Dalhousie University (Dr. Paul Amyotte)
Research Report

Type of Document
Final Report

Project Name
Inherently Safer Bow Ties for Dust Hazard Analysis

Project Number
20210002

Prepared By:
Kayleigh Rayner Brown, MASc, P.Eng.

Reviewed By:
P. Amyotte, C. Cloney, B. Laturnus

Obex Risk Ltd.
620 Nine Mile Drive, Suite 208
Bedford, NS, B4A 0H4
Canada
T: 782-640-9555
www.obexrisk.com

Date Submitted
December 21, 2021

Date Revised
June 29, 2022

UNRESTRICTED

This page is intentionally left blank

This page is for Content Controls that apply to this document. If no Content Controls apply, none will be listed.

UNRESTRICTED

Revision History

Rev. No.	Date	Details of Rev.	Prepared By	Reviewed By	Approved By
D1	December 21, 2021	Issued for Review and Comment	K. Rayner Brown	P. Amyotte C. Cloney B. Laturnus G. Murray C. Whelan F. Yazdanpanah	K. Rayner Brown
D2	January 6, 2022	Revisions Markup	K. Rayner Brown		K. Rayner Brown
D3	February 8, 2022	Revisions Markup	K. Rayner Brown		K. Rayner Brown
R1	February 14, 2022	Final Report	K. Rayner Brown		K. Rayner Brown
R2	June 29, 2022	Revised Final Report • Addressed reviewer feedback	K. Rayner Brown		K. Rayner Brown

Legal Notification

This report was prepared by Obex Risk Ltd. for the account of Dalhousie University for intended use by Dalhousie University, British Columbia Forest Safety Council (BCFSC), DustEx Research Limited, Wood Pellet Association of Canada (WPAC) and WorkSafeBC Research Services.

Any use which a third party makes of this report, or any reliance on or decisions to be made based on it, are the responsibility of such third parties. Obex Risk Ltd. accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this report.

Disclaimer

This report makes no endorsements of any products, services or companies mentioned.

List of Distribution

Report Distributed To:

Dr. Paul Amyotte, P.Eng.
Professor of Chemical Engineering
Dalhousie University

Bill Laturnus
Senior Safety Advisor, Manufacturing
BC Forest Safety Council

Cherie Whelan
Director, SAFE Companies
BC Forest Safety Council

Dr. Chris Cloney, P.Eng.
Director
DustEx Research Limited

Gordon Murray, RPF, CPA, CMA
Executive Director
Wood Pellet Association of Canada

Fahimeh Yazdanpanah, PhD, P.Eng., PMP
Director of Research and Technical Development
Wood Pellet Association of Canada

Obex Risk Ltd. Quality System Checks	
Project No.: 20210002	Date: June 29, 2022
Type of Document: Final	Revision No.: R2
Prepared By: Kayleigh Rayner Brown, MASc, P.Eng.	
Reviewed By: P. Amyotte B. Laturnus C. Cloney G. Murray C. Whelan F. Yazdanpanah	

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

This report describes the work completed under the project titled "Inherently Safer Bow Ties for Dust Hazard Analysis" funded by a WorkSafeBC Innovation at Work grant with partnership between Dalhousie University, DustEx Research Limited, Wood Pellet Association of Canada (WPAC) and BC Forest Safety Council (BCFSC).

The objective of the research was to incorporate the principles of inherently safer design (ISD) for the management of combustible dust hazards associated with wood pellet production. Process hazard analysis (PHA) was completed using the bow tie method to assess and manage combustible dust hazards related to wood pellet and MDF (medium density fiberboard) manufacturing. These bow tie analyses were developed as part of WPAC's Critical Controls Management (CCM) project. Additionally, a bow tie analysis focusing on combustible dust hazards in a direct-fired belt dryer was completed as part of WPAC's Belt Dryer Working Group (BDWG). The top events that were analyzed were combustible dust layer fire, combustible dust explosion, combustible dust deflagration, and ignition. The bow tie diagrams that were developed included the consideration of degradation factors and controls.

Following the development of the bow ties, the ISD protocol for PHA (described by Rayner Brown et al., 2020) was applied. This protocol is based on the incorporation of the hierarchy of controls within bow tie analysis to identify barriers with respect to the preferred order of consideration. This protocol was used to identify potential opportunities to incorporate the principles of ISD (minimization, substitution,

moderation, and simplification). Furthermore, opportunities to consider additional barriers in the hierarchy of controls (engineered passive, engineered active, and administrative) were identified.

Example-based guidance, as well as ISD checklist questions, were used to identify ISD barriers. This project involved the collection of example-based guidance for combustible wood dust hazards in wood processing industries. Resources for this example-based guidance included NFPA standards, archival journal articles, CSB incident investigation reports, Center for Chemical Process Safety (CCPS) resources, and other technical literature describing good engineering practice.

Using bow tie analysis to explicitly consider ISD within PHA, ISD barriers for combustible dust hazards in wood pellet production were successfully identified. Examples of ISD barriers include:

- substituting conductive material for piping instead of plastic to displace static electricity and decrease risk of ignition (substitution),
- using supply chain considerations to minimize the amount of foreign material (e.g., rocks, and other ferrous and non-ferrous contaminants) in the feedstock to prevent potential ignition sources from entering the process (minimization),
- operating rotating elements, such as screw augers, below a tip speed of 1 m s^{-1} to prevent the generation of mechanical or frictional sparks from metal-on-metal contact and the dispersion and suspension of combustible dust clouds (moderation),

- where operator grounding is required, using static dissipative footwear and flooring rather than leg or wrist straps that must be attached prior to performing an operation (simplification),
- using paved surfaces on which to store feedstock to minimize rocks entering process and presenting risk of ignition sources,
- using reduced sized silos to minimize inventory and increase turnover frequency,
- removing unnecessary or hazardous equipment, like fans, following a redesign or recapitalization, and
- relocating hazardous equipment, like cyclones, outside and away from personnel.

Several knowledge transfer and exchange (KTE) efforts that were undertaken during the project to engage stakeholders and enhance knowledge of ISD and bow tie analysis. KTE initiatives include webinar presentations, conference presentation, podcast interviews, and articles in industry trade publications. Manuscript submission to an archival journal is also in preparation. These KTE projects were targeted at both wood pellet producers and wood processing facilities in British Columbia and across Canada, as well as global process safety and combustible dust researchers and practitioners. Dalhousie personnel were also involved with other projects related to ongoing process safety initiatives, including involvement with the belt dryer working group, as well as the completion of a project focussed on deflagration isolation (funding arranged by Dr. Paul Amyotte, work conducted by K. Rayner Brown of Obex Risk Ltd.).

It is recommended that operations examine the feasibility of incorporating ISD options identified through this work within facilities. These options may be considered during incident investigation when developing corrective action plans, as well as management of change. It is encouraged to follow the hierarchy of controls when considering the addition of safety measures.

Additional areas for future work include dedicated ISD workshops with wood pellet producers to enhance identification of ISD barriers that can be incorporated at operational facilities, enhancing the adoption of process safety management (PSM) in wood pellet operations, and further application of the ISD PHA protocol to other high-hazard industries for further improving ISD use in other fields.

LIST OF ABBREVIATIONS USED

BCFSC	British Columbia Forest Safety Council
BFD	Block Flow Diagram
BTA	Bow Tie Analysis
CCHS	Contra Costa County Health Services
CCM	Critical Controls Management
CCPS	Center for Chemical Process Safety
CSB	Chemical Safety Board
DHA	Dust Hazard Analysis
HAZOP	Hazard and Operability Study
HMI	Human-Machine Interface
IAW	Innovation at Work
ISD	Inherently Safer Design
ISO	*Industrial Safety Ordinance*
KTE	Knowledge Transfer and Exchange
PFD	Process Flow Diagram
PID	Piping and Instrumentation Diagram
PHA	Process Hazard Analysis
PSM	Process Safety Management
MEC	Minimum Explosible Concentration
MDF	Medium Density Fibreboard
MIE	Minimum Ignition Energy
MOC	Management of Change
NFPA	National Fire Protection Association
SME	Subject Matter Expert
TBD	To Be Determined
US CSB	United States Chemical Safety Board
WorkSafeBC	Workers' Compensation Board of British Columbia
WPAC	Wood Pellet Association of Canada

ACKNOWLEDGEMENTS

Obex Risk Ltd. acknowledges project funding provided by WorkSafeBC under a 2020 Innovation at Work Grant led by Principal Investigator Dr. Paul Amyotte (Professor, Chemical Engineering, Department of Process Engineering and Applied Science).

Obex Risk Ltd. wishes to sincerely thank all those involved with the research for providing input and expertise to the project, including all those from wood pellet and wood processing operations. Obex Risk Ltd. also acknowledges Dalhousie University, Wood Pellet Association of Canada (WPAC), BC Forest Safety Council (BCFSC), and DustEx Research Ltd. for their ongoing support of the IAW project. Thank you to Bill Laturnus, Tyler Bartels, and Cherie Whelan (BCFSC); Gordon Murray and Dr. Fahimeh Yazdanpanah (WPAC); Dr. Chris Cloney (DustEx Research Ltd.); and Dr. Paul Amyotte (Dalhousie University). Thank you as well to Karen Brandt (Brandt Strategy Inc.) and Michele Fry (BCFSC) for support with communications and Knowledge Transfer and Exchange (KTE) initiatives.

Lastly, Obex Risk Ltd. extends thanks to Dalhousie University for commissioning Obex Risk Ltd. to complete this final research report.

CHAPTER 1
INTRODUCTION

This report describes the work completed under the project titled “Inherently Safer Bow Ties for Dust Hazard Analysis” funded by a WorkSafeBC Innovation at Work grant with partnership between Dalhousie University, DustEx Research Limited, Wood Pellet Association of Canada (WPAC) and BC Forest Safety Council (BCFSC). The introductory chapter of this report provides an overview of inherently safer design (ISD), combustible dust hazards, and bow tie analysis, as well as the motivation, scope of work and objectives of the project. The organization of this report document is also outlined.

1.1 Combustible dust hazards

Definitions for combustible dust are provided in various NFPA (National Fire Protection Association) Standards. A combustible dust is defined by NFPA 652 (2019), NFPA 68 (2018), and NFPA 69 (2019), as "a finely divided combustible particulate solid that presents a flash fire hazard or explosion hazard when suspended in air or the process-specific oxidizing medium over a range of concentrations." In NFPA 77 (2019), a combustible dust is defined as "a combustible particulate solid that presents a fire or deflagration hazard when suspended in air or other oxidizing medium over a range of concentrations, regardless of particle size or shape."

The hazards presented by combustible dust include dust deflagration, dust explosion and flash fire. A dust deflagration is defined in NFPA 652 (2019) as “propagation of a combustion zone at a velocity that is less than the speed of sound in the unreacted medium.” NFPA 652 defines a Dust Hazard Analysis (DHA) as a “systematic review to identify and evaluate the potential fire, flash fire, or explosion hazards associated with the presence of one or more combustible particulate solids in a process or facility.”

NFPA 652 (2019) describes that a “dust explosion can exist when there is a combustible dust with a particle size small enough to propagate a flame front, there is a means of suspending or dispersing the particulate in air or other oxidizing atmosphere, there is a sufficient quantity of dust to achieve the minimum explosible concentration, there is a sufficient ignition source, and there is a sufficient degree of confinement such that damaging overpressure may develop as a result of the rapid increase in temperature associated with the combustion process.” There are five elements that must be present for a dust explosion to occur – fuel, dispersion, oxygen, an ignition source and confinement.

Lastly, combustible dust can present a flash fire hazard. If there is no or little confinement, a dust deflagration produces virtually no overpressure and is called a flash fire. NFPA 652 (2019) defines a flash fire as “a fire that spreads by means of a flame front rapidly through a diffuse fuel, such a dust, gas or the vapours of an ignitable liquid without the production of damaging pressure.” Although damaging pressures are not reached during a flash fire, thermal and radiative heating can damage equipment and severely injure workers.

1.2 Combustible dust in wood pellet manufacturing

Dust explosions can occur in any industrial application that involves the handling of bulk solids and powders, including the wood pellet manufacturing industry, lumber processing, and sawmills. Wood dust generated in wood pellet manufacturing presents combustible dust hazards (Hedlund & Astad, 2014; Melin, 2012). When wood dust is suspended in air, explosible dust clouds may be formed, which can be easily ignited by sources, like sparks, that are intrinsic to the manufacturing process. There have been devastating incidents involving combustible dust in woodworking facilities in Canada and the province of British Columbia. On January 20, 2012, there was a catastrophic sawmill explosion at Babine Forest Products in Burns Lake, BC where two workers were killed and 20 were injured (WorkSafeBC, 2012a). Shortly thereafter, on April 23, 2012, another tragic explosion involving wood dust occurred at the Lakeland Mills Forest Products company in Prince George, BC, which left two workers dead and 22 injured (WorkSafeBC, 2012b). These incidents emphasize the importance of managing combustible dust hazards in order to prevent loss producing incidents that are harmful to people, property, business operations and the environment. The next section discusses bow tie analysis, process hazard analysis (PHA) technique that can be used to examine combustible dust hazards.

1.3 Bow tie analysis

Bow tie analysis is a barrier-based risk management tool that demonstrates and communicates how various factors can cause loss of control of a hazard and lead to undesirable consequences (CCPS/EI, 2018). Bow tie analysis can also be referred to as a bow tie diagram. A bow tie diagram incorporates the use of barriers, which are controls or safeguards that can prevent or mitigate an unwanted event. These barriers are typically comprised of passive engineered barriers (e.g., corrosion resistant coatings), active engineered barriers (e.g., smoke detectors) and administrative barriers (e.g., safe work procedures). The next section introduces inherently safer design (ISD) and highlights how it can be explicitly incorporated into bow tie analysis.

1.4 Inherently safer design (ISD) and the hierarchy of controls

Inherently safer design (ISD) is an approach used to eliminate or reduce hazards, rather than focusing only on hazard control or management. ISD is based on four main principles: minimization, substitution, moderation and simplification (Kletz and Amyotte, 2010). The use of these measures leads to an inherently safer design because hazards are avoided due to the intrinsic and inseparable characteristics of the system, rather than reliance on add-on safety equipment or features. Minimization refers to eliminating or reducing the hazard by design, such as minimizing hazardous material inventories or equipment. Substitution involves replacing a hazardous material or method with a less hazardous one, such as using sodium hypochlorite instead of chlorine gas. Moderation is the use of less hazardous forms of materials or conditions to reduce the severity of hazards. Simplification includes designing processes to reduce equipment and chances for human error (Goraya et al., 2004; Kletz and Amyotte, 2010).

ISD is not a standalone concept – in order for it to be systematically and explicitly considered, it must be incorporated within an organization’s process safety management (PSM) framework (Amyotte et al., 2007; Rayner Brown et al., 2020). Rayner Brown et al. (2020) present a protocol for explicitly incorporating the principles of ISD within process hazard analysis, specifically the bow tie analysis methodology. This protocol involves the explicit consideration of ISD barriers to address threat and consequence lines prior to moving onto passive engineered, active engineered and administrative barriers.

The purpose of the research project described in this report is to use bow tie analysis to incorporate the principles of ISD within dust hazard analysis (DHA) for the management of combustible dust hazards.

1.5 Research motivation and relevance

The motivation for this research is that combustible dust related incidents are still occurring and there is an identified need for the prevention and mitigation of dust hazards using process safety tools. Inherently safer design (ISD) plays a critical role in risk management, and its continued adoption is further encouraged. Bow tie analysis is an effective hazard analysis method that can be used to manage risk in non-CPI (chemical process industry), high-hazard industries and is an intuitive visual tool that is easily understood by broad audiences. Dust hazard analysis is recognized as industry best practice for managing combustible dust hazards. This project blends these three key tools into an innovative, accessible format to achieve the incorporation of inherently safer design in bow tie analysis within the context of combustible wood dust hazard analysis.

1.6 Project objective

The objective of this work was to incorporate inherently safer design (ISD) into bow tie analysis for the management of combustible dust hazards. This project consisted of the following high-level work breakdown structure and milestones:

- Review of previously developed bow ties for combustible wood dust
    - A set of bow ties were initially developed by other industry stakeholders prior to the outset of this project. A high-level review of these previously completed bow ties was performed to identify additional areas of focus and help inform the development of another set of bow ties in collaboration with the Critical Controls Management (CCM) project undertaken by BCFSC and WPAC
- Development of combustible wood dust bow ties
    - Through collaboration with BCFSC and WPAC, during the course of the Critical Controls Management (CCM) project, bow tie analyses were conducted for process units of focus in wood processing plants, including wood pellet production and MDF (medium density fibreboard) production
- Collection of example-based guidance related to combustible dust hazards
    - The identification and collection of ISD example-based guidance related to combustible dust hazards was completed in this work to help identify ISD barriers.
- Protocol application and development of inherently safer bow ties
    - This work expands and builds on work completed by Rayner Brown et al., (2020). The current work involves the application of the inherently safer design – bow tie analysis (ISD-BTA) protocol described by Rayner Brown

et al. (2020) in a predictive and proactive manner with the objective of developing bow ties with the explicit incorporation of ISD barriers that may be used to contribute to the prevention of future incidents. In contrast, the earlier work involved application of the ISD-BTA protocol to incident case studies detailed by the US Chemical Safety Board (US CSB) and Contra Costa County Health Services (CCHS) in California, US. These incident case studies validated the newly developed protocol and retrospective opportunities for numerous ISD barriers were identified.

- Knowledge transfer and exchange
    - The importance of knowledge transfer and exchange (KTE) has been identified. Several KTE initiatives were completed to target different audiences, ranging from wood pellet producers to global process safety and combustible dust researchers and practitioners. Numerous information sharing strategies were used, including podcasts, white papers, articles in industry trade publications and webinar presentations.

1.7 Scope of work

This project focusses on the incorporation of the four principles of inherently safer design into the bow tie hazard analysis method for the management of combustible dust hazards associated with wood processing facilities. The facilities that were directly involved with the research were in British Columbia, Canada. However, given the extensive collaboration and involvement of this research project with the Wood Pellet Association of Canada (WPAC) and BC Forest Safety Council (BCFSC) for the Critical Controls

Management (CCM) project (discussed in Section 1.8), as well as the broader communication and knowledge dissemination (discussed in Chapter 11), this work will have a broader impact on the wood pellet industry and other industries handling combustible dust.

1.7.1 Wood processing facilities

There are 14 wood pellet manufacturing facilities and 1 medium density fiberboard (MDF) facility that are WPAC member plants in BC. The wood processing unit operations in the pellet mill that were analyzed in this project were the hammer mill, pelletizer, baghouse, indirect heated belt dryer, direct heated belt dryer, drum dryer and silo storage (finished product).

The wood processing unit operations in the MDF facility that were analyzed in this project were raw material handling, dryer (thermal oil heated flash dryers with gas burner trim), forming, baghouses, finishing end and pressing.

1.7.2 Inherently safer design

This work considers ISD with respect to the four main principles (minimization, substitution, moderation and simplification), as well as the sub-principles of moderation (limitation of effects and avoiding knock-on (domino) effects) and sub-principles of simplification (making incorrect assembly impossible, making status clear, tolerance of misuse, and ease of control).

In this work, ISD is considered in the form of example-based guidance, with support of ISD checklist questions, to identify ISD applications and barriers. Example-based guidance is described as specific, practical applications of ISD from industrial practice and the technical literature, which can be used to guide and inform other ISD opportunities (Amyotte and Khan, 2021). ISD checklist questions are open-ended questions based on the four principles of ISD that can be used to help brainstorm and generate ideas for incorporating ISD.

1.7.3 Dust hazard analysis

Dust hazard analysis (DHA) is defined in NFPA 652 (2019) (Standard on the Fundamentals of Combustible Dust) as “a systematic review to identify and evaluate the potential fire, flash fire, or explosion hazards associated with the presence of one or more combustible particulate solids in a process or facility.” Prior to the introduction of the term DHA, Process Hazard Analysis (PHA) was used to analyze hazards in combustible dust-handling operations (Perry et al., 2009). This project employs the bow tie analysis methodology to conduct process hazard analysis (PHA). In the scope of this project, the analysis is being completed for the hazard of combustible wood dust, which means the PHA is a dust hazard analysis (DHA). The primary research objective is to explicitly incorporate the principles of inherently safer design (ISD) in the PHAs being performed for wood pellet manufacturing facilities in British Columbia. This will lead to more effective treatment of hazards at their source, which will result in safer operations in wood pellet plants.

1.7.4 Bow tie analysis

Bow tie analysis is the process hazard analysis (PHA) methodology used in this project. Bow tie workshops were used to perform the analysis and develop the diagrams. The work related to bow tie diagrams is qualitative only. Other PHA techniques, including HAZOP (HAZard and OPerability), are out of scope of this work.

1.8 Collaboration with WPAC, BCFSC and Critical Controls Management (CCM) Project

Throughout the project, there was extensive engagement with Wood Pellet Association of Canada (WPAC) and BC Forest Safety Council (BCFSC) for the Critical Controls Management (CCM) project. Strong working relationships have been developed. The bow tie diagrams that were developed in workshops led by Dalhousie University personnel are a work product from the IAW project. These bow ties are the basis for identification of critical controls by operations and the bow tie validation process for all facilities involved in the CCM project.

1.9 Organization of report

The report structure is as follows:

- Chapter 1 presents an introduction to the project, along with the background information for the motivation, scope of work and objectives.
- Chapter 2 provides background information for the project focussing on combustible wood dust, bow tie analysis, inherently safer design and the ISD-BTA protocol.
- Chapter 3 discusses the development of bow ties for wood pellet production facilities.
- Chapter 4 discusses the development of bow ties for an MDF production facility.
- Chapter 5 describes the development of a bow tie focussed on a direct-fired belt dryer, a piece of equipment common to wood pellet production.
- Chapter 6 describes the collection of ISD example-based guidance for combustible dust hazards.
- Chapter 7 discusses the protocol application to bow ties developed for wood pellet production facilities.
- Chapter 8 discusses the protocol application to bow ties developed for an MDF production facility.
- Chapter 9 discusses the protocol application to the bow tie developed for a direct-fired belt dryer, a unit common in wood pellet production.
- Chapter 10 provides a discussion of other components of the project, including facilitating bow tie workshops remotely, the communication of bow ties to end-users, the selection of top events in bow tie analysis, and the incorporation of process safety management (PSM) in wood pellet plants

- Chapter 11 describes the communication of research and knowledge, transfer and exchange.
- Chapter 12 summarizes the conclusions of the report.

CHAPTER 2 BACKGROUND

This chapter provides background information on wood processing, bow tie analysis, inherently safer design, and combustible dust.

2.1 Wood processing

This section provides a high-level overview of the processes used for wood pellet manufacturing and MDF manufacturing. This section also describes direct heated belt dryers, which are commonly used in wood pellet manufacturing.

2.1.1 Wood pellet manufacturing process

The following is a general, high-level description of the wood pellet manufacturing process (Drax, 2021). The process begins with wood fibre arriving at the plant, after which it is cleaned and screened to remove foreign material like rocks and steel. The fibre then travels to a dryer, which reduces the moisture content of the fibre for the pelleting process. The fibre then enters a hammer mill that reduces the fibre's size. The shredded, fine wood powder is then fed to a pelletizer, which involves pressing the fibre through small holes in a metal ring dye to form compressed wood pellets. The newly made pellets are damp and hot and are sent to a cooler to cool and harden prior to shipping offsite. The finished pellets are kept in storage silos and then transported offsite to be delivered to customers. Readers are encouraged to review Pacific Bioenergy (2021) for a simple infographic of the process. Figure 2-1 is a block flow diagram (BFD) that highlights the main steps in the wood pellet manufacturing process.

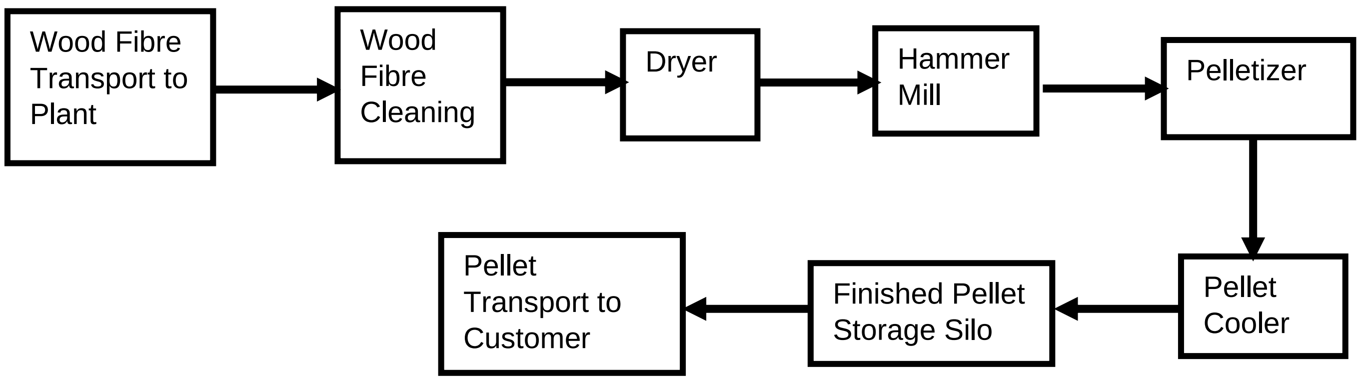


Figure 2-1. Block flow diagram of wood pellet manufacturing process

2.1.2 MDF manufacturing process

The MDF (medium density fibreboard) process involves pulping wood chips, also known as refining, into fibre. The fibre is then dried and combined with additives, like resin and wax, in a blender. This resonated fibre is transported to a forming machine, and then to a hot press. The heat and pressure applied by the press cause the resin to bind the fibres into a solid panel. Lastly, the boards are finished, which includes cooling, sanding, trimming, and sawing to desired dimensions. Readers are encouraged to read US EPA (1998) which provides a more detailed description of the MDF manufacturing process, as well as a process flow diagram (PFD) of a typical MDF process.

2.2 Dust hazard analysis (DHA)

The main purpose for performing a DHA is to evaluate existing controls and develop recommendations for additional protections as appropriate. A DHA involves the comprehensive consideration of combustible dust present within the scope of the work area, the equipment used, the process operations used, and the buildings containing these equipment and processes. The features that comprise the minimum requirements for performing a DHA include the following basic steps (Frank, 2019):

- Identify hazards associated with operations.
- Identify credible scenarios through which the potential loss associated with the hazards could be manifested.
- Determine the potential harm (consequences) associated with these scenarios.
- Determine the likelihood of the scenarios occurring.
- Identify existing engineered and administrative safeguards that could effectively prevent or mitigate the scenarios.
- Evaluate the risk of operations and determine if additional safeguards are warranted.
- Propose additional appropriate safeguards if warranted; then re-evaluate the risk.

2.3 Bow tie analysis

This section is largely based on the following references, with relevant excerpts from Rayner Brown (2020): CCPS/EI (2018) *Bow Ties in Risk Management: A Concept Book* *for Process Safety*; Vaughen and Bloch (2016) *Use the Bow Tie Diagram to Help Reduce Process Safety Risks*; Klein and Vaughen (2017) *Process Safety: Key Concepts and Practical Approaches*; CGE (2019b) *CGE Knowledge Base Website*; Hatch et al. (2017) *Visual HAZOP: Exploiting the Power of Bowties to Improve Study Effectiveness and Enhance Engagement*; and Hatch et al. (2019) *Enhancing PHAs: The Power of Bowties*.

A generic bow tie diagram is shown in Figure 2-2 . The elements of a bow tie diagram are as follows: hazard, top event, threats, consequences, prevention barriers, mitigation barriers, degradation factors, and degradation factor controls. The definitions of these bow tie elements are shown in Table 2-1 (CCPS/EI, 2018; CGE 2017).

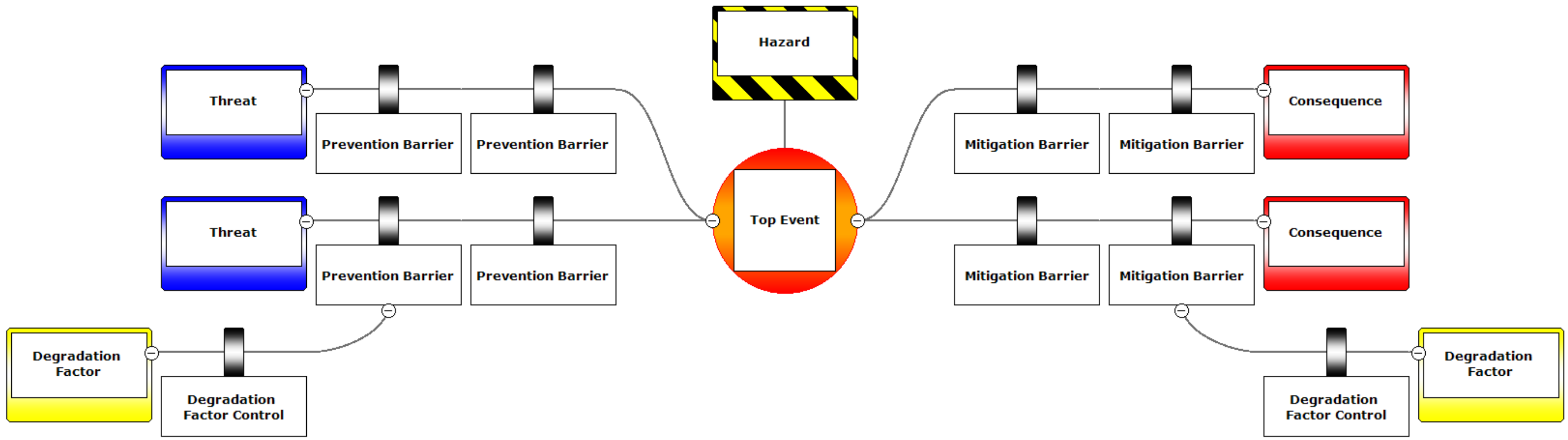


Figure 2-2. Generic bow tie diagram

Table 2-1. Bow tie element definitions (CCPS/EI, 2018; CGE, 2017)

Hazard	An operation, activity or material with the potential to cause harm to people, property, the environment or business; a source of harm
Top Event	Within the bow tie diagram, a central event between a threat and a consequence corresponding to the loss of containment or loss of control of the hazard
Threats	A possible initiating event that can result in a loss of control or containment of a hazard (the top event)
Consequences	The undesirable result of loss of containment or control (top event); usually measured are health and safety effects, environmental impacts, loss of property and business interruption
Barriers	A control measure that on its own can prevent a threat developing into a top event (prevention barrier) or can mitigate the consequence of a top event after it has occurred (mitigation barrier). A barrier must be effective, independent and auditable.
Degradation Factors	A situation, condition, defect or error that compromises the function of a main pathway barrier by defeating it or degrading its effectiveness.
Degradation Controls	Measures that help prevent the degradation factor from impairing the barrier. They lie on the pathway connecting the degradation threat to the main pathway barrier.

The process in Figure 2-3 can be used to build a bow tie.

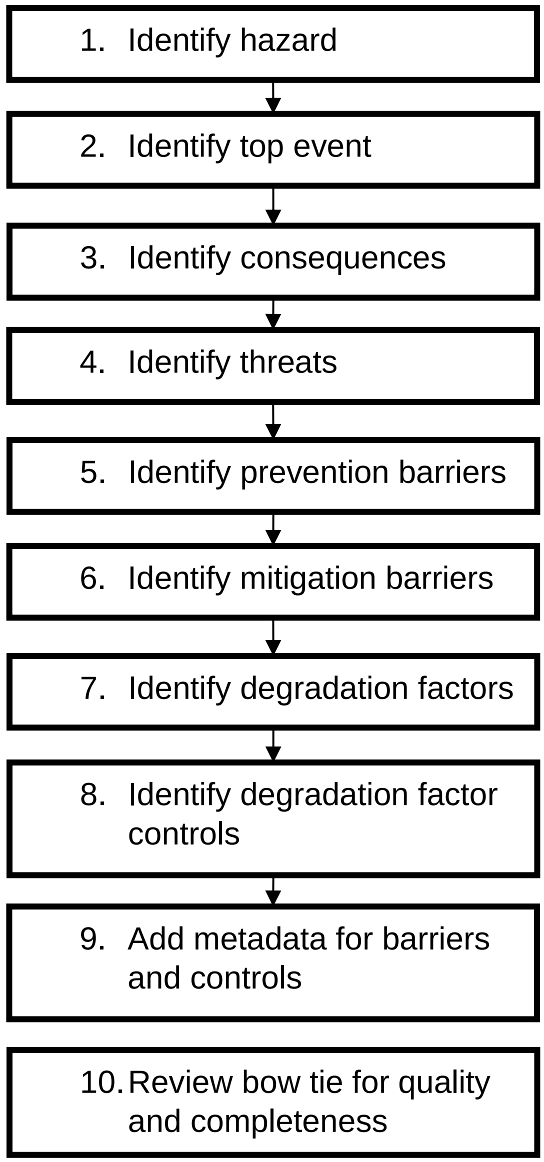


Figure 2-3. Process for building bow tie diagram (CCPS/EI, 2018; CGE, 2017).

Bow tie diagrams were adopted in the 1990s by Shell (CCPS/EI, 2018). One of the greatest strengths and benefits of bow tie diagrams is that they are a visual tool able to communicate hazardous scenarios to a wide range of audiences. Bow ties show direct cause and effect lines, which can make it easier to understand how hazardous events and consequences can occur. Hatch et al. (2017) outline the strengths of the bow tie approach compared with the HAZOP method for completing a PHA. Bow tie diagrams allow barrier weaknesses and degradation factors to be clearly displayed. This is compared with the single 'safeguard' column used in standard HAZOP formats; due to the lack of a visual, it can be challenging to understand the efficacy and criticality of safeguards. As with other tools, the bow tie methodology is not perfect. A challenge associated with bow ties is that while it is ideal that barriers be independent of each other, barriers may have commonalities and common failure modes and they are not always independent (CCPS/EI, 2018).

2.3.1 Bow tie analysis software

Commercial off the shelf (COTS) software for drawing bow tie diagrams and performing related tasks is available. BowTieXP is an example of this software (developed by CGE Risk Management Solutions). The bow tie diagrams, like the one in Figure 2-2, and others within this report, have been drawn using the BowTieXP software. This bow tie software allows metadata about the barriers, such as barrier type (which can be directly related to the hierarchy of controls) to be captured and displayed. This helps a user understand the types of barriers that are being deployed (CGE, 2019a).

2.3.2 Bow tie workshops

This section highlights the basics of bow tie workshops, including guidance from CCPS/EI (2018). A bow tie workshop is a team-based brainstorming session to assess each of the bow tie elements, considering threats, consequences, the barriers in place, how barriers can be degraded and the measures that are in place to ensure barriers are more effective. When considering a bow tie workshop, several different aspects of the analysis must be considered, including the intended audience, scope of the study, objectives of the study, and scenarios or unwanted events that are being prioritized for analysis. Additionally, given that the success of the workshop is highly dependent on the workshop team and personnel involved, it must be determined if there is enough time and specialist team members/subject matter experts (SMEs) available.

Collection and review of documentation is another important aspect of workshop pre-work, along with review of previous incidents and investigation findings. Documents such as process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), and previous process hazard analysis (PHA) studies are important reference documents for the team members to familiarize themselves with prior to the workshop.

The composition of the workshop team should include a facilitator, a scribe or note taker, and the team members consisting of SMEs knowledgeable in the operation and maintenance of the facility and the equipment. These team members include maintenance specialists, electrical and instrumentation specialists, and process operators, as well as safety coordinators.

Prior to the workshop taking place, onsite logistics and scheduling need to be completed. A Purpose, Scope, Objectives (PSO) or Terms of Reference document should be developed and provided to the workshop team before the workshop. This document describes the purpose, scope and objectives of the workshop, as well as the terminology and methodology that will be used during the workshop. Basic education and training on the bow tie methodology should also be provided to the project participants, which can also be included in the Terms of Reference document. Additionally, ground rules should be outlined to ensure the workshop time is used effectively.

For additional information on conducting effective bow tie analysis workshops, readers are referred to CCPS/EI (2018).

2.4 Modelling combustible dust hazards with bow tie analysis

Bow tie analysis to model combustible hazards has been previously addressed in the technical literature. Murphy and Hatch (2020) describe the use of bow ties to perform a DHA and highlight the benefits the bow tie structure lends to understanding dust explosion scenarios by effectively communicating the relationships between causes of uncontrolled ignition, the consequences of such events, and the barriers that prevent or mitigate the event. A bow tie presented by Murphy and Hatch (2020) describes how the hazard “filter receiver combustible dust” can be associated with the top event “ignition” due to threats including sparks from tramp material and static electricity. The bow tie also shows consequences, including how such an ignition could lead to an explosion in the receiver or how the ignition source could propagate upstream or downstream and cause explosions in those units. Prevention and mitigation barriers identified include rotary valves and explosion venting (Murphy and Hatch, 2020).

Figure 2-4 and Figure 2-5 are high-level, generic bow tie diagrams representing the general structure of modelling hazardous scenarios associated with combustible dust. The diagrams in Figure 2-4 and Figure 2-5 are not comprehensive but can be used as general guidance to support the development of bow tie diagrams. The emphasis of these examples is the presence of all three elements of the fire triangle and all five elements of the explosion pentagon, as well as the types of consequences that could arise. The top events used in Figure 2-4 and Figure 2-5 are dust layer fire and dust explosion, respectively. Yuan et al. (2013) and Chen and Wang (2018) both describe bow tie diagrams with the top event “explosion.” Other top events are also possible, including dust ignition (as outlined by Murphy and Hatch, 2020) and dust deflagration.

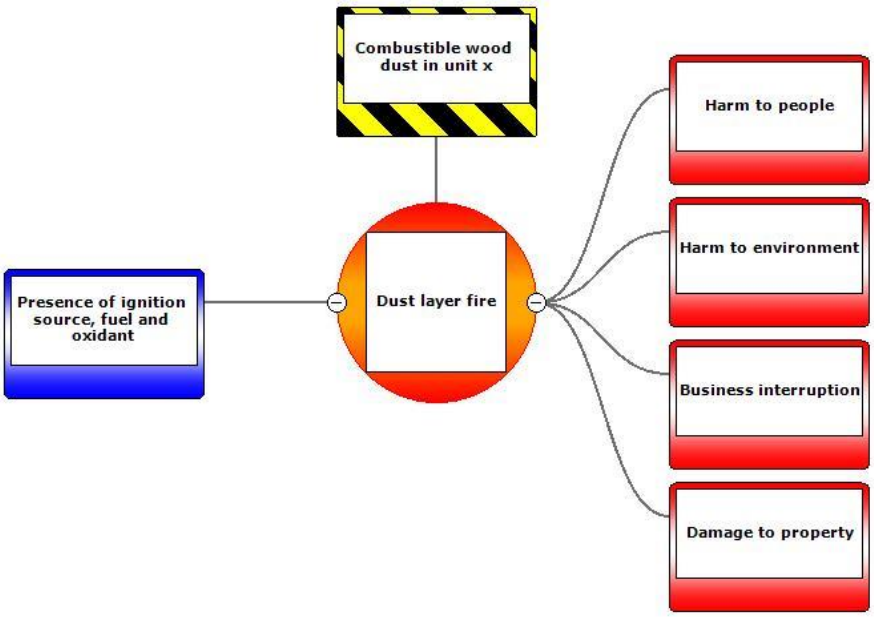


Figure 2-4. High-level bow tie diagram representing the hazard “combustible wood dust in unit *x*” and the top event “dust layer fire.”

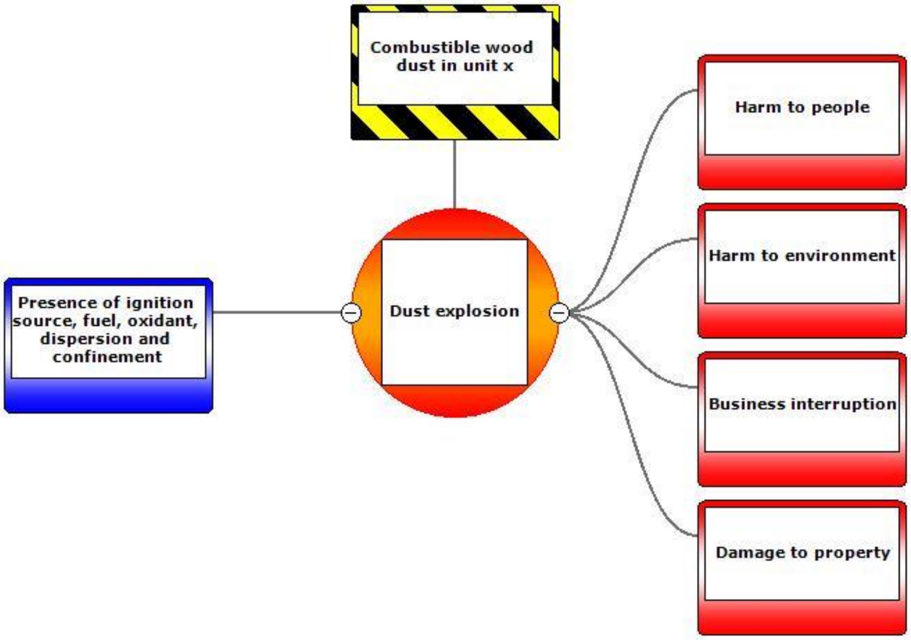


Figure 2-5. High-level bow tie diagram representing the hazard "combustible wood dust in unit *x*" and the top event "dust explosion."

In practice, additional details in the bow tie elements would need to be specified as follows:

- the processing unit of interest (e.g., hammer mill), would need to be identified and specified in the hazard. This is referred to as "unit x" in the examples,
- other bow tie elements, including barriers, degradation factors and degradation controls, would also need to be identified and included, and
- additional details in the threats and consequences would also need to be specified (e.g., type of ignition source, type of environmental harm).

2.5 Review of previously completed combustible dust hazard bow ties

A series of bow ties were developed as part of the Process Safety Workshop on Bow Tie Analysis in November 2019 involving WPAC, WorkSafeBC, and a range of operations specialists and subject matter experts. These bow ties model scenarios involving combustible dust fires and explosions. These bow ties were reviewed and units and areas of focus for operations were identified, including dryers, hammer mills, storage silos, pelletizers, and conveyance systems. The review also highlighted bow tie components for additional consideration (i.e., intended audience and end-use, level of detail included for formulation of bow tie elements, identification of degradation factors and controls), which provided additional context for facilitating the bow tie workshops in the current work.

2.6 Inherently safer design (ISD) and hierarchy of controls

This section provides an overview of the fundamentals of ISD. It is largely based on CCPS (2019) and Kletz and Amyotte (2010), and includes relevant excerpts from Rayner Brown (2020).

ISD is the component of process safety that focusses on avoiding hazards or reducing their likelihood or severity rather than relying on the use of add-on devices and procedures (Kletz and Amyotte, 2010). ISD is the foundation of risk management within the hierarchy of controls, which is the system used to eliminate or reduce the risk arising from identified hazards. The hierarchy of controls – in order of preferred consideration – is composed of the following categories:

- Inherently safer design (ISD),
- Passive engineered,
- Active engineered, and
- Administrative.

The hierarchy of controls is illustrated in Figure 2-6:

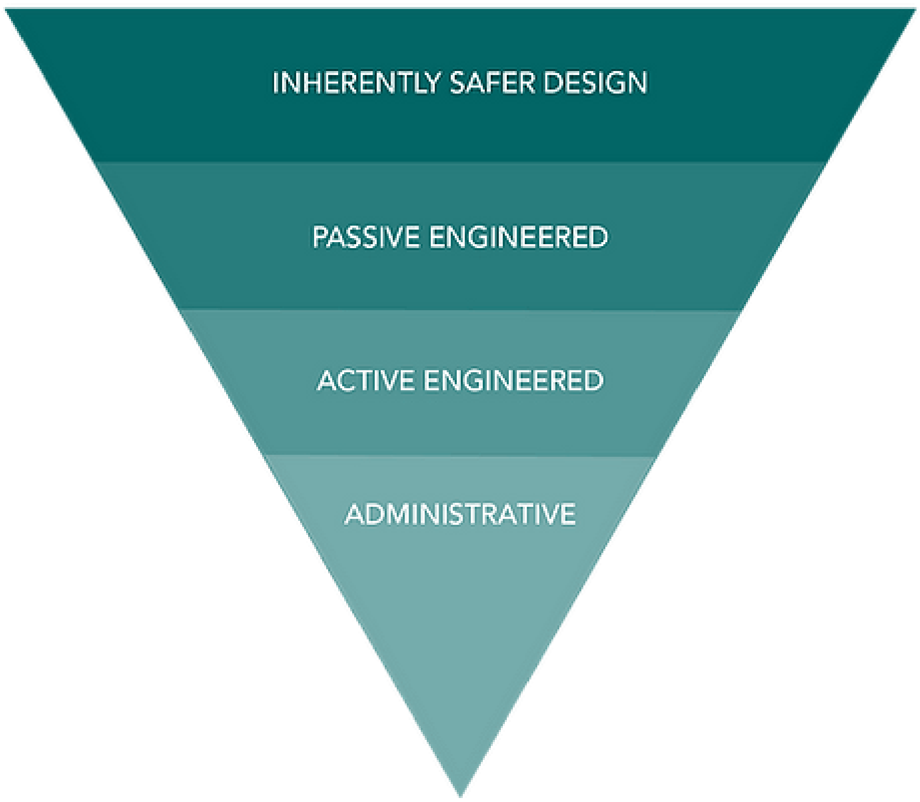


Figure 2-6. Hierarchy of controls

ISD is based on four main principles: minimization, substitution, moderation, and simplification. The use of these measures is referred to as ISD because hazards are avoided due to the inseparable characteristics of the process, rather than a dependence on add-on safety equipment and human intervention. Minimization refers to the reduction or elimination of the hazard, which, for example, may refer to the quantity of a toxic chemical used or stored, equipment inventory, or the size of equipment. Substitution involves replacing a hazardous chemical or process with a less hazardous alternative. Moderation reduces a hazard by using less hazardous forms of materials or process conditions. Moderation also refers to facility design that reduces the effect of a loss of containment of material or energy. Examples include using less hazardous operating temperatures or pressures, and chemical concentration or form. Limitation of effects and avoiding knock-on (domino) effects are sub-principles of moderation. Simplification reduces hazards by minimizing the complexity of equipment or a process; it encompasses design related to addressing human factors and reducing hazards associated with maintenance and operations (Kletz and Amyotte, 2010). Sub-principles of simplification include making incorrect assembly impossible, making status clear, tolerance of misuse, and ease of control.

Examples of ISD with respect to these principles are given below, based on CCPS (2019) and Kletz and Amyotte (2010) with relevant excerpts.

<u>Minimization:</u>

- Minimize the inventory of hazardous material through equipment selection (CCPS, 2009).
- Remove deadleg piping (CCPS, 2009).
- Use process intensification to reduce inventories (Kletz and Amyotte, 2010).

Substitution:

- Use alternate chemicals that are less hazardous (CCPS, 2009; Kletz and Amyotte, 2010).
- Use alternate processes that are less hazardous (CCPS, 2009; Kletz and Amyotte, 2010).
- Use more corrosion resistant materials of construction (Kletz and Amyotte, 2010).

Moderation:

- Make operating conditions less severe (e.g., lower temperatures and pressures by using a catalyst) (Kletz and Amyotte, 2010).
- Use less concentrated hazardous raw materials to reduce the hazard potential (e.g., aqueous ammonia or methylamine instead of the anhydrous material) (CCPS, 2009).
- Use limitation of effects – avoid hazardous equipment and operations (e.g., use closed loop sample stations to limit sampling procedure of hazardous materials; avoid glass sight glasses) (Kletz and Amyotte, 2010).
- Avoid domino/knock-on effects – use facility siting considerations/exclusion zones around process plant (Kletz and Amyotte, 2010).

Simplification:

- Reduce the number of bends in piping (potential erosion points) (CCPS, 2009).
- Reduce the potential of a hazard by eliminating liquid accumulation points or vibration stress (CCPS, 2009).

- Design equipment with an MAWP (maximum allowable working pressure) to contain the maximum pressure generated without reliance on pressure relief systems, even if the "worst credible event" occurs (CCPS, 2009).
- Design equipment that does not allow for incorrect assembly or at least allows an incorrect assembly to be apparent/determined (Kletz and Amyotte, 2010).

While it is most effective to include ISD concepts early in the design phase of a facility, plant or process, an operating facility still has opportunities for ISD during facility expansions and upgrades. ISD should also be included in safety evaluations, including PHA revalidations, management of change (MOC) and incident investigations (Maher et al., 2012). To help promote ISD throughout routine activities, inherent safety should be integrated into PHA, rather than only considering it occasionally during specialized reviews (Moore, 2003). This ensures that an organization is continually examining ways that hazards can be reduced or eliminated throughout the life cycle of a process.

2.7 Incorporation of ISD within PHA as part of Process Safety Management (PSM) Framework

The incorporation of ISD within process hazard analysis (PHA) as part of a process safety management (PSM) framework is discussed in this section. Relevant excerpts from Rayner Brown (2020) are included.

An area of interest to increase adoption of ISD is developing protocols for incorporating ISD concepts into process hazard analysis (PHA) methods. PHAs are tools used to examine hazards and hazardous situations, or the potential thereof, associated with process design, operability, equipment, human factors and materials (CCPS, 2008). PHAs are part of process safety management (PSM) systems, like that described in Table 2-2. Within this PSM system outlined by CSA (2017), PHAs fall within the element of *Process risk assessment and risk reduction*.

Table 2-2. CSA Process Safety Management (PSM) System (CSA, 2017).

Process Safety Management Elements			
Process safety leadership	**Understanding hazards and risks**	**Risk management**	**Review and improvement**
Accountability	Process knowledge and documentation	Training and competency	Investigation
Regulations, codes, and standards	Project review and design procedures	Management of change	Audits process
Process safety culture	Process risk assessment and risk reduction	Process and equipment integrity	Enhancement of process safety knowledge
Conduct of operations — senior management responsibility	Human factors	Emergency management planning	Key performance indicators

ISD should be explicitly considered and included in hazard analysis (CCPS, 2009). The incorporation of ISD within PHAs also supports the element *Process knowledge and documentation* with respect to maintaining company memory (Amyotte et al., 2007). This formalization of ISD consideration within a PHA ensures that proper documentation and the justification of design decisions are maintained. The protocol described by Rayner Brown et al. (2020) outlines an approach to the incorporating ISD within the PHA method, bow tie analysis. This protocol is discussed in the following section.

2.8 ISD-PHA protocol

This section describes the ISD-PHA protocol discussed in Rayner Brown et al. (2020); relevant excerpts from Rayner Brown (2020) are included. The ISD-PHA protocol described by Rayner Brown et al. (2020) is shown in Figure 2-7. The current state of the barriers – those in place and their type – must be understood first, after which potential ISD barriers can be considered prior to moving on to other controls in the hierarchy. The approach for identifying and considering barriers should follow the hierarchy of controls – ISD should be considered first, followed by passive engineered controls, then active engineered controls, and last administrative controls. This is aligned with the structure and approach to risk management similar to that outlined by Amyotte (2013), which describes a systematic approach to loss prevention incorporating the hierarchy of controls. First, hazards are identified and understood. Next, hazards are eliminated or the severity or likelihood are reduced using ISD principles. Add-on safety measures are incorporated by applying passive and active add-on controls next, followed by procedural measures. Lastly, residual risk is managed by applying safeguards until the risk is deemed tolerable.

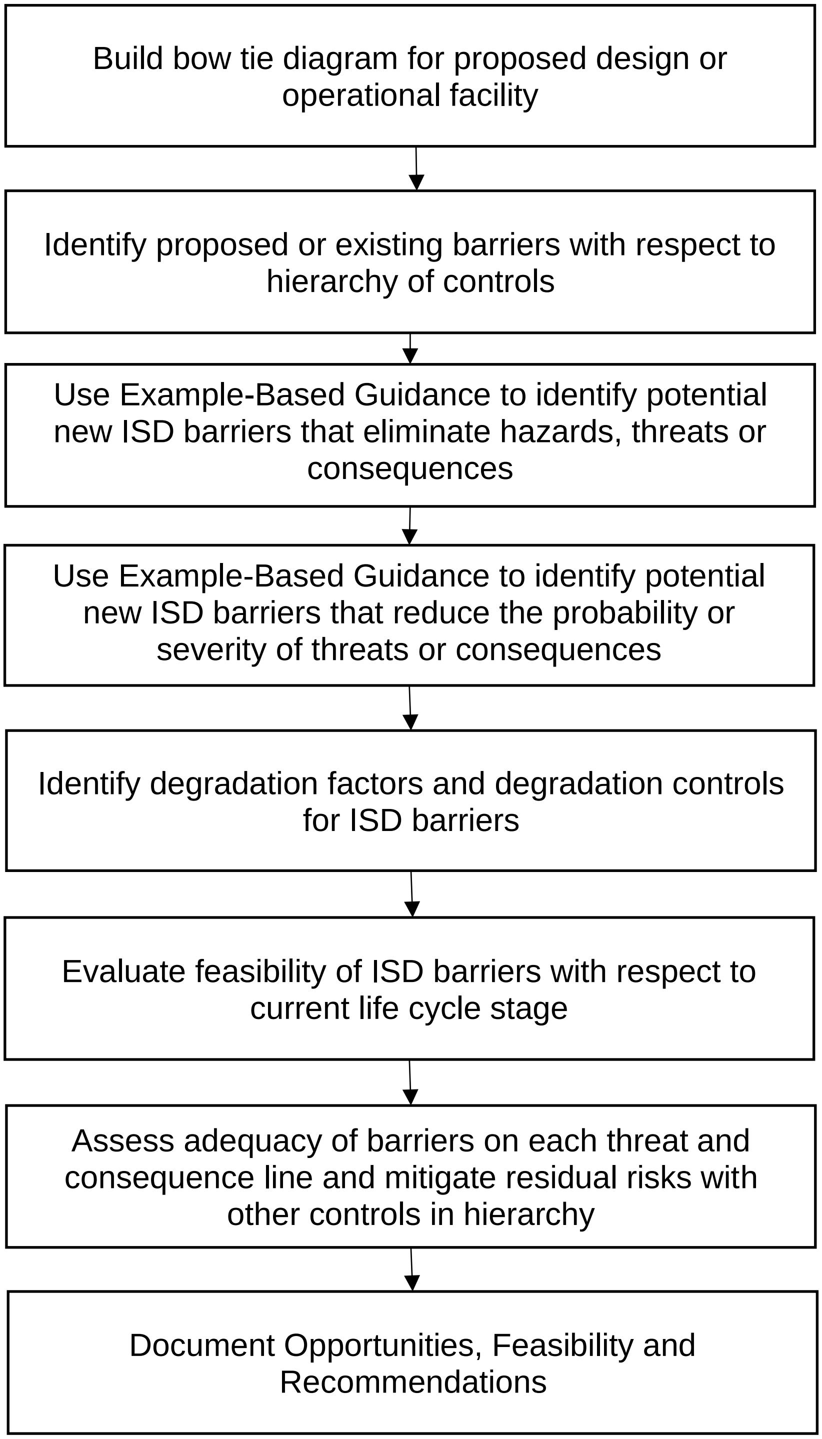


Figure 2-7. ISD-PHA protocol (Rayner Brown et al., 2020)

The ISD-BTA protocol shown in Figure 2-7 uses example-based guidance to help identify ISD barriers, which is discussed in the next section, along with ISD checklist questions.

2.9 ISD example-based guidance, guidewords and checklist questions

Example-based guidance is the phrase used to encompass specific, practical applications of ISD that can be used to guide and inform other ISD opportunities (Amyotte et al., 2007; Rayner Brown et al., 2020). Example-based guidance uses directive language and allows users to find specific applications of ISD that may be directly relevant to their facility and use examples of ISD applications as the basis for mind triggers to help them recognize opportunities specific to their facility and unique application. Example-based guidance is beneficial to help promote more targeted thinking.

ISD guidewords and checklist questions are another method that can be used to identify ISD barriers. ISD guidewords and checklist questions are broad ISD-based keywords to be used as mind triggers. Examples of these ISD guidewords include minimize, eliminate/reduce, intensify, substitute, moderate, separate, limit effects, simplify, and improve reliability. ISD checklist questions promote critical thinking. They are direct and pointed questions that have proven to be valuable in reducing hazards (CCPS, 2019). A disadvantage is since the questions are so broad and essentially rephrase the ISD principles, the solutions that are identified may be limited to the ISD-knowledge base of the PHA participants.

A sample of checklist questions is outlined in Table 2-3, organized with respect to guideword.

Table 2-3. Examples of ISD checklist questions (CCPS, 2009)

Guideword	**Checklist Question**
Minimize	Is the storage of all hazardous gases, liquids, and solids minimized?
	Are elbows, bends, and joints in piping minimized?
	Are all hazardous materials removed or properly disposed of when they are no longer needed or not needed in the next *x* days?
Substitute	Can a less toxic, flammable, or reactive material be substituted for use?
	Are there any other alternatives for substituting or eliminating the use of hazardous materials in this process?
	Is an alternate process available for this product that eliminates or substantially reduces the need for hazardous raw materials or production of hazardous intermediates?
Moderate	Can potential releases be reduced by lower temperatures or pressures, or elimination of equipment?
	Are all hazardous gases, liquids, and solids stored as far away as possible to eliminate disruption to people, property, production, and environment in the event of an incident?
	Can process units (for hazardous materials) be designed to limit the magnitude of process deviations?
Simplify	Is the workplace designed for consideration of human factors (that is, an ergonomically designed workplace)?
	Can equipment be designed such that it is difficult or impossible to create a potential hazardous situation due to an operating or maintenance error?
	Are there any other alternatives for simplifying operations involving hazardous materials in this process?

Since this project focusses on the management of combustible dust as the specific hazard, example-based guidance examples for combustible dusts were compiled. The collection of example-based guidance for combustible dust hazards is discussed in Chapter 6.

CHAPTER 3 DEVELOPMENT OF BOW TIES FOR WOOD PELLET FACILITIES

This chapter describes bow ties that were developed with wood pellet facilities. An overview of the different facilities where the bow tie analysis workshops were completed, as well as the scope of the workshop and analysis, is outlined. In this chapter, as well as Chapters 4, 5, 7, 8, and 9, excerpts of the developed bow ties are shown. Excerpts are used due to space considerations and to improve readability. The comprehensive and complete BowTieXP files were provided to BCFSC and WPAC personnel for knowledge transfer and exchange to pellet producers. This chapter also provides an overview of existing ISD barriers in wood pellet operations as part of the first step of the ISD-BTA protocol application

3.1 Overview of facilities and bow tie workshops analysis scope

The bow tie analysis workshops were completed in conjunction with the Critical Controls Management (CCM) project. Two bow tie analysis workshops for wood pellet production were conducted. The first workshop took place at Canfor Chetwynd and the second at Premium Pellets. An overview of the facilities and the timeline of bow tie analysis workshops is given in Table 3-1. These facilities were selected for the first bow tie workshops based on the fact that they are more established with respect to process safety maturity and the level of advanced controls and systems being used at the facilities. Canfor Chetwynd is a wood pellet facility located in Chetwynd, BC. The production capacity is 100,000 tonnes per year. Premium Pellet (part of Sinclar Group) is located in Vanderhoof, BC., with a production capability of 185,000 tonnes per year.

The analytical scope of the bow tie workshops was defined by the hazard of interest, combustible wood dust, and the scenarios of concern involving ignition the combustible wood dust leading to dust fires, explosions or deflagrations. The physical scope of the bow workshop was defined by the major process units in the pellet facility, which are as follows:

- hammer mill,
- dryer (belt or drum, direct or indirect heated),
- conveyance system,
- silo storage, and
- pelletizer.

As shown in Table 3-1, there were six bow ties developed for wood pellet operations involving the hazard of combustible wood dust. The bow ties that were developed are as follows, based on the process units and the top events as determined during the workshops by the workshop team:

- hammer mill – dust explosion
- baghouse – dust explosion
- belt dryer – wood fibre layer fire
- pelletizer – dust fire
- silo – finished product fire
- drum dryer – dust and syngas explosion

Table 3-1. Description of wood pellet manufacturing facilities and bow tie workshops facilitated

Bow Tie Workshop Date	Facility Name	Scale of Operations (tonnes/year) (Reference: Canadian Biomass (2021a))	Unit Operation	Bow Tie Developed (Hazard – Top Event)
October 26-30 2020	Canfor Chetwynd	100,000	Hammer Mill	Combustible Wood Dust in Hammer Mill – Dust Explosion
			Baghouse	Combustible Wood Dust in Baghouse – Dust Explosion
			Belt Dryer	Combustible Wood Dust in Belt Dryer – Wood Fibre Layer Fire
January 11-15, and January 28 & 29, 2021	Premium Pellet, Sinclar Vanderhoof	185,000	Pelletizer	Combustible Wood Dust in Pelletizer – Dust Fire
			Silo Storage	Combustible Wood Dust in Pelletizer – Finished Product Fire
			Drum Dryer	Combustible Wood Dust in Pelletizer – Dust and Syngas Explosion
February 2021[1]	Pacific Bioenergy, Prince George	350,000	Drum Dryer	Combustible Wood Dust in Pelletizer – Dust and Syngas Explosion

The bow tie workshop at each wood pellet production facility was completed over five to seven sessions (five hours per session) and involved diverse groups of subject matter experts, including operators, maintenance personnel, electricians, environment, health and safety specialists, supervisors, and managers. All bow tie workshop facilitation was provided online remotely through videoconferencing.

[1] This site visit was completed by BCFSC using the drum dryer developed at Premium Pellets as the basis. This bow tie was provided to Dalhousie personnel for ISD-BTA protocol application.

Workshops were led by Dalhousie personnel (K. Rayner Brown) with support from BCFSC personnel at Canfor Chetwynd and Premium Pellets (Sinclar Vanderhoof) (T. Bartels, B. Laturnus, and C. Whelan). BCFSC personnel continued the development of a drum dryer bow tie at Pacific Bioenergy. BCFSC personnel completed the validation process for other facilities involved in the CCM project.

3.2 Excerpt and discussion of developed bow tie – dust explosion in hammer mill

A bow tie was developed for a scenario of a combustible wood dust explosion in a hammer mill; an excerpt of the developed bow tie is shown here. The purpose of this section is to demonstrate the workshop development of the bow tie; figures that are shown are not comprehensive and are illustrative only. The bow tie elements that were developed are reflective of the facility at the time of analysis and does not include any planned or prospective changes (i.e., planned add-on safety equipment, such as explosion protection or explosion isolation).

Figures 3-1 to 3-5 show excerpts of the development of the bow tie through each of the bow tie elements. The hazard and top event, threats and consequences, prevention barriers, mitigation barriers, and degradation factors and controls, are shown, respectively.

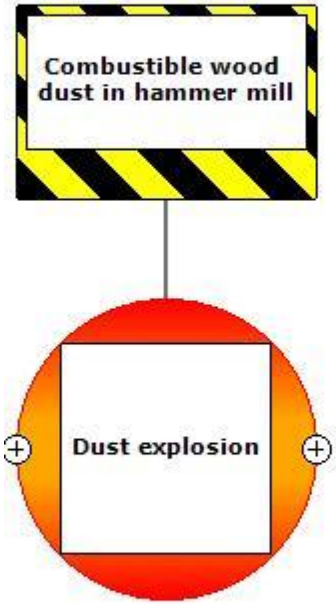


Figure 3-1. Hazard and top event identified in bow tie involving combustible wood dust in a hammer mill

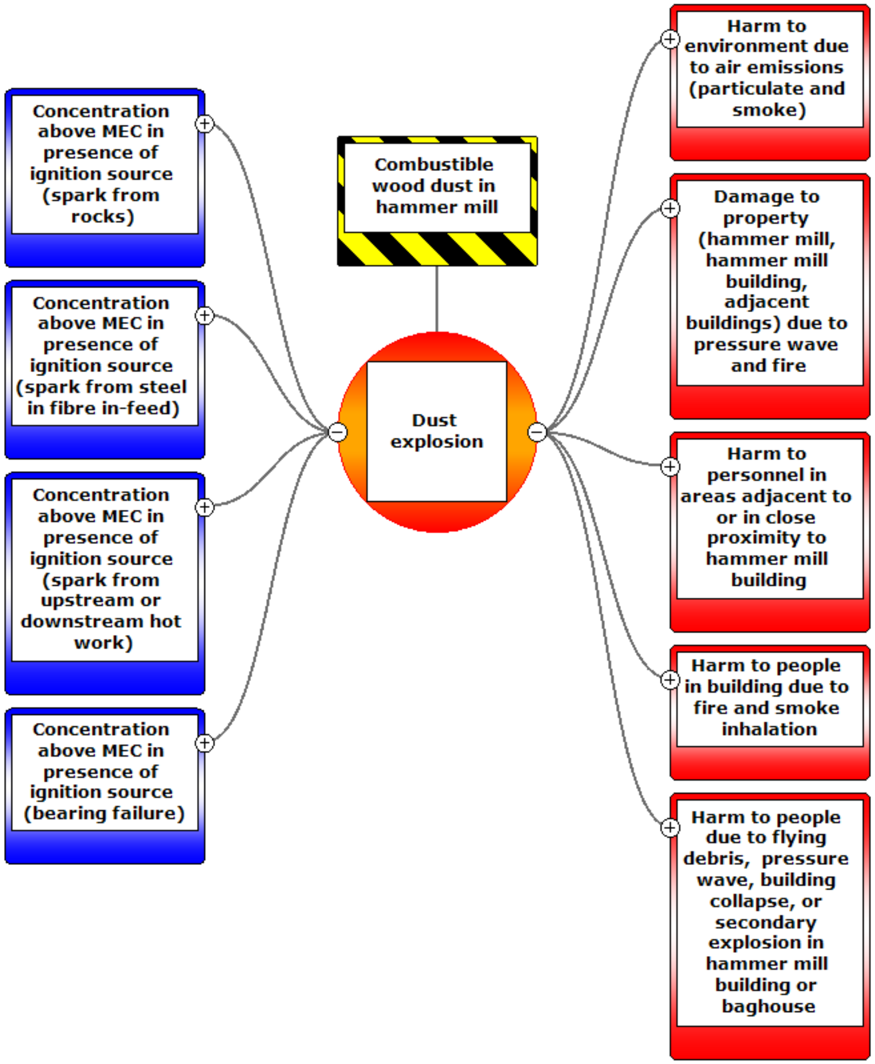


Figure 3-2. Excerpt of threats and consequences identified in bow tie involving wood dust in a hammer mill

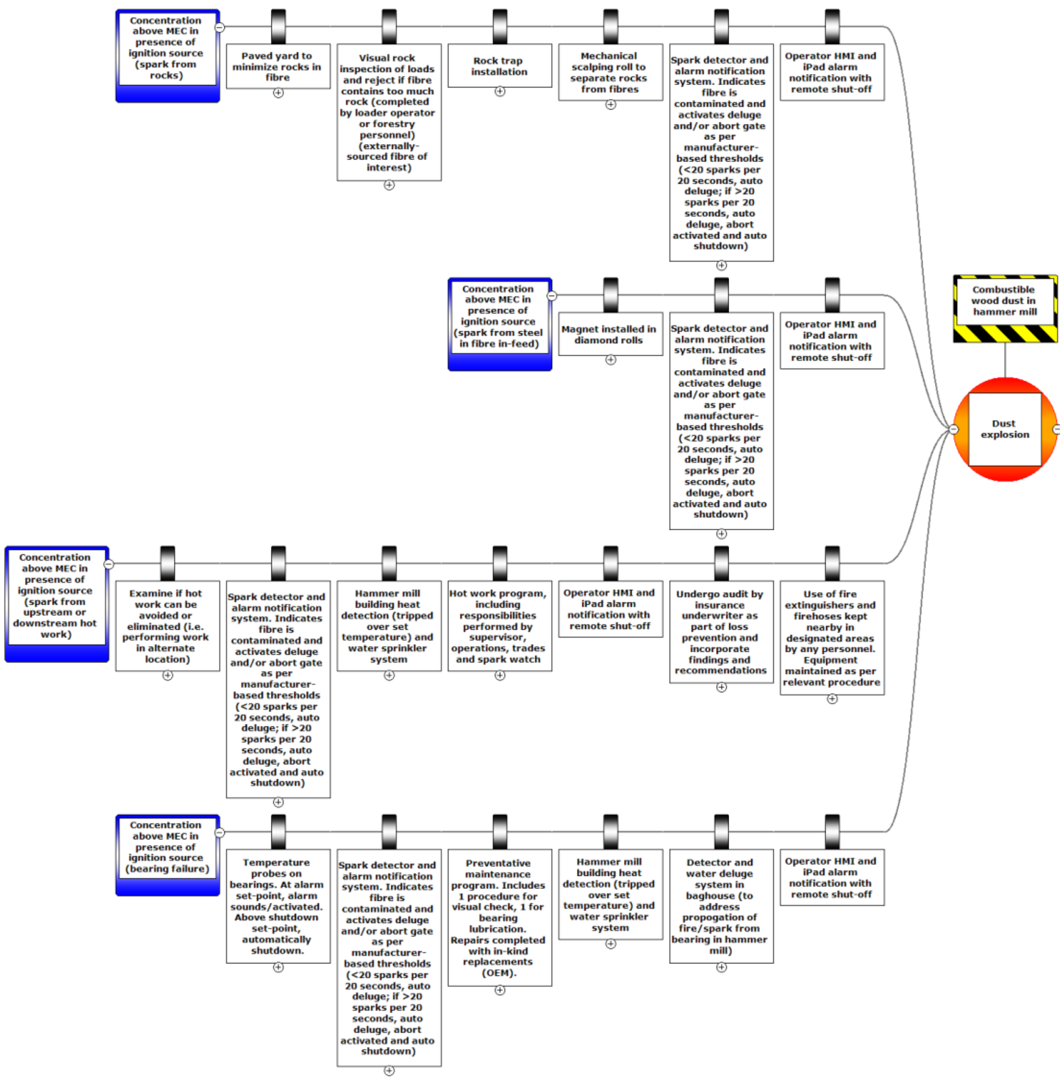


Figure 3-3. Excerpt of prevention barriers identified in bow tie involving combustible wood dust in hammer mill

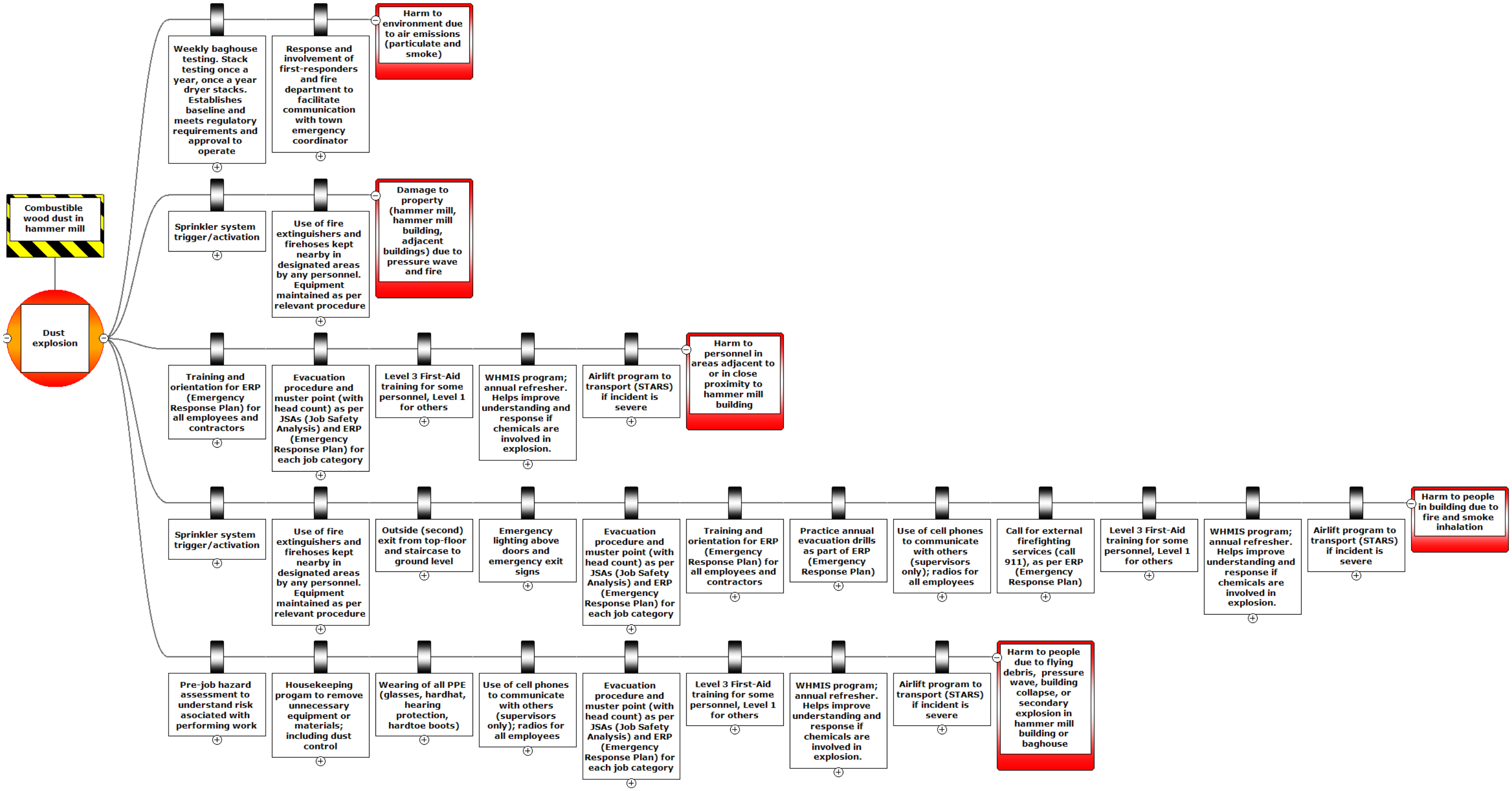


Figure 3-4. Excerpt of mitigation barriers identified in bow tie involving combustible wood dust in hammer mill

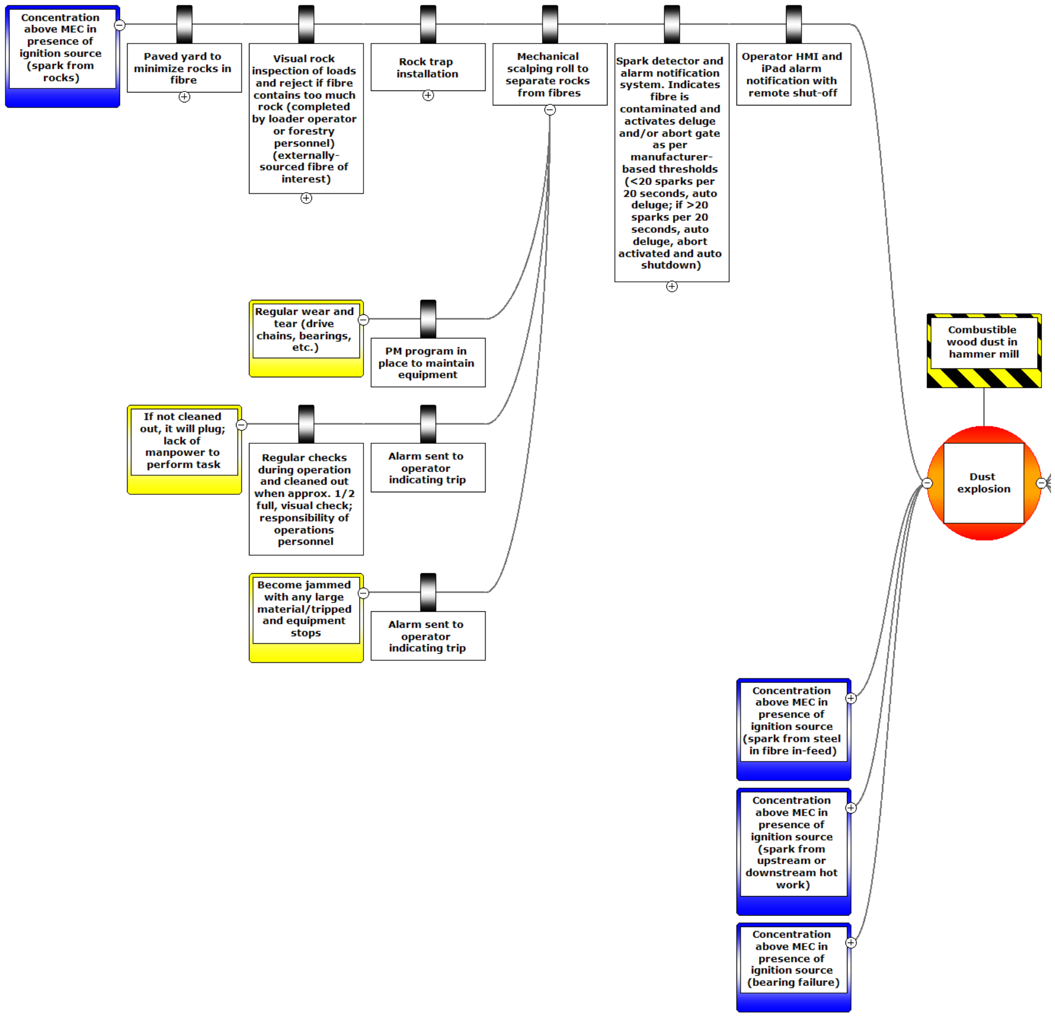


Figure 3-5. Excerpt of degradation factors and controls identified in bow tie involving combustible wood dust in hammer mill

During the bow tie workshop, the top event of dust explosion was identified and selected for this bow tie. Since the top event was dust explosion, the threats were developed to encompass each element of the explosion pentagon. Each threat included the different ignition sources, as well as other elements of the explosion pentagon. The hazard component of the bow tie diagram captured the dust explosion pentagon element of confinement by specifying the dust explosion was taking place in a hammer mill. When developing the threats, dust was assumed to be present in an amount above the minimum explosible concentration (MEC). Various potential ignition sources were considered, including hot work, static electricity, friction, smolder spots, self-ignition, mechanical sparks, electrical equipment, and hot surfaces. A broad range of barriers was identified, including spark detectors, deluge systems, scalping rolls, magnets, and preventive maintenance programs. The complete overview of barriers deployed can be found in each of the bow tie diagrams.

The consequences in the bow tie capture the four main types of loss relating to people, property, process (business), and the environment. When developing the bow ties for different process units and identifying mitigation barriers related to consequences common to each of the bow ties (business interruption, environmental impacts, use of community/public resources), the same mitigation barriers were used for each of the bow ties. The mitigation barriers for these consequences were not affected by the process unit.

3.3 Identification of existing inherently safer design barriers in wood pellet operations

During the bow tie workshop, when identifying barriers, the workshop facilitator (K. Rayner Brown) asked targeted questions around the ISD principles to help the workshop team identify existing ISD barriers in the plants. Some of these questions included:

- is the amount of wood fibre or finished product onsite minimized?
- are alternate equipment, systems or processes used that have reduced risk?
- have equipment or units been relocated to reduce risk?
- have processes or systems been simplified to reduce the chance for error or make systems more robust?

The ISD barriers that were identified are listed in Table 3-2 (categorized with respect to ISD principle). The identification and labelling of these ISD barriers were part of the first step of the ISD-BTA protocol application.

Table 3-2. Existing ISD barriers identified in wood pellet plants

Existing ISD Barrier in Facility	ISD Principle
Use of paved surface on which to store feedstock/shavings instead of rocks to minimize rocks entering process and presenting risk of ignition sources	Minimization
Examination whether hot work can be avoided or eliminated (i.e., performing work in alternate location)	Minimization
Silo sized small, which reduces inventory and increases turnover frequency	Minimization
Use of enclosed motor instead of non-enclosed motor to ensure dust is kept out to prevent fire	Substitution

Table 3-2 Existing ISD barriers identified in wood pellet plants continued

Existing ISD Barrier in Facility	ISD Principle
Use of indirect heated belt dryers instead of direct heating to reduce potential ignition	Substitution
Use of municipal water instead of pond water to minimize dissolved material in water to reduce scaling and clogging of water deluge systems/plugged nozzle or lines with water scale/hardness	Substitution
Heater design and selection (thermogenerator); temperature through the dryer is lower than the maximum possible	Substitution
Separation between units and activities to reduce damage to adjacent facilities	Moderation
Separation of finished product silo storage and railcar from rest of plant	Moderation
Only ABC-type extinguishers kept onsite to help avoid wrong type	Simplification

CHAPTER 4 DEVELOPMENT OF BOW TIES FOR MDF FACILITY

This chapter describes the development of bow ties for an MDF plant at WestPine MDF (a West Fraser facility) in Quesnel, BC. The chapter outlines the scope of the bow tie workshop and analysis, discusses the developed bow ties, and provides a summary of identified ISD barriers existing at the plant

4.1 Scope of workshop and analysis

The MDF process at WestPine MDF begins with raw material handling, followed by drying, forming, pressing and lastly finishing. The physical scope for the current analysis consisted of the process units of interest in the facility:

- Raw Material Handling
- Dryer (thermal oil heated flash dryers with gas burner trim)
- Forming
- Baghouses
- Finishing End
- Pressing

The analytical scope consisted of the hazard “combustible wood dust in [process unit x]” (where x is one of the process units listed above). The scenarios of concern involved ignition of the combustible wood dust leading to dust fires, explosions, or deflagrations.

The bow tie workshop at WestPineMDF was completed over eight sessions (five hours per session) and involved a diverse group of subject matter experts, including operators, maintenance personnel, electricians, instrumentation specialists, safety coordinators and supervisors.

4.2 Excerpt and discussion of developed bow tie

A bow tie was developed to model ignition of combustible wood dust in a baghouse – an excerpt of the developed bow tie is shown in Figures 4-1 to 4-4. As in the previous chapter containing bow tie excerpts, the purpose of this section is to demonstrate the development of the bow tie analysis; figures that are shown are not comprehensive and are illustrative only.

The top event for each bow tie was selected through brainstorming and discussions. The top event that was selected for each of the bow ties in the MDF facility was "ignition." (The identification and selection of top events is further discussed in Section 10.3.) The threats identified in the bow ties include those related to mechanical failure, hot work, and static electricity. The identified consequences demonstrate the potential for an ignition source to propagate from the baghouse to various interconnected equipment, including other baghouses and cyclones. Identified prevention barriers include preventative maintenance, and activities involved with the hot work program (e.g., spark watch, spark checks, permits, removal of combustible materials), as well as the use of appropriate epitropic bags[2]. Figure 4-4 highlights degradation factors and controls; for rotary valves, the issue of maintaining necessary tolerances is addressed by referring to the OEM (original equipment manufacturer) specifications and performing regular preventive maintenance to meet to ensure the tolerance is met.

[2] Epitropic bags contain fibres that conduct electricity and can be used to prevent the accumulation of static electricity but require grounding and bonding. It is important to ensure the connection between the conductive (metal) threads or tapes is not broken, as this would present an electrostatic hazard (Barton,

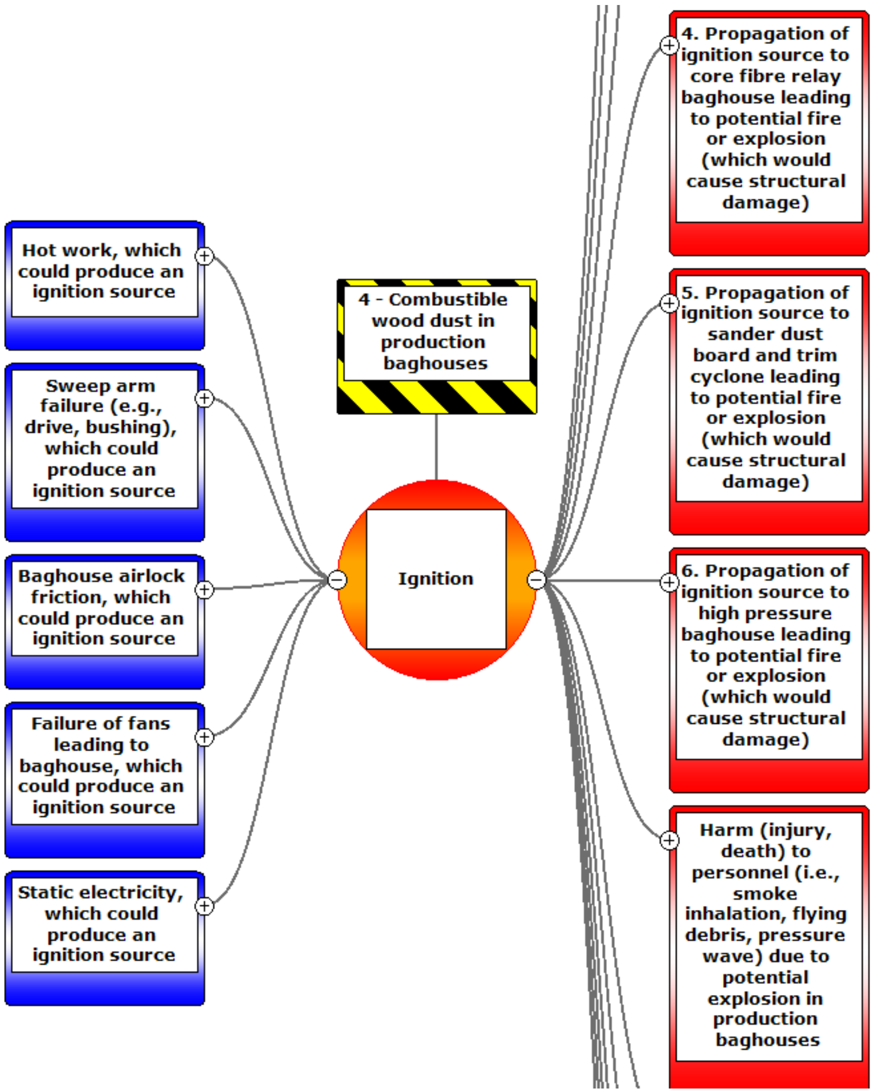


Figure 4-1. Excerpt of bow tie analysis of ignition of wood dust in production baghouses in MDF plant

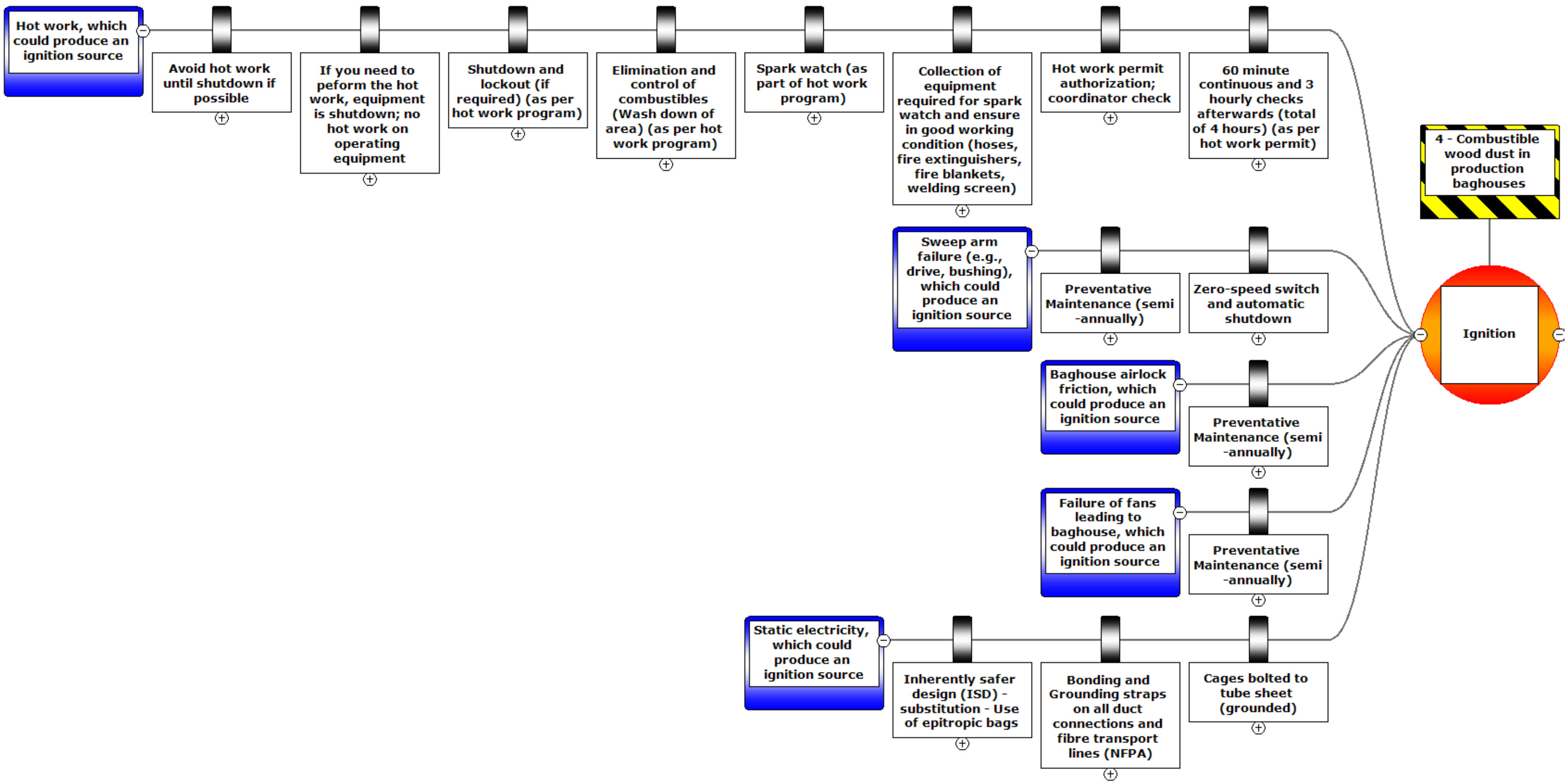


Figure 4-2. Excerpt of bow tie analysis (showing prevention barriers) of ignition of wood dust in production baghouses in MDF plant

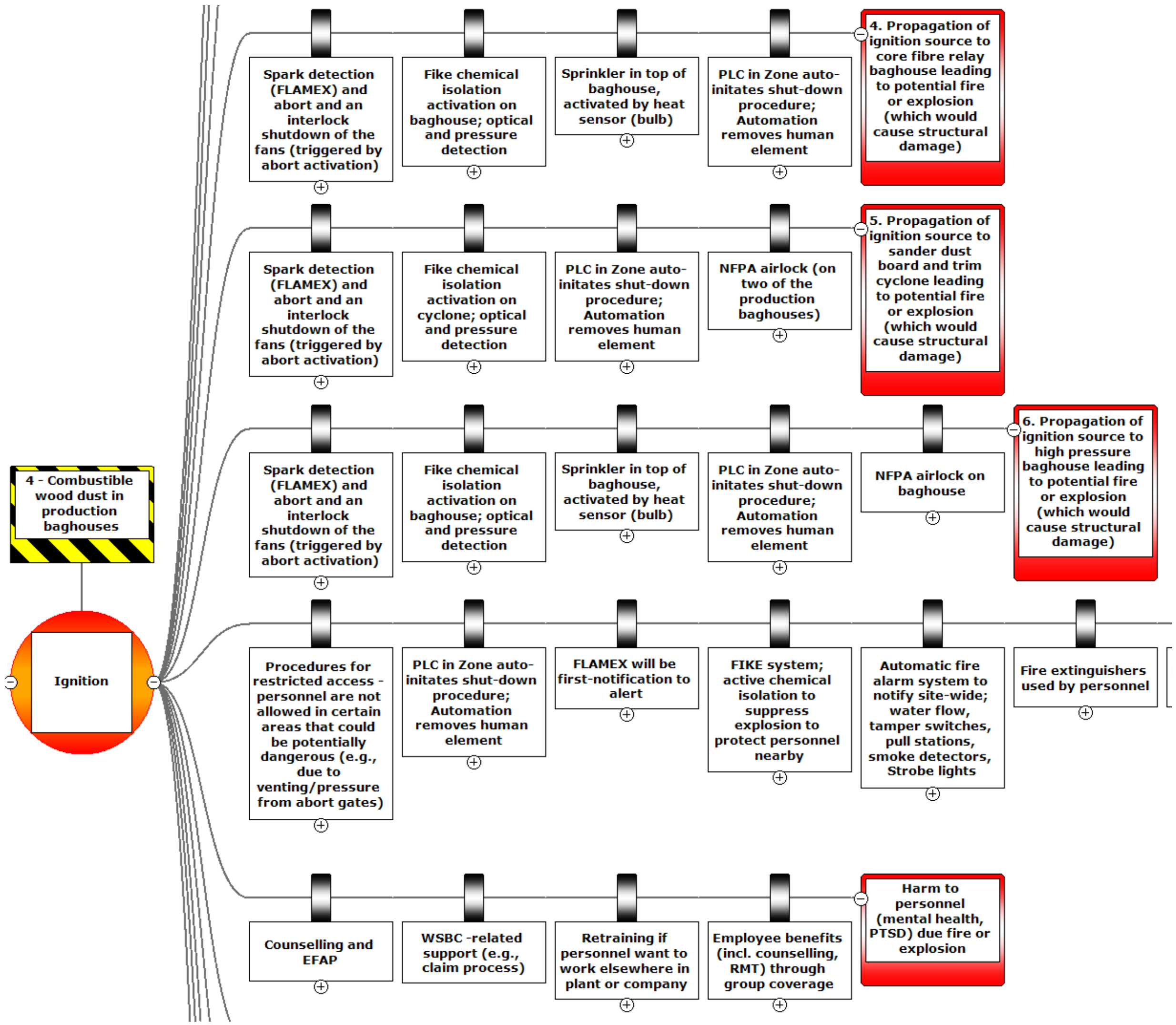


Figure 4-3. Excerpt of bow tie analysis (showing mitigation barriers) of ignition of wood dust in production baghouses in MDF plant

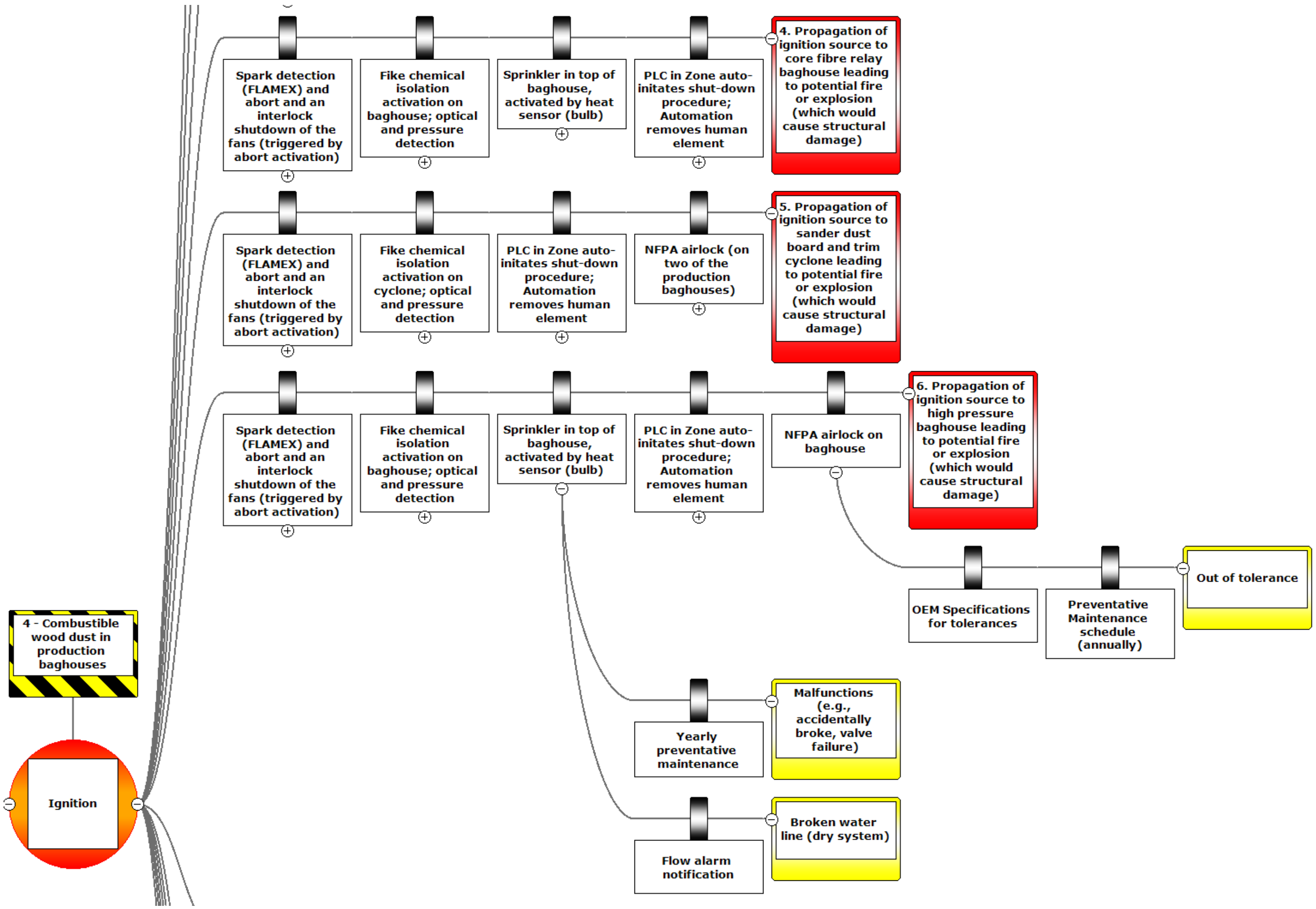


Figure 4-4. Excerpt of bow tie analysis (showing illustrative degradation factors and controls) of ignition of wood dust in production baghouses in MDF plant

4.3 Identification of existing ISD barriers in MDF plant

Following the same process performed during the bow tie workshops for the wood pellet facilities, targeted questions based on the ISD principles were used to help the workshop team identify existing ISD barriers in the plants. These ISD barriers (categorized with respect to ISD principle) are listed in Table 4-1. Table 4-1 lists many ISD barriers; this is further discussed in more detail in Section 8.2 with respect to incorporating ISD during the design life cycle stage.

Table 4-1. Existing ISD barriers identified in MDF plant

Existing ISD Barrier in Facility	ISD Principle
Reduction in amount of material being processed through the trim hog (50% capacity to 2-8%). Drastic material reduction for size of trim hog, which significantly reduces any chances of the trim hog plugging.	Minimization
Fans (in specific process area/unit) no longer used	Minimization
Removal of one of two rolls (in specific process area/unit) (no longer needed; process re-designed)	Minimization
Reduction in number of shave-off rolls from 3 to 1	Minimization
Reduction in hazardous equipment and inventory; reduced 3 formers to 2 formers	Minimization
Chain protected by UHMW [3]paddle instead of metal paddle (metal is substituted with UHMW)	Substitution
Use of polyester belt instead of paper back; lasts longer, does not break as easily	Substitution
Increase in shaft diameter to prevent the shaft from failing	Substitution

[3] ultra high molecular weight polyethylene (plastic with high abrasion and wear resistance)

Table 4-1. Existing ISD barriers identified in MDF plant continued

Existing ISD Barrier in Facility	ISD Principle
Incorporation of anti-static materials in certain areas; Micarta used instead of UHMW	Substitution
Use of epitropic bags	Substitution
Use motors suitable for Type Class 2 Division 2 hazardous areas (ISD)	Substitution
Relocation of ADS[4] fan and ADS cyclone from inside to outside	Moderation
Full set of control panels for remote control/shutdown; shutdown can be done from electrical room in maintenance area in separate/distanced area	Moderation
Facility siting; far away from more densely populated residential areas (approximately 0.5 mile (0.8 km) away)	Moderation
Lower roof line in fibre tower so cyclones could be located outside	Moderation
Relocation of fibre bins; streamlined process, and reduced traffic	Moderation
Relocation of fibre transport lines outside	Moderation
Relocation of cyclones from inside to outside; cyclones located in new tower and are all outside	Moderation
Relocation of fibre relay and shave-off vacuum fans outside	Moderation
Keeping fibre storage/material away from air intake screen for dryer	Moderation
Relocation of fibre relay fans from the weigh-scales from inside to outside	Moderation
Separation distance between cyclone and surrounding equipment and personnel to limit damage	Moderation
Cyclone built to withstand potential overpressure	Simplification
Oversized ventilation from hog for operating demand/flow rate (prevents hog from becoming clogged)	Simplification

[4] air density separator

Table 4-1. Existing ISD barriers identified in MDF plant continued

Existing ISD Barrier in Facility	ISD Principle
Removal of screw conveyors under weigh scale (minimization) and process changes to simplify with chutes (simplification)	Simplification
Robust construction of dryer and closed system; reduced potential for knock-on effects	Simplification
Human factors consideration – use of system that clearly indicates status	Simplification
Upgrading of spark detection system to more modern system with improved coverage; system also more user-friendly (easier to pinpoint sparks)	Simplification
Upgraded HMI that makes it easier to discern what is happening (human factors)	Simplification

CHAPTER 5 DEVELOPMENT OF DIRECT-FIRED BELT DRYER BOW TIE

This section provides an overview of a bow tie developed as part of the WPAC Belt Dryer Working Group (Sub-Group C), an initiative undertaken by the WPAC Safety Committee.

5.1 Overview of Belt Dryer Working Group Sub-Group C

The Belt Dryer Working Group was formed following WPAC's Belt Dryer Symposium (Canadian Biomass, 2021a) to review past incidents and lessons learned for safer uses of belt dryers in the pellet industry.

Sub-Group C (Safety Systems) was formed to examine the prevention and mitigation controls outside the dryer. Prevention barriers include: scalping rolls, magnets, foreign object removal and particle size control, spark detection, IR monitoring, belt wear, alignment sensors, current monitoring and belt defect monitoring. Mitigation barriers include sprinkler deluge systems, explosion venting, explosion suppression, and explosion isolation. The group decided that using bow tie analysis to model the different barriers and identify degradation factors would help clarify understanding around weaknesses and challenges associated with these barriers. Additionally, the identification of degradation factor controls to address and manage these weaknesses would help improve the effectiveness and reliability of these barriers.

5.2 Scope of workshop and analysis

The hazard modelled was “combustible wood fibre in direct heated belt dryer” and the top event was “combustible wood dust deflagration.” The bow tie analysis was performed over 6 sessions (1.5 hours per session) and involved a diverse group of subject matter experts (SMEs), including representatives from numerous explosion protection equipment suppliers and wood pellet facilities, as well as health and safety associations (HSA).

5.3 Overview and discussion of developed bow tie

As mentioned in the previous section, the bow tie analysis was conducted for the hazard “combustible wood fibre in direct-heated belt dryer” and top event “combustible wood dust deflagration.” An excerpt is shown in Figure 5-1. Numerous safety systems were identified, including deflagration isolation (e.g., chemical isolation), ensuring contaminants in in-feed are minimized, relocating dust generating activities away from burner, and effective combustible dust housekeeping programs to remove dust in surrounding areas, as well as fixing leaks/sources of dust. Degradation factor controls that have been identified include prescribed preventative maintenance and inspections of safety systems, identifying as many opportunities to automate as possible, and considering the use of micro mist systems that could extinguish fires quickly with very little residual water. Some of the barriers in Figure 5-1 are highlighted green, including those for screens, metal/foreign material detection, and selection of dryer (direct or indirect heated), which were highlighted by the workshop team as areas for improvement or additional consideration.

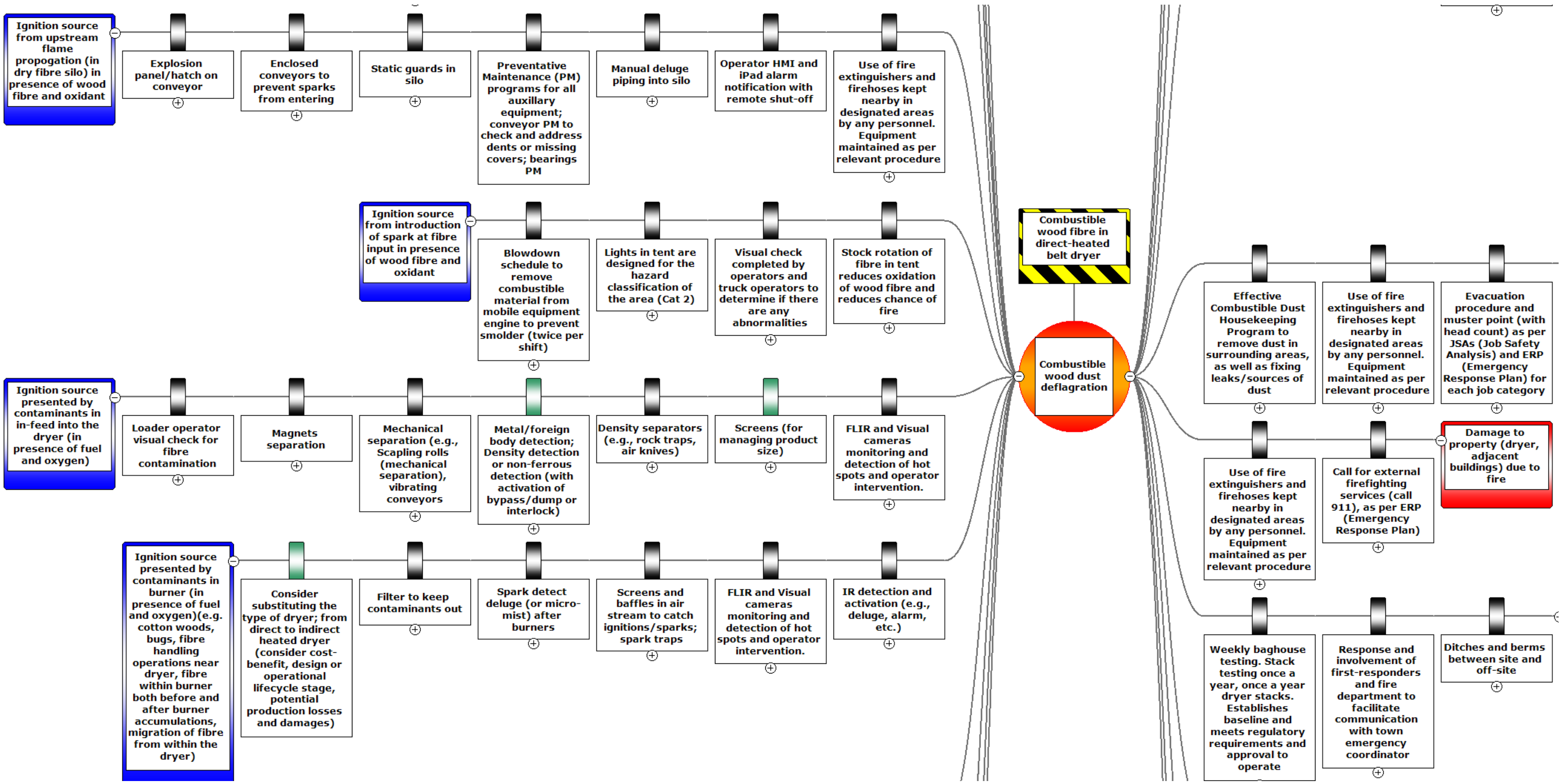


Figure 5-1. Excerpt of bow tie analysis of deflagration of combustible wood dust in direct heated belt dryer

CHAPTER 6

COLLECTION OF COMBUSTIBLE DUST HAZARD EXAMPLE-BASED GUIDANCE

This chapter describes the collection of example-based guidance for combustible dust hazards, including the literature review scope, methodology for identification and collection, and summary of example-based guidance.

6.1 Scope of example-based guidance collection and review

The emphasis in this project was on collecting qualitative information and example-based guidance to enhance knowledge of practical applications of ISD that could be considered in wood processing operations. To collect example-based guidance, resources and literature needed to be identified that discussed combustible dust hazards and that provided information about applications of ISD. The scope of example-based guidance collection here is different than that described in Rayner Brown et al. (2020). The work described by Rayner Brown et al. (2020) examined ISD example-based guidance focussed primarily on a collection of reports from Contra Costa County Health Services based in California, United States. These reports include examples of ISD applied in the facilities covered under the Contra Costa County Industrial Safety Ordinance (ISO), which are primarily in the petroleum refining and petrochemical manufacturing sectors. Within the current project, a review was completed to determine if such a collection of reports existed related to combustible dust handling and processing; none was identified, meaning that a different approach to identify example-based guidance had to be taken. Various literature resources were identified that provide detailed information about specific applications and examples of ISD that can be used by other facilities and organizations to consider within their own facilities. The main resources that were used within this current work for the collection of example-based guidance to guide ISD recommendations are as follows:

- NFPA standards
- CCPS (2005): *Guidelines for Safe Handling of Powders and Bulk Solids*
- Amyotte et al. (2009): *Application of inherent safety principles to dust explosion prevention and mitigation*
- Yuan et al. (2013): *Risk-based design of safety measures to prevent and mitigate dust explosion hazards*

Additional review of other resources for example-based guidance was completed. Internet searches were completed using keywords based on the names of equipment and ISD guidewords to identify any additional example-based guidance. As mentioned in Section 2.9, ISD checklist questions were also used to generate additional potential barriers.

Another source of example-based guidance was the bow ties that were developed during the bow tie workshops with the facilities. Barriers that could be identified as ISD considerations that are currently being used in facilities were also identified as example-based guidance and are listed in Tables 3-2 and 4-1.

6.2 Review of NFPA standards for ISD

The selection of NFPA standards listed in Table 6-1 were selected for review for ISD example-based guidance. This selection was based on their titles and descriptions, which indicated they were either directly applicable to wood pellet processing (e.g., NFPA 664 Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities) or based on their title could have some relevance or useful information regarding ISD applications (e.g., NFPA 61 Agricultural and Food Processing). It is important to note that while Section 6.4 refers to a number of different NFPA standards for example-based guidance, the NFPA standard may or may not be applicable to wood pellet or MDF manufacturing. This example-based guidance is included to be illustrative and serve as mind-triggers to help identify application of ISD, and not the application of the requirements of the standard. The text of the example-based guidance drawn from NFPA standards has been adopted to reflect this purpose.

Table 6-1. List of NFPA standards that were examined for ISD chapters and ISD example-based guidance

Standard Number	Standard Name	Does the standard have an explicit section or paragraph on ISD? (Yes/No)	Reviewed for ISD Example-Based Guidance (Yes/No)
NFPA 46	Recommended Safe Practice for Storage of Forest Products	N/A	No NFPA 46 was withdrawn and incorporated into NFPA 230.
NFPA 61 (2020)	Agricultural and Food Processing	No	Yes
NFPA 68 (2018)	Standard on Explosion Protection by Deflagration Venting	No	Yes

Table 6-1. List of NFPA standards that were examined for ISD chapters and ISD example-based guidance continued

Standard Number	Standard Name	Does the standard have an explicit section or paragraph on ISD? (Yes/No)	Reviewed for ISD Example-Based Guidance (Yes/No)
NFPA 69 (2019)	Standard on Explosion Prevention Systems	No	Yes
NFPA 77 (2019)	Recommended Practice on Static Electricity	No	Yes
NFPA 91 (2020)	Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Particulate Solids	No	Yes
NFPA 499 (2021)	Recommended Practice for the Classification of Combustible Dusts and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas	No	Yes
NFPA 652 (2019)	Standard on the Fundamentals of Combustible Dust	Yes	Yes
NFPA 654 (2020)	Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids	No	Yes
NFPA 664 (2020)	Standard for the Prevention of Fires and Explosions in Wood Processing and Woodworking Facilities	Yes (reserved) (not populated yet)	Yes

6.3 Methodology for collecting ISD example-based guidance: Categorizing barriers with respect to the hierarchy of controls and ISD principles

The methodology described by Rayner Brown et al. (2020) was followed. Ground rules were established to properly categorize example-based guidance. First, the data was categorized with respect to the hierarchy of controls (ISD, passive, active, or administrative). Next, if the barrier was identified as ISD, the barrier was identified with respect to one of the ISD principles (minimization, substitution, moderation, or simplification) based on the definitions described by Kletz and Amyotte (2010).

A measure categorized as "inherent" is one that reduces the hazard by directly modifying the design without the addition of add-on safety devices. The measure fundamentally and inseparably changes the design to eliminate the hazard. NFPA 652 (2019) Standard on the Fundamentals of Combustible Dust provides the basic principles and requirements for identifying and managing the fire and explosion hazards of combustible dusts and particulate solids. Examples of ISD from NFPA 652 (2019) are highlighted in Table 6-2.

Table 6-2. Examples of ISD to manage combustible dust hazards from NFPA 652 (2019)

ISD Principle	Example
Minimization	Design facilities to minimize horizontal surfaces where dust can accumulate
Substitution	Replace bucket elevator with dense phase conveying system
Moderation	Use processing methods that minimize fine dust generation
Simplification	Locate dust collectors outdoors in unoccupied areas, where explosion vents can be used instead of more complex protection systems

“Passive” engineered controls refer to add-on features that itself do not require event detection and actuation of moving parts other than caused by the upset condition. An example in this category is air intake screens or explosion vents.

“Active” engineered controls refer to add-on features that require event detection and actuation of moving parts. An example in this category is a chemical isolation system that detects a deflagration using pressure or optical sensors and triggers the discharge of a suppressant such as sodium bicarbonate.

“Administrative” controls refer to procedures and programs with human input (e.g., safe work procedures). These types of controls are also known as “procedural.” This report uses the terminology of “administrative” to emphasize the inclusion of training, policies and management systems. Examples of administrative controls are hot work programs and housekeeping programs to removal combustible dust deposits.

With respect to categorizing barriers based on ISD principles, categorization was aligned with Kletz and Amyotte (2010). The use of equipment, processes or designs that directly eliminate or reduce a hazardous quantity was categorized as minimization. The use of alternate technology or equipment that removes the hazard was designated as substitution. The use of design changes that reduce the likelihood or severity of hazards was categorized as moderation. Lastly, measures that reduce the potential of a hazard by simplifying the process were categorized as simplification. Table 6-3 contains examples of data found in the various resources and their respective categorization based on the above ground rules.

Table 6-3. Examples of categorization of example-based guidance for combustible dust hazards

Control Type	ISD Principle	Example	Reference
ISD	Minimization	Reduce hazardous material inventory by designing building to minimize areas that dust can accumulate	NFPA 652 (2019)
	Substitution	Replace bucket elevator with dense phase conveying system	NFPA 652 (2019)
	Moderation	Reduce the potential of a hazard by moving to an alternate location (e.g., dust collector outside and away from personnel)	Amyotte (2013)
	Simplification	Reduce potential of human error by upgrading human-machine interface	(Kletz and Amyotte, 2010)
Passive	N/A	Use explosion venting to relieve pressure	NFPA 652 (2019)
Active	N/A	Use active chemical isolation system to prevent propagation of deflagration between interconnected equipment	(CCPS, 2005)
Administrative	N/A	Reduce potential of error by standardizing into procedure or program (e.g., management of change)	(CCHS, 2013)

After establishing the previously described ground rules, the process for the collection of example-based guidance was as follows:

1) Collected: Examples of example-based guidance were collected and entered into a table in Microsoft Word.
2) Analyzed: Each example was analyzed with respect to the definitions of the hierarchy of controls and ISD principles.
3) Identified: Each measure was identified as ISD, passive, active or administrative. If the measure was identified as ISD, it was further identified as minimization, substitution, moderation, or simplification. Measures categorized as ISD were captured as example-based guidance.
4) Documented: The example-based guidance was documented for incorporation into the bow tie diagrams. The language was modified to be present-tense and directive to serve as guidance to users.

To help incorporate example-based guidance within the bow tie diagrams as barriers, the example-based guidance was organized in Table 6-4 with respect to high-level categories of threats, consequences or hazards. The objective of this organization was to create an intuitive way that users could refer to the example-based guidance to identify specific ISD applications for their scenario, as highlighted in Rayner Brown et al., (2020). Section 6.4 presents the example-based guidance for combustible dust hazards that was collected.

6.4 Summary of collected example-based guidance

The collected ISD example-based guidance is listed in Table 6-4. Table 6-4 is not exhaustive but can serve as mind-triggers to encourage brainstorming to identify ways that ISD could be incorporated in a given facility to help manage combustible dust hazards. Example-based guidance collected for other controls in the hierarchy (passive engineered, active engineered and administrative) is given in Table 6-5. Again, Table 6-5 is not exhaustive or comprehensive, but is a selection of other safeguards that were identified that could be incorporated to help manage combustible dust hazards.

Table 6-4. ISD example-based guidance for combustible dust hazards

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Minimization	**Material Inventory**	Use cutting methods that produce less combustible dust	NFPA 652 (2019)
		Reduce the size and number of vessels that handle combustible dust and produce dust clouds	NFPA 652 (2019)
		Design facilities to minimize horizontal surfaces where dust can accumulate. Horizontal surfaces that can benefit from a sloped cover include girders, beams, ledges, and equipment tops. Surfaces should be as smooth as possible to minimize dust accumulations and to facilitate cleaning.	Amyotte et al. (2009); NFPA 652 (2019)
		Design equipment to eliminate any blind spaces or areas where product can accumulate for extended periods of time.	Process Heating (2016)
		Design and construct interior surfaces where dust accumulation can occur to facilitate cleaning and to minimize combustible dust accumulations	Amyotte et al. (2009); NFPA 652 (2019)
		Seal enclosed building spaces inaccessible to routine housekeeping to prevent dust accumulation	NFPA 652 (2019)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Minimization	**Material Inventory**	Design enclosed building spaces that are difficult to access for routine housekeeping to facilitate routine inspection for the purpose of determining the need for periodic cleaning	NFPA 652 (2019)
		Ensure the housekeeping program does not disperse combustible dust in potentially explosive concentrations, as well as cause it to settle on elevated flat surfaces throughout facility. Ensure housekeeping program effectively removes combustible dusts accumulated above production lines. Note: housekeeping procedures are administrative and result in minimized fuel loadings.	Amyotte et al. (2009)
		Perform housekeeping activities to ensure that dust accumulations do not exceed 1/32 inches anywhere in the vicinity of equipment or on elevated surfaces. Note: housekeeping procedures are administrative and result in minimized fuel loadings.	NFPA 652 (2019); NFPA 664 (2020)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Minimization	**Material Inventory**	Regularly clean the interior of conveyor dryers (belt dryer) to keep dust and resin deposits to a minimum. Note: housekeeping procedures are administrative and result in minimized fuel loadings.	NFPA 664 (2020)
	Equipment and Piping Inventory	Convey combustible dust shortest distance possible; avoid opportunities for accumulation in ducts. Make ductwork as short as possible with a minimum number of bends.	HSE (2011)
	Pipe Dead Legs	Eliminate dead spaces at end of lines where fine dust can accumulate to prevent accumulation	Cross and Farrer (1982)
	Static Electricity	Use short lengths of transparent plastic as flow visualizers because they have been known to give rise to propagating brush discharges capable of igniting dusts	NFPA 77 (2019)
	Processing and Operations	Perform a hazardous procedure as few times as possible when a procedure is unavoidable	Amyotte et al. (2009); NFPA 652 (2019)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Minimization	**Foreign Material Contamination**	Use supply chain considerations to minimize the amount of foreign material (e.g., rocks, other ferrous and non-ferrous contaminants) in the feedstock to prevent or minimize potential ignition sources from entering the process	WPAC Belt Dryer Working Group (BDWG)
Substitution	**Hazardous Material**	When conveying dry raw materials into a liquid mix vessel, use a liquid eductor to combine the dry and wet ingredients and convey them together	Amyotte et al. (2009); NFPA 652 (2019)
		Replace material with a less hazardous material	Amyotte et al. (2009); NFPA 652 (2019)
	Equipment	Use explosion proof vacuum to clean dust instead of sweeping (which causes mixing of dust in air)	Amyotte et al. (2009); NFPA 652 (2019)
		Replace bucket elevators and other mechanical conveying systems with dense-phase pneumatic transport	Amyotte et al. (2009); Amyotte (2013); NFPA 652 (2019)
		Choose correct electrical equipment. Any electrical components installed in areas where combustible dust clouds or accumulations may exist should be properly classified for Class II hazardous areas.	Yuan et al. (2013); NFPA 499 (2021)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Substitution	**Equipment**	Use proper lubricant (ensure it is the correct amount and that it is free of contaminants)	Yuan et al. (2013)
		Consider alternate separators that would be less likely to jam (e.g., air separators, grates, coarse screens) for nonferrous metal or other objects (e.g., rocks) that could enter the product stream and cause an ignition hazard	Conifer (2012)
		Where flammable or combustible materials are conveyed at concentrations greater than or equal to 10 percent of the MEC, use Type A, B, or C spark-resistant construction fans and blowers	NFPA 91 (2020)
	Material of Construction	Use conductive material for piping instead of plastic to displace static electricity and decrease risk of ignition. Duct systems should be of metallic (conductive) construction to prevent buildup of electrostatic charges which can lead to electrostatic discharge. Pipes and ducts should be metal; nonconductive pipe or ductwork should not be used.	NFPA 77 (2019); NFPA 662 (2020)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Substitution	**Material of Construction**	Equipment to which the conduits connect should be metal and grounded to dissipate the charge impressed on it by the transport of the material	NFPA 77 (2019)
		Use non-combustible duct material	NFPA 91 (2020)
		Avoid unnecessary use of insulating materials (i.e., glass-lined pipe at the bottom of a hopper)	Amyotte et al. (2009)
	Process Route	Replace a processing route with one that does not involve a hazardous material	NFPA 652 (2019)
	Operations	Replace a hazardous procedure with one that is less hazardous	NFPA 652 (2019)
Moderation	**Operating Conditions**	Operate rotating elements, such as screw augers, below a tip speed of 1 m/s to prevent the generation of mechanical or frictional sparks from metal-on-metal contact and the dispersion and suspension of combustible dust clouds	CCPS (2005); Rodgers and Erdem (2011)
		Optimize the transport (or conveying) velocity to minimise dust deposits	HSE (2011)
	Material Characteristics	Use powdered materials having a larger particle size distribution or higher moisture content	NFPA 652 (2019)
		Perform size reduction processes on moist material prior to drying	NFPA 652 (2019)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Moderation	**Material Characteristics**	Change the order of addition of raw materials. For example, add combustible dust to a vessel prior to adding a flammable solvent.	NFPA 652 (2019)
		Use particle configuration with higher minimum ignition energy (MIE) or surface treat particles to change conductivity and resistivity properties that reduce the chance of a static charge buildup	(CCHS, 2011b)
		Increase dust particle size so as to decrease its reactivity	Amyotte (2013)
		Use hazardous materials in their least hazardous forms (i.e., the same substance but in a safer format/formulation)	Amyotte (2013)
		Add inert dust	Yuan et al. (2013)
	Process Design	Avoid the formation of hybrid mixtures of explosible dusts and flammable gases	Amyotte et al. (2009)
		Identify processing options that involve less severe processing conditions	NFPA 652 (2019)
Moderation – Limitation of Effects	**Ignition Propagation**	Use of product choke can help prevent downstream damage by replacement of a portion of the auger in a screw-feed system with a straight section of pipe.	Amyotte et al. (2009)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Moderation – Avoidance of Domino (Knock-On) Effects	**Equipment and Process Unit Siting**	Segregate, separate or detach areas where a dust deflagration hazard exists in a building or building compartment (excluding hazard within equipment) from other occupancies to minimize damage from a fire or explosion	NFPA 652 (2019)
		Consider compartmentalization of equipment, isolation of areas, provision of barriers or enclosures to prevent or contain the spread of fire. Note: Physical barriers are passive engineered controls.	NFPA 122 (2020)
Moderation	**Equipment and Process Siting**	Identify activities or processes that could produce particulate that could enter the burner of a direct-fired dryer (e.g., feedstock handling) and consider relocating these activities away from the dryer to minimize the likelihood of these ignition sources	WPAC Belt Dryer Working Group
		Arrange deflagration venting to avoid injury to personnel by the vent discharge, avoid ignition of adjacent property, avoid blast damage to adjacent property. Note: Explosion venting is a passive engineered control.	NFPA 68 (2018)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Simplification	**Human Factors - Operation and Maintenance**	Design processes, processing equipment and procedures to eliminate opportunities for errors by eliminating excessive use of add-on safety features and protective devices.	Kletz and Amyotte (2010)
		Use static dissipative footwear and flooring rather than leg or wrist straps that must be attached prior to performing an operation (where operator grounding is required)	NFPA 652 (2019)
	Equipment and Unit Design	Locate dust collectors outdoors in unoccupied areas, where explosion vents can be used instead of more complex protection systems	NFPA 652 (2019)
		Perform milling and drying in one step vs. two-step drying then milling process	NFPA 652 (2019)
		Reduce long dust-extraction vents	Amyotte et al. (2009)
		Design all dust-producing equipment for dust tight operation. All components of enclosed systems that handle combustible particulate solids shall be designed to prevent the escape of dust, except for openings intended for intake and discharge of air and material. Note: this can also be viewed as minimization as it results in reduced fuel loadings.	NFPA 664 (2020); NFPA 652 (2019)

Table 6-4. ISD example-based guidance for combustible dust hazards continued

ISD Principle	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Simplification	**Robustness of Equipment and Materials of Construction**	Design enclosures built to segregate dust explosion hazard areas from other areas such that they will not fail before the explosion pressure is vented to a safe outside location	NFPA 61 (2020)
		Make process equipment robust enough to withstand process upsets and other undesired events; pressure- or shock-resistant design. Use process equipment designed to contain the maximum foreseeable process pressures. Design equipment to be capable of withstanding the maximum explosion overpressure based on the Pmax of the material handled in accordance with NFPA 69 (2019).	Amyotte et al. (2009); NFPA 69 (2019)
		Use ductile design considerations for materials subject to brittle failure, such as cast iron	NFPA 68 (2018)
	Materials Characteristics	Use clear, unambiguous information on hazardous materials and how to properly handle them; adequately identify dust explosibility parameters (e.g., MEC, MIE) and the hazards that may be expected to arise through material handling and processing	Amyotte et al. (2009)

Table 6-5. Example-based guidance for combustible dust hazards for other types of controls in the hierarchy of controls (passive engineered, active engineered, administrative)

Type of Control	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Passive	**Ignition Propagation**	Install passive isolation device (e.g., flap valve)	Yuan et al. (2013)
		Use of baffle plates	Frank et al. (2012).
	Equipment and Unit Design	Install firewall/ shielding/isolation for high temperature equipment	Yuan et al. (2013)
		Air-moving devices: consider flexible connections to minimize the transmission of vibration	NFPA 91 (2020)
	Explosion Protection	Install explosion protection device (e.g., vent)	NFPA 68 (2018)
Active	**Dryers**	Consider installing carbon monoxide (CO) sensors to detect the onset of combustion	Process Heating (2016)
	Loaders/Mobile Equipment	Install fire suppression systems on loaders to extinguish fire if ignition occurrs	WestPine MDF bow tie workshop
	Ignition Propagation	Install active isolation device (e.g., active chemical isolation)	Yuan et al. (2013)
Administrative	**Loader/Mobile Equipment**	Complete visual check of engine compartment for the buildup of combustibles as part of mobile equipment pre-use inspection	BCFSC MAG (2021)
	Raw Material	Establish integrated management system for raw materials	Yuan et al. (2013)

Table 6-5. Example-based guidance for combustible dust hazards for other types of controls in the hierarchy of controls (passive engineered, active engineered, administrative) continued

Type of Control	Hazard, Threat or Consequence Category	ISD Example-Based Guidance	Reference
Administrative	**Human Factors**	Provide supervision and training through written communication rather than oral communication	Yuan et al. (2013)

CHAPTER 7 PROTOCOL APPLICATION – WOOD PELLET FACILITIES

This chapter discusses the application of the ISD-BTA protocol on a bow tie developed for a wood pellet facility. First, the configuration of the BowTieXP software used to develop the bow tie diagrams is described. Second, the workflow of the protocol application is outlined. Lastly, the protocol is applied, and the findings are discussed. Relevant excerpts from Rayner Brown (2020) are included.

7.1 Configuration of BowTieXP software

Look Up Tables are a BowTieXP software feature that can be leveraged for the protocol application. Using the Look Up Tables, a BowTieXP user can add metadata about the bow tie elements. The two Look Up Tables primarily used within this work are the Barrier Type and Barrier Category.

The Barrier Type Look Up Table can be configured to the hierarchy of controls (ISD, passive engineered, active engineered, and administrative). The benefit of categorizing the barriers by control type is that this encompasses and displays all the layers of protection. The barrier type can be displayed on the bow tie and, along with colour coding, these labels allow users to easily understand the diversity of barrier types being deployed. The Barrier Category Look Up table is also beneficial for this protocol and is populated with the ISD principles to make it easier to see the different ISD principles that are being applied.

The Barrier Type can also be used to identify new barriers that are added to the bow tie as the protocol application is completed; using the Code field in Barrier Type, “Potential” was added to demarcate these barriers added during the protocol application.

As mentioned above, colour coding can be used to make it easier to distinguish barrier types and categories. Table 7-1 outlines the barrier colour coding configuration in BowTieXP. Figure 7-1 is an image of the barrier categories and types in BowTieXP.

Table 7-1. BowTieXP Look Up Table colour code configuration of barriers

Barrier Type Name	Barrier Type Code	Colour	Barrier Category Name	Barrier Category Code	Colour
Inherently Safer Design	ISD		Minimization	MIN	
	Potential ISD		Substitution	SUB	
			Moderation	MOD	
			Simplification	SIM	
Passive Engineered	PAS		N/A	N/A	
Passive Engineered	Potential PAS		N/A	N/A	
Active Engineered	ACT		N/A	N/A	
Active Engineered	Potential ACT		N/A	N/A	
Administrative	ADM		N/A	N/A	
Administrative	Potential ADM		N/A	N/A	

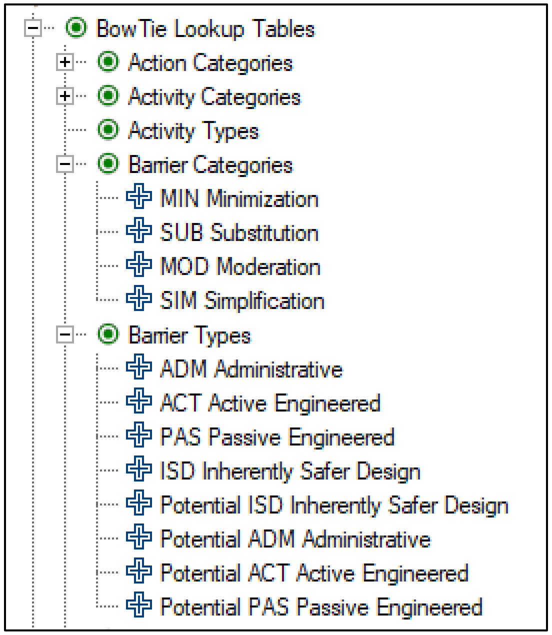


Figure 7-1. BowTieXP Look Up Table configuration in software

7.2 Protocol application and development of bow ties with ISD barriers

The following workflow was used to execute the protocol shown in Section 2.8:

1. Build the bow tie diagram.
2. Identify the barriers with respect to the hierarchy of controls. Examine each of the barriers and analyze them with respect to the barrier definitions described in Section 6.3. Determine the type of barrier (ISD, passive engineered, active engineered, and administrative). Use the Barrier Type Label in BowTieXP to label the barriers with respect to the hierarchy of controls. Arrange the barriers left-to-right in the order of ISD, passive engineered, active engineered, and administrative. If the barrier is ISD, use the Barrier Category Label in BowTieXP to label the barrier with respect to the ISD principle.
3. Identify potential barriers: Use example-based guidance and supporting literature review to:
    - Identify additional ISD barriers
    - Identify additional barriers of other types in the hierarchy
    - Identify additional degradation factor controls with consideration of the hierarchy of controls; ISD degradation factors are most preferred, followed by passive engineered, active engineered, and administrative
4. Document recommendations and feasibility.

The scope of the protocol application included identifying potential ISD recommendations and as well as identifying other barriers in the hierarchy. The protocol stage that involves examining the use of other types of controls in the hierarchy to mitigate residual risk after ISD has been incorporated, was attempted based on learnings and knowledge obtained from the bow tie workshops and discussions with other project stakeholders. While the operations and team members have intimate knowledge of their organizations and specific procedures, alarms and training, the bow ties were examined to help identify recommendations of additional safety measures in the hierarchy (passive, active and administrative controls) that could be applicable to a given facility. The barriers listed are not exhaustive but are the barriers identified through a single analyst approach used for this research (e.g., Dalhousie personnel performing analysis independently from facilities). This single-analyst approach compared with an ISD workshop approach is discussed in Section 10.2

A minor variation in the protocol application from the flowchart presented in Section 2.8 was the two stages of ISD barrier identification. One stage focusses on the elimination of the hazard, threat or consequence, followed by another that focusses on reducing the likelihood or severity. These were considered concurrently in the protocol application, rather than separately as outlined in the protocol flowchart.

Excerpts of the developed bow ties are shown here. Excerpts are used due to space considerations and to improve readability. The purpose of this section is to demonstrate the protocol application; the bow tie analysis figures that are shown are not comprehensive and are illustrative only. As stated previously, the comprehensive and complete BowTieXP files were provided to BCFSC and WPAC personnel for knowledge transfer and exchange.

Expanding on the bow tie outlined using excerpts in Section 3.2, each barrier was categorized with respect to the hierarchy of controls and existing ISD barriers were identified. This bow tie is shown in Figures 7-2 and 7-3. The barriers were labelled and colour-coded based on the barrier type, which helps to easily communicate the different types of barriers being deployed. Figures 7-2 and 7-3 show that many of the barriers identified are administrative. An active engineered barrier that appears in numerous threat lines to prevent a dust explosion is spark detection and deluge (explosion prevention measure). Two existing ISD barriers are as follows:

- Use paved yard to minimize rocks in fibre.
- Examine if hot work can be avoided or eliminated (i.e., performing work in alternate location).

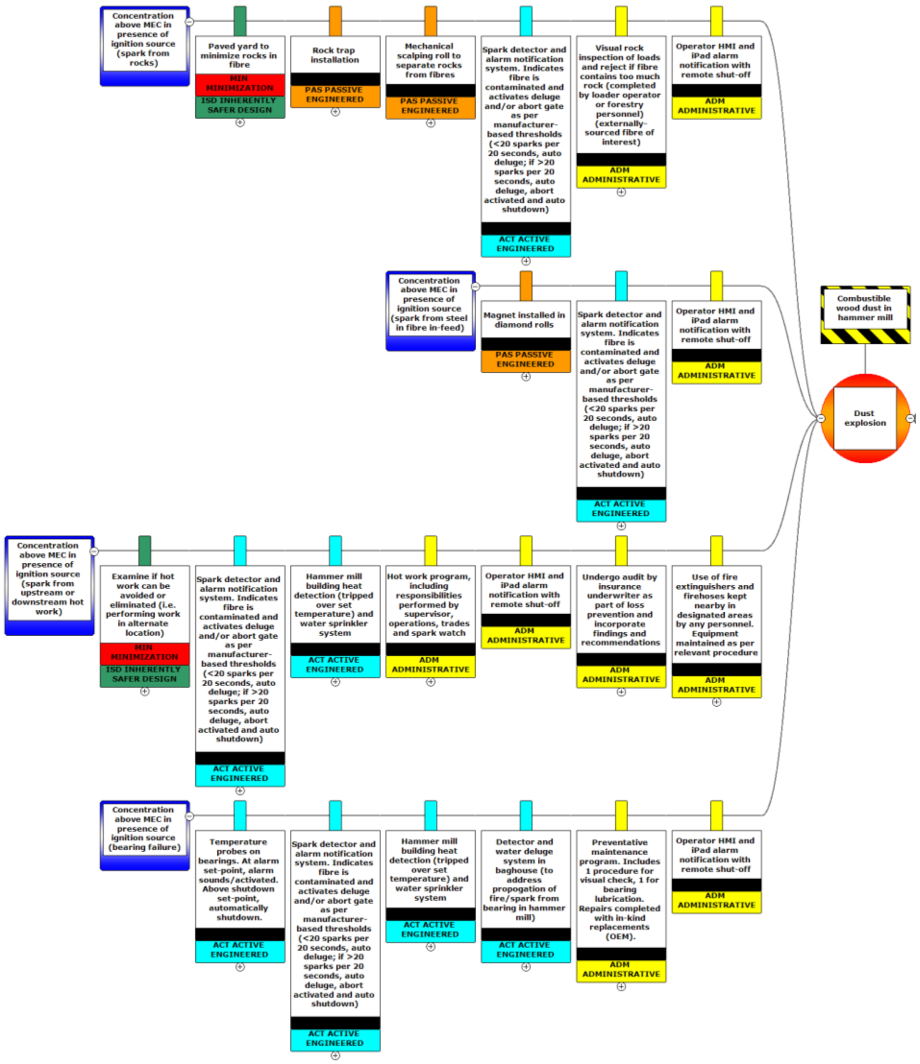


Figure 7-2. Bow tie analysis of combustible wood dust in hammer mill with prevention barrier types labelled (left-hand side)

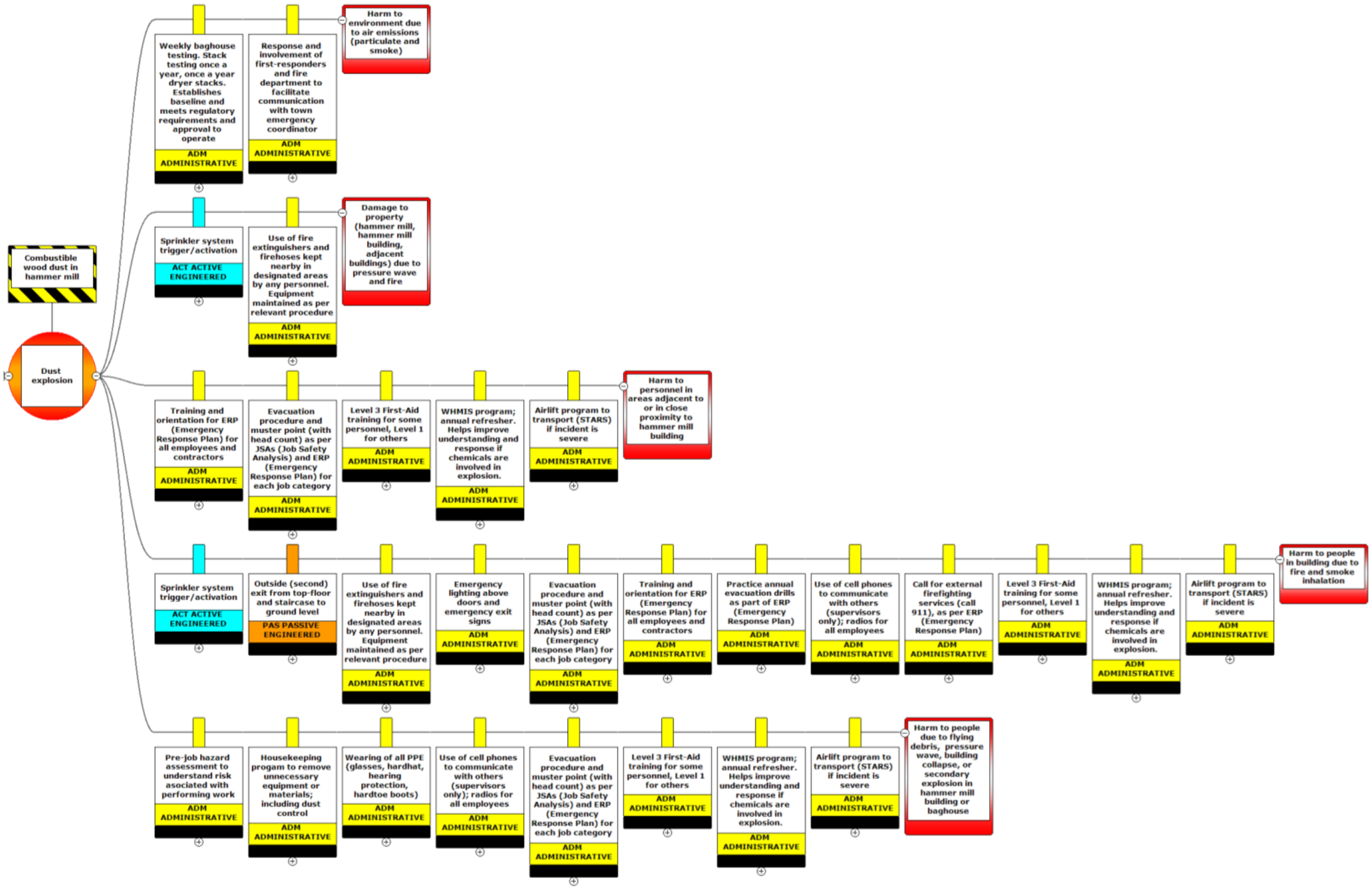


Figure 7-3. Bow tie analysis of combustible wood dust in hammer mill with mitigation barrier types labelled (right-hand side)

Figures 7-4 and 7-5 show the results of application of the ISD-BTA protocol. ISD barriers that can be considered include:

- Use supply chain considerations to minimize the amount of foreign material (e.g., rocks, and other ferrous and non-ferrous contaminants) in the feedstock to prevent or minimize potential ignition sources from entering the process.
- Segregate, separate or detach areas where a dust deflagration hazard exists in a building or building compartment (excluding hazard within equipment) from other occupancies to minimize damage from a fire or explosion.
- Create buffer zone around hammer mill building to reduce personnel being adjacent to hammer mill building.
- Consider any steps in the emergency procedure that could be automated (e.g., installation of new control schemes).
- Minimize horizontal surfaces where dust can accumulate. Horizontal surfaces that can benefit from a sloped cover include girders, beams, ledges, and equipment tops. Surfaces should be as smooth as possible to minimize dust accumulations and to facilitate cleaning.
- Ensure that spaces inaccessible to housekeeping are sealed to prevent dust accumulation.
- Perform housekeeping activities to ensure that dust accumulations do not exceed 1/32 inches anywhere in the vicinity of equipment or on elevated surfaces (NFPA 652, 2019). Note this control is administrative with ISD

overtones; housekeeping procedures are administrative and result in minimized fuel loadings.

- Consider use of product choke, which can help prevent downstream damage by replacement of a portion of the auger in a screw-feed system with a straight section of pipe.

Other potential barriers in the hierarchy of controls that were identified include:

- Place barriers around hammer mill building to reduce personnel being adjacent to hammer mill building.
- If practical, consider procedural control for restricting access/limiting personnel in hammer mill building when hammer mill is operating.
- Use passive or active deflagration isolation equipment to prevent propagation.

The new elements in Figure 7-4 and 7-5 added from Figure 7-2 are highlighted in red boxes.

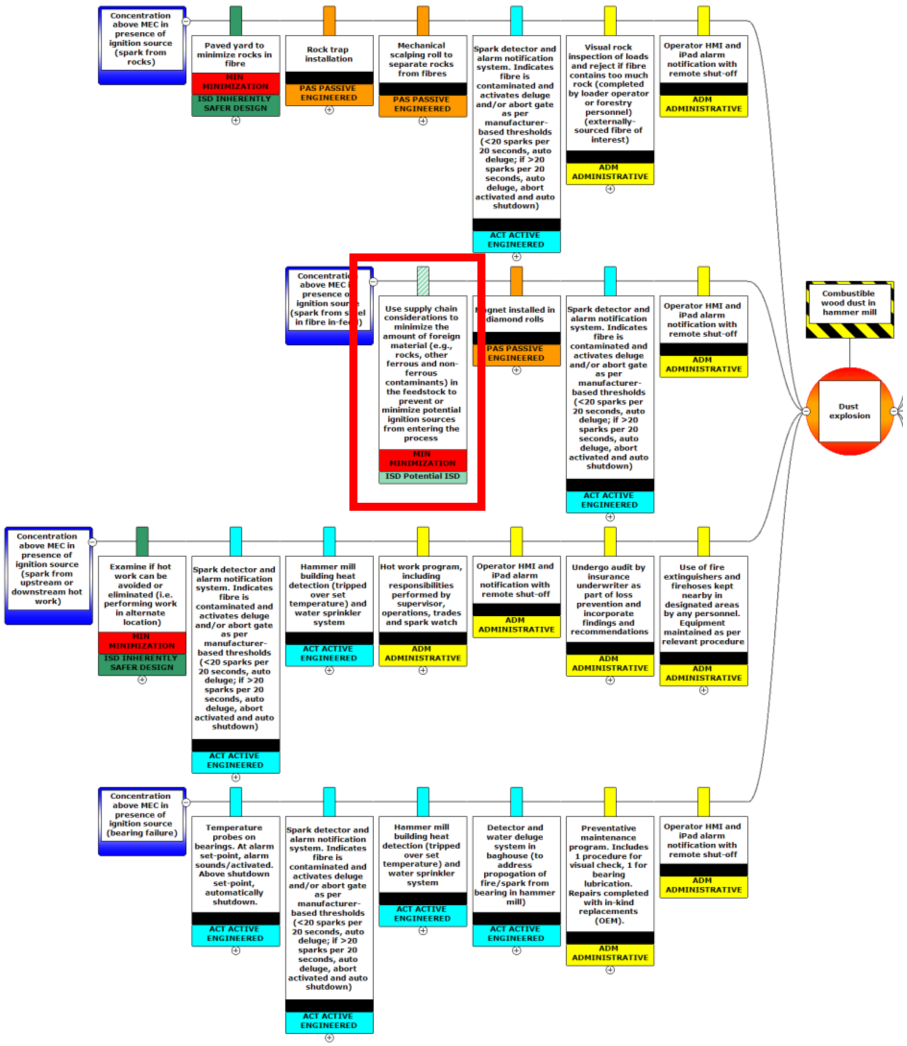


Figure 7-4. Bow tie analysis of combustible wood dust in hammer mill after ISD-BTA protocol application (left-hand-side)

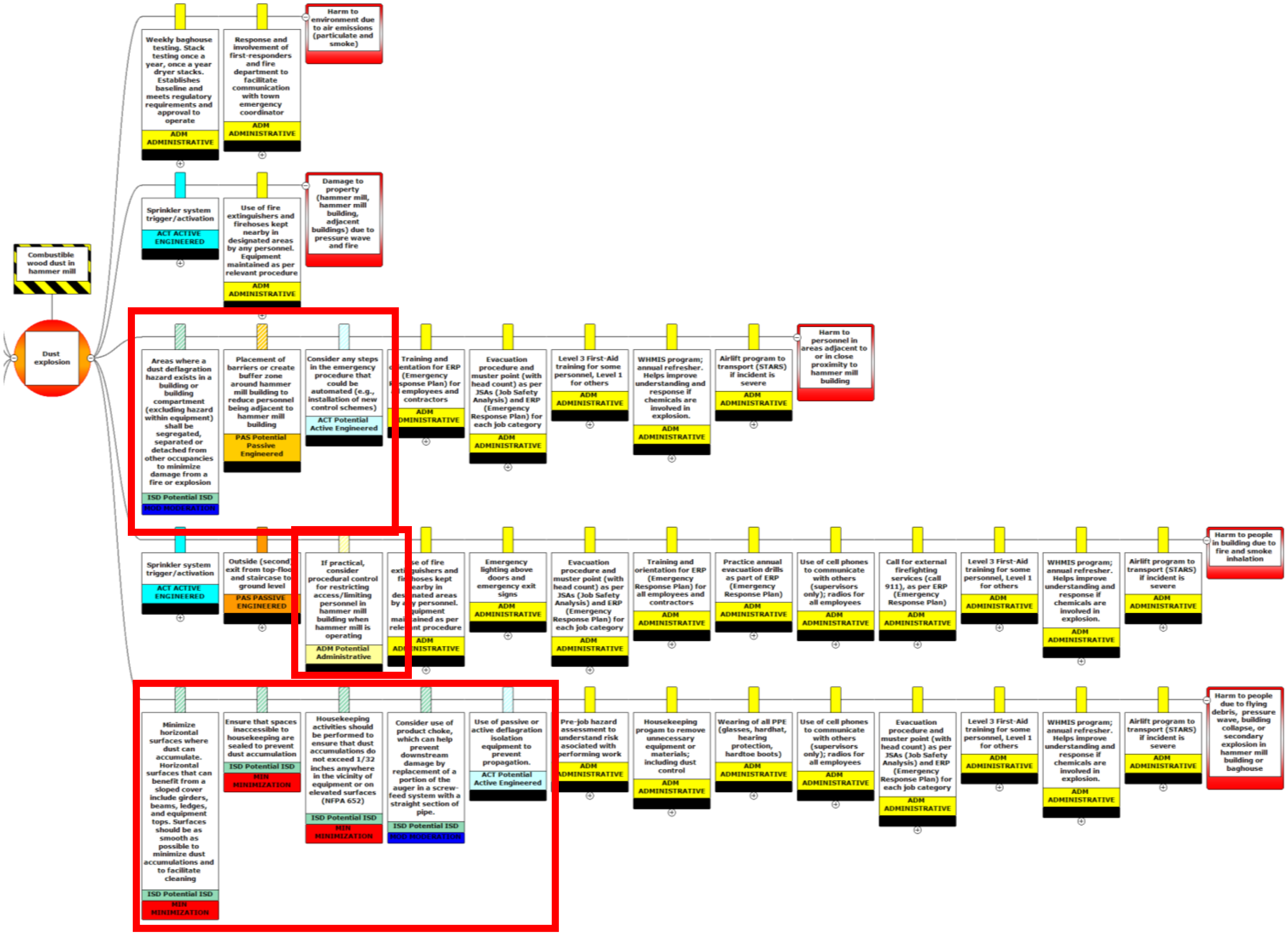


Figure 7-5. Bow tie analysis of combustible wood dust in hammer mill after ISD-BTA protocol application (left-hand-side)

The consideration of the hierarchy of controls is also applicable for the degradation factors and controls. In Figure 7-6, the degradation factor controls have been categorized with respect to the hierarchy of controls. Figure 7-6 shows the ISD barrier of “municipal water used instead of pond water to minimize dissolved material in water” (which is the ISD principle of substitution). Using the protocol application, opportunities for other potential degradation factor controls that are higher in the hierarchy of controls than administrative were examined. The following active engineered barrier was identified:

- Consider using spark detector that has self-monitoring optics feature which alerts the user of a reduction of detector capability caused by damage or lens contamination.

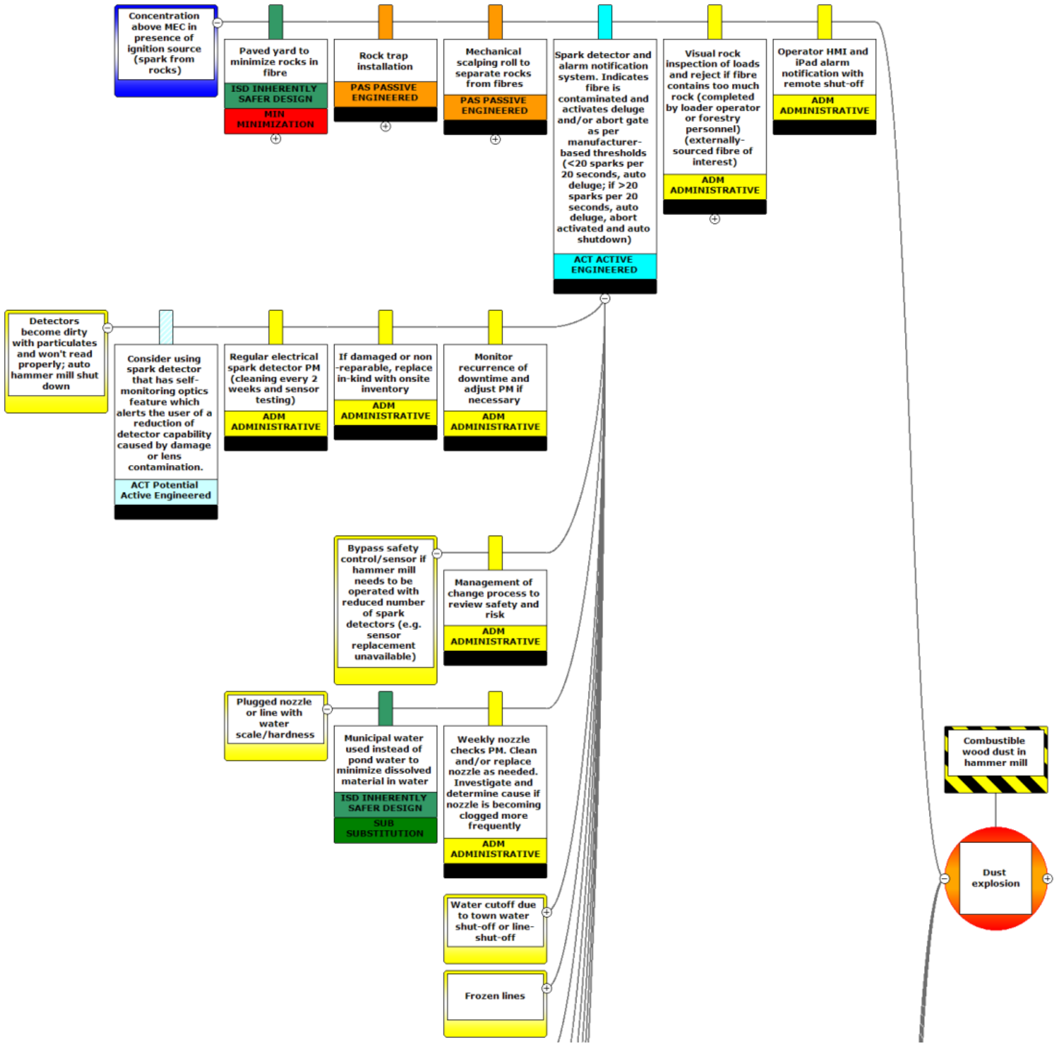


Figure 7-6. Excerpt of bow tie analysis with degradation factor controls labelled with respect to the hierarchy of controls with ISD considerations included

7.3 Discussion of protocol application – feasibility and recommendations

It is recognized that this analysis was performed on an operational facility and that not all ISD barriers will be feasible to incorporate at this life cycle stage. As described by CCPS (2019), when ISD opportunities are identified, a “screening evaluation” should be performed to determine the feasibility. Factors to consider include cost, technology limitations, security, operability, safety or other contributors. The consideration of life cycle within this protocol encompasses some of the aforementioned factors, including cost. A cost-benefit analysis will be needed to choose between the identified options; a simple qualitative judgement by an experienced study team may be sufficient (Ellis, 2014).

Considering the operational life cycle stage, the ISD barriers identified for wood pellet operations that may be feasible to incorporate include the following:

- Minimize horizontal surfaces where dust can accumulate. Horizontal surfaces that can benefit from a sloped cover include girders, beams, ledges, and equipment tops. Surfaces should be as smooth as possible to minimize dust accumulations and to facilitate cleaning.
- Use conducting material for conveyance. If material is conductive and properly grounded, static electricity charge will safely dissipate. If the material is nonconductive, a static charge will build up on its interior surface and could discharge with enough energy to ignite wood dust.
- Where operator grounding is required, use static dissipative footwear and flooring rather than leg or wrist straps that must be attached prior to performing an operation.

- Provide clear, unambiguous information on hazardous materials and how to properly handle them; adequately identify dust explosibility parameters (MEC, MIE, etc.) and the hazards that may be expected to arise through material handling and processing.
- Use supply chain considerations to minimize the amount of foreign material (e.g., rocks and other ferrous and non-ferrous contaminants) in the feedstock to prevent or minimize potential ignition sources from entering the process.
- Ensure supply chain management system is clear and well-defined in order to identify if materials or equipment are incorrect or low-quality.
- Ensure that procedures and installation manuals are written clearly to reduce confusion or misinterpretation to reduce likelihood of improper installation.
- Use equipment that makes incorrect installation or incorrect assembly difficult/impossible.
- Operate rotating elements, such as screw augers, below a tip speed of 1 m/s to prevent the generation of mechanical or frictional sparks from metal on metal contact and the dispersion and suspension of combustible dust clouds.
- Ensure that spaces inaccessible to housekeeping are sealed to prevent dust accumulation.
- Design housekeeping activities to ensure that dust accumulations do not exceed 1/32 inches anywhere in the vicinity of equipment or on elevated surfaces. Note that housekeeping procedures are administrative and result in minimized fuel loadings.

- Consider use of a product choke, which can help prevent downstream damage by replacement of a portion of the auger in a screw-feed system with a straight section of pipe.
- Use lights in bulk raw fibre storage tent designed for the hazard classification of the area.
- Convey combustible dust the shortest distance possible; avoid opportunities for accumulation in ducts.
- Use all ABC-type extinguishers to help avoid using wrong type.
- Use automatic greasers to reduce subjectivity and improve consistency.
- Design and locate abort gates and blast panels to ensure exhaust in a controlled and safe area to protect personnel.

Other barriers in the hierarchy of controls that may be feasible to incorporate during facility operation include:

- Use passive or active deflagration isolation equipment to prevent propagation.
- Consider steps in the emergency procedure that might be automated by installing new control schemes.
- Add fire suppression on loader (automatic and manual).
- Consider installing carbon monoxide (CO) sensors or multiple gas detectors to detect the onset of combustion or pyrolysis.
- Install firewalls.

Other identified ISD barriers are clearly more feasible and effective when considered in the design phase, including:

- Use separation between units and activities to reduce damage to adjacent facilities.
- Reduce silo size to reduce inventory and increase turnover frequency.
- Use pipes and sprinkler heads constructed of most appropriate material for service/water characteristics to reduce corrosion.

The imperfect nature of passive engineered, active engineered and administrative barriers is evident by their associated degradation factors displayed in the bow tie diagrams presented here. An important consideration for barrier effectiveness and reliability arises when there is an administrative barrier (e.g., housekeeping program to remove dust deposits) and all the degradation factor controls are administrative (e.g., training, housekeeping schedule, audits) – which was commonly observed in the bow tie analyses conducted in the current work. In this case, it is very important to ensure that each of these controls is actually being completed. It would be beneficial to have other types of barriers and degradation controls in place; for example, the ISD barrier "install dust tight equipment to minimize the escape of dust" would be more effective than solely relying on housekeeping programs.

ISD barriers also have degradation factors associated with them that must be considered. For example, for the ISD barrier of "paved yard to minimize rocks in fibre," an identified degradation factor is "high maintenance cost and capital expenditure" and an identified degradation factor control is “business case based on access to fibre and reduced wear and tear of vehicles.” The importance of capturing this information is reflected in the need to justify and clarify that having a well-maintained paved yard plays a critical role in keeping fibre clean and reducing rock contamination that could present a potential ignition source. It is vital to have a business case demonstrating payback to justify using capital to fund appropriate ISD barriers.

CHAPTER 8 PROTOCOL APPLICATION – MDF FACILITY

This chapter discusses application of the ISD-BTA protocol on a bow tie developed for an MDF facility. Excerpts of the complete bow tie analysis are shown in this chapter. The barriers listed are intended for illustrative purposes, given that they were identified through the single-analyst approach used in this phase of the research. The incorporation of ISD barriers during the design life cycle stage is discussed based on the rebuild and redesign of this facility that took place following an incident.

8.1 Protocol application and development of bow ties with ISD barriers

Prior to the protocol application, the bow ties developed during the workshop had numerous ISD barriers included, as previously shown in Section 4.3. In addition to these feature described in Section 4.3., the dryer used at the MDF plant is thermal oil heated (indirect heated), rather than direct heated (with combustion gases), which eliminates threats relating to ignition sources from foreign material directly entering the burner and coming into contact with the fibre. This is an example of ISD (substitution), where a direct-heated dryer was substituted with an indirect-heated unit. Another example of ISD evident is the use of a flash dryer, instead of a tray dryer type (CCPS, 2019), which minimizes the amount of combustible material inside the dryer.

An excerpt of the threats and consequences identified in a bow tie analysis of ignition of combustible wood dust in MDF forming is shown in Figure 8-1. The extensive list of threats details the numerous potential ignition sources that could arise; also illustrated are the different consequences that could arise should ignition in the forming line occur, including propagation of the ignition source to various pieces of connected process equipment.

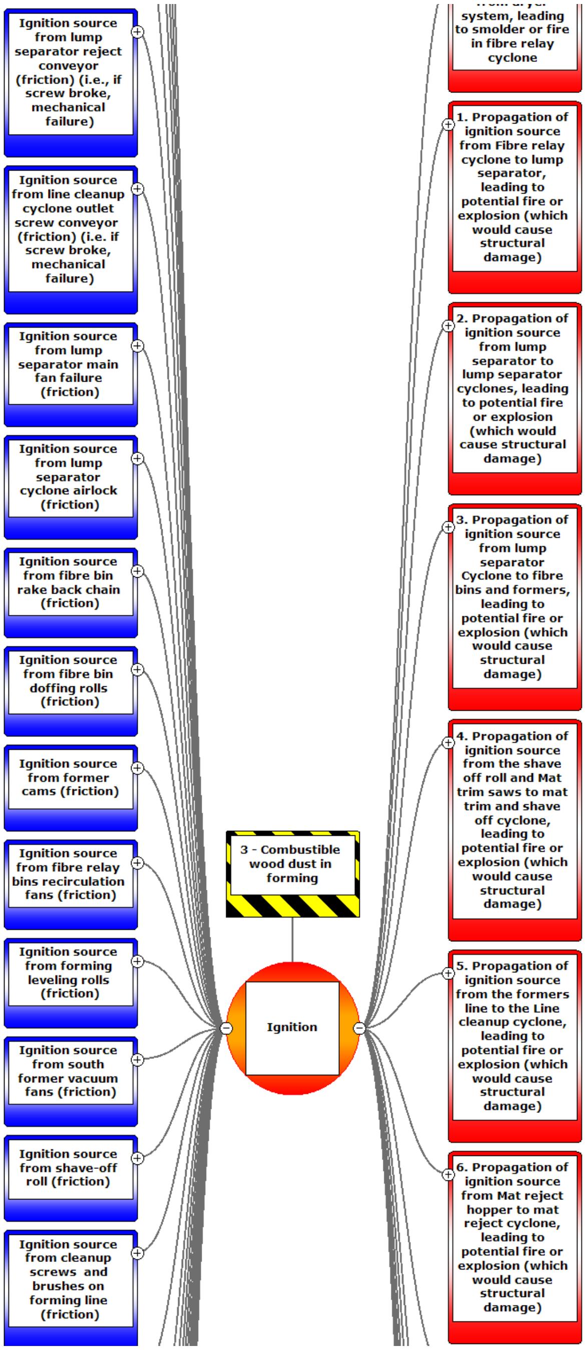


Figure 8-1. Excerpt of threats and consequences identified for bow tie analysis involving ignition of combustible wood dust in MDF forming process

As described above, the bow tie developed in the workshop contained existing ISD barriers, including those highlighted in the excerpt in Figure 8-2, prior to the protocol application. The mitigation barriers highlighted by the red box are for the consequence "harm (injury, death) to personnel (i.e., smoke inhalation, flying debris, pressure wave) due to potential explosion in former system."

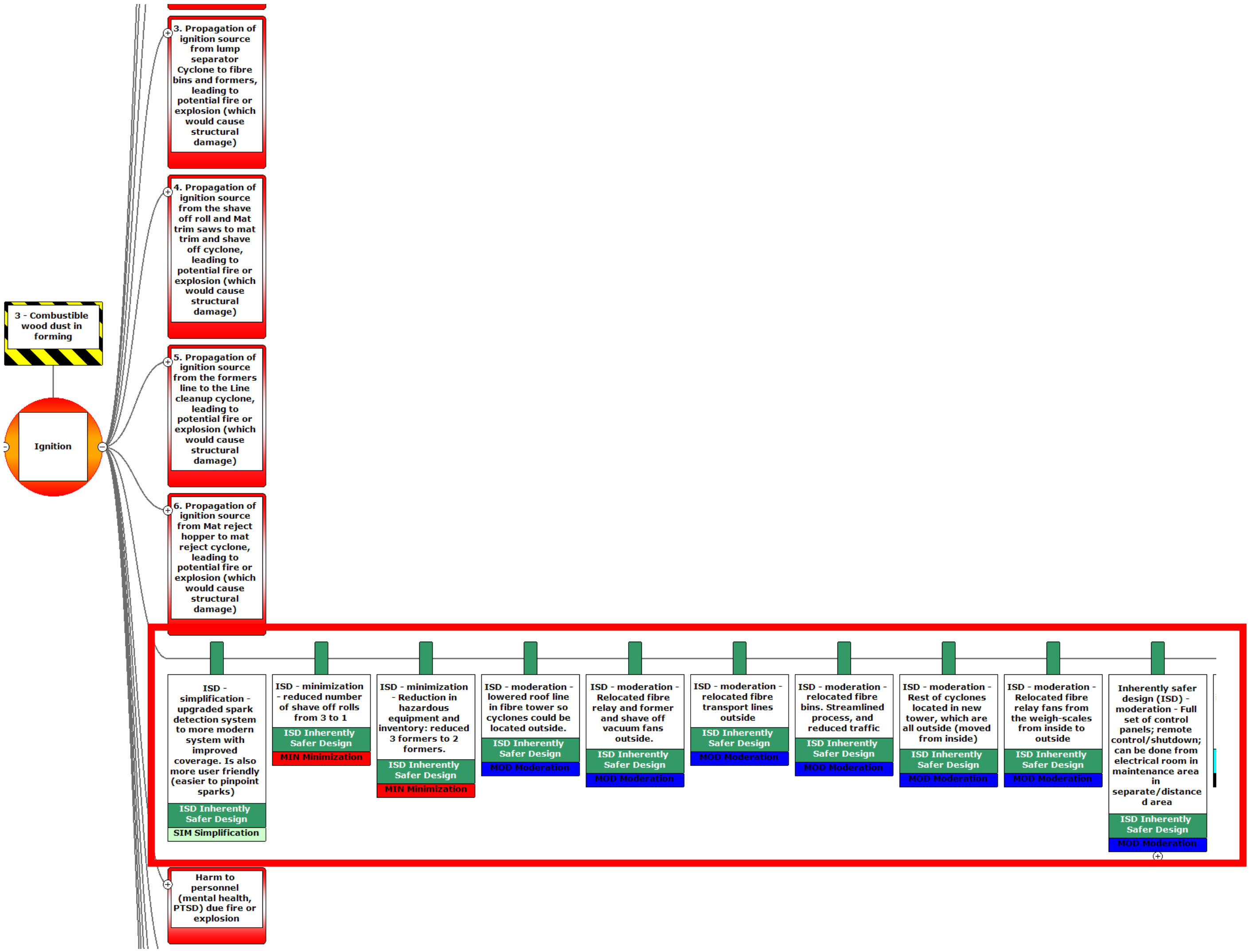


Figure 8-2. Excerpt of ISD mitigation barriers for the consequence "harm (injury, death) to personnel (i.e., smoke inhalation, flying debris, pressure wave) due to potential explosion in former system"

To highlight another bow tie developed, excerpts of a bow tie produced for raw material handling is shown in Figures 8-3 and 8-4 following the protocol application. Note that in Figure 8-4, the acronym "RMS" appears – RMS stands for raw material storage (also referred to as raw material handling).

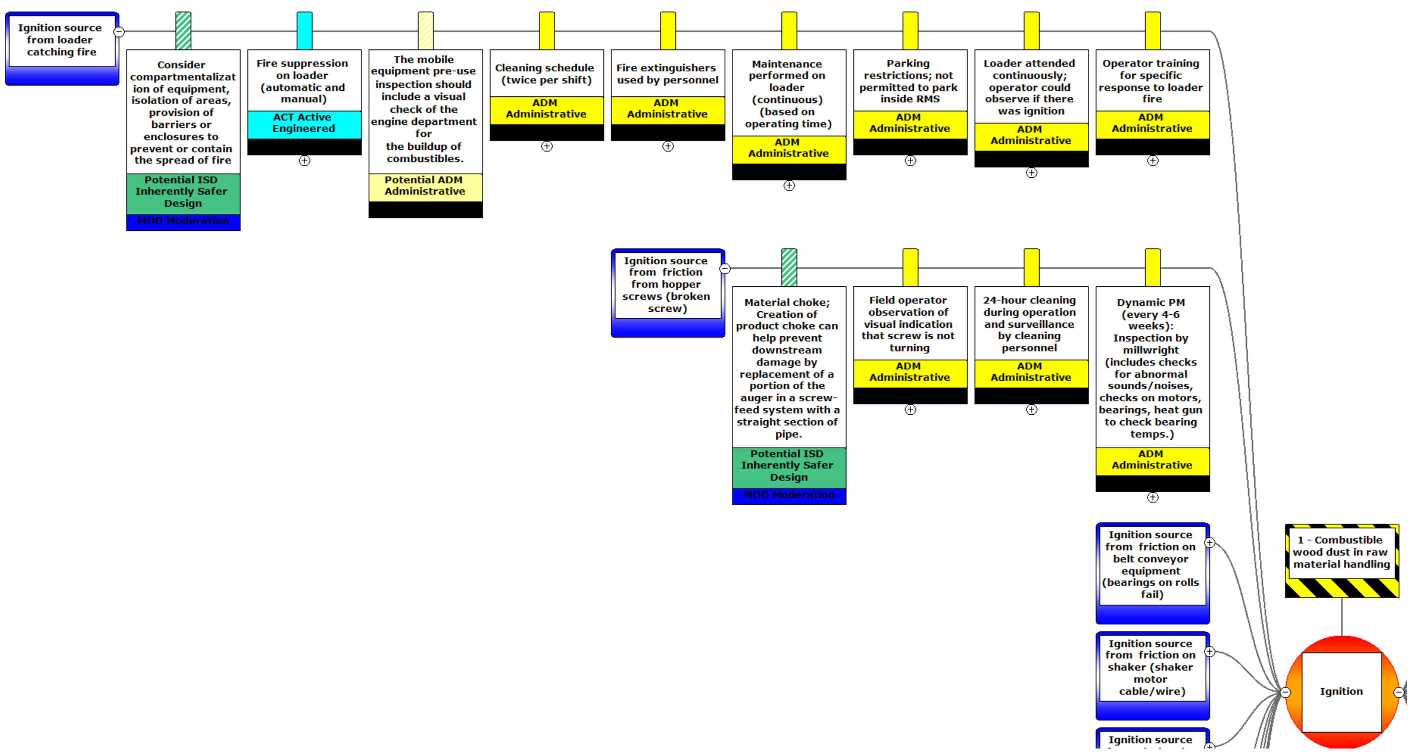


Figure 8-3. Excerpt of bow tie for ignition of combustible wood dust in raw material handling following protocol application (left-hand side)

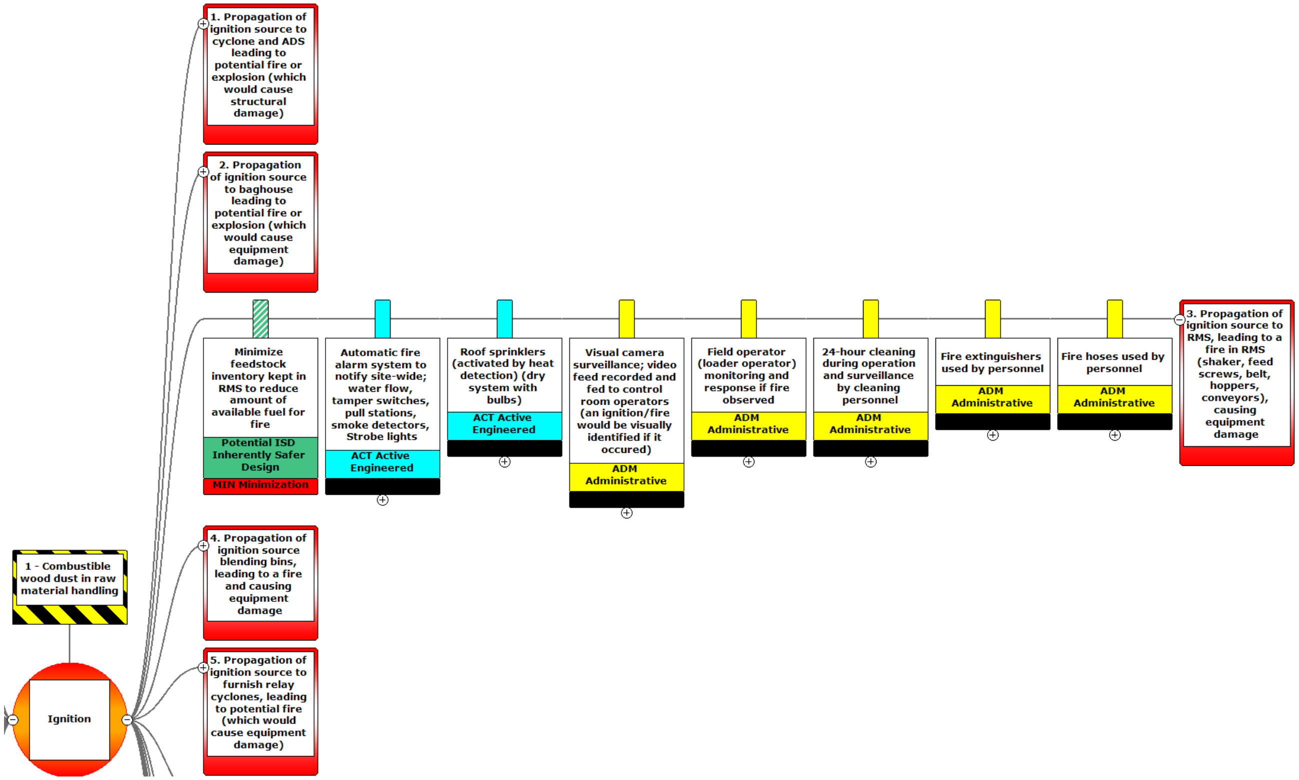


Figure 8-4. Excerpt of bow tie for ignition of combustible wood dust in raw material handling following protocol application (right-hand side)

8.2 Discussion of protocol application and ISD Consideration During Design Stage

Following an incident at the plant, an analysis of the process determined that all major fibre handling equipment (e.g., fans, cyclones, ducts, fibre storage bins) was located inside the mill and that the equipment was extensively interconnected. A detailed assessment of dust hazards associated with various vessels was completed and the explicit consideration of the hierarchy of controls was used to manage fire and explosion hazards. The hierarchy of controls presented in Section 2.6 is also commonly presented as Elimination, Engineering Controls and Administrative Controls; this framework was leveraged by this facility. The vessel assessments were undertaken in a collaborative manner comprised of a multi-disciplinary team, including personnel from operations, maintenance, and health and safety.

Applying the concept of hazard elimination, numerous design decisions were made to relocate fans, ducting and cyclones outdoors. A passive engineered safeguard, explosion venting, is widely used in industry. A critical consideration for explosion venting is ensuring the explosion is vented in a safe location away from normally occupied areas to protect personnel and equipment. In this facility, explosion venting alone could not be used as it could not be ensured that personnel would not be nearby the explosion venting zone. Moving the equipment outdoors separated personnel from the risk. Active explosion suppression systems (active engineered control) were also installed to mitigate the effects of a deflagration.

When ISD and the hierarchy of controls are explicitly included in corporate policies, including incident investigation (root cause analysis/RCA) and management of change, these important process safety concepts can be used to address new risks and identify corrective actions. Including ISD considerations as part of capital project planning also allows ISD to be leveraged during design.

CHAPTER 9 PROTOCOL APPLICATION – DIRECT-HEATED BELT DRYER

This chapter outlines the support provided by Dalhousie personnel on the WPAC Belt Dryer Working Group to conduct bow tie analysis as part of the Sub-Group C (Safety Systems) work. The bow tie developed underwent protocol application and the result of such is highlighted here.

Some content included in this chapter was written by the author (K. Rayner Brown) and provided to personnel at BC Forest Safety Council and University of British Columbia (UBC) Biomass and Bioenergy Research Group (BBRG) for inclusion in the summary document deliverable for the belt dryer working group. Further, portions of the material presented in this chapter have been previously described in Chapter 5; they are repeated here for the sake of completeness.

9.1 Bow tie development

For Sub-Group C (Safety Systems), a bow tie analysis was completed to assess combustible wood dust hazards and controls that are present in a direct-heated belt dryer. The sub-group elected to perform a bow tie analysis due to a number of reasons. The intuitive structure of bow tie analysis allows for systematic identification of the different safety systems used in belt dryers to manage combustible dust hazards. The assessment of degradation factors and controls was another important and valuable component of the work. This allowed the group to systematically identify how these safety systems can degrade or fail, and the measures that must be taken to ensure they will perform as intended when needed.

The bow tie analysis was performed over 6 sessions (1.5 hours per session) and involved a diverse group of subject matter experts (SMEs), including representatives from numerous explosion protection equipment suppliers, wood pellet facilities, and health and safety associations (HSA). The bow tie analysis was led by an experienced workshop facilitator and represents the information that was provided by the participants. Information from previously completed bow ties (including one for a direct-heated belt dryer) as part of the WPAC Critical Controls Management project has also been incorporated. The bow tie contains barriers that are currently existing in facilities, as well as some barriers that are present at some facilities and have been identified by the workshop participants as potential areas for improvement and consideration for other facilities.

The bow tie analysis was conducted for the hazard "combustible wood fibre in direct-heated belt dryer" and top event "combustible wood dust deflagration." The resulting bow tie provides extensive information on:

- how a deflagration could occur in a direct-heated belt dryer,
- what the potential outcomes of a deflagration are,
- the barriers that are in place to prevent a deflagration or mitigate the effects of one, and
- how the barriers can fail and the controls that are in place to ensure they are more reliable (degradation factors and controls).

9.2 Developed bow tie and discussion of protocol application

Following the development of the bow tie, the ISD-BTA protocol was applied to identify any additional potential ISD barriers, as well as passive engineered, active engineered, and administrative barriers. An excerpt of the developed bow tie is shown in Figure 9-1. As with the previous sections describing protocol application, the barriers listed are not exhaustive as they were identified through the single-analyst approach used for this research project.

Potential ISD barriers identified through the protocol application include the following:

- Use direct drive instead of belt drive system.
- Consider interface of how motors and equipment are installed relative to hazard. Decouple from hazard and create separation to keep ignition sources out.
- Consider equipment motor selection or use; certain equipment has higher duty rating that may be more resilient/robust; best-available equipment for application.
- Use conducting material for conveyance.
- Consider substituting the type of dryer; from direct to indirect heated dryer (consider cost-benefit, design or operational lifecycle stage, potential production losses and damages).
- Limit infeed material to appropriate fibre size and moisture content.
- Minimize horizontal surfaces where dust can accumulate.

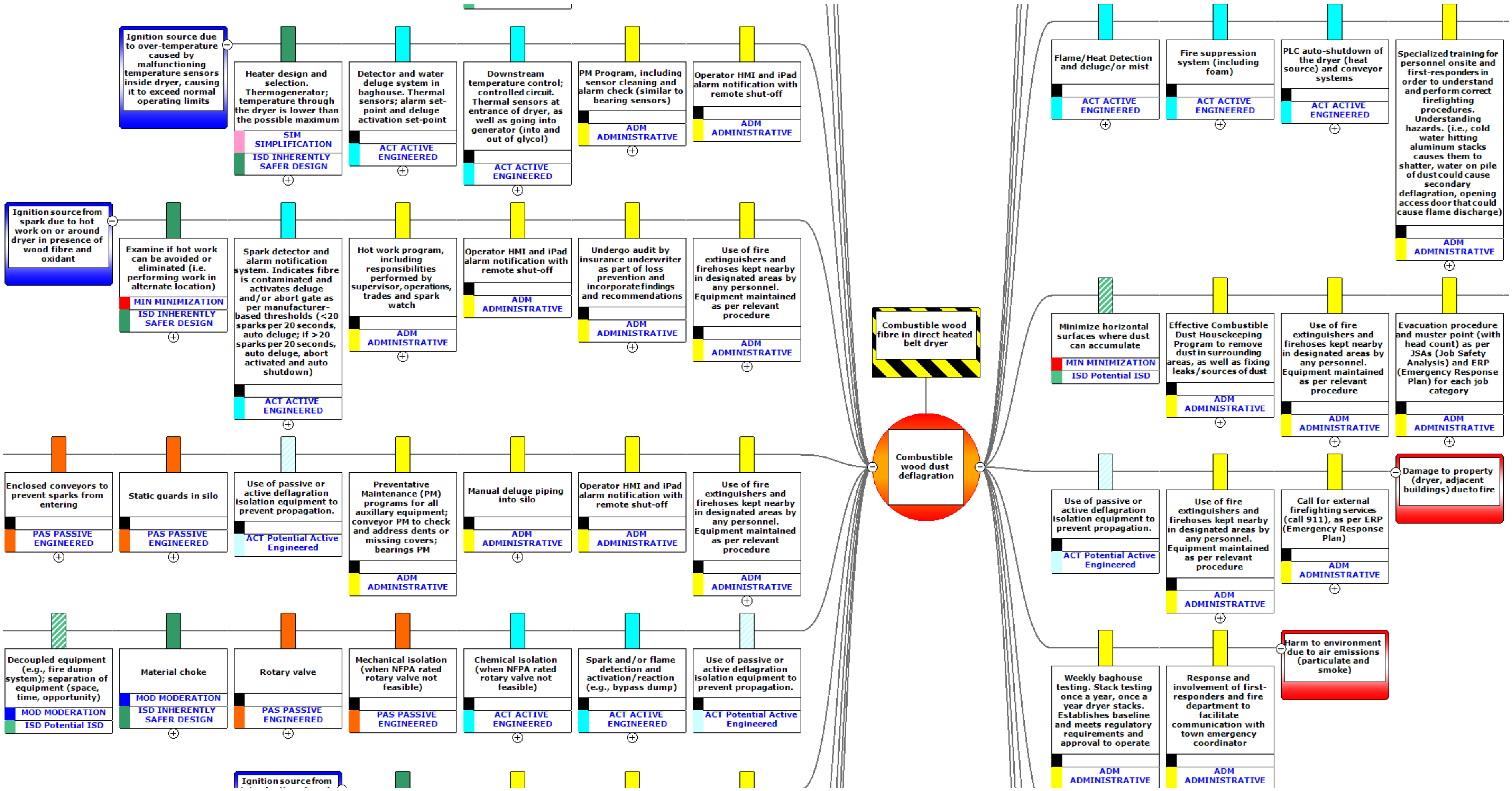


Figure 9-1. Excerpt of bow tie developed as part of WPAC Belt Dryer Working Group following protocol application

Another potential type of control that was identified through the ISD-BTA is the use passive or active deflagration isolation equipment to prevent propagation[5]. Figure 9-2 and Figure 9-3 highlight analysis of the degradation factors and controls for two deflagration isolation techniques – rotary valves and chemical isolation, respectively. This work was further expanded upon in a dedicated research project undertaken by WPAC, BC Forest Safety Council, and Dalhousie University, and conducted by Obex Risk Ltd. The research report is available online (WPAC, 2021a) and the executive summary is found in Appendix A of this report. Additional degradation factors and controls for rotary valves and chemical isolation systems are described in the full report (WPAC, 2021b).

[5] This barrier was already identified as a mitigation barrier for the consequence “flame and pressure propagation (i.e., bins, screws, conveyors, hammer mill, fan, exhaust stacks, etc.) leading to possible secondary explosion that could harm people and property.” and was also added to the prevention side to prevent an ignition source from upstream flame propagation from causing a fire in the dryer.

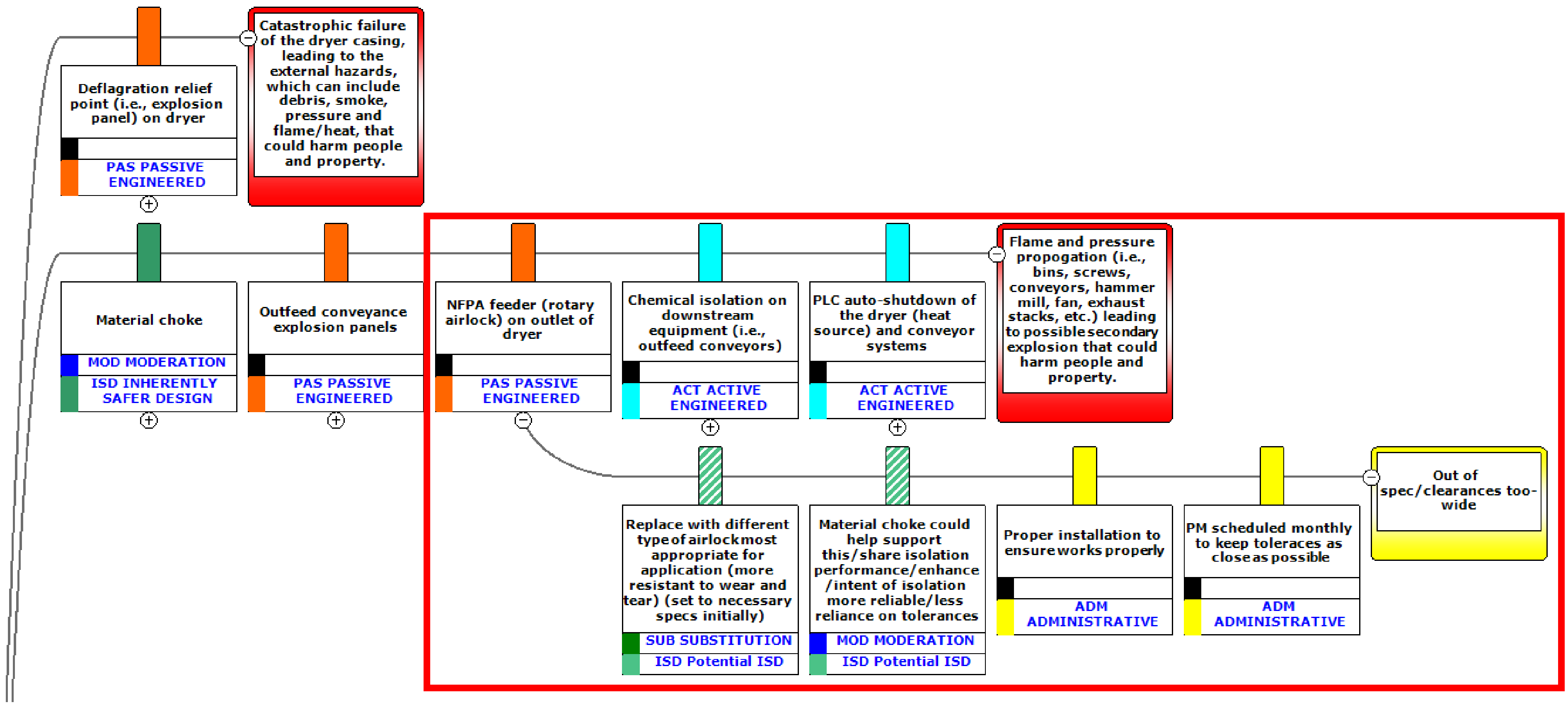
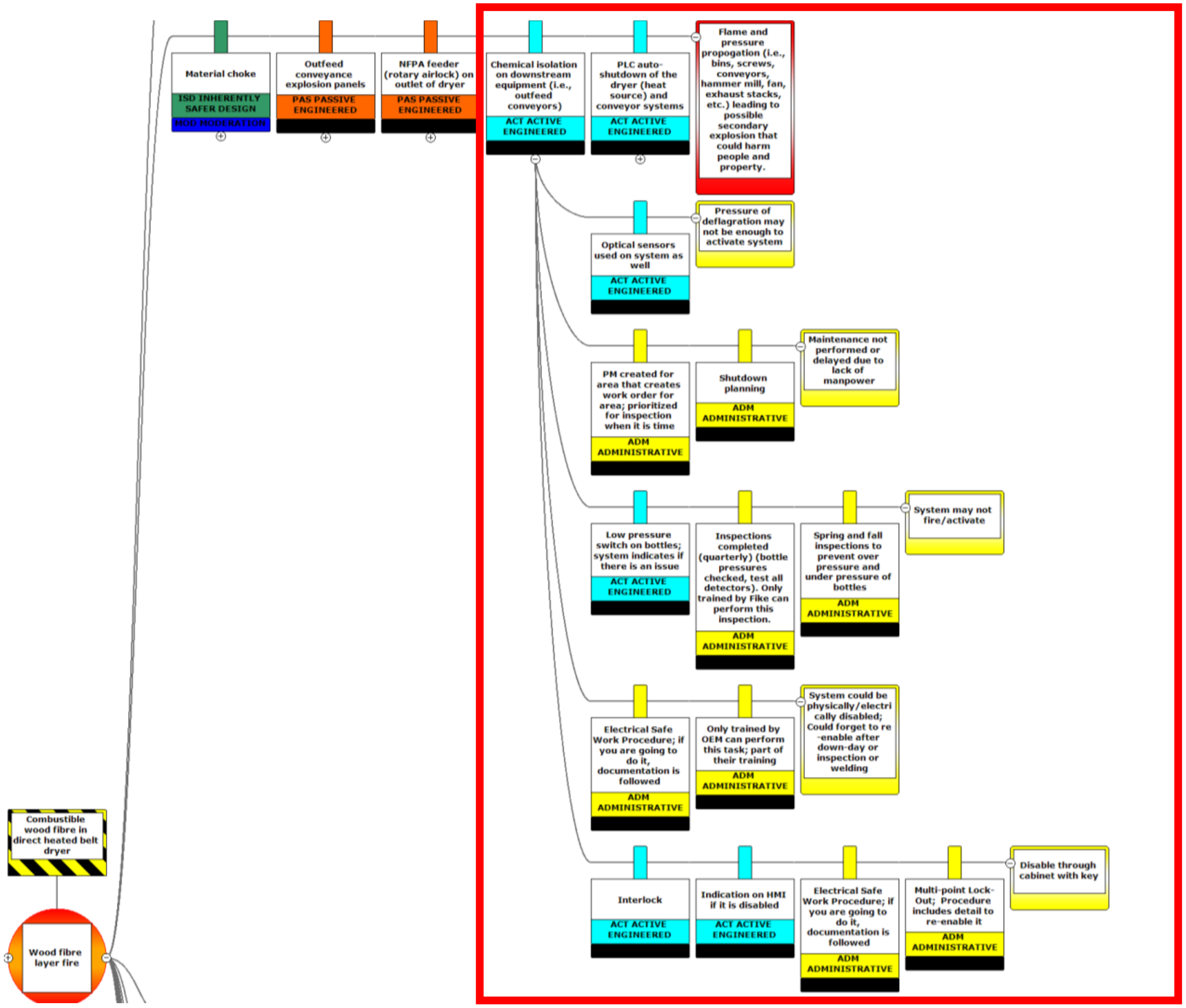


Figure 9-2. Excerpt of bow tie developed as part of WPAC Belt Dryer Working Group following protocol application; the identified degradation factors and controls for a deflagration isolation technique (rotary valve) are highlighted in red



Material choke
ISD INHERENTLY SAFER DESIGN
MOD MODERATION
Outfeed conveyance explosion panels
PAS PASSIVE ENGINEERED
NFPA feeder (rotary airlock) on outlet of dryer
PAS PASSIVE ENGINEERED
Chemical isolation on downstream equipment (i.e., outfeed conveyors)
ACT ACTIVE ENGINEERED
PLC auto-shutdown of the dryer (heat source) and conveyor systems
ACT ACTIVE ENGINEERED
Flame and pressure propogation (i.e., bins, screws, conveyors, hammer mill, fan, exhaust stacks, etc.) leading to possible secondary explosion that could harm people and property.
Optical sensors used on system as well
ACT ACTIVE ENGINEERED
Pressure of deflagration may not be enough to activate system
PM created for area that creates work order for area; prioritized for inspection when it is time
ADM ADMINISTRATIVE
Shutdown planning
ADM ADMINISTRATIVE
Maintenance not performed or delayed due to lack of manpower
Low pressure switch on bottles; system indicates if there is an issue
ACT ACTIVE ENGINEERED
Inspections completed (quarterly) (bottle pressures checked, test all detectors). Only trained by Fike can perform this inspection.
ADM ADMINISTRATIVE
Spring and fall inspections to prevent over pressure and under pressure of bottles
ADM ADMINISTRATIVE
System may not fire/activate
Electrical Safe Work Procedure; if you are going to do it, documentation is followed
ADM ADMINISTRATIVE
Only trained by OEM can perform this task; part of their training
ADM ADMINISTRATIVE
System could be physically/electrically disabled; Could forget to re-enable after down-day or inspection or welding
Interlock
ACT ACTIVE ENGINEERED
Indication on HMI if it is disabled
ACT ACTIVE ENGINEERED
Electrical Safe Work Procedure; if you are going to do it, documentation is followed
ADM ADMINISTRATIVE
Multi-point Lock-Out; Procedure includes detail to re-enable it
ADM ADMINISTRATIVE
Disable through cabinet with key
Combustible wood fibre in direct heated belt dryer
Wood fibre layer fire

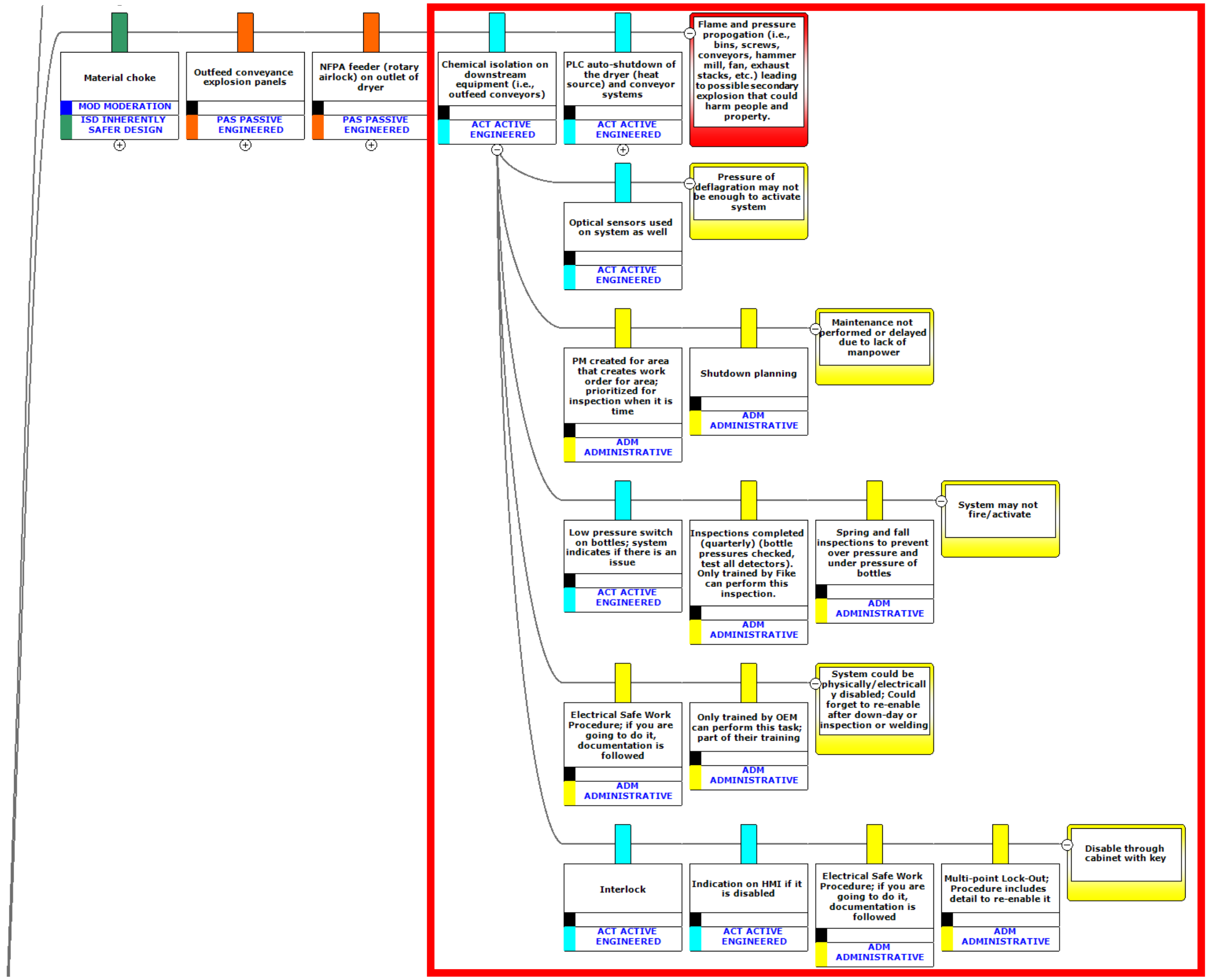


Figure 9-3. Excerpt of bow tie developed as part of WPAC Belt Dryer Working Group following protocol application; the identified degradation factors and controls for a deflagration isolation technique (chemical isolation) are highlighted in red

In each of the bow ties, the threats are generally focused on the presence of different ignition sources; for the threat to lead to the top event of a deflagration, the other four elements of the explosion pentagon (fuel, oxygen, dispersion and confinement) must be present. The hazard indicates that there is combustible wood dust present in the process (fuel), it is assumed that oxygen is present, and there would be a degree of dispersion of the wood dust and confinement within the dryer.

Numerous safety systems were identified, including deflagration isolation (e.g., chemical isolation), ensuring contaminants in in-feed are minimized, relocating dust generating activities away from burner, and effective combustible dust housekeeping programs to remove dust in surrounding areas, as well as fixing leaks/sources of dust. Degradation factor controls that have been identified include prescribed preventative maintenance and inspections of safety systems, identifying as many opportunities to automate as possible, and considering the use of micro mist systems that could extinguish fires quickly with very little residual water. An identified area for enhanced focus is a training program on explosion protection systems, including application, installation, and maintenance.

CHAPTER 10 DISCUSSION

This chapter includes additional discussion points not covered previously in discussion of the protocol application, including communication of the bow ties and ISD workshops, discussion of top event selection, and process safety management in wood pellet operations.

10.1 Remote bow tie workshop facilitation

All of the bow tie workshops were facilitated remotely due to COVID-19 travel restrictions. The workshop teams at the facilities were able to complete the workshop together onsite. Throughout the course of conducting bow tie workshops across three different sites, the process for facilitating the workshops was improved and streamlined. General remote facilitation tips (without reference to this specific project) were contributed to an IChemE (Institution of Chemical Engineers) document “IChemE Safety Centre Guidance: Good practice in virtual HAZOP.”

Literature, including CCPS/EI (2018), describes the importance of a bow tie workshop team comprised of a diverse range of personnel in operations, including maintenance specialists, operators, electricians, controls and instrumentation, environment, health and safety specialists, and supervisors. The validity of these recommendations was confirmed during the current research project. Workshop sessions were efficient and productive when these key people were involved in the analysis, but if personnel were unavailable due to competing priorities or scheduling, the analysis was more difficult. Usually, assistance would be sought via a phone call or flagging and deferring the question until expertise could be provided. It is important to emphasize that the group discussions provide a great deal of value to both participants and facility operations because they promote the sharing of information, as well as different experiences and perspectives, which enhances the collective understanding of the issues.

Due to the remote nature of the workshops, scheduling was an important consideration. Engaging the worksite as early as possible to begin coordinating key personnel is important, as well as collecting important documents like piping and instrumentation diagrams (P&IDs). It was also found that scheduling sessions in 5-hour blocks, rather than 8 hours, can help reduce fatigue. It may also be important to consider scheduling sessions early in the morning or at the beginning of shift for the workshop team to help minimize interruption. Another important consideration for remote facilitation is optimizing audio-visual set-up and communications. The facilitator may need to provide reminders to speak towards the teleconference phone unit, as well as provide instructions on how to reduce ambient noise (i.e., limit rolling chairs and reducing volume of cell phone notifications).

It was also observed that successful facilitation involves promoting productive discussion and encouraging brainstorming. It is important to encourage all people to participate and speak up. The facilitator also needs to recognize if discussions are reaching an impasse. If this happens, the facilitator should note the discussion point and encourage the team to move on.

10.2 Communication of bow ties and ISD workshop

A webinar is planned for 2022 to communicate the bow ties with key stakeholders in wood pellet operations in British Columbia and across Canada through WPAC members. This webinar will highlight the findings of the project and practical considerations for incorporating ISD within operating pellet facilities. As part of knowledge, transfer and exchange (KTE), a bow tie analysis webinar was developed for the WPAC Safety Foundations Webinar Series titled “Using Bow Tie Analysis to Assess Combustible Dust Hazards and Controls” (WPAC, 2021b). This webinar presents the principles of ISD and some common examples to introduce the concept. Chapter 11 further discusses the KTE initiatives undertaken for this project.

This project has identified the benefit of completing an ISD workshop in collaboration with wood pellet operations. The protocol application was effectively and efficiently undertaken using a single-analyst approach by Dalhousie personnel. Conducting an ISD workshop using the multi-disciplinary approach applied in the bow tie workshop would serve to enhance the ISD opportunities that were identified by leveraging key experience, knowledge, and insight of personnel. One approach to an ISD workshop is described by Edwards et al. (2015). In the context of wood pellet operations, an ISD workshop would involve a diverse workshop team comprised of key subject matter experts (including personnel from maintenance, operations, electrical and instrumentation, health and safety). The developed bow ties would be examined and example-based guidance, supported by ISD checklist questions, would be used to identify additional potential ISD barriers that could be implemented within a given pellet operation.

With respect to the collection and identification of example-based guidance that could be used in the protocol application and in ISD workshops, an area for additional research includes the OSHA (US Occupational Safety and Health Administration) citation database related to combustible dust. During the completion of this project, an initial search of the citation database was performed. Of the citations that were surveyed, each referenced various NFPA standards, and the priority of example-based guidance collection shifted from the OSHA citation database to NFPA standards instead. However, there may still be other opportunities to collect example-based guidance from the OSHA citation database.

10.3 Discussion of top event selection and analysis

The bow tie analysis conducted for the wood pellet processes and the MDF plant processes were developed with different top events. The wood pellet bow tie analyses specify the top events “fire” or “explosion”, and the MDF plant bow tie analysis specifies the top event “ignition.” As described by CCPS/EI (2018), it is possible to identify more than one top event for a hazard. The top event describes how control is lost over the hazard. Ignition, fire, and explosion all describe how control can be lost over combustible dust. Other ways that control can be lost over combustible dust that were not explored in bow tie workshops include suspension, smoldering fire, flash fire, and detonation[6]. Literature describing bow tie analysis involving the top events of fire or explosion of hazardous material includes Chen and Wang (2019), Pons (2016), and Yuan et al. (2013).

[6] Detonation involves the propagation of a combustion zone higher than the speed of sound, where deflagration involves the propagation of a combustion zone lower than the speed of sound (NFPA 69, 2019)

Literature describing bow tie analysis involving the top event ignition includes Murphy and Hatch (2020).

Bow tie analysis is performed to examine negative consequences involving harm to people, property, business, and the environment due to combustible dust. Ignition alone does not directly cause catastrophic outcomes, but ignition leading to a fire or explosion does. This additional detail is captured in the consequences in a bow tie with ignition as the top event. In a bow tie with fire or explosion as the top event, additional detail is included that the harm could arise due to the pressure wave, heat, flames, or smoke generated by the explosion or fire; as described in CCPS/EI (2018), consequences should be formulated as "[Damage] due to [Event]". The difference in wording the top events is consistent with guidance provided by CCPS/EI (2018); it is important that the wording of threats and consequences ensures that they flow well between each other (i.e., a threat causes the top event, and the consequence is caused by the top event). In bow ties with explosion as the top event, the threats were worded to ensure the five conditions needed for an explosion to occur are present. The additional detail regarding "concentration above MEC in…" could have been shifted to the hazard, as in Hatch and Murphy (2020), or could have been included with a list of assumptions with the bow tie to make it more concise. The other conditions needed for a dust explosion, for example, in a hammer mill, are implicit in the wording of the hazard – the hammer mill is confined (confinement), combustible dust is present (fuel), and oxygen is present (oxidant).

Both top events can be effective if the analysis is well-structured, and depending on the judgment of the workshop team, one top event may be more intuitive or better suited for analysis. When the bow ties with different top events were compared, no significant differences in the bow ties were observed. The broad range of ignition sources, including mechanical sparks, hot work, and sparks propagating from other equipment, were captured in the threats, and the four main categories of consequences (harm to people, process, property, environment) were analyzed. The top event has some influence on the timeline of events, and whether some barriers are preventing the top event or mitigating consequences. For example, with fire or explosion as the top event, spark detection and deluge systems are a prevention barrier on the left-hand side in order to prevent an ignition from escalating to the top event of an explosion (as seen in Figure 10-1). However, with ignition as the top event, the spark detection and deluge systems are a mitigation barrier that would act on the ignition source and mitigate it from escalating to the consequence of a fire or explosion; this is shown in Figure 10-2.

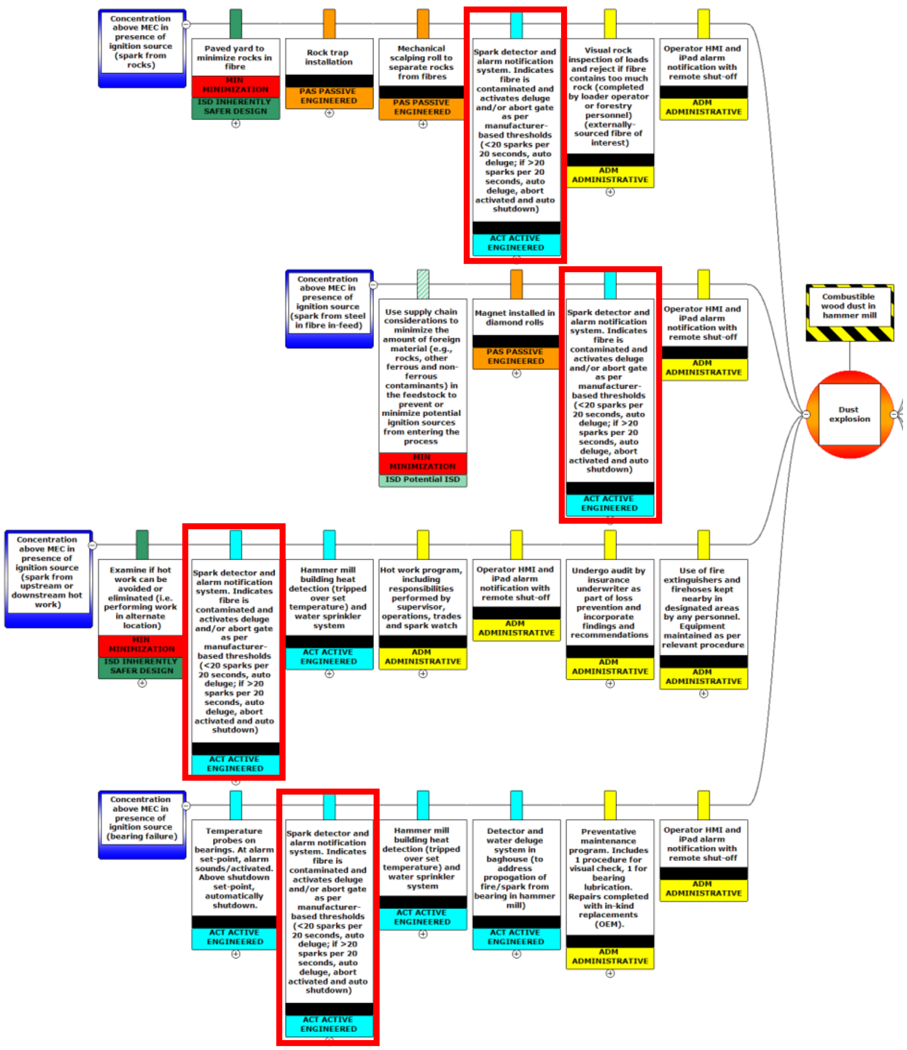


Figure 10-1. Excerpt of bow tie analysis for combustible wood dust explosion in hammer mill in wood pellet plant; spark detection and deluge system as prevention barrier highlighted in red.

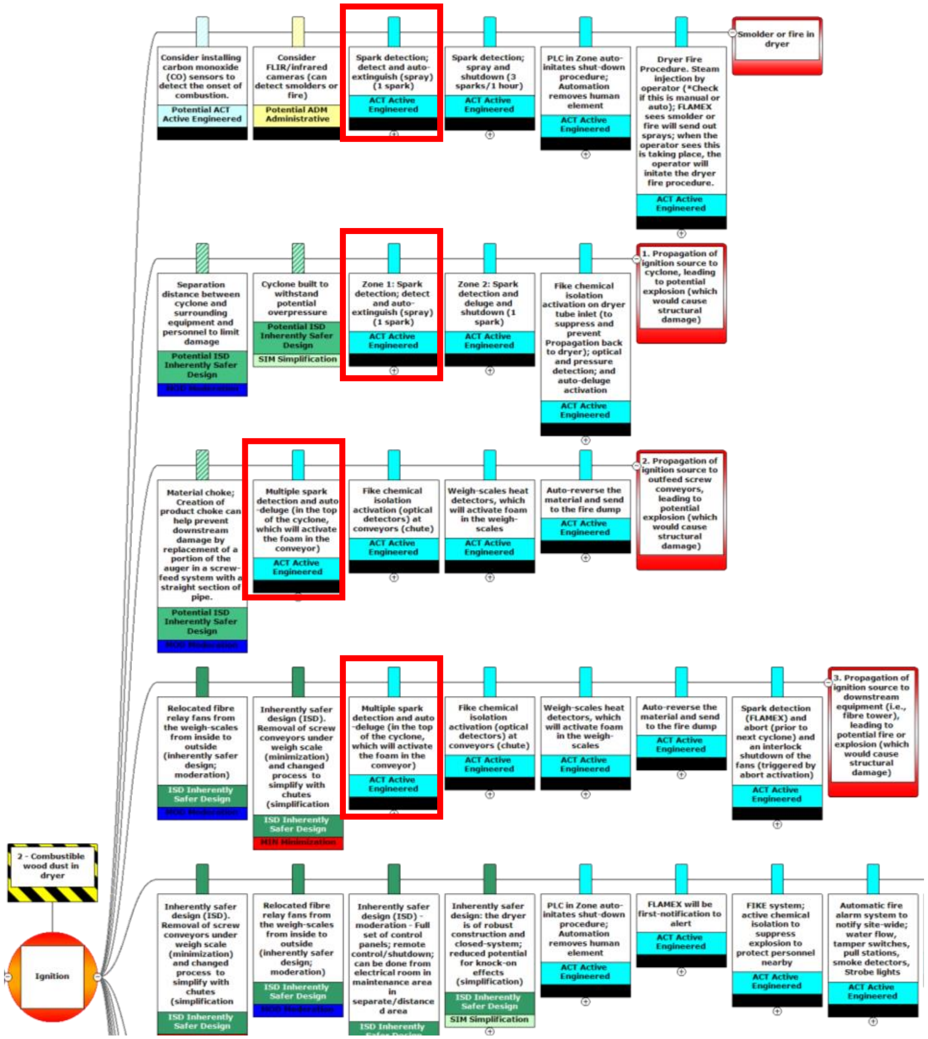


Figure 10-2. Excerpt of bow tie analysis for ignition of combustible wood dust in dryer in MDF plant; spark detection and deluge system as mitigation barrier highlighted in red.

The timeline and sequence of events is visually demonstrated in Figure 10-3, which uses a layers of protection concept with a timeline to demonstrate the difference between explosion prevention and explosion protection (Figure 10-3 courtesy of CV Technology). Here, explosion protection can be considered to be the same as mitigation described above.

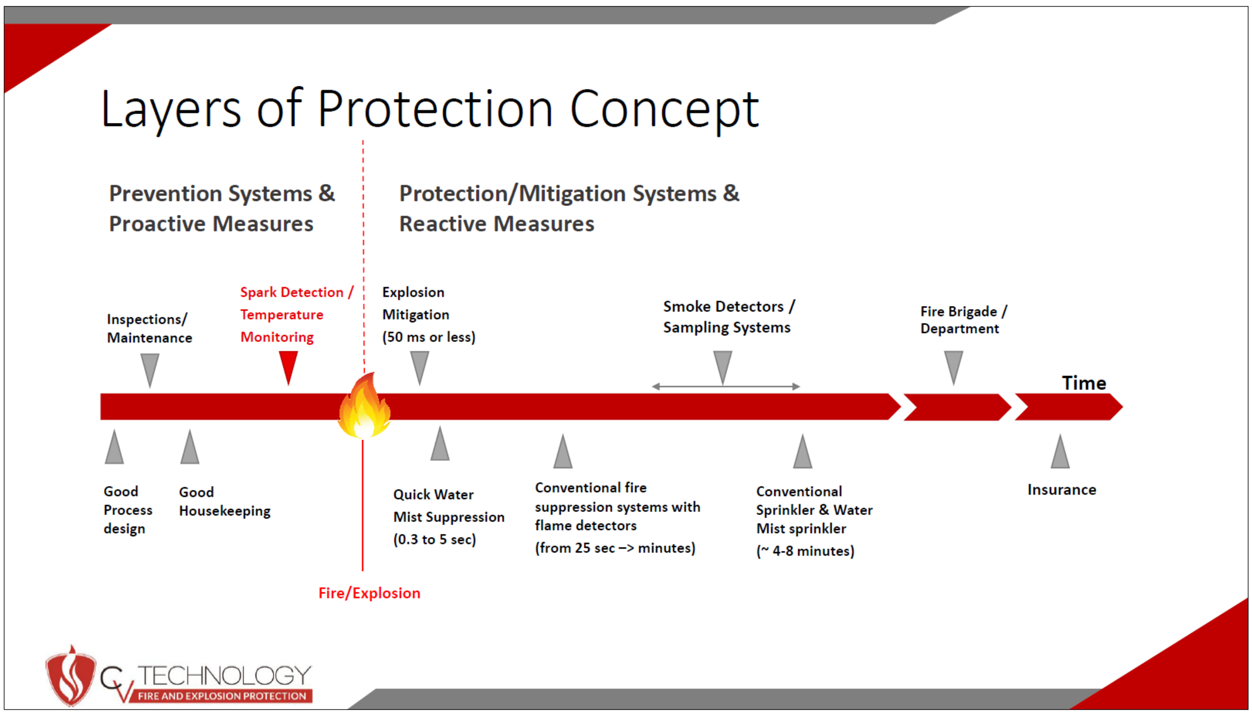


Figure 10-3. Layers of protection concept with timeline to demonstrate difference between explosion prevention and explosion protection (CV Technology, 2021) (used with permission)

10.4 Process safety management in wood pellet operations

Process safety management (PSM) is the focus of an upcoming project in 2022 funded by the WorkSafeBC Innovation at Work (IAW) research grant program titled

“Integrating process safety management into Canadian wood pellet facilities that generate combustible wood dust.” This work is being conducted through a collaboration of Dalhousie University, Wood Pellet Association of Canada (WPAC), BC Forest Safety Council (BCFSC) and DustEx Research Ltd. The objective of this project is the explicit and effective integration of process safety management (PSM) concepts into wood pellet facilities. The upcoming IAW 2022 research builds on the current project, which deals with a very specific aspect of process safety (process hazard analysis). The IAW 2022 project deals with the overarching general concept of process safety management (systems, metrics, and culture). The approach for this new work is as follows:

(i) understanding of the current level of adoption of PSM elements and concepts in the participating wood pellet plants, thereby identifying possible gaps,

(ii) development of a plan for increasing the level of adoption and closing of gaps over time, recognizing that the most appropriate design solution may not be a one-size-fits-all model, and

(iii) creation of tools (system elements, measurement indicators, and safety culture benchmarks) to help industry integrate PSM into their operations moving forward.

CHAPTER 11 KNOWLEDGE TRANSFER AND EXCHANGE (KTE)

The KTE goals described in the project proposal are as follows:

a) to create enhanced awareness of the insidious nature of the combustible wood dust problem – an issue that involves multiple threats to the well-being of workers, manufacturing equipment, and business operations,
b) to encourage and facilitate widespread adoption via example-based guidance of the principles of inherently safer design in combustible dust hazard analysis, and
c) to positively influence safety culture initiatives aimed at demonstrating management commitment to reducing the risk of wood dust fires and explosions.

Table 11-1 outlines the KTE initiatives that have been completed and that are currently underway. Some communication initiatives listed also overlap with those undertaken for the CCM project with the goal to "support the successful implementation and adoption of Critical Control Management through the effective and regular communications of new tools, milestones and achievements."

As shown in Table 11-1, there were several KTE initiatives focussed on reaching wood processing facilities in British Columbia and those across Canada through engagement with WPAC member companies using communications tools such as articles in the industry trade publication, *Canadian Biomass*. Other KTE initiatives focussing on providing training and improving competency include providing a webinar through the WPAC Safety Foundations webinar series, as well as providing foundational support to BCFSC personnel on the bow tie methodology.

Numerous KTE initiatives have thus been conducted and are planned for dissemination of the research to the broader process safety and global combustible dust research and practice community. These initiatives include contribution of learnings for facilitating bow tie analysis workshops remotely/virtually to an IChemE (Institution of Chemical Engineers) white paper, as well as a planned manuscript submission to an archival journal relevant for this research focussed on process safety and combustible dust in wood processing.

Table 11-1. Summary of KTE initiatives

KTE Deliverable	Date	Target Audience and End-Users	Stakeholder Engagement	Information Sharing Strategies	Reference
Developed a training package, webinar and quiz for WPAC safety foundations series.	October 2020	Wood pellet producers	Advertising through WPAC website, LinkedIn, emails to WPAC members	Presentation, continuing professional development quiz	WPAC (2021b)
Developed Terms of Reference document for CCM bow tie workshops	October 2020	Wood pellet producers	Emails to wood pellet producers involved with CCM pilots	Written document	N/A
Provided workshop facilitation and training support to BCFSC personnel for bow tie methodology	October 2020	Health and Safety Association (HSA)	Emails, on the job training and observation, sharing literature	Establishing working relationships, on-the-job training, sharing written documentation and summaries	N/A
Contributed to IChemE (Institution of Chemical Engineers) document on virtual workshop best-practices	April 2021	Global process safety field	Advertising by IChemE through IChemE website and LinkedIn	White paper	IChemE (2021)

Table 11-1. Summary of KTE initiatives continued

KTE Deliverable	Date	Target Audience and End-Users	Stakeholder Engagement	Information Sharing Strategies	Reference
Dust Safety Science podcast episodes: - Discussed the importance of combustible material particle size (E. Brideau) - WPAC / background (G. Murray) - CCM Project background (C. Whelan) - IAW Research project (P. Amyotte)	April 2021	Global combustible dust research and practice community	Advertising on LinkedIn and other social media channels, website,	Podcast	Dust Safety Science (2021a, b, c)
Presented at Global Dust Safety Conference	March 1-3 2021	Global combustible dust research and practice community	Advertising on LinkedIn and other social media channels, website,	Presentation	Dust Safety Science (2021d)
Provided training for bow tie analysis for dust hazards in Dust Safety Academy	January 2021	Global combustible dust research and practice community	Advertising on LinkedIn and other social media channels, website	Presentation	Dust Safety Science (2021d)

Table 11-1. Summary of KTE initiatives continued

KTE Deliverable	Date	Target Audience and End-Users	Stakeholder Engagement	Information Sharing Strategies	Reference
Wrote article discussing the importance of process safety management, bow tie analysis and ISD for *Canadian Biomass* magazine	January 2021	Wood pellet producers, facilities handling combustible dust	Advertising on LinkedIn and other social media channels, website, email	Industry trade publication	Canadian Biomass (2021d)
Completed project on deflagration isolation and wrote article introducing project for Canadian Biomass. Additional communications plan developed for: - 1-page factsheet targeted for operators - 2-page factsheet for broader industry audience - planning and delivery of 1-hour symposium panel presentation with subject matter experts	November 2021 and continued into 2022	Wood pellet producers, facilities handling combustible dust	Advertising on LinkedIn and other social media channels, website, email	Industry trade publication	WPAC (2021a)

Table 11-1. Summary of KTE initiatives continued

KTE Deliverable	Date	Target Audience and End-Users	Stakeholder Engagement	Information Sharing Strategies	Reference
Wrote article updating CCM, bow tie workshop progress update for *Canadian Biomass*	October 2021	Wood pellet producers	Advertising on LinkedIn and other social media channels, website, email	Industry trade publication	WPAC (2021c)
Planned - 14th International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions (14th ISHPMIE):	Planned - July 11-15, 2022	Global combustible dust research and practice community	Website, publication in special issue of Journal of Loss Prevention in the Process Industries	Peer-reviewed conference presentation	ISHPMIE (2021)
Planned – preparation and submission of manuscript to peer-reviewed journal	Early 2022	Global combustible dust research and practice community	Publication in established journal in relevant field	Archival journal article	
Presentation at WPAC AGM[7] (Safety Panel)	September 2021	Wood pellet producers, wood pellet industry stakeholders	Advertising on LinkedIn and other social media channels, website, email	Panel presentation	Canadian Biomass (2021e)

[7] Annual general meeting

Table 11-1. Summary of KTE initiatives continued

KTE Deliverable	Date	Target Audience and End-Users	Stakeholder Engagement	Information Sharing Strategies	Reference
Belt Dryer Working Group – contributions to Sub-Group C and white paper deliverable	October 2021	Wood pellet producers, regulator	Advertising on LinkedIn and other social media channels, website, email	White paper	Canadian Biomass (2021b); WPAC (2021d)
CCM factsheet	October 2021	Wood pellet producers	Advertising on LinkedIn and other social media channels, website, email	Industry trade publication	WPAC (2020)
Communications through BCFSC Forest Safety Newsletter (FSN)	Ongoing	Wood pellet producers	Advertising on LinkedIn and other social media channels, website, email	Industry trade newsletter	BCFSC (2021)
Planned – communications on findings of IAW project for wood pellet producers	2022	Wood pellet producers	Advertising on LinkedIn and other social media channels, website, email	Industry trade publication, others to be determined (TBD)	N/A
Wrote article discussing the importance of combustible material particle size for *Canadian Biomass* (E. Brideau)	October 2021	Wood pellet producers, facilities handling combustible dust	Advertising on LinkedIn and other social media channels, website, email	Industry trade publication	Canadian Biomass (2021c)

CHAPTER 12 CONCLUSIONS

In conclusion, ISD barriers to manage combustible dust hazards in wood product manufacturing, specifically wood pellet and MDF plants, were successfully identified using bow tie analysis to explicitly consider ISD within PHA. Numerous opportunities to consider ISD were identified, including using supply chain considerations to minimize the amount of foreign material (e.g., rocks and other ferrous and non-ferrous contaminants) in the feedstock to prevent potential ignition sources from entering the process, relocating hazardous equipment such as dust collectors outdoors away from personnel, and enhancing human-machine interfaces (HMI) to improve processes.

During the course of this project, other initiatives were also undertaken related to process safety and combustible dust safety in the wood processing industry, including the WPAC belt dryer working group, as well as the completion of a WPAC Safety Committee project focussed on deflagration isolation. Numerous knowledge transfer and exchange (KTE) efforts were completed, including webinar presentations, conference presentations, podcast interviews, and articles in industry trade publications, as well as the upcoming preparation of a manuscript for submission to an archival journal. KTE initiatives were targeted at both wood pellet producers and wood processing facilities in British Columbia and across Canada, as well as global process safety and combustible dust researchers and practitioners.

Further adoption of process safety elements in wood processing industries is recommended for the prevention and mitigation of combustible dust hazards. Process safety management (PSM) will be the focus of an upcoming Innovation at Work research project in 2022 titled “Integrating process safety management into Canadian wood pellet facilities that generate combustible wood dust.”

REFERENCES

Amyotte, P.R., Goraya, A.U., Hendershot, D.C., Khan, F.I. (2007). Incorporation of inherent safety principles in process safety management. *Process Safety Progress.* 26, 333–346.

Amyotte, P.R., Pegg, M.J., Khan, F.I. (2009) Application of inherent safety principles to dust explosion prevention and mitigation. *Process Safety and Environmental Protection*. 87, 35-39.

Amyotte, P.R. (2013). *An Introduction to Dust Explosions: Understanding the Myths and Realities of Dust Explosions for a Safer Workplace.* Butterworth-Heinemann, Oxford, UK.

Amyotte and Khan (2021). The role of inherently safer design in process safety. *The Canadian Journal of Chemical Engineering*. 99 (4), 853-871.

Barton, J. (2002). *Dust Explosion Prevention and Protection*. Institution of Chemical Engineers (IChemE), Rugby, UK.

BCFSC (BC Forest Safety Council). (2021). Forest Safety Newsletter, December 2021, Issue 4 Volume 8. Last retrieved December 16, 2021, from https://www.bcforestsafe.org/wpcontent/uploads/2021/11/FSNDec2021.pdf

BCFSC MAG (BC Forest Safety Council Manufacturing Advisory Group). (2021). Manufacturing Safety Alert – Loader Fire. Last retrieved December 16, 2021, from https://www.bcforestsafe.org/wp-content/uploads/2021/03/MAG_SafetyAlertFireLoader.pdf

Canadian Biomass (2020). WPAC Critical Controls Management factsheet. Last retrieved December 16, 2021, from https://www.pellet.org/wp-content/uploads/2021/02/CCM-Factsheet-FINAL.pdf

Canadian Biomass (2021a). Canadian Biomass 2021 Pellet Mill Map. Last retrieved December 16, 2021, from https://www.canadianbiomassmagazine.ca/canadian-biomass-pellet-mill-map/

Canadian Biomass (2021b). Key takeaways from WPAC's Belt Dryer Symposium. Last retrieved December 16, 2021, from https://www.canadianbiomassmagazine.ca/key-takeaways-from-wpacs-belt-dryer-symposium/

Canadian Biomass (2021c). Defining combustible dusts: does particle size matter? Last retrieved December 16, 2021, from https://www.canadianbiomassmagazine.ca/defining-combustible-dusts-does-particle-size-matter/#

Canadian Biomass (2021d). What you don't have, can't leak: Q&A with Kayleigh Rayner Brown on process safety. Last retrieved December 16, 2021, from https://www.canadianbiomassmagazine.ca/what-you-dont-have-cant-leak-qa-with-kayleigh-rayner-brown-on-process-safety/

Canadian Biomass (2021e). WPAC Conference & AGM 2021 – Day 1 – Panel: Innovating Our Way to a Safer, Better Future. Last retrieved December 16, 2021, from https://www.canadianbiomassmagazine.ca/ve-agenda/panel-innovating-our-way-to-a-safer-better-future/

CCHS (Contra Costa County Health Services). (2013). *Industrial Safety Ordinance Annual Performance Review and Evaluation Report – 2013.* Retrieved February 14, 2019, from http://www.ci.richmond.ca.us/DocumentCenter/View/26375/iso_report_feb-2013

CCPS (Center for Chemical Process Safety). (2005). *Guidelines for Safe Handling of Powders and Bulk Solids*. American Institute of Chemical Engineers, New York, New York, US.

CCPS (Center for Chemical Process Safety). (2019). *Inherently Safer Chemical Processes: A Life Cycle Approach* (3rd ed.). Hoboken, NJ: John Wiley & Sons, Inc.

CCPS/EI (Center for Chemical Process Safety/Energy Institute). (2018). *Bow Ties in Risk Management: A Concept Book for Process Safety.* Wiley, New York, NY/London, UK.

CGE Risk Management Solutions. (2017). *BowTieXP Methodology Manual*, Revision 16 (July 2017).

CGE Risk Management Solutions. (2019a). *Knowledge Base.* Retrieved November 27, 2019, from https://www.cgerisk.com/knowledgebase/Main_Page

CGE Risk Management Solutions. (2019b). *BowTieXP Software Manual,* Revision 39 (March 8, 2019).

Chen, M. and Wang, K. (2018). A Bow-tie Model for Analyzing Explosion and Fire Accidents Induced by Unloading Operation in Petrochemical Enterprises. *Process Safety Progress*. 38 (1), 78-89.

Conifer (2012). Wood Dust in Sawmills: Compilation of Industry Best Practices. Last retrieved December 16, 2021, from http://www.conifer.ca/files/6314/1600/6292/WoodDustSawmillsCompilation_May2012.pdf

Cross, J. and Farrer, D. (1982). *Dust Explosions*. Plenum Press, New York.

CSA (2017). *CAN/CSA-Z767-17, Process safety management.* CSA Group, Toronto, ON.

Drax (2021). This is how you make a biomass wood pellet. Last retrieved December 16, 2021, from https://www.drax.com/sustainable-bioenergy/this-is-how-you-make-a-biomass-wood-pellet/

Dust Safety Science (2021a). DSS131: History of the Wood Pellet Association of Canada with Gordon Murray. Last retrieved December 16, 2021, from https://dustsafetyscience.com/history-of-wpac-gordon-murray/

Dust Safety Science (2021b). DSS132: Identifying & Implementing Critical Controls in Wood Pellet Facilities with Cherie Whelan. Last retrieved December 16, 2021, from https://dustsafetyscience.com/identifying-and-implementing-critical-controls-wood-pellet-facilities-cherie-whelan/

Dust Safety Science (2021c). DSS133: Implementing Inherently Safer Design using Bowtie Analysis for Combustible Dust Hazards with Dr. Paul Amyotte. https://dustsafetyscience.com/implementing-inherently-safer-design-bowtie-analysis-paul-amyotte/

Dust Safety Science (2021d). Dust Safety Academy. Last retrieved December 16, 2021, from https://www.dustsafetyacademy.com/

Edwards, D., Foster, J., Linwood, D., McBride-Wright, M., Russell, P. (2015). Inherent Safety: It's Common Sense, Now for Common Practice!, In *Proceedings of Hazards 25, IChemE, Edinburgh, UK, (May 13-15 2015)* pp. 1–14.

Ellis, G.R. (2014). Making Facilities Safer By Design. In *Proceedings of Hazards 24*, *IChemE, Edinburgh, UK (May 7-9 2014),* pp. 1–6.

Rodgers, S. and Erdem, U. (2011). Practical issues with marginally explosible dusts—evaluating the real hazard. *Process Safety Progress.* 30 (3), 266-279.

Frank, W. and Rodgers, S. (2012). NFPA Guide to Combustible Dusts. NFPA (National Fire Protection Association), Quincy, MA.

Frank, W. (2019). *Dust Explosions: Hazard Identification,* Chapter 5 in *Methods in Chemical Process Safety*, Volume 3, P. Amyotte and F. Khan (Editors), Elsevier/Academic Press, Cambridge, MA, pp. 123-165.

Goraya, A., Amyotte, P.R., Khan, F.I. (2004). An inherent safety-based incident investigation methodology. *Process Safety Progress*. 23, 197–205.

Hatch, D., McCulloch, P., Travers, I. (2017). Visual HAZOP: Exploiting the power of bowties to improve study effectiveness and enhance engagement. *The Chemical Engineer*. 917, 27–32.

Hatch, D., McCulloch, P., Travers, I. (2019). Enhancing PHAs: The Power of Bowties. *Chemical Engineering Progress.* 115, 20-26.

Hedlund, F. H. and Astad, J. (2014). Solid Biomass Climate Change Interventions Examined in a Context of Inherent Safety, Media Shifting, and Emerging Risks. *Human and Ecological Risk Assessment: An International Journal.* 21, 1410–1427.

HSE (Health and Safety Executive). (2011). Safe collection of wood waste: Prevention of fire and explosion. Last retrieved December 16, 2021, from https://www.hse.gov.uk/pubns/wis32.pdf

IChemE (Institution of Chemical Engineers). (2021) IChemE Safety Centre Guidance: Good practice in virtual HAZOP. Last retrieved December 16, 2021, from https://www.icheme.org/media/16259/good-practice-in-virtual-hazop.pdf

ISHPMIE (International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions). (2021). Last retrieved December 16, 2021, from https://ishpmie2022.ptb.de/home

Klein, J.A. and Vaughen, B.K. (2017). *Process Safety: Key Concepts and Practical Applications.* CRC Press/Taylor & Francis, Boca Raton, FL.

Kletz, T.A. and Amyotte, P.R. (2010). *Process plants: A Handbook for Inherently Safer Design (2nd ed.)*. CRC Press/Taylor & Francis, Boca Raton, FL.

Kletz, T.A. and Amyotte, P.R. (2019). *What Went Wrong? Case Histories of Process Plant Disasters and How They Could Have Been Avoided (6th ed.).* Elsevier, Oxford, UK.

Maher, S.T., Norton, K.D., Surmeli, S. (2012). Design an inherently safer plant. *Chemical Engineering Progress.* January 2012.

Melin, S. (2012). Explosive Dust in Pellet Manufacturing Plants, Wood Pellet Association of Canada. Last retrieved October 13, 2021 from https://rib.msb.se/filer/pdf/26321.pdf

Moore, D.A., 2003. The regulation of inherent safety. In *Proceedings of Hazards 17*, *IChemE (March 25-27 2003),* pp. 517–522.

Murphy, M. and Hatch, D. (2020). Visual Dust Hazard Analysis – Understanding Threats and Assuring Controls. In *American Institute of Chemical Engineers 2020 Spring Meeting and 16th Global Congress on Process Safety.* March 30 – April 1, 2020. Houston, TX.

NFPA 68 (2018). Standard on Explosion Protection by Deflagration Venting. NFPA (National Fire Protection Association), Quincy, MA.

NFPA 77 (2019) Recommended Practice on Static Electricity. NFPA (National Fire Protection Association), Quincy, MA.

NFPA 652 (2019) Standard on the Fundamentals of Combustible Dust. NFPA (National Fire Protection Association), Quincy, MA.

NFPA 91 (2020). Standard for Exhaust Systems for Air Conveying of Vapors, Gases, Mists, and Particulate Solids. NFPA (National Fire Protection Association), Quincy, MA.

Pacific Bioenergy (2021). Wood Pellet Fuel Basics. Retrieved June 21, 2021, from https://www.pacificbioenergy.ca/our-products/

Perry, J. A., Ozog, H., Murphy, M. and Stickles, R. P. (2009), "Conducting Process Hazard Analyses for Dust-Handling Operations", *Chemical Engineering Progress*, 105, 28-35.

Pons, D. (2016). Pike River Mine Disaster: Systems-Engineering and Organisational Contributions. *Safety.* 2, 21-46.

Process Heating. (2016). Strategies to Manage the Risk of Fire and Explosions Inside Drying Equipment. Retrieved September 19, 2021 from https://www.process-heating.com/articles/91471-strategies-to-manage-the-risk-of-fire-and-explosions-inside-drying-equipment

Rayner Brown, K. (2020). *Inherently Safer Design Protocol for Process Hazard Analysis.* Master's thesis, Dalhousie University. Dalspace. http://hdl.handle.net/10222/78489

Rayner Brown, K., Amyotte, P.R., Khan, F.I., Hastie, M. (2020). Inherently Safer Design Protocol for Process Hazard Analysis. *Process Safety and Environmental Protection.* 149, 199-211.

US EPA (United States Environmental Protection Agency). (1998). Emissions Factor – Wood Products Industry - Medium Density Fiberboard Manufacturing.

Retrieved June 21, 2021, from https://www3.epa.gov/ttn/chief/old/ap42/ch10/s063/final/c10s0603_sep1998.pdf

Vaughen, B.K. and Bloch, K. (2016). Use the bow tie diagram to help reduce process safety risks. *Chemical Engineering Progress*. 112, 30–36.

Wood Pellet Association of Canada (WPAC) (2021a). Deflagration Isolation. Last retrieved December 16, 2021, from https://www.pellet.org/isolation-deflagration/

Wood Pellet Association of Canada (WPAC) (2021b). WPAC Safety Foundation Webinar Series. Last retrieved December 16, 2021, from https://www.pellet.org/webinars/wpac-safety-foundation-webinar-series/

Wood Pellet Association of Canada (WPAC) (2021c). Critical Control Management. Last retrieved December 16, 2021, from https://www.pellet.org/critical-control-management/

Wood Pellet Association of Canada (WPAC) (2021d). Belt Dryer Safety. Last retrieved December 16, 2021, from https://www.pellet.org/belt-dryer-safety/

WorkSafeBC. (2012a). Incident Investigation Report - Explosion and fire at sawmill in Burns Lake. Last retrieved January 26, 2022 from https://www.worksafebc.com/en/resources/health-safety/incident-investigation-report-summaries/explosion-and-fire-at-sawmill-in-burns-lake?lang=en

WorkSafeBC. (2012b). Incident Investigation Report - Explosion and fire at sawmill in Prince George. Last retrieved January 26, 2022 from https://www.worksafebc.com/en/resources/health-safety/incident-investigation-report-summaries/explosion-and-fire-at-sawmill-in-prince-george?lang=en

Yuan, Z., Khakzad, N., Khan, F., Amyotte, P., Reniers, G. (2013) Risk-based design of safety measures to prevent and mitigate dust explosion hazards. *Industrial and Engineering Chemistry Research.* 2013, 52, 50, 18095–18108.

APPENDIX A ISOLATION PROJECT EXECUTIVE SUMMARY

This appendix contains the Executive Summary of the report titled “Analysis of Deflagration Isolation in Wood Pellet Production for Safer Operation” funded by Dalhousie University and completed in collaboration with Wood Pellet Association of Canada (WPAC) and BC Forest Safety Council (BCFSC). The full research report is available online at https://www.pellet.org/isolation-deflagration/ (WPAC, 2021a). This Executive Summary was included as an appendix in this report to highlight the additional work that was undertaken to analyze explosion isolation, which is an important barrier that was frequently encountered in this current report.

There have been incidents involving the propagation of combustible wood dust deflagrations in wood pellet plants. Due to these similar incidents, WorkSafeBC has identified enhancing the understanding of deflagration isolation as an area for improvement. Deflagration isolation, as described by NFPA 69 (2019), prevents the propagation of flame and deflagration pressure to interconnected equipment.

The objective of this report (“Analysis of Deflagration Isolation in Wood Pellet Production for Safer Operation) is to serve as an easily digestible resource and reference for wood pellet producers that:

- Provides information on the different types of deflagration isolation systems that are available,
- Provides information on the installation, operation, and maintenance of these systems to improve understanding,

- Summarizes failure modes and degradation factors associated with these systems,
- Provides considerations for how these failure modes and degradation factors can be managed to make systems more reliable and effective.

This project involved extensive input from subject matter experts involved in the wood pellet industry, including wood pellet operations, process safety consulting, research and development, risk management and explosion protection equipment suppliers. Relevant information was collected from NFPA (National Fire Protection Association) standards. NFPA 69 (2019) is referenced in this report, as this standard encompasses the design, installation, maintenance and testing of systems for the prevention of explosions. Additional research was completed using archival literature, as well as bow tie analyses conducted as part of the WorkSafeBC Innovation at Work project (*Inherently Safer Bow Ties for Dust Hazard Analysis*).

This report describes the most common deflagration isolation techniques for wood pellet plants, which are chemical isolation, passive flap valves, fast-acting mechanical valves, and rotary valves. Inherently safer design (ISD) considerations for deflagration isolation are also discussed, including unit segregation for the avoidance of domino effects (moderation) and material chokes (moderation).

The different locations in a wood pellet plant that commonly require deflagration isolation are also discussed with respect to why isolation is needed and what isolation technique is most applicable. The equipment discussed are hammer mills, dust collectors, bucket elevators, drag chain conveyors and cyclones, which commonly need isolation due to the propensity of ignition sources and levels of suspended dust.

The different ways the deflagration isolation techniques can be degraded, or fail, are also identified. These failure modes and degradation factors associated with different deflagration isolation techniques include devices not actuating due to being locked out for maintenance, challenges associated with mechanical expansion and contraction, and process material adhering to device components. The approaches for managing these challenges (degradation factor controls) are also identified, which include important points such as inspections as per NFPA 69 (2019) and preventative maintenance as per manufacturer specifications.

A four-step guide for implementing deflagration isolation in a facility is described, which consists of the following:

1. Conduct a DHA (Dust Hazard Analysis)
2. Work with Equipment Suppliers on Recommended Deflagration Isolation Points
3. Install Deflagration Isolation Equipment
4. Maintain Deflagration Isolation Equipment

This report provides an extensive overview of dust hazard analysis (DHA), as performing a DHA is a critical step in managing combustible dust hazards. A DHA ensures that a facility’s hazards associated with combustible dust can be properly identified and managed. In Canada, an Authority Having Jurisdiction (AHJ) can request a DHA to be conducted.

Lastly, several challenges in the area of combustible dust hazards are discussed with recommendations on moving forward:

- Emphasizing the importance of a dust mitigation program,
- Enhancing combustible dust hazard awareness,
- Addressing issues and opportunities around explosion isolation - other recommended activities for facilities to consider, and
- Enhancing process safety management (PSM) and element of process safety culture.

It is recommended that pellet plant operations use this report to support activities around deflagration isolation, including enhancing training and awareness, as well as addressing any areas for improvement in programs and practices.