Sulfur Pit Explosion Protection by Deflagration Venting

WorleyParsons

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Disclaimer

The authors have prepared this paper for the purpose of presenting available information on the subject matter and discussing and evaluating the advantages and possible disadvantages of utilizing deflagration vents on sulfur pits. Neither the authors nor WorleyParsons make any recommendations or representations as to the merits of deflagration vents, and hereby disclaim any responsibility or liability with respect to decisions with respect to use or non-use of such vents or any other use of the information contained in this paper.
Introduction

Liquid sulfur produced by the Claus process contains dissolved H$_2$S, which when liberated into the vapor space of its container can form a flammable mixture with air. Concrete, underground storage pits have been the industry standard for the collection, degassing and storage of elemental sulfur, produced in the Claus process, for many years. Most sulfur pits include features designed to prevent deflagrations using the principle of combustible concentration reduction, whereby the concentration of H$_2$S is maintained below the lower flammability limit (LFL) by dilution with sweep air drawn through the vapor space of the pit using a steam ejector. Backup ejectors and natural draft “chimneys” (steam jacketed vents to atmosphere), together with safety interlocks monitoring H$_2$S concentration, sweep air and/or motive steam flow, are commonly used features designed to ensure that sweep air keeps flowing at an adequate rate, and to alert operators if there is a deficiency.

Should all of these protective features fail, many sulfur pits also include deflagration vents (or “explosion hatches”) designed to relieve pressure resulting from a deflagration, thereby preventing a full-blown explosion event that could compromise the structural integrity of the pit and injure personnel. NFPA 68 – Standard on Explosion Protection by Deflagration Venting, as well as some European standards, contain guidelines for designing deflagration vents. However, these standards can be challenging to interpret and apply. Something as seemingly straightforward as determining the strength of a concrete enclosure can be difficult. There are also different types of venting devices to choose from, ranging from explosion doors or hatches to rupture diaphragms, each with different efficiency, costs, operability and maintenance concerns.

Complicating matters even further is the fact that owners, operators and engineers don’t always agree on the need for deflagration vents and often ask, “are these really required?” This straightforward question is not always simple to answer, as some consider the sweep air and monitoring features to be sufficient, while others consider deflagration vents to be essential, similar to a relief valve on a pressure vessel.

This paper discusses some of the arguments for and against deflagration vents. It also provides interpretation of the guidelines and design methods included in the applicable NFPA standards and reviews the different types of vent designs commonly used. Alternative sulfur storage designs that can eliminate the need for deflagration vents altogether are also explored.

Sulfur industry literature is noticeably silent on this subject. This paper seeks to raise the profile of this important issue within the sulfur industry.
Typical Sulfur Storage Pit Design and Safety Features

Liquid sulfur produced by the Claus process typically contains about 300 ppmw of dissolved hydrogen sulfide (H\textsubscript{2}S) and hydrogen polysulfides (H\textsubscript{2}S\textsubscript{x}) [1]. Over time, polysulfides decompose to form H\textsubscript{2}S and sulfur by Reaction 1 below. As the sulfur cools, either from heat lost to the surroundings or with the aid of a sulfur cooler, the equilibrium of Reaction 1 shifts to the right. H\textsubscript{2}S is physically desorbed into the gas phase by Reaction 2, aided by any agitation that may take place in the rundown container.

\begin{align*}
\text{H}_2\text{S}_x & \leftrightarrow \text{H}_2\text{S}(l) + \text{S}_{x-1} \quad (1) \\
\text{H}_2\text{S}(l) & \leftrightarrow \text{H}_2\text{S}(g) \quad (2)
\end{align*}

Degassing technologies of various types may be used to speed up the process by increasing the level of agitation, improving the efficiency of vapor/liquid contact and/or via the addition of a catalyst to promote Reaction 1. However, even without a special degassing process, H\textsubscript{2}S will be released into the vapor space of the rundown container and, if not removed can accumulate and potentially form a flammable mixture with air. The lower and upper flammability limits (LFL and UFL) of H\textsubscript{2}S in air at 135 °C (275 °F) are 3.3 mol% and 50.4 mol%, respectively [11, 12]. Therefore, the rundown storage system must be designed to avoid this potentially flammable mixture, as well as possible ignition sources, during normal operation and maintenance activities.

NFPA 69 – Standard on Explosion Prevention Systems, describes systems for the prevention of explosions in enclosures that contain flammable concentrations of gases, vapors, mists, dusts or hybrid mixtures. These systems fall into six general prevention or control methods:

1. Deflagration prevention by oxidant concentration reduction
2. Deflagration prevention by combustible concentration reduction
3. Deflagration prevention by hot particle detection and intervention systems
4. Deflagration control by suppression
5. Deflagration control by isolation
6. Deflagration control by pressure containment

As explained above, it is possible for the vapor space of a molten sulfur enclosure to contain an explosive mixture of H\textsubscript{2}S and air; therefore, the prevention methods described in NFPA 69 should be applied. While methods 1, 2 and 6 are commonly employed in this service, the authors are not aware of any sulfur storage systems using methods 3, 4 or 5.

**Method 1**, deflagration prevention by oxidant concentration reduction, involves maintaining the oxidant concentration in the system low enough to prevent deflagration [NFPA 69 5.1.1]. This method has been employed in some sulfur plants using fuel gas, nitrogen or other inert gas as the purge gas [1] to maintain the oxidant concentration below the *Limiting Oxidant Concentration (LOC)*, below which a deflagration cannot occur [NFPA 69 3.3.23]. The primary drawback to this method is that iron sulfide is allowed to form and accumulate on steel surfaces when air is not continually present to oxidize it. Upon eventual contact with air (during maintenance, for example) the built-up, pyrophoric iron sulfide can spontaneously ignite, causing serious safety concerns [1].

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Most sulfur pits utilize method 2, combustible concentration reduction, for the prevention of explosive mixtures within the vapor space. In this method, the concentration of H₂S is maintained below the LFL by dilution with ambient air. By maintaining an oxidizing atmosphere, the buildup of iron sulfide is prevented.

Figure 1 – Typical Sulfur Pit with Sweep Air

Figure 1 illustrates a typical scheme of this type, including the following features:

1. A steam ejector located at one end of the pit is used to draw atmospheric air through air intakes at opposite corners of the pit, sweeping the entire vapor space and ensuring that no stagnant zones exist.
2. A backup steam ejector is often installed which can either be started manually or automatically, in the event that the normally-operating ejector fails.
3. A backup natural draft vent to atmosphere that can either be opened manually or automatically.
4. Well sealed pit roof penetrations to prevent air ingress through these connections rather than through the dedicated air-intakes.
5. In most systems, the sulfur pit ejector discharges the vent gas directly to the incinerator; however, tightening environmental regulations may force some systems to discharge the pit vent to the SRU Reaction Furnace for recovery of the H₂S and sulfur vapor in the stream. Implementation of a pit vent recycle scheme to the SRU Reaction Furnace requires additional controls and safeguards to prevent the backflow of hot furnace gas. Sulfur pit deflagration vents would not typically be designed to protect against this scenario because the carbon steel piping between the pit ejector and the reaction furnace would most likely fail before the furnace gases ever made it to the sulfur pit.
6. The flow rate of sweep air is monitored, typically at the air inlet(s) rather than at the ejector suction or discharge. Sweep air flow measurement at the air inlet
location is selected for two reasons: 1) to ensure that sufficient air is entering through the air intake line rather than through pit penetration leaks, creating the opportunity for stagnant zones and inadequate sweeping despite achieving what appears to be an adequate pit sweep flow rate through the ejector, and 2) to avoid plugging the instrument taps with sulfur. A low air intake flow alarm alerts operators or trigger an automated response to start the backup ejector or open the backup atmospheric vent.

(7) The flow rate of ejector steam is monitored and a low flow alarm alerts operators or triggers an automated response similar to the low sweep air flow response.

(8) An H₂S analyzer monitors the vapor space and a high alarm alerts operators or triggers an automated response to shut-off the degassing air, if present, start the backup ejector or open the backup atmospheric vent. NFPA provides guidelines on acceptable H₂S concentration limits. The combustible gas concentration shall be maintained at or below 25% of the LFL (up to 60% of LFL with automatic safety interlocks) [NFPA 69 6.3.1]. Operations shall be discontinued whenever instruments show a combustible gas concentration of 35% or more of the LFL and should not be resumed until the instruments indicate a concentration of 15% or less of the LFL [NFPA 655 5.2.3 and 5.2.4].

The above safety features are aimed at preventing the possibility of forming an explosive mixture. For additional precaution, the following safety features are designed to prevent a source of ignition:

- The liquid sulfur inlets use a dip tube to deposit the sulfur below the liquid level and adequate grounding is provided to avoid static charge.
- The oxygen-rich environment prevents the buildup of pyrophoric iron sulfide.
- All instruments use explosion-proof housings in accordance with the electrical area classification.

Other typical safety features, such as monitoring the vapor space temperature to detect a fire, or providing snuffing steam to extinguish a fire, while important, do not specifically prevent deflagrations.

Protection against overpressure due to phenomena other than internal deflagrations (e.g. water leaks from heating coils or a sulfur cooler which may result in overpressure due to the rapid vaporization of water) are not addressed by NFPA 68.

**Are Deflagration Vents Required?**

If all of the protective features designed to prevent a deflagration from occurring should fail, many sulfur pits also include deflagration vents (or “explosion hatches”) designed to relieve pressure resulting from a deflagration, thereby preventing a full-blown explosion event that could compromise the structural integrity of the pit and injure personnel.

Owners, operators and engineers don’t always agree on the need for deflagration vents and often ask, “are these really required?” This straightforward question is not always simple to answer, as some consider the sweep air and monitoring features to be sufficient, while others consider deflagration vents to be essential, similar to a relief valve on a pressure vessel.
Sulfur Industry Literature Sources

While a great deal of information related to deflagration venting is available in general literature, it is surprising that sulfur industry literature is noticeably silent on this subject. Many papers have been written on safe sulfur storage practices for sulfur pits [1, 2, 3], but few mention the role of explosion hatches in the overall safety scheme of the sulfur pit. Those that do, mention them only briefly and don’t discuss the specific details and challenges associated with their implementation in this service.

A literature search including Brimstone and Laurence Reid conference archives, ASRL Quarterly Bulletins, and other sulfur industry resources revealed only two references to explosion hatches specifically for sulfur storage. One was a slide presentation about safe sulfur storage in which a single bullet on a single slide said, “Include explosion hatches in design” [2]. The second was a Q & A style article about safe sulfur storage in which a question was asked, “Does anyone use explosion doors to minimize damage?” The answer was simply, “We have never used blow-off doors on pits” [3].

NFPA Standards

The National Fire Protection Association (NFPA) develops codes and standards intended to minimize the possibility and effects of fire and electrical risks in buildings, processing facilities and other industrial applications in the United States, as well as many other countries. These codes & standards may be adopted into law or adopted as design standards by private companies. NFPA is the recognized authority in the US for fire and explosion prevention.

The main NFPA standards applicable to deflagration prevention and control within sulfur storage enclosures are described below.


NFPA 655

NFPA 655 applies to the handling of sulfur in any form, liquid or solid [NFPA 655 1.1.1]. Chapter 5, Handling of Liquid Sulfur at Normal Handling Temperatures (246 °F to 309 °F), covers the “typical” deflagration prevention features of a sulfur pit, such as the need for an H₂S vent system, H₂S monitoring requirements, safe concentration limits of H₂S in the vapor space, avoiding static buildup/discharge, avoiding exposure of heating coils to air, plus other safety features unrelated to deflagration prevention. However, Chapter 5 does not require, or even mention, deflagration vents.

Chapter 6, Handling of Liquid Sulfur and Sulfur Vapor at Temperatures above 309 °F, explicitly requires that process equipment shall be provided with heated deflagration venting [NFPA 655 6.2.2.1]. This is perhaps because at temperatures above 309 °F,
sulfur is nearer the flash point - the minimum temperature at which a liquid or solid emits vapor sufficient to form an ignitable mixture with air near the surface [NFPA 68 3.3.14]. Reported flash points of sulfur vary but are consistently greater than 309 °F. However, since most sulfur pits operate well below 309 °F, NFPA 655 does not provide a clear mandate for deflagration vents in normal service.

**NFPA 69**

NFPA 69 covers the design of the H$_2$S vent systems, which are required by NFPA 655 Chapter 5. As discussed previously, the most commonly used deflagration prevention method for sulfur pits is combustible concentration reduction with sweep air.

NFPA 69 also covers deflagration control by method 6, pressure containment, which may be an alternative to deflagration venting. It is only practical where a pressure vessel is used instead of a concrete pit. However, there is no mandate in NFPA 69 that deflagration vents or containment be provided in addition to a sweep air system.

**NFPA 68**

NFPA 68 applies to the design, location, installation, maintenance and use of devices and systems that vent the combustion gases and pressures resulting from a deflagration within an enclosure so that structural and mechanical damage is minimized [NFPA 68 1.1].

NFPA 68 only applies where the need for deflagration venting has already been established [NFPA 68 1.3]. It does not itself establish the need for deflagration vents. That responsibility is left to the authority having jurisdiction (AHJ), which is a phrase used throughout NFPA documents to refer to the organization, office, or individual responsible for approving equipment, materials, an installation, or a procedure. The AHJ could be a government agency, insurance agency or the property owner [NFPA 68 A.3.2.2].

**European Standards**

NFPA is not the only organization which addresses electrical and fire safety. The European Committee for Standardization (CEN) is a significant contributor to the development and implementation of European standards and technical specifications. The CEN’s 33 national members work together to develop voluntary European Standards (ENs).

The main European standards that can be interpreted as being applicable to deflagration prevention and control within sulfur storage enclosures are:

- EN 1127-1:2007 – Explosive atmospheres - Explosion prevention and protection
- EN 14994:2007 – Gas Explosion Venting Protective Systems
- EN 14460:2006 – Explosion Resistant Equipment
- EN 14797:2006 – Explosion Venting Devices
The concepts in the European standards are similar to those in the NFPA standards but the specific requirements for their implementation and the formulas used for sizing, location, etc. are sometimes different. Nevertheless, one key consistency between the NFPA and CEN standards is that mandates for the installation of deflagration vents on sulfur pits are noticeably absent in each, despite that guidelines for their sizing and placement are provided.

In summary, there is no industry consensus with respect to the need for deflagration vents on sulfur storage enclosures, nor does there appear to be any definitive obligation to provide them in published safety standards. Therefore, the responsibility for deciding whether they are required belongs to the authority having jurisdiction, which is likely the facility owner in this case.

Making an Informed Decision

In order for the owner to make an informed decision about the need for deflagration vents, the topic should be investigated in-depth during the design phase of a project as part of the HAZOP review. However, it is possible that deflagration may not be properly considered during these safety reviews, as the vent devices may not always be shown prominently on P&IDs, which provide the primary basis for the HAZOP. They may be shown as combination maintenance/explosion hatch devices, which masks their importance as safety features. Furthermore, deflagration vent devices are rarely assigned tag numbers, possibly because they are considered an integral part of the concrete pit and so are designed by civil/structural engineers, who do not typically participate in HAZOP meetings.

The front-end designer typically does not have access to the details that will be developed in later phases of a project, such as sulfur pit detailed design calculations and construction techniques. Additionally, as mentioned previously, the owner’s operating, maintenance and safety philosophies/procedures are also very important in determining whether the installation of deflagration vents should be considered, yet the front-end designer may not have full access to the specific owner’s vigilance with respect to implementing and maintaining such practices. In the absence of these important details, in order to ensure a conservatively safe design, during the Basic Design stage of a project, deflagration vents may be suggested with a brief note on the sulfur pit data sheet; something like “Provide maintenance/explosion hatch. Size and number to be determined during detail engineering.”

Some of the detailed design and/or operational factors that may make it necessary to consider sulfur pit deflagration vents include:

- Backup protection against deflagrations is needed due to inadequate safeguards to ensure the reliability of the sweep air system.
- Lower than normal sulfur pit strength due to design, construction materials, field installation procedures and/or soil conditions.

Some of the reasons for attempting to avoid installing sulfur pit deflagration vents include:

- In the event of a deflagration relief, toxic gas must be vented into the atmosphere, possibly putting personnel at risk of exposure to flame, heat and/or SO2.
• The strength of the concrete pit may weaken over time to lower than the relieving pressure that the vents were originally sized for.
• Heated vents may be required to prevent plugging and/or maloperation.
• Onerous inspection and maintenance, of both the pit and the relieving devices, is required to ensure adequate protection as the facility ages.
• Depending on the strength of the pit, there may be insufficient area available on the pit roof for adequate venting.
• A sulfur pit equipped with deflagration vents may be more expensive, in terms of engineering and construction, than a sulfur pit without them.

Designing Deflagration Vents

If, in fact, it is concluded that deflagration vents are required, NFPA 68 provides guidelines for their design and implementation. The following sections discuss the basics of deflagration vent design, as described in NFPA 68. Many specific NFPA citations are provided, with accompanying interpretation which is specific to sulfur pit overpressure protection applications. The discussion and examples are intended to provide a general overview and point out some of the nuances that are specific to sulfur pits, but should not be considered a substitute for NFPA 68.

Fundamental Properties of Combustible Gases

The equations provided in NFPA 68 for sizing deflagration vents rely on two fundamental measured properties of the combustible gas: the Deflagration Index for Gases, $K_G$, and the Fundamental Burning Velocity, $S_u$.

The Deflagration Index for Gases, $K_G$, is determined by the maximum rate of pressure rise attained by combustion in a closed test vessel with volume, $V$, and is defined by the following equation:

$$K_G = \left( \frac{dP}{dt} \right)_{\text{max}} \cdot V^{1/3} \quad \text{NFPA 68 Equation 6.1.1}$$

The value of $K_G$ for H$_2$S is provided in NFPA 68, Annex E, Table E.1. The higher the value of $K_G$, the higher the rate of pressure rise upon deflagration of the particular gas. The value of $K_G$ for H$_2$S in Table E.1 is 45 bar-m/sec. The gas with the next closest value of $K_G$ in Table E.1 is CH$_4$ at 55 bar-m/sec.

The Fundamental Burning Velocity, $S_u$, is the rate of flame propagation, relative to the velocity of the unburned gas ahead of it, of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas. The values of $S_u$ for many gases have been measured and published in NFPA 68, Annex D, Table D.1(a). The value of $S_u$ for H$_2$S is not provided in this table; however, the value of $S_u$ for one flammable gas can be approximated from that of another flammable gas by the following equation:

$$\left( S_u \right)_2 = \left( S_u \right)_1 \cdot \left( \frac{K_G}_2 \right) \frac{1}{\left( K_G \right)_1} \quad \text{NFPA 68 Equation E.1}$$
Equation E.1 produces the most accurate values where the two flammable gases have similar values of $K_G$ [NFPA 68 E.1]; thus, $CH_4$ properties can be utilized to derive the value of $S_u$ for $H_2S$. The value of $S_u$ for $CH_4$ in Table D.1(a) is 40 cm/sec. Therefore, the value of $S_u$ for $H_2S$ calculated by equation E.1 is 33 cm/sec.

Gas Mixtures and Sulfur Mist

For the purpose of this paper, the flammable/explosive mixture is considered to be $H_2S$ in air. The concentration of sulfur vapor in the vapor space is assumed to be negligible compared to the concentration of $H_2S$. Sulfur mist in the vapor space is also considered negligible, as would be the case without sulfur degassing inside the sulfur pit and/or when in-pit degassing is limited to air sparging from the bottom of the pit, below the liquid sulfur level. However, where a significant quantity of sulfur mist is present, which may be the case for some degassing processes where liquid sulfur is sprayed into the vapor space through nozzles, a different approach may be required. For combustible mists, the $K_G$ for propane of 100 bar-m/sec or the equivalent $S_u$ for propane of 46 cm/sec shall be used unless specific test data are available [NFPA 68 7.1.3]. It is observed that these values are substantially higher than those for $H_2S$, resulting in greater consequences, should a deflagration occur.

It may also be necessary, in some circumstances, to consider the case where a sulfur seal fails and process gas from the sulfur condenser flows into the pit. In this case, the combustible gas might be a mixture of $H_2S$, $SO_2$, $CO_2$, $CO$, $COS$, $CS_2$, $H_2$, $N_2$, $H_2O$, sulfur vapor and air. The mixture may or may not be flammable depending on the dilution effect of inert species and quantity of oxygen available.

Another scenario that may be considered is the presence of contaminants, such as unburned hydrocarbons, dissolved in the liquid sulfur, which may be subsequently released into the pit vapor space. Each credible scenario should be evaluated and the controlling case chosen for the design of the deflagration vents.

Where the hazard consists of a flammable gas mixture, the vent size shall be based on the $K_G$ or $S_u$ of the mixture [NFPA 68 6.2.1.1]. Where the gas mixture composition is not certain, the vent size shall be based on the component having the highest $K_G$ or fundamental burning velocity [NFPA 6.2.1.2]. Hydrogen may present a serious concern in this case because it is a fast-burning gas with $K_G$ of 550 bar-m/sec and $S_u$ of 312 cm/sec. Fast-burning gas deflagrations can readily undergo transition to detonation, in which case NFPA recommends using alternative measures discussed in NFPA 69 [NPFA 68 A.7.1.1].

Effect of Turbulence

If the gas system is initially turbulent, or if internal structures promote turbulence, the rate of deflagration increases [NFPA A.7.5]. In most instances, the vapor space of the sulfur pit can reasonably be considered quiescent, or non-turbulent. However, for some upset scenarios that may be considered, such as failure of sulfur seals, turbulence may exist, hence requiring consideration in the deflagration calculations. To account for the effects of initial turbulence and internal structures for enclosures with initial pressures near atmospheric, the $K_G$ for
hydrogen (550 bar-m/sec) shall be used for gases that have values, in the quiescent state, that are close to or less than that of propane (100 bar-m/sec) [NFPA 7.5]. Thus, similar to the scenario where the presence of sulfur mist is considered, greater deflagration consequences would also be expected if turbulence was present in the sulfur pit vapor space.

Enclosure Design Pressure

NFPA 68 defines several terms related to the pressure inside on an enclosure, as follows:

- **Maximum Pressure** \( (P_{\text{max}}) \) is the maximum pressure developed in a contained deflagration of an optimum mixture.
- **Reduced Pressure** \( (P_{\text{red}}) \) is the maximum pressure developed in a vented enclosure during a vented deflagration.
- **Static Activation Pressure** \( (P_{\text{stat}}) \) is the pressure that activates a vent closure [NFPA 68 3.3.27].
- **Enclosure Strength** \( (P_{\text{es}}) \) is the static pressure that results in either the deformation (yield strength) or failure (ultimate strength) of the weakest structural component of an enclosure [NFPA 68 6.3.2].

The amount by which \( P_{\text{red}} \) exceeds \( P_{\text{stat}} \) is a complicated function of the rate of pressure development within the enclosure, vent size, and mass of the vent closure device. These relationships are illustrated in Figure 2. Where deflagration vent area to enclosure volume ratio is large, \( P_{\text{red}} \) approaches \( P_{\text{stat}} \) (C). As the vent area is reduced, \( P_{\text{red}} \) increases (B) and approaches \( P_{\text{max}} \) as the vent area goes to zero (A) [NFPA 68 A.6.3.1.1].

![Figure 2 – Pressure-time characteristics of vented and unvented deflagrations from initially closed vessels illustrating the relationship of \( P_{\text{max}}, P_{\text{red}}, P_{\text{stat}}, \) and \( P_{\text{es}} \).](image)

(Adapted from [13])
As illustrated in Figure 2, the pressure from a vented deflagration rises to a maximum then decreases over a short time period after the vent opens. The load on the enclosure is therefore dynamic rather than static, causing the peak load to be amplified. The degree of amplification is called the Dynamic Load Factor (DLF) and depends on factors such as the duration of the load and the natural frequency of the system. In the absence of detailed structural response analysis, it shall be permitted to assume a worst-case value of \( DLF = 1.5 \) [NFPA 68 6.3.2.1]. Therefore, \( P_{\text{red}} \) shall not exceed two-thirds of the ultimate strength of the vented enclosure where deformation of the equipment can be tolerated, or yield strength where deformation cannot be tolerated [NFPA 68 6.3.1]. For a concrete sulfur pit, deformation cannot be tolerated, and therefore yield strength would apply.

\[
P_{\text{red}} \leq \frac{P_{\text{red}}}{DLF}
\]

The structural design of the concrete pit and the design of deflagration vents are inseparable because the strength and geometry of the pit impacts the size and location of the vents. The following sections provide the methodology for determining the strength of the pit and corresponding venting requirements.

NFPA 68 provides different methods for sizing deflagration vents depending on the reduced pressure, \( P_{\text{red}} \). Low-Strength Enclosures are defined as those that are capable of withstanding reduced pressures of not more than 0.1 barg (1.5 psig). High-Strength Enclosures are defined as those that are capable of withstanding reduced pressures from 0.1 barg (1.5 psig) up to 2 barg (29 psig).

In general, the higher the reduced pressure, the smaller the vent area required for both high-strength and low-strength enclosures. Therefore, there is incentive to design the pit for a high strength. However, at some point, the cost of the extra concrete and reinforcing steel that is required to reinforce the pit will eventually outweigh the benefits of smaller vent area.

Figure 3 plots reduced pressure, \( P_{\text{red}} \) on the x-axis against required deflagration vent area, \( A_v \), on the y-axis for two sections of a hypothetical sulfur pit: a 30 ft wide x 30 ft long x 10 ft deep degassing section followed by a 30 ft wide x 80 ft long x 10 ft deep storage section. The plotted values were determined by calculation methodology provided in NFPA 68, which will be discussed in detail later in the paper. Figure 3 illustrates that for low strength enclosures, required vent area increases exponentially, as reduced pressure decreases. At the upper pressure limit of 1.5 psig for a low-strength enclosure, the deflagration vent area extends across 30-35% of the roof area. Increasing the reduced pressure to 3 psig (perhaps a practical maximum for a concrete sulfur pit), upgrades the pit to a high-strength enclosure, and allows the vent area to be reduced to about 12-17%.
Figure 3 – Vent Area vs. Reduced Pressure

Figure 3 begs the question, “can the pit be designed to withstand a higher pressure without increasing the cost significantly?” The answer to this question is not simple because the strength depends on many factors. Pit geometry, design of the roof, number and size of roof penetrations, the type of roof-to-wall joint, air and soil temperatures and the internal reduced pressure, all contribute to the ultimate pit design strength.

In most cases, if a low-strength design is chosen, based on the geometry and configuration of the enclosure, the sizing of the walls and slabs are minimally impacted by the internal design pressure. This is due to the fact that the thermal stress caused by the temperature gradient between the hot molten sulfur side of the concrete and the colder soil side will govern the design. Referring back to Figure 3, recall that this option will require at least 30-35% of the roof area to be apportioned for deflagration venting devices. With so much open area, along with other roof penetration requirements, it is challenging to incorporate adequate support which will ensure high structural integrity. On the other hand, if a high-strength design is selected, the higher internal design pressure (in excess of 1.5 psig) will reduce the required venting area, but may have a significant impact on the sizing of the walls and slabs, and may result in additional concrete and reinforcing steel.

Unlike a vessel that is fabricated and tested in a shop, field fabrication of sulfur pits results in many uncertainties, such as quality, storage and preparation of materials, installation skill level of laborers, and weather conditions, to name a few, that can detrimentally impact the actual strength of the pit, regardless of its design strength. With so many variables in play, it is impossible to determine the optimum enclosure strength that works for every situation. Thus, specific calculations should be conducted for each project during detailed design. And, if necessary, calculations should be revised following construction, if it is suspected that field
fabrication conditions may have contributed to a reduction in design pressure below the intended design value.

The calculation methodology which was used to derive the data included in Figure 3 is described in detail in the sections that follow.

**Enclosure Length-to-Diameter Ratio (L/D)**

The $L/D$ ratio of the enclosure is an important consideration, especially for high-strength enclosures where it can have an impact on the vent area sizing calculation.

$$\frac{L}{D} = \frac{H}{D_{he}} \tag{NFPA 68 6.4.3.7}$$

where:

- $H$ = Maximum flame length (in meters) along which a flame can travel based on the maximum distance, taken along the central axis, from the farthest end of the enclosure to the opposite end of the vent [NFPA 68 6.4.3.2]. The effective volume, $V_{eff}$, is the volume of that part of the enclosure defined by $H$.

- $D_{he}$ = Effective hydraulic diameter (in meters) and is calculated by following equation:

$$D_{he} = 4 \cdot \frac{A_{eff}}{p} \tag{NFPA 68 6.4.3.6}$$

Hydraulic diameter is used for noncircular cross-sections, where $A_{eff}$ is the cross-sectional area normal to the longitudinal axis of the space and $p$ is the perimeter of the cross-section [NFPA 68 3.3.18]. See Figures 4, 5 & 6.

The most conservative method for calculating $L/D$ is to determine $H$ and $V_{eff}$ based on the total enclosure, irrespective of vent location [NFPA 68 6.4.3.4], as illustrated in Figure 4. However, this method may result in a larger vent area than is actually required if $L/D$ greater than 2.
When multiple vents are provided, a single value of $H$, and $L/D$, shall be permitted to be determined for the enclosure based on the farthest vent [NFPA 68 6.4.3.2.1], as shown in Figure 5.

The value of $H$, and $L/D$, can also be determined for each section using the maximum distance from the closest end of one vent to the opposite end of the next vent [NFPA 68 6.4.3.2.2], as illustrated in Figure 6.
**Enclosure Internal Surface Area (A<sub>s</sub>)**

Internal surface area, \(A_s\), should include the areas of the roof, floor and walls [NFPA 68 7.2.4.1]. Since the liquid sulfur in the bottom of the pit is incompressible, it acts like a “floor;” thus, the level will be a factor in determining the effective wall area. The choice of liquid level to use for the worst case scenario depends on the circumstances and should consider startup and shutdown as well as normal operation. The most conservative approach is to base the wall area on the empty pit dimensions [10].

**Enclosure Compartments**

If the pit is subdivided into separate compartments, each compartment shall be provided with its own vent(s) [NFPA 68 7.2.6.2]. This may be the case where separate degassing and storage compartments are provided, as shown in Figure 1. The wall between the two compartments extends from the pit floor to within 1-2 feet of the roof. While the vapor space of the two compartments is contiguous, the relatively small opening acts as a restriction to movement of expanding gases during a deflagration. NFPA 68 is not entirely clear if the two compartments must be treated separately in this specific case, but it seems prudent to do so. One reason is that this geometry may lead to a phenomenon called *pressure piling*, which can occur when a deflagration takes place in a vessel that is interconnected, through a pipe or duct, to another vessel, as illustrated in Figure 7. The pressure front accelerates through the restriction, causing it to move faster than the reaction front, which increases the initial pressure, \(P_o\), ahead of it by about \(8 \times P_o\). When the reaction front arrives, the final pressure becomes \(8 \times 8 \times P_o = 64 \times P_o\). The restriction also increases the combustion-generated turbulence, which amplifies the combustion properties of the gas. These phenomena may lead to a *deflagration-to-detonation transition* (DDT) if enough energy accumulates in the pressure wave so that the adiabatic compression of the gas leads to autoignition and initiation of a detonation [12]. Given these possibilities, it is recommended that each compartment be treated as a separate enclosure for the purpose of sizing the deflagration vents in that particular compartment.

When carrying out vent area calculations for an individual compartment, the designer must keep in mind that some of the calculations depend upon the longest dimension of the enclosure or the \(L/D\) of the entire pit. Thus, while the overall pit may be rectangular with the longest dimension in the direction of the x-axis, for example, an individual compartment may have its longest dimension in the direction of the y-axis.
Venting Area Requirement for Low-Strength Enclosures

The following equation determines the minimum venting area required for a low-strength enclosure [NFPA 68]:

\[ A_v = \frac{C \cdot A_s}{P_{red}^{1/2}} \]  

**NFPA 68 Equation 7.2.2**

where:

- \( A_v \) = vent area (m^2)
- \( C \) = venting parameter (barg^{1/2})
- \( A_s \) = internal surface area of enclosure (m^2)
- \( P_{red} \) = maximum venting pressure (barg)

The venting parameter, \( C \), is determined by the following equation for a fundamental burning velocity, \( S_u \), less than 60 cm/s [NFPA 68]:

\[ C = 1.57 \times 10^{-5} \cdot (S_u)^2 + 1.57 \times 10^{-4} \cdot (S_u) + 0.0109 \]  

**NFPA 68 Equation 7.2.2.1a**

Where:

- \( S_u \) = fundamental burning velocity (cm/sec)

Note that for low-strength enclosures there are no dimensional restrictions on the enclosure or the placement of the vents as long as the vents are distributed as evenly as possible with respect to the longest dimension. If the vents are restricted to one end of the pit, the \( L/D \) ratio should not exceed 3 [NFPA 68 7.2.3.1].

It is observed that Equation 7.2.2 in NFPA 68 for venting gas or mist deflagration in low-strength enclosures is the same one used in EN 14491:2006 for venting dust deflagrations in buildings.
**Venting Area Requirement for High-Strength Enclosures**

For high-strength enclosures, the $L/D$ ratio of the enclosure, and of the sections between vents, can have an impact on the vent sizing.

If $L/D$ is 2 or less, the following equation determines the minimum venting area, $A_v$, required:

$$A_v = \left( (0.127 \log_{10}(K_G) - 0.0567) \cdot P_{\text{red}}^{-0.582} + 0.175 P_{\text{red}}^{-0.572} (P_{\text{stat}} - 0.1) \right) \cdot V^{2/3}$$

**NFPA 68 Equation 7.3.3.2**

where:

- $K_G \leq 550$ bar-m/sec
- $P_{\text{red}} \leq 2$ barg and at least $0.05$ barg $> P_{\text{stat}}$
- $P_{\text{stat}} \leq 0.5$ barg
- $V \leq 1000$ m$^3$
- Initial pressure before ignition $\leq 0.2$ barg

If $L/D$ is 2-5, $A_v$ shall be increased by adding more venting area, $\Delta A$, which is calculated using the following equation:

$$\Delta A = \frac{A_v \cdot K_G \cdot (L/D - 2)^2}{750}$$

**NFPA 68 Equation 7.3.3.3.1**

Notice that the larger $L/D$ becomes, the larger $\Delta A$ becomes, up to a maximum of 54% additional vent area for $L/D = 5$, in the case of H$_2$S. Therefore, when locating the vents along the major axis of the pit, as shown in Figure 6, it is best to limit the spacing so that the $L/D$ ratio of each section is 2 or less, if possible, to avoid the need for extra vent area.

**Effects of Vent Closure Panel Inertia**

The free area of a vent does not become fully effective in relieving pressure until the vent closure moves completely out of the way of the vent opening. Until this occurs, the closure obstructs the combustion gases that are issuing from the vent [NFPA 68 A.6.7.4]. For a given vent area, the reduced pressure increases with the specific mass (kg/m$^2$) of the vent closure panel because heavy panels take longer to clear the vent opening than light panels do [NFPA A.6.7.2].

The specific mass of a vent panel, $M$, is the total mass of the closure (including counterweights or insulation) divided by the area of the vent opening [NFPA 68 6.7.1, 6.7.3 and EN 14797:2006 3.10]. The threshold mass, $M_T$, is the specific mass above which a correction to the vent opening area is required to account for inertia effects. Where $M$ is less than $M_T$, no correction is required to the vent sizing equations given in NFPA 68 [NFPA 68 6.7.3]. Where $M$ is greater than $M_T$, but less than 40 kg/m$^2$, the venting area must be increased by $\Delta A$ as shown below.
\[ M_T = \left[ 6.67 \cdot \left( \frac{P_{\text{red}}}{K_G} \right)^{0.5} \cdot \left( \frac{V}{n^{0.3}} \right) \right]^{1.67} \]  

NFPA 68 Equation 7.2.2.5.2

where:

- \( M_T \) = threshold mass (kg/m\(^2\))
- \( P_{\text{red}} \) is in barg
- \( n \) = number of panels
- \( V > 1 \text{m}^3 \)

\[ \Delta A = A_v \cdot (0.0075) \cdot \frac{K_G^{0.5}}{n^{0.3} \cdot V \cdot \rho_{\text{red}}^{0.2}} \]  

NFPA 68 Equation 7.2.2.6

where:

- \( \Delta A \) = additional vent area required (m\(^2\))
- \( M \) = mass of vent panel (kg/m\(^2\))
- \( A_v \) = vent area (m\(^2\)) calculated by Equation 7.2.2 or 7.3.3.2

The value of \( K_G \) used in equation 7.2.2.6 shall be 75 bar-m/sec, if \( K_G \) for a certain component is less than 75 bar-m/sec.

Where \( M \) is greater than 40 kg/m\(^2\), it is necessary to perform testing to determine the efficiency of the vent closure or apply alternate explosion protection methods per NFPA 69, Standard on Explosion Prevention Systems [NFPA 68 A.7.2.2.5.2].

European Standards differ from NFPA 68 in the limits imposed on the value of \( M \) before it becomes necessary to perform testing.

\[ \Delta A = A_v \cdot \left( \frac{1}{E_f} - 1 \right) \]  

EN 14994:2007 5.2 (2)

\[ E_f = \frac{A_e}{A_d} \]  

EN 14797:2006 7.3.4

where:

- \( E_f \) is the dimensionless venting efficiency of the venting device
- \( A_e \) is the effective vent area of the device, m\(^2\)
- \( A_d \) is the actual vent area of the device, m\(^2\)

- \( E_f = 1 \) for explosion venting devices with \( M \) less than 0.5 kg/m\(^2\)
- \( E_f = 1 \) for explosion venting devices with \( M \) greater than 0.5 kg/m\(^2\) and smaller or equal to 10 kg/m\(^2\) provided \( A_v/V^{0.753} < 0.07 \), where \( A_v \) is the vent area and \( V \) the vessel volume. This is valid for \( P_{\text{stat}} \leq 0.1 \text{barg} \) and \( 0.1 \text{ barg} < P_{\text{red}} < 2 \text{ barg} \)
• for all other conditions and for explosion venting devices with an $M$ greater than 10 kg/m$^2$ the efficiency $E_f$ has to be determined by tests.

In summary, NFPA says that vent closures with $M > 40$ kg/m$^2$ require testing to determine their efficiency while European Standards set the limit much lower at $M > 10$ kg/m$^2$.

**Hazard Zone**

NFPA 68 discusses the hazard zone around the discharge of deflagration vents in the context of protecting personnel from the hot gases and material that may be ejected. It does not address the potentially toxic cloud that may result from the combustion of H$_2$S and/or other sulfur species, in the case of a sulfur pit deflagration. The determination of the hazard zone area is important because it may have some bearing on the location of deflagration vents on the sulfur pit roof and/or may present a requirement for cordonning off certain areas around the pit to prevent regular personnel access.

The fireball from a vented gas or dust deflagration presents a hazard to personnel who may be in the vicinity. People caught in the flame itself will be at obvious risk from burns, but those who are outside the flame area can be at risk from thermal radiation effects. The heat flux produced by the fireball, the exposure time, and the distance from the fireball are important variables to determine the hazard [NFPA 68 A.7.6.4].

The hazard zone from a vented gas deflagration is calculated by the following equation:

$$D = 3.1 \cdot \left( \frac{V}{n} \right)^{0.402}$$

**NFPA 68 Equation 7.6.4.1**

where:

$D =$ axial distance (front-centerline) from vent (m)
$V =$ volume of vented enclosure (m$^3$)
$n =$ number of evenly distributed vents

The hazard zone measured radially (to the sides, measured from the centerline of the vent) shall be calculated as one-half $D$ [NFPA 68 7.6.4.2]. Ducts should be carefully designed because they can impact the vent area sizing [NFPA 68 7.4].
Similar to API limitations for relief valve over-pressure, NFPA specifies permissible limits for deflagration vent activation pressure. Low strength and high strength enclosures each have their own specific requirements.

- For low strength enclosures, $P_{\text{red}}$ shall exceed $P_{\text{stat}}$ by at least 0.024 barg (0.35 psig) [NFPA 68 7.2.6.1].
- For high strength enclosures, $P_{\text{red}}$ shall exceed $P_{\text{stat}}$ by at least 0.05 barg (0.73 psig) and $P_{\text{stat}}$ shall be less than 0.5 barg (7.3 psig) [NFPA 68 7.3.3.2].

Deflagration vent closures should release at a $P_{\text{stat}}$ value that is as low as practical, yet should remain in place when subjected to external wind forces that produce negative pressures, to prevent vents from being pulled off. In most cases, a $P_{\text{stat}}$ value of 0.01 barg (0.14 psig) is acceptable. In areas subject to severe windstorms, release pressures up to 0.015 barg (0.21 psig) are used [NFPA 68 A.7.6.2.1].

**Vent Closure Types**

Similar to a relief valve, a vent closure is a device that is installed on a sulfur pit vent opening that is designed to open at a pre-determined pressure, $P_{\text{stat}}$, to prevent the pressure in the enclosure from exceeding $P_{\text{red}}$. Vent closures should withstand pressure fluctuations that are below $P_{\text{stat}}$ [NFPA 68 6.5.5]. For sulfur pits, this would include any slight vacuum potentially created by the sweep ejector.

Vent closures may have non-reusable elements or reusable elements. Those with reusable elements may automatically reclose following a deflagration or may require manual repositioning. Some common types of vent closures are described in the following sections.
Rupture Diaphragms

Rupture diaphragms (also called rupture or bursting panels, disks or membranes) are non-resealing, one-time use devices that rupture at a pre-determined differential pressure ($P_{stat}$). They can be round, square or rectangular and are typically mounted in a support frame which is attached to the enclosure (Figures 9-13). Individual panels are available in a range of sizes up to a few square meters in area. Flat panels can be used for vacuum service if backed by a support grid (Figure 10). Domed panels can resist vacuum conditions on their own without a support grid (Figure 11).

Thermally insulated vent panels are available (Figure 13) to reduce heat loss to the atmosphere, which can lead to sulfur condensation and/or solidification on and around the device, potentially hindering the relief device’s performance. Heat loss and sulfur condensation/solidification concerns associated with sulfur pit deflagration vents are specifically discussed in a subsequent section of this paper.

Rupture diaphragms are almost inertia-free, with a specific mass less than 0.5 kg/m$^2$, and do not impede the venting process. Therefore, they have a venting efficiency, $E_f = 1$. [EN 14797:2006 7.3.3.1].

Some benefits of rupture diaphragms include:

- They are cost effective when infrequent activations are expected. For example, indicative cost of materials for a total vent area of 70 m$^2$ is about $58,000 for rupture diaphragms, compared to $525,000 for explosion doors [15].
- They have low inertia and therefore no penalty on vent area.

Some drawbacks of rupture diaphragms include:

- Their service life may be negatively impacted by pulsation or vibration.
- They must be replaced after each incident.
Figure 9 – Rectangular Rupture Diagram
(Source: EN 14797:2006)

Key
1 fixed side
2 area of the explosion venting device
3 supporting frame
4 sides yielding during venting process

Figure 10 – Back Pressure Support
(Source: EN 14797:2006)
Figure 11 – Typical Domed Rupture Diaphragm (Round)
(Photo provided by BS&B Safety Systems)

Figure 12 – Typical Rupture Diaphragm (Square)
(Photo provided by BS&B Safety Systems)
Pop-Out Panels

Pop-out panels come in many forms; a few examples are shown in Figures 14 and 15. They may be semi-rigid panels, secured at the edges to a frame, designed to bend and become detached at the desired $P_{\text{stat}}$. They may also use rigid panels secured to the frame at the edges with clamping devices, designed to break or release at the desired $P_{\text{stat}}$. Pop-out panels may be of single-wall or double-wall construction with insulating material between, so called “sandwich panels”.

Pop-out panels may be installed in the vertical or horizontal orientation. If installed in the horizontal position, provisions to prevent the accumulation of snow, ice, rainwater or debris must be included in the design.

Pop-out panels have restraining devices (chain, wire, etc.) to prevent them from becoming projectiles. Restraining devices shall not impede the operation of the vent of vent closure device [NFPA 68 6.5.3].

The primary benefit of pop-out panels is that they may be reusable following an incident. The primary drawback is that broken clamps must be replaced after each incident.
Figure 14 – Restrained Pop-out Panel
(Source: EN 14797:2006)

Figure 15 – ATEX Reflex Pop-out Panel
(Photo provided by ATEX Explosion Protection L.P.)
**Explosion Doors**

Explosion doors are hinged devices, typically held shut with spring-loaded, magnetic or friction latches; some examples are shown in Figures 16 and 17. Hinged closures shall be permitted to be used, provided the following conditions are met [NFPA 68 6.7.4]:

1. There are no obstructions in the path of the closure that prevent it from opening.
2. Operation of the closure is not restrained by corrosion, sticky process materials, or paint.

Some benefits of explosion doors include:

- They are cost effective when multiple activations are expected or when the replacement of vents after opening is very difficult and/or time consuming.
- They can be made self-closing, which can limit oxygen supply and minimize the damage from fire.
- They can be field-calibrated for easy setup and maintenance testing.

Some drawbacks of explosion doors include:

- Explosion doors have greater inertia than rupture diaphragms and so may require additional vent area.
- Self-closing doors may create a vacuum in the pit resulting from cooling of the hot combustion gases following a deflagration.
- Explosion doors may be more challenging to heat, if required (this is discussed in more detail in a subsequent section of the paper).
- Maintenance of the hinge and latch mechanism is required.

![Figure 16 – Explosion Doors](Photo provided by ATEX Explosion Protection L.P.)
Vent Closure Inspection and Maintenance Requirements

Vent closures shall be inspected at least annually [NFPA 11.4.1]. The inspection frequency depends on the environmental and service conditions to which the devices are exposed, and on documented operating experience [A.11.4.2]. The inspector shall verify [NFPA 68 11.4.4]:

- The opening is free and clear of any obstructions
- The closure is not corroded or mechanically damaged
- The closure has no buildup of deposits on the inside surfaces or between layers of the vent
- The closure shows no fatigue and has not released
- Records of inspections shall be retained for a minimum of 3 years [NFPA 68 11.7.2].
- If process material has a tendency to adhere to the vent closure, the vent closure shall be cleaned periodically to maintain vent efficiency [NFPA 68 11.9.3]

Vent Closure Heating

Vent closure operation should not be hindered by snow, ice, corrosion, debris or buildup of deposits on the inside surfaces [NFPA 68 6.5.2]. For sulfur pits, this might require heating and insulating the vent closures to keep the inside surface temperature above 250 °F to prevent sulfur from freezing on the panel.
When designing the heating system, many variables need to be considered, including ambient air temperature, wind speed, sweep air temperature (heating the incoming sweep air may be required), size of the panel, insulation thickness, etc. ControTrace heating elements may be well suited to this type of application because they can be adapted to a variety of panel mounting frame shapes and styles. Heating elements should not be placed directly on top of the vent panel (Figure 18) if they interfere with the operation or increase the panel inertia. However, heating elements may be placed on the surrounding frame to which the panel is mounted, which allows heat to be transferred to the vent panel by conduction (Figure 19). For large vent panels, the convective heat loss to the surroundings may be too substantial to keep the center of the panel above 250 °F, even with insulation [14]. Adding a vent duct to block the wind (Figure 20) may resolve this. However, vent ducts should be carefully designed because, similar to the discharge piping on a relief valve, the additional backpressure imposed by a vent duct can increase the vent area required [NFPA 68 7.4].
Conclusions

The primary conclusions derived from this study can be summarized as follows:

• There is no clear consensus within the industry on the requirement for deflagration vents on sulfur pits.

• Owners need to make deliberate, informed decisions about the need for sulfur pit deflagration vents during the design phase HAZOP, in consultation with their detailed engineering contractor, while also considering site-specific operation procedures and safety practices.

• Sulfur pit deflagration vents are challenging to implement.

• If it is deemed that other safety devices, methods and procedures cannot adequately mitigate the possibility of forming explosive conditions within the vapor space of the sulfur pit without the installation of deflagration vents, the owner may elect to install a pressure vessel rated to withstand deflagration pressure, rather than installing a concrete pit with protection devices that are difficult to design and maintain.
References

10. B. Chase, Telephone interview. August 17, 2012. Mr. Chase is a technical expert with NFPA who provided informal interpretation of some sections of NFPA 68.