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Dust Explosions and Collapsed Ductwork

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Abstract

One of the more obvious consequences of a dust deflagration inside process equipment or a structure is the mechanical damage caused by shock (compression) waves. This overpressure damage is revealed through the displacement of equipment, the outward deformation or rupture of enclosures constructed of ductile materials, or the projection of missiles. However, a different type of damage is sometimes observed in the ductwork connecting process equipment. In particular, the ductwork is collapsed as if it were subjected to an external, rather than an internal pressure. The phenomenon that causes this collapse of thin-walled conduit is a gas dynamic process called an expansion wave. When a dust deflagration travels through a conduit, it accelerates and causing a rise in pressure. When the dust deflagration is vented (say through a deflagration vent), the discharge of the high pressure combustion products causes the formation of an expansion wave that travels in the reverse direction from the vent backwards. The expansion wave causes the pressure in the ductwork to fall below atmospheric pressure. The sub-atmospheric pressure, in turn, causes the ductwork to fail by buckling. In this study, we examine the gas dynamics of the expansion wave, demonstrate how to calculate the degree of pressure drop caused by the expansion wave, and illustrate the concept with case studies of dust explosions.

Keywords: Incident Investigation, Dust Explosion

1 Introduction

Incident investigation plays an important role in process safety management. The objective of incident investigation is to prevent a recurrence of the same incident. The investigation of an accidental dust deflagration is oftentimes challenging due to the severity of both mechanical and structural damage. The dynamics of the deflagration event can be especially difficult to trace in a process unit with process lines and vents connecting multiple pieces of equipment. In a unit with interconnected equipment, it is not unusual to find evidence of overpressure damage such as bulged or ruptured process vessels. Ductwork, on the other hand, tends to exhibit less damage associated with deformation directed outwards from the duct interior. Instead, if it exhibits any damage at all, ductwork and process vents tend to exhibit a collapsed appearance.

There are two potential mechanisms for the collapse of a length of duct. One mechanism requires that the external pressure on the duct is greater than the internal pressure. In this circumstance, it is possible that the dust deflagration inside the building caused the positive overpressure on the outside of the duct. This hypothesis would lead the investigator to search for signs of a deflagration propagating through the room. The second mechanism requires that the internal pressure inside the duct is less than the ambient (atmospheric) pressure in the room. The mechanism that can cause this to occur is an expansion wave, a gas dynamic phenomenon discussed in the next section. An expansion wave is a consequence of a deflagration propagating inside the duct.

2 Flame Acceleration and Pressure Waves

If a large combustible dust cloud is ignited at its center, a flame will propagate outwards in a radial direction. This radial expansion will continue until either the flame reaches the edge of the dust cloud or it encounters a solid boundary. If the dust flame propagates inside a duct or channel, the dynamic behavior of the flame changes. The duct confines the flame and the hot combustion products thus preventing the three-dimensional expansion process. Instead, the flame and combustion products can expand in only one direction. Because the fluid medium—air—is a compressible medium, the gas velocity increases as the hot gaseous combustion products expand. The expansion process causes an acceleration of the flame speed which results in turbulence.[1] The turbulent mixing of the flow field causes the mass burning rate to increase. This leads to a positive feedback loop with flame speed, turbulent mixing, mass burning rate, and gas expansion rate all increasing. This process is illustrated in Figure 1.

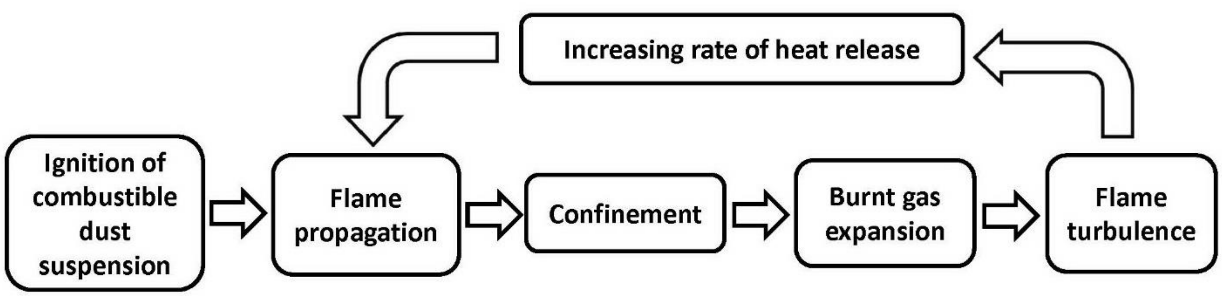

Figure 1 Flame acceleration caused by turbulence

This positive feedback loop leads to the formation of a pressure wave called a compression wave. The compression wave steepens as it travels down the duct eventually forming a shock wave. The compression wave is a pressure disturbance. It travels in the same direction as the gas

[1] The flame speed should not be confused with the burning velocity. The flame speed is the velocity of the flame as measured by an observer using a fixed, stationary coordinate system. The burning velocity is the velocity of the unburnt mixture relative to a coordinate system fixed to the flame.

flow. Figure 2 illustrates the flow field of an accelerating flame with a shock wave and the associated pressure profile for an instant in time.

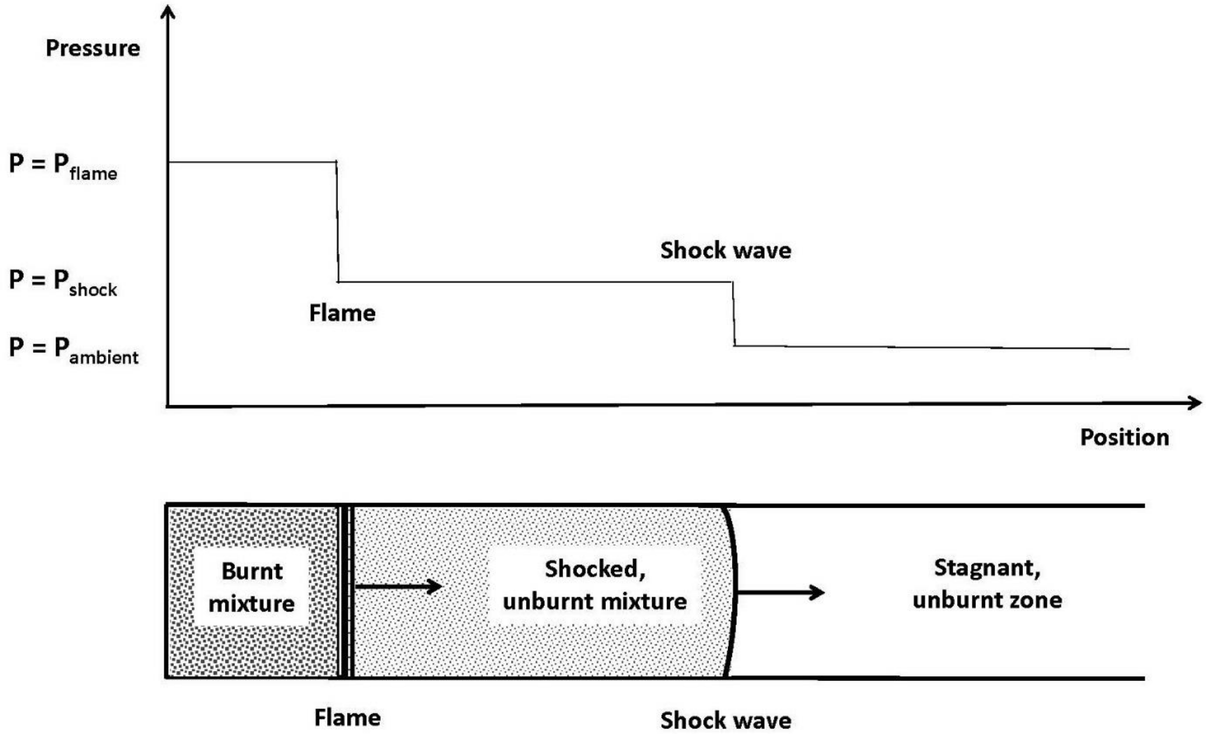

Figure 2 Illustration of a flame accelerated shock wave propagating down a tube

The positive overpressure of the shock wave, generated by flame acceleration, can damage equipment downstream of the point of ignition. Overpressure damage is the type of damage one most often associates with an explosion.

The dynamics of the compression wave process is characterized by two velocities: the speed of sound in the unburnt gas and the flame speed. The sound speed is a measure of how quickly a pressure disturbance travels in the gaseous medium. For an ideal gas, the sound speed can be calculated with the equation

$$a = \sqrt{\frac{\gamma\, R_g\, T}{\mathcal{M}}}$$

where a is the sound speed, γ is the specific heat ratio, R_g is the universal gas constant, T is the absolute temperature, and $\mathcal{M}$ is the molar mass of the gas. The significance of wave interactions depends on the acoustic time scale of the flow. The time scale for an acoustic disturbance in a conduit is the time it takes a sound wave to travel the distance of the conduit. The acoustic time scale is simply the length of the conduit divided by the sound speed. For a conduit length of 10 m and a sound speed of 350 m/s, the acoustic time scale is approximately 29 ms.

The flame speed is generally a measured quantity. The strength of the overpressure is related to the magnitude of the flame speed. This relationship can be calculated using the normal shock relations for an ideal gas.[2] However, these equations form a set of nonlinear algebraic equations which tend to obscure the relationship between flame speed and overpressure. In many cases, the overpressure can be estimated by a simpler linear equation based on an acoustic approximation.[3] The equation takes the following form:

$$\Delta P = \rho_u \, a_u \Delta v$$

In this equation ΔP is the overpressure (final minus initial) across the shock wave, $\rho_u$is the unburnt gas-dust mixture density, a_u is the sound speed of the unburnt gas-dust mixture, and Δv is the flame speed. This relation more clearly indicates the importance of flame speed and shock overpressure. It gives reasonable estimates of the overpressure for flame speeds up to approximately 400 m/s. Using the properties of air at an ambient pressure of 1.013 bar absolute and a temperature of 300 K, a flame speed of 100 m/s gives a shock overpressure of 0.41 bar gauge. An overpressure this large can cause the failure of non-reinforced concrete block wall panels.

A dust deflagration can travel down a duct as long as there is fuel to sustain it. If the deflagration runs out of fuel, the high pressure gas column will expand and reduce the magnitude of the overpressure behind the flame. The dissipation of the shock wave below the level of damaging overpressures will usually require a travel distance much greater than the length of conduits typically found in industrial facilities. Thus, even if it runs out of fuel, the high pressure gas formed by the deflagration will vent to the atmosphere by causing a failure of containment or by design through an explosion vent. Explosion vents are a common safeguard used to mitigate a potential dust deflagration. Venting of high pressure gas into the ambient environment can lead to an external shock wave, flames, and hot gases, all of which may cause injury or property damage. Hence, explosion venting must occur in a location that will maintain the risk of injury or damage to an acceptable level.

However, the venting of the flame and the gaseous combustion products is not the end of the story. The venting of the high pressure gases leads to the formation of another pressure wave called an expansion (or rarefaction) wave. An expansion wave is the fluid dynamic process by which the gas pressure in a vessel or conduit achieves its final pressure in hydrostatic equilibrium with the ambient pressure. In complex conduit networks with multiple lines, elbows, tees, and process equipment, a very complex set of wave interactions can occur. These complex wave interactions are beyond the scope of this paper. A key feature of an expansion wave in a long conduit is its ability to cause the formation of a partial vacuum (pressure below atmospheric pressure).

An expansion wave is a pressure disturbance that travels in the opposite direction of the gas flow. To understand how an expansion wave works, we must first distinguish between a slow leak process and a fast leak process. Consider a conduit filled with high pressure gas (i.e., the gas pressure is at least several multiples of ambient pressure). If a very small hole is formed in one

[2] Anderson, J.D. *Modern Compressible Flow with Historical Perspective*. New York: McGraw-Hill, pp.54-63 1982.

[3] Ogle, R.A. *Dust Explosion Dynamics*. Oxford, Butterworth-Heinemann, pp. 513-516, 2017.

end of the conduit, a steady leak of gas will occur. If the time to depressurize the conduit is several multiples of the acoustic time scale for the conduit, any spatial gradients are smoothed by the multiple reflections inside the conduit and the leak is considered slow. A slow leak of high pressure gas from a closed volume exhibits a gradual, spatially uniform decrease in pressure. The pressure declines monotonically and asymptotically approaches the ambient pressure. An example of how to analyze this system as a control volume with no spatial gradients is available in gas dynamics textbooks.[4,5]

If a large hole is created in the conduit, such that the depressurization time approaches the acoustic time scale, then the leak is considered fast. A fast leak of high pressure gas exhibits a spatially nonuniform pressure profile called an expansion wave. With a fast leak the expansion wave creates axial gradients within the conduit (a gradient in the direction of flow) in pressure, temperature, and gas density. A complete description of the fluid dynamic processes involved during gas venting would require a numerical solution of the governing equations for a compressible fluid. The method of characteristics is ideal for this challenge. However, such a simulation would not only be complex but it would also be too specific to the particular situation analyzed. Some insight to the venting process can be obtained by considering a simpler problem that yields an analytical solution.

The simpler problem assumes that the conduit is permanently closed on one end and closed on the other end with a frangible diaphragm. The conduit is initially filled with high pressure gas (gas at a pressure greater than atmospheric pressure). At time zero the frangible diaphragm is broken and the gas is vented out of the open end into the atmosphere. This version of the expansion wave problem is equivalent to the withdrawal of a piston from a conduit.[6],[7] In the spirit of developing the simplest description of the situation, attention is focused on the propagation of a single expansion wave. In reality, one would expect to observe multiple expansion waves with wave reflection off of the closed end. Consideration of a single expansion wave will convey the essential physics. Figure 3 depicts the trajectory of this expansion wave process.

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4 Saad, M.A. *Compressible Fluid Flow*. Englewood Cliffs, Prentice-Hall, pp. 98-101, 1985.
5 Zucrow, M.J.. and Hoffman, J.D. *Gas Dynamics, Volume 1*. New York, John Wiley, pp. 177-178, 1976.
6 Anderson, J.D. *Modern Compressible Flow with Historical Perspective*. New York: McGraw-Hill, pp. 196-202, 1982.
7 Thompson, P.A. *Compressible Fluid Dynamics*, New York: McGraw-Hill, pp. 392-398, 1972.

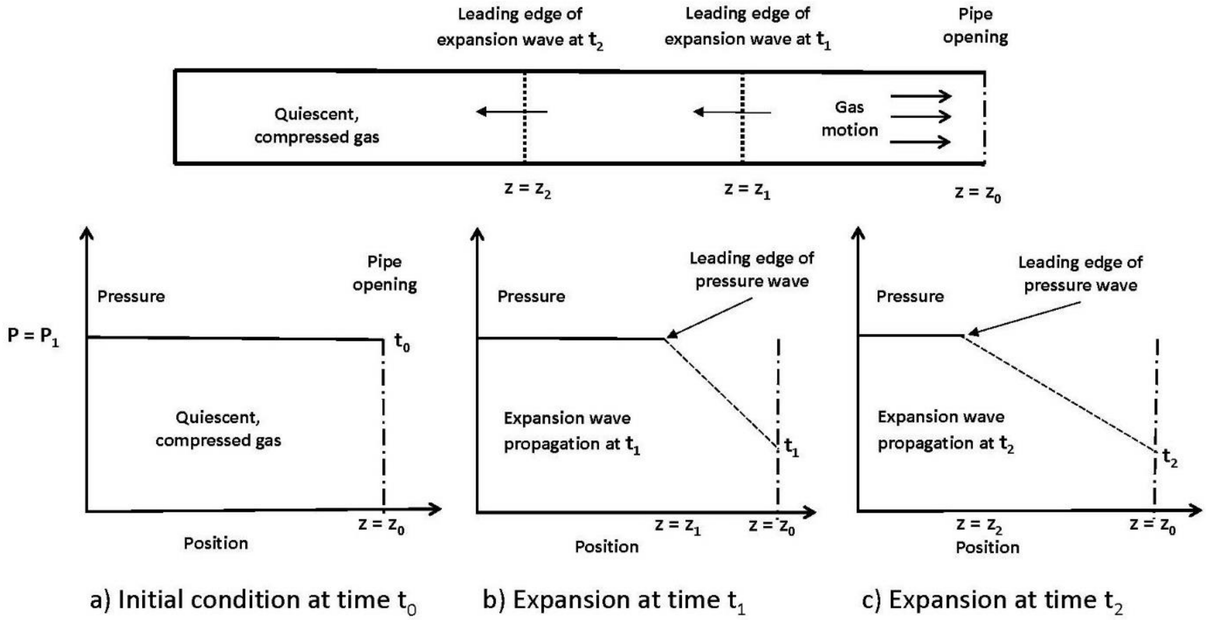

Figure 3 Progression of an expansion wave in a conduit

The expansion waves causes the pressure inside the conduit to fall below the initial pressure. The magnitude of this pressure decline depends on the speed of the piston which in this example is equal to the flame speed. The pressure behind the expansion wave can be calculated from the following equation:

$$\frac{P_2}{P_1} = \left[1 - \frac{1}{2}(\gamma - 1)\frac{\Delta v}{a_1}\right]^{\frac{2\gamma}{\gamma-1}}$$

where P_2 is the absolute pressure in the expanded region, P_1 is the absolute pressure in the undisturbed region, γ is the specific heat ratio, Δv is the flame speed, and a_1 is the speed of sound in the undisturbed region. If the piston speed is sufficiently fast, the pressure inside the conduit can drop to a level below atmospheric pressure. The influence of flame speed on the final expansion pressure is demonstrated in

Table 1 using two fluids for comparison: air and combustion products.

Table 1 Expansion pressure ratio for different flame speeds

Flame speed, m/s	Pressure ratio, air[8]	Pressure ratio, combustion products[9]
10	0.960	0.968
30	0.885	0.905
100	0.660	0.716
300	0.265	0.356

Once the expansion wave hits a solid boundary, it is reflected and travels back towards the opening. In a matter of seconds, this wave reflection process eventually brings the conduit to a quiescent condition at atmospheric pressure. However, even though it is transient, the partial vacuum condition in the conduit can cause the cylindrical geometry to become unstable leading to its collapse. The mechanics of the collapse is the subject of the next section.

3 Mechanics of Collapsed Ducts

When the pressure inside of a duct (P_i) differs from the pressure outside of the duct (P_o), stress is imposed on the duct wall (see Figure 4). If the difference in pressures becomes too large for the wall to withstand, the duct itself may fail. However, the failure mode differs if due to an internal overpressure (i.e., $P_i > P_o$) than if due to an external overpressure or an internal vacuum (i.e., $P_i < P_o$). As a result, the critical pressure difference that may result in failure can vary significantly. The difference can be explained by examining the nature of the failure mode for each limit: excess internal pressure causes the duct to rupture,[10] whereas excess external pressure causes the duct to collapse (or buckle).[11]

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8 The properties of air are assumed to be T = 300 K, P_1 = 2 bar, γ = 1.4, and M = 29 kg/kmol, a_1 = 347 m/s.

9 The properties of the combustion products are assumed to be T = 400 K, P1 = 5 bar, γ = 1.2, M = 30 kg/kmol, a_1 = 364 m/s.

10 Methods for the Calculation of Physical Effects due to Releases of Hazardous Substances. TNO Yellow Book.

11 de Paor, et al. Prediction of vacuum-induced buckling pressures of thin-walled cylinders. *Thin-Walled Structures.* 55 (2012) 1-10.

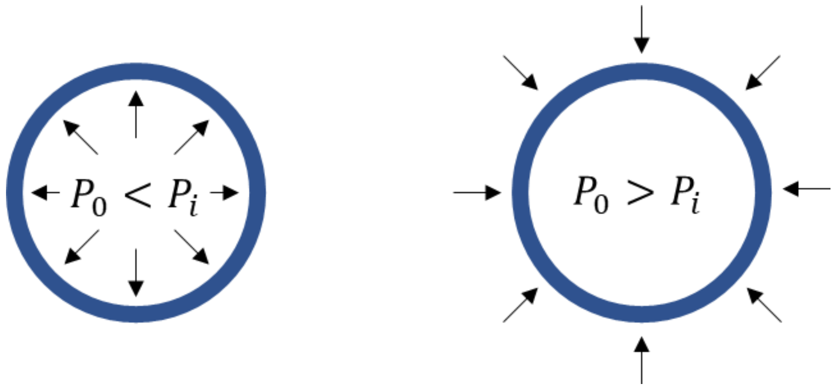

Figure 4. Conceptual diagrams for a thin walled cylinder subjected to (left) an internal overpressure and (right) and external overpressure.

Consider the following related analogy: a typical aluminum beverage can will withstand large internal pressure imposed by carbonated beverages (e.g., up to 6 bar or 90 psi).[12] The elevated internal pressure keeps most of the carbon dioxide in solution, ensuring a fizzy (not flat) beverage. However, once the can is opened, the internal pressure will relieve through the opening, and the shell is now considerably more fragile to external forces than it was to internal forces. The most basic explanation is as follows: for the container to deform any significant amount due to internal overpressure would require the metal either stretch or fracture. However, a collapse merely requires bending. The thin aluminum forming a beverage can has high tensile strength but has very little resistance to bending. Thus, it is easy to crush the can but hard to rupture it from internal overpressure. Related phenomena explain why ducts designed to convey combustible dust may not rupture during an explosion event, despite significant overpressure, but rather may collapse due to the subsequent compression waves that create a relatively mild internal vacuum. In the following sections, we discuss these phenomena in greater detail.

3.1 Theory of Shells

To understand the difference between rupture and collapse, it is worth briefly discussing the theory of shells, a key tool utilized to describe how relevant structures respond to external forces. A thorough treatment of the theory of shells is given in the book by Ventsel and Krauthammer, titled *Thin Plates and Shells*.[13] In this context, a shell is defined as a body bounded by two curved surfaces, where the distance between the surfaces is small in comparison with other body dimensions. By surfaces, this definition refers to the inner and outer surfaces of the wall, e.g., the inside and outside of a spherical or cylindrical vessel. Thus, for the theory of shells to be applicable, the vessel should have curved walls that are thin relative to the other dimensions of the vessel. A shell can be approximated by integrating the stress distribution throughout the shell

12 Ward-Bailey, J. "The surprising science behind the aluminum soda can." The Christian Science Monitor. April 14, 2015. url:https://www.csmonitor.com/Science/Science-Notebook/2015/0414/The-surprising-science-behind-the-aluminum-soda-can

13 Ventsel, E. and Krauthammer, T. *Thin Plates and Shells*. 2001.

into a “middle” surface that reduces the governing equations to two dimensions (axial and circumferential, in the case of a cylinder).

The primary distinction between a shell and a plate is the inherent curvature that influences the shell’s behavior under loading. As a result, bending cannot be separated from stretching, and so compressive and tensile displacements are coupled. Shells are categorized by their type of curvature and their thickness. Here, we focus on circular cylinders with thin walls, where the maximum ratio of the wall thickness to the radius of curvature is much smaller than unity. Most circular ducts used to transport combustible dust meet this description.[14]

3.2 Rupture vs Collapse

A thin, elastic shell supporting an external load by means of internal forces (stress resultants) may be appropriately loaded and supported such that the bending and twisting moments are negligible.[15] This state of stress is referred to as the membrane (or momentless) state of stress, and it permits a further reduction of the governing equations into what is referred to as the membrane theory of shells. This theory is applicable when bending cannot occur inextensionally, i.e., these surfaces cannot be deformed without stretching or shrinking the middle surface. One family of such surfaces are convex, closed surfaces, such as a cylindrical duct supported by circular rings. For example, a cylinder cannot be bent while maintaining a circular cross-section without the “middle surface” stretching in some areas and shrinking in others. Consider the extremum where a cylinder is bent until its flat (circular) ends meet, forming a torus (or doughnut-shaped shell). A torus has a different outer circumference than inner circumference. Thus, to deform the straight cylinder into the round torus, portions of the cylinder must be stretched while other portions must be compressed. On the contrary, a flat sheet can be bent into a cylinder without elongating the middle surface, and thus membrane theory is not appropriate.

3.2.1 Critical Pressure for Rupture

If the internal pressure of a duct increases, the tendency of the material is to deform to increase the internal volume accordingly. However, if the duct wall is in the membrane state of stress, the resistance to this stretching is provided by the strength of the material involved. Because a cylindrical duct is a confex, closed surface, it cannot increase its volume any further without stretching; thus, additional pressure results in additional stress in the duct wall. The wall can accommodate this stress up to a point without deforming permanently. However, if the internal pressure continues to rise, the wall will ultimately yield and/or fracture, rupturing the duct.[16]

Figure 5 shows a simplified force balance around a long, thin-walled duct of radius *r* and thickness *t*, assuming the circumferential stress is uniform throughout the thin wall. This force

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[14] Note, because square and rectangular ducts lack inherent curvature, their mechanics are not properly described by this theory.

[15] Ventsel, E. and Krauthammer, T. *Thin Plates and Shells*. 2001. Chapter 13

[16] Premature failures may also be induced by factors such as corrosion, erosion, overheating, fatigue, or material defects, or external impact. However, these are outside of the scope of the current discussion. More information can be found in sources such as Lee’s Loss Prevention in the Process Industries, section 17.27, or Methods for the Calculation of Physical Effects due to Releases of Hazardous Substances. TNO Yellow Book. p. 7.16.

balance reveals two principal stresses: a hoop stress along the circumference of the duct, given by:[17]

$$\sigma_h = \frac{\Delta P * r}{t}$$

and a longitudinal stress along the axis of the duct, given by:

$$\sigma_l = \frac{\Delta P * r}{2t}$$

These stresses are explicitly dependent on the pressure difference between the inside and outside of the duct, $\Delta P = P_i - P_o$, as well as the radius of the duct, r, and the thickness of the duct, t. Note, the hoop stress is exactly twice the longitudinal stress, and thus represents the largest principal stress.

Figure 5. Simplified force balance around a cylindrical shell where a constant stress across the wall is assumed.

The simplest approximation for the critical pressure at which the cylinder will burst is given by the maximum-stress theory of failure, which assumes that failure occurs when the largest principal stress reaches the yield stress.[18] That criteria is given by:

$$\Delta P_{cr,rupture} = \sigma_{cr}\left(\frac{t}{r}\right)$$

where σ_{cr} is the critical stress at the point of rupture. More accurate estimates for the critical pressure can be calculated but are beyond the scope of this discussion. For an existing vessel with specified maximum allowable working pressure (MAWP), it is common to estimate the critical pressure for rupture to be four or five times the maximum allowable working pressure.[19]

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[17] Avallone, E.A. and Theodore, T.B. *Marks' Standard Handbook for Mechanical Engineers*. 10th Edition. 1996. p. 5-45.

[18] Avallone, E.A. and Theodore, T.B. *Marks' Standard Handbook for Mechanical Engineers*. 10th Edition. 1996. pp. 5-48 and 5-49.

[19] Crowl, D.A. and Louvar, J. F. *Chemical Process Safety*. 2nd Ed. 2002. p. 356.

3.2.2 Critical Pressure for Collapse

A duct subjected to an external overpressure (or internal vacuum) is subject to a different scenario than the membrane stress state, and its failure is more challenging to predict.[20] In practice, many vessels and ducts are designed without any intension for use under internal vacuum or external overpressure. These shells can be economically designed with thin walls made of materials with high tensile strength, ideally suited for service in a membrane stress state. However, these shells are not as robust to the compressive stresses and may collapse (or buckle) at much lower magnitude vacuum pressure than might be anticipated based upon their design overpressure.

The first systematic experimental effort to understand the phenomenon of duct collapse was performed in 1858 by Fairbairn.[21] At that time, the nascent steam boiler industry was increasing working pressures from 10 psi to 50 psi, and in some cases approaching 150 psi, but the "principles of construction [had] not kept pace." The primary focus of the study was the growing use of internal flues and tubes subjected to external pressures within the boiler. The practical conclusion of the report was that the external shell of a boiler of "ordinary construction" was capable of supporting internal pressures three to four times greater than the internal flues could withstand without collapse. This study helped explain an increase in the number of boiler explosions that initiated due to the collapse of an internal flue.

While several modeling efforts attempted to explain the 1858 results, the next significant development in the understanding of the observed phenomena occurred in 1906, when a pair of systematic experimental studies were published by Stewart and by Carmen and Carr.[22,23] A primary learning from these studies was that, for tubes longer than a critical length, an empirical relationship could be formulated between critical pressure and the ratio of pipe thickness to pipe radius cubed.[24] A more generalized form of the empirical relationship was presented in a 1941 article by Sturm, which continues to be provided in modern references:[25,26]

$$\Delta P_{cr,collapse} = KE\left(\frac{t}{d}\right)^3$$

Where d is the diameter the shell, t is the thickness, and K is a numerical coefficient whose form varies depending upon the type of loading, the type of supports, the length, radius, and outer-

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20 Ventsel, E. and Krauthammer, T. *Thin Plates and Shells*. 2001. Chapter 19.

21 Fairbairn, W. On the Resistance of Tubes to Collapse. *Philosophical Transactions of the Royal Society of London*. Vol. 148. 1858. pp. 389-413.

22 Stewart, R.T. Collapsing Pressure of Bessemer Steel Lap-Welded Tubes, Three to Ten Inches in Diameter. *Transactions of the American Society of Mechanical Engineers*. Vol. 27. 1906. pp. 730-822.

23 Carmen, A.P. and Carr, M.L. Resistance of Tubes to Collapse. *University of Illinois Engineering Experiment Station.* Bulletin No. 5. June 1906.

24 Windenburg, D.F. and Trilling, C. Collapse by Instability of Thin Cylindrical Shells Under External Pressure. *Transactions of the American Society of Mechanical Engineers*. Vol. 56, No. 11. 1934.

25 Sturm, R.G. A Study of the Collapsing Pressure of Thin-Walled Cylinders. *University of Illinois Engineering Experiment Station*. Bulletin No. 329. Vol. 29, No. 12. 1941.

26 Avallone, E.A. and Theodore, T.B. *Marks' Standard Handbook for Mechanical Engineers*. 10th Edition. 1996. pp. 5-45 and 5-46.

shell diameter of the duct. The modulus of elasticity, E, may also be substituted for modified forms to capture non-linear or plastic action. For very long cylinders, the problem can be reduced to a stability analysis of a ring of unit length with the same radius and thickness as the cylinder. In this case, minimum value of critical pressure for collapse is given by:[27,28]

$$\Delta P_{cr,collapse} = \frac{E}{4(1-\nu^2)}\left(\frac{t^3}{r^3}\right)$$

where the additional parameter υ is Poisson's ratio for the material. This would represent a lower bound for the critical pressure for collapse of cylindrical shells, since shorter cylinders should be more stable. The critical length above which a cylinder can be considered "very long" varies by source, but one such example, attributed to Southwell, is:[29]

$$L_c = \left(\frac{16\sqrt{3}\pi}{27}\sqrt[4]{1-\nu^2}\right) r\sqrt{\frac{r}{t}}$$

For typical values of ν for steel and aluminum (0.25 and 0.33 respectively),[30,31] the coefficient is between 3.13 and 3.17. Thus, for a duct about 1 ft in diameter (300 mm) with a 0.02 inch (0.5 mm) wall thickness, the critical length is about 26 feet (8 m) for both steel and aluminum. Using the same parameters, and typical values of the modulus of elasticity for steel and aluminum (200 GPa and 69 GPa respectively), the above equation predicts a critical pressure for collapse of about 0.3 psig for steel and 0.1 psig for aluminum.[32,33] Note, these value assumes geometrically perfect cylinders, and imperfections present in real cylinders reduce the buckling capacity under uniform external pressure.[34] To account for the effects of real geometry, an empirical formula was developed for steel tubes by averaging the collapse pressure of "a great many commercial steel tubes taken at random from stock."[35,36] The result was an equation that reduced the predicted critical pressure by about 25% from the analytical result above.

Although, estimates are further complicated by the fact that these results represent collapse values for long, unstiffened cylinders, and in practice, ducts often have stiffeners, joints, or other

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27 Windenburg, D.F. and Trilling, C. Collapse by Instability of Thin Cylindrical Shells Under External Pressure. *Transactions of the American Society of Mechanical Engineers*. Vol 56, No. 11. 1934.

28 Ventsel, E. and Krauthammer, T. *Thin Plates and Shells*. 2001. Equations 19.51-52.

29 Southwell, R.V. On the Collapse of Tubes by External Pressure. *Phil. Mag.*, I, May, 1913, pp. 687-698; II, Sept., 1913, pp. 502-511; III, Jan., 1915, pp. 67-77.

30 MatWeb Material Property Data for Steels, General Properties. Accessible at matweb.com.

31 Properties of Wrought Aluminum and Aluminum Alloys. ASM Handbook, Volume 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. 1990.

32 MatWeb Material Property Data for Steels, General Properties. Accessible at matweb.com.

33 Properties of Wrought Aluminum and Aluminum Alloys. ASM Handbook, Volume 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. 1990.

34 de Paor, et al. Prediction of vacuum-induced buckling pressures of thin-walled cylinders. *Thin-Walled Structures.* 55 (2012) 1-10.

35 Windenburg, D.F. and Trilling, C. Collapse by Instability of Thin Cylindrical Shells Under External Pressure. *Transactions of the American Society of Mechanical Engineers*. Vol 56, No. 11. 1934.

36 Carmen, A.P. and Carr, M.L. Resistance of Tubes to Collapse. *University of Illinois Engineering Experiment Station*. Bulletin No. 5. June 1906.

structural components that result in collapse pressures that are often significantly higher than the long cylinder limit. Cylindrical shells of subcritical length have been studied using structural stability theory, but the predicted critical pressure for collapse is strongly dependent upon geometry and boundary conditions.[37] As a result, the onset of failure of a specific duct is difficult to accurately predict without detailed measurements of the real duct geometry and the use of numerical methods. Nonetheless, a variety of equations have been developed from classical theory for use in different circumstances which perform relatively well against experimental results.[38,39]

3.3 Comparison of Rupture and Collapse Pressures

Fairbairn's 1858 study compared the expected rupture pressure of the external walls of a boiler to the collapse pressure of the internal flues, noting the ratio was between three and four. However, Fairbairn did not experimentally determine the rupture and collapse pressures of similarly constructed cylindrical shells, and no subsequent studies appear to have explored this comparison. To that end, rupture and collapse pressures for commercially available steel spiral pipe two different manufacturers was obtained and examined.[40] Data was available across a range of diameters and gauges (a measure of wall thickness). In total, burst and collapse pressures were available for 61 different products (combinations of diameter and gauge) from Manufacturer 1, and 47 different products from Manufacturer 2.

Figure 6 shows the ratio of rupture pressure to collapse pressure plotted against the ratio of the radius of the duct to the wall thickness (r/t), as reported by their manufacturers Manufacturer 1 (top) and Manufacturer 2 (bottom), on the same scale for comparison. Note, as the gauge number increases, the thickness decreases. Also, the ratio r/t was much less than unity in this data set, so the x-axis was scaled by a factor of 10^3.

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[37] de Paor, et al. Prediction of vacuum-induced buckling pressures of thin-walled cylinders. *Thin-Walled Structures.* 55 (2012) 1-10.

[38] de Paor, et al. Prediction of vacuum-induced buckling pressures of thin-walled cylinders. *Thin-Walled Structures.* 55 (2012) 1-10.

[39] Windenburg, D.F. and Trilling, C. Collapse by Instability of Thin Cylindrical Shells Under External Pressure. Transactions of the American Society of Mechanical Engineers. Vol 56, No. 11. 1934.

[40] Sheet Metal Connectors, Inc. and Spiral Manufacturing Co., Inc.

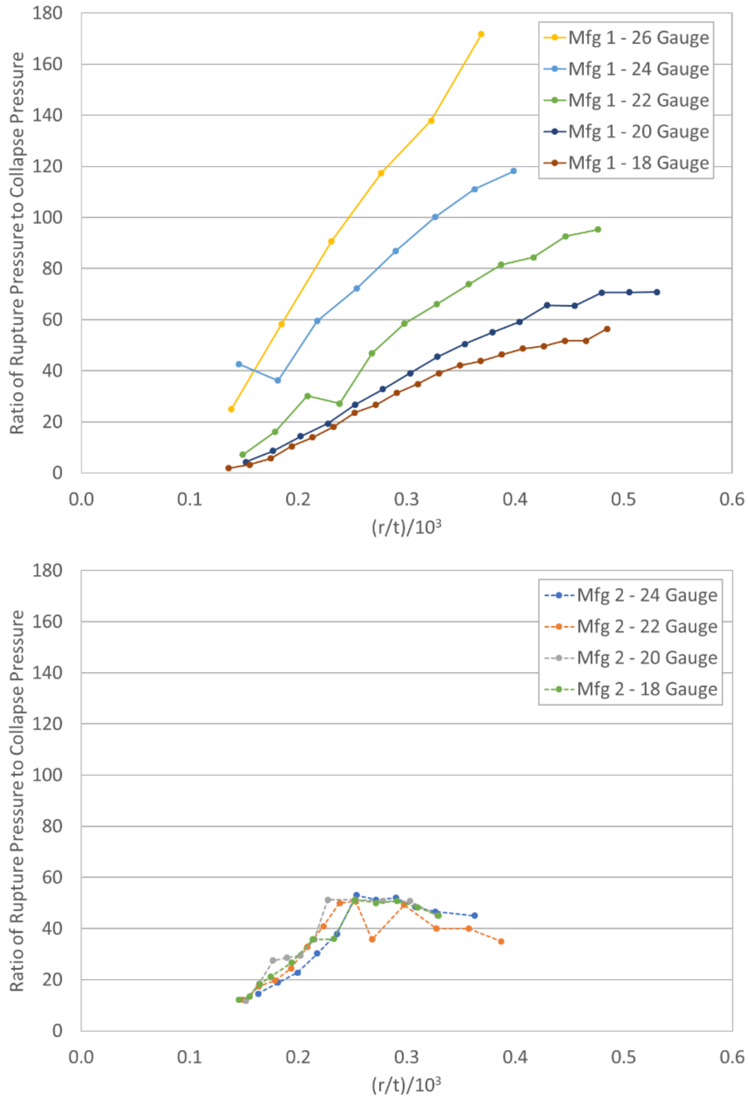

Figure 6. Plot showing the ratio of the burst and collapse pressures versus ratio of the radius and wall thickness (r/t) for spiral ducts of varying manufacturer and gauge.

In both cases, the ratio of rupture pressure to collapse pressure initially increases as the ratio of the radius to the thickness increases. For Manufacturer 1, the trend is approximately linear, but there is a different slope for each gauge (although 18 gauge and 20 gauge were similar in slope). For Manufacturer 2, the curves are much more nonlinear, but the scaled behavior is much more quantitatively similar, regardless of gauge. The ratio of pressures also initially increases, but the increase is less linear and relatively insensitive to gauge (beyond the dependence embedded in the x-axis scaling). Once r/t exceeds around 0.2, ratio becomes relatively constant at values between 35 and 55. Clearly, there is a significant potential for variability in rupture and collapse performance between manufacturers, and between different combinations of diameter and thickness. The ratio of rupture pressure to collapse pressure was close to 1 for the thickest, smallest radius duct from Manufacturer 1 (1.8 for a 14-inch diameter, 18 gauge duct), but it was two orders of magnitude greater for the thinnest, smallest radius duct from the same manufacturer (up to 172 for a 16-inch diameter, 26 gauge duct). On the contrary, it was a relatively tight range of ratios, between 12 and 53 for the entire data set of 47 products offered by Manufacturer 2.

The relationship between the rupture pressure and the collapse pressure for a duct can vary widely, and the collapse pressure is sensitive to a broad set of factors. As is evident, there can be significant variability in performance of ductwork, especially when comparing ducts manufactured by one company versus another. Thus, when critical pressure for collapse is relevant, either from a design or a forensic perspective, it may be prudent to inquire with the manufacturer.

4 Case Studies

The authors of the current study have observed the phenomenon of duct collapse most frequently after combustible dust deflagrations. These observations can result in confusion and misunderstanding, as the common expectation after an explosion is to see signs of internal overpressure. The possibility of developing an internal vacuum is less well-known. Some representative examples are discussed below.

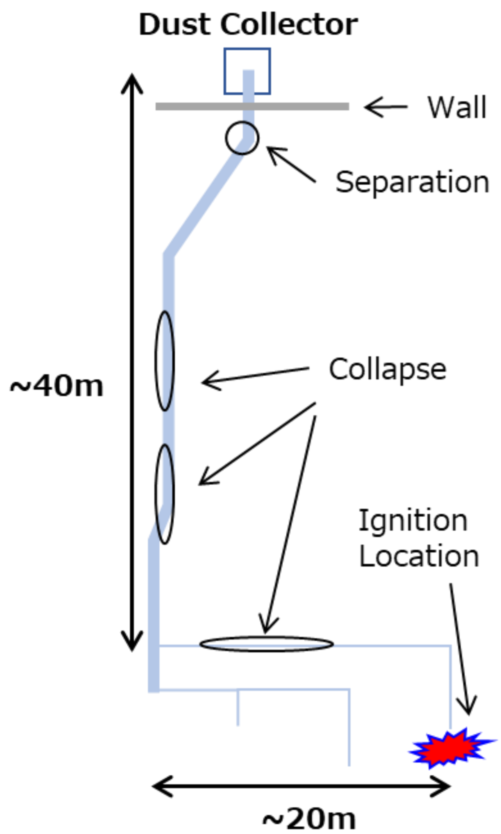

Figure 7. Approximate sketch of the dust collector system pictured in the previous figure. Ignition occurred at one of three process locations served by the dust collection system. The dust collector was protected by explosion panels, which functioned during the event.

The first case study examines an explosion that occurred at a facility that processed polymeric material. A process upset occurred that resulted in a partial shutdown of an extruder. The partial shutdown included shutting down a nitrogen purge line, but the extruder screws remained operational. As a result, material in the extruder was heated to autoignition, and a resulting deflagration spread into the dust collector system. Dust sediment present in the ducts became involved in the deflagration, which ultimately propagated to the dust collector and was vented through explosion panels. The layout of the dust collection system relative to the ignition location and the dust collector is shown in Figure 7. The damage was limited to the extruder equipment and the dust collection system. Three separate portions of duct collapsed (buckled) as a result of the incident, and duct separated at a 45-degree elbow immediately prior to exiting the building. Photos of the collapsed duct are shown in Figure 8.

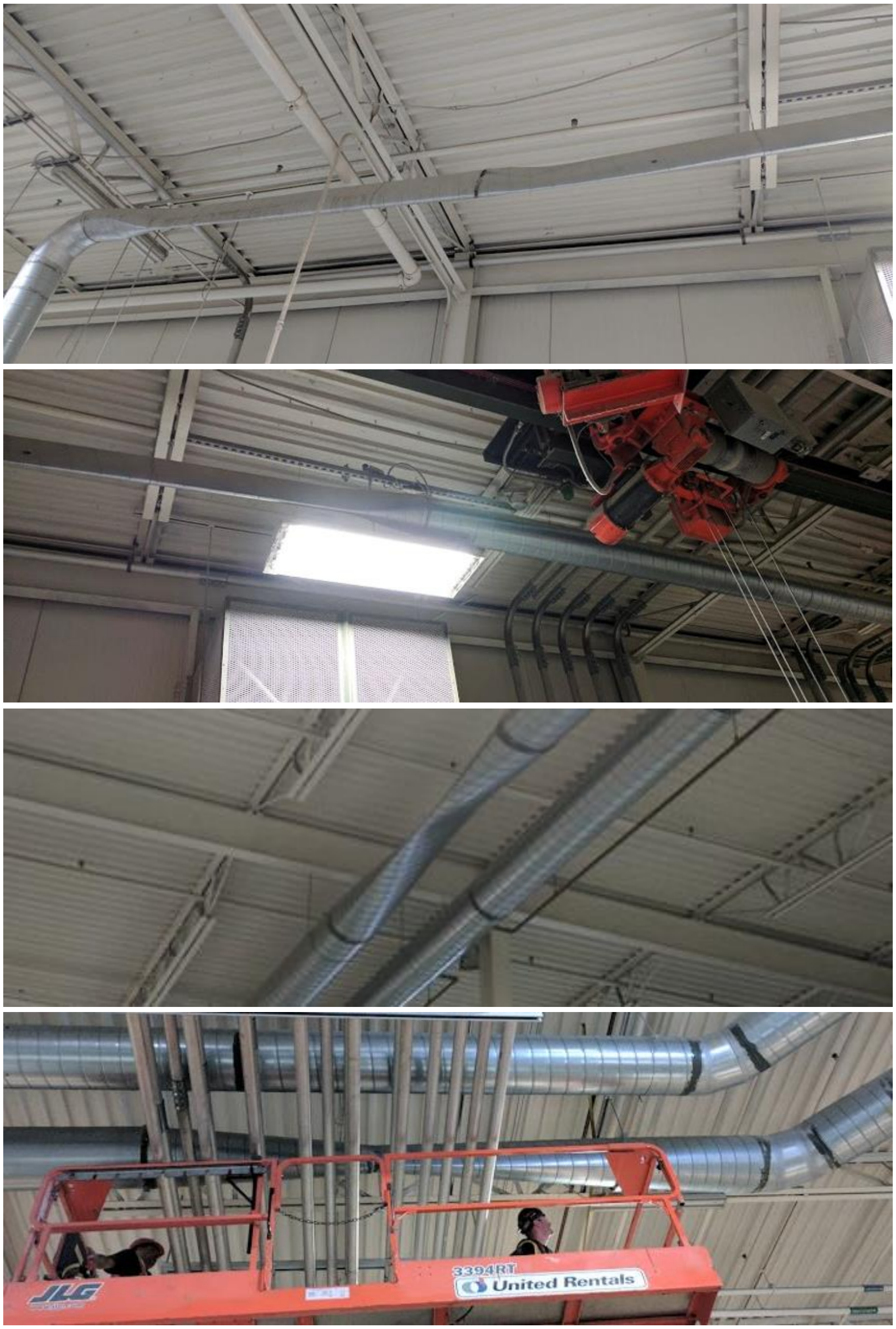

Figure 8. Three different collapse locations after a dust deflagration. The top two images capture the extents of a very long, continuous collapse of a 10-inch spiral duct. The bottom image two images are from different portions of the dust collection system, closer to the dust collector, where the diameter was 18 inches. The duct also separated at a 45-degree elbow immediately prior to exiting the building. The relative location of the collapses

Another case study prominently featuring collapsed duct involved a dust explosion at a grain elevator. Material that had self-heated to the point it began to smolder was being removed when an explosion involving carbon monoxide and smoke occurred. This explosion propagated to an elevator leg and then into the dust collection system, which included ducts that ran along the exterior of the structure to an external dust collector. Portions of this exterior duct collapsed as a result, as shown in Figure 9.

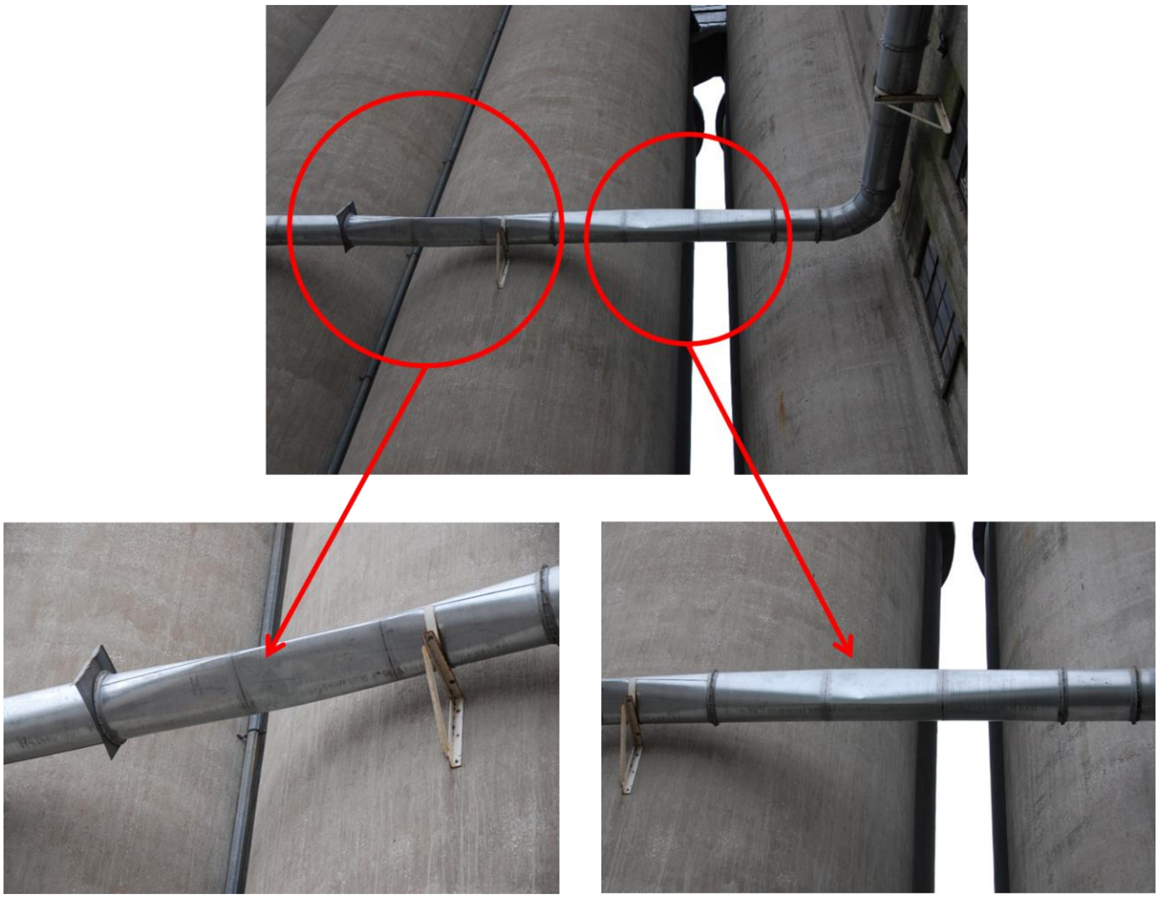

Figure 9. Duct leading to an exterior dust collector from a series of drag conveyors and bucket elevators. Two connected ducts collapsed, but the buckling was mediated by the flange connecting the two ducts.

A third case study involved a dust deflagration that initiated in a process vessel. While there was no indication that the deflagration wave propagated into the dust collection system, a pressure pulse did travel through the ductwork, which was followed by a compression wave. As a result, the large duct shown in Figure 10 collapsed. While the exact dimension is unknown, a relative scale can be deduced from the person seen in the lower left corner.

Figure 10. A duct (featured from two angles) that collapsed.

Finally, a fourth case study involved another grain elevator explosion. In this case, the origin and cause of the explosion was not identified, but the explosion propagated throughout much of the facility, including through the four elevator legs in the center of the concrete structure. As a result, several rectangular ducts associated with an elevator leg collapsed, shown in Figure 11.

A common thread amongst the four case studies was that a positive pressure wave propagated through each of the ducts prior to their collapse. This fact puzzled stakeholders in each case. If an explosion occurred, and a pressure wave propagated inside the duct, why did it collapse and not rupture? A likely explanation is the partial vacuum created when the subsequent expansion wave passed through the same conduit. Evidently, the ducts were capable of handling the overpressure without rupture, but they could not withstand the vacuum, and collapsed.

Figure 11. Collapsed rectangular duct. Note that the shorter section in the top photograph did not collapse, whereas longer sections did.

5 Conclusions

The propagation of a dust deflagration in interconnected process vessels can result in a broad diversity of damage patterns. While damage patterns consistent with positive overpressure are to be expected, the ductwork that connects these vessels will often exhibit signs of collapse. As demonstrated in this paper, the collapsed state can occur due to one of two causes: an externally applied overpressure (external pressure greater than internal pressure) or the formation of a partial vacuum due to the propagation of expansion waves inside the duct. In the authors' experience the expansion wave mechanism is the more common explanation. The utility of these observations is the contribution towards better understanding of the dynamic events associated with a dust deflagration.

6 References

Footnotes will be converted to reference citations.