Combustible Dust
Flame Propagation and
Quenching in Pipes and
Ducts

FINAL REPORT BY:

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FOREWORD

A technical basis is required for determining when pipes or ducts are too small in diameter to permit the propagation of combustible dust deflagrations. This must be evaluated considering the characteristics of the equipment system (pipe/duct diameter and length), properties of the combustible dust, and operating conditions (pressure, temperature, flow rate, etc.). The knowledge will permit establishing rational protection requirements in NFPA’s various combustible dust fire and explosion prevention standards. There is also a lack of knowledge around conditions influencing the explosion propagation through piping, especially small diameter piping. Having a clear understanding of experimental testing data would allow analysis to see what conditions and parameters will affect the explosion propagation and also point out where there are knowledge gaps.

This comprehensive literature review project seeks to identify the parameters affecting flame propagation involving combustible dusts within pipes and ducts, and seeks to determine the conditions under which a combustible dust flame will not propagate (i.e., will quench) within a piping or ductwork system. The following tasks have been carried out for this project:

1) Identify the conditions under which combustible dust deflagration will not propagate within a piping or duct work system.
2) Identify the factors (pipe diameter, pipe length, dust type, and dust concentration) affecting the explosion propagation through pipes from relevant literatures.
3) Identify the gaps from previous studies in the literature and in previous data compilations.
4) Prepare a final report based on the information gathered from tasks 1, 2 and 3.

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About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: combustible dust, flame propagation, quenching, pipes, ducts, deflagration index.

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Executive Summary

Technical research is needed to support industry practice in explosion protection of piping and duct work. This literature review report seeks to identify the parameters affecting flame propagation involving combustible dusts within pipes and ducts, and seeks to determine the conditions under which a combustible dust flame will not propagate (i.e., will quench) within a piping or ductwork system. Dust deflagrations in piping and ductwork smaller than four inches does occur and can be confirmed through a number of studies, proving experimentally, that deflagration in small diameter piping and ductwork is possible. It should also be noted that even though flame propagation through small diameter piping and ductwork is possible in many cases, the likelihood of a propagation goes down as the diameter decreases.

For systems that contain dusts in piping and ductwork there are two general categories that emerge when studying how dust deflagrations interact with explosion protection of these systems. The first category are the parameters of the dust in the system. Properties such as $K_{st}$, MEC, MIE, and diameter of the dust particles all affect how the dust will behave in the system and determine deflagration properties such as quenching length and maximum explosion pressure. Beyond the properties of the dust itself, dust concentration in the system is clearly important with regard to propagation. The second category are the parameters of the piping and ductwork, mainly conveying velocity and materials of construction. It was found that through review of the NFPA dust documents, deflagration protection and prevention documents, and the flammable and combustible material conveying documents that those documents contain prescriptive minimum requirements for safe pneumatic conveying of dusts. The other key finding is how the physical phenomena of a dust deflagration makes it hard to prevent deflagration propagation or re-ignition without some form of isolation. This is because of the heterogonous burning of the dust, when turned into a product of combustion there is still a hot solid particle that can convey in the air and further travel down piping. The current knowledge gaps and possible future research needs are also presented in the report.
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Introduction

Dust has always been a unique hazard in the fire protection world. When lofted into the air and ignited, dusts can burn vigorously, producing heat and, when confined, pressure that can harm people and damage property and equipment. Unfortunately, incidents involving fires and explosions are not uncommon, and there have been 281 incidents between 1980 and 2005 that have killed 119 workers and injured 718, according to the Chemical Safety Board (CSB) (2005)\(^1\), with many more occurring in the 13 subsequent years. Well known incidents such as the dust explosion at the Imperial Sugar Refinery in Port Wentworth, Georgia have caused numerous deaths, 14 in the case of the Imperial Sugar refinery, and millions of dollars in property loss. The hazard dust poses is not limited to one industry and can commonly occur in industries such as food processing, pharmaceutical, metal processing, wood processing, and many other industries.

In response to this ever-present need for dust deflagration and explosion prevention and mitigation codes and standards organizations (e.g., National Fire Protection Association (NFPA)) and regulatory agencies (e.g., Occupational Safety and Health Administration (OSHA)), have developed a number of standards and guidelines to help manage the risk of dust deflagrations or explosions. The NFPA dust standards (e.g., NFPA 654: Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids, and NFPA 652: Standard on the Fundamentals of Combustible Dust) seek to control the hazards of combustible dusts through the prescription of both active and passive methods of dust fire and explosion protection. These standards often contain prevention knowledge based on both industry best practice and technical data gathered from research. Standards are intended to define the minimum level of safety and should be based on proven science and research.

One instance where technical research is needed to support an industry practice is explosion protection of piping and duct work, specifically in small diameter piping and duct work. NFPA 654

previously contained language specifying that explosion protection was not required for small
diameter piping and met other requirements such as not conveying a metal dust or hybrid
mixture (see NFPA 654 7.1.6.2 2013). However the technical committee for NFPA 654 removed
this exception after determining that there was not enough technical data to substantiate
waiving a requirement for explosion protection on small diameter piping in addition to the other
factors in the requirement.

Objective

This comprehensive literature review project seeks to identify the parameters affecting flame
propagation involving combustible dusts within pipes and ducts, and seeks to determine the
conditions under which a combustible dust flame will not propagate (i.e., will quench) within a
piping or ductwork system. The following tasks have been carried out for this project:

1) Literature Review I: Identify the conditions under which combustible dust deflagration will
not propagate within a piping or duct work system.
2) Literature Review II: Identify the factors (pipe diameter, pipe length, dust type, and dust
concentration) affecting the explosion propagation through pipes from relevant literatures.
3) Identify Gaps: Identify the gaps from previous studies in the literature and in previous data
compilations.
4) Final Report: Publish a final report based on the information gathered from tasks 1, 2 and 3.

Background

Fire requires three elements known to start and continue, which are fuel, oxidizer, and heat.
These three elements are often depicted as the fire triangle any fire will always have these three
elements and, if any one side of the triangle is removed, then the fire will die out. Dust explosions
require two additional elements, dispersion, and confinement, to create the dust explosion
pentagon. Dispersion is required to create a combustible dust cloud, and confinement is required
to allow pressure to accumulate to a potentially damaging level. In terms of this project, piping
and ductwork will establish containment for dust clouds, and depending on the type of piping or duct work (e.g., pneumatic conveying), dust will also be dispersed into the air. Thus for this project it is more than reasonable to assume that there is a chance for both fire and explosion, compared to normal scenarios of general dust accumulation and dispersion.

Dust has both the ability to deflagrate and detonate. According to NFPA 68: Standard on Explosion Protection by Deflagration Venting, 2018 Edition, Deflagration is the “Propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium” while detonation is the “Propagation of a combustion zone at a velocity greater than the speed of sound in the unreacted medium”. Typically, flame propagation happens by the transfer of heat from the reaction zone to the reactants. Flame speed is the speed of the flame front relative to a fixed reference point. At a minimum, the flame speed is equal to the fundamental burning velocity times an expansion factor related to the density ratio of the unburned gas to the burned gas. Burning velocity is the rate of flame propagation relative to the velocity of the unburned gas ahead of it and fundamental burning velocity is the burning velocity of a laminar flame under stated conditions of composition, temperature, and pressure of the unburned gas. These two methods of measurement also allow a standard method of comparison between different tests and experiments.

**NFPA Codes and Standards**

The NFPA has been developing combustible dust codes and standards since the 1920s and through the ANSI standards process, has brought together multiple technical committees of various interest categories to responsibly develop safety codes and standards based off of best industry practices, research, and subject matter expertise. These codes have become generally accepted within industry. In order to provide the best deliverable the following definitions have been extracted from NFPA codes. [© copyright NFPA]. The extract tags below provide the NFPA document number first, section number second, and the edition year last.
**Minimum Explosible Concentration (MEC):** The minimum concentration of a combustible dust cloud that is capable of propagating a deflagration through a uniform mixture of the dust and air under the specified conditions of test. [NFPA 68 3.3.22 2018]

**Minimum Ignition Energy (MIE):** The minimum amount of energy release at a point in a combustible mixture that causes flame propagation away from the point, under specified test conditions. [NFPA 68 3.3.23 2018]

**Hydraulic Diameter:** A diameter for noncircular cross sections that is determined by $4 \left( \frac{A}{p} \right)$, where $A$ is the cross-sectional area normal to the longitudinal axis of the space and $p$ is the perimeter of the cross section. [NFPA 68 3.3.19 2018] In this paper when pipe is referred to it means a circular pipe with a set diameter, while ductwork refers to square or non-circular piping. When diameter is used in relation to ductwork for this paper it is the hydraulic diameter.

**Isolation:** A means of preventing certain stream properties from being conveyed past a predefined point [NFPA 69 3.2.24 2014]. When isolation is referred to in this paper it covers generally all forms of isolation as there are various properties that need to be stopped from being transmitted down the full length of piping or ductwork and into another area or vessel. NFPA 69: Standard on Explosion Prevention Systems lists four types of isolation, chemical, deflagration, flow, and ignition source isolation. Deflagration and ignition source isolation are highlighted below as they are the two types of isolation that are important to keep in mind for the results section.

- **Deflagration Isolation:** A method employing equipment and procedures that interrupts the propagation of a deflagration flame front past a predetermined point. [NFPA 68 3.3.24.2 2018]
Ignition Source Isolation: A method employing equipment and procedures that interrupts the propagation of an igniting medium past a predetermined point [NFPA 68 3.3.24.4 2018]

The goal of quenching a deflagration is to prevent that flame from igniting further reactants and further causing any damage to interconnected equipment. If a flame continues to propagate down the pipe and fails to quench, deflagration isolation will be necessary. If a flame is quenched by the small diameter of the piping, then the products of combustion or the preheated dust particles that remain, could ignite other dust particles further along in the pipe or in a vessel downstream. This is possible because the burning characteristics of dust deflagrations (e.g. heterogeneous burning) can change with the properties of the dust cloud in the piping. For example, if the flame is quenched and the remaining products continue to travel to a wider section of pipe where the dust concentration or geometry is different, the flame might reignite. Thus, ignition source isolation would be necessary to prevent this potential occurrence.

**Duct:** Pipes, tubes, or other enclosures used for the purpose of pneumatically conveying materials. [NFPA 91 3.3.4 2015] While NFPA 91: Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Particulate Solids, 2015 Edition has the above definition, for this paper ducts and pipes will be separated out for clarity. This is because, while similar in purpose and construction (i.e. physically confined spaces), the geometries are different and a majority of the research found in the literature review specifically focused on piping.

The literature gathered through this review were sorted into three broad categories in order to better organize and disseminate the information gathered. The three categories are as follows:

1. Dust Parameter Information,
2. Dusts in Piping and Ductwork, and
3. Dust Flame Quenching.

Literature in the Dust Parameter Information category discusses the parameters that propagate a dust fire or explosion, as well as how the fire or explosion is affected. Methods of dust ignition
in general and in piping and ductwork scenarios are included in this category. The Dust in Piping and Ductwork category contains all the literature with either experimental or modeling data that looks into the deflagration or detonation of dusts in piping or duct work. The literature in this category has technical data examining some aspect of how dusts interact with piping and ductwork. The third category, Dust Flame Quenching, groups together the literature that discusses how dust flames can be quenched, in both piping and duct work. Annex. 3 provides a summary table of all the reviewed sources, while Annex. 2 provides an annotated extract of certain key sources reviewed in this study.

Dust Parameter Information

As mentioned in the background, dust flame propagation requires each of the three sides of the fire triangle; fuel, oxygen, and heat. Dust parameters affect how these three elements come together to propagate flame. Propagating a flame in a gas is easier than propagating a flame in a dust mixture since it requires one more leg of the dust pentagon (dispersion) and it is also highly dependent on the parameters of each specific dust. It should also be noted that dusts with similar properties. For this paper, the quenching distance will be defined as the minimum pipe diameter or ductwork wall distance required to prevent flame propagation\(^2\)\(^,\)\(^3\). This would be analogous to the term quenching diameter as most of the literature reviewed focuses on piping systems which have a diameter. Quenching length would be the length the flame front travels down the tube before quenching. Dust deflagration quenching involves loosing enough heat to the walls of the pipe or duct so that the combustion front is interrupted and extinguishes

**Deflagration index, K\(_{st}\)**

The dust deflagration index (K\(_{st}\)) is the normalized maximum rate of pressure rise. It measures the relative explosion severity compared to other dusts, with larger values of K\(_{st}\) being


characteristic of dusts with the potential for a more severe explosion. Below (Figure 1) is a chart showing the range of deflagration indices and typical explosion characteristic as well as materials that typically have $K_{st}$ in the appropriate ranges.

<table>
<thead>
<tr>
<th>Dust Explosion Class</th>
<th>$K_{st}$ (bar.m/s)*</th>
<th>Characteristic*</th>
<th>Typical Material**</th>
</tr>
</thead>
<tbody>
<tr>
<td>St 0</td>
<td>0</td>
<td>No explosion</td>
<td>Silica</td>
</tr>
<tr>
<td>St 1</td>
<td>&gt;0 and ≤200</td>
<td>Weak explosion</td>
<td>Powdered milk, charcoal, sulfur, sugar and zinc</td>
</tr>
<tr>
<td>St 2</td>
<td>&gt;200 and ≤300</td>
<td>Strong explosion</td>
<td>Cellulose, wood flour, and poly methyl acrylate</td>
</tr>
<tr>
<td>St 3</td>
<td>&gt;300</td>
<td>Very strong explosion</td>
<td>Anthraquinone, aluminum, and magnesium</td>
</tr>
</tbody>
</table>

* OSHA CPL 03-00-008 – *Combustible Dust National Emphasis Program*

** NFPA 68, *Standard on Explosion Prevention by Deflagration Venting*

It is important to realize that the $K_{st}$ is a relative scale and is not a material property of the dust. Any dust with a $K_{st}$ value that is greater than zero can propagate a deflagration. However, the $K_{st}$ is determined in a standard 20-L test chamber or one cubic meter vessel and is not representative of all geometry scenarios. This means that the $K_{st}$ could be higher or lower in different geometries which could require different types of guidance for the situation (pneumatic conveying, pipes, etc.). Additionally dependent on the type of dust used, it is possible for the dust to further fracture and fragment, which would change the $K_{st}$ of a dust at a minimum, which would again affect prescriptive rule making. In experimental tests, see table below, done by Kris Chatrathi,\(^4\)

he noted that a correlation between $K_{st}$ and flame velocity could not be made as dusts with a higher $K_{st}$ had a lower flame velocity consistently.

Table 2: Pneumatically conveyed dust deflagration flame velocities (152.4 MM Pipe) Reproduced from [4]

<table>
<thead>
<tr>
<th>Dust</th>
<th>$K_{st}$ (bar m/s)</th>
<th>Air Velocity (m/s)</th>
<th>Flame Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornstarch</td>
<td>214</td>
<td>6.86</td>
<td>106</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.43</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.78</td>
<td>73</td>
</tr>
<tr>
<td>Calcium Stearate</td>
<td>302</td>
<td>6.86</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.43</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.78</td>
<td>70</td>
</tr>
</tbody>
</table>

Other literature\textsuperscript{5,6} also concludes that the link between correlations of $K_{st}$ and deflagration or maximum deflagration pressure cannot be accurately made, as their results and analysis revealed that under the same experimental conditions different dusts with the same $K_{st}$ have different explosion intensity. Thus deflagration strength cannot be accurately tied to $K_{st}$ in piping and duct work in instances where there are no vented vessels. While $K_{st}$ cannot be used to conclusively prove deflagration strength in piping or duct work in a rigorous manner for guidance, it can be noted that as the magnitude of $K_{st}$ increases, the ease of flame propagation in the tube will go up.\textsuperscript{7}

\textsuperscript{5} Taveau, J. (2013). Dust explosion propagation: myths and realities. DOI:https://doi.org/10.1016/j.jlp.2017.04.019
Ignition

If ignited, the deflagration or explosion strength is affected by a number of other ignition factors such as ignition location, ignition strength, and type of ignition. Ignition is important for any dust flame propagation, however the strength of the ignition source can determine whether the dust cloud ignites, does not ignite, or over ignites which can change the flame dynamics of the system. The ignition of a dust is dependent on heat transfer in terms of how fast or how slowly energy can reach the suspended dust particles dictating the time to ignition. In a piping or ductwork system there are heat transfers from the flame front to three areas; (1) between the dust particulates, (2) the walls of the system, and (3) the conveying media.

To ignite a single particle it is necessary for heat to transfer into the particle to reach the ignition temperature. According to the works of Marino\(^8\) and Bidabadi et al.\(^9\) there is a clear relationship between ignition temperature and particle diameter as can be seen in the graph below. Larger the particle diameter, the higher ignition temperature required.

<table>
<thead>
<tr>
<th>Particle Diameter (millimeters)</th>
<th>Ignition Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.50</td>
<td>975</td>
</tr>
<tr>
<td>9.92</td>
<td>1183</td>
</tr>
<tr>
<td>19.90</td>
<td>1497</td>
</tr>
<tr>
<td>29.73</td>
<td>1819</td>
</tr>
</tbody>
</table>

Logicaly this correlation makes sense as the larger the particle the more energy is required to heat it to the ignition point. Since this increase in particle diameter will also affect other

\(^8\) Marino, T. A. (2008). Numerical analysis to study the effects of solid fuel particle characteristics on ignition, burning, and radiative emission. Thesis (PhD), The George Washington University

parameters such as the conveying velocity necessary to keep the particle dispersed and the MEC; it is necessary that those parameters be considered when making decisions on particle size. If particle size is increased to prevent ignition by increasing the minimum amount of energy required, the particle might no longer pneumatically convey the same or have the same calculated explosive concentration. Shoshin et al.\textsuperscript{10} also correlated burning time to particle diameter for aluminum dusts where burning time of the particle ($\tau$) was correlated to the following function,

$$\tau \text{ [sec]} = 310 \; D_p,$$

where $D_p$ is the particle diameter in meters.

Burning time will affect how effectively dust flame is quenched in piping and duct work as particles that are still smoldering could later ignite further along in the piping or duct work even after flame has been quenched.

Strength of the ignition source does play a role in determination of dust ignition and propagation. It is entirely possible that a dust when exposed to a weaker ignition source (e.g. electrostatic spark) does not ignite or have strong propagation, while when exposed to a stronger chemical ignitor or larger flame, the dust will ignite and propagate. Tests currently use a variety of ignition sources dependent on the industry, and the choice of ignition source should reflect the appropriate hazard in the system.\textsuperscript{11} Maximum deflagration pressure versus dust turbulence can be seen in the graph below and shows that initial turbulence will increase the maximum deflagration pressure. For example if while pneumatically conveying a dust or collecting a dust the air velocity is high but not high enough to prevent propagation of a flame front, the highly turbulent conditions could favor a stronger deflagration.


Table 4: Influence of initial turbulence on explosion rate of a dust cloud\textsuperscript{10} (Reproduced from Shoshin et. al.)

<table>
<thead>
<tr>
<th>Delay between dust dispersion and ignition (ms)</th>
<th>(dP/dt)$_{\text{max}}$ (bar/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>162.03</td>
<td>316.82</td>
</tr>
<tr>
<td>199.04</td>
<td>429.80</td>
</tr>
<tr>
<td>246.75</td>
<td>313.41</td>
</tr>
<tr>
<td>331.51</td>
<td>325.71</td>
</tr>
<tr>
<td>421.44</td>
<td>155.78</td>
</tr>
<tr>
<td>542.66</td>
<td>70.58</td>
</tr>
<tr>
<td>593.44</td>
<td>48.42</td>
</tr>
<tr>
<td>700.72</td>
<td>32.37</td>
</tr>
<tr>
<td>771.31</td>
<td>29.01</td>
</tr>
<tr>
<td>824.97</td>
<td>28.83</td>
</tr>
<tr>
<td>872.98</td>
<td>25.54</td>
</tr>
<tr>
<td>906.85</td>
<td>19.15</td>
</tr>
<tr>
<td>946.39</td>
<td>19.02</td>
</tr>
</tbody>
</table>

Strength and location of Ignitions
Spark ignitions are also susceptible to variation in required energy to spark different dust clouds, as difference in sparker traits can lead to MIE that are order of magnitudes different from one another.\textsuperscript{12} Thus the ignition source strength and type should reflect the scenario the dust is exposed to as the maximum deflagration pressure could greatly vary, changing the protection or isolation needs required. Turbulence and conveying velocity have a greater influence on weaker ignition sources such as hot surfaces, particles, and electric sparks, as rapid convection will transfer heat away from the ignition locations and increase the ignition energy required of the

dust in the system. Table 5 below from Eckhoff\textsuperscript{12} shows the correlation between MIE and the initial turbulence of the system, showing that the more turbulent the system the higher the MIE for sparking ignitions.

![Influence of Initial Turbulence on MIE of a Dust Cloud](image)

\textit{Table 5: Influence of initial turbulence (turbulence at the moment of ignition) on minimum electric spark ignition energy (MIE) of a dust cloud. Experiments with various dusts in a 20-litre closed explosion bomb\textsuperscript{9} (Reproduced from Shoshin et. al.)}

Ignition location will affect the maximum deflagration pressure as well as the location can change the fluid dynamics of the system by increasing turbulence of the system, which will affect the combustion dynamics in the same way as above. This plays a key role in the combustion dynamics of a vessel system interconnected by pipe or ductwork as, if the ignition is in one of the vessels, it acts as a pre-volume flame ignition, which can propagate flame more intensely and more importantly, can propagate unburnt volumes of dust into the piping or ductwork to continue further deflagration. The deflagration if it reaches the end of the piping or ductwork and continues into the second interconnected vessel can then act as a jet flame, increasing the turbulence in the second vessel volume and then increase the maximum deflagration pressure.

Flame propagation following the initial ignition has four zones; the system walls, preheating zone, flame or reaction zone, and post flame zones. In addition to heated gases, the flame and post-flame zones contain burning and burnt particles and these are sources of heat energy. These two
zones will provide heating to the walls and the preheating zones. The estimation of this heat transfer can be found in Bidabadi et al.\textsuperscript{13} and a diagram of Bidabadi et al.’s system has been reproduced below. Note that this system is describing a one dimensional narrow channel and the effects of pressure are not exactly representative of enclosed piping and ductwork.

![Diagram of Bidabadi et al.'s system](image)

*Figure 1: Schematic of lumped capacitance assumption for layers and one-dimensional heat transfer to walls (reproduced from Bidabadi et al.\textsuperscript{13} (Recreated from Bidabadi et al.)*

The preheating zone is the key to further flame propagation in terms of heat loss or quenching distance. In this zone the heat loss is a function of preheating time duration, wall temperature and channel width, and corresponds to equation 12 (reproduced below) in Bidabadi et al.\textsuperscript{13}

\[
T_{\text{Layer}} = T_{\text{Source}} - T_{\text{Sink}}
\]

By increasing the dust concentration, the amount of energy released through the combustion process is greater as long as the increase approaching the stoichiometric concentration from the lean side. The preheating time is reduced and the flame propagation speed increases. Additionally reducing the preheating time will reduce the heat loss to the surrounding walls, which, because of the higher dust concentration will lead to a smaller quenching distance. Additionally higher dust concentration does have another effect on dust ignition in terms of affecting the MIE which is shown in the experimental data from Bartknecht\textsuperscript{14} reproduced in Eckhoff’s work. The minimum and inflection point on the graph is the worst case dust concentration, which will yield the greatest combustion rate while having the lowest MIE.\textsuperscript{15}

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Table 6: Influence of average dust concentration on the minimum electric spark ignition energy (MIE) of clouds of an anti-oxidant in air, in the standard 1-m³ closed vessel (Reproduced from Shoshin et. al.)

<table>
<thead>
<tr>
<th>Dust Concentration (g/m³)</th>
<th>MIE (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>262.98</td>
<td>3.36</td>
</tr>
<tr>
<td>541.56</td>
<td>0.92</td>
</tr>
<tr>
<td>810.14</td>
<td>3.16</td>
</tr>
<tr>
<td>1105.98</td>
<td>9.95</td>
</tr>
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</table>

Minimum Explosible Concentration (MEC)

The minimum amount of dust dispersed in air that will cause an explosion is called the minimum exposable concentration or MEC. This is a similar concept to the lower flammable limit (LFL) in gases, in which there is a necessary minimum amount of gas that must be mixed with air to undergo a combustion reaction. While at the MEC there is a chance of deflagration the maximum deflagration pressure, as well as the propagation dynamics, are affected by increasing dust concentration as will be explained in the following section.

While both gasses and dusts have a LFL or MEC respectively, dusts do not have an upper flammable limit (UFL) like gasses do. Flammable gasses have a range of vapor to air concentrations at which will ignite and propagate flame between the LFL and upper flammable limit (UFL), with the UFL being the point at which the air vapor mixture becomes too rich to burn. Studies have shown that dusts do not have an upper explosive concentration or a rich limit in which the air and dust concentration will be too high to burn and not propagate flame. At higher concentrations (> 200 g/m³), dust pressure and pressure rise for typical organic dusts level off at constant rate dependent on the dust type. The graphs below, reproduced from K. Cashdollar¹¹, shows the explosion pressure data versus dust concentration for two dusts and methane gas for comparison and the broad peak that the dusts reach at higher concentrations.
One explanation for this trend is the difference in the matter states for dusts and gasses, the particulate dust source must pyrolyze into vapor and mix with air or gaseous oxygen to then ignite and burn. If the fuel source is already in the vapor phase, it can more readily ignite with the oxygen, as they are in a homogenous mixture with the air. This would be what is considered homogeneous burning, where the fuel and oxygen are burning from the same state of matter. An exception to this phenomena are certain metal dusts which result in surface reactions rather than volatizing. Dust, however is a solid particle that must locally vaporize before igniting with oxygen. While the energy required to ignite dust particles is much less than igniting a larger solid mass of the same substance, the physical mechanics of pyrolyzing into vapor are still the same. When a dust ignites it continues to pyrolyze further dust particles, and once there is a sufficient concentration of pyrolyzed volatiles from those dust particles, they are ignited and become part of the flame front. This volatile ignition prevents a further build-up of excess volatiles, preventing a rich limit from forming and choking out the mixture’s ignition potential. With no practical UFL of dusts, conveying a higher concentration of dusts does not prevent flame propagation through
concentration richness or excess alone.\textsuperscript{11} In order to prevent flame propagation in dense phase conveying, the conveyed dust would have to remain in a dense conveying state (e.g., through material chokes) in order to lose enough energy to the adjacent dust particles not to burn. This would provide for an upper limit due to the released energy from the initial burning particles being absorbed by adjacent particles that the temperature of those particles do not reach a pyrolysis condition. Additionally, if the dust is not oxidized and the temperature of the burning dust will drop after it reaches a stoichiometric mixture as the oxygen becomes the limiting factor in the combustion of the dust.

**System Parameters for dust conveying systems**

When designing systems for conveying combustible dusts, NFPA standards have a number of requirements for the designs of these systems that are intended to provide a minimum level of safety. Again pneumatic conveyance is a concern for this project because under certain conditions pneumatic conveyance, it provides the potential for a dust deflagration or explosion, since it provides dispersion and confinement, respectively.

**Conveying Velocity**

Chapter 7 in NFPA 654: Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids, addresses pneumatic conveyance, dust collection, and centralized vacuum cleaning systems and provides design and operational guidelines for these systems. These requirements cover two elements of conveying: startup and shut down procedures and system design velocity. First the system design velocity must be specified such that there is no residual material accumulation in the piping and duct work. Secondly, when starting up or shutting down the system the appropriately designed velocity is achieved before the dust being conveyed is introduced or there is no more dust in the system before the conveying gas is shut off.
Materials of Construction

Chapter 6 in NFPA 91 Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Particulate Solids has requirements for ignition control of when flammable or combustible materials are conveyed at concentrations greater than one percent of the LFL such that the rotating element of the air-moving device is nonferrous, or the air-moving device is constructed so that a shift of the rotating element or shaft does not permit two ferrous parts to rub or strike, in order to prevent sparking.

Chapter 9 Ignition Sources in NFPA 654, contains guidance on control of ignition sources which includes requirements for the materials of construction of process systems. For example for control of static electricity as an ignition source section 9.3.2.1 states that all system components should be conductive. To normally meet this requirement, metal piping is used in order to avoid having to provide extra bonding and grounding. Additionally depending on the conductivity of the dust particle being conveyed it is possible for the dust and piping to create a static charge which could be an ignition source.\(^\text{16}\)

If materials of construction are properly chosen, ignition sources are better controlled which can help to prevent or drive further flame front propagation (see Ignition).

Dust Quenching

The flame propagation is dependent on the geometry of the pipe. The length and diameter of the pipe will determine how the deflagration will carry down the pipe and either quench itself or accelerate or transitioning into a detonation.\(^\text{17}\) Longer pipes with smaller diameters will quench the flame front more readily as enough heat is lost to the walls of the pipe.\(^\text{18}\) Additionally the smaller diameters hinder the development of friction creating turbulence which will help to


further propagate a deflagration and potentially turn it into a detonation given appropriate length. While smaller diameter piping, 1/2” in the case of Cassel et. al., could not propagate flames, it should be noted that if the dust particles are still hot they can be sources of ignition farther along in the pipe or interconnected vessel. While propagation in small diameter piping is entirely possible, the probability that a flame front will propagate down small diameter piping is significantly reduced. Through the literature review conducted, a table of diameters versus flame propagation (see table 7 below) was constructed to show the smallest diameter that flame can propagate down piping or duct work. The table primarily focuses on studies that tested pipe diameters smaller than four inches as it can be readily shown that dust explosions can occur and propagate at diameters greater than four inches. In Table 7 below the yellow highlighted section calls attention to the smallest diameter piping in which flame propagated in the cited tests.

Table 7: Diameter Size versus Flame Propagation.

<table>
<thead>
<tr>
<th>D in (mm)</th>
<th>Flame Propagation?</th>
<th>Dust</th>
<th>Length of Propagation</th>
<th>Concentration</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21 (5.5)</td>
<td>Yes</td>
<td>Cornstarch</td>
<td>1.880 m</td>
<td>800 g/m³ (Rich)</td>
<td>Taveau, J. (2017) (Citing and analyzing J. Jarosinski et. Al. (1986))</td>
</tr>
<tr>
<td>0.40 (10.4)</td>
<td>Yes</td>
<td>Aluminum</td>
<td>1.880 m</td>
<td>850 g/m³ (Rich)</td>
<td>Taveau, J. (2017) (Citing and analyzing J. Jarosinski et. Al. (1986))</td>
</tr>
<tr>
<td>0.5 (13)</td>
<td>No</td>
<td>Al, Dextrin</td>
<td>0.91 m</td>
<td>315 g/m³ (Lean)</td>
<td>Cassel, H. M., Das Gupta, A. K., &amp; Guruswamy, S (1949)</td>
</tr>
</tbody>
</table>

Summary of Key Findings

Dust deflagrations in piping and ductwork smaller than 4 inches does occur and can be confirmed through a number of studies, proving experimentally, that deflagration in small diameter piping and ductwork is possible (see Table 2).

For systems that contain dusts in piping and ductwork there are two general categories that emerge when studying how dust deflagrations interact with explosion protection of these systems. The first category are the parameters of the dust in the system. Properties such as $K_{st}$, MEC, MIE, and diameter of the dust particles all affect how the dust will behave in the system and determine deflagration properties such as quenching length and maximum explosion pressure. Beyond the properties of the dust itself, dust concentration in the system is clearly important with regard to propagation.

The second category are the parameters of the piping and ductwork, mainly conveying velocity and materials of construction. It was found that through review of the NFPA dust documents, deflagration protection and prevention documents, and the flammable and combustible material

<table>
<thead>
<tr>
<th>0.82 (21)</th>
<th>No</th>
<th>Coal</th>
<th>40-60 L/D (0.84-1.32 m)</th>
<th>500 g/m$^3$</th>
<th>Kordylewski, W., &amp; Wach, J. (1986)</th>
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<tbody>
<tr>
<td>1 (25.4)</td>
<td>Yes (Limited)</td>
<td>Not specified</td>
<td>Approximately 7 m</td>
<td>Multiple concentrations</td>
<td>Chatrathi, K., &amp; Going, J. (1996)</td>
</tr>
<tr>
<td>2 (50.8)</td>
<td>Yes</td>
<td>Wheat Flour, Freyming Coal, Rubber, Wood Flour, Polyester</td>
<td>20-40 m</td>
<td>Multiple concentrations</td>
<td>Chatrathi, K., &amp; Going, J. (1996)</td>
</tr>
</tbody>
</table>
conveying documents that those documents contain prescriptive minimum requirements for safe pneumatic conveying of dusts.

The other key finding is how the physical phenomena of a dust deflagration makes it hard to prevent deflagration propagation or re-ignition without some form of isolation. This is because of the heterogenous burning of the dust, when turned into a product of combustion there is still a hot solid particle that can convey in the air and further travel down piping.

**Knowledge Gaps and Next Steps:**

It has been proven through multiple research studies (See Table 2), that dust deflagration can occur in piping smaller than 4 inches all the way down to 5.5 mm depending on the type of dust. If the flame front travels long enough for down the piping it could possibly transition into a detonation, or it could reach a downstream process area and cause a deflagration or explosion in those downstream pieces of equipment. Part of the idea of quenching the flame is to have it lose a substantial amount of heat to the walls over the pipe length to extinguish the flame front. This is a function of both diameter and pipe length. The studies noted in the table, cover the diameter aspect in their testing, but length was not tested. It is suggested that determination of the length of propagation is necessary in order to better understand if there is or what the maximum propagation is, for some of the small diameter piping systems. Additionally, by determining the likely length of flame propagation, the type of protection for such piping can better be determined. It should also be noted that even though flame propagation through small diameter piping and ductwork is possible in many cases, the likelihood of a propagation goes down as the diameter decreases. Although it does not give a definitive outcome for safety requirements, it helps provide design guidelines for engineering.

Part of the dust pentagon is dispersion and as mentioned earlier in the report for piping and ductwork dispersion is assumed for the systems. Dust, unlike a gas or a vapor, can settle out of the atmosphere, and for a piping and ductwork the likelihood of entrained dust is a function of pipe orientation, pressure, and velocity. When combustion occurs pressure increases and as the
flame front propagates the pressure front does too. The propagating pressure wave typically decreases the velocity in the pipe, which could then drop entrained dust out of suspension as the velocity is not high enough. When the dust drops out of suspension the increase of material could dune up and form blockages. Further analysis of this phenomena is needed in order to determine if it can work to prevent or reduce flame propagation. On a similar note study into this area will also help determine what is the dominant driving force for flame extinction, whether it is dropping out of suspension, heating loss, or increase in dust concentration exceeding the limiting oxygen concentration. Additionally it might be possible to determine a theoretically correlated upper flammable limit using Ma’s thermal balance method (See Annex B of NFPA 69 2014), by correlating effective heat of oxidation using data from the heat of combustion and the MEC.

There is some question as well to whether the flame front propagation in piping or ductwork is due to its own self-sustaining propagation or if it is based on the expansion from the ignition in the vessel. Albrecht Vogl’s work in is 1996 paper on flame propagation in pneumatic conveying systems, where he used active conveyance to show that the self-sustaining flame propagation is what drives the propagation.²⁰

One parallel track for further research into flame propagation in small diameter piping is correlating data from maximum experimental safe gap (MESG) testing to flame propagation. MESG is the maximum clearance between two parallel metal surfaces that has been found, under specified test conditions, to prevent an explosion in a test changer from being propagated to a secondary chamber containing the same dust at the same concentration. While this report did not consider this area of work, if correlation between testing done in this area and flame propagation can be made, then that could help better determine this safety in this area.

Another aspect of flame quenching that will make a difference in protection is the aspect of hot or smoldering dispersed dust particles. The small diameter might quench the active flame front propagating down the tube in select instances, but it does not stop hot or smoldering dust

particles dispersed in the air flow from continuing to travel down the piping or ductwork. Further research is needed to determine if the dust particles from the quenched flame front are still hot enough to then either reignite further down the tube or ignite other dust in equipment that is down stream of the pipe.

The literature review conducted mostly discovered sources in which the experiments were conducted in pipes rather than pieces of duct work. Even though flame propagation in ducts can be related to pipe flame propagation using hydraulic diameter, further research is required in order to quantify the effects of different duct geometries in small diameter cases.

While this work focused on dust deflagration in piping and duct work, there are multiple other works covering research into gaseous deflagration in piping. Gaseous deflagration in piping and duct work is a well-studied area of fire and explosion protection in which various aspects such as the effects of gas concentration, geometry, and flow characteristics have been studied and used in recognized and generally accepted good engineering practices. Additionally the area hybrid dust-gas mixtures also have a number research works in that area of study. Dust deflagrations, while having also a large and comprehensive volume of work, are difficult to study and consistently and universally apply. For example while gas deflagrations have constant values such as laminar burning velocity which are universally recognized, dust deflagrations do not have the same type of constant values. The value with the biggest change and variability according to how it is tested is $K_{st}$. $K_{st}$ is highly sample specific (e.g. composition, moisture content, particle size) and also changes when different testing vessels are used. This unfortunately does not allow for accurate correlation between a $K_{st}$ value and a specific property, such as burning velocity for example. This means that if you have aluminum dust, the laminar burning velocity of all aluminum dusts are not the same. Similarly if the dust has a $K_{st}$ of 275 for example it will not have the same laminar burning velocity of a different dust with the same $K_{st}$. Further research into determining property correlation to values that do not vary according to test method is needed. Secondly if that correlation is made, work into correlating the connection between dust and gas deflagrations would also advance knowledge into the effect small diameter piping has on dust
deflagration quenching. This is because producing repeatable test results with dusts is difficult because of the dispersion factor necessary for dusts. For example gas evenly disperses in a volume given time, while dust needs to be lofted, but in the process of lofting it disturbs other factors such as turbulence of the mixture. If a dusts properties (e.g., particle size, material) can be accurately correlated to gas properties (e.g., burning velocity) then testing can be done with gas and then correlated to dusts.
Annex 1: Summary of Test Methodology

The experimental work was carried out in a vertical steel tube with a 0.190 meter inner diameter and a length of 1.880 meters long. Flame quenching diameter was determined by a series of parallel plates varied with spacers. Fuel air concentration mixture was also varied to determine the limit concentration for each spacing configuration. The dusts were distributed through a dispersion system in which the initial air pressure of the system below the plates was lower than the initial pressure of the system above the plates, which would draw the dust through the plates as the system went to equilibrium. The system was ignited with a black powder match.

Cassel, H. M., Das Gupta, A. K., & Guruswamy, S (1949)

The experimental apparatus consisted of a dust dispersion vessel connected to a 3 foot long 1 inch vertical glass tube. Dust was dispersed by blowing gas jets on to a vibrating iron diaphragm which would loft the dust into the air in which the gas stream would carry the dust upward through the vertical tube. The ignition source was an aluminum fuse renewal link. Quenching diameter was measured at the top of the apparatus in which the quenching diameter was correlated to the effective tube diameter based on the flame front and flow at the top.

Kordylewski, W., & Wach, J. (1986)

The experiment was conducted in a standard 22 liter sphere used for Kst testing. A steel tube was connected to the sphere with one end open to the atmosphere and the other open to the sphere. These tubes had internal diameters of 2.1, 2.5, or 3.5 cm and had a length to diameter ratio between 0 and 200. Dust was dispersed through the ring with a chemical match as the ignition source located in the center of the sphere.

Chatrathi, K., & Going, J. (1996)

Test methodology not specified.


The experimental set up consisted of dust from a hoper being fed into a rotary feeder type system with powder being blow into the rotary feeder mouth conveying the dust through steel pipes between 3 or 4 inch diameters to a dust filter unit. The ignition source was either an explosion flame of acetylene-air or a continuous induction spark 11 or 10 meters away from the mouth of the dust feeder.
Annex 2: Selected Annotated Bibliography

   - Article discusses how radiation quenching affects flames at 0.5 inches

   - Discusses the potential role of air velocity on quenching and discusses thoughts on the key parameters of

   - States that the minimum pipe diameter that supports a dust deflagration is 2-4 inches, and additionally presents research into the subject matter

   - Discusses deflagrations of varying dusts in various diameters of piping and vessels. Additionally discusses the effects of pressure as well as deflagration to detonation transition. Discussed a minimum deflagration diameter for piping.

   - Provides notes on guidance for linked vessels and discusses the appropriate parameters

   - Discusses the influence of ducting, on pressure, secondary explosions, and over pressure
   - Discusses computational modeling of various dust parameters in relation to ignition and propagation. Ignition chances go down with diameter. Quenching in terms of length and diameter discussed as well.

   - Discusses channel height and its effect on an explosion in relation to secondary vessels.

   - Discusses flame propagation in piping in relation to the volume ratio. Diameter and pressure parameters also discussed.

    - Discusses diameter effects on conveying velocity and the parameters of quenching compared to conveying velocity.

    - Discusses flame propagation in ducts conveying coal dust, discusses the parameters and ignition strength in relation to the explosion potential.

    - Discusses the stages of dust explosions in piping as well as in depth explanation of how quenching diameter works. Other geometric configurations are also discussed.
   DOI: https://doi.org/10.1016/j.jlp.2017.04.019
   - Discusses other literature that supports the idea that dust can propagate in piping less than 4”.

   - A presentation on the lack of technical substantiation for explosion isolation devices being excluded from piping less than 4”.

   - Discusses compiled literature contesting that there is explosion propagation in piping smaller than 4”. 

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# Annex 3: Summary of Literature Review

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