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INTRODUCTION

1.1 PURPOSE

The purpose of this concept book is to establish a set of practical advice on how to conduct bow tie analysis and develop useful bow tie diagrams for risk management. It describes the intended audience, gives directions on how to use the concept book and provides a basic introduction to the method, which is expanded in the following chapters. It explains the rationale for developing bow tie diagrams and how they fit into an overall risk management framework.

CCPS concept books address newer techniques in process safety that have not yet become accepted standard practice or where there is not yet industry consensus on approach. In EI publications, concept books are termed Research Reports in its series of technical publications. Concept books introduce these valuable tools in a simple and straightforward manner. CCPS and EI encourage the use of this concept book to aid the industry in developing better quality bow tie diagrams with a consistent methodology and preferred terminology for their use. Implementation of the methodology outlined in this CCPS / EI book should improve the quality of bow tie analysis and bow tie diagrams across an organization and industry.

1.2 SCOPE AND INTENDED AUDIENCE

This concept book provides practical advice on how to develop bow tie diagrams and in their use. This will help to:

- ensure consistent use of methodology and terminology;
- establish a valid approach to defining hazards, top events, threats, and consequences;
- establish criteria for barriers and degradation controls linked to degradation factors;
- identify common errors which may occur when constructing bow ties;
- provide a method to incorporate human and organizational factor issues in bow ties;
- provide guidance on how bow ties can be used for risk management purposes through the effective depiction of barriers;
- discuss basic and advanced uses of bow tie diagrams; and
- review an overall strategy for barrier management.

The intended audience for this book is primarily anyone involved with or responsible for managing process safety risks, although the concepts within the book are applicable to all bow tie risk management practices and not limited to process safety (e.g., for other safety and environmental applications and Enterprise Risk Management). It is designed for a wide audience, from beginners with little to no background in barrier management, to experienced professionals who may already be familiar with bow ties, their elements, the methodology, and their relation to risk management.

The origin of bow ties and their main use to date has been in managing process safety risks particularly relating to major accidents. They have been applied in the chemical / petrochemical and oil and gas industries as well as other industries (such as maritime, aviation, rail, mining, nuclear, and healthcare). However, the logic and approach described here may also be used to manage strategic risks, financial risks, risks of losing critical sales, etc. As these applications are less common, the examples in this book are focused on safety risks but also include human health, environmental impact, asset damage, and reputation loss.

Several software tools are available to aid in the development of the diagrams. The level of detail displayed using software tools can be complete or partial depending on the audience needs. This book does not endorse any particular software tool; however, Appendix A provides a summary of several widely available software tools known to the authors at the time of publishing.

1.3 ORGANIZATION OF THIS CONCEPT BOOK

This book is organized in a way that follows the logical flow of constructing bow ties and then conducting bow tie barrier analysis. Several examples are used to demonstrate this advice; however, these often only cover parts of a bow tie under discussion. More detailed, complete examples are found in Appendices B and C. The examples relate to the topics in each chapter and provide a story line concerning the development and use of bow ties. A summary of the content of each chapter is provided below.

Chapter 1 – Introduction

- Purpose and scope;
- Introduction to the bow tie concept;
- Linkage between bow ties, fault trees, and event trees.

Chapter 2 – The Bow Tie Model

- Define terminology and elements of the bow tie diagram;
- Illustrate robust and weak examples of bow tie elements;
- Define and discuss the types of barriers, including criteria for validity and quality.

Chapter 3 – Bow Tie Development

- Discuss the process of bow tie development including their initial development in team workshops;
- Discuss common errors and quality checks during development of bow tie diagrams.

Chapter 4 – Addressing Human Factors in Bow Tie Analysis

- Discuss how to include human and organizational factors in bow tie diagrams;
- Show how human factors can be addressed using a basic approach, but also introduce the concept of a multi-level bow tie which provides an extended analysis with greater utility, albeit with some complexity;
- Discuss metrics for human and organizational factors.

Chapter 5 – Basic Use of Bow Ties

- Discuss common uses of bow tie tools in analyzing barriers and identifying safety critical elements and tasks.

Chapter 6 – Management of Bow Ties

- Discuss use of bow ties as part of a barrier management strategy utilizing a lifecycle approach;
- Discuss links between bow ties and management system elements (e.g., Management of Change, maintenance, training, audits).

Chapter 7 – Additional Uses of Bow Ties

- Discuss the application of bow ties as a communication tool and to help demonstrate ALARP;
- Illustrate how bow ties are used to aid in decision making for various activities in an organization and for risk management;
- Show how real-time bow ties can interface with an organization’s management system.

Appendices

- Appendix A – Software Tools; provides a table listing various software tools available to develop bow ties and their capabilities;
- Appendix B – Case Study for a pipeline; provides an example of a full bow tie with an emphasis on technical threats;
- Appendix C – Case Study for Multi-Level Bow Ties; provides an example bow tie incorporating human and organizational factors and demonstrating the concept of multi-level bow ties.

1.4 INTRODUCTION TO THE BOW TIE CONCEPT

The oil and gas industry has achieved a very impressive improvement in occupational safety. The fatality rate within the IOGP member companies has declined by an order of magnitude over the past 20 years, Figure 1-1 (IOGP, 2015).

However, the reduction in major process accidents has been less impressive than for occupational safety (Pitblado, 2011) and insured losses due to major accidents in the oil and gas and process industries have not reduced in the last 30 years (Marsh, 2016). Current risk approaches have tended to focus more on demonstrating design safety and less on maintaining operational safety.

The development and appropriate use of bow tie barrier diagrams have the potential to significantly improve process safety. They do this by focusing on the operational aspects, clearly highlighting all important safety barriers, helping in the assessment of barrier adequacy, communicating this visually to all staff and contractors, and providing a framework to continually monitor the effectiveness of these barriers. Bow ties can also be used in the design phase to test the adequacy and relevance of barriers and if additional barriers and degradation controls are required.

Once constructed, the bow tie purpose is best used to support risk management and risk communication. The bow tie diagram can provide a clear graphical representation of the output of the risk assessment and management process (threats, consequences, barriers and degradation controls) which is readily understood by people at all levels – from operational personnel and senior managers, to regulators, and to members of the public. The bow tie illustrates both the prevention barriers, which stop the top event from occurring, and the mitigation barriers, which reduce the consequence severity should the top event occur. For the full unmitigated consequence (i.e., major accident event), all of the barriers along the relevant pathway between the threat and the consequence must

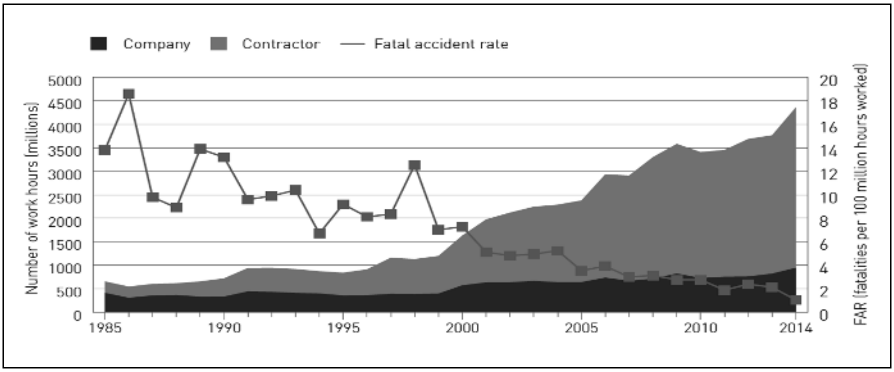

Figure 1-1. Fatal Accident Rate vs Total Hours Worked (Global Data)

fail or be degraded. Other factors not related to barriers may also contribute to the magnitude of the consequence (release orientation, wind direction, etc.).

Major accidents rarely result from a single failure, but rather from multiple barrier failures, which collectively result in a loss of control situation that further escalates to significant consequences. Common mode failures can be relevant in multiple barrier failures (e.g., underfunding or delayed maintenance can affect many barriers simultaneously). The bow tie approach helps the operational and maintenance teams to focus on barriers and the degradation controls which are relied upon to maintain their effectiveness. The effective management of all barriers is a key aspect of risk-based process safety management (CCPS, 2007).

1.4.1 Reason's Swiss Cheese, Models of Accident Causation and Bow Ties

James Reason (1990 and 1997) developed the idea of the 'Swiss Cheese Model' of system failure presented in Figure 1-2. The model builds on the principles of 'defense in depth,' with slices of Swiss cheese representing protective layers (i.e., barriers) preventing hazards from being realized and allowing consequences to happen. Reason observes that barriers are never 100% effective and each has unintended intermittent weaknesses. The holes in the cheese slices represent degradation factors (i.e., reductions in effectiveness or reliability) in individual parts of the system and are continually varying in size and position in all slices. For a major accident to occur, holes in the Swiss cheese need to align allowing for an 'accident trajectory' so that a threat passes through all of the holes in all of the defenses (i.e., barriers) leading to a failure or major accident. It also shows that if one barrier fails, then subsequent barriers are challenged. Using this model, a risk management strategy is successful when barriers are managed to ensure that they perform as intended at all times throughout the life cycle of the facility. When compared to the Swiss cheese model, bow ties add structure and give a better representation of the barriers associated specifically with multiple threat and consequence legs.

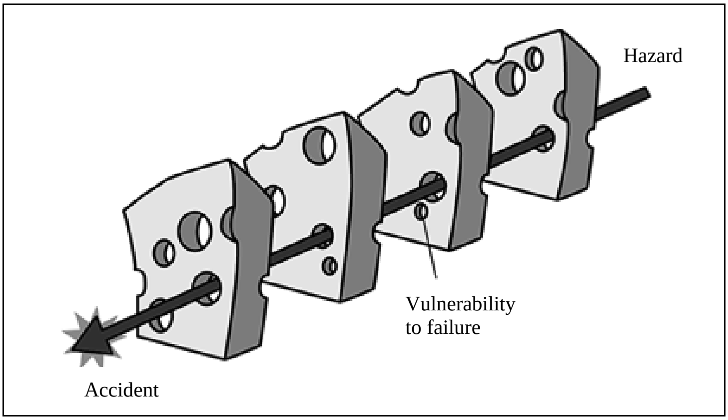

Figure 1-2. Swiss Cheese Model (James Reason)

Assumptions are frequently made, based on the visual structure of the representation, that bow ties assume a linear, event-driven model of technical systems and how they fail, i.e. a linear model of accident causation. It has been argued for some time that this type of model is inadequate as a means of understanding the dynamics of modern complex socio-technical systems or the ways they can lead to loss (Leveson, 2011; Hollnagel, 2012), particularly where there is both tight coupling and complex interaction between system elements (Perrow, 1999). However, adopting the concepts and structures of bow tie analysis need make no assumptions about the mechanisms and processes that lead to incidents (McLeod and Bowie, 2018). Reason's Swiss Cheese model appears linear in the time sequence in which barriers operate; development of the holes - i.e. the mechanisms of causation - can however proceed through either linear or non-linear processes (Hudson, 2014). Similarly, bow tie analysis, and the understanding of barriers, failure mechanisms and controls that it can generate, is neutral in terms of any underlying model of accident causation.

The bow ties and the model presented here of barriers and barrier degradation and control do not assume any particular mechanisms that might lie on the path between threats and the top events and consequences they can lead to. There is no reason why a bow tie model should not be based on non-linear analyses such as HAZOP (CCPS, 2008a), STAMP (Leveson, 2011) or FRAM (Hollnagel, 2012). In essence, rather than asking what could go wrong, and how to prevent it, the focus of bow tie analysis is on what needs to go right, and how to assure it (McLeod and Bowie 2018).

1.4.2 History and Regulatory Context of Bow Ties

It is generally accepted that the earliest mention of the bow tie methodology appeared in the ICI (Imperial Chemical Industries) course notes of a lecture on hazard analysis given at The University of Queensland, Australia in 1979, but how and when the method found its exact origin is not completely clear. Shell is acknowledged as the first major company to fully integrate the bow tie methodology into its business practices, and by the end of the 1990s, the approach became a common method within many other companies.

A large EU research project, called ARAMIS, investigated the use of bow tie risk assessment methodology in the framework of the Seveso II Directive. This project is described in a special issue of the Journal of Hazardous Materials (Salvi & Debray, 2006), which covers several aspects of bow ties, including their use and success for communication and as a means for organizational learning.

Regulatory regimes and standards are increasingly embracing the barrier concept as a means to assist in the management of risks during the operational phase and to communicate this effectively. In the process and oil and gas industries, the following list provides examples of the current major regulatory and industry bodies and how they are adopting a barrier-based approach:

- The American Petroleum Institute (API) – Recommended Practices 96, 65-2 and 90 are based on a barrier approach for offshore operations;
- UK Health and Safety Executive – guidance on safety management of major hazard industries (UK HSE, 2013a) recognizes bow ties as a tool or model for the barrier based approach. Following guidance from the UK, COMAH Competent Authority (SEPA, 2016a) has been extended to support assessment of environmental major accidents. As a consequence of this, many COMAH sites in the UK have included bow ties in their safety reports;
- The European Commission, under the 'Safety of Offshore Oil and Gas Operations Directive' – has put in place a set of rules to help prevent accidents as well as respond effectively, which requires a risk assessment and the identification of barriers;
- International Association of Drilling Contractors (IADC) – has developed a new WellSharp program, which includes a barrier-based approach to redefine well control training and assessment;
- The National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA), Australia – under Guidance Notes, N04300-GN0271, states that a barrier based layer of protection analysis may be required to prevent or mitigate hazards;
- The International Association of Oil & Gas Producers (IOGP), Reports 456 and 544 – recognizes the importance of barrier management and discusses methods for maintaining and keeping barriers up to date; and
- The Petroleum Safety Authority (PSA), Norway, 'Principles for Barrier Management in the Petroleum Industry' guidance document – focuses on barriers, barrier performance and barrier management as a means to reduce risk of accidents. PSA conducts audits based on barrier management.

1.4.3 What Bow Ties Address

Bow ties are a useful tool to assist analysis of process and non-process industry risks. The general focus of bow ties in the process industry is towards Major Accident Events (MAEs – see Glossary for definition) as staff need to understand how these may occur and the barriers and degradation controls deployed to prevent them. While this implies large scale events with serious consequences, some companies choose to develop bow ties for less serious events, including occupational safety events such as 'fall from height'. This can be beneficial for risk management as it uses a common format; however, every bow tie requires some significant effort to create and ongoing efforts to communicate and remain current. Companies limiting bow tie applications to MAEs can reduce the total effort by using simpler methods for less serious events. Therefore, whether to limit bow ties to MAEs is a choice companies can make. Early applications were for large refinery, petrochemical or offshore facilities, but they also have important uses in small- and medium-size enterprises. They can also be applied to other industrial processes such as chemicals handling, transportation, storage facilities, and medical applications. Bow ties can support a structured approach to risk assessment for facilities that do not have P&IDs and so hamper conventional PHA (HAZOP) studies (e.g., mining, steel and other metal working industries). The emphasis is also different. HAZOP is used to identify hitherto unknown failure scenarios in complex systems, while bow ties demonstrate the barriers deployed for these scenarios. Bow ties also document how these barriers may fail and the processes and systems in place to prevent this from happening.

1.4.4 Key Elements of a Bow Tie

The bow tie diagram is shown in Figure 1-3 with the following elements:

1. **Hazard:** the bow tie starts with the hazard.
2. **Top Event:** the loss of control of the hazard.
3. **Threats** are depicted on the left side (customarily the prevention side) of the bow tie diagram.
4. **Consequences** of loss of control of the hazard are depicted on the right side (customarily the mitigation side) of the bow tie diagram.
5. **Prevention Barriers** on the left side of the diagram represent prevention barriers, which stop threats from resulting in the top event.
6. **Mitigation Barriers** shown to the right of the top event represent mitigation barriers, which mitigate the top event (i.e., reduce the scale of and possibly stop undesired consequences).
7. **Degradation Factors** can be applied to both prevention and mitigation barriers and these can lead to impairment or failure of the barrier to which they are attached.
8. **Degradation Controls** act to mitigate the Degradation factors, helping maintain the main pathway barrier at its intended function. Degradation controls can, but do not necessarily satisfy, the effective, independent, and auditable criteria for barriers.

Barriers and degradation controls are illustrated to show these as fundamental elements of the safety management system. Altogether, the diagram provides a holistic picture of the risk management system. The elements of the bow tie model are further discussed in Chapter 2.

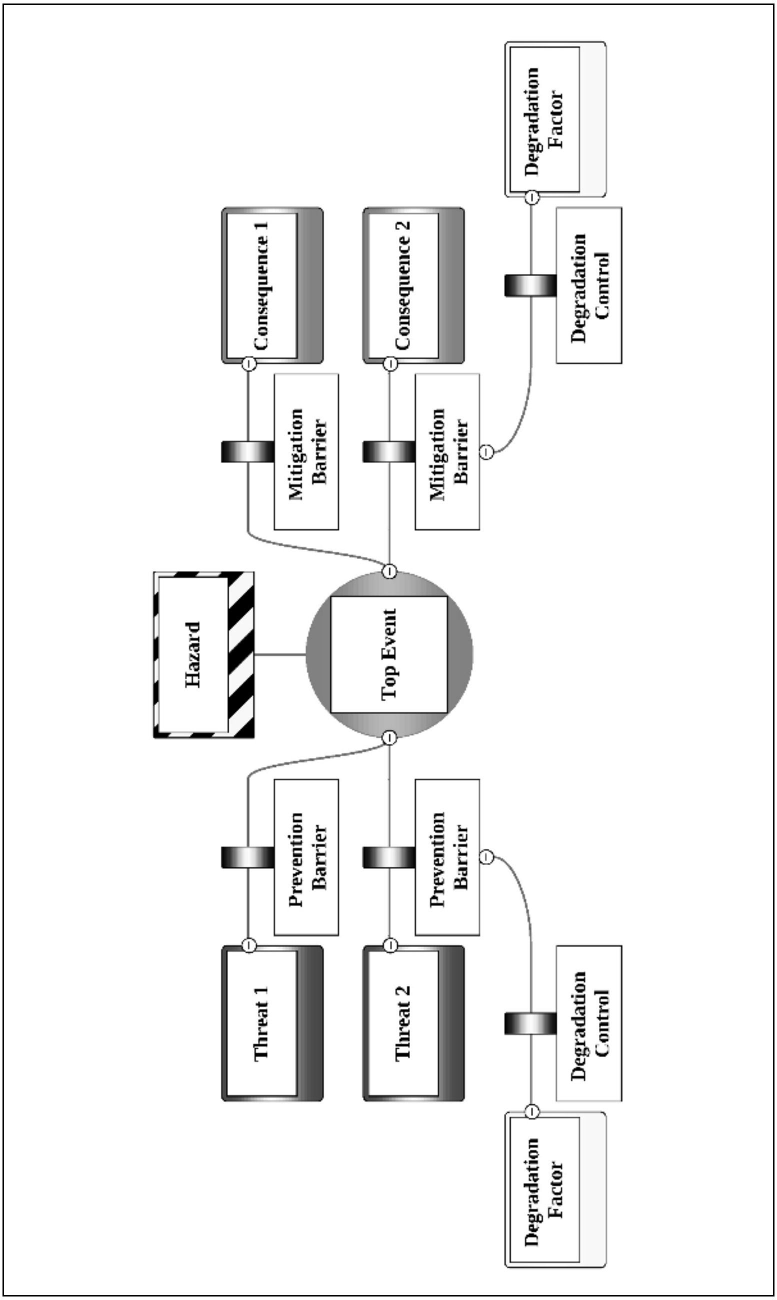

Figure 1-3. Bow Tie Model

1.4.5 Benefits of Bow Ties

Effective risk management requires a thorough understanding of all important incident pathways and implementation of applicable and reliable safety barriers that are in place to prevent and mitigate the risks. Well-drawn bow tie diagrams are visually obvious to a wide range of possible users, unlike numerical and complex results from other risk assessment methods such as QRA, LOPA, FTA and ETA which have different objectives and are more useful for specialists. For non-experts, the workforce, engineers and managers, bow ties provide a readily understandable and simple visualization of the relationships between the causes of events that lead to loss of control of the hazard, the potential consequences resulting from such events, the barriers preventing the event from occurring, and then the mitigation measures in place to limit its consequence. Most commonly, they are used when there is a need to demonstrate how hazards are controlled and to illustrate the direct link between risk controls and elements of the management system.

In order to develop a bow tie, it is necessary to first identify those hazards requiring such analysis. Most companies involved in hazardous activities have an existing process safety management system containing formal procedures and/or guidance for identification of potential hazards and assessment of risks. Bow tie analysis is not a methodology for identification of hazards; for this refer to 'Guidelines for Hazard Evaluation Procedures, 3rd Edition' for guidance (CCPS, 2008a). However, once hazards have been identified, the bow tie method can be applied to graphically demonstrate the management of the hazard and provide a framework for demonstrating effective control.

Bow tie analysis overlaps with LOPA in that they both examine barriers on pathways for major accidents. This is discussed more fully in Chapter 7.

To summarize, the main reasons to create and implement bow tie diagrams are to:

- provide a systematic analysis of the barriers along threat and consequence pathways that can prevent or mitigate a Major Accident Event. This can support the design process, or the operational or maintenance activities to raise awareness and understanding of the barriers in place and the role of individuals in operating or maintaining barriers;
- provide a cumulative picture of risk through the visualization of the number and types of barriers and degradation controls and their condition. This can support the identification and prioritization of actions to strengthen degraded barriers and degradation controls; and
- provide a structured process where identified hazards, threats and consequences can be related in cause and effect scenarios, and to assist in the development and understanding of how unwanted events can occur.

More advanced uses of bow ties for operational safety, integrating human factors, barrier management, incident investigation, and supporting dashboards are provided in Chapters 4 to 7.

Bow ties can demonstrate the link between controls and the management system, specifically those relevant to the management of risks (e.g., safety critical elements, critical roles / tasks / activities). Once all the barriers and degradation controls are identified, then an ongoing management program is required to ensure that the barriers are maintained at their specified effectiveness and that degradation controls are as robust as they reasonably can be. The bow tie diagram helps to ensure that this happens by clearly indicating the barriers in place, and the degradation controls associated with maintaining those barriers. The identification of safety critical elements and systems can then support the establishment of performance standards. These concepts are developed in Chapter 2.

Bow ties help with accountability by documenting barrier owners who can track the condition of their barriers and how often any are involved in incidents. Bow ties can identify critical tasks and hence link these to competency requirements for procedures and administrative controls, and to required training and development for employees. They can also be used to enhance incident investigations to identify patterns of barrier failures, and to assist organizational learning.

There are different depths of treatment that are possible with bow ties. Some companies focus on the communications aspects only, while others attempt to develop real-time monitoring of barrier conditions using bow ties as the basis. Organizations need to consciously determine their strategy for incorporating bow ties into their process safety management system and to keep this up to date.

There can be drawbacks with the bow tie approach and this is acknowledged. If bow ties are poorly drawn showing too many non-applicable barriers, this can give users a false sense of security. This can be because degradation factors are shown as barriers or there may be dependencies between barriers that suffer from a common cause fault. Such barrier diagrams also make the communication task more difficult. It is also possible that PHA scenarios may not be accurately transposed into the bow tie diagram and important scenarios are omitted. Suggestions later in this book assist those creating bow tie diagrams from making these types of errors.

Bow ties have multiple functions in the realm of risk management, much more than simply communication of risk, although this is a key use. They address major accident risks during the operational phase in a format that is useful for operational and maintenance personnel. Bow ties can also be used in the design phase, although use in the operational phase dominates as many important operational barriers are not defined until that stage. Basic uses of bow ties are discussed more fully in Chapter 5, while additional uses appear in Chapter 7.

1.4.6 Linkage between Bow Ties, Fault Trees, and Event Trees

The bow tie methodology is sometimes described as a combination of two existing risk analysis tools, Fault Tree Analysis and Event Tree Analysis. These techniques are presented with examples in Guidelines for Chemical Process Quantitative Risk Assessment (CCPS, 2000). Optically rotating an FTA clockwise (as these are usually drawn vertically) and connecting it to an ETA (usually drawn horizontally) creates a bow tie connected at the top event, but there are significant differences. FTA and ETA can be quantitative, while bow ties are qualitative and focus on creating a visually simple representation of hazards, threats, top events, barriers, degradation factors and controls, and consequences.

A FTA describes an incident (top event) in terms of the combinations of underlying failures that can cause them and connecting these with AND or OR gates, while bow tie analysis places no visible Boolean logic between barriers. However, a bow tie 'barrier' would be represented in a Fault Tree as a 'demand on barrier' AND 'barrier fails', so the bow tie can include Boolean logic but it is usually hidden as it is unnecessary for the user. Different threats in bow ties are in effect OR gates directing into the top event (i.e., the top event may be caused by threat 1 OR threat 2 OR threat 3, etc.). In FTA the top event can be either the loss of control or loss of containment as is the case in a bow tie, or it can go further towards the undesired consequence. Some of the rule set for FTA also applies to bow ties. This includes the requirements for independence.

ETA requires identification of safety functions or barriers. It also considers hazard promoting factors excluded from bow ties, such as wind direction, early or late ignition, etc. ETAs have branches with 'barrier fails' and 'barrier succeeds' as the two distinct outcomes. In an ETA, 'barrier success' terminates the event; that arm is discarded or the branch determines a different outcome, for example, immediate ignition 'flash fire' or delayed ignition 'explosion'. The bow tie does not display arms that terminate, only arms that continue on to a consequence.

Since FTA and ETA may be quantitative and since the bow tie represents these visually, it may be possible in the future that researchers may be able to extend bow tie analysis to quantitative applications, but that is not addressed in this concept book. Some bow tie software tools do permit quantitative LOPA analysis using a bow tie as a starting point.

1.5 CONCLUSIONS

The bow tie methodology has been in use for over 20 years, and its focus has been towards the management of major accidents in multiple industries. It builds on the Swiss cheese model of accident causation and illustrates diagrammatically how threats can act on hazards to generate a loss of control, which may result in undesired consequences. In the bow tie diagram, prevention barriers are located on the left side and mitigation barriers are located on the right side. A well-drawn bow tie clearly shows all barriers that can prevent the top event from occurring or mitigate the consequences (see Appendix B for an example bow tie). Additional information can be incorporated in the bow tie to show degradation factors acting on barriers and the degradation controls that are implemented to maintain barriers at their intended functionality. Other information such as barrier effectiveness, type, ownership, and status can also be displayed.

A bow tie diagram is a powerful tool for communicating how the control of major accident hazards is achieved. It is focused on the operational phase although it has design applications as well, and since it is diagrammatic and non-quantitative, it can be used more easily for risk communication than quantitative risk tools.

Ongoing process safety management requires that all barriers perform at their expected level of effectiveness throughout a facility lifetime and that the degradation controls that are relied on to support barriers are actually in place. A bow tie diagram can be used to help monitor and provide prioritization to maintain the integrity of all barriers and degradation controls. The diagrams then become an integral part of the facility process safety management program.