

A COMMUNICATION FRAMEWORK FOR IMPROVING AWARENESS OF
COMBUSTIBLE DUST HAZARDS

by

Morgan Mackenzie

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Abstract

The hazards associated with combustible dusts are not universally well known, particularly when compared to a somewhat similar hazard, flammable gas. The primary resources currently used in communication about dust explosions are journal publications and conference proceedings. The knowledge presented in these sources would need to be translated and presented in a range of formats for it to become relevant and available to all those who could benefit from the knowledge. Different groups require different approaches in terms of the complexity and depth of the information, its format, and the method of delivery, among other factors. A literature review was conducted on topics such as communication, knowledge management, and diffusion of innovations. This allowed for a better understanding of how to best communicate information to diverse groups to their benefits. A communication strategy framework was developed for the purpose of improving safety awareness of combustible dust hazards among a diverse audience. Eight diverse target groups were identified as needing access to dust explosion information. The needs of each of these groups were evaluated, and recommendations were made in terms of resource development, resource dissemination and in support of an open organizational culture. This knowledge was implemented in the development of a specific combustible dust hazard resource. A teaching module geared specifically towards undergraduate engineering students was developed.

List of Abbreviations and Symbols Used

| | |
|-------|---|
| CCOHS | Canadian Centre for Occupational Health & Safety |
| CSB | US Chemical Safety and Hazard Investigation Board |
| OHS | Occupational Health & Safety |
| OSHA | Occupational Safety & Health Administration |

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Chapter 1: Introduction

This work aims to improve awareness and communication of dust explosion resources in a manner that reaches an extensive audience, ideally any group who may benefit from the information. As part of this research a communication framework was developed to help reach a wider audience.

1.1 Scope

For this project a dust explosion communication strategy framework was developed. This project has both an applied science and a social science aspect. The applied science aspect is to understand combustible dust hazards and translate resources. The social science aspect is to determine the best ways to communicate the hazard to reach a variety of target audiences, and in ways that work well for each group.

The needs and communication tools best suited for each target group were determined. Once these are understood, resource types appropriate for each group can be identified. The identified resource types need to be made more readily accessible to the relevant groups, so that a much broader audience can be reached.

1.2 Motivation

The motivation for this project is to improve safety awareness through better communication of combustible dust hazards. The current communication media are rather limited and consist primarily of journal publications and conference proceedings. This reaches a very limited and typically highly educated audience. Not only does this information reach a limited audience, but the information is also only relevant for certain groups. A much broader audience needs to be reached, from plant-floor workers, to students and technical professionals. Different groups require different information in

terms of the complexity and depth of the information, the format, and the method of delivery, among other factors.

1.3 Objectives

The primary objective of this work is to improve the safety awareness for combustible dust hazards. The hazard of dust explosions is one that is not very well known. This project aims to improve awareness through the development, and initial implementation of a dust explosion communication/ education strategy.

The second objective is to identify how dust explosion resources can be made more readily available, and to a much greater and varied audience. One method through which this objective is implemented is an educational module aimed towards upper-level undergraduate engineering students.

1.4 Brief Methodology

A communication matrix has been developed as part of the project framework. Research has also been conducted into the social sciences communication perspective of the project.

A three-case approach was taken in order to explore how to best communicate and translate dust explosion hazards effectively to different groups. This three-case approach is demonstrated in Fig 1.1. First a step back from dust explosions must be taken and the broad case of knowledge management and communication must be explored. There must be an understanding of how to best communicate in order to convey information to different diverse communities to their individual benefits. Then this knowledge can be implemented for the specific case of dust explosions. Only after taking these steps would it be possible to effectively communicate to an individual target group, this being the very

specific case. One example of a very specific case is the creation of an educational module for undergraduate engineering students.

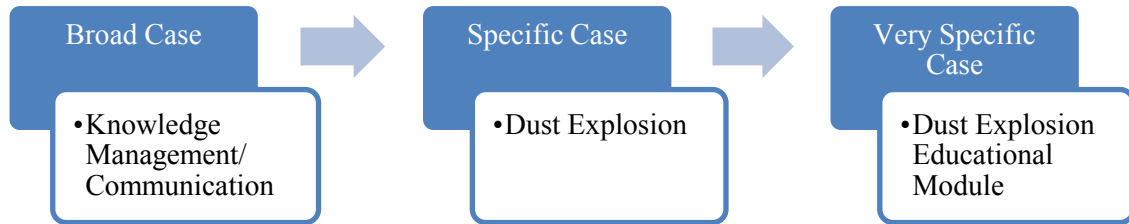


Figure 1.1. Three-case approach utilized for this research.

Chapter 2: Literature Review

It is not uncommon for people in industry to be unfamiliar with the occurrence of dust explosions. Following the dust explosion at a sawmill in Burns Lake, British Columbia in 2012, people were caught off guard and thought it was a unique, uncommon occurrence, but within a few short months it happened again at another British Columbia sawmill (Lian, 2012). Even regulatory/governmental groups can be behind the times on these matters. The Nova Scotia Occupational Health & Safety Division developed and released a dust explosion hazard alert in October 2014, more than two years after the British Columbia sawmill incidents, using research from a US Chemical Safety and Hazard Investigation Board (CSB) study from 2006 (Nova Scotia Occupational Health & Safety Division, 2014).

2.1 Communication

There are four primary human factors that make up the root cause of most incidents: organizational decisions/influences, unsafe supervision/training, preconditions for unsafe acts, and the unsafe acts themselves (Reason, 1990). The issue of poor communication could fall within the category of unsafe supervision (Fishwick, 2011).

2.1.1 Written Communication

Language-related issues were found to be a cause in 5-10% of major incidents internationally (Lindhout & Kingston-Howlett, 2011). Language issues, which fall into the realm of human error, consist of a number of contributing factors such as poor education and training, poor written or verbal communication, and foreign language issues (Lindhout & Kingston-Howlett, 2011). Results of language issues include

misunderstandings, deviating from instructions, or skipping necessary actions (Lindhout & Kingston-Howlett, 2011).

It is a common practice to check the quality of written instructions by trialing them on employees, which can be risky as the inability to understand a safety document can be detrimental to personal safety (Lindhout & Kingston-Howlett, 2011). Whether it is an issue of poor literacy and education, or foreign workers, a document may be written at a reading level that is above that of many workers (Lindhout & Kingston-Howlett, 2011). With the foreign language issue, it may not be enough to have documentation translated for a foreign sub-population. Though this may reduce the risk in many cases, there is also the possibility that the foreign worker may also have poor reading and writing skills in their native language, as rates of illiteracy vary greatly among countries. For example, 48% of the population of Portugal and 80% of the population of Afghanistan is illiterate (Lindhout & Kingston-Howlett, 2011). The workforce is becoming increasingly diverse, yet written information continues to be frequently used, with little consideration given to the language capabilities of those who may require the information (Lindhout & Kingston-Howlett, 2011).

Written documents do have their place though. Words can express complexities far better than imagery can (Humphrys, 2006). The best method and medium should be determined based on the content of the message and its audience. Messages can be verbal, audio, visual, or written (Carson & Mumford, 2011).

2.1.2 Information Limitations

There is abundant information available on dust explosions. But having or providing the information does not result in effective communication (Carson &

Mumford, 2011). The limitation exists in finding an effective way to get the information to all the people who need it (Carson & Mumford, 2011). All employees need access to key safety information, and so do contractors, visitors, emergency personnel and neighbouring members of the public. It is the duty of the employer to be familiar with possible dangers in their industry, just as it is management's duty to provide the relevant information to their employees and other stakeholders (Carson & Mumford, 2011).

There should be opportunities for feedback throughout the communication process. This can ensure the message was received as intended. This also allows for a message to be re-sent or modified if it was not received or understood properly (Carson & Mumford, 2011).

2.1.3 Information Exchange

Proper training and instruction, while beneficial, is not always remembered by all employees. Retraining and emphasis on the importance of properly following safety measures is vital ("Communication – in brief", 2011). Another issue lies within the realm of ignoring common sense. This is where employees act in terms of a short-term gain or advantage, rather than considering the long-term benefit of their actions. They do not consider what might happen as a result of their actions (Fishwick, 2011). Instructions and procedures may be ignored for commercial or other gains (Carson & Mumford, 2011). Information exchange relies on the sender to formulate the message correctly and for the receiver to translate and understand the message as intended. Language, culture, personal skills and competencies can all influence how the message is sent and received (Carson & Mumford, 2011).

2.1.4 Attention Span

Limited attention spans can also influence knowledge capture. PowerPoint has the advantage of reminding a listener of what was recently said, which they may have already forgotten (Kletz, 2011). Documents that are too lengthy can be a poor source of written communication (Lindhout & Kingston-Howlett, 2011). Also, with constant Internet use, young individuals' brain functions have changed from that of previous generations. Students are now less capable of the linear thought process required for extensive reading and writing (Greenfield, 2010).

2.1.5 Communication Strategies

Carson & Mumford (2011) have listed a number of strategies to minimize communication breakdown around safety critical tasks:

- Identify the communication needs of all persons involved
- Consider both the medium and the method of communication
- Ensure literacy level, language and terminology is appropriate for the workforce in question
- Use at least two methods/media
- Use signage as part of the communication process where appropriate, but do not rely on it as a substitute for communicating
- Use training as part of the process

2.2 Knowledge & Knowledge Management

Knowledge is assimilated into a knower's belief system from information, which itself is assimilated from data (Hansson, 2002). Data consists of raw descriptions and observations, whereas information is the patterns that are found within the data (DeLong

& Fahey, 2000). Knowledge is the stories, concepts, and rules that are produced by human experience and reflection (DeLong & Fahey, 2000). The information must be both understood and believed in order to be assimilated into knowledge (Hansson, 2002). Additionally, beliefs that are incorrect or that cannot be justified are not considered knowledge (Hansson, 2002). As such, Hansson (2002) defines knowledge as a “true, justified belief”.

Knowledge may be either tacit or explicit (DeLong & Fahey, 2000). Tacit knowledge is subjective, cognitive or experiential (Gupta, Iyer, & Aronson, 2000), and cannot be easily explained (DeLong & Fahey, 2000; Gupta et al., 2000). Explicit knowledge is objective, rational and technical (Gupta et al., 2000). Examples of explicit knowledge can be found within rules, processes, procedures, and documents (DeLong & Fahey, 2000; Gupta et al., 2000).

Figure 2.1 depicts risk as a function of knowledge and uncertainty. A risk is present when there is a gap in knowledge (an unknown or unknown outcome). Therefore there is some degree of uncertainty (Hansson, 2002).

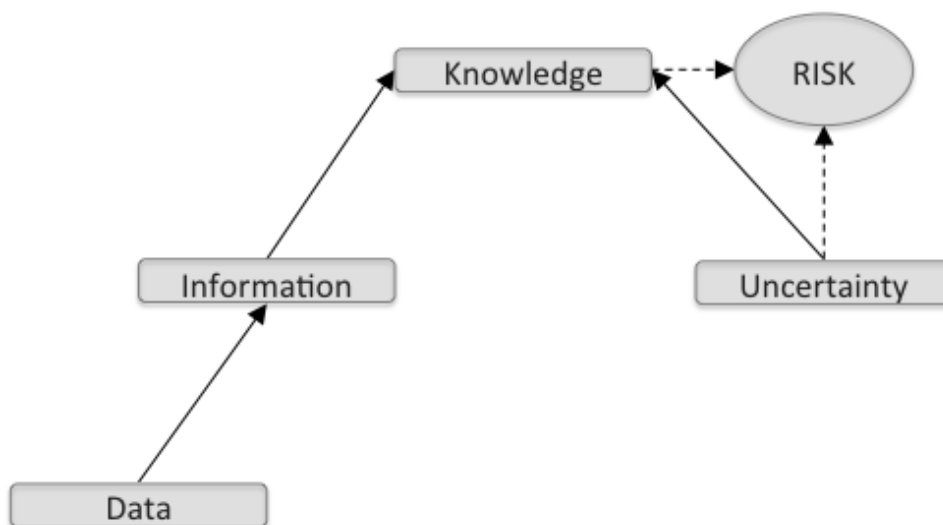


Figure 2.1. Risk in terms of knowledge and uncertainty. From Hansson (2002).

DeLong & Fahey (2000) classify knowledge further into three distinct types: human, social and structured knowledge. Human (or individual) knowledge is exhibited through skills and expertise, and represents what individuals know. It can be explicit or tacit. Social knowledge comes about through collaboration among individuals. It is a collective knowledge greater than the combined knowledge of all members of the group. As such it is primarily tacit. Structured knowledge is exhibited in the processes, tools, systems and routines of an organization, existing as organizational resources. It is explicit (DeLong & Fahey, 2000). There is a tendency to focus only on one of the three knowledge types, despite the fact that the existence of all three is critical to effective decision-making. For example, technologically oriented individuals may focus on text-based information, which falls into the structured knowledge category (DeLong & Fahey, 2000).

Effective knowledge management aids in the acquisition, management, and transfer of information that is important to the organization (Gupta et al., 2000). What an organization knows, and how they use this acquired knowledge gives them a competitive advantage (Gupta et al., 2000).

2.2.1 Culture in Organization

An organization's culture is revealed through its values, norms and practices. Values can be difficult to change. Norms, which are derived from values, are somewhat more vulnerable to change. But changing practices is the most effective way of altering organizational behaviours in order to promote knowledge creation (DeLong & Fahey, 2000). For example, the practices utilized in a meeting, such as how differences of

opinion and conflict are addressed can influence how likely the team is to generate and leverage knowledge (DeLong & Fahey, 2000).

The culture of an organization can prevent the sharing of information if employees feel they need to hold onto their individual knowledge base (Gupta et al., 2000). If it is believed that sharing individual knowledge poses a risk to their job safety then the exchange of knowledge will be limited (DeLong & Fahey, 2000). The culture is an important factor in the creation and sharing of knowledge (Gupta et al., 2000). An open culture, which provides incentive to integrate individual knowledge into the organization's knowledge base, will be more successful (Gupta et al., 2000). Achieving this level of effective knowledge sharing can be a challenge, and requires managerial commitment to new practices (Gupta et al., 2000).

2.2.2 Knowledge Conversion

An organization's knowledge assets can only be fully utilized through effective knowledge transfer between individuals. Nonaka & Takeuchi (1995) identify four common processes for knowledge conversion and transfer: socialization, externalization, combination and internalization. Socialization is the sharing of experiences by observing, imitating and practicing. Externalization is the conversion of knowledge from tacit to explicit. One such example would be report writing. Combination is the process of copying and distributing the explicit information. Internalization is the process of associating explicit sources with tacit experiences (Nonaka & Takeuchi, 1995).

2.2.3 Verbal Communication

In a technologically driven world, it is easy to neglect human interactions as a source of knowledge. Davenport (1994) states that managers get two-thirds of their

information from in-person and telephone interactions. While this fraction may have decreased since the time the above paper was published, as a result of increased use of technology, it serves as a reminder that there can be a vast amount of untapped tacit knowledge being obtained among individuals. An organization needs a process of codification of this tacit knowledge into explicit knowledge if it wants to have a more solid corporate memory (Gupta et al., 2000).

2.2.4 Cultural Influences on Knowledge

Cultures and subcultures have an influence on what knowledge is deemed to be useful to the organization. As a result, cultures will influence which knowledge a group focuses on. Different subcultures will have different interpretations of what is important. As these sub-cultures will value knowledge differently, this can result in miscommunication among groups (DeLong & Fahey, 2000).

Culture determines whether a certain item of knowledge belongs to an organization or to its individuals. Culture also dictates who is in control of knowledge, who is obligated to share it and who may hoard it. This is all dependent upon the degree of trust between the organization and its individuals. An organization with a low-trust culture will not see very much sharing and creation of knowledge. For example, an organization with a history of downsizing will have constricted information flow among employees, and trust will need to be rebuilt in order to encourage employees to share their knowledge and expertise without worry. Knowledge sharing among groups may also be limited when it is evident that some groups are more highly valued by the organization. This will cause subcultures to feel the need to protect their knowledge assets (DeLong & Fahey, 2000).

Culture influences how individuals interact, and hence create, share and use knowledge. In a closed culture there can be intimidation and a fear of appearing incompetent when engaged in vertical interactions with upper levels of the hierarchy. Knowledge creation can be improved through discussion of sensitive topics becoming more acceptable, as well as senior management being perceived as approachable (DeLong & Fahey, 2000).

It is possible for knowledge development to be improved through an increased volume of interactions between individuals and groups. Likewise, collaboration among groups within an organization allows for interactions that may lead to creation and sharing of new knowledge. Teaching allows for the teacher to improve upon their existing knowledge. How mistakes are dealt with will influence social interaction. They should be used as a learning source, and as a means of creating new knowledge (DeLong & Fahey, 2000).

An organization's culture determines how new knowledge from external sources is adopted. New knowledge can be either adopted at face value from external sources, or the knowledge can be created internally by reinterpreting external information in a context that is applicable to the organization. In the latter case, external knowledge is the beginning, not the end of new innovations. Participation in debating and synthesizing knowledge is encouraged for important issues (DeLong & Fahey, 2000).

2.3 Diffusion of Innovations

Rogers (2003) outlines a set of six key attributes (Table 2.1) to take into account when trying to have a group adopt an innovation. An innovation will most likely be adopted when these considerations have been taken into account. However, these

attributes alone cannot guarantee adoption. The adoption's success is dependent upon how an individual perceives the value of the innovation as compared to alternative ways of reaching a goal; however, this can vary greatly among individuals (Dearing, Meyer, & Kazmierczak, 1994). Other attributes that influence adoption include: risk, knowledge requirements and support (Greenhalgh, Robert, Macfarlane, Bate, & Kyriakidou, 2004).

Table 2.1. Key attributes of innovation. From Rogers (2003).

| An innovation will be more easily adopted if... | |
|--|--|
| Relative Advantage | It has a clear unambiguous advantage |
| Compatibility | It is compatible with the values, norms and needs of the adopter |
| Complexity | It is believed to be simple or easily broken down |
| Trialability | It is possible to experiment with on a limited basis |
| Observability | Its benefits are visible |
| Reinvention | It can be adapted, refined or modified |

2.3.1 Adoption by Individuals

Traits of individuals that impact how they interact with innovations include intellect, learning style, drive, and values (Greenhalgh et al., 2004). If an innovation meets a particular need of an individual, or if it is in line with his or her values, goals, and beliefs, it is more likely to be adopted (Gladwin, Dixon, & Wilson, 2002; Wejnert, 2002). Although authoritative decisions around an innovation may initially improve the likelihood of adoption, it may worsen the long-term success of a sustainable routinization (Rogers, 2003).

2.3.2 Diffusion & Dissemination

Interpersonal social networking is the primary mechanism for the diffusion (passive spread) of innovations (Greenhalgh et al., 2004). Adoption by individuals is more effective if they share similar backgrounds (e.g. socioeconomic, cultural, educational) with current innovation users (Rogers, 2003). A boundary spanner is an individual with social ties within and external to the organization, who is able to link the two environments, and who may then identify ideas to become new organizational innovations. Organizations can support the development of boundary spanning roles in an effort to capture and assimilate innovations (Tushman, 1977).

The effectiveness of a formal dissemination program depends upon recognition of the needs and perspectives of adopters; strategies tailored to the demographic, structural and cultural characteristics of each subgroup; effective style, imagery and metaphors within the message; use of appropriate communication channels; and evaluation and monitoring of goals and milestones (Rogers, 2003).

2.3.3 Organizational Precursors & Readiness for Innovation

An organization that has an absorptive capacity for new knowledge will be more effective at assimilating innovations. A learning culture and strong leadership geared towards knowledge sharing are imperative (Barnsley, Lemieux-Charles, & McKinney, 1998). Knowledge depends on interpersonal social networks in order for it to spread (Greenhalgh et al., 2004).

Consideration of the innovation can allow an organization to become “ready” for that innovation (Greenhalgh et al., 2004). If there is “tension for change”, that is, a belief that the present situation is not tolerable, assimilation is more likely (Greenhalgh et al.,

2004). If the innovation is aligned with the values, norms and practices of an organization it is also more likely to be assimilated (Rogers, 2003).

2.3.4 Interorganizational Networks & Collaboration

There are also external influences that may affect an organization's adoption decision. If enough comparable organizations have already adopted a particular innovation that it is considered the "norm", it will be promoted through interorganizational networks (Westphal, Gulati, & Shortell, 1997). A policy push can improve the likelihood of an innovation's success, in part as a result of dedicated funding (Fitzgerald, Ferlie, Wood, & Hawkins, 2002). Political mandates can increase an organization's motivation, but they will not increase its capacity to implement an innovation. These regulations may divert focus or diminish financial incentives (Meyers, Sivakumar, & Nakata, 1999).

2.3.5 Implementation

An organizational structure that is flexible and adaptive will improve the chances for implementation of the innovation (Meyers et al., 1999). Dedicated funding for an innovation's implementation improves the likelihood of implementation (Fitzgerald et al., 2002). Finally, timely feedback will increase the chance of successful implementation (Grimshaw et al., 2004).

Chapter 3: Communication Improvements

This section discusses the current limitations of combustible dust hazard resources, identifies individuals needing access to the information, and recommends several communication improvement strategies. The results of this thesis will also have some applicability in improving communication about other hazards.

3.1 Limitations

Different individuals or groups require different information in regards to combustible dust hazards. Their needs can vary in terms of the complexity and depth of the information, the format, media type and method of delivery, among other factors. The primary sources of information (journal publications and conference proceedings) are only available to a limited audience. Not only are these resources relevant only to a limited audience in their current form, their applicability is also limited because these resources are only accessible to those with subscriptions or other access to the print or online media.

There should be examination into why there has been non-adoption of the information to date, in order to aid in improving communication. In general, when information is provided, it is assumed to be valuable, without any follow-up to confirm this. If an individual does not know anything about combustible dust hazards, then they have no way of preventing a dust explosion. This could be categorized as an 'unknown known' event risk, an event that has occurred before but for which there is no awareness (Paltrinieri, Øien, & Cozzani, 2012). In this case, individuals within a certain company or industry have not learned from the lessons of others, and are unaware of possible hazards.

Even if an explosion incident were then to occur it may be perceived by those in the same industry, who have now become aware, as having been a “black swan” event. A black swan event is a low probability, high consequence event. The interpretation of a black swan event can be based upon an individual’s knowledge (Aven, 2013). While those who are familiar with the hazard certainly would not consider a dust explosion a black swan, there are those who are completely unfamiliar with dust explosions who would perceive it as a black swan. Upon hearing of such an event at another location within the same industry type, individuals may still believe it to be a fluke incident. They may not look into it any further and continue operations as before. The two dust explosions that occurred at sawmills in British Columbia in 2012 potentially illustrates this. According to the director of the western Canada district of the United Steelworkers, following the first incident no one he spoke with could recall such a significant explosion in a sawmill having occurred before, and many believed it to be a unique incident that would not reoccur. But they were wrong as a second incident occurred three months later (Lian, 2012).

In the development of dust explosion resources, there are a few questions that should be asked in order to address certain limitations:

- What audience are we developing this for?
- Are we publishing this in the right journal, or other publication medium for this resource? Are we reaching the desired audience?
- Are we reaching enough different audiences through our work?

3.2 Non-Adoption Issues

There has been a lack of adoption of combustible dust hazard prevention and mitigation information as indicated by several explosion incidents (US Chemical Safety and Hazard Investigation Board (CSB), 2006). These incidents are not due to a lack of available information. One of the issues surrounding non-adoption is that information is provided and assumed to be valuable. But it is not enough to simply provide the information. It needs to get into the right hands. Then in order to encourage adoption of the information, it can help to make meaningful connections. One example of a way to create a strong connection is through personal stories (L. Taylor, personal communication, November 2, 2012).

A further issue with non-adoption is a culture or sub-culture within an organization that is not conducive to safety, an anti-safety culture of sorts. There is a lack of perception of vulnerability with some individuals. They see no need to follow safety rules, as they believe they will not get hurt. These could include young employees who believe they are invincible, and “macho” employees who believe safety practices are unimportant.

There is also the issue of normalization of deviance. This is when unsafe behaviours and practices become normalized, and deemed acceptable (Vaughan, 1996). The dust explosion incident at the Imperial Sugar Company in Port Wentworth, GA, US was in part due to normalization of deviance. Employees at Imperial Sugar were accustomed to the layers of sugar dust throughout the facility. There were occasional small fires, and workers knew there were flammability issues, but they did not properly understand the magnitude of the problem. Despite minor fire incidents, and a much better

understanding of explosibility risks than the workers had, management did little to improve housekeeping efforts (CSB, 2009).

3.3 Target Groups

A number of target groups have been identified who may have the need for dust explosion resources. This list encompasses a varied spectrum of individuals, with these diverse target groups all having different needs in terms of information, each of which may be addressed through different communication approaches. Table 3.1 provides a list of the target groups along with a brief overview of the identified needs for each group.

3.3.1 Geographic Scope

A geographic scope has been determined, though it varies for different groups. For the Government group there is a need to limit the scope to Canada, as every country would have different needs and requirements, and it would not be feasible to cover them all. For example, in terms of Occupational Health & Safety, for the United States, the Occupational Safety & Health Administration (OSHA) acts as a federal enforcement agency. In Canada, the Canadian Centre for Occupational Health & Safety (CCOHS) is a “not-for-profit federal department corporation” (Canadian Centre for Occupational Health & Safety, 2014), which offers health and safety services to the workplace. Occupational Health and Safety legislation is governed by provincial/territorial jurisdictions.

For other groups it makes less sense to have a geographic scope. For example, plant-floor workers could make use of the same information regardless of the country. For these groups, the information is more or less universal, so a geographic scope has less relevance. However, what may work for one country may not work for another. Some of

Table 3.1. Needs of identified target groups.

| Target Group | Needs |
|--|---|
| 1. Plant-floor Workers | Housekeeping practices. Non-technical background information. Geared towards personal safety. |
| 2. Workplace Supervisors & Management | Hazard identification. Background on prevention and mitigation. Low-moderate technical level. Geared towards protection of employees and process. |
| 3. Industry Associations, Technical Societies | Educating members for personal and process safety. Moderate technical level. |
| 4. Government (Policy Makers, Regulators, Occupational Health & Safety (OHS)) | Information to create policy, regulations, educational information to protect Canadians and Canadian companies. Moderate technical level. |
| 5. Engineering Students | Identification of hazards and introduction to prevention and mitigation strategies. Moderate to high technical level. |
| 6. Continuing Education for Practicing Engineers | Prevention and mitigation. Moderate to high technical level. |
| 7. Industry Stakeholders (executives, administration, finance, shareholders, etc.) | Collective responsibility for safety. Effects of loss from dust explosions (people, property, production, environment). Low technical level. |
| 8. Public & the Media | Non-technical background information. See Section 3.3.2 |

the differences include native language, cultural differences and level of literacy. For the current purpose, any recommended resources would be in English.

Cultural differences may influence attitudes around safety. Gladwell (2008) discusses Korean Airlines' history of plane crashes in terms of Korea's cultural respect and value for authority. Between 1988 and 1998 Korean Airlines had an airplane loss rate of 4.79 per million departures. For comparison, this is over seventeen times higher than the loss rate of United States-based United Airlines over the same time period. As a result of Korea's cultural beliefs around hierarchy, the captain was always in control and a first officer or flight engineer would be unlikely to correct the captain if they believed he was making a mistake. This was identified among the causes of the crashes through black box recordings (Gladwell, 2008).

In some countries, such as China for example, many labour-level workers cannot read or write. Literacy issues limit the types of resources that can be used. It should be noted that as a result of an increased diversity in workforces, including immigrant workers and temporary foreign workers, these language and cultural differences may influence information needs within Canada. For these remaining groups the scope can be expanded. The focus still remains toward improving communication for Canadians, but much of the information would be relevant for use elsewhere, particularly with westernized countries.

3.3.2 Public & the Media

The "Public & the Media" is a special case group. One might question whether they really need information. They have been included because while their need for information is not as great as those who work directly in or with industry, they do have a

certain degree of need for information. In the event of a dust explosion where there are injuries and/or fatalities, there will be several members of the general public who know those who were directly affected by the incident. Hence, these family and friends are also influenced by the event, albeit to a lesser degree. Also there is power in a larger group of people to effect change, to prevent future incidents from occurring and affecting those they know and love. However, it is unfavourable to incite unnecessary fear in the public, so knowledge must be appropriate and accurate. This is where the media fit in. The general public would generally become knowledgeable through popular media sources, and it is in their best interests for media sources to be accurate and factual. Certain members of the general public may also be at risk, such as individuals working in wood shops, on farms, and within small businesses that may not have access to the same types of resources as larger industries. If dust explosion risks can be explained in general enough terms to make the public understand, it should then be possible to reach the rest of the groups.

3.3.3 Resource Types

Resource types are not limited exclusively to written works, and may also be verbal, audio, or visual. Some examples of resource types include: posters, databases, case studies, presentations, videos, FAQs, personal stories. Some of the identified target groups may also act as a resource for other target groups. For example, workplace supervisors & management must educate the plant-floor workers under their care. Also, industry associations & technical societies will educate others through training and conferences. Finally, government will influence the actions of all within industry.

3.4 Communication Matrix

In Section 2.3, six key attributes of innovation were discussed. A matrix has been developed which explores each of these attributes in terms of the eight identified target groups. The innovation contained within a dust explosion resource will most likely be adopted when the key attributes have been taken into account in the development and distribution of the resource. As such the matrix gives some insight into the different resource needs for each target group. It can be seen that although there may be some similarities between groups, the exact needs will not be the same for different groups.

The identified resource needs should in no way be deemed the sole solutions to the problem at hand. Also, when brought down to the specific level of an individual within each target group, the answers to each of the attributes would likely vary. The resource needs identified within the matrix provide general ideas that would be applicable for the majority of individuals within each target group.

3.4.1 Matrix Development

The observations made for each target group/attribute of innovation combination were based on evaluation of the attribute definition as well as a few related questions, as it pertained to the relevant target group. The questions were based upon a comprehensive review paper on diffusion of innovations (Greenhalgh et al., 2004) and in collaboration with Dr. Lynn Taylor. The attributes of innovation and their related questions are as follows:

1. Relative Advantage: clear unambiguous advantage.
 - What's in it for me? (Adopters' needs and perspectives)
 - Is there "tension for change"?

2. Compatibility: compatible with the values, norms and needs of the adopter.
 - To what extent are new practices consistent with current beliefs and practices?
 - Does the employer support change?
 - Resources?
 - Employee support/participation in decision-making?
3. Complexity: believed to be simple or easily broken down.
 - How difficult will it be to learn new practices?
 - Are some things already being done?
 - How can I access resources?
4. Trialability: possibility to experiment with on a limited basis.
 - Will the new practice work?
 - Can it be introduced on a small scale?
 - How can confidence be built in the new practice?
5. Observability: benefits are visible.
 - Is anyone else doing this?
 - Is there a social network for communicating?
6. Reinvention: can be adapted, refined or modified.
 - Can the practice be customized for my context?
 - Can it be modified to suit local situation?

3.4.2. Target Groups 1 & 2

The matrix developed for the plant-floor workers group and the workplace supervisors & management group can be seen in Table 3.2.

Table 3.2. Matrix for target groups 1 & 2

| | Target Group 1 Plant-Floor Workers | Target Group 2 Workplace Supervisors & Management |
|------------------------------|--|--|
| 1. Relative Advantage | - Personal safety | - Collective safety, assets |
| 2. Compatibility | - Graphics - Learning culture with Workplace Supervisors & Management | - Myths/ realities - Support culture of workplace safety - Learning culture with Plant Floor Workers |
| 3. Complexity | - FAQs - Mechanisms to listen to concerns | - Trade journals/ "popular" articles, newsletters |
| 4. Trialability | - Collaborative initiatives | - Collaborative initiatives: respect workers knowledge & contribution |
| 5. Observability | - Positive "story" of case studies | - Positive "story" of case studies |
| 6. Reinvention | - Non-technical - Personal safety perspective | - Low-moderate technical - Loss prevention (operations) perspective |

A resource for plant-floor workers should address their specific need of protecting their own personal safety. Graphics/imagery can be used as a possible resource type. A shared learning culture with workplace supervisors & management demonstrates the needs for both employers to support change, as well as employees to participate in decision-making. FAQs allow for information to be simplified. Additionally, mechanisms to listen to concerns help to limit the difficulties in learning a new practice. Collaborative initiatives allow for a new practice to be experimented with and initially introduced on a smaller scale. Positive case “stories” show what others are doing in the industry, making the benefits of dust explosion prevention visible. Making the material non-technical, and gearing it towards a personal safety perspective modifies the information to make it more appropriate for this target group.

A resource for workplace supervisors & management should address their occupational obligations for the safety of their employees as well as the protection of other assets of the company (e.g. property, production). One example of a resource type would be to introduce the myths and realities of dust explosions based upon “An

Introduction to Dust Explosions” (Amyotte, 2013). Supporting a culture that promotes workplace safety expresses that the employer supports change. Again, the learning culture with plant-floor workers shows the need for employee participation in decision-making. This group would be able to access the information through their respective trade journals, newsletters and other popular article sources. Collaborative initiatives allow for a new practice to be experimented with and introduced on a limited basis initially. Positive “stories” derived from case studies show the benefits of dust explosion prevention. A low to moderate technical level and a focus on loss prevention make the resource more appropriate for this target group.

3.4.3. Target Groups 3 & 4

The matrix developed for the industry associations & technical societies group and the government group can be seen in Table 3.3.

Table 3.3. Matrix for target groups 3 & 4

| | Target Group 3 Industry Associations, Technical Societies | Target Group 4 Government (Policy Makers, Regulators, OHS) |
|------------------------------|---|---|
| 1. Relative Advantage | - Grow the industry, reputation, research and development | - Legal responsibility |
| 2. Compatibility | - Technical papers and conferences | - Public perception - Technical papers and conferences |
| 3. Complexity | - Translate book knowledge | - Translate book knowledge |
| 4. Trialability | - Funding/ technical support | - Funding/ initiatives |
| 5. Observability | - Target conferences | - Target conferences |
| 6. Reinvention | - Technical information - Personal/ collective safety (of members) perspective | - Technical information - Industry/ collective safety perspective |

A resource for industry associations and technical societies should address the industry’s needs, including industry growth, reputation, research and development. Possible resources include technical papers and conferences, which are consistent with what is currently available. Information can be further broken down through appropriate

translation of book knowledge, for example “An Introduction to Dust Explosions” (Amyotte, 2013) and other texts on dust explosion. Opportunities to experiment with new information will rely upon funding and technical support. Information is available through conferences, and this allows for a social network to grow and develop information within the community. Technical information is appropriate for this group, and resources should be geared towards the personal/ collective safety of the members these groups are representing, in addition to other identified needs of their members.

A resource for governments should address the need of the government’s responsibility to its citizens. The importance of a positive public perception shows that the government supports change. Technical papers and conferences, which are currently available, are appropriate for this group. Information can be further simplified through translation of authoritative texts on the subject. Opportunities to experiment with new information would depend upon funding and initiatives. Relevant conferences exist and serve as a social network. Technical information is appropriate for this group, and resources should be geared towards overall industrial safety and the collective safety of individuals within the industries.

3.4.4. Target Groups 5 & 6

The matrix developed for the engineering students group and the practicing engineers group can be seen in Table 3.4.

The advantage to engineering students is in their future responsibilities as practicing engineers. Students would become knowledgeable through their program’s curriculum, which remains consistent with other practices for how students obtain knowledge. Instilling beliefs regarding safety culture prior to introduction into the

Table 3.4. Matrix for target groups 5 & 6

| | Target Group 5 Engineering Students | Target Group 6 Continuing Education for Practicing Engineers |
|------------------------------|---|---|
| 1. Relative Advantage | - Future trigger: responsibility as practicing engineer | - Liability/ ethical responsibility |
| 2. Compatibility | - Curriculum - Instill safety culture beliefs prior to entering industry | - Ethics/ safety culture - Technical papers and conferences |
| 3. Complexity | - Safety and Chemical Engineering Education/ Minerva Safety Modules | - Technical journals/ papers |
| 4. Trialability | - Integration into curriculum | - Conferences and technical journals |
| 5. Observability | - Minerva Safety Module integration | - Target conferences - Positive case studies |
| 6. Reinvention | - Modules/ curriculum modifiable to meet needs of students and instructor - Local case studies | - Technical information - Loss prevention/ collective safety perspective |

workforce is compatible with the needs of an engineering student. Resources would be available through organizations that develop educational safety material for engineering students, such as Safety and Chemical Engineering Education (SACHE) and Minerva. Integration of material into the curriculum within specific programs could be done on a trial basis. Minerva Canada’s development of safety modules (including the module found in Appendix A) is an example of integration of safety material into curriculums already in process. Teaching modules can easily be modified to meet the needs of either the instructor or that of the students. Utilization of local case studies would provide an added impact by creating a stronger connection than that of case studies from elsewhere. For example, in Nova Scotia students could learn about the explosion at Westray Coal Mine, and students in British Columbia could learn about recent incidents in BC sawmills.

A resource for practicing engineers should address their ethical responsibilities regarding safety. Ethics surrounding safety culture should be compatible with an engineer’s values. Existing technical papers and conferences are an appropriate resource

for this group. Appropriate technical papers already exist and are appropriately simplified for this group. Targeted conferences can act as a social network for further improving communication. Positive case studies show a clear benefit of dust explosion prevention practices. Technical information is appropriate for this group, and resources should be geared towards loss prevention and collective safety.

3.4.5. Target Groups 7 & 8

The matrix developed for the industry stakeholders group and the public & the media group can be seen in Table 3.5.

Table 3.5. Matrix for target groups 7 & 8

| | Target Group 7 Industry Stakeholders | Target Group 8 Public & The Media |
|------------------------------|--|--|
| 1. Relative Advantage | - Collective responsibility for safety, asset protection, legal responsibility, reputation | - Safety of loved ones working in industry |
| 2. Compatibility | - Profitability of safe company | - Videos - News articles/ news segments (written, online, video, audio) |
| 3. Complexity | - Translate book knowledge | - Web-based - Graphics/ images/ stories |
| 4. Trialability | - Collaborative initiatives | |
| 5. Observability | - Protection of assets and lives | - Power of people (numbers) to save lives |
| 6. Reinvention | - Low technical - Loss prevention perspective | - Personal Stories - Non-technical |

Resources for industry stakeholders should address the industry’s need for collective responsibility, asset protection, and legal responsibility. Profitability and success, as a result of a safe company, is compatible with the values and needs of this group. Information can be simplified through translation of authoritative texts on the subject of dust explosion. Collaborative initiatives allow for a new practice to be experimented with and introduced on a smaller scale. There is a clear benefit to the

protection of assets and lives as a result of dust explosion prevention work. Resources should be limited in terms of technical information and should be geared toward loss prevention.

Resources for public & the media should address the desire of the public to keep their loved ones working in industry safe. Resource types could include videos and news articles. Resources could be accessed through the Internet (web-based). Information can be simplified through graphics, images and stories. The power of the public creates a social network for change. Personal stories aid impact and allow for modification to suit local situations. Information would need to be non-technical.

3.4.6 Key Themes

There are a few themes and important distinctions that are identified across the matrix. The first is the learning culture between plant-floor workers and workplace supervisors & management. This allows for the groups to learn from incidents (i.e., loss-producing events), near-misses (i.e., no loss), and poor conditions/practices, and make appropriate changes. This also means plant-floor workers feel comfortable reporting issues, and that supervisors & management encourage reporting and take appropriate action to remedy issues. Members from both groups can be involved in proposing improvements. Both target groups should work together to learn from and teach one another.

The item “collaborative initiatives” appears under trialability for plant-floor workers, workplace supervisors & management, and industry stakeholders. One example of a collaborative initiative would be a safety committee with representatives from all levels and groups in the organization. Within this committee there would need to be

respect and recognition of all members' knowledge and contributions. This concept also revolves around having an organizational culture that supports safety, and in which all individuals have a collective responsibility for having a safe working environment. While different groups would have different roles within the collaboration, all levels of industry should have some involvement in the process.

One identified gap, which would be useful for all groups, is the current lack of positive case studies. These are studies of “good” industries and facilities where dust explosion incidents have been successfully prevented or mitigated. Instead, case studies generally focus on incidents that have occurred. Individuals need to be shown what to do, not just what not to do. While the way in which these case studies would be presented for individual groups would need to be different, they could be of benefit for nearly all groups.

Varying degrees of technical information have been assigned for different groups. In general, those who can make use of technical material will not need current resources to be significantly translated or reinvented. They can make sense of journal papers and other technical literature. For these groups, the issue is getting the information to them that meets their specific needs. For those with lesser technical abilities, the resources currently available are more limited and material needs to be translated into more applicable styles and format.

3.5 Recommended Communication Strategies

In order to increase the number of individuals who are familiar with dust explosion hazards, the existing research and information on the topic must be put into context for the individuals so that it can become part of their knowledge base. Creating

new resources or a database of existing resources (e.g. a website) is not enough to solve the problem. It is not enough to have the resources available, because only those who already know about the issue, and who are looking for more information would find it. All individuals who would benefit from the information must be reached, not just those who already have some background knowledge.

To improve adoption of information, resources have to meet the needs of the individuals within each group. The needs of the identified target groups have been explored in Tables 3.1-3.5. Knowledge transfer can be enhanced if the individual perceives a benefit as a result of adoption of the concepts within the resource. For example, for plant-floor workers the message can be framed from the perspective of personal health and safety. Additionally, for those working in management and administrative positions (industry stakeholders group), the message can be framed in terms of the consequences of a dust explosion in terms of both fatalities and costs from property, production, and other losses.

In meeting the needs of individuals, language and learning style barriers must also be addressed. Using a variety of communication media will help in reaching the communication needs of a greater proportion of individuals. Communication can be verbal, audio, visual, or written. Whenever possible, at least two different communication media should be used. For example, a training meeting (primarily verbal with possible written/visual components) could be held, and then posters (visual) could be displayed as an ongoing reminder.

Meaningful connections should to be made with the identified groups, to improve the value of the information. Personal stories are one way of making this connection. For

example, C. Kronisch (personal communication, June 26, 2013) tells of two examples of how she, and many other Germans are familiar with dust explosions. Firstly, bakers in Germany are aware of the dangers of flour in the air, and refer to it as ‘burning air’. Secondly, there is a well-known German children’s story (and subsequent movie), *Krabat*, by Otfried Preußler. The story takes place primarily in a flourmill. It is mentioned throughout the text that the workers in the mill must be careful to prevent flour in the air from exploding, and the mill does explode at the end. The title of the story has been translated in English to read as “The Satanic Mill” or “The Curse of the Darkling Mill”.

The use of positive case studies shows the success of a “safe” organization. It creates a role model for the industry, as well as demonstrating the positive outcomes of dust explosion awareness and prevention. The outcomes expressed in these resources can be tailored to the needs and values of the target group who would be making use of the resource. For example, these outcomes may be expressed in terms of assets, production, or personal safety.

Figure 3.1 summarizes the recommended strategies. These strategies were identified through the literature review process and in the development of the communication matrix, and have been explored earlier in this text. This framework makes recommendations for resource development, resource dissemination, and elements of an open organizational culture.

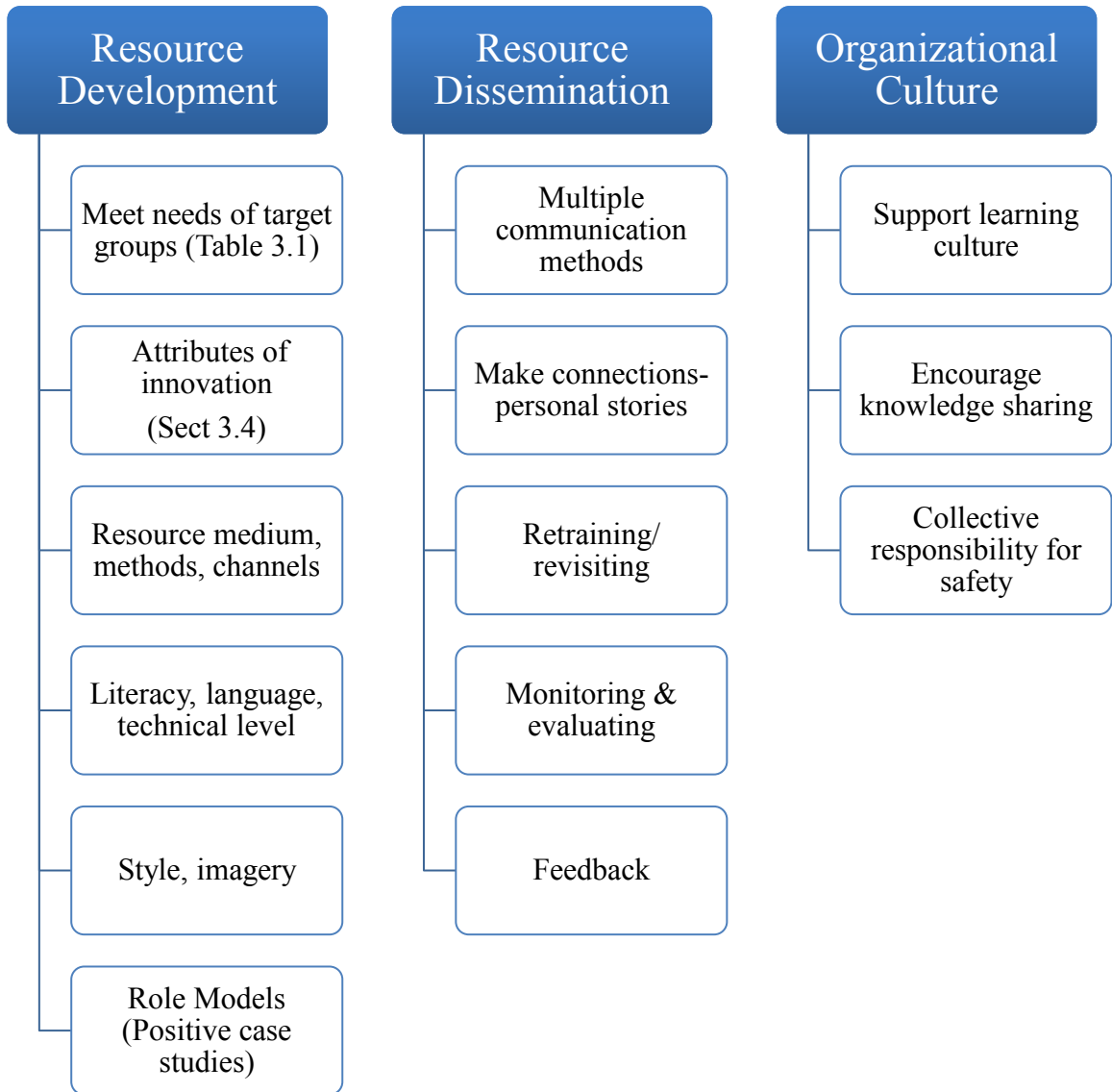


Figure 3.1. Framework for improvements in combustible dust hazard communication.

Chapter 4: Teaching Module

As a major contribution to this research, a teaching module was developed by the author, with input from Dr. Paul Amyotte and Mr. Manny Marta. This module was developed for the purpose of educating undergraduate engineering students about the prevention and mitigation of dust explosions. The module, seen in Appendix A is titled “Fires, Explosions, and Combustible Dust Hazards”. This module acts as a vehicle to achieve the objectives of this research. However, it is not an overall solution to the problem. While this module was designed specifically for the target group of undergraduate engineering students, it may have some applicability to other identified target groups (e.g. practicing engineers), though not to all groups in its current form.

This module introduces the topic of combustible dust hazards, with a focus primarily on dust explosions. It is comprised of 124 PowerPoint slides with notes. The content is largely based on the book “An Introduction to Dust Explosions” (Amyotte, 2013). The outline of the module is as follows:

- Basic Fire Principles
- Basic Explosion Principles
- Dust Explosion Fundamentals
- Fuel
- Ignition Source
- Oxidant
- Mixing
- Confinement
- Dust Layer Fires

- Prevention and Mitigation
- Case Studies
- Resources
- Evaluation

The module was developed to meet the specific needs of the given target group. This was accomplished by taking into account the following aspects: objectives & motivation, format & style, and content & technical level.

4.1 Objectives & Motivation

Teaching objectives and sample evaluation questions were developed based on the revised Bloom's Taxonomy. The six levels of the taxonomy (remember, understand, apply, analyze, evaluate, and create) allow for different, and deeper levels of comprehension and understanding (Anderson et al., 2001).

As this module is geared towards undergraduate students, they will be introduced to the topic prior to their entry into the workforce. As such, the information may act as a trigger in the future, and may help them identify possible hazards when they are working in industry. This also provides the opportunity, once they are working in industry, to get the information out to their supervisors, who may not yet have been introduced to the topic. In this way the former student becomes a "resource" for their employers.

This module was developed for Minerva Canada, a non-profit organization dedicated to improving workplace safety through post-secondary education in business and engineering programs (Minerva Canada, n.d.-b). The module is part of a series of health and safety teaching modules developed for engineering students. This series of modules can be found on Minerva's website (Minerva Canada, n.d.-a). These are free

teaching resources for inclusion within the engineering curriculum. The topics of the modules address health and safety needs, including core topics required for engineering graduates, as well as additional topics important to industry that are not currently widely taught in academia.

4.2 Format & Style

The module was developed as a PowerPoint presentation. The slides provide information through text or a figure. Each slide comes with an extensive notes section. The extensive notes allow for someone who is not intimately familiar with the concept of dust explosions to be able to teach the material, and to be able to provide information beyond what is shown on the PowerPoint slide. As a result this material can be taught in either of two manners. The module could be used in a typical classroom lecture setting by an instructor who may or may not be intimately familiar with the topic, though the instructor should have an understanding of the topic that is greater than or equivalent to the content of the module. The second method would be as a self-study by the individual students, provided with both the slides and respective notes.

PowerPoint presentations have the advantage of providing an overview of what is about to be, or has just been, discussed. It can also be reviewed at a later date, to serve as revision of the discussion. One limitation of PowerPoint, since it generally consists primarily of bullet points and/or figures, is that some important details may be omitted from the slides themselves. These points may be filled in by the presenter or a corresponding paper (Kletz, 2011). The extent of this limitation has been minimized by providing further information to the discussion directly beneath the respective slides (i.e. notes).

4.3 Content & Technical Level

The content includes a moderate level of technical detail. This level of technical detail could be included because upper-level engineering students have a good understanding and appreciation of technical detail. This module was designed to be incorporated into classroom lecture time. As such there may be time constraints for the material to be taught within. Additional optional resources were included for those students who may be interested in learning more on their own. These additional resources include incident investigation reports, testing and risk control standards, peer-reviewed journal papers and textbooks.

With a total of 124 slides, the module was designed so as to be able to be completed within 1-2 classes, plus additional time for evaluation. This is based upon the assumption that the material can be completed at a rate of approximately 1 slide per minute.

4.4 Key Attributes of Innovation

In Table 4.1 we revisit the key attributes of innovation initially introduced in Section 2.3. In the table each of the six attributes are related to the development of the module.

Table 4.1. Key attributes of innovation in relation to module.

| Attribute | Module |
|--------------------|--|
| Relative Advantage | Will act as a trigger in the student's future career, in terms of their responsibility as a practicing engineer. |
| Compatibility | Taught in a classroom setting in a manner comparable to typical teaching methods. |
| Complexity | Developed at an appropriate technical level for undergraduate students. |
| Trialability | Instructor trials in classrooms using included evaluation questions to gauge comprehension and understanding. |
| Observability | Included case studies demonstrate what can go wrong if insufficiently aware of hazard. |
| Reinvention | PowerPoint file is easily modifiable to meet student and instructor needs. |

Chapter 5: Conclusion

In closing, this research explored the communication issues surrounding combustible dust hazard awareness. This was conducted using the three case approach seen in Fig 1.1. The first step of this approach was to explore the broad case of communication and knowledge management. The next case was to apply this information to the specific case of dust explosions. Finally, the very specific case was to create a dust explosion resource for a particular group needing this information.

In the broad case, literature research was conducted on topics surrounding communication and knowledge management. These topics included written communication, language issues, communication strategies, information exchange, knowledge, organizational culture and its influence on knowledge, knowledge conversion, diffusion of innovations and adoption of innovations by individuals.

In the specific case of dust explosions, the current limitations of dust explosion resources as well as the issue of non-adoption was first explored. Then eight target groups who would benefit from having knowledge about combustible dust hazards were identified. Six key attributes of innovation were analyzed for each target group to better identify the different needs and benefits for each group. A framework for communication improvements was developed based on the broad research as well as on the attributes of innovation matrix.

In the very specific case, a module was developed for the education of undergraduate engineering students on the topic of combustible dust hazards. An exploration of how this module was developed to meet the students' needs was

conducted. This included looking at the objectives and motivation for the module, as well as its format, style, content and technical depth.

5.1 Recommendations for Future Work

The following recommendations are made for the continuation of this work:

- Search for additional resources that meet the needs of varying target groups. It is unlikely that enough high-quality resources exist to meet the needs of each identified target group. In this case, resources should be developed to meet these needs. This also includes the search for and development of positive case studies.
- Consideration of the development of a database (e.g. website) to compile all identified resources. It should be noted that the existence of a database only serves those who know the database exists and those who are familiar with combustible dust hazards and who actively search for further information and find this database. Providing information alone does not constitute knowledge development, and further actions are also needed.
- Further research into determining methods to raise awareness for those who are unfamiliar with combustible dust hazards. These individuals have no way of preventing combustible dust hazards, because they are unaware of the hazards. Determination of effective ways to share this information with more people to limit those who are unaware is needed.


References

- Amyotte, P.R. (2013). *An introduction to dust explosions. Understanding the myths and realities of dust explosions for a safer workplace*. Waltham, MA: Elsevier/Butterworth-Heinemann.
- Anderson, L.W. (Ed.), Krathwohl, D.R. (Ed.), Airasian, P.W., Cruikshank, K.A., Mayer, R.E., Pintrich, P.R., ... Wittrock, M.C. (2001). *A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives*. New York, NY: Longman.
- Aven, T. (2013). On the meaning of a black swan in a risk context. *Safety Science*, 57: 44-51.
- Barnsley, J., Lemieux-Charles, L., & McKinney, M.M. (1998). Integrating learning into integrated delivery systems. *Health Care Management Review*, 23(1): 18-28.
- Canadian Centre for Occupational Health & Safety. (2014, March 20). About CCOHS. Retrieved from <http://www.ccohs.ca/ccohs.html>
- Carson, P.A., & Mumford, C.J. (2011). Communication failure and loss prevention. *Loss Prevention Bulletin*, 218, 5-14.
- “Communication – in brief”. (2011). *Loss Prevention Bulletin*, 218, 23-25.
- Davenport, T.H. (1994). Saving IT’s soul: Human-centered information management. *Harvard Business Review*, 72(2), 119-131.
- Dearing, J.W., Meyer, G., & Kazmierczak, J. (1994). Portraying the new: Communication between university innovators and potential users. *Science Communication*, 16(1):11-42.
- DeLong, D.W., & Fahey, L. (2000). Diagnosing cultural barriers to knowledge management. *Academy of Management Executive*, 14(4), 113-127.
- Fishwick, T. (2011). Communications, common sense and loss prevention – is there a link?. *Loss Prevention Bulletin*, 218, 31-32.
- Fitzgerald, L., Ferlie, E., Wood, M., & Hawkins, C. (2002). Interlocking interactions, the diffusion of innovations in health care. *Human Relations*, 55(12): 1429-1449.
- Gladwell, M. (2008). *Outliers: The story of success*. New York, NY: Little, Brown and Company.
- Gladwin, J., Dixon, R.A., & Wilson, T.D. (2002). Rejection of an innovation: Health information management training materials in East Africa. *Health Policy and Planning*, 17(4): 354-361.

- Greenfield, S. (2010, February 12). Computers in schools could do more harm than good. *The Telegraph*. Retrieved from: <http://www.telegraph.co.uk/education/7220021/Computers-in-schools-could-do-more-harm-than-good.html>
- Greenhalgh, T., Robert, G., Macfarlane, F., Bate, P., & Kyriakidou, O. (2004) Diffusion of innovations in service organizations: systematic review and recommendations. *Milbank Quarterly*, 82(4), 581-629.
- Grimshaw, J.M., Thomas, R.E., MacLennan, G., Fraser, C., Ramsay, C.R., Vale, L., ... Donaldson, C. (2004). Effectiveness and efficiency of guideline dissemination and implementation strategies. *Health Technology Assessment*
- Gupta, B., Iyer, L.S., & Aronson, J.E. (2000). Knowledge management: practices and challenges. *Industrial Management & Data Systems*, 100(1), 17-21.
- Hansson, S.O. (2002). Uncertainties in the knowledge society. *International Social Science Journal*, 54(171), 39-46.
- Humphrys, J. (2006). *Beyond words*. London, UK: Hodder & Stoughton.
- Kletz, T. (2011). Powerpoint – good or bad?. *Loss Prevention Bulletin*, 218, 15-16.
- Lian, J. (2012). Dust to dust. *OHS CANADA*, 28(5), 24-29.
- Lindhout, P., & Kingston-Howlett, J.C. (2011). Language issues, an underestimated safety risk. *Loss Prevention Bulletin*, 218, 26-30.
- Meyers, P.W., Sivakumar, K., & Nakata, C. (1999). Implementation of industrial process innovations: Factors, effects, and marketing implications. *Journal of Product Innovation Management* 16(3): 295-311.
- Minerva Canada. (n.d.-a). *Minerva Canada – Health and safety teaching modules*. Retrieved from: <http://www.safetymanagementeducation.com/en/?sv=&category=Resources&title=HealthSafety>
- Minerva Canada. (n.d.-b). *Minerva Canada – Legal*. Retrieved from: <http://www.safetymanagementeducation.com>
- Nonaka, I., & Takeuchi, H. (1995). *The knowledge-creating company*. New York, NY: Oxford University Press.
- Nova Scotia Occupational Health & Safety Division. (2014). *Dust explosion hazard*. Retrieved from: <http://novascotia.ca/lae/healthandsafety/documents/DustExplosionHazardAlert.pdf>
- Paltrinieri, N., Øien, K., & Cozzani, V. (2012). Assessment and comparison of two early warning indicator methods in the perspective of prevention of atypical accident scenarios. *Reliability Engineering & System Safety*, 108, 21-31.

- Reason, J. (1990). *Human error*. New York, NY: Cambridge University Press.
- Rogers, E.M. (2003). *Diffusion of innovations* (5th ed.). New York, NY: Free Press.
- Tushman, M.L. (1977). Special boundary roles in the innovation process. *Administrative Science Quarterly*, 22(4): 587-605.
- US Chemical Safety and Hazard Investigation Board. (2006). *Investigation report – Combustible dust hazard study*. Washington, DC.
- US Chemical Safety and Hazard Investigation Board. (2009). *Investigation report – Sugar dust explosion and fire*. Washington, DC.
- Vaughan, D. (1996). *The Challenger launch decision: Risky technology, culture, and deviance at NASA*. Chicago, IL: The University of Chicago Press.
- Wejnert, B. (2002). Integrating models of diffusion of innovations: A conceptual framework. *Annual Review of Sociology*, 28, 297-326.
- Westphal, J.D., Gulati, R., & Shortell, S.M. (1997). Customization or conformity? An institutional and network perspective on the content and consequences of TQM adoption. *Administrative Science Quarterly*, 42(2), 366-394.

Appendix A: Teaching Module





The cover slide features a white background with a grey vertical bar on the left and a grey horizontal bar at the top right. The title is in large, bold, black font. Below the title, the authors' names and affiliations are listed in a smaller, black font. At the bottom, there are three logos: Dalhousie University, MINERVA, and NOVA Chemicals.


FIRES, EXPLOSIONS, AND COMBUSTIBLE DUST HAZARDS

Morgan Worsfold & Paul Amyotte
Dalhousie University, Halifax, NS, Canada

Manny Marta
NOVA Chemicals, Sarnia, ON, Canada

 **DALHOUSIE UNIVERSITY**
Inspiring Minds

 **MINERVA**
Safety Management Education

 **NOVA Chemicals**

This educational module on Fires, Explosions, and Combustible Dust Hazards was developed by MAsc candidate Morgan Worsfold. The project was conducted under the supervision of Dr. Paul Amyotte and with the industrial mentorship of Mr. Manny Marta. Funding in the form of a Mitacs grant was provided by Minerva Safety Management Education.

The module is designed for use in either of two ways. First, the slides can be shown as a presentation to multiple participants in a workshop/seminar format. The presenter would first gain familiarity with the slide material by reviewing the content of the notes page accompanying each slide. Second, the module can be completed by an individual in a self-study format. In this case, the "notes page" feature of PowerPoint would enable the participant to view the slides and accompanying notes at the same time.

Module Basics

- Scope
 - Fires, explosions, and combustible dust hazards
- Motivation
 - While these incidents and hazards are prevalent in the process industries, practitioner knowledge gaps exist
- Objective
 - Achievement of specific learning objectives by the target audience of undergraduate engineering students

2

The module introduces undergraduate engineering students to the fundamentals of process fires and explosions, with an emphasis on combustible dust hazards and the prevention and mitigation of dust explosions.

Combustible dust hazards – in spite of their potentially severe explosion consequences – are not well-known or understood by many industrial practitioners. Improved education and communication avenues are key to creating heightened awareness. This particular module is aimed at raising awareness within one group of people in need of this information – undergraduate engineering students. Specific learning objectives have been developed as indicated in the next two slides.

Learning Objectives

- Remembering
 - Define combustible dust
 - Identify the three elements of the fire triangle and the five elements of the explosion pentagon
- Understanding
 - Explain how gaseous, liquid and solid fuels burn
 - Describe the fundamentals of a dust explosion according to the explosion pentagon
- Applying
 - Calculate the airborne concentration resulting from the dispersion of a dust, given its bulk density, ρ_s , layer thickness and enclosure height

This slide shows the module learning objectives for the first three levels in Bloom's Taxonomy. The evaluation section at the end provides a test of whether these learning objectives have been achieved following completion of the module.

Learning Objectives (Continued)

- Analyzing
 - Identify combustible dust hazards in a given example
- Evaluating
 - Determine appropriate prevention and mitigation strategies for a specific case study and explain reasoning
- Creating
 - Formulate a dust explosion prevention plan for a given scenario, taking into account each element of the explosion pentagon

This slide shows the module learning objectives for the next three levels in Bloom's Taxonomy. The evaluation section at the end provides a test of whether these learning objectives have been achieved following completion of the module.

Module Outline

- Basic Fire Principles
- Basic Explosion Principles
- Dust Explosion Fundamentals
- Fuel
- Ignition Source
- Oxidant
- Mixing
- Confinement
- Dust Layer Fires
- Prevention and Mitigation
- Case Studies
- Resources
- Evaluation

The module first provides an overview of the basic principles of fires and explosions. Dust explosion fundamentals are then introduced, followed by an examination of the five requirements for a dust explosion: fuel, ignition source, oxidant, mixing and confinement. The issue of dust layer fires is briefly covered and considerable time is spent discussing techniques for the prevention and mitigation of dust explosions. Three case studies are presented, helpful resources are indicated, and an evaluation of the achievement of learning objectives is conducted.

Basic Fire Principles | Basic Explosion Principles | Dust Explosion Fundamentals | Fuel | Ignition Source | Oxidant
Mixing | Confinement | Dust Layer Fires | Prevention and Mitigation | Case Studies | Resources | Evaluation

Basic Fire Principles



6

In this section we introduce some of the basic principles of fires. We begin with a look at the three elements of the fire triangle. Various flammability parameters are defined and the consequences of concern for fires are described. The section concludes with an examination of the types of fires typically encountered in the process industries, as well as examples of large-scale fires that have impacted our understanding of these events.

Much of the material in this section is drawn from the following reference:
Crowl, D. A. and Louvar, J. F., "Chemical Process Safety. Fundamentals with Applications", 3rd edition, Prentice Hall PTR, Upper Saddle River, NJ (2011).

Fire triangle elements

- Fire definitions
 - Chemical reaction (combustion) in which a substance combines with an oxidant and releases energy, part of which is used to sustain the reaction
 - Process of combustion characterized by heat, smoke, flame or any combination thereof
- Fuel – gas, liquid, solid
- Oxidant – gas, liquid, solid
- Ignition source – many types widely found in industry

The first definition of a fire comes from Crowl and Louvar (2011). This definition has the advantage of addressing the need for continuing reaction beyond the initial fuel/oxidant ignition. This additional requirement of a chemical chain reaction is sometimes represented as a fourth criterion in what is known as the fire tetrahedron. The second definition of a fire has been proposed by the UK Institution of Chemical Engineers, or IChemE, and has the advantage of addressing key consequences of concern for fires: damaging heat fluxes, toxic combustion products, and direct flame impingement.

The fuel for a fire can be in any of the gaseous, liquid or solid states. Examples include gasoline, wood dust and propane, respectively (Crowl and Louvar, 2011). Regardless of the original fuel state, actual combustion occurs homogeneously in the vapour phase. This is of course not an issue for gaseous fuels, but it means that liquid and solid fuels must first undergo phase transitions to vapours before combustion can occur. The heterogeneous combustion of fine carbon powder is one of the few exceptions to this requirement.

The oxidant also can be in any of the gaseous, liquid or solid states. Examples include fluorine, hydrogen peroxide and ammonium nitrite, respectively (Crowl and Louvar, 2011). By far, the most prevalent oxidant is oxygen – either on its own or more commonly in the ambient air.

Ignition sources are varied and widely available in industry. Common sources include open flames, hot surfaces, electric sparks and electrostatic discharges. In theory, removal of **any one** of the fire triangle elements will prevent a fire from occurring. In practice, however, reliance on removing **only one** of these elements is not undertaken as a primary line of defense against fires. This is

Flammability parameters

- Flash point: FP
- Vapour pressure: p^{sat}
- Lower flammability limit: LFL
- Upper flammability limit: UFL
- Flammability range: LFL → UFL
- Minimum ignition energy: MIE
- Autoignition temperature: AIT



5

It is important to recognize that, for the most part, the flammability parameters shown on this slide are not intrinsic material properties. However, when determined by qualified personnel using standardized test procedures and standardized equipment, they afford the best available information for understanding fire behaviour. The parameters presented here relate to the likelihood of occurrence component of risk.

Flash point (FP) is defined as the lowest temperature at which a liquid gives off sufficient vapour to form an ignitable mixture with air (Crowl and Louvar, 2011). From a safety perspective, one would want the flash point of a liquid fuel to be high. It should be noted that the flash point of some materials (e.g., octane with FP = 13.3 °C) is such that the risk will vary depending on geographical location and ambient conditions.

Vapour pressure (p^{sat}) is defined as the equilibrium pressure of a vapour above its liquid in a closed container. Although called "vapour" pressure, p^{sat} is a property of the liquid phase. It can be thought of as the driving force for evaporation of a liquid; therefore, from a safety perspective, one would want the vapour pressure of a liquid fuel to be low.

Gases, and vapours generated from liquids, are flammable only between certain concentrations (typically specified as volume percentages in air). The lowest concentration at which such fuels will burn is called the lower flammability (flammable) limit (LFL), or the lean limit. Similarly, the highest concentration at which such fuels will burn is called the upper flammability (flammable) limit (UFL), or the rich limit. The spread between the lower and upper limits is the flammability range. Ideally the LFL will be high and the flammability range narrow. Fortunately, the flammability range is indeed narrow for most hydrocarbons (e.g., 2.2 % - 9.5 % for propane). Acetylene on the other hand has a wide range from 2.5 % - 80.0%.

Minimum ignition energy (MIE) is the lowest electric spark energy that will ignite a given fuel/air mixture. Autoignition temperature (AIT) applies to a different ignition scenario, and is defined as the temperature above which sufficient energy is available in the oxidizing environment to ignite a given fuel/air mixture.

In later sections of the module we will look at other parameters such as limiting oxygen concentration

Fire consequences

- Flame
- Heat
- Smoke



The Other Side



One Side of the Chevron Richmond Refinery Fire

There are several consequences that can result from a process fire.

Flame temperatures for many materials (e.g., solvents) are around 1000 °C (Crowl and Louvar, 2011). Direct flame impingement is therefore extremely harmful. Given the magnitude of these temperatures, radiation is a dominant heat transfer mechanism and heat fluxes can rapidly escalate to levels where damage occurs (e.g., cabling can be damaged by a heat flux of only 2 kW/m²). Additionally, smoke and other combustion products (some toxic) can impair human health and impede evacuation and rescue efforts.

The slide shows two sides of a poster handed out by a concerned citizens group at the April 19, 2013 public hearing of the US Chemical Safety Board in the matter of the Chevron Richmond Refinery fire. Quoting from the CSB investigation report (CSB, "Interim Investigation Report. Chevron Richmond Refinery Fire", U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2013)):

On August 6, 2012, the Chevron U.S.A. Inc. Refinery in Richmond, California, experienced a catastrophic pipe failure in the #4 Crude Unit. The pipe ruptured, releasing flammable, hydrocarbon process fluid which partially vaporized into a large vapor cloud that engulfed nineteen Chevron employees. All of the employees escaped, narrowly avoiding serious injury. The flammable portion of the vapor cloud ignited just over two minutes after the pipe ruptured. The ignition and subsequent continued burning of the hydrocarbon process fluid resulted in a large plume of unknown and unquantified particulates and vapor traveling across the Richmond, California, area. In the weeks following the incident, approximately 15,000 people from the surrounding area sought medical treatment due to the release.

On "one side" of the poster, you can see the refinery flare on the right and the hydrocarbon combustion plume on the left. The "other side" of the poster gives a sober reminder of the fragile social license under which the chemical process industries operate.

Fire types

- Pool fire
- Jet fire
- Fireball
- Flash fire
- Dust layer fire



Pool Fire



Jet Fire

10

Some of the more common process fires are identified in this slide. The handbook by Nolan is a helpful resource on this topic: Nolan, D.P., "Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical, and Related Facilities", 2nd edition, Gulf Professional Publishing/Elsevier, Burlington, MA (2011). Also helpful is the guideline produced by the Center for Chemical Process Safety of the American Institute of Chemical Engineers: CCPS, "Guidelines for Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities", American Institute of Chemical Engineers, New York, NY (2003).

As the name implies, a pool fire occurs when a pool of liquid (actually the vapour just above the liquid surface) ignites. Further vapour is rapidly generated from the pool as it is heated by the flame through convective and radiative transfer mechanisms (Nolan, 2011).

A jet fire is a pressurized stream of combustible gas or atomized liquid that is burning, such as might occur as a result of a rupture in a high-pressure pipeline (Nolan, 2011). Strong momentum vectors are associated with jet fires.

A fireball is defined in CCPS (2003) as *an intense spherical flame resulting from a sudden release of pressurized liquid or gas that is immediately ignited*. Fireballs are most commonly caused by BLEVEs, which are described in the next module section.

A flash fire occurs when a combustible gas release forms a plume or cloud that is not immediately ignited. The cloud will disperse according to the prevailing weather conditions; if ignition occurs without an ensuing explosion, the cloud will burn as a flash fire that rapidly consumes the gas (Nolan, 2011). Under these circumstances, the degree of confinement plays a key role in determining whether a flash fire or vapour cloud explosion occurs. Flash fires can also occur with combustible dusts, as discussed later in the module.

Dust layer fires are covered in a later section of the module.

Fire examples



Piper Alpha



Buncefield



Deepwater Horizon

11

This slide shows three major process incidents involving fires that were all initiated by explosions. Numerous references are available for each incident; a simple internet search will generate multiple sources.


Piper Alpha was an offshore production platform in the North Sea. On July 6, 1988, explosions and subsequent oil and gas fires killed 167 men and destroyed the facility.

Buncefield is an oil storage depot in Hertfordshire, UK. On December 11, 2005, a petrol (gasoline) vapour cloud explosion and subsequent fire caused several injuries, significant asset damage, and substantial business interruption.

Deepwater Horizon was an offshore production platform in the Gulf of Mexico. On April 20, 2010, a gas explosion and ensuing fire killed 11 workers and caused enormous environmental losses.

Basic Fire Principles **Basic Explosion Principles** Dust Explosion Fundamentals Fuel Ignition Source Oxidant
Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Basic Explosion Principles



12

In this section we introduce some of the basic principles of explosions. We begin with a look at the five elements of the explosion pentagon. Various explosibility parameters are defined and the consequences of concern for explosions are described. An examination is then undertaken of the types of explosions typically encountered in the process industries, as well as examples of large-scale explosions that have impacted our understanding of these events. The section concludes with an explanation of the relationship between fires and explosions, and the importance of considering whether domino or knock-on effects are possible in a given scenario.

Note that confinement does not need to be complete for a fast-burning flame to transition to an explosion, regardless of fuel type. Partial confinement and turbulence-generating obstacles leading to a high degree of congestion can also be effective in this regard. These points are further explained later in the module.

Much of the material in this section is drawn from the following reference:
Crowl, D. A. and Louvar, J. F., "Chemical Process Safety. Fundamentals with Applications", 3rd edition, Prentice Hall PTR, Upper Saddle River, NJ (2011).

Explosion pentagon elements

- Explosion definition
 - Rapid expansion of gases resulting in rapidly moving pressure or shock wave
 - Expansion can be mechanical (e.g., rupture of pressurized cylinder) or result of rapid chemical reaction
 - Explosion damage caused by pressure or shock wave that does work on its surroundings
- Fuel – as per fire triangle
- Oxidant – as per fire triangle
- Ignition source – as per fire triangle
- Mixing – of fuel and oxidant
- Confinement – for overpressure development

13

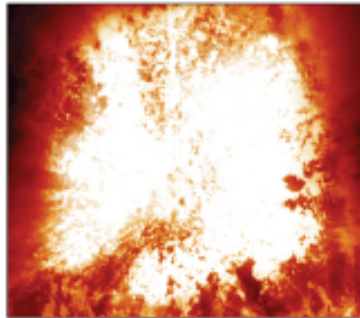
The defining features of an explosion are drawn from Crowl and Louvar (2011). Perhaps the most fundamental point to be made is that thermodynamically, in moving from the initial pre-explosion state to the final post-explosion state, mechanical work is done by the exploding system on its surroundings. This is primarily what distinguishes a fire from an explosion. (See also the second-last slide in this section where this distinction is made in the equivalent terms of energy release rate.)

The explosion pentagon includes the three elements of the fire triangle, with the two additional requirements of mixing of the fuel and oxidant, and sufficient confinement of the reacting mixture to generate a destructive overpressure.

The explosion pentagon elements are examined later in considerable detail for the unique category of explosions involving combustible dust.

Explosibility parameters

- Maximum explosion pressure: P_{\max}
- Maximum rate of pressure rise: $(dP/dt)_{\max}$
- Volume normalized maximum rate of pressure rise: K_G for gases and K_{St} for dusts



14

As was the case for the flammability parameters discussed in the previous section, it is important to recognize that the explosibility parameters shown on this slide are not intrinsic material properties. However, when determined by qualified personnel using standardized test procedures and standardized equipment, they afford the best available information for understanding explosion behaviour. The parameters presented here relate to the severity of consequences component of risk.

Many of the other parameters discussed in the previous section on flammability are applicable to the current consideration of explosibility parameters (although from the perspective of likelihood of occurrence of an explosion). This would include, for example, the lower flammability limit (LFL) and minimum ignition energy (MIE).

Maximum explosion pressure (P_{\max}) is the peak overpressure attained in a constant-volume explosion by a given fuel/air system. P_{\max} is a thermodynamic parameter that depends largely on the initial and final conditions of the reacting mixture. Typical units of P_{\max} are bar(gauge) or bar(g).

Similarly, maximum rate of pressure rise ($(dP/dt)_{\max}$) is the peak rate of pressure rise attained in a constant-volume explosion by a given fuel/air system. $(dP/dt)_{\max}$ is a kinetic parameter that can be significantly influenced by mixture and boundary conditions enroute to the completion of reaction. Typical units of $(dP/dt)_{\max}$ are bar/s.

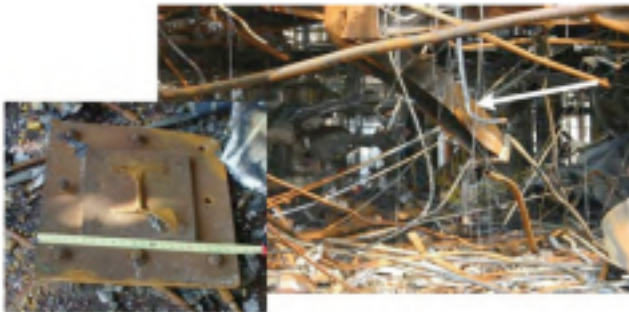
Rates of pressure rise are of course dependent on the volume in which the explosion occurs. In an attempt to volume-normalize the maximum rate of pressure rise, a cubic relationship has been developed to define the parameters K_G (for gases) and K_{St} (for dusts) as the product of the maximum rate of pressure rise and the cube-root of the volume in which the explosion occurs. Units of K_G and K_{St} are therefore bar·m/s. A full explanation of the use and validity of the cubic relationship is beyond the scope of the current module.

Explosion consequences

- Overpressure →
- Missile fragments ↓



Heat Exchanger Rupture



Support Column Sheared Off Baseplate

15

As previously described, it is the work done by the pressure or shock wave that causes damage in an explosion. Destructive overpressures can threaten the integrity of the enclosure in which the explosion occurs, or can travel over distance and damage nearby equipment. An additional consequence could be the generation of missile fragments that can cause structural damage and harm to personnel. Also, consequences related to flame, heat and smoke will be pertinent if the explosion involves combustible material.

The right-hand photograph in the slide shows some of the damage resulting from overpressurization and subsequent rupture of a heat exchanger. There was no chemical reaction involved in this explosion.

(Source: CSB, "Case Study. Heat Exchanger Rupture and Ammonia Release in Houston, Texas. The Goodyear Tire and Rubber Company", No. 2008-06-I-TX, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).)

The lower photograph in the slide shows damage that occurred as a result of a runaway chemical reaction and subsequent explosion of a residue treatment tank. Missile fragments from the tank struck the structural column (indicated by the white arrow in the photograph), shearing the column off from the steel baseplate also shown in the photograph.

(Source: CSB, "Investigation Report. Pesticide Chemical Runaway Reaction. Pressure Vessel Explosion. Bayer CropScience, LP", Report No. 2008-08-I-WV, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).)

Explosion types

■ General categories

- Physical
- Chemical



BLEVE

■ Speed of reaction front

- Deflagration
- Detonation

16

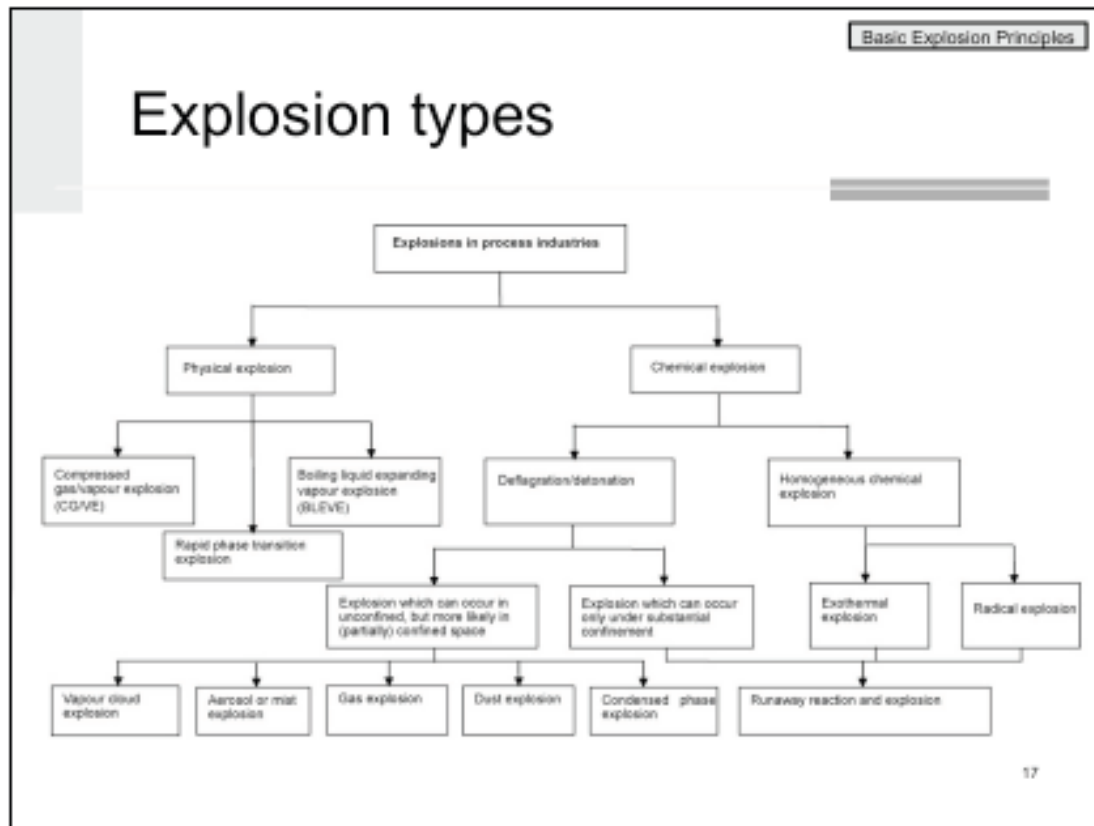
The broadest way to categorize explosions is by whether there is a chemical reaction involved. Physical (or mechanical) explosions result from the sudden failure of a vessel containing a non-reactive gas under high pressure (Crowl and Louvar, 2011). Chemical explosions, as the name implies, involve a chemical reaction. As we will see shortly, a dust explosion is a chemical explosion because it involves a chemical reaction – in this case, a propagating combustion reaction that is transmitted spatially through the reaction mass.

A somewhat special class of explosion is the BLEVE – Boiling-Liquid Expanding-Vapour Explosion. An excellent description of this event is given by Crowl and Louvar (2011): *A BLEVE occurs if a vessel that contains a liquid at a temperature above its atmospheric pressure boiling point ruptures. The subsequent BLEVE is the explosive vaporization of a large fraction of the vessel contents; possibly followed by combustion or explosion of the vaporized cloud if it is combustible. This type of explosion occurs when an external fire heats the contents of a tank of volatile material. As the tank contents heat, the vapor pressure of the liquid within the tank increases and the tank's structural integrity is reduced because of the heating. If the tank ruptures, the hot liquid volatilizes explosively.*

Thus, a BLEVE may be a purely physical explosion with no chemical reaction if the liquid is non-reactive. If, however, the liquid is combustible, then the physical phenomena associated with a BLEVE will quickly devolve to a reaction scenario that leads to a chemical explosion and/or fireball. This is essentially the situation depicted in the photograph shown in the slide. On November 19, 1984, the PEMEX LPG (Liquefied Petroleum Gas) terminal in Mexico City experienced a series of BLEVEs that resulted in over 600 fatalities and over ten times that number in injuries.

For chemical explosions, a further distinction based on the speed of the reaction (flame) front is important. In a deflagration, the reaction front travels at subsonic speed; in a detonation, the reaction front moves at sonic or supersonic speed (relative to the speed of sound in the unreacted medium). Thus, a deflagration is characterized by the flame front trailing behind the shock wave produced by the explosion; detonations involve coupling of the reaction front and shock wave and can lead to overpressures significantly higher than those experienced with deflagrations.

Explosion types



17

The classification scheme given in this slide has been proposed by: Abbasi, T., Pisman, H.J. and Abbasi, S.A., "A Scheme for Classification of Explosions in the Chemical Process Industry", *Journal of Hazardous Materials*, **174**, 270-280 (2010).

Look back over the past few slides in this section. You should find that the current slide is generally consistent with the previous discussion.

The next module section commences our detailed examination of dust explosions. According to the above figure from Abbasi et al. (2010), dust explosions are chemical explosions that occur as either deflagrations or detonations and are more likely to occur in an at least partially confined space than in an unconfined environment. The only caveat we would add to this description is that dust detonations, although not unknown, are quite uncommon. The vast majority of dust explosions occur as deflagrations.

Explosion examples



Flixborough



Toulouse AZF

BP Texas City



15

This slide shows three major process incidents involving explosions. Numerous references are available for each incident; a simple internet search will generate multiple sources.

The Flixborough (UK) Works of Nypro Limited was a manufacturer of caprolactam – a raw material for nylon production (Crowl and Louvar, 2011). On June 1, 1974, a cyclohexane vapour cloud explosion killed 28 workers, injured 36 others, and destroyed the facility.

AZF operated a fertilizer plant in Toulouse, France. On September 21, 2001, an ammonium nitrate explosion killed 31 people, injured countless others, and caused significant damage at the plant site and in the surrounding community.

The BP Texas City Refinery is located in Texas City, Texas. On March 23, 2005, a hydrocarbon vapour cloud explosion occurred, killing 15 workers, injuring 180 other people, and causing widespread facility damage.

Fires ↔ explosions

The major distinction between fires and explosions is the rate of energy release. Fires release energy slowly, whereas explosions release energy rapidly.

Fires can also result from explosions, and explosions can result from fires.

A good example of how the energy release rate affects the consequences of an accident is a standard automobile tire. The compressed air within the tire contains energy. If the energy is released slowly through the nozzle, the tire is harmlessly deflated. If the tire ruptures suddenly and all the energy within the compressed tire releases rapidly, the result is a dangerous explosion.

19

This slide gives three quoted passages from Crowl and Louvar (2011). The explanations and analogies are complementary to the discussion in the current and previous module sections.

Fires are different from explosions; both, however, can cause harm to people, asset damage, business interruption, and degradation of the environment.

Domino effects

| Primary Scenario | Escalation Vector | Expected Secondary Scenario ^a |
|--|----------------------------------|---|
| Pool fire | Heat radiation, fire impingement | Jet fire, pool fire, BLEVE, toxic release |
| Jet fire | Heat radiation, fire impingement | Jet fire, pool fire, BLEVE, toxic release |
| Fireball | Heat radiation, fire impingement | Tank fire |
| Flash fire | Fire impingement | Tank fire |
| Mechanical explosion ^b | Fragments, overpressure | All ^c |
| Confined explosion ^b | Overpressure | All ^c |
| BLEVE (boiling liquid expanding vapour explosion) ^b | Fragments, overpressure | All ^c |
| VCE (vapour cloud explosion) | Overpressure, fire impingement | All ^c |
| Toxic release | – | – |

^aExpected scenarios also depend on the hazards of the target vessel inventory.

^bFollowing primary vessel failure, further scenarios may occur (e.g., pool fire, fireball, toxic release).

^cAny of the scenarios listed in the first column (primary scenario) may be triggered by the escalation vector.

20

The table in this slide is drawn from: Cozzani, V., Gubinelli, G. and Salzano, E., "Escalation Thresholds in the Assessment of Domino Accidental Events", *Journal of Hazardous Materials*, **129**, 1-21 (2006).

We present this slide to further illustrate the relationship between fires and explosions (as well as toxic releases, which are outside the scope of the current module). An additional objective is to summarize the module content to this point before moving on to specific discussion of dust explosions. There is a lot of information in this slide; study it carefully to reinforce your understanding of the basic principles of fires and explosions.

Domino or knock-on effects occur when a "primary" event propagates by means of an escalation vector to nearby equipment or facilities, and triggers one or more "secondary" events. As we will see later in the module, dust explosions typically occur via the domino sequence of a primary event (explosion or otherwise) and then a secondary dust explosion. This is consistent with the table shown in the slide, given that the classification of confined explosion (primary scenario) includes dust explosions.

Basic Fire Principles Basic Explosion Principles **Dust Explosion Fundamentals** Fuel Ignition Source Oxidant
Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Dust Explosion Fundamentals



Play Video 

21

This section examines the fundamentals of dust explosions. We first reintroduce the fire triangle and explosion pentagon, and describe how dusts explode. We then go over dust explosion testing and explosibility parameters, as well as some engineering standards associated with dust explosions.

Play the video embedded in the current slide; you will see an actual dust explosion. The apparatus shown is a device known as the MIKE3, housed in the Dust Explosion Research Laboratory at Dalhousie University. Watch carefully and you will see the formation of a cloud of polyester dust, ignition by electric spark, and subsequent flame propagation.

Dust can explode!



Methane-triggered coal dust explosion - Westray Coal Mine (26 fatalities)



Aluminum dust explosion - Hayes Lemmerz International - Huntington (1 fatality)



Polyethylene dust explosion - West Pharmaceuticals (6 fatalities)



Sugar dust explosion - Imperial Sugar Company (14 fatalities)

22

Dusts can explode. This is a surprising fact to some people but it should not be a surprise to those who handle and process combustible dusts in industry. The slide gives four examples of process incidents to illustrate that dust explosions can and do occur, and that the consequences can be devastating. Unfortunately there are many more dust explosion incident descriptions available in the public domain literature. Other examples are given throughout the module.

Of the incidents shown on the slide, Westray and Imperial Sugar are examined in greater detail in the Case Studies section; West Pharmaceuticals is the subject of one of the exercises in the Evaluation section.

Photographs

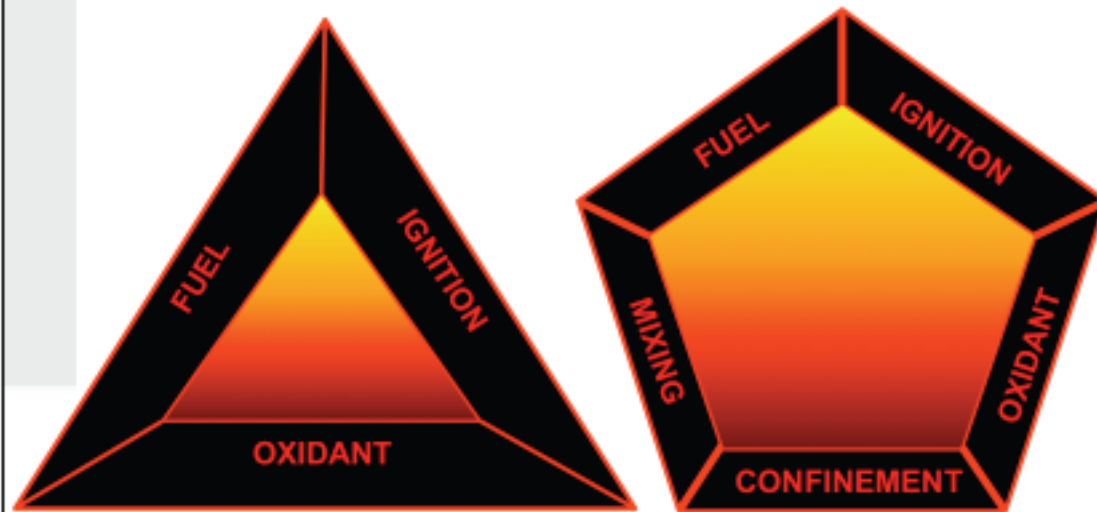
Top Left: Richard, K.P., Justice, "The Westray Story – a Predictable Path to Disaster. Report of the Westray Mine Public Inquiry", Province of Nova Scotia, Halifax, NS (1997).

Top Right: CSB, "Investigation Report. Aluminum Dust Explosion. Hayes Lemmerz International-Huntington, Inc.", Report No. 2004-01-I-IN, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2005).

Bottom Left: CSB, "Investigation Report. Dust Explosion. West Pharmaceutical Services, Inc.", Report No. 2003-07-I-NC, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2004).

Bottom Right: CSB, "Investigation Report. Sugar Dust Explosion and Fire. Imperial Sugar Company", Report No. 2008-05-I-GA, U.S. Chemical Safety and Hazard

Fire triangle and explosion pentagon



23

Recall the previous discussion concerning the fire triangle and explosion pentagon elements. In a dust fire or explosion, the fuel is of course a solid. It is therefore possible for combustible dust to form layers on equipment and facility surfaces; these layers may burn but they will not explode.

The mixing criterion introduces perhaps the most fundamental difference between gas and dust explosions – again based on the physical state of the fuel. In a dust/air mixture, the dust particles are strongly influenced by gravity; an essential prerequisite for a dust explosion is therefore the formation of a dust/oxidant suspension. An airborne dust cloud will either burn as a flash fire or will explode depending on the degree of confinement.

As noted previously, confinement does not need to be complete for a fast-burning flame to transition to an explosion, regardless of fuel type. Partial confinement and turbulence-generating obstacles leading to a high degree of congestion can also be effective in this regard.

Later in the module, we will examine in detail each element of the dust explosion pentagon as well as the special case of dust fires. Before doing that, let's look at a practical example of the dust explosion pentagon in the next slide.

Hammermill – pentagon in practice



24

A hammermill is a process unit used for pulverizing raw material. The slide shows a hammermill (with the cover open) used in a wood-processing facility to accomplish size reduction of sawdust and wood chips (FUEL). Magnetic devices are placed on the feed side of the mill to prevent tramp metal from entering (IGNITION SOURCE). Inside the hammermill, the pulverizing process produces a cloud (MIXING) of wood dust and air (OXIDANT). With the cover closed (CONFINEMENT), the pentagon is complete.

In spite of all best efforts to remove potential ignition sources, hammermills are prone to experience dust explosions. They are therefore designed and built strong enough to withstand the overpressure originating from such an event inside them.

Photograph: Amyotte, P.R., Pegg, M.J., Khan, F.I., Nifuku, M. and Yingxin, T., "Moderation of Dust Explosions", *Journal of Loss Prevention in the Process Industries*, 20, 675-687 (2007).

How dusts explode

- Chemical explosion
 - Propagating combustion reaction
- Reaction mechanism
 - Dust/air mixture heterogeneous; reaction may be heterogeneous (few) or homogenous (most)
 - Most dusts explode as gas explosions
 - Volatiles from solid material
- Explosion: **FUEL** (dust) and **OXIDANT** are **MIXED**, ignited by **IGNITION SOURCE**, and sufficient **CONFINEMENT** results in overpressure development

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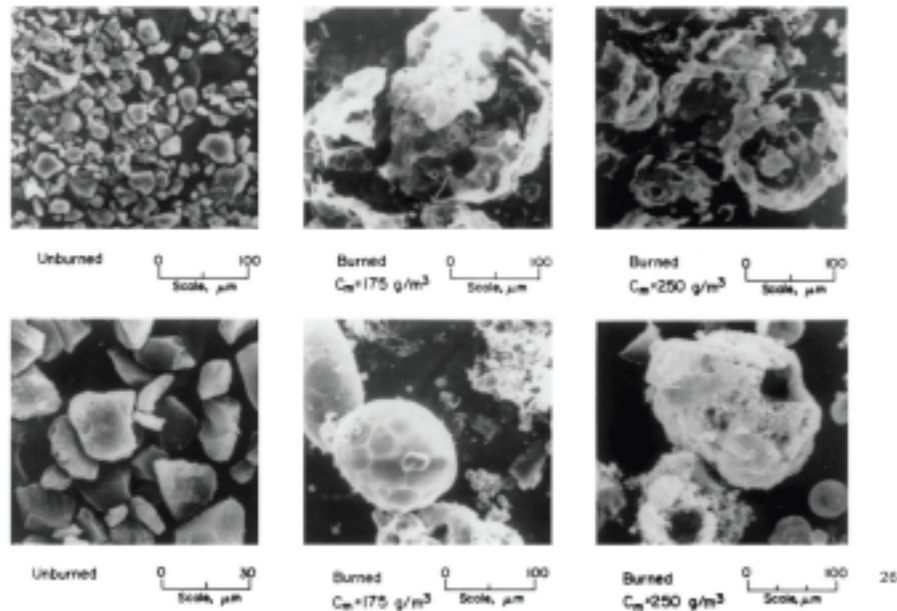
A dust explosion occurs as a result of a chemical reaction (combustion), which is propagated or transmitted spatially through the reaction mass. A dust explosion is therefore a chemical explosion as opposed to a physical explosion.

A dust/air mixture is heterogeneous (two phases). The combustion reaction can be either heterogeneous or homogeneous (one phase). However, only a few dusts undergo heterogeneous combustion, such as the reaction of fine carbon dust with gaseous oxygen.

The vast majority of dust explosion reactions are homogeneous. In these cases, the dust explosion actually occurs as a gas explosion following the generation of volatile matter from the solid dust. Using the example of polyethylene plastic, the plastic would first melt and vapourize, creating a gaseous fuel that would undergo homogeneous combustion with oxygen. This is a step-wise process that may involve the additional complication of a solid, outer oxide layer as in the case of some metals such as aluminum. The next slide shows evidence of this reaction sequence for an organic dust (coal).

Globally – as per the explosion pentagon we have seen previously – the dust and oxidant mix, and the airborne cloud is ignited by an ignition source. Sufficient confinement results in overpressure development from the reaction. The result is an explosion with potentially destructive capabilities.

How coal dust explodes



Coal dust explodes in a sequence involving heating to the point of pyrolysis followed by ignition of the evolved volatile matter and subsequent gas-phase flame propagation.

The slide shows scanning electron microscope (SEM) pictures of Pittsburgh seam bituminous coal dust before and after explosion in a laboratory-scale chamber. The burned char residue is seen to consist of rounded particles (or censpheres), some of which have become fractured or display "blow holes" from which volatiles have been emitted. It is these volatiles that burn in a coal dust explosion leading to increased temperature and pressure in an enclosed volume.

Photograph: Cashdollar, K.L., "Overview of Dust Explosibility Characteristics," *Journal of Loss Prevention in the Process Industries*, 13, 183-199 (2000).

Note that C_m is the dust cloud concentration at the time of explosion.

Dust explosion parameters

- Laboratory-scale testing can determine dust explosion parameters for hazard/risk determination
- Likelihood of occurrence
 - MEC: Minimum Explosible Concentration
 - MIE: Minimum Ignition Energy
 - MIT: Minimum Ignition Temperature
 - LOC: Limiting Oxygen Concentration
- Severity of consequences
 - P_{max} : Maximum explosion pressure
 - $(dP/dt)_{max}$: Maximum rate of pressure rise
 - $K_{St} = (dP/dt)_{max} \cdot V^{1/3}$

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Text books and data bases can be helpful as indicators of explosibility, but they cannot be seen as a substitute for actual test data on the material being processed. The next slide shows some of the standards and laboratory-scale equipment available for acquiring data for the various explosion parameters shown in the current slide.

Each of these parameters can be categorized according to one of the two components of risk – likelihood of occurrence or severity of consequences. As such, their usefulness lies in developing adequate measures for either the prevention or mitigation of a dust explosion. As we will see in detail later in the module, there are several ways to reduce dust explosion risk once the basic explosibility parameters shown in this slide are known.

Likelihood of Occurrence

MEC, or minimum explosible concentration, is the term used for the LFL, or lower flammability limit, of a dust cloud. Typical units of MEC are g/m³.

MIE, or minimum ignition energy, is (according to the definition previously given) the minimum electric spark energy that will ignite a dust cloud. Typical units of MIE are J.

MIT, or minimum ignition temperature, is the term used for the AIT, or autoignition temperature of a dust cloud. (MIT is sometimes called MAIT, or minimum autoignition temperature). Typical units of MIT are °C.

[There is another minimum ignition temperature parameter for dust layers called the LIT, or layer ignition temperature. Typical units of LIT are °C.]

LOC, or limiting oxygen concentration, is the minimum oxygen concentration in the atmosphere required for flame propagation in a dust cloud. Typical units are volume %.

Severity of Consequences

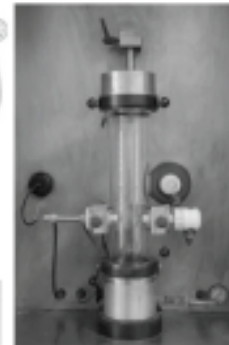
P_{max} , $(dP/dt)_{max}$ and K_{St} are all as previously defined with the previously identified typical units. Note that in K_{St} the St subscript comes from the first two letters of the German word for dust (*staub*).

Testing standards and equipment

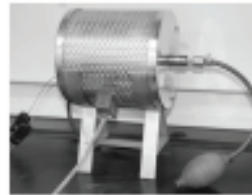
- ASTM E1226-12a: Standard Test Method for Explosibility of Dust Clouds
- ASTM E1515-07: Standard Test Method for Minimum Explosible Concentration of Combustible Dusts
- ASTM E2019-03 (2013): Standard Test Method for Minimum Ignition Energy of a Dust Cloud in Air
- ASTM E1491-06 (2012): Standard Test Method for Minimum Autoignition Temperature of Dust Clouds



20-L Apparatus



MIKE3 Apparatus



BAM Oven

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This slide shows examples of ASTM International testing standards as well as dust explosion test equipment manufactured by Kuhner AG in Basel, Switzerland. There are other global testing standards and manufacturers of laboratory-scale dust explosion equipment.

P_{max} , $(dP/dt)_{max}$ and K_{st} can be determined according to ASTM E1226 in the 20-L apparatus (or 20-L Siwek chamber, after its designer).

MEC can be determined according to ASTM E1515 in the 20-L apparatus.

MIE can be determined according to ASTM E2019 in the MIKE3 apparatus.

MIT can be determined according to ASTM E1491 in the BAM oven.

As indicated in the Resources section of the module, these and other testing standards are available on the ASTM International web site.

Risk control standards

- NFPA 61 – Agriculture and Food Industries
- NFPA 68 – Deflagration Venting
- NFPA 69 – Prevention Systems
- NFPA 120 – Coal Mines
- NFPA 484 – Combustible Metals
- NFPA 499 – Electrical Installations
- NFPA 654 – Manufacturing, Processing and Handling Dusts
- NFPA 664 – Wood Processing

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The National Fire Protection Association (United States) has published several standards relating to the prevention and mitigation of dust explosions:

NFPA 61 – Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities

NFPA 68 – Standard on Explosion Protection by Deflagration Venting

NFPA 69 – Standard on Explosion Prevention Systems

NFPA 120 – Standard for Fire Prevention and Control in Coal Mines

NFPA 484 – Standard for Combustible Metals

NFPA 499 – Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas

NFPA 654 – Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids

NFPA 664 – Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities

As indicated in the Resources section of the module, these and other risk control standards are available on the NFPA web site.

Similar to the testing standards listed on the previous slide, there are other global risk control standards. Examples include the European (EN) Standards and the VDI Guidelines in Germany. The Health and Safety Executive or HSE (United Kingdom) web site (www.hse.gov.uk) gives a good overview of two European Directives for controlling explosive atmospheres – ATEX 95 (ATEX Equipment Directive) and ATEX 137 (ATEX Workplace Directive).

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals **Fuel** Ignition Source Oxidant
Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Element 1 of 5 – Fuel

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This section covers dust as a fuel source. Combustible dust is defined, including conditions of particle size and shape, and examples of combustible dusts and typical process units that experience dust explosions are given. Dust layers and airborne concentrations arising from layers are described. Finally, the unique fuel system known as a hybrid mixture is examined.

Dust and combustible dust

- NFPA definition of dust
 - Any finely divided solid, 500 μm or less in diameter
- NFPA definition of combustible dust
 - A combustible particulate solid that presents a fire or deflagration hazard when suspended in air or some other oxidizing medium over a range of concentrations, regardless of particle size or shape.

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The NFPA distinguishes between a dust and a combustible dust. By these definitions, not all dusts are combustible dusts and not all combustible dusts are dusts!

Confusing? A bit perhaps, but the takeaway lesson here is that the important definition for our purposes is **combustible dust**. Throughout this module, whenever the word dust is used, it should be taken to mean a combustible dust as per the above NFPA definition.

One should not view a defined boundary of 500 μm as a sharp delineation between dusts that are explosible and those that are non-explosible. What determines whether a given particulate material represents a dust explosion hazard is its actual chemical composition in addition to physical parameters such as particle size and particle shape.

Examples of combustible dusts

- Coal and coal products
- Food products
- Metals and alloys
- Rubber and plastics
- Wood products
- Textiles
- Pharmaceuticals
- Pesticides



DeBruce Grain Elevator Explosion

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Combustible dusts can be found across many industries. The following is a list of just some of the many types of combustible dusts: coal and coal products such as activated carbon, bituminous coal and pulverized coal; food products such as grain dust, flour, sugar, coffee and dextrose; metals and alloys such as aluminum, bronze, silicon, zinc and titanium; rubber, plastics, polymer and resins; wood and paper; cotton and wool; pharmaceuticals; pesticides.

Because dust explosions arise from the reaction of a fuel with oxygen to generate oxides and heat, they cannot occur with materials that are already stable oxides (such as silicates and carbonates).

References for this slide and further examples can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

Photograph: Kauffman, C.W., "The DeBruce Grain Elevator Explosion", Proceedings of the Seventh International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions, Volume III, St. Petersburg, Russia (July 7-11, 2008), pp. 3-26.

Examples of process units

- Silos
- Hoppers
- Dust collectors
- Grinders
- Dryers
- Furnaces
- Mixers
- Pulverizing units
- Conveying systems



Bucket Elevator

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The previous list of combustible dusts largely defines the industrial plant in which dust explosions are most commonly experienced. Examples of process units that have been subject to the dust explosion problem are given in this slide. Dust collectors are arguably the most at risk in this regard.

References for this slide and further examples can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

How much layered dust is too much?



Sugar dust accumulation on steel belt drive motor



Cornstarch accumulation under cornstarch silo

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Dust explosions occur either inside process vessels in which a dust cloud already exists, or as a result of a dust cloud formed by dispersion of a dust layer. (These mechanisms are treated in more detail later in the module.)

For the latter case, how thick a dust layer is needed to support a dust explosion if the layer forms an airborne cloud? The answer is not very thick – typically on the order of a millimeter or so.

In general, there is too much layered dust if it creates an opaque layer over the surface; for example – if you can't tell the colour of the surface beneath the layer. Or, there is too much layered dust if you can leave visible markings in the dust, such as leaving footprints or being able to write your initials or "clean me" in the dust.

The slide gives two examples of dust layers. The photograph on the right shows a significant spill, which would easily be considered "too much". The photograph on the left shows a much thinner dust layer, but it too would be considered "too much".

Photographs: CSB, "Investigation Report. Sugar Dust Explosion and Fire. Imperial Sugar Company", Report No. 2008-05-I-GA, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2009).

Calculation of dust concentration

$$C = \rho_{\text{bulk}} (h/H)$$

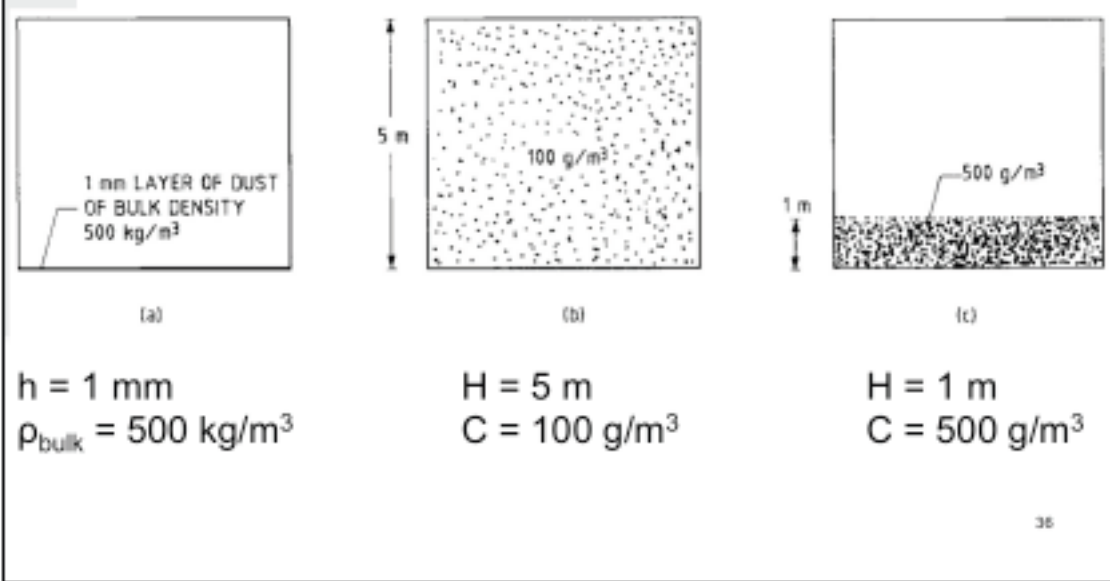
- C = dust concentration
- ρ_{bulk} = bulk density of dust layer
- h = thickness of dust layer
- H = height of dust cloud produced from dust layer

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The concentration of a dust cloud resulting from dispersion of a dust layer in air can be determined by the equation shown in the slide. This is an estimate that assumes complete, uniform dust dispersion. Nevertheless, this simple expression is helpful in demonstrating that very thin layers of combustible dust can be hazardous. An example of the use of this equation is given in the next slide.

Equation Source: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Example: $C = \rho_{\text{bulk}} (h/H)$



The figure in the slide shows two scenarios for a given dust layer thickness (1 mm) and bulk density (500 kg/m³).

With uniform dispersion throughout a 5-m high enclosure, the resulting dust cloud will have an average concentration of 100 g/m³. Such a concentration is of the order of the minimum amount required to initiate an explosion – i.e., the MEC – for many dusts.

With only partial dispersion up to 1 m above the enclosure floor, the resulting dust cloud will have an average concentration of 500 g/m³. Such a concentration is of the order of the optimum concentration – i.e., the concentration producing the most destructive overpressures and rates of pressure rise – for many dusts.

Figure: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Particle size

- In general, as particle size of a given dust decreases, there is an increase in both explosion severity and likelihood
 - P_{\max} increases
 - K_{St} increases (potentially significantly)
 - MEC, MIE and MIT all decrease
 - Smaller particle → larger surface area → higher reactivity
- For nanomaterials, testing to date indicates an increase in explosion likelihood but no significant increase in severity
 - Limited severity effect likely caused by particle agglomeration during dispersion

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The particle size of a given combustible dust has a significant influence on its explosibility. In general, a decrease in particle size has been shown to increase the likelihood of occurrence of a dust explosion as well as its consequence severity. P_{\max} increases. $(dP/dt)_{\max}$ and hence K_{St} also increase; this increase can potentially be substantial. MEC, MIE and MIT all decrease with decreasing particle size. This is due to surface area effects – a smaller particle means a larger surface area and therefore enhanced reactivity. The fine particles (typically $< 75 \mu\text{m}$) in a wide particle size distribution make the greatest contribution to dust reactivity and explosibility.

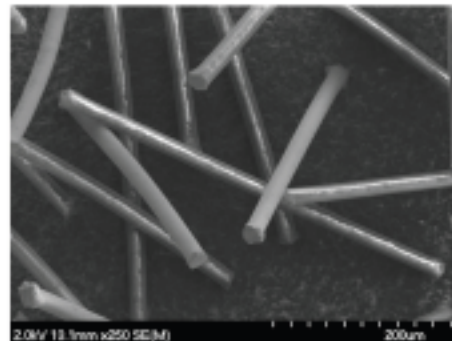
One exception to this general behaviour is nanomaterials. Although only limited test results are currently available, as particle size decreases into the nano-range, there appears to be no significant increase in explosion severity – yet explosion likelihood can increase dramatically. Nanomaterials are extremely sensitive, and may self-ignite under certain testing and handling conditions. Agglomeration of primary nanoparticles into micron-size aggregates during dust dispersion is thought to be responsible for the limited increase in P_{\max} and K_{St} .

Particle shape

- Non-spherical particles can be combustible
 - Flake-like particles
 - Flocculent particles (fibers with L/D ratio)



Wood Fibers



Nylon Flock

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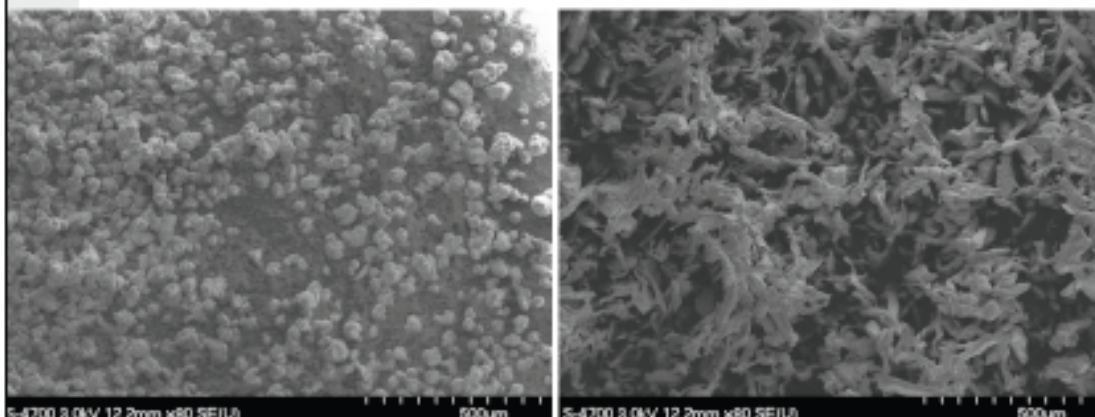
Dust particles do not need to be spherical or near-spherical to be combustible. Flake-like particles and flocculent materials (fibrous materials better characterized by a length-to-diameter ratio than a particle diameter) can also pose an explosion hazard.

The slide gives two photographs. The one on the left (taken with a normal digital camera) shows combustible wood fibers. The SEM image on the right shows combustible nylon (polyamide 6.6) flock.

Photograph (Left): Amyotte, P.R., Cloney, C.T., Khan, F.I. and Ripley, R.C., "Dust Explosion Risk Moderation for Flocculent Dusts", *Journal of Loss Prevention in the Process Industries*, 25, 862-869 (2012).

Photograph (Right): Iarossi, I., Amyotte, P.R., Khan, F.I., Marmo, L., Dastidar, A.G. and Eckhoff, R.K., "Explosibility of Polyamide and Polyester Fibers", *Journal of Loss Prevention in the Process Industries*, 26, 1627-1633 (2013).

Both of these dusts are combustible



Spherical Polyethylene

Fibrous Polyethylene

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Each of the spherical and fibrous polyethylene samples shown in the SEMs on this slide pass through a 200-mesh sieve, and are therefore nominally $< 75 \mu\text{m}$ in size. Explosion testing for these samples determined that each was capable of generating overpressures of approximately 7 bar(g) – i.e., seven times atmospheric pressure – and rates of pressure rise as high as 300 – 400 bar/s in a volume of 20 L.

Photographs: Amyotte, P.R., Cloney, C.T., Khan, F.I. and Ripley, R.C., "Dust Explosion Risk Moderation for Flocculent Dusts", *Journal of Loss Prevention in the Process Industries*, 25, 862-869 (2012).

Hybrid mixtures

- Flammable gas and combustible dust
 - May each be present in concentrations less than their individual LFL (gas) and MEC (dust), and still be explosible
- Result in increased explosion severity and likelihood
- Examples
 - Methane gas and coal dust
 - Natural gas and fly ash
 - Hydrocarbon gases and resins

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A hybrid mixture explosion can occur as a result of the mixing of a flammable gas and a combustible dust. The gas concentration may be less than its lower flammability limit (LFL) and/or the dust concentration may be less than its minimum explosible concentration (MEC), and yet the mixture can still be explosible. The focus when discussing hybrid mixtures is often on admixture of a flammable gas in concentrations below the LFL of the gas itself, to an already explosible concentration of dust.

In a hybrid mixture explosion, there would be higher values of P_{max} and $(dP/dt)_{max}$, and lower values of MEC and MIE (with respect to the dust alone), which results in an increase in both explosion severity and likelihood of occurrence.

A well-known example of a hybrid mixture is methane gas and coal dust in an underground coal mine. Other examples include natural gas and fly ash in fossil-fuel power plants, and gaseous hydrocarbons and resins in plastic powder production facilities.

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel **Ignition Source** Oxidant
Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

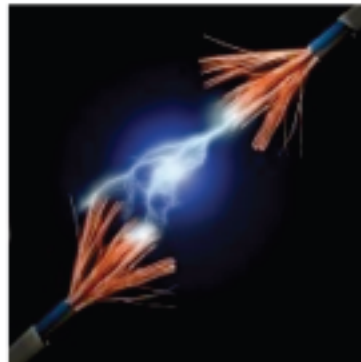
Element 2 of 5 – Ignition Source

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This section deals with possible dust explosion ignition sources, as well as introducing minimum ignition energy and minimum explosion temperature testing and results. The relationship between gas and dust MIE values is also described.

Examples of ignition sources

- Flames and direct heat
- Hot work
- Incandescent materials
- Hot surfaces
- Electrostatic sparks
- Electrical sparks
- Friction sparks
- Impact sparks
- Self-heating
- Static electricity
- Lightning
- Shock waves



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Dust explosion triggers include the following:

- flames and direct heat,
- hot work (e.g., welding and cutting),
- incandescent material (e.g., smoldering particles),
- hot surfaces, (e.g., overheated bearings),
- electrostatic sparks (caused by electrostatic discharge from electrical equipment),
- electrical sparks (such as may be caused by switching operations),
- friction sparks and hot spots (caused by rubbing between solids and friction-induced heating, respectively),
- impact sparks (ignition by surface heating resulting from metal-on-metal impact),
- self-heating (spontaneous combustion),
- static electricity (electrostatic sparks caused by process operations such as pouring and size reduction),
- lightning, and
- shock waves.

Reference: Abbasi, T. and Abbasi, S.A., "Dust Explosions – Cases, Causes, Consequences, and Control", *Journal of Hazardous Materials*, **140**, 7-44 (2007).

MIE and MIT testing

- MIE and MIT testing can be conducted to better identify potential ignition source hazards
- MIE and MIT test results are applicable to efforts aimed at dust explosion prevention
 - Removal of ignition sources
 - Grounding and bonding
 - Control of process/surface temperatures

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Many ignition sources involve either an energetic spark or a hot-surface temperature. To better identify potential ignition source hazards in terms of both energy and temperature requirements, minimum ignition energy and minimum ignition temperature testing of a given dust can be conducted.

Test results can be implemented in applications such as removal of ignition sources, grounding and bonding as a form of protection against static electricity build-up and electrostatic discharges, and control of process and surface temperatures.

MIE values of some dusts

| Material | MIE with inductance [mJ] | MIE without inductance [mJ] |
|--------------------------|--------------------------|-----------------------------|
| Epoxy coating powder | 1.7 | 2.5 |
| Polyester coating powder | 2.9 | 15 |
| Polyamide coating powder | 4 | 19 |
| Magnesium granulate | 25 | 200 |
| Flock | 69-98 | 1300-1600 |

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Decades ago, it was believed that all dusts had MIEs greater than 10 mJ. As testing methods were improved, it was discovered that many dusts had much lower MIEs, in the range of 1 mJ or less. The table in the slide shows MIE values for different particulate materials.

MIE is tested both with and without inductance in the spark circuitry. It has been found that the use of inductance usually lowers the MIE, and sometimes the reduction is quite significant as we can see in this table. This is because the use of inductance results in a longer spark duration (i.e., protracted spark), and therefore a higher probability of ignition.

Note: These values, although typical for their dust types are not specific to all similar dusts. A dust source must be tested in order to obtain specific values. Additionally, although particle size is not given for these examples, we know from previous discussion in this module that particle size does have an effect on MIE.

Table adapted from: von Pidoll, U., "The Ignition of Clouds of Sprays, Powders and Fibers by Flames and Electric Sparks", *Journal of Loss Prevention in the Process Industries*, 15, 305-310 (2002).

Ignition of titanium dust

| Size | MIE [mJ] | | MIT [°C] |
|-----------------------|--------------------|-----------------------|-------------|
| | With inductance | Without inductance | |
| <150 μm | 10-30 | 1-3 | >590 |
| <45 μm | 1-3 | 1-3 | 460 |
| $\leq 20 \mu\text{m}$ | <1 | <1 | 460 |
| 150 nm | Not determined | <1 | 250 |
| 60-80 nm | Not determined | <1 | 240 |
| 40-60 nm | Not determined | <1 | 250 |

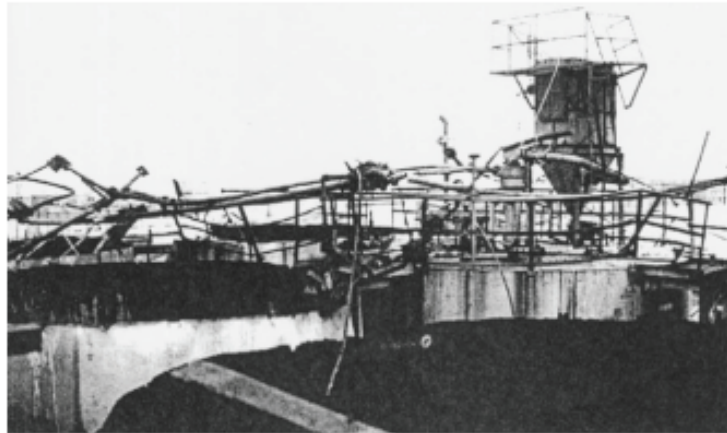
45

Nano-size metals such as aluminum and titanium have been shown to have very low ignition energies of less than 1 mJ, which is the lower testing limit of the MIKE3 apparatus (shown in a previous slide).

In this table we see these low MIE results for nano-titanium. We also see that even the micron-size dusts have low MIE values. And we also see the decrease in minimum ignition temperature (MIT) from micron- to nano-size titanium.

Table adapted from: Boilard, S.P., Amyotte, P.R., Khan, F.I., Dastidar, A.G. and Eckhoff, R.K., "Explosibility of Micron- and Nano-Size Titanium Powders", *Journal of Loss Prevention in the Process Industries*, 26, 1646-1654 (2013).

Destruction at 10 mJ



ABS (Acrylonitrile-Butadiene-Styrene) Plant

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Flammable gases typically have lower ignition energies than combustible dusts. For example, the CSB report on the Hoeganaes incidents presented in the later module section on Case Studies gives an MIE of 0.02 mJ for hydrogen and > 500 mJ for the iron dust involved in the actual incidents. (CSB, "Case Study. Hoeganaes Corporation: Gallatin, TN. Metal Dust Flash Fires and Hydrogen Explosion", No. 2011-4-I-TN, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).)

But don't be fooled into thinking that the relatively higher MIEs of combustible dusts mean that dust explosions – once initiated – are not potentially devastating. The figure in this slide indicates otherwise. (Figure: Kao C.-S. and Duh, Y.-S., "Accident Investigation of an ABS Plant", *Journal of Loss Prevention in the Process Industries*, 15, 223-232 (2002).)

Kao and Duh (2002) describe a series of dust explosions in the silo area of an ABS (acrylonitrile-butadiene-styrene) plant; the participating materials were ABS (which is a rubber-containing plastic) and SAN (polystyrene-acrylonitrile). Several silos were affected, with the top-plate and bag-filter (dust collector) for each being destroyed. An indication of the plant damage is given by the figure in this slide.

The incident investigation team eventually concluded that the explosion was initiated in one of the silos undergoing gravitational filling of ABS powder, with flame propagation to the other involved silos occurring through interconnecting pipes. The most likely ignition scenario in the first silo was thought to be a bulked brush (conical pile or cone) discharge between the compacted powder and the grounded silo wall. Such discharges are relatively intense and have energies up to several hundred mJ. The MIE of the ABS powder was measured as 10 mJ.

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel Ignition Source **Oxidant**
Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Element 3 of 5 – Oxidant

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This section examines two aspects related to oxygen as the most common oxidant for combustion: (i) the concept of the limiting oxygen concentration, or LOC, and (ii) the use of inert gases as an explosion prevention technique. LOC is defined and representative values are given. Various candidate inert gases are identified and their effect on key explosion parameters is illustrated.

Limiting oxygen concentration

- Oxygen is the most common oxidant
- Does not have to be completely removed to prevent a dust explosion
- Limiting oxygen concentration (LOC)
 - Highest oxygen concentration in a dust/air/inert gas mixture at which an explosion fails to occur
 - Value for a given dust depends on inert gas used
 - Industry application – inerting

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Oxygen is the most common oxidant found in industry. Air is typically comprised of 21 % by volume of oxygen.

While an oxidant must be present for combustion to occur, its removal does not need to be complete to prevent the occurrence of a dust explosion. The limiting oxygen concentration (LOC) is defined as the highest oxygen concentration at which an explosion fails to occur in a given dust/air/inert gas mixture.

The inert gas used for this purpose affects the measured value of LOC; the effectiveness of different inert gases is shown in a later slide. LOC data can be applied in industry to a prevention technique known as inerting (in which a process is operated under a blanket of inert gas). However, inerting may not always be feasible, and there can be hazards other than explosions associated with inerting. Some of these hazards are shown in the following slide.

Use of inert gas

- Inert gas examples – carbon dioxide, nitrogen argon, helium, steam, flue gas
- Inerting can introduce new hazards
 - Asphyxiation from reduced oxygen levels in air
 - Reaction of inert gas with dust
 - Electrostatic discharge when CO₂ is drawn from high-pressure or cryogenic tanks
 - Leakage of inert gas in systems under pressure
 - Introduction of ignition sources from inerting equipment such as vacuum pumps

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Candidate inert gases include: carbon dioxide, nitrogen, argon, helium, steam and flue gas.

Inerting can greatly reduce the risk of a dust explosion. In the act of removing one hazard, however, new hazards may be introduced as shown by the list given in the slide. Asphyxiation is a key and insidious hazard; safe oxygen levels for human beings are between 19.5 and 23.5 volume %. Carbon dioxide has been known to react with aluminum dust, and nitrogen with magnesium dust at high temperatures.

References for this slide and further examples can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

LOC values of some dusts

| Material | LOC with nitrogen [volume %] |
|---------------------------|---|
| Pea flour | 15.5 |
| Calcium stearate | 12.0 |
| Wheat flour | 11.0 |
| High-density polyethylene | 10.0 |
| Sulfur | 7.0 |
| Aluminum | 5.0 |

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In this table we see representative values of LOC for various materials. Aluminum dust is highly reactive and therefore has a low LOC.

In industry – to account for operating errors and upset conditions – a safety factor is normally applied to the measured LOC (e.g., the LOC percentage minus a further set percentage such as 2 volume %).

Note: These values, although typical for their dust types are not specific to all similar dusts. A dust source must be tested in order to obtain specific values. Additionally, although particle size is not given for these examples, it should not come as a surprise that particle size has an effect on LOC.

Table and text adapted from: Hoppe, T. and Jaeger, N., "Reliable and Effective Inerting Methods to Prevent Explosions", *Process Safety Progress*, **24**, 266-272 (2005).

Inert gas effectiveness

Magnesium Dust

| Inert Gas | LOC [volume %] |
|----------------------------|-----------------------|
| Nitrogen (diatomic) | 6.8 |
| Carbon dioxide (triatomic) | 5.5 |
| Argon (monatomic) | 4.0 |

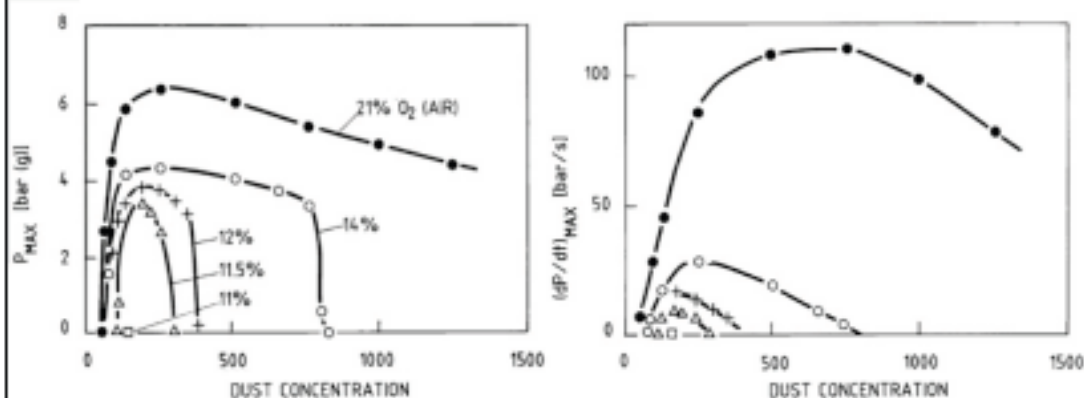
51

Inert gases have different degrees of effectiveness. This table shows the LOC values for three different inert gases with a specific sample of magnesium dust. Gases with multiatomic molecules have a greater capacity for energy absorption, and hence would be more effective at inerting than monatomic gases, resulting in a higher LOC value. This is why argon (monatomic) has the lowest LOC of the three gases shown.

Table adapted from: Li, G., Yuan, C.M., Fu, Y., Zhong, Y.P. and Chen, B.Z., "Inerting of Magnesium Dust Cloud with Ar, N₂ and CO₂", *Journal of Hazardous Materials*, **170**, 180-183 (2009).

Effect on P_{\max} and $(dP/dt)_{\max}$

Brown Coal Dust/Air/Nitrogen



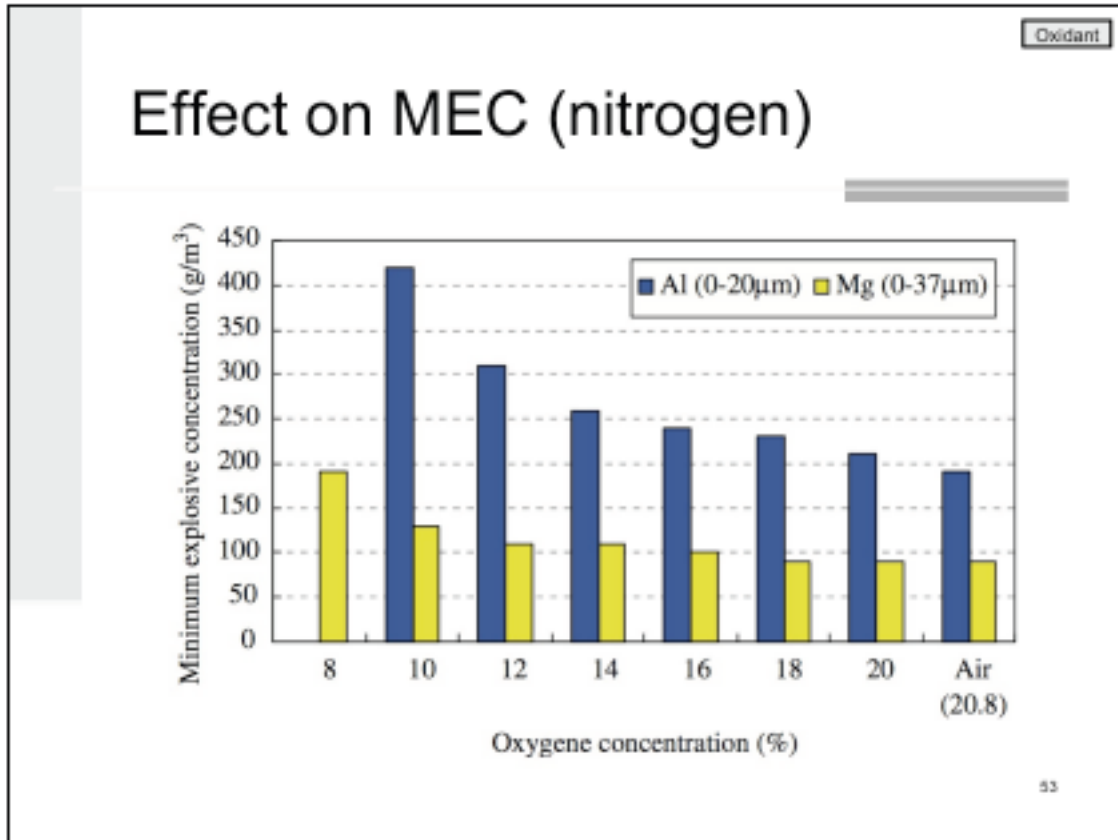
52

This figure shows the inerting effectiveness of nitrogen on the maximum explosion pressure and maximum rate of pressure rise of a sample of brown coal.

It can be seen that the limiting oxygen concentration (LOC) was 11 volume %, as an explosion was no longer possible at this level (zero values of overpressure and rate of pressure rise). We can also see that there was a steady reduction in overpressure and rate of pressure rise as the oxygen concentration was reduced below 21 volume %, until the limiting oxygen concentration was reached.

Figure: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Original Source: Wiemann W., "Influence of Temperature and Pressure on the Explosion Characteristics of Dust/Air and Dust/Air/Inert Gas Mixtures", In: Cashdollar K.L. and Hertzberg M. (Editors), "Industrial Dust Explosions. ASTM Special Technical Publication 958", American Society for Testing and Materials, Philadelphia, PA (1987).



This figure shows the inerting effectiveness of nitrogen on the minimum explosible concentration of samples of aluminum and magnesium.

It is clear that the trend with oxygen level reduction is toward a limiting oxygen concentration at which explosions are no longer possible.

Figure: Nifuku, M., Koyanaka, S., Ohya, H., Barre, C., Hatori, M., Fujiwara, S., Horiguchi, S. and Sochet, I., "Ignitability Characteristics of Aluminum and Magnesium Dusts that are Generated During the Shredding of Post-Consumer Wastes", *Journal of Loss Prevention in the Process Industries*, **20**, 322-329 (2007).

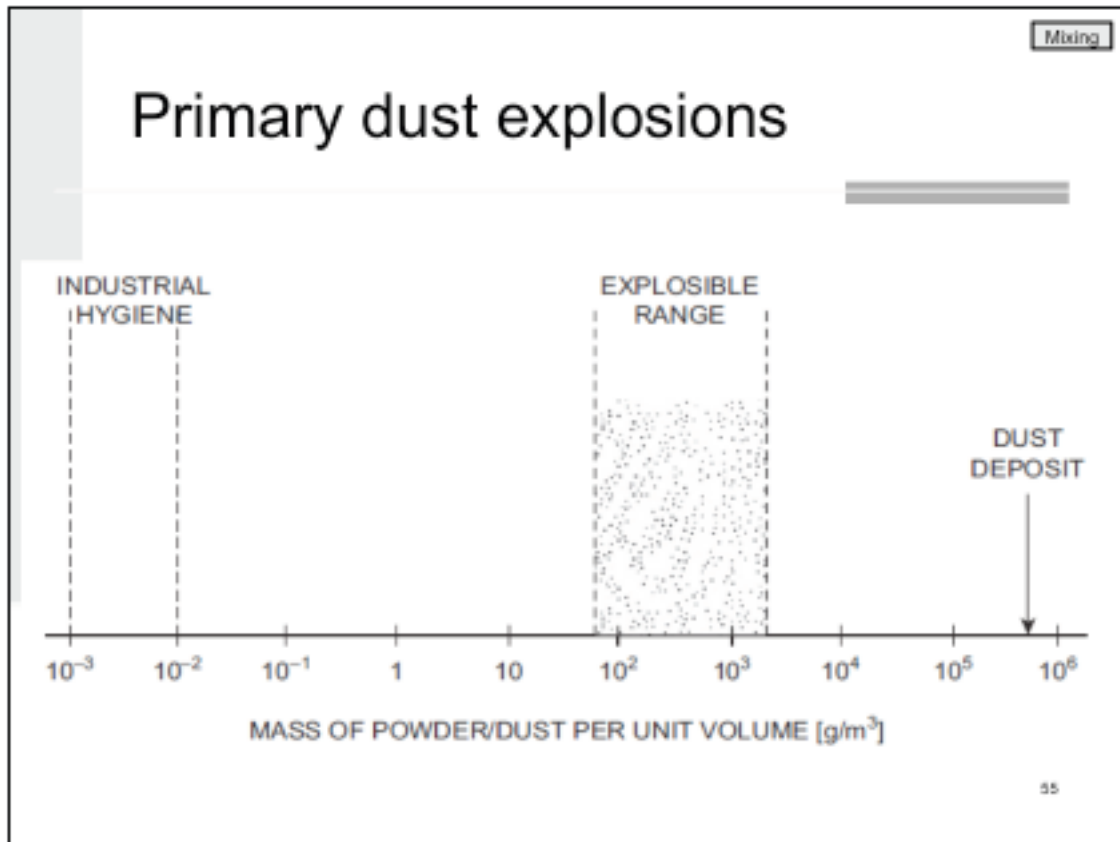
Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel Ignition Source Oxidant

Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Element 4 of 5 – Mixing

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This section covers the various factors affecting dust layer dispersion. The sequence of primary and secondary explosions is explained, and turbulence effects are discussed.

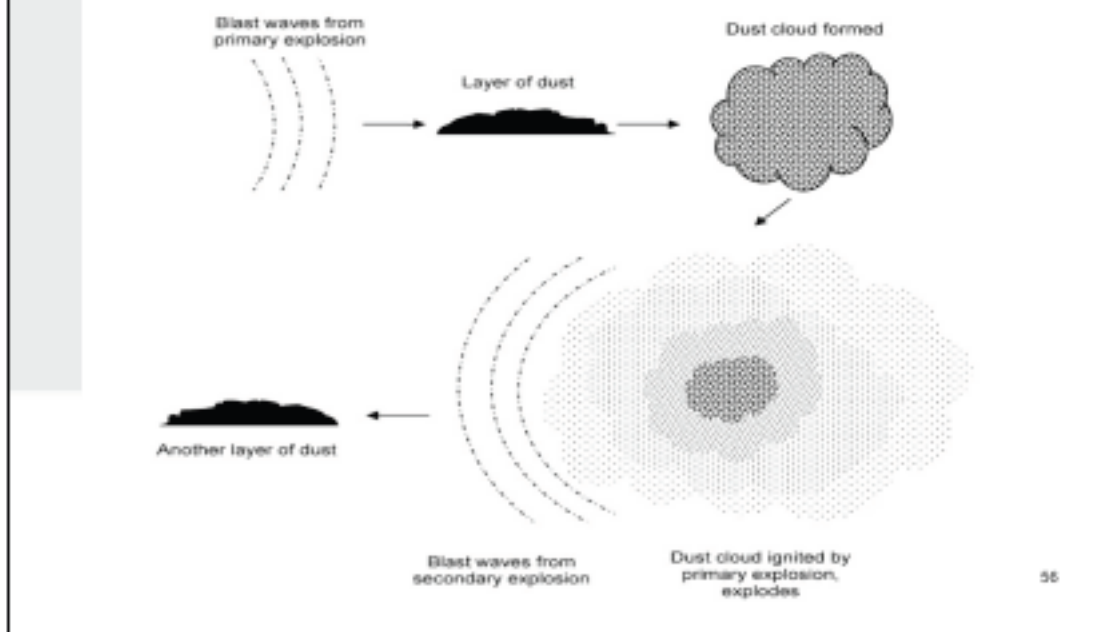


Explosible dust clouds are optically thick. Eckhoff (2003) puts this in practical terms by quoting the observation that a glowing 25-W light bulb cannot be seen through 2 m of a dust cloud at concentrations exceeding 40 g/m³. Such a concentration is lower than the MEC for many dusts.

Initiation of primary dust explosions therefore usually happens in dust clouds present in process vessels and units such as mills, grinders and dryers – i.e., inside equipment where the conditions of the explosion pentagon are satisfied. The reason for this occurrence is further explained by the figure in the slide. Here, the range of explosible dust concentrations in air at normal temperature and pressure for a natural organic dust (e.g., cornstarch) is compared with the typical range of maximum permissible dust concentrations that are relevant in the context of industrial hygiene, and with a typical density of deposits or layers of natural organic dusts. Clearly, the range of explosible concentrations is orders of magnitude greater than the concentrations permitted in areas inhabited by workers.

Figure: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Secondary dust explosions



56

Industry experience tells us that dust explosions also occur in process areas, not just inside process units. A *secondary* explosion can be initiated due to entrainment of dust layers by the blast waves arising from a *primary* explosion as illustrated by the figure in this slide.

The primary event might be a dust explosion originating in a process unit, or could be any disturbance energetic enough to disperse combustible dust layered on the floor and other surfaces (such as improper cleaning practices using compressed air rather than an explosion-proof vacuum).

Figure: Abbasi, T. and Abbasi, S.A., "Dust Explosions – Cases, Causes, Consequences, and Control", *Journal of Hazardous Materials*, **140**, 7-44 (2007).

Primary/secondary dust explosions

- Primary dust explosions generally occur inside process vessels and units
 - Mills, grinders, dryers, etc.
- Secondary dust explosions are caused by dispersion of dust layers by an energetic disturbance
 - Upset conditions/poor housekeeping practices
 - Vigorous sweeping; cleaning with compressed air
 - Blast wave from primary explosion
 - Gas or dust explosion; other explosion types

57

This slide gives a summary of the points made in the previous two slides and accompanying notes. Understanding the concept of primary and secondary dust explosions is one of the most important features of dust explosion risk reduction.

Dustiness/dispersibility

| Characteristic | Influence on Dispersion |
|--------------------------------|--|
| Particle size | Larger diameter → higher settling velocity |
| Particle specific surface area | Larger specific surface area → lower settling rate |
| Dust moisture content | Higher moisture content → reduced dispersibility |
| Dust density | Higher density → higher settling velocity |
| Particle shape | Asymmetry and roughness → lower settling velocity |
| Agglomeration processes | Impact effective particle diameter |

56

How long a dust cloud remains in suspension depends on its dispersibility or dustiness. Dustiness is defined as the tendency of a dust to form clouds, and is influenced by the six characteristics shown in the table (Klippel, A., Scheid, M. and Krause, U., "Investigations into the Influence of Dustiness on Dust Explosions", Proceedings of the Ninth International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions, Krakow, Poland (July 22-27, 2012).)

Particle size – For a given dust density, the terminal settling velocity of spherical particles increases with an increase in particle diameter.

Particle specific surface area – Higher specific surface area leads to a lower settling rate because of greater drag force acting on the particles.

Dust moisture content – Cohesion caused by inter-particle adhesion forces results in a decrease in dispersibility with an increase in dust moisture content.

Dust density – For a given particle diameter, the terminal settling velocity of spherical particles increases with dust density.

Particle shape – Features such as asymmetry in particle shape and roughness in surface texture have been shown to result in lower terminal settling velocities than for smooth, spherical particles due to rotational settling and eddy formation. Flocculent or fibrous dusts would be expected to settle at rates dependent on the orientation of the cylindrical-shaped particles to both the flow and gravitational fields.

Agglomeration processes – Two key aspects of the tendency of dusts to agglomerate become important when considering the concept of an effective particle diameter: (i) attraction between particles in dust layers due to inter-particle cohesion forces, and (ii) rapid coagulation of particles in a dust cloud. In the first instance, dispersion of agglomerates into primary particles is made more difficult; the second case means that even if a dust is well-dispersed, the formation of larger agglomerates in suspension remains a possibility.

Further references for this slide can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/ Butterworth-Heinemann, Waltham, MA (2013).

Turbulence

- Some degree of turbulence will always exist in a dust cloud
 - No such thing as a quiescent dust cloud within the confines of the earth's gravitational field
- Effects of turbulence
 - Increased ignition requirements
 - Highly turbulent dust clouds are harder to ignite
 - Heightened combustion rates
 - Once ignited, highly turbulent dust clouds yield more severe consequences

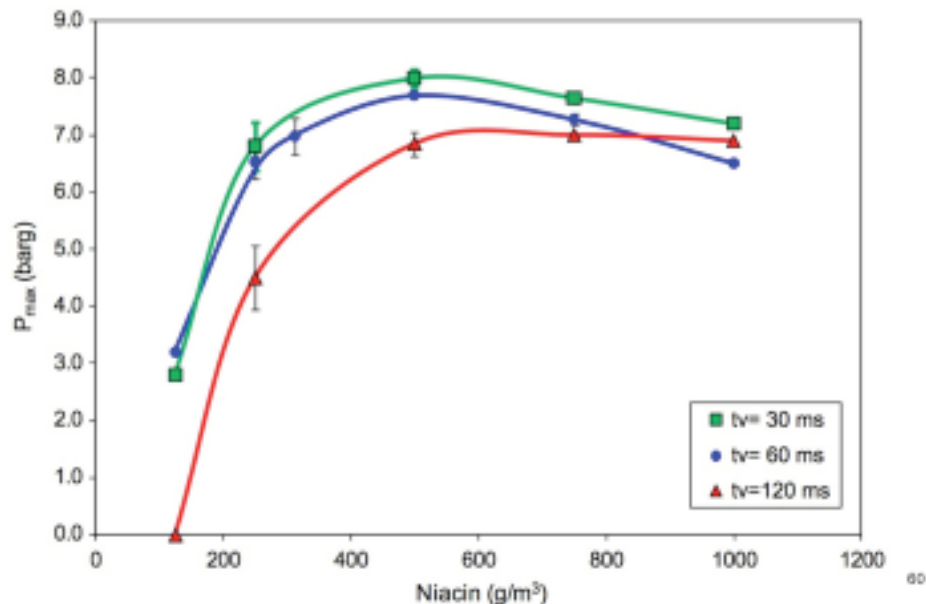
39

Turbulence is the state of rapid, internal random movement of elements within a dust cloud relative to one another. Some degree of turbulence must exist within a dust cloud to allow for fuel and oxidant mixing.

Ignition temperature and ignition energy requirements both increase at higher turbulence levels. There is also more rapid combustion and overpressure development at higher turbulence levels.

Reference: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Turbulence and overpressure

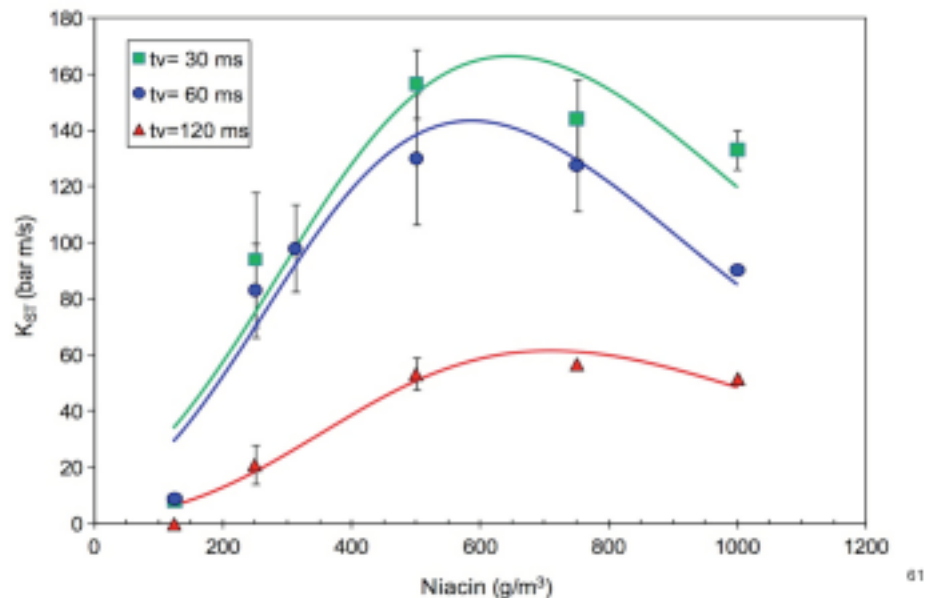


Overpressure is a thermodynamic parameter and as such, turbulence does not have a significant impact on it.

This figure shows the effects of turbulence on explosion overpressure of the pharmaceutical dust, niacin, in the Siwek 20-L apparatus. In the figure, t_i refers to the ignition delay time (time between dust dispersion and ignition source activation). As the delay time increases, turbulence intensity decreases and the dust begins to settle out. We see only a small increase in overpressure with a higher level of turbulence (shorter ignition delay time).

Figure: Sanchirico, R., Di Benedetto, A., Garcia-Agreda, A. and Russo, P., "Study of the Severity of Hybrid Mixture Explosions and Comparison to Pure Dust-Air and Vapour-Air Explosions", *Journal of Loss Prevention in the Process Industries*, **24**, 648-655 (2011).

Turbulence and rate of pressure rise



The rate of pressure rise is a kinetic parameter, and is proportional to the flame propagation rate.

This figure shows the effects of turbulence on rate of pressure rise of niacin dust in the Siwek 20-L apparatus. Here, we see that a higher turbulence level (shorter ignition delay time, t_v) leads to a pronounced increase in rate of pressure rise. As the delay time increases, turbulence intensity again decreases and the dust begins to settle out.

Figure: Sanchirico, R., Di Benedetto, A., Garcia-Agreda, A. and Russo, P., "Study of the Severity of Hybrid Mixture Explosions and Comparison to Pure Dust-Air and Vapour-Air Explosions", *Journal of Loss Prevention in the Process Industries*, **24**, 648-655 (2011).

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel Ignition Source Oxidant
Mixing **Confinement** Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Element 5 of 5 – Confinement

62

This section examines the role of confinement in the explosion pentagon. Various degrees of confinement and the role of obstacle-generated turbulence (congestion) are described. Venting, the most commonly applied explosion mitigation measure, is also introduced.

Role of confinement

- Confinement allows for overpressure development

$$PV=nRT \Rightarrow \text{fixed } V, R=\text{const}, n \approx \text{const} \rightarrow \uparrow T \rightarrow \uparrow P$$

- Confinement does not need to be total for a dust explosion to occur
 - Semi-confined spaces
 - Unconfined spaces with high blockage ratio (congestion) and subsequent turbulence generation

63

Confinement allows for the development of explosion overpressure. The ideal gas law illustrates the role of confinement in overpressure development. The molar amounts of reactants and products do not usually differ significantly and the universal gas constant does not change. So in a confined, fixed-volume system, the pressure and temperature changes would be proportional. In other words, for the equal sign to hold true, the increase in temperature due to combustion must be matched by a proportional change in pressure.

However, confinement does not need to be total (or complete) for a dust explosion to occur. Dust explosions can occur in semi-confined spaces, or in unconfined spaces with a high blockage ratio due to flow obstruction (congestion) and ensuing turbulence generation in the unburned dust cloud (explained further in a later slide).

Further references and points of discussion for this slide can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

Degree of confinement

- No confinement/low confinement
 - Flash fire
 - Dust explosion rare occurrence
- Partial confinement
 - Fireball with limited pressure rise and flame propagation
 - Explosion development possible
- Complete confinement
 - Full overpressure development

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The degree of confinement influences the effects of ignition of a combustible dust.

If there is limited confinement, a flash fire can occur with the potential for secondary fires. An unconfined dust explosion would be expected to be a rare occurrence as pressure development in the dust cloud would need to exceed the rate of pressure dissipation at the cloud edge. A combination of rapid combustion reactions such as from flow obstruction, as well as high dust reactivity would be needed.

If there is partial confinement, a fireball with limited pressure rise inside the enclosure, and flame propagation outside the enclosure may occur. Dust explosions can also occur, such as in underground mine workings.

With complete confinement such as inside process vessels, full overpressure can develop.

Further references and points of discussion for this slide can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

Partial confinement



Methane-triggered coal dust explosion
with fireball emerging from mine portal
Bruceton Experimental Mine
Pittsburgh, PA

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As noted in the previous slide, a dust explosion can occur when there is only partial confinement. An example of such an event would be an explosion in an underground mine. This series of photographs shows the progression of a fireball caused by a methane-triggered coal dust explosion as it emerges from a mine portal.

The next slide explains the underlying physical and chemical phenomena involved in this process.

Photographs courtesy of K.L. Cashdollar.

Partial confinement

- Underground mine workings
- Approximate mine gallery as a corridor with one end open, ignition occurring at opposite end
- Explosion development and flame propagation follows corridor
- Burned gases expand behind flame front and push unburned fuel/air mixture toward open end of corridor, generating turbulence
- Flame front accelerates as it reaches turbulent flow field
- Self-accelerating feedback mechanism

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Explosion development and flame propagation in underground mine workings can be approximated by considering a mine gallery to be a corridor with one end open and ignition occurring at the other closed end.

The piston-like effect of the burned gases expanding behind the flame front pushes the unburned fuel/air mixture toward the open end and results in the generation of post-ignition turbulence in the unburned mixture. The advancing flame front then accelerates as it encounters the turbulent flow field with the end-result being a self-accelerating feedback mechanism between flame speed and turbulence level in the unreacted flow field.

Further references and points of discussion for this slide can be found in: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

Congestion

- Obstacles can create congestion (blockage) and generate significant post-ignition turbulence

Boom Truck
Westray



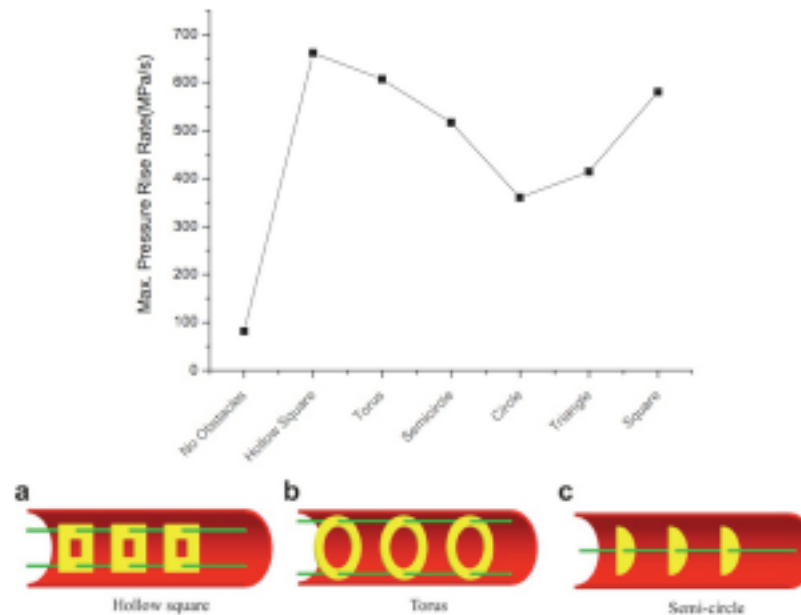
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Obstacles in the path of an advancing dust flame can create enough congestion or blockage to generate significant post-ignition turbulence. This results in both flame acceleration and increased pressure development.

An example of such a turbulence-generating obstacle is a boom truck (tractor) used in some underground coal mines. The photograph in the slide shows a boom truck post-explosion in the Westray mine (discussed in the Case Studies section of the module).

Photograph: Richard, K.P., Justice, "The Westray Story – a Predictable Path to Disaster. Report of the Westray Mine Public Inquiry", Province of Nova Scotia, Halifax, NS (1997).

Influence of obstacle type



These figures show how different obstacles can influence the rate of pressure rise. The laboratory-scale tests were conducted on coal dust/methane/air mixtures.

As described previously, obstacles create turbulence in the flow of the unburned fuel ahead of the flame. Once the flame reaches this turbulent flow field, the flame surface area is increased, resulting in an enhanced burning rate and higher burning velocity. This in turn creates more turbulence, leading to rapid flame acceleration and heightened rates of pressure rise.

Figures: Zhou, Y., Bi, M. and Qi, F., "Experimental Research into Effects of Obstacle on Methane-Coal Dust Hybrid Explosion", *Journal of Loss Prevention in the Process Industries*, 25, 127-130 (2012).

Explosion relief venting

- Dust explosion mitigation
 - Overpressure is reduced by relieving confinement



Corn Flour Explosion with Relief Venting

09

Explosion relief venting is a common – arguably the most common – approach to dust explosion mitigation (protection). Venting allows for reduction in overpressure as a result of confinement relief. This topic will be explored further in the module section on Prevention and Mitigation.

The photograph in the slide shows a vented corn flour dust explosion. It also illustrates the basic idea behind venting. Although flame, combustion products and unburned dust are ejected through the vent, the integrity of the vented enclosure is maintained.

Photograph: Holbrow, P., "Dust Explosion Venting of Small Vessels and Flameless Venting", *Process Safety and Environmental Protection*, **91**, 183-190 (2012).

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel Ignition Source Oxidant

Mixing Confinement **Dust Layer Fires** Prevention and Mitigation Case Studies Resources Evaluation

Dust Layer Fires

Magnesium Dust Layer Fire

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In this section, we briefly examine the issue of dust layer fires. Self-ignition of dust layers and ignition by an external source are discussed. The layer ignition temperature or LIT is defined and the effect of layer thickness on LIT is illustrated. Finally, the concept of normalization of deviance is used to explain why dust layer fires are sometimes ignored as predictors of larger fires or explosions.

The fire triangle is again pertinent to the discussion here as explained on the next slide. Note that there are no mixing and confinement elements involved. As we have just seen in the previous section, it is possible for a dust/air cloud to burn rather than explode when confinement is low. This event is termed a flash fire and is a different scenario than layer fires as presented in this section.

The figure in the slide shows a magnesium dust layer fire. The first stage (a) involves slow, lower temperature combustion. The second stage (b) involves rapid, higher temperature combustion of magnesium gas generated from the layer.

Figure: Gang, L., Chunmiao, Y., Peihong, Z. and Baozhi, C., "Experiment-Based Fire and Explosion risk Analysis for Powdered Magnesium Production Methods" *Journal of Loss Prevention in the Process Industries*, **21**, 461-465 (2008).

Ignition of dust layers

- Self-heating (self-ignition)
- External heat source
 - Pieces of metal
 - Nut or bolt (heated by repeated contact with equipment surfaces)
 - Overheated surface
 - Bearing or motor
- Layer Ignition Temperature (LIT)
 - Minimum temperature required to ignite a layer of dust of a certain thickness

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Dust layer fires involve a combustible dust, an oxidant (typically oxygen in air), and an ignition mechanism.

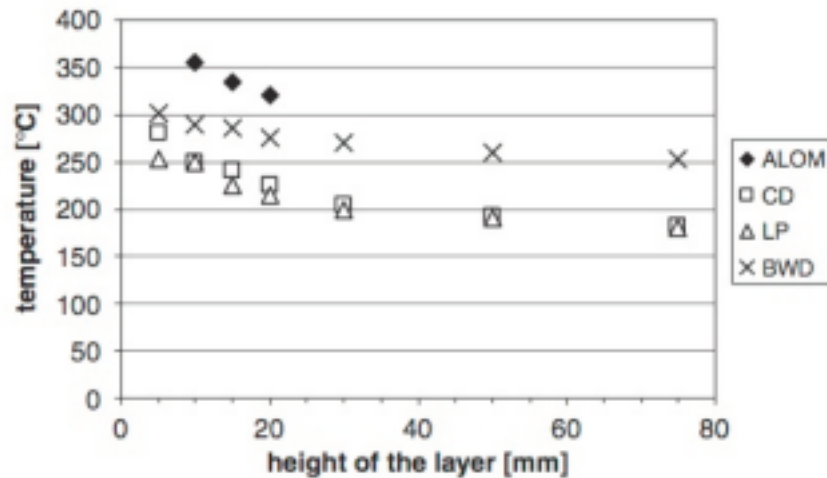
There are two ignition mechanisms for dust layers: self-heating (or self-ignition, or spontaneous combustion) and an external heat source. Self-ignition is described in a later slide.

Eckhoff (2003) gives two possible industrial scenarios for a hot object (external heat source) being in close proximity to a combustible dust: (i) a piece of metal (e.g., a nut or bolt) present in a bulk powder stream and which has been heated by repeated contact with the process equipment boundaries, and (ii) an overheated surface (e.g., a bearing or motor) covered with a layer of dust.

In the case of a dust layer that has accumulated on a heated surface, we can define the LIT (layer ignition temperature) as the lowest hot-surface temperature that will cause ignition of a dust layer having a specified thickness. There is an ASTM test method to measure LIT.

Reference: Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Effect of layer thickness



ALOM = Aluminum Oxide; CD = Coal Dust; LP = Lycopodium; BWD = Beechwood Dust

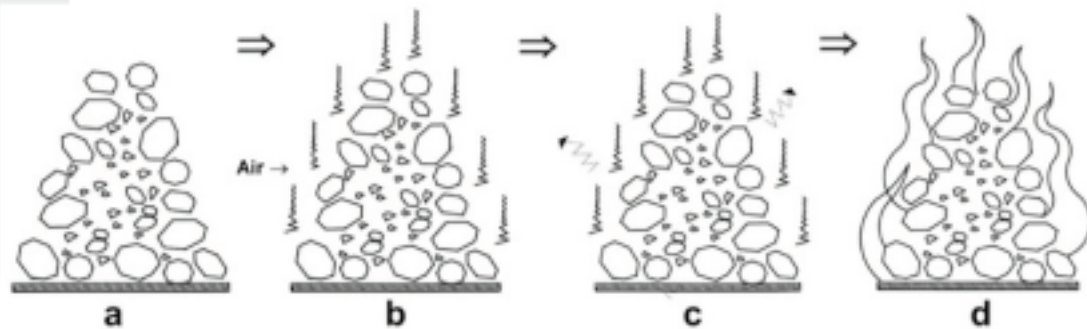
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The LIT of a given dust, like other explosion parameters (e.g., MIE), is not an intrinsic property of the material. Nevertheless, LIT values provide helpful information for industrial practice.

It must be remembered that LIT is a function of layer thickness. The figure in this slide shows LIT data for various dusts over a range of layer thicknesses (or heights). Clearly, LIT values are higher for thinner layers.

Figure: Querol, E., Torrent, J.G., Bennet, D., Gummer, J. and Fritze, J.-P., "Ignition Tests for Electrical and Mechanical Equipment Subjected to Hot Surfaces", *Journal of Loss Prevention in the Process Industries*, 19, 639-644 (2006).

Self-ignition



73

An external heat source may not be needed for layer ignition to occur. Under certain conditions, a dust pile can self-heat and then ignite. To initiate self-heating, there must be sufficient porosity for air to enter the pile and react with the fuel. Heat must be generated faster than it is lost. Once a critical temperature is achieved, ignition can occur due to thermal runaway.

In the figure shown in the slide we see:

- (a) a coal pile having various particle sizes,
- (b) air ingress and initial self-heating,
- (c) heat losses by conduction, convection and radiation at rates not exceeding the rate of heat generation, and
- (d) self-ignition at some critical temperature.

Figure: Sipila, J., Auerkari, P., Heikkila, A.-M., Tuominen, R., Vela, I., Itkonen, J., Rinne, M. and Aaltonen, K., "Risk and Mitigation of Self-heating and Spontaneous Combustion in Underground Coal Storage", *Journal of Loss Prevention in the Process Industries*, 25, 617-622 (2012).

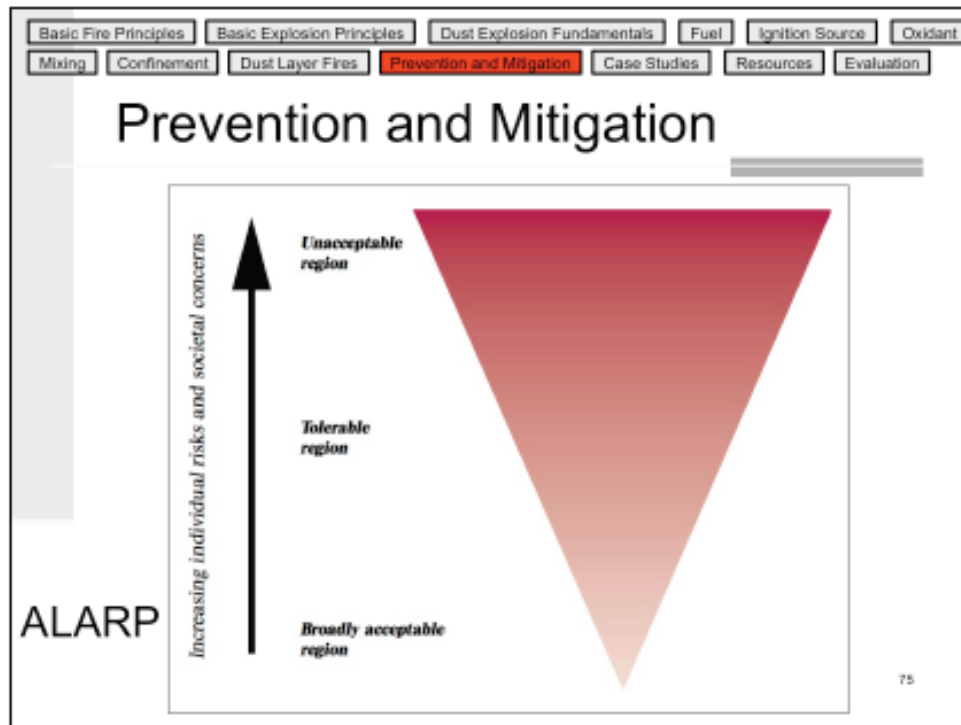
Normalization of deviance

- Dust fires are sometimes ignored or normalized
 - Accepting as normal (and then ignoring) negative events
 - Culture of risk-denial
 - Counter to concept of safety culture
- Evidence that something is not right in the workplace
 - Nothing normal about an unintentional dust fire

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Dust layer fires generally do not cause the same degree of damage and injury as dust explosions. As such, they might be ignored, or become accepted as normal to operations – simply “the cost of doing business”, or “the way things are done around here”.

This phenomenon is termed *normalization of deviance* and is part of a workplace culture known as *risk-denial*. Normalizing evidence that in fact should be seen as a predictor or warning sign of an impending catastrophe, is completely counter to a well-functioning safety culture. We return briefly to this topic in the next section on Prevention and Mitigation.



This section presents techniques and strategies for preventing and mitigating dust explosions. **Although the discussion is specific to dust explosions, the basic principles illustrated are also applicable to gas and vapour explosions.**

We begin with a look at an overall approach to risk reduction known as the hierarchy of controls. The various levels in the hierarchy are then examined: (i) inherent safety, (ii) passive engineered safety, (iii) active engineered safety, and (iv) procedural safety. We conclude with the concepts of a safety management system and safety culture.

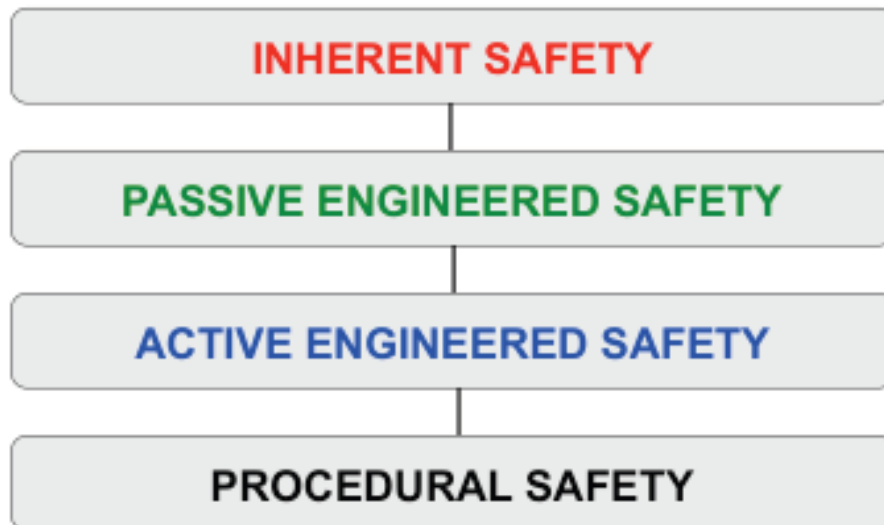
Prevention and mitigation efforts are aimed at risk reduction. Prevention deals with lessening the likelihood of occurrence of a dust explosion and mitigation with protecting people and plant from the consequences of such an event. In spite of our best efforts to eliminate hazards, there will always be residual risk that must be properly managed.

The figure in this slide gives a representation of the ALARP (As Low As Reasonably Practicable) principle. Vinem (2012) explains that use of the ALARP principle requires examination of both risk levels and risk prevention/mitigation costs, with risk reduction measures being implemented according to cost effectiveness considerations. Thus, a process can be made safer than it was before the introduction of additional safety measures but it cannot be made 100 % safe. More to the point, the potential benefits of attempting to drive process risk to zero will likely be grossly disproportionate to the cost involved. We should talk about safer alternatives, not safe processes.

Figure: Vinem, E., "Ethics and Fundamental Principles of Risk Acceptance Criteria", *Safety Science*, 50, 958-967 (2012).

Much of the material in this section is drawn from: Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/ Butterworth-Heinemann, Waltham, MA (2013). Original references can be found there.

Hierarchy of controls

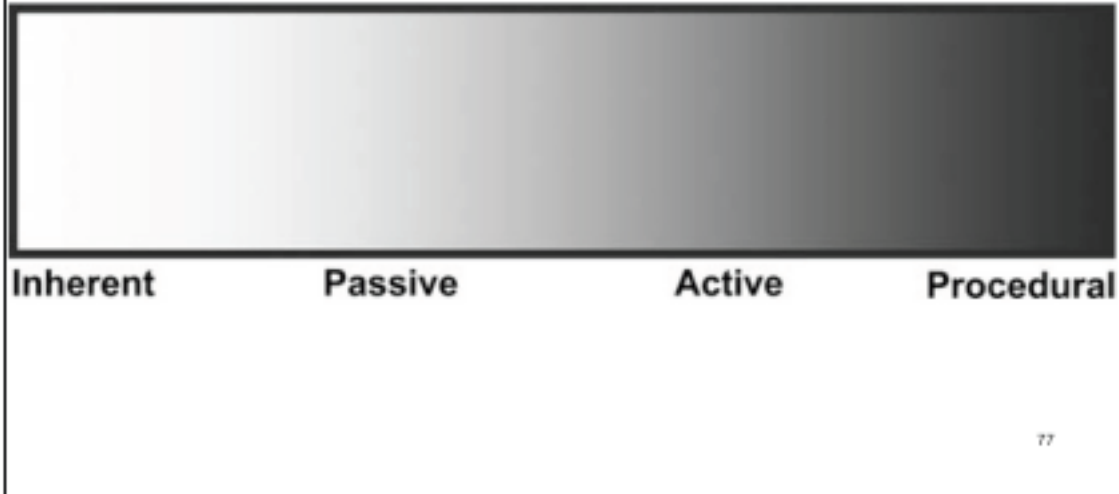


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The hierarchy of controls is an ordered arrangement of general risk reduction measures. Inherent safety, being the most effective approach to risk reduction, sits at the top of the hierarchy; it is followed in order of decreasing effectiveness by passive engineered safety devices (e.g., explosion relief vents), then active engineered safety devices (e.g., automatic suppression systems), and finally procedural safety measures (e.g., ignition source control by hot-work permitting).

Each of the four levels, with specific examples for dust explosion control, is explained in this section.

Hierarchy as a continuum



The figure in this slide illustrates an often overlooked feature of the hierarchy of controls – that it actually represents a continuum of safety measures. It is helpful to view the hierarchy as a spectrum of options rather than as distinct entities having sharply defined boundaries. Hendershot (2010) remarks that while people may disagree about the category in which a given approach falls, what really matters is whether the approach is effective from an engineering design viewpoint.

For example, use of safe work procedures is a procedural safety measure. If the procedures are clearly written and easy to follow, this can also be viewed as an application of the inherent safety principle known as *simplification*. Also, some might view housekeeping (in which dust accumulations are removed from the workplace) as purely a procedural safety measure, whereas others would see overtones of the inherent safety principle of *minimization*.

Figure: Hendershot, D.C., "A Summary of Inherently Safer Technology", *Process Safety Progress*, 29, 389-392 (2010).

Inherent safety

- Proactive approach to reduce reliance on engineered or add-on safety devices (both passive and active) and procedural measures
- Four basic principles
 - Minimization
 - Substitution
 - Moderation
 - Simplification

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Inherent safety is a proactive approach in which hazards are eliminated or lessened so as to reduce risk with decreased reliance on engineered (add-on) devices and procedural measures.

There are a number of inherent safety principles, of which the most fundamental ones are:

- Minimization,
- Substitution,
- Moderation, and
- Simplification.

Minimization

Minimize amount of hazardous material in use (when use of such materials cannot be avoided – i.e. elimination)



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With respect to dust explosions, minimization includes:

- Avoidance of the formation of combustible dust clouds. Because of the large quantities of particulate material present in powder handling equipment (which as previously described is where most primary dust explosions occur), it can be difficult, however, to achieve operation at dust concentrations below the MEC.
- Removal of dust deposits (avoidance of dust layers). Minimization of fuel loadings in this case is critical to the prevention of secondary dust explosions.

Substitution

Replace substance with less hazardous material; replace process route with one involving less hazardous materials



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With respect to dust explosions, substitution includes:

- Replacement of bucket elevators and other mechanical conveying systems with dense-phase pneumatic transport.
- Substitution of process hardware with less hazardous materials of construction (e.g., avoiding unnecessary use of insulating materials).
- Use of mass flow silos and hoppers rather than funnel flow silos so as to avoid undesired particle segregation and uncontrolled dust cloud formation.
- Alteration of a process route that involves handling an explosible powder (e.g., earlier introduction of an inert powder that is a component of the final product).
- Replacement of a combustible dust with one that is less hazardous. While this may be difficult to achieve in many cases, opportunities can arise when other factors such as cost motivate process change. For example, petroleum coke is a safer fuel than higher volatile-matter coal (from the perspective of rate of pressure rise). When used in a blended fuel as a partial replacement for pulverized coal in the feed to utility boilers, this inherent safety benefit of petroleum coke is evident.

Moderation

Use hazardous materials in least hazardous forms; run process equipment with less severe operating conditions



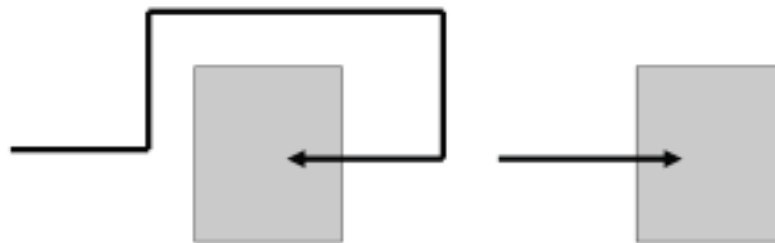
81

With respect to dust explosions, moderation includes:

- Altering the composition of a dust by admixture of solid inertants (pre-explosion); an example is shown in a later slide (Minimum Inerting Concentration).
- Increasing the dust particle size so as to decrease its reactivity.
- Avoiding the formation of hybrid mixtures of combustible dusts and flammable gases.
- Using powders in paste or slurry form.

Simplification

Simplify equipment and processes that are used; avoid complexities; make equipment robust; eliminate opportunities for error

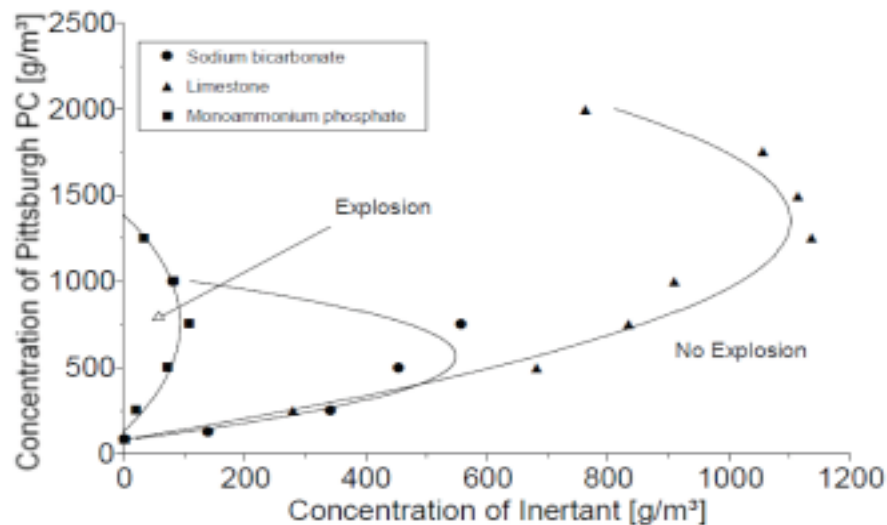


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With respect to dust explosions, simplification includes:

- Employing the concept of error tolerance by designing process equipment robust enough to withstand process upsets and other undesired events (e.g., shock- or pressure-resistant design). An example here is the hammermill shown in the Dust Explosion Fundamentals section.
- Ensuring information on the hazardous properties of combustible dusts is clear and unambiguous (e.g., by means of thorough and complete Safety Data Sheets).

Minimum inerting concentration



As we just saw, the direct mixing of a combustible dust and a non-combustible dust (inertant) is an application of the inherent safety principle of moderation. The mixing is done pre-explosion to in fact prevent an explosion from occurring. Inerting in this manner is conducted in coal mines to render coal dust non-explosible by mixing it with sufficient quantities of inert rock or stone dust (such as limestone or dolomite). Of course, this technique cannot be used if the dust is the desired product and must be free of contaminants (for example, in the food processing industry).

The amount of inertant needed depends on the actual inerting mechanism – thermal (heat sink) or chemical (reaction termination). The figure in this slide shows the results of testing conducted to determine the minimum inerting concentration (MIC) for mixtures of Pittsburgh pulverized coal dust and each of three inertants – limestone, sodium bicarbonate (SBC) and monoammonium phosphate (MAP).

The area to the left of each curve represents the explosible region for the fuel/inertant mixture. The area to the right of each curve represents the non-explosible region; here there is sufficient inertant to prevent an explosion. The nose of each curve (or envelope) represents the least amount of inertant that would prevent an explosion regardless of fuel concentration – i.e., the MIC.

The figure clearly illustrates that for inerting of Pittsburgh pulverized coal, limestone is the least effective inertant and MAP is the most effective. Limestone is a pure thermal inhibitor whereas MAP exhibits both thermal and chemical inhibition.

Figure: Dastidar, A.G., Amyotte, P.R., Going, J. and Chatrathi, K., "Flammability Limits of Dusts - Minimum Inerting Concentrations", *Process Safety Progress*, 18, 56-63 (1999).

Passive engineered safety

- Add-on safety devices
 - Explosion relief vents
 - Physical barriers
- Have no function other than to act when called upon to mitigate consequences of an explosion
- Do not require event detection or device activation
- More reliable than active devices

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The passive engineered safety level in the hierarchy of controls involves the use of safety devices that are added on to the process/facility unit. These devices do not play a production role; rather their extremely important role is to function in accordance with their design purpose to mitigate explosion consequences and protect people and plant.

Passive devices do not require detection of the explosion or activation of moving parts to perform their intended function. As such, they are more reliable than active engineered devices (described later). Like any mechanical device, however, passive engineered features must be properly designed, installed and maintained.

Examples include explosion relief vents to relieve overpressure (mitigation), and physical barriers to limit the propagation of flame and damaging overpressures downstream (mitigation).

Venting



Corn Flour Explosion with Relief Venting

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Venting is the most common approach used to mitigate dust explosion overpressure. As we saw in the Containment section, this is achieved by relieving the confinement criterion of the explosion pentagon. We have also previously seen the above photograph in the Containment section as an example of venting in practice.

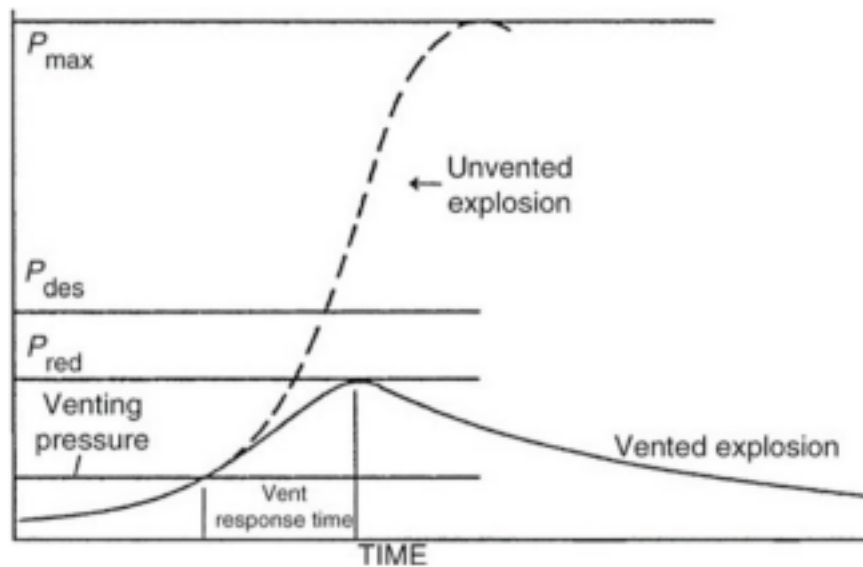
An explosion vent is a weak area in the wall of a building (e.g., a relief panel) or a dust-handling unit (e.g., a rupture disk). It is important to properly size the vent; acquiring data from standardized explosion testing of the specific dust is required to perform this task.

Undersized vents may be unable to sufficiently mitigate an explosion as the design pressure of the enclosure will be exceeded. The vent must also be designed to open without obstruction, as a possible obstruction will keep the degree of confinement too high to allow for sufficient overpressure relief.

The protection of plant personnel from relieved overpressure and the expelled mixture of combustion products and burning and unburned dust (as shown in the photograph in the slide), must be taken into account. One approach is to use vent ducting to eject any dust, whether burned, burning or unburned, to a safer location. Another approach is flameless venting, which is described in a later slide.

Photograph: Holbrow, P., "Dust Explosion Venting of Small Vessels and Flameless Venting", *Process Safety and Environmental Protection*, **91**, 183-190 (2012).

Venting process



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This figure illustrates the venting process in schematic format.

P_{max} = maximum explosion pressure generated in the unvented enclosure

P_{des} = maximum pressure the protected enclosure can withstand

P_{red} = maximum pressure allowed to be generated in the enclosure during explosion

Venting pressure = pressure at which the vent opens (also known as P_{stat})

Figure: Pekalski, A.A., Zevenbergen, J.F., Lemkowitz, S.M. and Pasman, H.J., "A Review of Explosion Prevention and Protection Systems Suitable as Ultimate Layer of Protection in Chemical Process Installations", *Process Safety and Environmental Protection*, 83, 1-7 (2005).

Relief panels and rupture disks



These are pictures of typical relief panels and rupture disks (i.e., explosion relief vents).

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Flameless venting



Corn Flour Explosion with Flameless Venting ⁸⁸

Flameless venting can help to prevent the ejection of dust and flames through the opening of the relief vent. This is achieved by means of a flame arresting device composed of mesh layers with quenching channels that is fitted in conjunction with the vent.

The photograph in this slide shows the same test rig as seen previously, only this time it is fitted with both a relief vent and a flame arrester. Here we see the effectiveness of the flameless venting device in eliminating flame propagation through the vent and permitting the passage of only smoke, water vapour and some dust.

There are two concerns of note with this method of venting. First, there is a possibility of a reduction in venting efficiency as compared to the relief vent alone. Second, flameless venting into an enclosed area, such as a building, will result in increased pressure within this enclosure which may also then require venting.

Photograph: Holbrow, P., "Dust Explosion Venting of Small Vessels and Flameless Venting", *Process Safety and Environmental Protection*, **91**, 183-190 (2012).

Flame quenching devices



These are pictures of typical flame quenching devices for use in the technique known as flameless venting.

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Active engineered safety

- Add-on safety devices
 - Inerting (gas) systems
 - Automatic explosion suppression
 - Explosion isolation valves
- Have no function other than to act when called upon to mitigate consequences of an explosion
- Require event detection and device activation
- Less reliable than passive devices

90

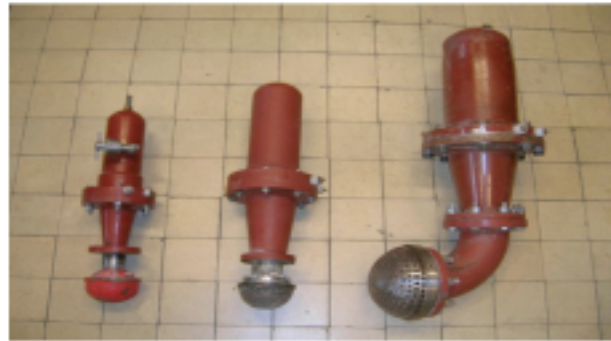
The active engineered safety level in the hierarchy of controls involves the use of safety devices that are added on to the process/facility unit. These devices do not play a production role; rather their extremely important role is to function in accordance with their design purpose to prevent explosions or mitigate explosion consequences and protect people and plant.

Active devices require detection of the explosion and activation of moving parts to perform their intended function. As such, they are less reliable than passive engineered devices (described earlier). Like any mechanical device, active engineered features must be properly designed, installed and maintained.

Examples include systems using inert gases (prevention), automatic suppression systems (mitigation), and isolation valves to limit the propagation of flame and damaging overpressures downstream (mitigation).

The use of inert gases was previously described in the Oxidant section of the module. Being preventive in nature, these systems themselves do not involve event detection and device actuation. However, they require constant monitoring of oxygen levels by other devices and are often used in conjunction with automatic suppression systems. Inert gas systems should therefore be placed in the active engineered category.

Suppression – HRD canisters



91

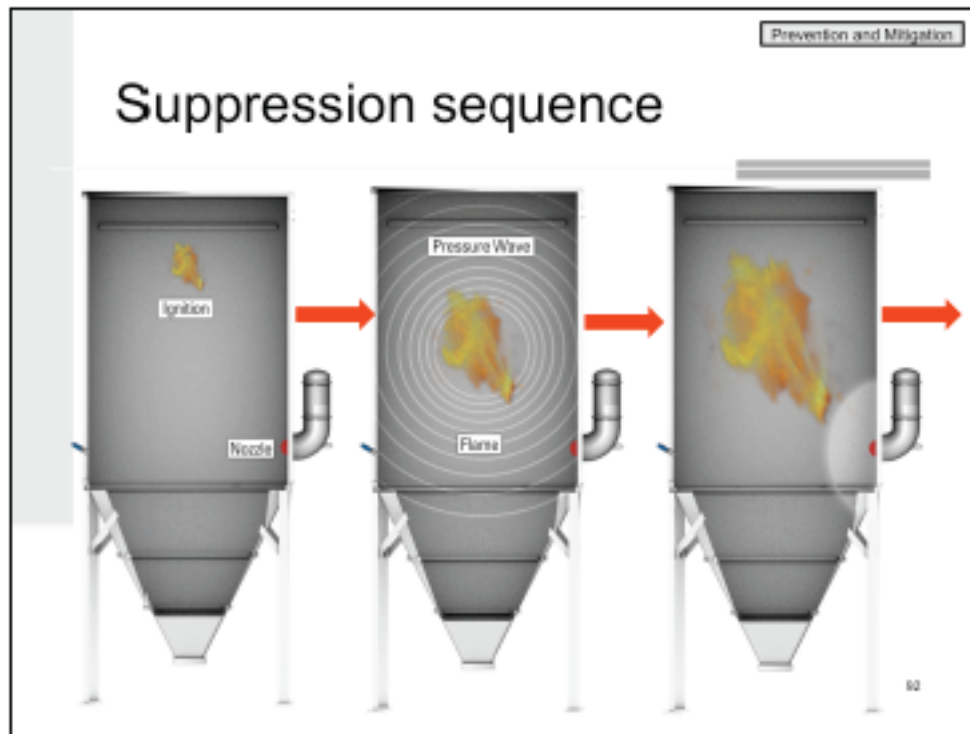
As described previously during the discussion on inherent safety, the term *inerting* arises when focusing on *preventing* the occurrence of a dust explosion; use of an inert dust admixed in sufficient amount to a fuel dust can lead to removal of the heat necessary for combustion. Also as seen previously in the module, this is analogous to explosion prevention by use of an inert gas (e.g., nitrogen) to ensure that process operation occurs at oxygen concentrations below the maximum permissible level.

On the other hand, the term *suppression* arises when focusing on *mitigating* the consequences of a dust explosion. The intent is the same as with inerting – to remove the heat necessary for sustained combustion and thus to limit the generation of destructive overpressures in an enclosed volume. In the case of suppression, however, the inert dust is injected into the just-ignited explosible dust/air mixture rather than being intimately premixed with the explosible dust prior to ignition, as in the case of inerting. Hence, suppression is an active engineered measure.

Suppression systems require the use of HRD (high-rate discharge) canisters to house the inert dust, as shown in the above pictures. The inert dust might be sodium bicarbonate or monoammonium phosphate, although in this application the material should technically be called a suppressant rather than an inertant.

Image on left courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Image on right from: Klemens, R., "Explosions of Industrial Dusts – From Ignition Source to Suppression", Plenary Paper, Proceedings of Ninth International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions, Krakow, Poland (July 22-27, 2012).



The series of steps that occur during successful suppression of a dust explosion are illustrated in this slide and the next one. We see a process unit with a suppressant-containing HRD canister mounted on the exterior of the unit.

In the first figure, ignition of a cloud of combustible dust cloud has occurred. All the elements of the explosion pentagon are present.

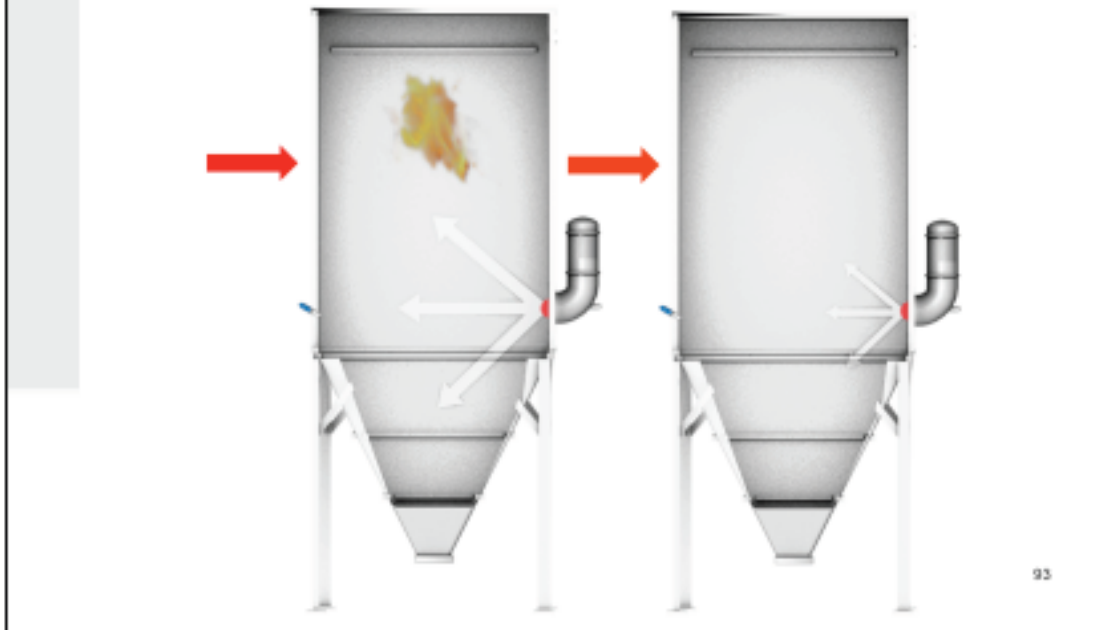
The second figure shows flame and pressure development inside the unit. The dust explosion is in progress.

By the time of the third figure, the developing overpressure has been detected by the suppression system and a signal has been sent to release the pressurized suppressant through the nozzle.

Please go to the next slide.

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Suppression sequence (continued)



In the first figure on this slide (fourth figure overall in the sequence), the suppressant material is being delivered into the unit. Flame is being extinguished by thermal and/or chemical means depending on the nature of the suppressant, and overpressure is being lowered.

The second figure on this slide (last figure overall in the sequence) shows a suppressed dust explosion with no flame and an intact process unit.

Images courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Isolation valves



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If a dust explosion occurs in a process unit, flame and pressure waves will be transmitted through connecting pipes and ducting. To protect downstream equipment, an isolation valve can be a helpful active engineered solution.

Upon pressure detection, a slide-plate rapidly closes to isolate the rest of the facility from damaging overpressures. Care must be taken to ensure that the plant is able to withstand the overpressure in the vicinity of the isolation valve.

Image courtesy of Jerome Taveau, Fike Corporation (Blue Springs, MO).

Procedural safety

- Safe work practices and procedures
 - Grounding and bonding
 - Hot-work permitting
 - Permit-to-work system
 - Housekeeping
- Directly involves people
 - Human error possible
 - Training essential
- Least effective category in hierarchy

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Procedural safety involves people performing various tasks, often in the current context for prevention of ignition sources (electric sparks, electrostatic discharges, hot surfaces, open flames, etc.). Step-by-step procedures and more general practices such as grounding and bonding, the use of hot-work permits, and a robust permit-to-work system are all essential in this regard. Rigorous housekeeping must be performed to remove accumulated dust layers and thereby prevent dust layer fires and secondary dust explosions.

Procedural safety, although absolutely essential to the overall risk reduction approach, falls in the fourth and least effective category of the hierarchy of controls. The reason is straightforward – procedural safety involves human beings and human beings make mistakes. Human error is an ever-present possibility, and effective training and human factors programs are critical components of dust explosion prevention and mitigation efforts.

Housekeeping

- Primary line of defence against dust explosions
- Design
 - Eliminate cleaning
 - Make cleaning easier
 - Scheduling
 - All surfaces cleaned
 - Performed safely



Dust Collection to Measure Accumulation

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The removal of dust deposits by good housekeeping practices is a primary line of defence against dust explosions.

Frank and Holcomb (2009) offer the following advice to effectively address the housekeeping design challenge (in the desired order of application):

- Design and maintenance of equipment to contain dust so that it does not escape and does not have to be cleaned up,
- Dust capture at release points,
- Use of physical barriers to limit the extent of dust migration and the size of room to be cleaned,
- Facility design for easy and effective cleaning,
- Establishing and enforcing housekeeping schedules,
- Ensuring that housekeeping programs address all areas in which dust might accumulate, and
- Ensuring that housekeeping activities are performed safely.

In the words of Frank and Holcomb (2009): *The easiest/most effective housekeeping is the housekeeping you do not need to do.*

The photograph in the slide illustrates the use of a portable vacuum for dust collection from round ductwork to enable measurement of dust accumulation rates.

Photograph: Frank, W.L. and Holcomb, M.L., "Housekeeping Solutions", Proceedings of Symposium on Dust Explosion Hazard Recognition and Control: New Strategies, The Fire Protection Research Foundation, Baltimore, MD (May 13-14, 2009).

Photograph courtesy of Kimberly-Clark Corporation.

Safety management systems

- Accountability: Objectives and Goals
- Process Knowledge and Documentation
- Capital Project Review and Design Procedures
- Process Risk Management
- Management of Change
- Process and Equipment Integrity
- Human Factors
- Training and Performance
- Incident Investigation
- Company Standards, Codes and Regulations
- Audits and Corrective Actions
- Enhancement of Process Safety Knowledge

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To conclude this section on prevention and mitigation of dust explosions, we make brief mention of two important concepts – safety management systems and safety culture. The mention is indeed brief, but only because a full discussion is outside the scope of the current module. There should be no doubt, however, that without the will to implement dust explosion risk reduction measures in a systematic and organized manner, all technical solutions are wasted. This statement will be borne out by the case studies explored in the next module section.

Safety management systems are recognized and accepted worldwide as best-practice methods for managing risk. They typically consist of 10 – 20 program elements that must be effectively carried out to manage the risks in an acceptable way. This need is based on the understanding that once a risk is accepted, it does not go away; it is there waiting for an opportunity to happen unless the management system is actively monitoring company operations for concerns and taking preventive actions to correct potential problems. The cycle of *plan, do, check* and *act* is the mantra of the management system approach to safety.

As a primary corporate objective, dust explosion prevention and mitigation fall within the scope of a process safety management system (i.e., a management system for process-related hazards such as fire, explosion and release of toxic materials). PSM, or Process Safety Management itself, is defined as the application of management principles and systems to the identification, understanding and control of process hazards to prevent process-related injuries and accidents.

The version of PSM recommended by the Canadian Society for Chemical Engineering (CSCHE) consists of the 12 elements given in this slide. The web site of the PSM Division of the CSCHE should be consulted for further information: <http://www.cheminst.ca/connect/forums/psm> (as of May 18, 2014).

Safety culture

- Provides the link between an organization's beliefs and prevention and mitigation strategies
- Safety culture
 - Reporting culture
 - Just culture
 - Learning culture
 - Flexible culture
- Collective mindfulness
- Risk awareness

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The collective beliefs of an organization regarding safety have a strong link with technical issues surrounding dust explosion prevention and mitigation. An organization with a positive safety culture will believe that they can achieve a higher safety standard and that safety is equal in importance to production.

Sociologist Andrew Hopkins (Hopkins, 2005) describes three concepts that address a company's cultural approach to safety, and makes the argument that the three are essentially alternative ways of talking about the same phenomena: (i) safety culture, (ii) collective mindfulness, and (iii) risk-awareness.

He further defines a safety culture as embodying the following subcultures: (i) a *reporting culture* in which people report errors, near-misses, and substandard conditions and practices, (ii) a *just culture* in which blame and punishment are reserved for behaviour involving defiance, recklessness or malice, such that incident reporting is not discouraged, (iii) a *learning culture* in which a company learns from its reported incidents, processes information in a conscientious manner, and makes changes accordingly, and (iv) a *flexible culture* in which decision-making processes are not so rigid that they cannot be varied according to the urgency of the decision and the expertise of the people involved.

Reference: Hopkins, A., "Safety, Culture and Risk. The Organizational Causes of Disasters", CCH Australia Limited, Sydney, Australia (2005).

Keys to success

- Hierarchy of controls
 - Inherent safety
 - Passive engineered safety
 - Active engineered safety
 - Procedural safety
- Safety management system
- Safety culture

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In summary, a dust explosion risk reduction program must incorporate the following elements to be successful:

- Hierarchy of controls,
- Safety management system, and
- Safety Culture

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel Ignition Source Oxidant
Mixing Confinement Dust Layer Fires Prevention and Mitigation **Case Studies** Resources Evaluation

Case Studies

- *To paraphrase G. Santayana, one learns from history or one is doomed to repeat it*
- Westray
 - Coal mine
 - Methane-triggered coal dust explosion
- Hoeganaes
 - Atomized iron production facility
 - Iron dust flash fires
- Imperial Sugar
 - Sugar refinery
 - Sugar dust explosion

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The quote paraphrasing G. Santayana is taken from the following reference:
Crowl, D. A. and Louvar, J. F., "Chemical Process Safety. Fundamentals with Applications", 3rd edition, Prentice Hall PTR, Upper Saddle River, NJ (2011).

Case studies are extremely helpful in enhancing the overall safety initiative. They incorporate the concept of *lessons learned* as the primary motivation for their use. This usually means that the most effective case studies are those giving details of a failure or shortcoming of some sort; it is human nature to pay attention when a story is being told and a loss – whether catastrophic or not – is involved. The quote from Crowl and Louvar (2011) illustrates the importance of learning from case histories and avoiding hazardous situations; the alternative is to ignore the mistakes of others and be involved in potentially life-threatening incidents.

In this section of the module, we briefly present three case studies. The incidents have been selected to cover a range of industries, fuels and event types. Further details can be found in the primary references identified for each incident.

Westray: what happened

Methane-triggered coal dust explosion

Plymouth, NS

May 9, 1992

26 fatalities



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Primary References

Richard, K.P., Justice, "The Westray Story – a Predictable Path to Disaster. Report of the Westray Mine Public Inquiry", Province of Nova Scotia, Halifax, NS (1997).

Amyotte, P.R. and Oehmen, A.M., "Application of a Loss Causation Model to the Westray Mine Explosion", *Process Safety and Environmental Protection* (Transactions of the Institution of Chemical Engineers, Part B), **80**, 55-59 (2002).

Westray was an underground coal mine in Plymouth, Nova Scotia (just outside of New Glasgow). On May 9, 1992 a methane-triggered coal dust explosion occurred, resulting in twenty-six fatalities. The overpressures generated underground were powerful enough to result in damage at the surface, as we can see in this photograph from the public inquiry report (Richard, 1997).

Westray: why

- Substandard practices
 - Poor housekeeping with respect to coal dust
 - Inadequate rock dusting
 - Continuation of mining in spite of inoperable methane detection devices
 - Storage of fuel and re-fueling of vehicles underground
- Substandard conditions
 - Inadequate ventilation system design and capability
 - Thick layers of coal dust with unacceptably high levels of combustible matter
 - Inadequate system to warn of high methane levels

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With its poor working conditions, Westray was an incident waiting to happen. Inadequate mine ventilation resulted in methane concentrations that were consistently higher than those permitted by regulations. Coal dust accumulation levels were also high, and there was a lack of rock dusting (inerting of the coal dust with limestone or dolomite). As indicated in the slide, other standard practices were also occurring in the mine (Amyotte and Oehmen, 2002).

Westray: lessons learned

- Poor safety culture
 - Lack of management commitment and accountability to safety matters
 - Fear of reprisal on part of workers
- Ineffective safety management system
 - Human factors
 - Training
 - Poor compliance to best industry practices and legislated safety requirements

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These substandard practices and conditions were a result of the lack of concern management had with respect to safety issues at the mine.

There was a poor safety culture at Westray, and production was prioritized at the expense of employee safety. Employees had a fear of reprisal, which undermined the possibilities for just and reporting cultures, and did not provide an opportunity for the existence of learning and flexible cultures.

Additionally, there was no effective safety management system at Westray. Employees generally had a lack of experience and knowledge of safe underground working practices. There was also a lack of safe work practices and procedures in place, indicating that employees were poorly trained.

Westray clearly demonstrates that a safety management system approach and the concept of safety culture go hand-in-hand when it comes to assuring worker safety (Amyotte and Oehmen, 2002).

Westray: lessons learned



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Workers paid the ultimate price for management's shortcomings at Westray. This is a photograph of the Westray Memorial in New Glasgow, NS (photograph courtesy of United Steelworkers; photograph by Peter Boyle). The Memorial displays a miner's lamp with thirteen rays of light emanating from each side of the lamp. Each ray contains the name and age of a Westray miner killed in the explosion.

Westray has left an indelible legacy on the people of Nova Scotia and Canada. It is widely accepted that the structure of the current Nova Scotia Occupational Health and Safety Act was hugely influenced by the Westray coal mine explosion. Bill C-45, a 2004 amendment to the Canadian Criminal Code, is known colloquially as the "Westray Bill" or "Westray Amendment". According to the Canadian Centre for Occupational Health and Safety, Bill C-45

- Created rules for establishing criminal liability to organizations for the acts of their representatives, and
- Establishes a legal duty for all persons "directing the work of others" to take reasonable steps to ensure the safety of workers and the public.

Hoeganaes: what happened

Iron dust flash fires

Gallatin, TN

Jan 31, 2011

2 fatalities

March 29, 2011

1 injury

May 27, 2011

3 fatalities,

2 injuries



105

Primary Reference

CSB, "Case Study. Hoeganaes Corporation: Gallatin, TN. Metal Dust Flash Fires and Hydrogen Explosion", No. 2011-4-I-TN, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2011).

The material on the notes pages for the Hoeganaes case is drawn from the above CSB report (CSB, 2011). Photographs shown on the slides can be found in the report (CSB, 2011) or on the CSB web site (www.csb.gov).

Hoeganaes Corporation is a producer of atomized steel and iron powders. In 2011, there were three flash fire incidents at the Hoeganaes facility in Gallatin, Tennessee. This particular Hoeganaes plant manufactured atomized iron powder for the production of metal parts in the automotive and other industries. The first incident occurred when a bucket elevator was restarted. Iron dust was dispersed into the air and ignited; the resulting flash fire killed two workers. The second incident occurred while igniters were being replaced on a band furnace. A hammer was being used to force reconnection of a gas port, in the process dispersing dust from a surface on the side of the furnace. The dust ignited and the ensuing flash fire injured one employee. In the third incident (described in more detail later in this case study presentation), a hydrogen explosion and resulting iron dust flash fires, claimed three lives and injured two other workers.

The photographs show fine iron dust present at the facility (with a penny for scale); layered iron dust observed post-explosion; and a laboratory-scale demonstration of an iron dust flash fire.

Hoeganaes: why

- No employee training
- Accumulations of iron dust
 - Inadequate housekeeping
 - Elevated surfaces



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Although employees were aware that iron dust flash fires could occur, they were not trained to appreciate the potential severity of such events or to identify combustible dust hazards. There were also significant accumulations of combustible iron dust throughout the facility. Dust collection systems were unreliable, housekeeping procedures were inadequate, and there were numerous elevated surfaces on which dust could accumulate (one of which is shown in the photograph).

Hoeganaes: lessons learned

Safety Culture

- Ignoring known hazards
- Reporting culture
 - Frequent minor flash fires not reported
- Learning culture
 - Repetition of similar incidents
- Flexible culture
 - Decision-making flawed

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There were issues with safety culture at Hoeganaes. Management was aware prior to the first incident in 2011 that there were combustion hazards associated with the iron dust in the facility, yet no actions were taken to mitigate these hazards. Flash fires occurred periodically at the plant, but prior to the incident in January 2011 there had been no serious injuries. Thus, the incidents became normalized and minor flash fires and near-misses were not reported. Three major incidents in such a short period of time, in addition to many previous minor events, indicate that nothing was learned and that known combustible dust hazards were not addressed. Decisions leading up to the incidents were not made by those most knowledgeable, and were made with little thought to possible consequences. This is clear from the description of the third incident – a hydrogen explosion and iron dust flash fires – given in the next slide.

Hoeganaes: lessons learned



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The third incident was initiated by a hydrogen leak in a process-pipe trench. (Hydrogen was used in the plant's continuous annealing furnaces to prevent oxidation of the iron powder). The hole in the pipe can be seen in the photograph. The trench held nitrogen piping and cooling water runoff in addition to the hydrogen piping. When a leak within the trench was identified, it was assumed to be the nitrogen pipe leaking as a result of a recent nitrogen leak elsewhere in the facility. There were no procedures in place to mitigate gas leaks. Even though it was known that hydrogen piping was also present in the trench, no effort was made to test the atmosphere to determine the source of the leak. Maintenance personnel opted to remove trench covers to identify the source of the leak. They used a forklift to remove the trench covers, which created frictional sparking that ignited the accumulated hydrogen gas. The explosion overpressure dispersed iron dust from elevated surfaces, igniting the dust and creating multiple flash fires.

Just as some people are surprised to learn that a dust can actually explode, some are also surprised by the fact that metal dusts can explode. Some metals such as fine, unoxidized aluminum powder are highly reactive and are among the most hazardous of combustible dusts. Other metals such as iron dust have higher ignition energies and generate lower overpressures and rates of pressure rise. Given the relatively low reactivity of the iron dust at Hoeganaes and the limited confinement in the plant building, it is not surprising that flash fires rather than dust explosions occurred. But consider these questions:

- What if the iron dust had been finer and therefore more reactive?
- What if the degree of confinement or the blockage ratio had been greater?
- Does it really matter to an injured party whether the injuries were caused by a flash fire or by an explosion?

Imperial Sugar: what happened

Sugar dust explosion

Port Wentworth, GA

Feb 7, 2008

14 fatalities

36 injuries



109

Primary Reference

CSB, "Investigation Report. Sugar Dust Explosion and Fire. Imperial Sugar Company", Report No. 2008-05-I-GA, U.S. Chemical Safety and Hazard Investigation Board, Washington, DC (2009).

The material on the notes pages for the Imperial Sugar case is drawn from the above CSB report (CSB, 2009). Photographs shown on the slides can be found in the report (CSB, 2009) or on the CSB web site (www.csb.gov).

The Imperial Sugar Company in Port Wentworth, Georgia, refined raw sugar into granulated sugar and packaged the final product. On February 7, 2008 a primary dust explosion occurred inside an enclosed conveyor belt under several storage silos. This event triggered multiple secondary explosions that propagated through the packaging buildings, bulk sugar loading buildings, and parts of the raw sugar refinery. Concrete floors buckled, a wooden roof collapsed, and sprinkler systems failed because the explosion had ruptured the water pipes. Employees had no time to react. Eight workers died at the scene, four of whom were trapped by falling debris and collapsing floors. Nineteen workers were severely burned and six later succumbed to their injuries.

Imperial Sugar: why

- Conveyor belt: no dust removal system or explosion vents
- Inadequate housekeeping
- Inadequate evacuation plan



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The conveyor belt where the primary explosion occurred was enclosed to prevent contamination. However, it was not equipped with a dust removal system or explosion relief vents. Routine housekeeping procedures were not implemented at the facility. As such there were significant accumulations of sugar and sugar dust in the refinery, as shown in the photograph. Compressed air was used for housekeeping, resulting in dust accumulations on elevated surfaces. It is believed that the secondary explosions and resulting damage and fatalities would likely not have occurred if proper housekeeping procedures had been enforced.

The emergency evacuation plan was also inadequate. This deficiency, along with poor lighting, large pieces of equipment and conveyors on or near the floor, and no emergency alarm system, all hindered the evacuation and safety of employees.

Imperial Sugar: lessons learned



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This photograph shows a conveyor belt removed after the incident. The granulated sugar on conveyor belts had previously been exposed to possible contamination from falling debris, and so in 2007 the conveyor belts were enclosed with top and side panels. While this addressed the issue of contamination, it inadvertently created a much higher level of confinement. This is an example of inadequate safety management, specifically management of change, where a new hazard was introduced as a result of a change to process equipment.

The high concentrations of sugar dust in such a relatively small enclosure created an ideal environment for a dust explosion, yet as previously mentioned – no dust removal systems, explosion vents, or other prevention and mitigation strategies were implemented. As a result, a primary explosion occurred within the enclosure, causing several secondary explosions and fires to propagate through the facility. Management of change, or MOC, is one of the most important safety management system elements to consider in a processing facility.

Imperial Sugar: lessons learned

- Previous fires and near-misses
- Management knew about hazards



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There were previously reported incidents of fires and near-misses. Two weeks prior to the 2008 catastrophic explosion, there was a small explosion in a dust collector, which had been safely vented. Management was therefore aware of the existing hazards at the facility. However, plans for improvements in the past, such as with housekeeping procedures, were either forgotten or neglected. The refinery was able to function successfully despite unfavorable conditions, since any incidents to-date had always been relatively minor. Rather than attempting to identify and correct underlying causes, evidence of deviations was accepted and normalized.

The photograph (circa 1990) illustrates that the issues surrounding housekeeping were a longstanding problem at this facility.

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel Ignition Source Oxidant
Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Resources

- Videos
- Reports
- Data Bases
- Standards
- Papers
- Books

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A large amount and variety of resources on dust explosions are available. Here we present examples of resource material in the form of a video, incident investigation reports, an explosion parameter data base, testing and risk control standards, peer-reviewed journal papers, and text books.

Videos, reports, data bases



Video

Marta, M., "Probable Dust Explosions in B.C. Opportunity to Understand Possible Contributing Factors, At-Risk Industries, Basic Safeguarding Measures, Standards, Regulations", 62nd Canadian Chemical Engineering Conference, Vancouver, BC (2012).

Available at: <http://vimeo.com/50925194> (last accessed May 9, 2014).

This video will be helpful in considering the Babine Forest Products incident as part of the Evaluation (Analyzing) exercise in the next module section.

Incident Investigation Reports

Another excellent resource is the web site of the United States Chemical Safety and Hazard Investigation Board (Chemical Safety Board or CSB): www.csb.gov. This web site contains all of the CSB reports referenced in the module as well as additional investigation reports of dust explosion incidents. The more recent reports are typically accompanied by an explanatory video.

Explosion Parameter Data Base

The IFA GESTIS-DUST-EX data base contains values of explosion parameters for many dusts. A cautionary note must be made, however, that there is no substitute for standardized-test data for a given dust being handled in industry.

Available at: <http://www.dguv.de/ifa/Gefahrstoffdatenbanken/GESTIS-STAU-EX/index-2.jsp> (last accessed May 9, 2014).

Standards



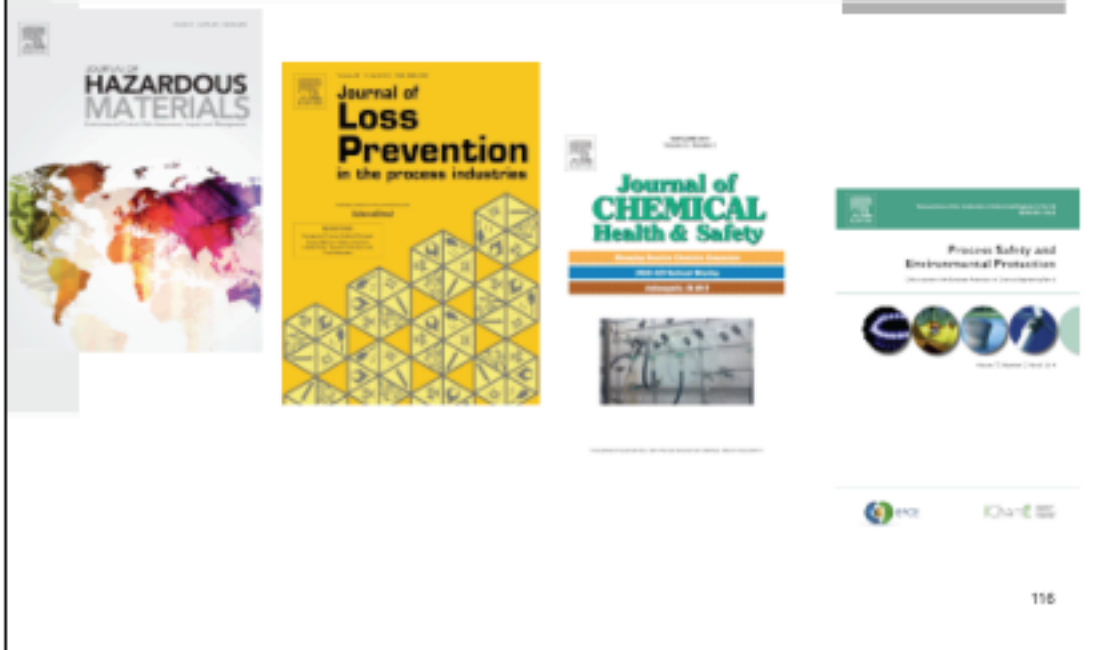
Testing Standards

The dust explosibility testing standards referenced in the module (and others) are available on the ASTM International web site: www.astm.org. As of May 9, 2014, there is a fee to download these standards.

Risk Control Standards

The risk control standards referenced in the module (and others) are available on the National Fire Protection Association (NFPA) web site: www.nfpa.org. As of May 9, 2014, there is no fee to download these standards.

Papers



Peer-Reviewed Journal Papers

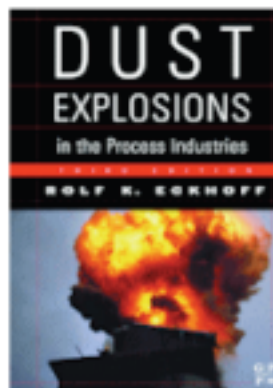
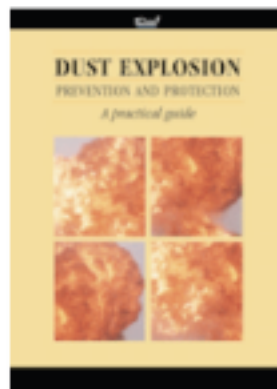
Abbasi, T. and Abbasi, S.A., "Dust Explosions – Cases, Causes, Consequences, and Control", *Journal of Hazardous Materials*, **140**, 7-44 (2007).

Eckhoff, R.K., "Understanding Dust Explosions. The Role of Powder Science and Technology", *Journal of Loss Prevention in the Process Industries*, **22**, 105-116 (2009).

Amyotte, P.R. and Eckhoff, R.K., "Dust Explosion Causation, Prevention and Mitigation: an Overview", *Journal of Chemical Health and Safety*, **17**, 15-28 (2010).

Amyotte, P.R., "Some Myths and Realities about Dust Explosions", *Process Safety and Environmental Protection* (2014), <http://dx.doi.org/10.1016/j.psep.2014.02.013>.

Books



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Text Books

Barton, J. (editor), "Dust Explosion Prevention and Protection. A Practical Guide", Institution of Chemical Engineers, Rugby, UK (2002).

Eckhoff, R.K., "Dust Explosions in the Process Industries", 3rd edition, Gulf Professional Publishing/Elsevier, Boston, MA (2003).

Amyotte, P., "An Introduction to Dust Explosions. Understanding the Myths and Realities of Dust Explosions for a Safer Workplace", Elsevier/Butterworth-Heinemann, Waltham, MA (2013).

Basic Fire Principles Basic Explosion Principles Dust Explosion Fundamentals Fuel Ignition Source Oxidant
Mixing Confinement Dust Layer Fires Prevention and Mitigation Case Studies Resources Evaluation

Evaluation

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"Plan, Do, Check, Act" is the continuous improvement cycle that characterizes all safety management efforts. Work is planned and performed, and the results are checked and acted upon for commendation or correction. In that same spirit, this evaluation section of the module is aimed at checking whether the learning objectives identified at the outset have been achieved.

Recall that these learning objectives are structured according to Bloom's Taxonomy. The next three slides address the three lower levels in the taxonomy: remembering, understanding and applying. The questions are closed-ended and the answers are brief and fairly well-defined. The subsequent three slides address the three higher levels in the taxonomy: analyzing, evaluating and creating. The questions are open-ended and the answers are longer and more involved. The information required to answer all of these questions can be found in the module and associated readings.

Remembering

Define what is meant by a “combustible dust”.

Identify all of the elements of the fire triangle and the explosion pentagon.

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A combustible dust is defined as a combustible particulate solid that presents a fire or deflagration hazard when suspended in air or some other oxidizing medium over a range of concentrations, regardless of particle size or shape. This is the NFPA (US National Fire Protection Association) definition. It is the most appropriate definition of a combustible dust because it does not impose artificial criteria related to the size or shape of the particles.

The elements of the fire triangle are: fuel, ignition source and oxidant. Being a triangle, there must of course be three elements. It is important that the energy released during the combustion process is sufficient to sustain the chemical reactions occurring. This additional requirement of a chemical chain reaction is sometimes represented as a fourth fire criterion in what is known as the fire tetrahedron.

The elements of the explosion pentagon are: fuel, ignition source, oxidant, mixing and confinement. Being a pentagon, there must of course be five elements. The first three are the familiar fire triangle elements of fuel, ignition source and oxidant. The two additional elements of mixing and confinement illustrate key differences between a fire and an explosion. For an explosion to occur, there must be adequate mixing of the fuel and oxidant prior to ignition. There must also be sufficient confinement of the reacting mixture such that an overpressure is developed.

Understanding

Explain how a gaseous, liquid or solid fuel actually burns. (What is the physical state of the reacting fuel?)

Describe the fundamentals of a dust explosion according to the explosion pentagon.

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The fuel for a fire can be in any of the gaseous, liquid or solid states. Regardless of the original fuel state, actual combustion occurs homogeneously in the vapour phase. This is of course not an issue for gaseous fuels, but it means that liquid and solid fuels must first undergo phase transitions to vapours before combustion can occur. The heterogeneous combustion of fine carbon powder is one of the few exceptions to this requirement.

Fundamentals of a dust explosion according to the explosion pentagon:

FUEL – The fuel in a dust explosion is a combustible particulate solid (i.e., combustible dust). There are many materials that will burn when in fine particulate form – coal, wood, aluminum, polyethylene, rubber, etc. The particles can be spherical, flocculent (fibrous) or any shape that supports combustion. The dust must be present in an amount equal to or greater than its minimum explosible concentration (MEC).

IGNITION SOURCE – Typical industrial ignition sources for dust explosions include flames, hot surfaces, smoldering particles, electrical sparks and electrostatic discharges. The required spark ignition energy for a dust explosion is called the minimum ignition energy (MIE); the required hot-surface ignition temperature for a dust explosion is called the minimum ignition temperature (MIT).

OXIDANT – The oxidant for most dust explosions is the oxygen present in air. For a dust explosion to occur, the actual oxygen concentration must exceed the dust-specific limiting oxygen concentration (LOC).

MIXING – Because dust must be airborne for it to explode, mixing is a key step on the path to a dust explosion. Layered dust can be raised into suspension (i.e., dispersed) by an aerodynamic disturbance such as a blast of compressed air or the shock wave produced by a precursor explosion event, thus forming a dust cloud. Alternatively, a dust cloud may already exist inside a process unit due to the nature of the operation being performed (e.g., particle size reduction).

Applying

Calculate the airborne concentration in an enclosure with a height of 5 m resulting from the dispersion of a 0.8-mm thick layer of corn flour having a bulk density of 0.82 g/cm³.

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Here we use the equation: $C = \rho_{\text{bulk}} (h/H)$

C = dust concentration

ρ_{bulk} = bulk density of dust layer = 0.82 g/cm³

h = thickness of dust layer = 0.8 mm

H = height of dust cloud produced from dust layer = height of enclosure = 5 m

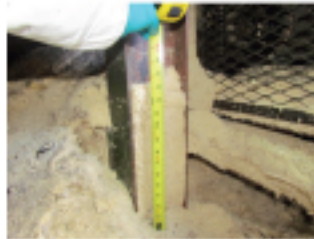
With the above equation, given data and appropriate unit conversion, we calculate the resulting airborne dust concentration (C) as 130 g/m³.

The exercise can be extended by posing the following question. What risk-based conclusion would you make if you knew that the minimum explosible concentration of the corn flour had been determined to be 60 g/m³?

Answering this question will require recognition that the dust concentration (130 g/m³) exceeds the MEC (60 g/m³). It now appears that the fuel, oxidant, mixing and confinement criteria of the explosion pentagon are satisfied. All that is needed for a dust explosion to occur is the presence of an adequate ignition source.

Analyzing

Identify the possible fuel sources that could have been involved in the explosion at the Babine Forest Products facility in Burns Lake, BC on January 20, 2012. Discuss which of these involved combustible dust hazards.



Note: This incident was investigated by WorkSafeBC; the investigation report is available on their web site: www.worksafebc.com.

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You will first have to read the WorkSafeBC investigation report to answer this question; the photograph in the slide is taken from this report. As previously indicated in the Resources section of this module, the video by Manny Marta will also be helpful.

Section 2.3 of the WorkSafeBC report analyzes the various fuel sources that could possibly have played a role in the explosion. Section 2.5.2 of the report provides details on the explosibility of wood dust samples taken from the Babine sawmill post-explosion.

Evaluating

Determine several strategies that might have been helpful in preventing and mitigating the polyethylene dust explosion at the West Pharmaceuticals facility in Kinston, NC on January 29, 2003. Be sure to justify your choices.



Note: This incident was investigated by the US Chemical Safety Board; the investigation report is available on their web site: www.csb.gov.

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You will first have to read the CSB investigation report to answer this question; the photograph in the slide is taken from this report. Chapter 2 (Analysis of Incident) and Chapter 6 (Root and Contributing Causes) will be particularly helpful.

There are different ways to structure your answer. An effective approach would be to use the hierarchy of controls as a framework, and to clearly differentiate between those measures that are preventive in nature and those that are aimed at mitigation of consequences. For example, avoidance of ignition sources is primarily a procedural measure aimed at explosion prevention. Explosion relief venting, on the other hand, is a passive engineered measure aimed at mitigation of destructive overpressures. A critical aspect of your evaluation is to be specific in relating these general measures to the actual case of West Pharmaceuticals. This will be necessary to justify your choices, as some risk reduction measures might be inappropriate or unfeasible. Remember also that application of the principles of inherent safety – if possible – will be the most effective approach.

Creating

Formulate a dust explosion prevention plan for the scenario described below. Be sure to account for each element of the explosion pentagon.



A fine aluminum powder is being processed at a facility involving numerous physical operations such as grinding, pulverizing and sieving. Workers are largely unaware of combustible dust hazards and plant management has not shown itself to be very supportive of loss prevention efforts.

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Your answer to this question must focus on two main points: (i) prevention of dust explosions, and (ii) each of the five elements of the explosion pentagon (fuel, ignition source, oxidant, mixing and confinement).

Preventive approaches can again be placed in a hierarchical order ranging from inherent safety principles, to engineered safety devices (passive and active), to procedural measures.

The first sentence of the scenario statement gives significant clues as to the nature of all five explosion pentagon elements. Fine aluminum powder is a highly reactive fuel. Physical operations such as grinding, pulverizing and sieving will likely involve unique ignition sources, an air atmosphere, dust dispersions, and complete confinement. As with the previous exercise on evaluating, a particular challenge in this exercise on creating is to be specific in relating general prevention measures to the actual scenario (which is quite open-ended in this case).

The last sentence of the scenario statement indicates that measures other than the hierarchy of controls will require attention. You will find it necessary to consider the concepts of safety culture and a management system approach to safety (including training and hazard awareness).