2.)

Rupture of paper, plastic or metal diaphragms when an explosion begins is greatly facilitated by saw-toothed or piercing cutters along the periphery or at the center of the diaphragms, thereby permitting the use of smaller relief vents than if no cutters are used.

Effect of Shape of Vent

Unrestricted rectangular vents are as effective as square vents of equal area for venting explosion pressure; but square vents closed by a given diaphragm material are somewhat more effective than closed rectangular vents of the same area.

Factors Affecting Rupture Pressures of Diaphragms

Pressures required to rupture diaphragms of a given material and thickness decrease with increase in area of the diaphragm. (See Appendix II, Figures 6 and 7.)

Pressure required to rupture diaphragms of the same area and material but of different thickness increases with the thicker diaphragms. (See Figure 5; also Appendix II, Figures 6 and 7.)

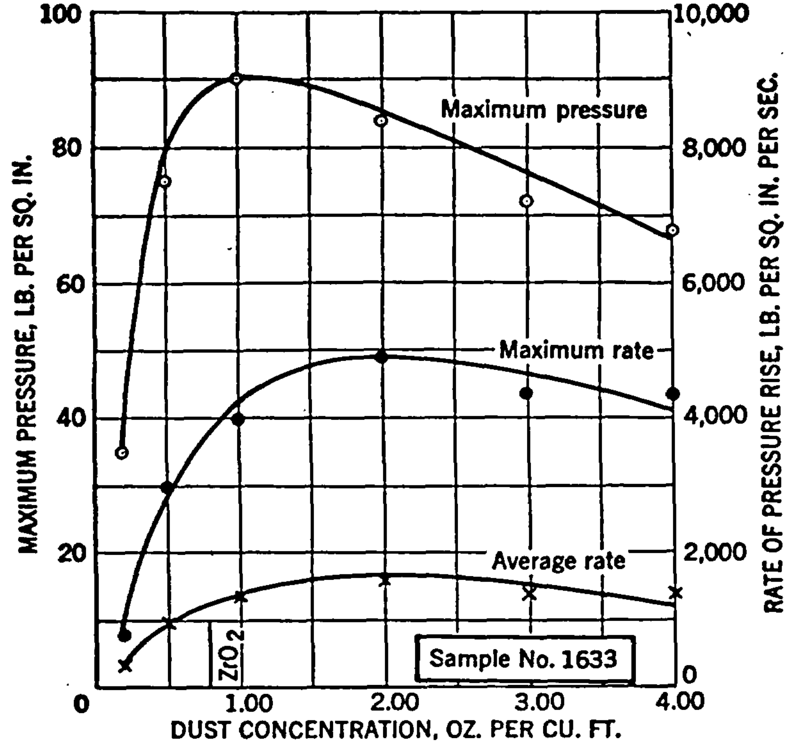

Figure 4. Maximum pressure and rates of pressure rise developed by explosions of zirconium. (Reprinted from U. S. Bureau of Mines Report of Investigation 4835.)

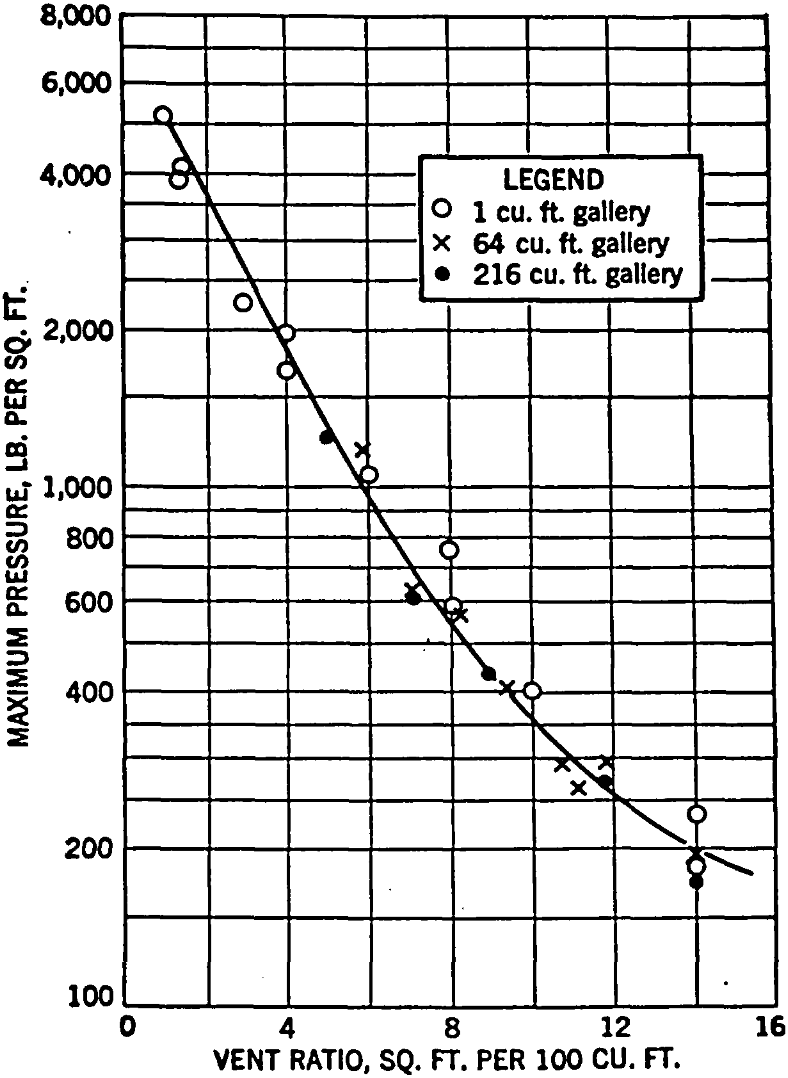

Figure 5. Effect of unrestricted relief vents on pressure developed by explosions of cornstarch in three galleries. (Reprinted from U.S. Bureau of Mines Report of Investigation 4725).

The rupturing pressures of diaphragms (3 inches in diameter or larger) is almost independent of the maximum rate of pressure rise; therefore, information concerning a specific diaphragm material may be applied with some reservations to other explosive mixtures.

Variation of Vent Ratio with Rate of Pressure Rise

Explosive mixtures having a high rate of pressure rise will produce greater open vent pressures than explosive mixtures having a low rate of pressure rise, and will, therefore, require more vent area for effective venting of the explosion products. (See Appendix II, Tables 3, 4 and 5 for the rates of pressure rise of different materials.)

Effectiveness of Swinging Panels

Light, hinged swinging panels are nearly as effective as unrestricted vents. For the release of relatively slow explosions such as coal dust, chlorinated solvents, etc., results have shown in some cases that they are more effective than heavy-paper diaphragms.

For the release of rapid, violent explosions, any obstruction will decrease the effectiveness of the vent and closures of high inertia should be avoided. Counterweights add to the inertia of vents and should be avoided if possible.

Prevention of Negative Pressures

When swinging panels, windows or other hinged devices are used, care must be taken to prevent closure of the vent opening after the initial positive pressure wave of the explosion subsides so as to prevent the development of destructively high negative pressures as the remaining combustion products cool down.

Vent Obstructions

Explosions vents should not be obstructed by other objects, nor should ice crystals or snow loads be allowed to interfere with proper operation of the vent.

Location of Vents

Vents should be located as near as possible to the expected point of origin of an explosion when it can be determined.

In irregularly shaped enclosures, placing of vents may be planned by dividing the volume up into imaginary cubes and supplying each space with sufficient venting capacity.

Construction of Explosion Venting Ducts

Whenever ducts are used to direct the products of an explosion to a safe location, they should be as short and direct as possible, and so located as to vent in the direction of least exposure. It should be realized that any duct will decrease the effectiveness of the vent in proportion to the duct length.

Ducts should be constructed of sufficient strength, as far as practicable, to withstand the maximum (vented) explosion pressure.

Effect of Wind Pressure on Vent Design

Because external wind pressure or suction may operate venting devices, these effects must be considered in their design. Wind pressures in very severe storms may reach over 30 pounds per square foot, and if vents were designed to open at a higher pressure in the event of an explosion it would be too high for building safety. Therefore, a compromise must be found, depending upon local conditions, between building safety and frequent wind pressure operation of the explosion vents.

Wall and Roof Hatches

Hatches in walls or roofs of heavily constructed buildings provide a means of explosion venting. However, these types of vents require frequent inspection and maintenance where snow loads, ice crystals and corrosion may impair the effectiveness of the vent.

Lightweight Wall Sections

Relief of explosion pressures can be achieved, also, by the installation of lightweight wall sections of weak construction which will blow out easily upon impact of the explosion. Counterweighing such sections is not recommended as counterweights add to the inertia of the vent.

Segregation of Hazardous Processes

Hazardous processes and equipment should be segregated in small detached buildings, or separate, vented units with fire walls.

Good Housekeeping

Good housekeeping is a factor of utmost importance in the elimination of secondary explosions.

CHAPTER 3. VENT AREA RECOMMENDATIONS

A. Exothermic Runaway Reactions

For calculating venting of process equipment for runaway exothermic reactions, refer to J. E. Huff, Loss Prevention, Vol. 7, CEP Technical Manual published by American Institute of Chemical Engineers, 1973, pp. 45–47. (Reference 37 — Appendix I).

Although this paper was written from the standpoint of polymerization reactors, these recommendations apply equally to venting for monomeric exothermic reactions, which usually involve liquids of lower viscosity than do many polymerization reactions.

B. Venting of Combustion of Gas Mixtures and of Gas-Dust Mixtures

1. General Comments

At the time of drafting this Guide, the state of technology for combustion venting is still only partially developed. Combustion venting involves many variables, only some of which have been investigated. Even the investigation of any particular variable has been limited in scope. The investigations which have been done do allow certain generalizations to be made. From these have been developed the recommended calculation bases given below. The calculation bases must be recognized as approximate only. An attempt was made to evaluate the data and correlations in recently published papers and to make use of those which were considered reliable. (See Appendix I, References.)

Many variables affect the maximum pressure which can develop during combustion venting. This pressure can be significantly higher than the pressure at which the venting device releases. Among the variables which affect the pressure which will develop during combustion venting are the following:

a. size of vent relative to size of space to be vented;
b. vent release pressure;
c. vent inertia;
d. effective length, cross section, and geometry (e.g., bends) of pipe or duct, if any, both upstream and downstream of vent;
e. location of vent on container to be vented;
f. initial pressure in the container before ignition occurs;
g. initial temperature;
h. initial composition of gas mixture or of gas-dust mixture, and degree of uniformity of composition throughout the space;

i. initial turbulence, and degree of uniformity of that turbulence;
j. size of containing space;
k. shape of containing space;
l. identity of fuel; (chemical and physical properties)
m. identity of oxidant; (chemical and physical properties)
n. number of ignition sources;
o. location of ignition source or sources.

2. Venting of Gas Combustion Inside Buildings

Buildings are usually not designed to withstand high pressures from within. Buildings will often be blown apart by sustained internal pressures of 1 psi (7 kN/m^2) or even less. Combustion venting of buildings therefore normally implies the need to vent in a manner such that the maximum pressure development is low. This maximum pressure must be lower, by a safety margin, than that pressure which the weakest building member, desired not to break or vent, can withstand. This weakest building member may be not only a wall but also the roof or, if the building be elevated, the floor.

Much consideration needs to be given to building venting panels. Above all they need to have the lowest feasible inertia and no counterweights; counterweights add to inertia. Vent panel release pressure needs to be as low as feasible relative to anticipated wind forces. The release pressure can usually be in the range of 20 to 30 lbf/ft^2 (1 to 1.5 kN/m^2). The vent panels may be restrained at one end by a simple hinge or chain or cable. The purpose of this is to prevent the vent panels from flying away from the building when they do open to vent combustion.

Special consideration should be given to the material of construction of the vent panel. It should not be of a material that tends to break into pointed shards; specifically it should not be of glass or the cement-asbestos type board. A material which meets most of the desired criteria fairly well is thin gage corrugated paneling made of fiberglass-reinforced plastic with a flame spread rating no higher than 25 according to NFPA No. 255, 1972, Test of Surface Burning Characteristics of Building Materials.

A precautionary note is needed. It may be necessary to install indoor railings along floor edges near venting panels in order to prevent people from inadvertently knocking the panels open and falling out. Consideration also needs to be given to the space outside the building, into which the vent panels will open.

A number of factors complicate combustion inside buildings as discussed in Appendix 1, in References 36, 43, 51, 55. These references also present two different equations for building venting and discuss limitations of the equations. The equations are presented here for convenience.

References 36 and 55 discuss the "Runes" equation, which is as follows:

$$A_v = \frac{kL_1L_2}{\sqrt{P}} \tag{1}$$

A_v = necessary building vent area, ft.^{2} or m^2
k = constant characteristic of the fuel gas, as discussed below.
NOTE: k is dependent upon the units (English or SI) used.
L_1 = smallest dimension of the rectangular building enclosure to be vented, ft. or m.
L_2 = second smallest dimension of the rectangular building enclosure to be vented, ft. or m.
P = maximum internal building pressure which can be withstood by the weakest building member which is desired not to vent or break, lbf/in^2 or kN/m^2

For most gases such as natural gas, propane, gasoline, benzene, acetone, and many others the values of maximum fundamental burning velocity are nearly the same. For such gases the value of *k* in Equation 1 is approximately 2.6 for use of the English units, 6.8 for use with SI units. Note in this connection that the actual flame speed in a building will be many times the fundamental burning velocity. The value of *k*, in fact, allows for the actual flame speed under conditions of flame turbulence increase due to (1) physical obstructions, such as process equipment, piping, building structural members, etc., (2) flow induced turbulence due to venting, and (3) turbulence induced directly by a large sized flame. For ethylene the suggested value for *k* is 4 in English units, 10.5 for SI units; for hydrogen, 6.4 in English units, 17 for SI units. The last two values suggested for *k* have not been tested in actual building venting incidents. The first value suggested for *k* has been tested in only one building venting incident. Turbulence conditions, and hence flame speeds, can differ as turbulence producing conditions vary.

It is believed that the venting equation is suitable for combustion venting of spaces in buildings having a nominal length/width (i.e., L/D) ratio up to 3. For a space having an L/D greater than 3 the space should be subdivided into multiple units, each having an L/D of no more than 3. Each unit should then have its own venting area. In a rectangular building, when L_1 and L_2 are not equal, the effective value of D is $\sqrt{L_1L_2}$.

Wherever it is possible, combustion vents for a building should be distributed over the walls of that building rather than confined to one wall.

References 43 and 51 discuss the Rasbash equation, which is as follows:

$$P_m = 1.5P_v + 0.5K \text{ (English units)}$$
$$P_m = 1.5P_v + 3.5K \text{ (metric units)} \quad (2)$$

where

P_m = maximum pressure reached during venting of the combustion, $lbf/in.^2$, or kN/m^2

P_v = pressure within the building space at which the vent opens, $lbf/in.^2$, or kN/m^2

K = venting ratio, A_c/A_v (dimensionless)

A_c = smallest cross-sectional area of the building space

A_v = total area of combustion vents

Reference 51 states the following limitations to Equation 2:

a. Maximum and minimum dimensions of the vented space have a ratio less than 3.
b. the value of K is between 1 and 5.
c. The inertia of the building vent does not exceed 5 lb/ft^2 (25 kg/m^2).
d. The pressure needed to move the vent does not exceed 1 $lbf/in.^2$ (7 kN/m^2) and the pressure is virtually exhausted after the vent cover has traveled a few millimeters. It was stated that a door held by small springs or latches can serve this function.

Reference 51 also states that when the explosive gases either are turbulent when ignited, or become turbulent during the course of the combustion, pressures considerably in excess of those calculated by Equation 2 may be obtained. Reference 36 points out that considerable turbulence can develop as a result of physical obstructions present within the space to be vented. Examples of physical obstructions are process vessels of all kinds, piping, structural members of buildings, and partial floors.

Equation 2 is stated to apply specifically to propane. Reference 43 states that the pressure reached during venting of the combustion, in the case of natural gas and air, will be about 0.8 times that calculated by Equation 2. For town gas (about 60% hydrogen) the pressure reached will be about 2.5 times that calculated by Equation 2.

In planning combustion venting for buildings use the larger of the two venting areas calculated by Equations 1 and 2.

Two important points relative to spill situations should be noted about the venting of combustion inside buildings: (1) Building ventilation rates even as high as one-air-change-per-minute will not necessarily prevent formation of flammable mixtures inside the building. (2) Concentrations of gas from spills inside buildings can vary greatly throughout the building space. Gas at a concentration above the upper flammable limit can burn because the thermal drafts caused by the initial flame will promote further mixing of air into the unburned fuel gas. Furthermore, the initial flame raises the temperature of the unburned mixture, thereby increasing the flammability limits.

Location of flammables handling equipment outdoors obviates many of the problems of gas accumulation in buildings and of necessary building venting. See Flammable and Combustible Liquids Code — NFPA No. 30, 1973.

3. Venting of Dust Combustion Inside Vessels

The most comprehensive known data on dust combustion venting are given in Reference 18. These data resulted from a very extensive test program. This program involved combustion venting tests with four dusts in containers of four sizes, 1, 10, 30, and 60 cubic meters. The author graphed the data, and from the graphs, prepared a table of necessary venting areas as a function of the class of dust, the vessel volume and the relieving pressure of the combustion vent.

The tables shown here as Tables 1a and 1b give the necessary venting area to prevent pressures during venting from exceeding a specific value.

Combustible dusts were divided into three classes according to maximum rates of pressure rise obtained in the Hartmann bomb test apparatus of the Bureau of Mines, U. S. Dept. of Interior. Those dusts giving maximum rates of pressure rise up to 7300 psi/sec., or 50,000 kN/(m^2) (sec.), were designated Dust Class St–1. Those giving rates of 7300–22,000 psi/sec., or 50,000–150,000 kN/(m^2) (sec.), were designated Dust Class St–2. Those above 22,000 psi/sec., or 150,000 kN/(m^2) (sec.), Dust Class St–3.

Abbreviations in Tables 1a and 1b are as follows:

P_{max} = maximum pressure reached during combustion venting
P_v = pressure at which combustion vent opens
V = vessel volume

The large boxes of numbers in Tables 1a and 1b are the required combustion vent areas.

The tests were made from initial pressures of essentially atmospheric. On this basis the table, strictly interpreted, applies only to venting of dust combustion in equipment which is at essentially atmospheric pressure at the time of combustion initiation. Most dust handling equipment operates at pressures near atmospheric. No specific correlations have been developed and extensively tested for converting the numbers in Tables 1a and 1b to the case of initial pressure substantially different from

(*continued on page* 34)

TABLE 1a

REQUIRED VENT AREA AS A FUNCTION OF DUST CLASS, RELIEF PRESSURE (P_v), CONTAINER VOLUME AND MAXIMUM PRESSURE DEVELOPED DURING VENTING (Pmax)

(Numbers are in English units)

Class St.— 1 Dusts giving maximum rates of pressure rise up to 7,300 psi/sec.

	Pmax (lbf/in.²) / V (ft³)	Dust Class St. — 1							
		2.8	7.1	9.9	14.2	21.3	28.4	35.5	42.6
P_v = 1.4 PSIG	35	1.3	0.65	0.52	0.43	0.32	0.29	0.25	0.22
	177	4.3	1.9	1.6	1.4	1.01	0.81	0.70	0.65
	353	7.5	3.2	2.6	2.1	1.7	1.4	1.2	0.97
	530	10.8	4.5	3.5	2.8	2.3	2.0	1.8	1.6
	706	14.0	5.7	4.4	3.6	2.9	2.6	2.3	2.0
	883	17.2	6.9	5.4	4.3	3.4	3.0	2.7	2.5
	1059	19.9	8.1	6.2	5.1	4.2	3.6	3.2	2.9
	1412	25.9	10.2	7.6	6.4	5.0	4.5	4.0	3.7
	1766	31.2	12.3	9.2	7.5	6.0	5.4	4.7	4.3
	3532	—	20.5	15.2	12.4	9.7	8.6	7.5	7.0
P_v = 2.8 PSIG	35	3.9	0.80	0.58	0.48	0.37	0.30	0.26	0.23
	177	11.3	2.4	1.7	1.6	1.3	0.90	0.75	0.56
	353	17.8	4.1	2.9	2.5	1.9	1.6	1.2	1.1
	530	23.2	5.7	4.0	3.4	2.7	2.3	1.9	1.7
	706	28.0	7.8	5.2	4.2	3.2	2.8	2.6	2.4
	883	32.3	8.1	6.2	5.2	3.4	3.2	3.0	2.8
	1059	38.6	9.9	7.8	6.0	4.7	3.8	3.5	3.3
	1412	43.1	12.5	9.2	7.5	5.6	4.8	4.3	3.9
	1766	—	15.1	11.3	8.8	6.7	5.9	5.4	4.8
	3532	—	25.9	19.4	15.1	11.8	9.7	8.6	7.5
P_v = 7.1 PSIG	35	—	3.9	1.1	0.75	0.46	0.35	0.29	0.25
	177	—	10.8	3.4	2.3	1.4	1.0	0.86	0.73
	353	—	17.8	6.5	4.3	3.0	2.2	1.9	1.7
	530	—	23.7	9.1	6.2	4.2	3.1	2.4	2.3
	706	—	28.5	12.1	8.2	5.4	3.9	3.2	3.0
	883	—	33.4	14.9	10.1	6.4	4.6	4.1	3.5
	1059	—	36.6	17.2	11.8	7.0	5.4	4.7	4.2
	1412	—	43.1	21.5	15.1	9.1	6.9	6.0	5.4
	1766	—	—	25.8	18.3	10.8	8.4	7.3	5.8
	3532	—	—	38.8	29.1	16.1	12.4	10.8	8.6

Vent Area, Sq. Ft.

Table 1a — Continued

Class St. — 2 Dusts giving rates of 7,300 — 22,000 psi/sec.

	V (ft³) \ Pmax (lbf/in²)	Dust Class St — 2									
		2.8	7.1	9.9	14.2	21.3	28.4	35.5	42.6	49.7	56.8
P_v = 1.4 PSIG	35	2.9	1.9	1.6	1.3	0.97	0.86	0.65	0.54	0.48	0.40
	177	8.9	5.4	4.8	3.8	2.9	2.4	1.9	1.5	1.3	1.1
	353	15.3	10.3	8.9	6.8	5.6	4.8	3.8	3.2	2.8	2.5
	530	20.7	15.1	12.9	10.8	8.1	6.9	5.7	4.8	3.4	3.8
	706	25.8	19.4	17.2	13.7	10.2	8.6	7.5	5.4	5.7	5.1
	883	31.2	23.7	21.0	17.0	12.9	10.8	9.1	8.1	7.0	6.2
	1059	36.1	28.0	24.8	19.9	15.1	12.9	10.8	9.5	8.1	7.3
	1412	43.0	36.1	31.8	26.4	18.8	16.2	13.5	12.2	10.8	9.5
	1766	—	43.1	38.2	32.3	23.7	19.4	16.2	14.3	12.9	11.3
	3532	—	—	—	—	37.7	30.2	25.9	23.7	21.5	18.3
P_v = 2.8 PSIG	35	4.7	2.4	1.7	1.4	1.1	0.86	0.69	0.58	0.50	0.43
	177	14.0	6.5	5.1	4.2	3.1	2.8	2.0	1.9	1.5	1.3
	353	21.5	11.3	9.3	7.8	5.9	5.4	4.2	3.7	3.2	2.7
	530	28.0	16.1	14.0	11.8	9.5	7.5	6.2	5.4	4.8	4.1
	706	33.9	20.5	18.3	14.5	11.3	9.7	8.1	6.8	6.2	5.6
	883	39.3	24.7	22.6	18.3	13.8	11.8	9.7	8.6	7.9	6.8
	1059	—	29.1	25.9	21.1	16.1	14.0	11.6	10.2	9.1	8.1
	1412	—	37.7	33.4	28.0	20.5	17.2	14.6	12.9	11.8	10.2
	1766	—	—	39.8	34.5	24.8	20.5	17.2	15.1	14.0	12.4
	3532	—	—	—	—	43.1	34.5	28.0	24.8	22.6	19.4
P_v = 7.1 PSIG	35	—	4.7	3.0	2.2	1.3	0.97	0.75	0.62	0.54	0.47
	177	—	12.9	8.6	6.5	4.3	3.3	2.7	2.3	1.9	1.8
	353	—	21.5	15.1	11.3	7.9	6.2	5.0	4.3	4.0	3.3
	530	—	28.0	20.5	15.6	11.3	9.0	7.3	6.4	5.7	4.8
	706	—	33.8	25.4	20.2	14.5	11.8	9.7	8.6	7.5	5.4
	883	—	38.4	29.9	24.3	17.5	14.4	11.8	10.6	9.1	8.0
	1059	—	42.0	34.1	28.2	20.5	16.9	14.0	12.5	10.8	9.5
	1412	—	—	40.9	35.5	25.9	21.5	17.8	15.9	13.8	12.1
	1766	—	—	—	42.0	30.1	25.9	21.0	19.0	16.7	14.7
	3532	—	—	—	—	43.1	38.9	32.3	30.1	24.8	21.5

Vent Area, Sq. Ft.

Table 1a — Continued

Class St. — 3 Dusts giving rates above 22,000 psi/sec.

P_v	V (ft^3) \ Pmax (lbf/in^2)	Dust Class St. — 3							
		14.2	21.3	28.4	35.5	42.6	49.7	56.8	71.0
P_v = 1.4 PSIG	35	3.0	1.7	1.3	1.0	0.86	0.75	0.62	0.56
	177	8.1	5.9	4.3	3.6	3.0	2.7	2.3	1.9
	353	12.9	9.7	8.4	7.0	5.9	5.2	4.8	4.3
	530	16.8	13.5	11.8	10.8	9.1	8.2	7.5	6.9
	706	20.5	17.2	15.4	14.0	12.3	11.3	10.8	9.7
	883	24.1	20.5	18.3	17.2	15.6	14.5	13.5	12.4
	1059	26.9	23.7	21.7	20.5	18.3	17.7	16.2	14.5
	1412	33.4	29.7	28.0	25.9	23.7	22.6	21.5	19.4
	1766	38.8	35.5	33.4	30.1	28.0	26.9	25.9	22.6
	3532	—	—	—	—	—	—	—	—
P_v = 2.8 PSIG	35	6.2	2.7	1.7	1.3	1.0	0.86	0.75	0.62
	177	16.1	8.1	5.4	4.3	3.8	3.2	2.7	2.5
	353	22.4	12.9	9.1	7.5	7.0	6.2	5.9	4.3
	530	26.9	16.1	12.9	11.3	10.2	9.1	8.6	7.5
	706	30.1	19.9	16.7	14.5	13.4	12.4	11.3	10.2
	883	32.8	23.1	19.9	17.8	16.1	15.4	14.5	12.9
	1059	35.0	25.8	22.6	20.7	19.4	18.3	16.7	15.1
	1412	38.8	31.2	28.0	26.4	24.8	23.3	21.5	19.9
	1766	43.1	36.6	33.4	32.3	30.1	28.0	26.9	24.3
	3532	—	—	—	—	—	—	—	—
P_v = 7.1 PSIG	35	—	—	3.8	2.4	1.7	1.4	1.1	0.75
	177	—	—	10.8	7.0	5.4	4.3	3.9	3.2
	353	—	—	15.1	11.3	9.1	7.5	7.0	5.9
	530	—	—	17.8	14.5	12.4	10.8	9.9	9.1
	706	—	—	19.9	17.2	15.9	14.0	12.9	11.8
	883	—	—	21.1	19.9	18.8	16.7	15.6	14.5
	1059	—	—	23.7	22.6	21.1	19.4	18.3	17.2
	1412	—	—	29.1	27.6	25.8	24.8	23.7	21.1
	1766	—	—	34.5	32.3	31.2	30.1	29.1	26.9
	3532	—	—	—	—	—	—	—	—

Vent Area, Sq. Ft.

TABLE 1b

Required vent area as a function of Dust Class, relief pressure (P_v), Container volume and maximum pressure developed during venting (Pmax)

	Pmax (kN/m²) / V (m³)	St. — 1								St. — 2			
		20	50	70	100	150	200	250	300	20	50	70	100
P_v = 10 kN/m²	1	0.12	0.05	0.048	0.04	0.03	0.029	0.023	0.02	0.27	0.16	0.15	0.12
	5	0.4	0.18	0.145	0.13	0.034	0.075	0.055	0.06	0.83	0.5	0.45	0.35
	10	0.7	0.3	0.25	0.2	0.15	0.13	0.11	0.09	1.42	0.95	0.83	0.63
	15	1.0	0.42	0.33	0.28	0.21	0.19	0.17	0.15	1.93	1.4	1.2	1.0
	20	1.3	0.53	0.41	0.33	0.27	0.24	0.21	0.19	2.4	1.8	1.6	1.27
	25	1.5	0.64	0.50	0.40	0.32	0.28	0.25	0.23	2.9	2.2	1.95	1.58
	30	1.85	0.75	0.58	0.47	0.39	0.33	0.30	0.27	3.35	2.5	2.3	1.85
	40	2.4	0.95	0.71	0.58	0.48	0.42	0.37	0.34	4.0	3.35	2.95	2.45
	50	2.9	1.14	0.85	0.70	0.56	0.50	0.44	0.40	—	4.0	3.55	3.0
	100	—	1.9	1.4	1.15	0.9	0.80	0.70	0.65	—	—	—	—
P_v = 20 kN/m²	1	0.36	0.074	0.054	0.045	0.034	0.028	0.024	0.021	0.44	0.22	0.16	0.13
	5	1.05	0.22	0.18	0.15	0.12	0.086	0.07	0.062	1.3	0.6	0.47	0.39
	10	1.65	0.38	0.27	0.23	0.18	0.15	0.115	0.1	2.0	1.05	0.86	0.72
	15	2.15	0.53	0.37	0.32	0.25	0.21	0.18	0.15	2.5	1.5	1.3	1.1
	20	2.6	0.68	0.48	0.39	0.3	0.25	0.24	0.22	3.15	1.9	1.7	1.35
	25	3.0	0.8	0.58	0.48	0.32	0.3	0.28	0.25	3.65	2.3	2.1	1.7
	30	3.4	0.97	0.68	0.56	0.44	0.35	0.33	0.31	—	2.7	2.4	1.96
	40	4.0	1.16	0.85	0.7	0.52	0.45	0.4	0.36	—	3.5	3.1	2.6
	50	—	1.4	1.05	0.82	0.67	0.55	0.5	0.45	—	—	3.7	3.2
	100	—	2.4	1.8	1.4	1.1	0.9	0.8	0.7	—	—	—	—
P_v = 49 kN/m²	1	—	0.36	0.105	0.07	0.043	0.033	0.027	0.023	—	0.44	0.28	0.2
	5	—	1.0	0.32	0.21	0.13	0.090	0.08	0.068	—	1.2	0.8	0.5
	10	—	1.65	0.6	0.4	0.28	0.2	0.18	0.15	—	2.0	1.4	1.05
	15	—	2.2	0.85	0.58	0.39	0.29	0.22	0.21	—	2.6	1.9	1.49
	20	—	2.55	1.12	0.76	0.5	0.35	0.3	0.28	—	3.14	2.36	1.88
	25	—	3.1	1.38	0.94	0.59	0.43	0.38	0.33	—	3.56	2.75	2.26
	30	—	3.4	1.6	1.1	0.68	0.5	0.44	0.38	—	3.9	3.17	2.62
	40	—	4.0	2.0	1.4	0.85	0.64	0.58	0.5	—	—	3.8	3.3
	50	—	—	2.4	1.7	1.0	0.78	0.68	0.53	—	—	—	3.9
	100	—	—	3.6	2.7	1.5	1.15	1.0	0.8	—	—	—	—

Relief surface F (m^2)

Notes to Table 1b

(Numbers are in SI Units)

Class St. — 1 Dusts giving maximum rates of pressure rise up to 50,000 kN/(m²) (sec)
Class St. — 2 Dusts giving maximum rates of pressure rise of 50,000 — 150,000 kN/(m²) (sec)
Class St.— 3 Dusts giving maximum rates of pressure rise above 150,000 kN/(m²) (sec)

St. — 2						St. — 3							
150	200	250	300	343	392	100	150	200	250	300	343	392	490
0.09	0.08	0.05	0.05	0.045	0.031	0.26	0.16	0.12	0.095	0.08	0.07	0.052	0.052
0.27	0.22	0.18	0.14	0.12	0.1	0.75	0.55	0.4	0.33	0.28	0.25	0.21	0.18
0.52	0.45	0.35	0.3	0.26	0.23	1.2	0.9	0.78	0.65	0.55	0.48	0.45	0.4
0.75	0.64	0.53	0.45	0.4	0.35	1.58	1.25	1.1	1.0	0.85	0.76	0.7	0.64
0.85	0.8	0.7	0.5	0.52	0.47	1.9	1.5	1.43	1.3	1.14	1.05	1.0	0.9
1.2	1.0	0.85	0.75	0.65	0.58	2.24	1.9	1.7	1.6	1.45	1.35	1.25	1.15
1.4	1.2	1.0	0.88	0.75	0.68	2.5	2.2	2.0	1.9	1.7	1.64	1.5	1.35
1.75	1.5	1.25	1.12	1.0	0.88	3.1	2.76	2.6	2.4	2.2	2.1	2.0	1.8
2.2	1.8	1.5	1.33	1.2	1.05	3.6	3.3	3.1	2.8	2.6	2.5	2.4	2.1
3.5	2.8	2.4	2.2	2.0	1.7	—	—	—	—	—	—	—	—
0.1	0.087	0.064	0.054	0.046	0.04	0.58	0.25	0.16	0.12	0.095	0.08	0.07	0.055
0.29	0.26	0.19	0.18	0.14	0.12	1.5	0.75	0.5	0.4	0.35	0.3	0.25	0.23
0.55	0.5	0.39	0.34	0.3	0.25	2.08	1.2	0.85	0.7	0.65	0.58	0.55	0.45
0.88	0.7	0.58	0.5	0.45	0.38	2.5	1.5	1.2	1.05	0.95	0.85	0.8	0.7
1.05	0.9	0.75	0.53	0.58	0.52	2.8	1.85	1.55	1.35	1.24	1.15	1.05	0.95
1.26	1.1	0.9	0.8	0.73	0.63	3.05	2.15	1.85	1.65	1.5	1.43	1.35	1.2
1.5	1.3	1.08	0.95	0.85	0.75	3.25	2.4	2.1	1.92	1.8	1.7	1.55	1.4
1.9	1.6	1.36	1.2	1.1	0.95	3.6	2.9	2.6	2.45	2.3	2.16	2.0	1.85
2.3	1.9	1.6	1.4	1.3	1.15	4.0	3.4	3.1	3.0	2.8	2.6	2.5	2.3
4.0	3.2	2.6	2.3	2.1	1.8	—	—	—	—	—	—	—	—
0.125	0.09	0.07	0.058	0.05	0.044	—	—	0.35	0.22	0.16	0.13	0.1	0.07
0.4	0.3	0.25	0.21	0.18	0.17	—	—	1.0	0.65	0.5	0.4	0.35	0.3
0.73	0.58	0.45	0.4	0.37	0.31	—	—	1.4	1.05	0.85	0.7	0.55	0.55
1.05	0.84	0.58	0.6	0.53	0.45	—	—	1.55	1.35	1.15	1.0	0.92	0.85
1.35	1.1	0.9	0.8	0.7	0.6	—	—	1.85	1.6	1.48	1.3	1.2	1.1
1.63	1.34	1.1	0.98	0.85	0.74	—	—	2.05	1.85	1.75	1.55	1.45	1.35
1.9	1.57	1.3	1.16	1.0	0.88	—	—	2.2	2.1	1.95	1.8	1.7	1.6
2.4	2.0	1.65	1.48	1.28	1.12	—	—	2.7	2.56	2.4	2.3	2.2	2.05
2.8	2.7	1.95	1.76	1.55	1.37	—	—	3.2	3.0	2.9	2.8	2.7	2.5
4.0	3.8	3.0	2.8	2.3	2.0	—	—	—	—	—	—	—	—

Relief surface F (m^2)

atmospheric. The original tests on which Tables 1a and 1b are based were made with dusts in turbulent condition. The data thus apply to the usual industrial equipment handling dusts.

For large vessels such as vertical cylindrical storage hoppers or silos for combustible dusts, the required venting area may be as large as, or larger than, the cross section of the vessel. In this case the entire vessel roof can be made a venting area by constructing it as a weak seam roof as described in American Petroleum Institute Standards 650 and 2000. Space must be available above the roof for it is to open sufficiently. Usually such a roof opens only part way around its periphery to vent a dust combustion. Obviously the roof thickness should be as small as possible consistent with the strength demands upon it.

If the required vent area be larger than the vessel cross section, the vessel needs to be further strengthened to take a pressure consistent with the vent area that can be provided. In all cases the total volume of the vessel should be assumed to contain the combustible dust in suspension. That is, no credit should be taken for the vessel being partly full of settled material.

The use of vent ducts following explosion vents can lead to substantially increased pressure. If the duct is to be of any length at all, its cross section should be substantially greater than that of the vent itself. The effect of elbows or bends needs to be considered in estimating the effective duct length. Palmer, et al, Reference 46 and 66, found that the maximum pressure developed during combustion venting will increase approximately as the square of the duct length. In one case a duct length of 10 ft. (3 meters) resulted in a pressure increase of 1 $lbf/in.^2$ (7 kN/m^2) over that for no duct; doubling the duct length resulted in a pressure increase of 4 lbf/in^2 (28 kN/m^2). Palmer, et al, also found pressure during venting to increase linearly with vent inertia.

Venting panels or "doors" are often used for venting equipment such as bag filters. Such vent panels should have inertias no greater than 2 lb/ft^2 (10 kg/m^2) of effective vent opening.

4. Venting of Gas Combustion Inside Vessels

In the usual industrial situation the venting of gas combustion inside vessels is the most difficult of the different types of combustion venting. Many of the variables listed above under Section B.1. may come into play in a single case. It is not at all unusual for the gases to be at an initial elevated pressure. There may also be a significant degree of turbulence, and of turbulence nonuniformity, in the gas mixture. Often the turbulence is brought about by the mode of introduction of feed gas streams into the vessel. For various reasons the vent opening pressure may have to be appreciably above atmospheric. Geometry of the gas space in a vessel may be far from an ideal shape such as a sphere or cube. For various geometry reasons the vent may have to be at a nonpreferred location. The likely location of ignition source usually cannot be determined. Hence it usually cannot be known whether the gases going through a vent, after opening, will be primarily unburned or burned or a mixture of the two.

It is on account of such factors as the above that estimation of necessary combustion venting area for a vessel is complicated. Yet the estimation is frequently necessary. Because of uncertainties yet existent in combustion venting technology the most conservative case should be assumed. For example, even though a mixture of fuel gas and oxidant in a vessel would normally be outside the flammable limits, for combustion venting it should be assumed that the mixture is such as to give the maximum pressure during combustion venting. Venting is ineffective for detonations. This Guide relates to venting for deflagrations only.

The following guidelines are based on the technology available at the time of writing of this Guide. Because of technology limitations the guidelines cannot be guaranteed to be adequate for every situation:

a. Effect of Vessel Size. The most comprehensive known data on effect of vessel size are given in Reference 17. Combustion venting tests were made for propane-air mixtures in vessels of 1, 10, 30, and 60 cubic meter size. The gas mixtures were initially at atmospheric pressure and were quiescent at times of ignition. The vents had low inertia and no ducts. Vent opening occurred at pressures of 1.4, 2.8, and 7.2 psig. (10, 20 and 50 kN/m^2). The results thus obtained are summarized in Tables 2a and 2b. Suitable interpolations can be made between the numbers in the table.

It has been proposed by some that the "cubic law" for combustion in unvented vessels be extended to the combustion venting case. For combustion in a closed vessel the cubic law has been stated as:

$$\left(\frac{dp}{dt}\right)_{max} V^{1/3} = \text{constant}$$

where

$\left(\frac{dp}{dt}\right)_{max}$ = maximum rate of pressure rise during combustion in the unvented vessel

V = volume of the unvented vessel

The data in Tables 2a and 2b do not fully support extension of the cubic law to combustion venting. The data do show, however, that the required vent area for a range of vessel size is not a constant vent area per unit volume of vessel.

Table 2a

Vent areas, ft², required for venting of combustion of propane-air mixture inside vessels of L/D approximately 1: C. Donat, Reference 17 (Note: Numbers are in English units).

Max press., during venting, psig	4.35	7.25	14.5	21.8	29.0	36.3
Vessel Vol., ft³						
	Vent burst pressure = 1.45 psig.					
35.3	3.34	2.69	1.61	0.97	0.48	—
353	22.6	16.1	8.6	5.9	4.30	3.23
1059	32.3	24.2	16.1	9.7	6.5	4.84
2118	51.6	32.3	12.9	—	—	—
	Vent burst pressure = 2.9 psig.					
35.3	3.82	3.23	2.26	1.56	1.02	0.75
353	23.5	18.3	11.5	8.0	5.1	3.98
1059	29.1	21.8	14.5	10.4	7.8	5.7
2118	—	40.5	—	—	—	—
	Vent burst pressure = 7.3 psig.					
35.3	—	—	2.10	1.29	0.92	0.70
353	—	—	13.0	8.5	6.0	4.52
1059	—	37.5	20.2	14.5	10.4	7.8
2118	—	56	23.9	—	—	—

Data in Reference 22, for venting of pentane combustion in a 60 ft.³ (1.7m³) vessel check fairly well with the data in Reference 17, for venting of propane in a 1 cubic meter vessel.

b. Effect of Fundamental Burning Velocity. The pressure developed during combustion venting is determined in part by the speed with which gases burn before and during venting. This burning speed is determined in part by the characteristic rate at which flames proceed through different fuel gases. This characteristic rate is normally measured in terms of the maximum fundamental burning velocity, tables of values for which can be found in various handbooks. Some characteristic values are given in Table 3.

TABLE 2b

Vent areas, m^2, required for venting of combustion of propane-air mixture inside vessels of L/D approximately 1: C. Donat, Reference 17 (Note: Numbers are in SI units)

Max press. during venting, kN/m^2	30	50	100	150	200	250
Vessel Vol. m^3						
	Vent burst pressure = 10 kN/m^2					
1	0.31	0.25	0.15	0.09	0.045	—
10	2.1	1.5	0.80	0.55	0.4	0.3
30	3.0	2.25	1.5	0.9	0.6	0.45
60	4.8	3.0	1.2	—	—	—
	Vent burst pressure = 20 kN/m^2					
1	0.355	0.3	0.21	0.145	0.095	0.07
10	2.18	1.70	1.07	0.74	0.47	0.37
30	2.70	2.03	1.35	0.97	0.72	0.53
60	—	3.76	—	—	—	—
	Vent burst pressure = 50 kN/m^2					
1	—	—	0.195	0.12	0.085	0.065
10	—	—	1.21	0.79	0.56	0.42
30	—	3.48	1.88	1.35	0.97	0.72
60	—	5.22	2.22	—	—	—

TABLE 3

Gas	Maximum fundamental burning velocity ft./sec.	meters/sec.
Methane (natural gas)	1.2	0.37
Propane	1.5	0.46
Butane	1.3	0.4
Hexane	1.3	0.4
Ethylene	2.3	0.7
Acetylene	5.8	1.8
Hydrogen	11.0	3.4

The above values are definitely not the speeds with which flames will move through a flammable mixture in a vessel. Flame speeds in a vessel are normally much higher than the fundamental burning velocity. However, the fundamental burning velocity is a basic measure of the flame characteristics of a fuel gas.

Significantly the gases of most organic compounds have nearly the same fundamental burning velocity. Thus their flame speeds, and the pressure developed during venting, will be nearly the same. In addition to the first four compounds listed in Table 3, this includes gases of such compounds as acetone, benzene and ethyl alcohol. Substitution of a halogen, such as chlorine, or certain other atoms in a molecule slows down the combustion. On the other hand, introduction of unsaturation into the molecule, as in the cases of ethylene and acetylene, speeds up the combustion.

Data from References 9 and 17, can be used to compare the pressures developed during combustion venting for propane-air and hydrogen-air mixtures. For the same initial pressure in the vessel, the same vent bursting pressure, and the same sizes of vessel and vent, the pressure developed during combustion venting for hydrogen-air is a maximum of about 1.55 times that developed during combustion venting for propane-air. This ratio decreases somewhat as initial pressure and vent bursting pressures are increased. However, to be on the conservative side as mentioned earlier, it is recommended that the 1.55 ratio be used throughout. It should be noted that this ratio has not been tested for vessel sizes above 1 cubic meter. However, it is recommended that it be used for the larger vessel sizes when extrapolating from Tables 2a and 2b for combustion venting for hydrogen.

The ratio of the fundamental burning velocity of hydrogen to that for propane is 11/1.5 = 7.34. The number, 7.34, must be raised to the 0.22 power to obtain the ratio, 1.55, stated above. If this same power exponent of 0.22 were applied to the ethylene case, the ratio would be 1.1. However, it is recommended that, in calculating combustion venting for ethylene, the pressure during combustion venting be assumed to be 1.2 times that determined from Tables 2a and 2b for propane. It is further suggested that the pressure from combustion venting of gases having about the same fundamental burning velocity as that of propane be assumed to be the same as that for propane. This again is confirmed by comparisons of data from Reference 17, for propane and Reference 22, for pentane.

c. Effect of Initial Pressure. The effect of initial pressure must be correlated on the basis of absolute pressures. The data from Reference 9, serve as a basis for correlating pressures developed during venting as a function of the initial absolute pressure of gases in a vessel and as a function of the absolute pressure at which a vent opens. If the ratio of vent bursting pressure to initial gas pressure in a vessel be kept constant, and if vessel size and vent size be kept constant, the pressure developed during venting of propane combustion will vary as about the 1.5 power of the initial pressure. The power exponent for propane varies from about 1.2 for large vent ratios (6 $ft.^2/100\ ft.^3$) to about 1.5 for small vent ratios (2 $ft.^2/100\ ft.^3$). For hydrogen the exponent ranges from 1.1 to 1.2.

It is recommended that the 1.5 power be used in extrapolating from the data in Tables 2a and 2b, which are for propane-air mixtures at an initial pressure of 1 atmospheric absolute. (See sample calculation — Appendix V.)

For hydrogen the recommended exponent for increased initial pressure is 1.2. For ethylene it is recommended that an exponent of 1.4 be used; this is untested.

d. Effect of Initial Turbulence. Initial turbulence presents special problems in approximating combustion venting requirements. Industrially it is often difficult to quantify turbulence inside equipment at the time ignition may occur. This is on account of several factors. The turbulence of the gas in a vessel, if that gas be in motion, is apt to be nonuniform. At the time of ignition the gas flows may be at abnormal rates. Ignition may even be caused by breakage of some internal piece of the equipment, and that breakage may result in change in the turbulence pattern.

Some few tests have been reported on the effects of turbulence on pressure developed during combustion venting. However, in most cases the turbulence in the gas mixture was quantified in terms of operation of the device used to create the turbulence. References 1, 22, and 44, serve as bases for estimating effects of turbulence on pressures developed during combustion. All these references give data on turbulence effects for venting aliphatic hydrocarbon-air flames only. The available data show that the absolute pressure resulting from venting initially turbulent gas mixtures is in the range of about 1 to 3 times that resulting from venting initially quiescent gas mixtures. From these numbers it is suggested that a factor of 2 be used for turbulent aliphatic hydrocarbon-air mixtures normally encountered in industry. The same factor is suggested for other gases having similar flame speeds.

For hydrogen-air mixtures it is estimated that the turbulence effect on pressure developed during venting will be less than that in the case of the slow flame speed gases. In the absence of dependable data for hydrogen and acetylene it is suggested that a factor of 1.5 be used. For the case of ethylene it is suggested that a factor of 1.9 be used; again as in the case of hydrogen, this is untested.

e. Effect of Initial Temperature. This Guide, in Appendix 11, gives data for effect of temperature on combustion properties of a number of organic compounds when burned in a closed container. Increase of temperature in most cases results in an increase in maximum rate of pressure rise in the container. However, the increase in temperature also results in a decrease in number of moles of gas inside the container at a fixed pressure. This decrease in moles results in a corresponding decrease in the pressure generated from the combustion. It is found that the decrease in the generated pressure approximately offsets the increase in flame speed. Therefore, for a fixed initial pressure in a vessel, it is believed that no adjustment in estimated pressure development during combustion venting needs to be made for increase in temperature. The same is probably true for temperature decrease below ambient, but this is not proved.

f. Effects of Combinations of Variables. At the present state of technology there are insufficient data to tell definitely just how combinations of variables may affect the maximum pressure developed during combustion venting. For the present it is suggested that the effects of the variables be assumed to be cumulative. This pertains to the variables discussed in sections a through e above.

g. Effects of Additional Variables.

(1) Inertia of Vents. Sometimes a rupture disc will not provide a suitable vent, and a hinged panel or similar device must be used instead. Again, inertia of such a device must be as low as possible. Tonkin and Berlemont (66) presented test data on effects of vent panel inertia or pressure developed during the venting of dust combustion. Doubling of the weight per unit area, of a vent panel of a fixed area, i.e., doubling the inertia resulted in a doubling of the pressure developed during combustion venting. Tripling of the inertia resulted in a tripling of the pressure developed during the combustion venting.

(2) Vent Ducts. There should preferably be no duct in the venting system. If a duct must be employed, it should have just as short an effective length (including effective length of bends in producing pressure drop) as possible. For any appreciable duct length the duct cross sectional area should be at least twice that of the vent device. It should be noted that combustion can take place in the vent duct itself, i.e., unburned gases may be the first to exit from the vent. This has two implications. The first is that the duct should be capable of withstanding a pressure at least as high as that expected to develop in the vessel during venting. The second is that high turbulence can develop in a duct. In the case of gas burning within the duct, that turbulence could possibly lead to transition of the deflagration to detonation. In that case, far higher pressure could develop in the duct.

(3) Ignition Source Location. There are few data on the effect of ignition source location on the pressure developed combustion venting. No allowances for this effect can be recommended.

In cases where multiple simultaneous sources of ignition are probable, it is suggested that the multiple ignition be assumed to producė the effect of initial turbulence.

(4) Other Oxidants. There are little data on effect of other oxidants than air. Other oxidants include oxygen, oxygen-enriched air, oxides of nitrogen, halogens, etc. Oxygen enrichment leads to higher pressures and an increased probability to transition into detonations. If direct data are not available for the system being considered, tests are recommended.

(5) Fogs and Mists. It is noteworthy that flames can propagate through fogs and mists at mixture temperatures below the flash point of the liquid involved. It is suggested that fogs and mists be treated as gases in estimating pressures developed during combustion venting.

5. Venting of Gas Combustion Inside Long Ducts

Most of the cases of flammable gas mixtures inside ducts of the ventilation type occur at initial internal pressure of near-atmospheric. The venting of such ducts is covered in Appendix IV.

Chapter 4. Description of Vents and Vent Closures

Explanatory

The vents described in this section have been designed or developed for the release of pressure from equipment, enclosures or buildings in which explosions of dust, gas or vapor may occur. In most cases, the described vents are effective only in explosions in which the rate of pressure rise is moderate and where, in large enclosures, only a part is involved in the explosion. The devices described are not generally suitable for protection of pressure vessels which is outside the scope of this guide, nor for protection against pressure or shock waves produced in detonations of high explosives.

Some types of vent closures are commercially available and may be purchased ready to install in buildings or equipment. The following descriptions should be used as the basis for development of suitable vents and vent closures which will provide the desired protection. (Some illustrations of vents and vent closures are shown in Appendix III.)

Open or Unobstructed Vents

The most effective vent for the release of explosion pressure from equipment, enclosures, or buildings is an unobstructed opening. However, there are comparatively few operations with inherent explosion hazards that can be conducted in open equipment installed in buildings without walls. Usually some form of vent closure must be provided to protect against the weather, to conserve heat, to bar unauthorized entry, to preclude dissemination of the combustible material or to prevent contamination of the product by the entrance of dirt or moisture from the outside.

Open equipment is recommended wherever a more serious explosion hazard is not created through dispersion or dissimination of the material and where closed equipment is not necessary to prevent contamination of the material.

Weather conditions and unauthorized entry are the controlling factors which govern the use of buildings without walls or with large apertures. In warm climates where building walls are not necessary, large overhanging eaves can be provided to keep rain from entering the open sections of the building. Unauthorized entry can be prevented by locating processes that require open wall venting on upper floors of the building.

Louvers

Although openings containing louvers cannot be considered completely unobstructed vents, they do provide a large percentage of free space for the release of explosion pressure and have served effectively as vents when explosions occurred in industrial plants. They are recommended especially as wall vents where windows are not required to maintain controlled atmospheric conditions within the enclosures. Louvers can be used effectively as vents where it is necessary or desirable to prevent unauthorized entry or egress.

Hangar-type Doors

Large hangar-type or steel curtain doors installed in side walls of rooms or buildings can be opened to provide unobstructed vents during the operation of any process or equipment in which there is an inherent explosion hazard. Such doors can be closed to prevent unauthorized entry when the equipment is unattended or not in operation. This type of venting has been effective and is highly recommended, but strict supervisory control is essential in cold climates to insure that employees do not sacrifice safety for comfort by keeping the doors closed during operations.

Open Roof Vents

Large roof openings protected by weather hoods can serve as explosion vents on one-story buildings or the top story of a multiple story building. This type of venting is effective particularly where lighter-than-air gases may escape from processing equipment and create an explosion hazard near the ceiling of the enclosure. In addition to serving as vents for the release of pressures, such roof openings reduce the possibility of an explosion by providing a channel through which the gas can escape from the building. On the other hand, this type of vent is a potential source of flying debris which could cause injury to personnel or property. Roof openings permit large quantities of warm air to escape during normal operations and for this reason they are not extensively used in cold climates.

All types of weather hoods serve to reduce the effectiveness of vents, hence, they should be as light as possible and attached in a manner that will permit them to be blown off quickly when an explosion occurs.

Closed or Sealed Vents

Where large openings cannot be permitted in a building, the most desirable arrangement is an isolated single-story building. Such a building can be most easily designed for explosion resistance and venting. Equipment which requires venting should be located close to outside walls so that duct-work, if necessary, can be short.

Building vent closures are necessary in air-conditioned plants or where heat is provided for the comfort of occupants during all or part of the year. Vent closures are required on processing equipment whenever it is necessary to retain dust or gas or where processes are conducted under pressure, vacuum or other controlled atmospheric conditions.

The fundamental principle in the design of any vent closure is that the vent will open quickly and automatically under increased pressure from within. The effect of various vent closures is illustrated in Table 2.

It is not possible to describe all of the devices that have been developed to serve as vent closures, but certain representative types can be grouped under separate headings.

Building or Room Vent Closures

Under this heading are grouped such manually or mechanically operated closures as doors, windows, and skylights as well as weak structural features such as large glass areas or light wall and roof panels built or sealed in place but designed to open due to explosion pressure.

Doors, to serve effectively as building vent closures, must be installed to swing outward and have latches or locking hardware that will function automatically to permit the door to open under slight internal pressure. Friction, spring or magnetic latches of the type designed for doors on driers and japanning ovens are recommended.

Windows, normally installed to provide light or ventilation, can frequently be arranged or adapted to serve as explosion vent closures when they are properly hinged to open outward. A number of different styles designed especially for this purpose are commercially available.

Movable sash, of the top or bottom hinged, or projected type which are commercially available have been widely used for explosion venting. It is usually necessary to have such sash equipped with some form of latch or friction device to prevent undesired opening due to wind action or to prevent intrusion, but care should be taken to avoid the use of any latch or lock which is not well maintained and always ready to operate when an explosion occurs.

Roof or wall panels, which are more economical than fixed sash or moveable windows often provide very effective protection against explosion damage. In this style of venting, a portion of the roof or an exterior wall between strong partition walls is constructed to blow out readily if an explosion occurs. The panels may be of very light construction such as sheet metal, or building paper or roofing paper supported by coarse mesh wire. In some instances, the entire roof over a room or bin has been constructed as a panel or cover to lift or blow off if an explosion occurs. *However, the roof must be securely anchored to prevent the wind from blowing it off.* (The authority having jurisdiction should be consulted regarding required type of anchorage for the panels.) Metal roofs can be designed and installed with crimped edges like can lids that will normally hold them in place.

Fixed sash, should be sent in place with very light wall anchorages, or, if tight, should be securely fitted and glazed with plastic panes in plastic putty.

Table 2. Maximum Pressures Produced by Explosions in Enclosures with Unrestricted Openings or Different Types of Vent Closures*

Type of Dust	Vent Ratio	Type of Vent or Vent Opening: Unrestricted Opening	Heavy Paper Diaphragm	Light Swinging Door	Heavy Swinging Door
	Sq. ft./100 cu. ft.	Pressure in lbs. per sq. ft.			
Coal	1.56	81	292	101	—
Coal	3.52	29	158	36	55
Aluminum (Atomized, fine).	3.52	71	205	161	232

* Reprinted from U. S. Bureau of Mines Report of Investigation 3924.

Skylights or monitors, with moveable sash that will open outward or fixed sash containing panes of glass or plastic that will blow out readily under pressure from within can be used to supplement wall vents or windows in buildings. This makes it possible to use larger floor areas than would be permissible when only side wall vents are used. Resistance to displacement or opening of skylights or monitor windows by explosions pressure should be as low as consistent with the requirements for structural strength. Counterbalanced or heavily constructed vents are not as effective as lightweight construction because they add to inertia of the vent. They are not recommended.

NOTE: Experiments have shown that the strength or resistance to explosion pressure of glass installed in windows or skylights can be reduced by scoring the panes on the outside with a diamond or steel wheel cutter. Best results are obtained when an X is cut with the lines starting about 2 inches from each corner with a 2-inch gap at the center to prevent cracking by vibration.

Healing action may occur after prolonged exposure to the sun or oily atmospheres permitting the scored glass to regain a part of its original strength. Care must be exercised to guard exposures and personnel from the flying splinters when the scored glass breaks. Frangible plastic panes lightly anchored have been found satisfactory for use in place of scored glass in many instances.

Equipment Vent Closures

Very few types of equipment can be operated without closures and numerous methods of providing satisfactory closures have been developed by plant operators, engineers and equipment builders. Some of the closures described may have a very limited application, but the general principle involved can frequently be used in the design of somewhat similar devices for other specific purposes. Equipment should be vented directly to the outside of the building through short ducts of adequate cross-sectional area.

Charging doors or inspection ports, may be designed to function as automatic vent closures when their action does not endanger personnel. They can be used frequently on totally enclosed mixers, blenders, driers and similar equipment. Hinged doors or covers held shut with spring latches are most frequently used for this form of protection. It is difficult to vent equipment of this type especially if the shell, drum or enclosure revolves, turns or vibrates; devices of the kind described in this paragraph are recommended only where venting through ducts to the outside of the building is not possible.

Poppet type closures, generally used on tanks or equipment that are normally closed at all times, are not intended to be used as doors or inspection ports and are expected to open only when the internal pressure exceeds a predetermined limit. The cover of the vent opening is usually fitted with a gasket and held in place by spring action. In applications of this principle on larger equipment, on low pressure air ducts, settling chambers, etc., the travel of the cover can be restricted by chains installed at corners or points on the periphery. Magnetic latches, where the magnetic lines of force must be ruptured, can be adjusted to release at a predetermined pressure.

Diaphragms, of many different kinds of materials, have been used or are available for use as closures on explosion vents. Only a few of the many types can be described, but mention of these few will, no doubt, suggest others which may prove to be equally or more effective. Criterion in choosing a vent material shall be that its bursting strength will be considerably less than the walls of the enclosure.

PAPER. Waterproofed Kraft paper, building paper, and roofing paper have all been used as explosion vent closures. The usual method of application consists of pasting or clamping a sheet of paper onto a wooden or metal frame designed to fit over the vent opening or to slide into a vent duct. The breaking strength of the paper and the resistance to be offered to normal pressure within the enclosure will determine the best type of paper to select. Papers that weaken when exposed to water or moisture should be used only in dry places. Flameproof paper and several different types of plastic impregnated paper have been developed and used effectively under certain conditions for vent closures.

CLOTH. Cloth impregnated with paraffin or plastic, varnished cambric and plastic covered cloth netting are a few of the different forms of cloth diaphragms used as explosion vent closures. These materials are generally available in rolls or sheets and the vent closures are made by cutting pieces to the proper size and gluing, tacking, clamping, or otherwise fastening them over the openings through which explosion pressure is to be released. Such vent closures have certain properties that make them suitable for use in places where paper diaphragms would not be satisfactory.

PLASTIC. Plastic vent closures are of two types: flexible and frangible. Both types are usually available in sheets. Pieces cut to the desired size may be installed in place of glass in window or observation port frames. The material may also be used instead of paper or cloth to seal vents.

(a) Flexible plastic sheets are usually installed in slotted frames in such a way that pressure from within bulges the sheet and releases it from the holding frame. Transparent or translucent flexible plastic sheets can be used instead of glass in certain types of window frames that will permit the sheet to function as a pull-out diaphragm vent closure.

(b) Frangible sheets are usually selected to serve as vent closures on the basis of their brittleness. It is possible to obtain thin sheets of plastic that will crack or rupture under less pressure than single strength glass. For this reason, it is sometimes advantageous to use transparent or translucent sheets instead of glass in window sash.

METAL. Metal foil is sometimes used to seal explosion vents. This type of material can be substituted for flexible diaphragms where the material being processed would react with the diaphragm. Under other conditions where higher pressure is maintained within the enclosure or the vent area is very large, heavier, rigid sheets of metal may be used as explosion vent covers.

DIAPHRAGM CUTTERS. Cutters, designed to expedite the openings of vents closed or sealed with diaphragms have been used in many instances. Even a delay of a few thousandths of a second in releasing explosions of dusts, gases, or vapors having high rates of pressure rise may cause extensive damage to equipment. To reduce this delay between the initial indication of pressure within an enclosure and the opening of the vent, some plant operators have installed saw teeth, spear points and other cutting devices designed to initiate the tearing or rupturing of the diaphragm as soon as explosion pressure causes the least distortion from the normal position of the vent closure.

Appendix I

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NFPA Publications

Many standards, fire reports and other publications containing information relating to various phases of explosion prevention and protection have been published by the NFPA. A complete list of publications will be mailed on application to the National Fire Protection Association, 470 Atlantic Avenue, Boston, MA 02210.

Appendix II

Experimental Data and Curves

Explosion Data for Some Vapors and Gases — Table 3

The data contained in this table demonstrate that the explosion characteristics, *i.e.*, the maximum pressure, the rate of pressure rise (maximum and average) and the time required to attain tje maximum pressure, of vapors and gases, vary with the nature of the material and its concentration in air.

Explosion Data for Some Vapors and Gases When the Temperature is Varied — Table 4

The data show that when the temperature of an explosive mixture is increased (pressure and concentration remaining constant), the final explosion pressure decreases; but the rate of pressure rise increases.

Explosion Characteristics of Various Dusts — Table 5

The pressures and rates of pressure rise produced in dust explosions depend among other things on the fineness of the dust particles, dust concentration, source of ignition, size and shape of the explosion chamber and the uniformity of the dust cloud. The data in Table 3 were obtained (in the laboratory of the U. S. Bureau of Mines) in experiments with "through 200-mesh" dusts at a concentration of 0.500 oz..cu. ft., using equipment described in R.I. 3751 (see Appendix I). In more recent research at the Bureau of Mines (see for example, Bureau of Mines R.I. 4835) the technique of forming dust clouds in the test bomb has been improved, and as a result it has been possible to initiate experimental explosions in which much highef (from 50 to several hundred percent) pressures and rates are produced.

Rupture Pressure vs. Vent Area of Various Venting Materials — Figure 6

The graphs show that the bursting pressure of venting materials is a function of the vent area.

Relation of Maximum Explosion Pressure to Bursting Strength of Vent Diaphragms (for coal dust explosions) Figure 7

A brief description of the vent materials is given and a graph demonstrates that the pressure relieving capacities of the venting diaphragms are roughly inversely proportional to the bursting strengths.

Table 3. Explosion Data for Certain Vapors and Gases*

	Per Cent by Volume of Vapors and Gases														
	2	2.5	3	4	5	6	7	8	9	10	12	14	15	16	18
Acetone															
Maximum pressure	–	–	48	62	79	83	80	76	61	–	–	–	–	–	–
Time to attain max. press.	–	–	0.44	0.20	0.08	0.07	0.08	0.16	0.52	–	–	–	–	–	–
Max. rate of press. rise	–	–	134	500	1538	2000	1500	900	158	–	–	–	–	–	–
Av. rate press. rise	–	–	110	300	1000	1200	1000	475	110	–	–	–	–	–	–
Acrylonitrile															
Maximum pressure	–	–	–	62	80	98	104	109	–	108	104	97	–	–	–
Time to attain max. press.	–	–	–	0.132	0.104	0.049	0.044	0.042	–	0.068	0.13	0.23	–	–	–
Max. rate of press. rise	–	–	–	500	925	2275	2500	2800	–	2500	2000	890	–	–	–
Av. rate press. rise	–	–	–	300	775	2000	2400	2600	–	1600	800	400	–	–	–
Butane															
Maximum pressure	–	–	72	97	97	70	–	–	–	–	–	–	–	–	–
Time to attain max. press.	–	–	0.132	0.057	0.0567	0.407	–	–	–	–	–	–	–	–	–
Max. rate of press. rise	–	–	715	2100	2300	256	–	–	–	–	–	–	–	–	–
Av. rate press. rise	–	–	550	1700	1700	170	–	–	–	–	–	–	–	–	–
Benzene															
Maximum pressure	72	–	93	97	77	43	–	–	–	–	–	–	–	–	–
Time to attain max. press.	0.14	–	0.05	0.06	0.14	0.84	–	–	–	–	–	–	–	–	–
Max. rate of press. rise	850	–	2300	2300	1000	70	–	–	–	–	–	–	–	–	–
Av. rate press. rise	500	–	1850	1600	550	50	–	–	–	–	–	–	–	–	–
Butyl Alcohol															
Maximum pressure	–	–	70	95	94	104	–	97	–	96	81	70	–	–	–
Time to attain max. press.	–	–	0.26	0.088	0.08	0.064	–	0.11	–	0.11	0.36	0.56	–	–	–
Max. rate of press. rise	–	–	425	1920	2000	2700	–	1600	–	1550	375	250	–	–	–
Av. rate press. rise	–	–	275	1100	1200	1600	–	975	–	950	225	125	–	–	–
Diethyl Ether															
Maximum pressure	47	–	77	75	104	100	80	–	–	–	–	–	–	–	–
Time to attain max. press.	0.36	–	0.107	0.101	0.051	0.056	0.40	–	–	–	–	–	–	–	–
Max. rate of press. rise	366	–	925	1250	3000	2100	370	–	–	–	–	–	–	–	–
Av. rate press. rise	125	–	725	750	2000	1800	200	–	–	–	–	–	–	–	–

* These data were obtained from tests conducted by the Eastman Kodak Company, Rochester, N. Y. The tests were conducted at 150° F. in a closed bomb having a volume of 10 liters. See Table 4 for results of tests conducted at other temperatures. The pressures are in pounds per square inch; the rates of pressure rise are in pounds per square inch per second, and the time is in seconds.

Many values of the maximum rates of pressure rise shown in this table differ from those recorded in more recent experiments.

Table 3. Explosion Data for Certain Vapors and Gases (continued)

	Per Cent by Volume of Vapors and Gases														
	5	7	8	10	12	13	14	15	16	18	20	25	30	35	40
Acetaldehyde															
Maximum pressure	–	76	32	94	94	–	90	–	78	65	–	–	–	–	–
Time to attain max. press.	–	0.088	0.070	0.049	0.051	–	0.068	–	0.192	0.42	–	–	–	–	–
Max. rate of press. rise	–	1025	1250	2100	2000	–	1400	–	510	200	(ignites with difficulty)				–
Av. rate press. rise	–	850	1150	1900	1800	–	1300	–	400	150	–	–	–	–	–
Acetylene															
Maximum pressure	79	121	134	144	148	150	146	144	138	–	112	100	–	–	–
Time to attain max. press.	0.0336	0.0192	0.0185	0.012	0.015	0.017	0.02	0.024	0.025	–	0.048	0.175	–	–	–
Max. rate of press. rise	2500	6300	10,000	11,000	12,000	12,000	11,000	8000	6500	–	4500	1400	–	–	–
Av. rate press. rise	2300	6000	7250	12,000	10,000	8800	7300	6000	5500	–	2400	575	–	–	–
Ethyl Alcohol															
Maximum pressure	49	–	92	97	99	–	96	–	89	80	73	–	–	–	–
Time to attain max. press.	0.94	–	0.06	0.056	0.064	–	0.084	–	0.23	0.33	0.72	–	–	–	–
Max. rate of press. rise	75	–	2050	2500	2300	–	2075	–	1200	325	238	–	–	–	–
Av. rate press. rise	50	–	1500	1700	1550	–	1150	–	400	240	100	–	–	–	–
Hydrogen															
Maximum pressure	–	–	–	–	–	–	–	61	–	–	65	68	99	101	99
Time to attain max. press.	–	–	–	–	–	–	–	0.029	–	–	0.028	0.025	0.011	0.010	.0112
Max. rate of press. rise	–	–	–	–	–	–	–	2750	–	–	3000	3100	9900	11,000	10,000
Av. rate press. rise	–	–	–	–	–	–	–	2100	–	–	2300	2700	9000	10,000	8800
Methyl Alcohol															
Maximum pressure	–	–	65	79	85	–	–	90	–	84	76	–	–	–	–
Time to attain max. press.	–	–	0.22	0.08	0.08	–	–	0.06	–	0.10	0.18	–	–	–	–
Max. rate of press. rise	–	–	475	1818	2000	–	–	3030	–	1750	1000	–	–	–	–
Av. rate press. rise	–	–	300	1000	1050	–	–	1500	–	840	400	–	–	–	–
Methylene Chloride 89% Methyl Alcohol 11%															
Maximum pressure	–	–	–	–	–	–	–	–	–	60	70	44	–	–	–
Time to attain max. press.	–	–	–	–	–	–	–	–	–	0.72	0.48	0.72	–	–	–
Max. rate of press. rise	–	–	–	–	–	–	–	–	–	100	238	75	–	–	–
Av. rate press. rise	–	–	–	–	–	–	–	–	–	85	150	60	–	–	–

Table 3. Explosion Data for Certain Vapors and Gases (continued)

	Per Cent by Volume of Vapors and Gases														
	1.2	2	2.5	3	4	5	6	7	8	9	10	11	12	14	15
Butyrolactone (350°F)															
Maximum pressure	-	-	-	34	54	69	73	78	80	76	70	-	67	-	-
Time to attain max. press.	-	-	-	0.60	0.105	0.069	0.047	0.046	0.0415	0.059	0.07	-	0.079	-	-
Max. rate of press. rise	-	-	-	75	865	1925	2500	2750	3100	2300	1625	-	860	-	-
Av. rate press. rise	-	-	-	550	510	1000	1550	1700	1900	1300	1000	-	850	-	-
Cyclohexane															
Maximum pressure	-	90	-	104	67	53	-	-	-	-	-	-	-	-	-
Time to attain max. press.	-	0.03	-	0.052	0.112	0.92	-	-	-	-	-	-	-	-	-
Max. rate of press. rise	-	1500	-	2200	960	85	-	-	-	-	-	-	-	-	-
Av. rate press. rise	-	1250	-	2000	600	60	-	-	-	-	-	-	-	-	-
Ethane															
Maximum pressure	-	-	-	-	68	84	93	98	85	76	52	50	-	-	-
Time to attain max. press.	-	-	-	-	0.0856	0.06	0.048	0.047	0.079	0.149	0.80	0.88	-	-	-
Max. rate of press. rise	-	-	-	-	900	1675	1975	2500	1100	780	104	88	-	-	-
Av. rate press. rise	-	-	-	-	800	1400	1900	2100	1050	500	65	55	-	-	-
Ethylene															
Maximum pressure	-	-	-	-	-	92	96	104	119	113	106	94	80	60	-
Time to attain max. press.	-	-	-	-	-	0.041	0.038	0.034	0.018	0.020	0.044	0.105	0.20	0.40	-
Max. rate of press. rise	-	-	-	-	-	2500	2600	3125	8500	8300	3200	2250	750	200	-
Av. rate press. rise	-	-	-	-	-	2250	2500	3000	6600	5600	2400	900	400	125	-
Ethylene Dichloride															
Maximum pressure	-	-	-	-	-	-	-	76	89	-	94	-	71	62	-
Time to attain max. press.	-	-	-	-	-	-	-	0.28	0.207	-	0.18	-	0.23	1.34	-
Max. rate of press. rise	-	-	-	-	-	-	-	460	660	-	910	-	500	92	-
Av. rate press. rise	-	-	-	-	-	-	-	275	450	-	525	-	300	45	-
Hexane															
Maximum pressure	73	88	92	91	54	-	-	-	-	-	-	-	-	-	-
Time to attain max. press.	0.12	0.08	0.06	0.10	0.72	-	-	-	-	-	-	-	-	-	-
Max. rate of press. rise	850	1700	2500	1540	111	-	-	-	-	-	-	-	-	-	-
Av. rate press. rise	600	1100	1500	900	75	-	-	-	-	-	-	-	-	-	-

Table 3. Explosion Data for Certain Vapors and Gases (continued)

	Per Cent by Volume of Vapors and Gases														
	1.5	2	2.5	3	4	5	6	7	8	9	10	11	12	13	14
Isopropyl Alcohol															
Maximum pressure	-	-	-	-	66	85	92	-	89	-	69	-	-	-	-
Time to attain max. press.	-	-	-	-	0.23	0.08	0.072	-	0.12	-	0.70	-	-	-	-
Max. rate of press. rise	-	-	-	-	475	1560	1925	-	1325	-	145	-	-	-	-
Av. rate press. rise	-	-	-	-	280	1050	1300	-	750	-	100	-	-	-	-
Isopropyl Ether															
Maximum pressure	-	65	90	102	-	-	-	-	-	-	-	-	-	-	-
Time to attain max. press.	-	0.22	0.088	0.061	(Results are difficult to reproduce)										
Max. rate of press. rise	-	640	1325	1675	-	-	-	-	-	-	-	-	-	-	-
Av. rate press. rise	-	300	1000	1650	-	-	-	-	-	-	-	-	-	-	-
Naphtha															
Maximum pressure	80	69	94	-	70	-	-	-	-	-	-	-	-	-	-
Time to attain max. press.	0.11	0.07	0.06	-	0.36	-	-	-	-	-	-	-	-	-	-
Max. rate of press. rise	1000	2500	2500	-	303	-	-	-	-	-	-	-	-	-	-
Av. rate press. rise	725	1250	1550	-	200	-	-	-	-	-	-	-	-	-	-
Propane															
Maximum pressure	-	-	-	74	92	96	84	48	-	-	-	-	-	-	-
Time to attain max. press.	-	-	-	0.098	0.057	0.056	0.129	1.36	-	-	-	-	-	-	-
Max. rate of press. rise	-	-	-	1250	2400	2500	1375	35	-	-	-	-	-	-	-
Av. rate press. rise	-	-	-	760	1600	1700	650	35	-	-	-	-	-	-	-
Propylene Dichloride															
Maximum pressure	-	-	-	-	-	83	88	-	56	-	-	-	-	-	-
Time to attain max. press.	-	-	-	-	-	0.20	0.174	-	0.22	-	-	-	-	-	-
Max. rate of press. rise	-	-	-	-	-	675	1100	-	775	-	-	-	-	-	-
Av. rate press. rise	-	-	-	-	-	410	500	-	250	-	-	-	-	-	-
Toluene															
Maximum pressure	40	78	-	88	92	66	-	-	-	-	-	-	-	-	-
Time to attain max. press.	1.28	0.16	-	0.08	0.10	0.26	-	-	-	-	-	-	-	-	-
Max. rate of press. rise	43	850	-	2200	2400	400	-	-	-	-	-	-	-	-	-
Av. rate press. rise	30	500	-	1100	920	250	-	-	-	-	-	-	-	-	-

Table 4. Effect of Temperature on Explosion Data*

	80° F.	100° F.	150° F.	200° F.	250° F.	300° F.	350° F.	400° F.
Acetone (6% concentration in air)								
Maximum pressure	-	-	94	92	82	79	73	70
Time to attain maximum pressure	-	-	0.07	0.063	0.065	0.056	0.05	0.045
Maximum rate of pressure rise	-	-	2000	2200	2300	2800	3000	3000
Average rate pressure rise	-	-	1300	1450	1250	1400	1450	1550
Methyl Alcohol (15% concentration in air)								
Maximum pressure	-	-	90	90	86	77	76	70
Time to attain maximum press.	-	-	0.06	0.052	0.049	0.046	0.043	0.039
Maximum rate of pressure rise	-	-	3030	3100	2800	2800	3000	3000
Average rate pressure rise	-	-	1500	1600	1750	1700	1750	1800
Ethyl Alcohol (95%) (8% concentration in air)								
Maximum pressure	-	-	92	90	85	78	72	71
Time to attain maximum pressure	-	-	0.06	0.057	0.054	0.045	0.042	0.042
Maximum rate of pressure rise	-	-	2050	2300	2300	3000	3100	3150
Average rate pressure rise	-	-	1500	1550	1575	1750	1700	1700
Iso-Propyl Alcohol (5% concentration in air)								
Maximum pressure	-	-	85	85	83	78	73	68
Time to attain maximum pressure	-	-	0.08	0.07	0.065	0.060	0.054	0.045
Maximum rate of pressure rise	-	-	1560	1925	2000	2000	2200	2300
Average rate pressure rise	-	-	1050	1200	1250	1300	1350	1500
Butyl Alcohol (5% concentration in air)								
Maximum pressure	-	-	104	96	89	83	76	76
Time to attain maximum pressure	-	-	0.064	0.05	0.049	0.05	0.049	0.038
Maximum rate of pressure rise	-	-	2700	2800	3100	3100	3150	3200
Average rate pressure rise	-	-	1600	1900	1800	1600	1550	2000

* These data were obtained from tests conducted by the Eastman Kodak Company, Rochester, N.Y.

Many values of the maximum rates of pressure rise shown in this table differ from those recorded in more recent experiments.

Table 4. Effect of Temperature on Explosion Data (continued)

	80° F.	100° F.	150° F.	200° F.	250° F.	300° F.	350° F.	400° F.
Naphtha (2% concentration in air)								
Maximum pressure	-	-	89	86	84	76	69	66
Time to attain maximum pressure	-	-	0.07	0.068	0.057	0.056	0.052	0.050
Maximum rate of pressure rise	-	-	2000	2000	2100	2100	2300	2300
Average rate pressure rise	-	-	1275	1275	1475	1350	1300	1325
Benzene (3% concentration in air)								
Maximum pressure	-	-	93	89	84	79	72	69
Time to attain maximum pressure	-	-	0.05	0.05	0.048	0.048	0.042	0.042
Maximum rate of pressure rise	-	-	2300	2550	2780	3000	3000	3100
Average rate pressure rise	-	-	1850	1750	1750	1650	1700	1650
Toluene (3% concentration in air)								
Maximum pressure	-	-	99	92	86	82	75	70
Time to attain maximum pressure	-	-	0.067	0.058	0.056	0.055	0.048	0.042
Maximum rate of pressure rise	-	-	2200	2300	2400	2400	2500	2500
Average rate pressure rise	-	-	1475	1600	1550	1500	1550	1650
Hydrogen (30% concentration in air)								
Maximum pressure	108	105	99	90	84	80	76	66
Time to attain maximum pressure	0.008	0.0104	0.011	0.012	0.013	0.0135	0.0135	0.013
Maximum rate of pressure rise	10000	10000	8900	9000	9000	9800	9800	10000
Average rate pressure rise	13500	10000	9900	7500	6500	6000	5600	5100
Propane (5% concentration in air)								
Maximum pressure	104	98	96	89	84	88	75	72
Time to attain maximum pressure	0.059	0.058	0.056	0.054	0.048	0.044	0.043	0.041
Maximum rate of pressure rise	2250	2275	2500	2600	2750	2800	3000	3150
Average rate pressure rise	1750	1700	1700	1650	1750	2000	1750	1750

Table 5. Explosion Characteristics of Various Dusts*

Type of dust	Ignition temp. of dust cloud, deg. C.	Min. spark energy for ignition, millijoules	Min. explosive concentration, oz. per cu. ft.	Max. explosion pressure, psi	Rates of pressure rise, psi per sec.		Limiting** oxygen % to prevent ignition of cloud by electric sparks
					Avg.	Max.	
Metal powders							
Aluminum, atomized	700	50	0.040	58	1,050	2,250	3
Aluminum, stamped	645	20	0.035	89	2,150	5,700	
Iron, hydrogen reduced	315	160	0.120	29	650	1,200	13
Magnesium, atomized	600	240	0.030	57	750	1,450	<3
Magnesium, milled	520	80	0.020	65	1,500	3,150	b
Magnesium, stamped	520	20	0.020	72	4,400	4,750	b
Manganese	450	120	0.210	25	200	300	15
Silicon	775	900	0.160	62	450	1,200	15
Tin	630	160	0.190	26	250	400	16
Titanium	480	120	0.045	44	750	1,100	b
Vanadium	500	60	0.220	34	200	300	13
Zinc	680	900	0.500	13	150	300	10
Zirconium	a	15	0.040	42	1,450	4,000	b
Dowmetal	430	80	0.020	56	1,600	2,550	b
Ferrotitanium, low-carbon	370	80	0.140	34	600	1,400	13
Ferrosilicon (88% Si)	860	400	0.425	36	200	300	19
Magnesium-aluminum (50-50)	535	80	0.050	61	2,250	3,000	b
Plastics							
Allyl alcohol resin	500	20	0.035	68	1,750	3,550	
Casein	520	60	0.045	49	200	500	17
Cellulose acetates	320	10	0.025	82	1,200	2,400	14.5
Cellulose propionate	460	60	0.025	66	1,350	2,350	
Coumarone-indene resin	520	10	0.015	63	1,350	3,000	14.5
Hexamethylenetetramine	410	10	0.015	64	950	2,550	14.5
Legnin resin	450	20	0.040	69	750	2,700	17
Methyl methacrylate	440	15	0.020	57	550	1,200	14.5
Pentaerythritol	450	10	0.030	65	1.000	2,150	14.5
Phenolic resin	460	10	0.025	61	1,350	3,150	14.5
Phthalic anhydride	650	15	0.015	49	1,250	1,700	14.5
Polyethylene resin	450	80	0.025	83	400	1,250	15
Polystyrene	490	120	0.020	44	350	650	17
Shellac, rosin, gum	390	10	0.015	58	1,250	3,000	14.5
Synthetic rubber, hard	320	30	0.030	59	750	1,850	15
Urea molding compound	450	80	0.075	63	700	1,800	17
Vinyl butyral resin	390	10	0.020	60	450	1,000	14.5
Agricultural products							
Alfalfa	530	320	0.100	66	500	1,100	
Cellucotton	440	60	0.050	70	800	2,250	
Citrus peel, dehydrated	490	45	0.065	51	600	1,000	
Clover seed	470	80	0.060	49	.....	......	17
Cornstarch, modified	470	40	0.045	72	1,050	2,150	
Corncob, ground, dried	400	60	0.030	64	1,300	2,150	
Garlic, dehydrated	360	...	0.100	65	500	1,300	
Guar seed	500	60	0.040	70	550	1,250	
Onion, dehydrated	410	...	0.130	60	400	1,300	
Pea, dehydrated	560	..	0.050	68	800	1,950	
Peanut cracklings	570	370	0.085	41	200	350	
Rice	490	80	0.045	61	850	1,350	
Soybean	560	100	0.040	65	800	2,450	17
Tung kernels	540	240	0.070	74	650	1,950	
Wheat, cracked	470	160	0.060	58	......	......	
Miscellaneous							
Aluminum stearate	400	15	0.015	62	750	2,100	
Bark dust, Douglas fir	540	40	0.030	60	800	1,800	
Coal, bituminous	610	40	0.035	46	350	800	16
Coal-tar pitch	...	80	0.080	49	350	650	15
Crude rubber, hard	350	50	0.025	57	850	3,350	15
Dinitro-ortho-cresol	440	..	0.025	55	1,300	2,250	15
Gilsonite	580	25	0.020	56	900	1,850	
Liver protein	520	45	0.045	68	600	1,300	
Napalm	450	40	0.020	51	600	1,350	12
Phenothiasine	540	...	0.015	43	600	1,450	16
Soap	430	60	0.045	60	660	1,300	
Sulphur	190	15	0.035	41	700	1,950	11
Thyroid, desiccated	610	60	0.060	64	550	1,200	
Wood flour	430	20	0.040	62	850	2,100	17

See foot of page 68-61 for notes to Table 5.

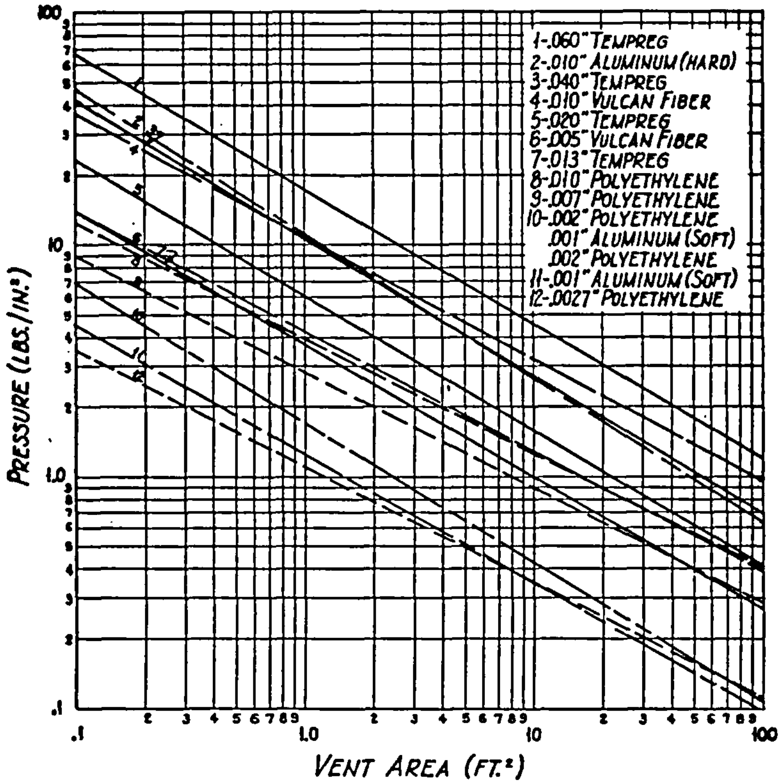

Figure 6. Rupture pressure vs. vent area of various venting materials. The graph shows that the bursting pressure of venting materials is a function of the vent area.

Notes for Table 5

a When zirconium powder was dispersed into air at room temperature, it ignited under some conditions, apparently due to static electric discharge between the particles in the dust cloud.

b The oxygen reduction tests were made in air-CO_2 mixtures. Dust clouds of zirconium, magnesium, titanium, and certain magnesium-aluminum alloys ignited in pure CO_2.

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**Oxygen percent is determined by volume percent.

Many values of the maximum rates of pressure rise shown in this table differ from those recorded in more recent experiments.

Description of Vent Closures for Fig. 7

(*Reprinted from U. S. Bureau of Mines, R. I.* 4636)

To facilitate reference to the several vent closures investigated, all were given identifying numbers, as listed below. The list includes a description of each closure. The diaphragms used were commercial products purchased in rolls or flat sheets; the glass panes were standard 14- by 20-inch size, obtained from the manufacturers; the hinged panels were made in the Bureau's shops.

1. PLASTIC-COVERED CLOTH NETTING. The over-all thickness of the netting is 0.045-inch.
2. VARNISHED CAMBRIC. The cloth is 0.008-inch thick.
3. PLASTIC-IMPREGNATED CLOTH. It is 0.010-inch thick.
4. PLASTIC-IMPREGNATED CLOTH. This is similar to No. 3, but 0.015-inch thick.
5. PARAFFIN-IMPREGNATED CLOTH. It is 0.013-inch thick.
6. FLAMEPROOF KRAFT PAPER. The paper is 0.0055-inch thick. It had been rendered flameproof by chemical treatment.
7. KRAFT PAPER. This is a heavy (0.008-inch thick) brown wrapping paper.
8. BUILDERS' SHEATHING PAPER. It is 0.0085-inch thick, made of a light-gray fibrous paper base that has been rosin-sized.
9. BUILDERS' PAPER. It consists of two greenish sheets with a bitumen-cement filler and cloth threads approximately ½-inch apart. The thickness, including the thread, is 0.020-inch.
10. PLASTIC-IMPREGNATED PAPER. This was obtained in sheets 0.013-inch thick. It is made by impregnating a paper approximately p.0025-inch thick with a plastic lacquer.
11. PLASTIC-IMPREGNATED PAPER. This was obtained in sheets 0.010-inch thick. It is a laminated product with a strong paper base, similar to No. 10 but made by a different manufacturer.
12. PLASTIC-IMPREGNATED PAPER. This is similar to No. 11, but 0.015-inch thick.
13. ALUMINUM FOIL. This foil is 0.0007-inch thick.
14. ALUMINUM FOIL. Similar to No. 13, but 0.0010-inch thick.
15. ALUMINUM FOIL. Similar to No. 13, but 0.0015-inch thick.
16. ALUMINUM FOIL. Similar to No. 13, but 0.0020-inch thick.
17. LIGHT SWINGING PANEL. This was prepared of galvanized sheet steel, 1/16-inch thick.
18. HEAVY SWINGING PANEL. This was similar to No. 17, but it was made of ¼-inch thick hot-rolled sheet steel.
19. PLASTIC-COVERED WIRE NETTING. A transparent plastic filler sheet approximately 0.0015-inch thick coats the screening and makes it nonporous.
20. GRADE "A" DOUBLE-STRENGTH WINDOW GLASS. The panes have a nominal thickness of ⅛-inch, but actual measurements disclosed a range from 0.114 to 0.125-inch.

21. Heat-absorbing Glass. The panes have a nominal thickness of ⅛-inch, but actual measurement showed a range from 0.104 to 0.129-inch.

22. Ribbed Glass. This glass has 22 ribs per linear inch. The overall thickness of the panes, including the ribs, ranged from 0.157 to 0.167-inch, and the average depth of the ribs was 0.0035-inch.

23. Unrestricted Vent. A thin sheet of manifold paper (0.0007-inch thick) was attached lightly to the opening, to prevent the dispersion of dust, during the initial stages of the explosion and to reduce the effects of extraneous air currents.

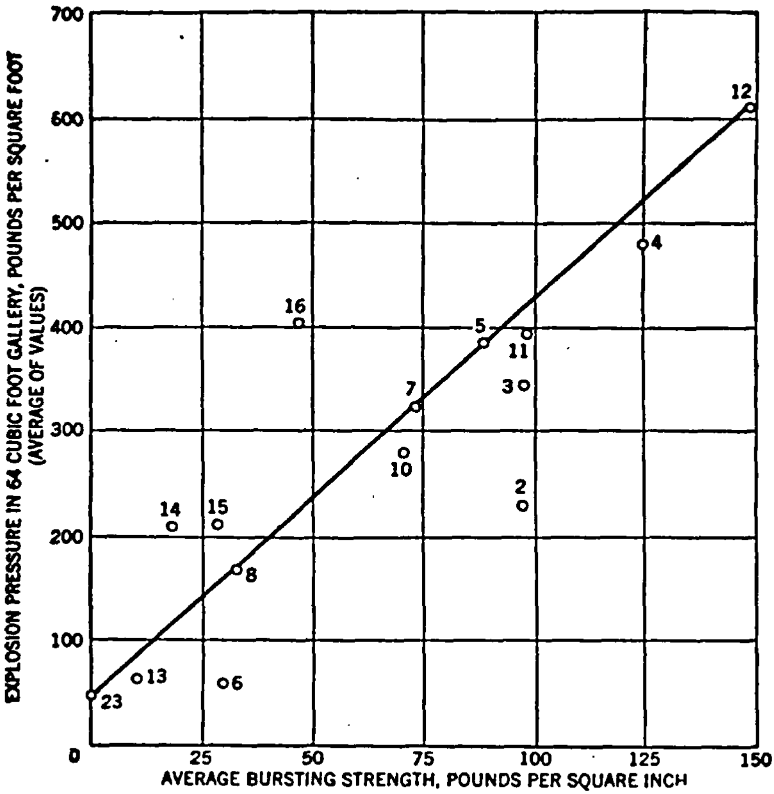

Figure 7. Relation of maximum explosion pressure to bursting strength of vent diaphragms. (Coal dust explosions.) (Reprinted from U. S. Bureau of Mines Report of Investigation 4636.)

Appendix III

Illustrations of Explosion Venting

Venting a Starch Dust Explosion — Figure 8
Photo shows explosion in building of light construction being vented through hinged windows and hinged doors.

Venting a Large Cylindrical Tank — Figure 9
Photo shows explosion vents on walls of large cylindrical tank.

Method of Converting Standard Steel Sash to Explosion Venting Type — Figure 10

Dust Explosion Venting Methods for Conveyor Ducts, Separators and Arrestors — Figure 11.

Dust Explosion Venting Methods for Bins, Blenders and Elevators — Figure 12

Dust Explosion Venting Methods for Bulk Storage Bins or Silos — Figure 13

Explosion Hatches for Coating machines; Explosion Diaphragm for Solvent Recovery System — Figure 14.

Explosion Doors for Spray Drying Tower — Figure 15.

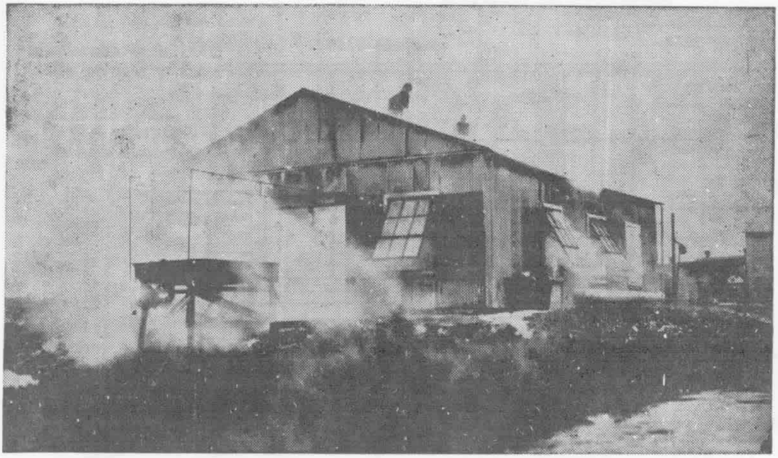

Figure 8. Venting an explosion of starch dust through hinged windows and hinged doors in a building of light construction.

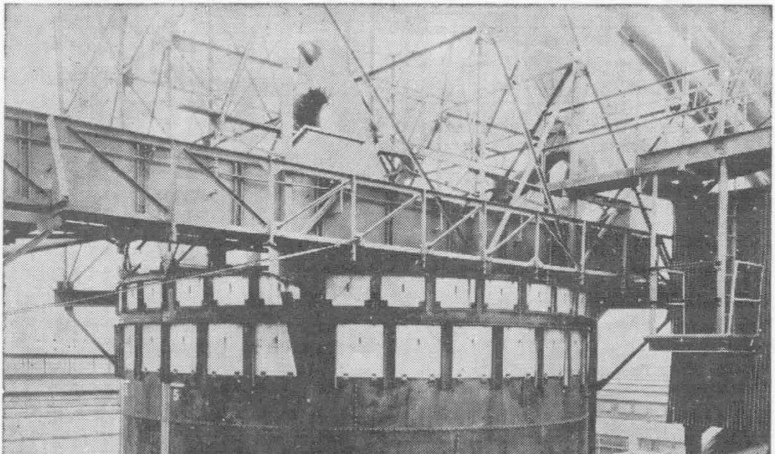

Figure 9. Method of venting a large cylindrical tank and dust collectors. Note in addition to the vents on the tank wall the coops or boxes with light covers located on top of the tank and on the conveyor housing.