2. Literature Review

To introduce the results of the literature review, subchapter 2.1 will review the importance of evaluating barrier effectiveness in the framework of outlining the consequences of not doing so. Following this, subchapter 2.2 will review the existing definitions for understanding barrier effectivenes in other industries, and will include discussion as to where in onshore drilling operations would barriers be considered for application. The last subsection of this chapier is 2.3, and this section will end the literature rveiew chapter with a review of existing techniques which are commonly used for barrier consideration in risk management scenarios.

Research of existing literature

The research conducted for this paper was done from the expertise and perspective of a safety professional in the oil and gas industry, as well as from a doctoral perspective as a student in safety studies. The exposure gained as a professional and student exposed to hazard mitigation revealed a clear gap in the most heavily utilized barrier evaluation techniques. Research on available barrier techniques was conducted via searching for the historical material available on barrier types and applications as pertaining to the oil and gas industry, or industries similar in hazard mitigation approach such as the chemical arena.

Specific databases were relied upon for finding credible reference. Contexts were most heavily weighted for works published after 2010, works published specifically for upstream oil and gas activity, and works that resounded a problem / solution framework. For the referenced databases, specific keywords were used to generate relevant results. The majority of such keywords are as follows:

i. Process safety and major accident hazard
ii. Barrier performance parameters
iii. Barrier failure and risk impact

iv. Barrier based framework (qualitative and quantitative)
v. Scope of risk assessments
vi. Drilling and H_2S related risk assessments / related paper on H_2S hazards - barrier related approaches
vii. Dynamic risk assessment models

As previously noted, maintaining the integrity of barriers is a major key component in accident prevention. To maintain a barrier is to maintain its' optimal level of effectiveness. Understanding a barriers' effectiveness is essential in contextualizing how it should perform and what outcome it is expected to generate or prevent. The next section will explore the notion of clearly understanding barrier effectiveness before it is chosen for an application.

2.1 Significance of Evaluating Barrier Effectiveness

Progressing from understanding the role safety barriers are expected to play in preventing and minimizing risk and loss, it is time now to consider the importance of evaluating barrier effectiveness for an application before it is chosen. As a matter of course, barriers are regularly used as a form of preventative and reactive protection from hazards in the oil industry. Despite barrier application, catastrophic events continue to occur which are often deemed to be preventable upon post-analysis. Many of such incidents may have been simply prevented if a different barrier had been deployed as opposed to the barrier chosen. Such a critical mistake leads to great consequence. To demonstrate the magnitude of choosing an inadequate barrier, the following will review an abbreviated history of incidents resulting in loss as a consequence of ineffective barriers.

Review of major process safety incidents – cause and impact perspective

First, this review of incidents will focus on the hydrocarbon industry as a whole. In the last 30 years, Marsh (2011) has consolidated a list of top 20 losses for the hydrocarbon industry based on the industry segment and the asset loss value which is compiled below. This view will be inclusive of upstream, refinery, gas processing, and petrochemical industry segments.

Table 2.1: 20 largest losses -1972 – 2011 (Source: Marsh, 2011)

Year	**Plant Type**	**Event Type**	**Location**	**Property Loss (USD Million)**
1988	Upstream	Fire/ Explosion	Piper Alpha, North Sea, UK	1800
1989	Petrochem	Vapor cloud explosion	Pasadena, Texas, USA	1400
2009	Upstream	Collision	Ekofisk, North Sea, Norway	830
1989	Upstream	Fire/ Explosion	Baker, Gulf of Mexico, USA	820
1991	Upstream	Structural Failure	Sleipner, North Sea	780
2001	Upstream	Explosion/ Fir/Sinking	Campos Basin, Brasil	770
1998	Gas Processing	Explosion	Longford, Victora, Australia	740
1988	Upstream	Fire	Campos Basin, Brasil	690
2001	Petrochem	Explosion	Toulouse, France	670
1988	Petrochem	Explosion	Henderson, Nevada, USA	630
2004	Gas Processing	Fire/ Explosion	Skikda, Algeria	630
1988	Refinery	Vapor cloud explosion	Norco, Louisiana	600
2011	Refinery	Fire/ Explosion	Fort McKay, Alberta	600

2000	Refinery	Fire/ Explosion	Mina Al-Ahmadi, Kuwait	590
2010	Upstream	Fire/Explosion/Blowout	Gulf of Mexico, USA	590
2008	Refinery	Hurricane	Texas, USA	540
1992	Upstream	Mechanical Damage	North west Shelf, Australia	520
1987	Petrochem	Vapor cloud explosion	Pampa, Texas, USA	470
2005	Upstream	Fire/ Explosion	Mumbai High field, India	470
1997	Gas Processing	Fire/ Explosion	Bintulu, Sarawak, Malaysia	460
			Total	**14600**

Based on the above data, losses have been grouped based on the plant type to understand the percentage contribution in Figure 2.1.

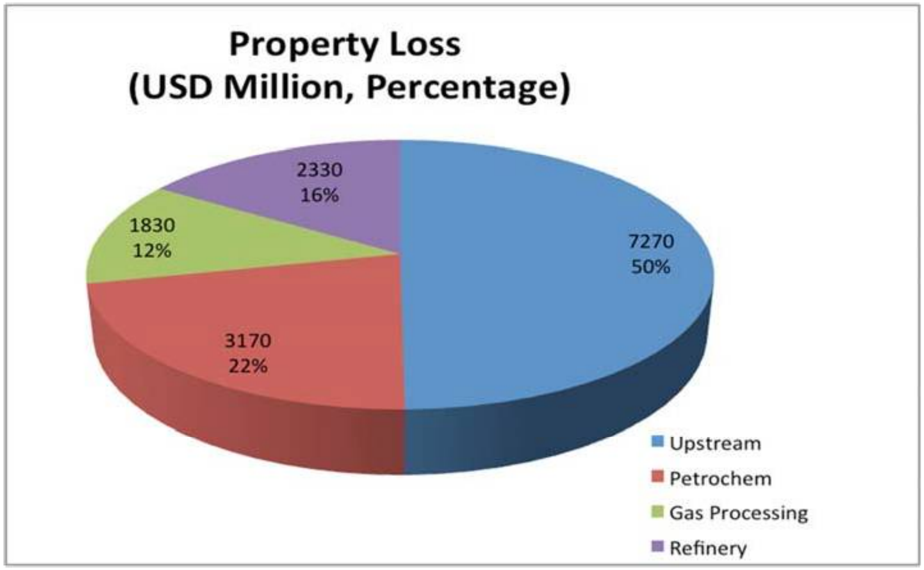


Figure 2.1:Sector wide property loss

Based on the data shown in Figure 2., half of the incidents have occurred in the upstream industry. It can also be inferred that the cumulative losses of the upstream incidents are close USD 7.3 billion. Kletz (2001) has reviewed some of the major process safety incidents to identify causal factors and the impact of them on the society, shown in Table 2.2.

Table 2.2: Review of major incidents – cause and impact analysis

Lessons learned from Flixborough Vapor Cloud Explosion (Leak of cyclohexane from one of the ignited reactors resulted in a VCE)	**Causes:**
	1. Handling excess inventory than required
	2. Poor management of change procedure during installation of temporary pipe
	3. Temporary pipe was in use for 3 months
	4. Poor control room design
	Impact: 28 fatalities, USD 750 million
Lessons learned from Seveso release (Leak of toxins)	**Causes:**
	1. HAZOP did not consider service lines
	2.Failure to fit catch pot after relief devices (Similar release had occurred in 2 other plants)
	Impact: 250 people developed the skin disease, 450 people burned by caustic soda, 17 sq. kms area was contaminated
Lessons learned from Bhopal Disaster (Leak of MIC)	**Causes:**
	1.Handling excess inventory than required
	2. Lack of operator training
	3. Operators ignoring process excursions
	4. Control development near major hazards
	Impact: 10000 people died, 200000 people sick
Lessons learned from Piper Alpha	**Causes:**
	1. Blind eye to lapses of the PTW system
	2. Poor shift handover
	3. Poor emergency planning and response
	4. Lack of supervisor training to handle emergencies
	Impact 167 people died, USD 1.8 Billion

Based on the review of these incidents, a couple of recurring lessons have also been identified as part of the analysis (Kletz, 2001). The lessons are:

i. Early signals and warnings, lessons learned from similar facilities on the barrier failure were ignored or underestimated
ii. Lack of risk framework to evaluate the failure of barriers and its impact on Risk of Major Accident Hazard (MAH)

The above incidents have consequences inclusive of human and asset loss. Onshore blowouts occur more often in comparison to offshore with dangerous effects such as release of toxic gases, spills of oil and groundwater pollution (Newsmax, 2011). The losses reviewed from Table 2.1 over the 30 year period occurred in large part due to failure of multiple safety barriers. Many incidents with reported fatalities involved failed barriers as a direct cause of events (The International Association of Oil & Gas Producers, 2014). In the United Staets in particular, recent evidences show most of the US onshore blowouts occur at gas wells. The Texas Railroad Commission has reported 100 blowouts in the state, since 2006 while Louisiana has 96 onshore blowouts since 1987 (Jones, 2011). The investigation process has identified the incident was attributed due to a combination of both physical barriers (hardware or equipment) and management barriers.

Now there will be focus on one catastrophe in particular, which will reveal the role that safety barriers play in application and will show the specific outcomes that can arise when barriers fail. The Chongqing gas well experienced a notorious blowout on December 23, 2003. This blowout has highlighted the significant consequence of sour well release. The impact of this blowout resulted in 243 fatalities and equivalent USD 48 million to cover the losses by insurers. The event caused 1,242 hospitalizations and over 65,000 evacuations; the related economic loss of this event was near USD 10 million (Jianfeng, Li et al., 2009). Upon post-analysis, it was determined that the well blowout had occurred due to failure of multiple safety barriers such as (UNEP, 2004):

i. Insufficient time for circulation of drilling mud to control the pressure
ii. Pressure control valve had been removed mistakenly from equipment
iii. Failure to ignite the well when the sour gas leaked and reached the surface
iv. Slow emergency response

The failure of these barriers led to horrific circumstances with life and asset loss resulting. The underlying causes of major accidents such as what occurred with Chongqing is the under-estimation of a barrier failure and inability to predict the major accident hazard accurately. Based on Figure 2., 50% of the major hydrocarbon losses were due to incidents in the upstream industry and it is estimated that 33% of world gas fields are contaminated by hydrogen sulfide (Risktec, 2009). The recent Chongqing blowout in China offers background for appropriateness to focus upon onshore sour gas drilling specific to barrier aspects and risk assessment.

This concludes the section regarding review of the importance of evaluating barrier effectiveness. Clearly understanding the potential for barrier effectiveness leads to increased safety, while underestimating barrier effectiveness leads to barrier failure, which can lead to catastrophe of great magnitude. With the goals of preventing accidents and minimizing negative effects in the event an accident does occur, evaluation of the most effective barrier(s) for an application to avoid barrier failure has great importance.

In the following section, the discussion continues with evaluation of parameters influencing barrier performance defined from a cross-industry perspective. The purpose of this section is to understand by what factors a barrier is measured against for determining effectiveness in non-onshore contexts. The goal of this review is to develop a starting point of barrier evaluation strategies or evaluation techniques to apply to barrier evaluation in onshore activities.

2.2 Barrier Performance Parameters Cross-Industry Review

The parameters by which other industries evaluate performance were studied for various applications. Several accidental scenarios have confirmed that barrier performances are a critical part of risk analyses (Sklet, 2006) and this is an applicable truth across several high-risk industries. In the below section, a detailed review will be presented on the varied aspects and factors influencing barrier performance as listed by various researchers / publications. This review will offer a broad list of terms and parameters by which to start from in considering evaluation parameters which should be specific and applicable to onshore barrier evaluations.

The Petroleum Safety Authority identified seven (7) aspects related to barrier performance which pertain to general petroleum activities (PSA, 2002). The identified parameters include:

i. Capacity
ii. Reliability
iii. Availability
iv. Efficiency
v. Ability to withstand loads
vi. Integrity
vii. Robustness

Adding to this list of relevant factors, reliability and effectiveness were linked to barrier performance in the context of hazard protection (Neogy et al, 1996).

Another set of barrier performance parameters have been defined by Hollnagel (1995), who discusses a set of parameters applicable to the definition of barrier quality. The parameters included:

i. Efficiency or adequacy
ii. Resource requirements
iii. Robustness

iv. Implementation delay
v. Safety-critical task applicability
vi. Availability
vii. Evaluation
viii. Human dependence

A decade later, Hollnagel (2004) also defined the requirements related to barrier quality using four (4) parameters:

i. Adequacy
ii. Availability / reliability
iii. Robustness
iv. Specificity

Hollnagel focused on defining terms for evaluating barrier quality, and separately, petroleum professionals in the Norwegian region furthered the discussion to focus on performance parameters.

Barrier performance has been studied in specific to the Norwegian continental shelf and the Norwegian Petroleum operations. With relation to the Norwegian Offshore Industry, five parameters were identified to characterize safety barrier performance (Sklet, 2006):

i. Functionality / effectiveness
ii. Reliability / availability
iii. Response time
iv. Robustness
v. Triggering event / conditions

In addition, a letter to the oil companies by the Norwegian Safety Authority has identified three (3) parameters for barrier performance namely functionality / efficiency, availability / reliability and robustness (PSA & RNNS, 2002).

Another set of barrier performance parameters were identified as a result of an accident review. The parameters were identified as follows (Rollenhagen, 2003):

i. Validity
ii. Reliability
iii. Completeness
iv. Maintainability

These four (4) parameters are duplicated from the previous sources' parameters collectively, but are unique from the next set of parameters.

ARAMIS, a framework defined as consequence after the SEVESO II directive for risk assessment has identified three (3) parameters pertaining to barrier performance (Salvi & Debray, 2005). The listed parameters consist of the following:

i. Effectiveness
ii. Response time
iii. Level of confidence during operations

From a human effect on barrier performance, a set of human influencing factors such as human error was also identified as being related to the review of current taxonomies (Kim, 2003).

Based on the above citations, a consolidated list of 19 variables related to evaluating barrier effectiveness were collated in
based on cross industry literature review. This list also lists the operative definition of these parameters.

Table 2.3: Definitions of barrier performance parameters from literature review

Barrier Performance parameters	**Operative Definitions**
Functionality / reliability	Extent to which barrier performance measure yields the same results on repeated trials
Response time	Length of time taken for a barrier to react to a given stimulus or event
Robustness	The ability of a safety barrier to perform effectively even when the underlying variables or assumptions are altered
Triggering event	A tangible or intangible barrier or occurrence that once breached or met, causes another event to occur
Capacity	Maximum limit to which the barrier can perform
Efficiency	Ratio of the useful work performed by a barrier to the total energy input
Ability to withstand loads	Ability to execute the safety function intended by the barrier without being destroyed
Integrity	Defined as a state of the barrier being whole or undivided
Implementation delay	Delay in execution of an idea, it may refer to the process of setting up a new hardware / software after purchase is made
Adequacy	Adequacy defines the extent to which a properly functioning Barrier will interrupt a particular scenario.
Safety critical tasks applicability	Defines the applicability of safety critical tasks for successful barrier performance

Human dependence	Dependence on human action for barrier performance
Availability	Percentage of time a barrier is considered ready to use when tasked
Validity	Refers to whether or not it measures what it is supposed to measure (execute the objective function of the safety barrier)
Completeness	Having all the required characteristics to fulfil the function of safety barrier
Maintainability	Measure of the ease and rapidity with which a safety barrier can be restored to operational status following a failure.
Lagging indicators	Measure of past performance of the safety barriers
Effectiveness	Degree to which a barrier is successful in producing a desired result
Level of confidence during operation	Percentage of all possible safety barriers that can be expected to include the true population parameter (of a safety barrier)

The purpose of this section is to consider the evaluation criteria for barriers to be deemed “effective”. Effectiveness in this study is related to a barrier’s ability to prevent hazards from occurring, particularly in the oil and gas industry. The barrier approach is used to contain and prevent hazards in drilling operations. As was reviewed in previous sections, failed barrier performance has great implications for the safety of individuals, health of the environment, and economic performance of organizations.

While barrier effectiveness parameters were borrowed from other industries, their impact to upstream onshore activities were deemed relevant in this work. There is clearly much room for safety improvement in the area of barrier effectiveness as according to the World Offshore Accident Dataset (WOAD); a report reiterated in 2012 cited 6,183 records reported for accidents and near-misses from 1970 to 2009 in the upstream industry (Christou, Konstantinidou; 2012). Barriers are meant to minimize the chances of near-misses and accidencts fom becoming recordable incidents, and are ultimately meant to keep people and assets safe. The International Association of Oil & Gas Producers (IOGP) supports the approach that one of the most significant ways to avoid or minimize the risk of accidents is through multi-barrier applications in the upstream industry. Now that a broad industry review of how a barrier can be critiqued for effectiveness has been completed, the following will discuss practical barrier application in the narrowed context of being relevant for drilling operations.

Barrier relevance in drilling

There is great importance on the evaluation of a barrier in the process of determining what barrier(s) would be most appropriate for an application. To simply employ barriers will only be sufficient to the extent that they are relevant; relevance is a key factor in whether a barrier will be successful (Ognedal, 2013; p. 4). Relevance will increase chances of effectiveness in the scenarios in which barriers are to be relied upon for hazard prevention or mitigation.

In fact, relevance is so important that it is required by respected authorities, such as the Petroleum Safety Authority of Norway, that operators identify the relevance when considering effectiveness of barriers holistically, including considerations for conditions under which a barrier should operate optimally (Sklet et al, 2006). When considering barrier evaluation techniques, it was noted that “relevance” of a barrier has been a commonly missed aspect in present techniques. Without the aspect of understanding the relevance of a barrier in a given condition, the evaluation of proper barrier choice is underqualified.

To determine relevance of a barrier, risk assessments can be conducted. Risk assessments can review the choice of a particular barrier and simulate an answer as to whether a barrier will meet the objective of preventing, controlling, or minimizing the occurrence of a hazardous event. Before proceeding to talk about risk and barrier assessments currently available, there will now be a brief overview to understand a drilling scenario where such an assessment would be applicable.

Barrier application and drilling sequence

For context on the drilling processes where barriers are leveraged for safety, in both preventative and containment scenarios, the following will briefly summarize the typical sequence of drilling operations for a surface well. This sequence is lent from the members operating current drill plan for an onshore drilling company in UAE.

A typical drilling program *(Abu Dhabi Gas Development Company Limited, 2015)* will leverage cementing, application of sand to avoid hydrocarbon gas bubbles arising from the formation, and a final barrier solution of gas monitors and breathing apparatuses to be issued to all personnel at risk of gas exposure. Gas rising from the well formation is one of many concerns that arise during a drill program which can be mitigated through use of barriers, and is a risk that is present throughout the drilling sequence.

The sequence of events for drilling a well includes a tiered progression of wellhead and casing to be drilled and set. The casing program is designed specifically for the well based on temperatures, depths, reservoir conditions, and whether the well will be drilled directly or horizontally. An example sequence of events for drilling a well is excerpted from an onshore drilling program:

i. Spud well
ii. Drill vertical 26" hole to ±1,600ft, run and cement 20" surface casing
iii. Drill 16" BU section to ±7,690ft
iv. Perform open hole wireline logs on TLC
v. Run and cement 13 3/8" casing
vi. Drill 12¼" BU section to ±12,075ft
vii. Perform open hole wireline logs on TLC

viii. Run and cement 9 5/8” x 10 ¾” production casing

ix. Drill 8.5” tangent section to ±12,147ft

x. Core 8.5” section to ±13,130ft

xi. Perform open hole wireline logs (including MDT’s) on TLC

xii. Drill 8.5” tangent section to ±15,041ft

xiii. Perform open hole wireline logs on TLC

xiv. Run and cement 7” liner in place

xv. Prepare for well test

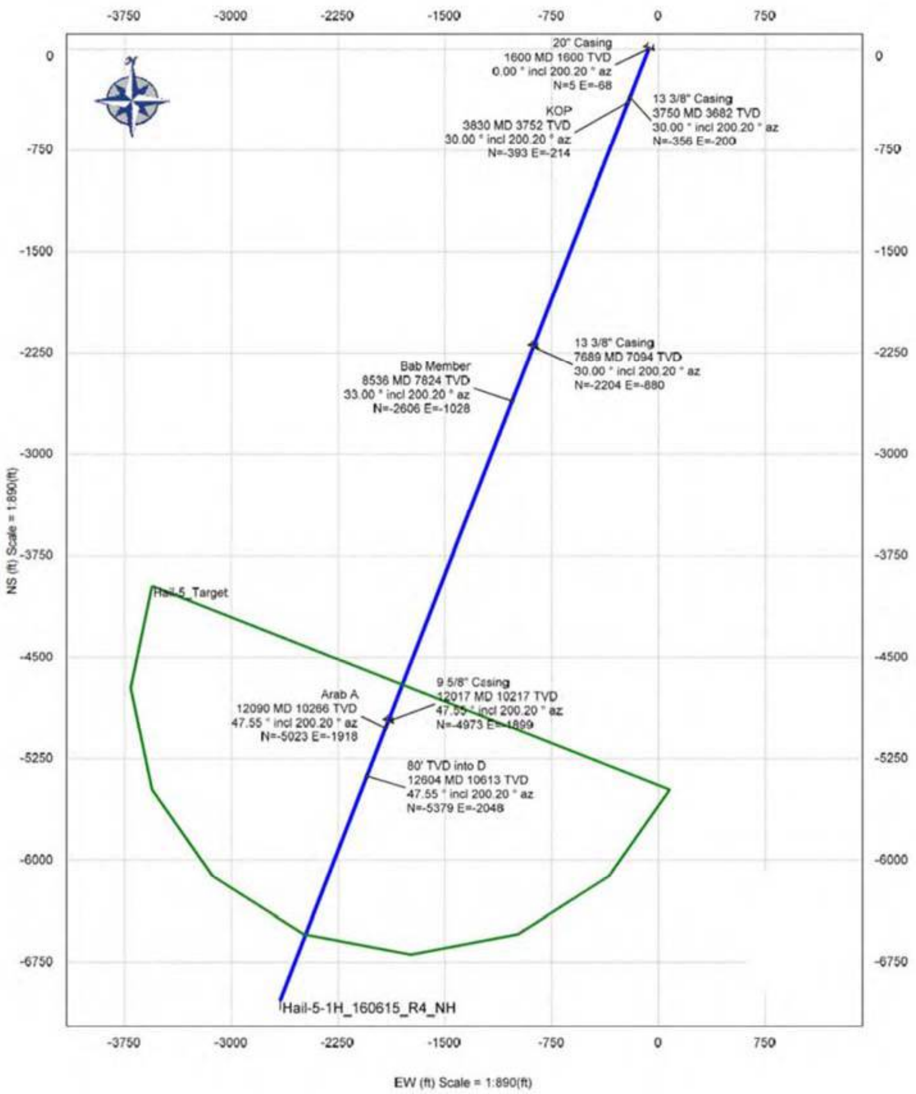


Figure 2.2: Typical onshore drilling plot (Abu Dhabi Gas Development Company Limited, 2015, p. 19)

In order to safely proceed with such a sequence, barriers must be selected strategically to be proper and effective for each relevant stage in operation. One barrier may offer protection for one step in the sequence, or may apply to multiple phases in the sequence. The most effective choice of a barrier in isolation, as well as consideration for how layering barriers would impact barrier effectiveness, must be considered when evaluating which barriers to apply.

Before a barrier can be chosen, the available options must be evaluated for fit and function as being the correct choice for application. Having multiple barriers in place to minimize risk is one side of the solution; choosing the appropriate barriers and ensuring they are optimized for success is another aspect of the solution that must be considered. This discussion will now review common barrier analysis techniques that are meant to help evaluate the effectiveness, applicability, or inadequacy of barriers.

2.3 Available Models for Evaluating Barrier Effectiveness

The following will introduce further context for evaluating barriers. The first section will review the purpose of barrier analysis and will introduce the Bow-Tie framework as the foundation for understanding other barrier analysis techniques. The Bow-Tie framework is the basis for many other evaluation methods and frameworks, so it will preclude discussion of any other evaluation method for this study. Once the Bow-Tie is explained, the subsequent sections will review seven (7) common barrier evaluation methods. The final sections will offer a comparison of the methods presented, and will produce a conclusion regarding the effectiveness of these long-used methods.

In principle, a barrier has a role in preventing the occurrence and / or consequences of an undesired event or accident (Sklet, 2006). Therefore, the effectiveness of a barrier is critical to evaluate in its application and should be considered with a two-part risk assessment. The first part should consist of a frequency assessment to understand how frequently the barrier prevents the occurrence of the event as intended. The second part should consist of a consequence assessment to understand how effectively the barrier responds to and mitigates the negative consequences of an event after it occurs. In order to conduct this assessment, existing barriers must be clearly identified. Developing a Bow-Tie framework is one commonly used method for identifying preventative and reactive barriers in a safety system. This framework will be reviewed in the following section.

Background – Bow-Tie and barrier classifications

Barriers are intended to inhibit a hazard from harming people or assets. Trost and Nertney (1995) expressed barrier functionality in the context of prevention, control or minimization. Real time risk management and response are evaluated through transformation of risk management tools to a real time risk management environment, and the Bow-Tie is an early step in this desired outcome (Jose et al, 2014). Barriers can be proactive or reactive, and can be simplistic or highly intricate. The Bow-Tie framework offers a visual context for understanding the purpose and scope of a barrier in simplistic terms. The following will expound on the origins and intent of this framework.

Visualizing barriers and inadequaces via a Bow-Tie framework

The oil and gas industry has developed a Bow-Tie framework along with the related multi barrier approach to effectively visualize the management of barriers (Flitchy, Jose, & Arango, March 2014). Such approach helps to identify missing or ill designed barriers and their influence on risk management (Jacinto & Silva, 2010). The Bow-Tie Model originated from the Swiss Cheese Model (Reason, 2000). The model focused primarily on latent and active failure with focus on psychological factors (Reason, 2000). From an industry perspective, Royal Dutch / Shell group was the pioneer in integrating the Bow-Tie methodology into its business practices (Primrose et al., 1996). The method was developed as an assurance tool that confirmed fit-for-purpose risk controls were consistently implemented throughout all their worldwide operations. Meanwhile, regulators recognized the importance of a risk based approach to evaluate major accident hazard risks during the operational stage of an asset lifecycle (POST, 2001). As described by the IAOGP in 2008, the Swiss Cheese Model depicted in Figure 2.3 shows how a multi-barrier approach mitigates the limitations of any one barrier through the layering of barrier applications. This layering of barriers helps to minimize the chance of hazards occurring due to

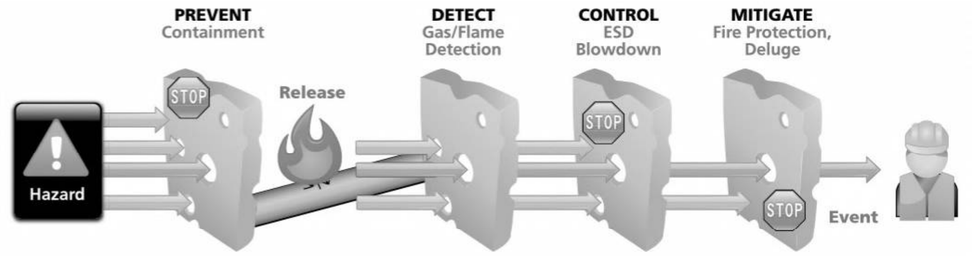


Figure 2.3: Swiss cheese framework (IAOGP, 2008)

The Bow-Tie framework is similar to the Swiss Cheese Model in that it evaluates barriers for prevention, but it differs in that it expands to evaluate the consequences and post-incident barriers as well. The Bow-Tie Model centers around a central "critical event" or "top event" which is linked to a corresponding fault tree on the left and a corresponding event tree is linked to

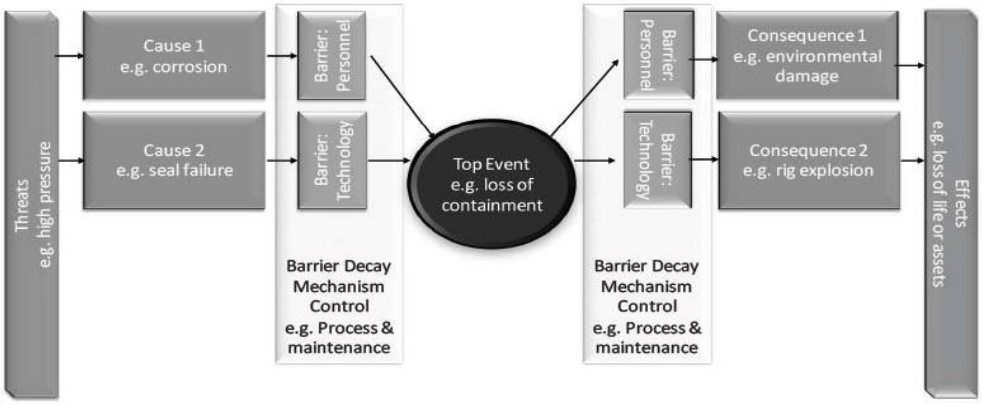


Figure 2.4: Typical Bow-Tie (original visual adapted from RasGas Company Limited, 2013 & Pitblado and Nelson, 2013)

As noted, Bow-Tie frameworks can be visualized as a set of fault trees. Such fault trees are linked to barriers to the left of the top event; these barriers are meant to prevent threat occurrence. A set of event trees and linked barriers to the right of the top event are conversely linked to mitigation of the consequence effects.

In the Bow-Tie visual, risk presents when threats are able to pass through the prevention barriers to reach the top event. The top event in process safety parlance relates to a loss of containment or loss of control. The succession path from top event to consequence effects are controlled by mitigation barriers. Events occurring to the right of the top event are consequences of failed mitigation barriers after the top event has been initiated, such as subsequent damage and explosion. The barriers considered in the Bow-Tie can be hardware controls, administrative controls and procedural controls. Barrier decay mechanisms are typically in place to maintain the integrity of barrier performance; these may also be referred to as "escalation factor controls" (Risk Support, 2007).

Barrier classifications

Barrier classifications as introduced by Sklet (2006) include a combination of concepts for passive barrier systems (Hale, 2003) and active technical barriers systems (IEC 61511, 2002). Figure 2.5 represents the flow chart of barrier classification developed by Sklet, (2006).

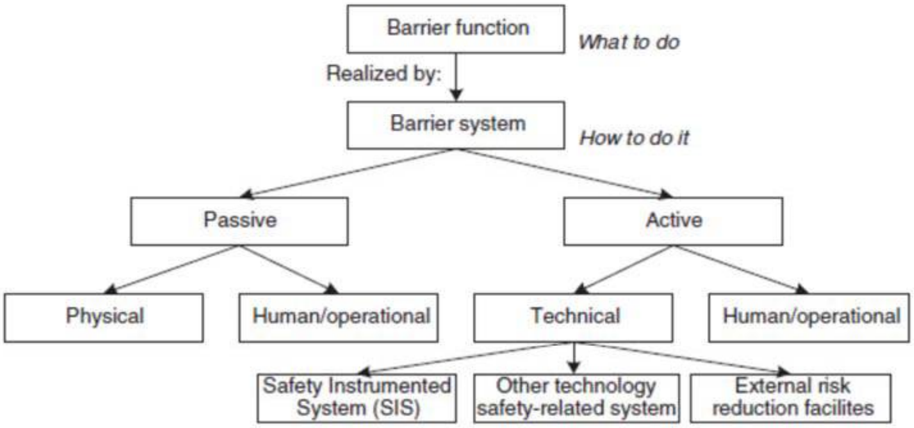


Figure 2.5: Barrier classification (Sklet, 2006)

Passive physical barriers are those that are existing from the time of installation without the need for activation, such as bunds, fences or firewalls (Reuvid, 2012). Passive physical barriers are considered almost fail-safe in commencement and are desirable as they are purposeful when needed and are correlated with low complexity (Trbojevic, 2008).

Passive human or operational barriers are those which are present and may be activated during critical activities. An example of a passive human barrier is safe design feature at the time of construction that allows for adequate separation distances between process units. Such a barrier can have significant effectiveness in preventing both hazard prevention and in hazard perpetuation (Mannan, Richardson; 2015).

Active human or operational barriers may be in continuous operation mode. An example of active human barriers may be manual processes or responses as part of work procedures or as a result of personal expertise. Active human barriers are activated on demand, such as through third party control of work (Sklet, 2006) or through critical decision making in a time of crisis or identification of a potential hazard.

Active technical barriers are linked to safety instrumented functions. An example of a safety instrumented function is a pressure relief system. A pressure relief system prevents uncontrolled rupture, which is a risk in high-pressure environments. Such a system is activated on demand due to process digressions or specific trigger events.

It is important to understand that barrier effectiveness can be evaluated from different perspectives, methods and techniques. The following sections will examine seven (7) barrier effectiveness evaluations available beyond the simplistic Bow-Tie framework. The Bow-Tie framework will be the baseline comparison for evaluating other barrier types and evaluation approaches.

2.4 Evaluating Barrier Effectiveness Approaches

The following will review select barrier evaluation methods available. First, in section 2.4.1, the Barrier Inefficiency Method will be reviewed. Then, section 2.4.2 outlines the Accidental Risk Assessment Methodology for Industries (ARAMIS) approach. After that, section 2.4.3 considers the Advanced Safety Barrier Method. Following ARAMIS, the Bayesian Belief Network (BBN) will be reviewed in section 2.4.4, which is a real-time risk assessment model. The subsequent topic in section 2.4.5 will be specific to analyzing barriers related to the prevention of hydrocarbon release via the Barrier and Operational Risk Analysis of hydrocarbon releases (BORA) method, an important analysis as hydrocarbon release is an issue that is of critical concern in the oil and gas industry. In section 2.4.6, the Layer of Protection Approach (LOPA) will be described. The final method in to be discussed is shown in section 2.4.7 and is a recently developed Six Step KPI Method purposed for methodically identifying critical barriers and developing strategy for ongoing evaluation of those key barriers. The goal of this discussion is to contextualize the gaps in each approach, and to challenge these commonly used methods as being complete in isolated use.

2.4.1 Barrier Inefficiency Method

The Barrier Inefficiency Model is a classification-based approach to categorize barrier inefficiencies. It is appropriately considered a preliminary screening method to evaluate high-level barrier applications. It is a model which is generic, and is not specific enough to review preventative or mitigating barriers. The following will review the context, execution, and limitations of the Barrier Inefficiency Method.

Context

Barrier functionality has been described in three terms: prevention, control or minimization. The Barrier Inefficiency Method is an approach consisting of a list of questions to identify the effectiveness of barriers in an application (Haddon, 1980). This approach regards barriers placed on the energy source, barriers placed on the impacting person / objects, and barriers placed between the energy source and impacting person / object.

Execution

Barrier ineffectiveness was defined and classified (Trost and Nertney, 1995) to identify ineffective barrier groups. The categories of barrier ineffectiveness crafted by Trost and Nertney are shown in Figure 2.6.

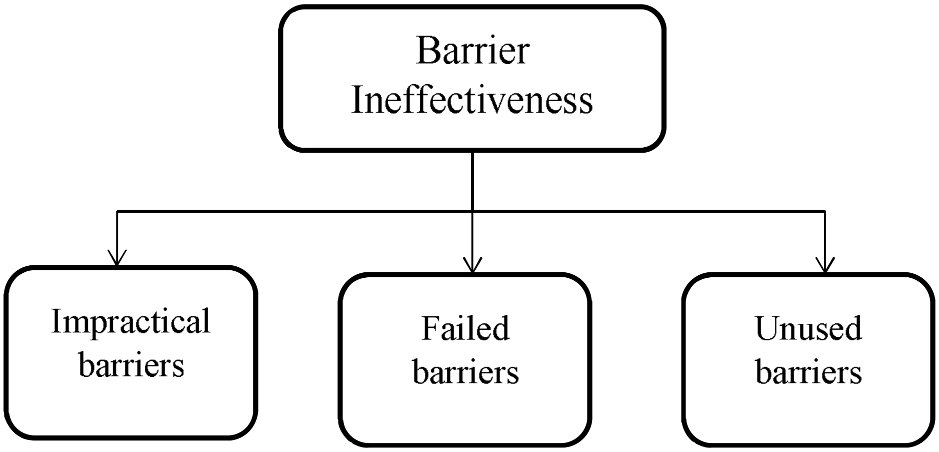


Figure 2.6: Barrier ineffectiveness categories (Trost and Nertney, 1995)

The first category of ineffective barriers is visualized as theoretical barriers. These were the barriers that are screened after conceptual level. These barriers were not considered to be worthy of implementation due to technical or economic conditions. The second category of impractical barriers is related to the inherent failure of the barriers. The third category of barriers is referred as unused barriers. These barriers are designed and built correctly but failed during implementation. The failure of these barriers can be attributed to task performance or worker error.

From a technical perspective, it is important to understand and acknowledge that each barrier cannot be considered completely effective, which is the same concept depicted by the previously mentioned Swiss Cheese Model. The component of ineffectiveness ranges from partial to total and is also a function of time. For example, lubricants applied to withstand an understood pipeline corrosion rate may be considered to be very effective at the time of installation, but may be deemed unacceptable based on unforeseen environmental changes such as variations in temperature or salt content that accelerate corrosion rates (Hasan, 2010).

Limitations

Trost and Nertney (1995) do not clearly establish the process to identify the barrier effectiveness in their classification methodology apart from providing the classification of ineffective barriers. During the evaluation of barrier ineffectiveness, it is important to factor the inherent failure of the barrier even if the source of failure is seemingly unpredictable. The Bow-Tie Model assumes minimized risk through barrier layering to account for barrier failure, while the Barrier Ineffectiveness Model does not approach this level of depth. It also lacks differentiation between barrier classifications and passive versus active barrier types.

The Barrier Ineffectiveness Model has been reviewed. The model is intended to identify barrier effectiveness, and has clear limitations in such intent. The next barrier evaluation method to review is the ARAMIS technique.

2.4.2 Accidental Risk Assessment Methodology for Industries (ARAMIS) barrier evaluation technique (Based on SEVESO II Directive)

The Accidental Risk Assessment Methodology for Industries (ARAMIS) is a barrier evaluation technique that relies upon quantifying Level of Confidence (LC), efficiency, and response time associated with a barrier. The focus of the ARAMIS model is on the importance of human influence as an external factor on barrier performance, which is significant as 80% of major accidents have root causes related to human or organizational errors (Debray & Salvi, 2006). The ARAMIS model links an organizations' safety management system with a barrier's performance to offer a future estimate of barrier effectiveness. This approach does not consider barrier interdependancy on other non-human barriers and does not account for risk analysis or failure of the barrier due to technical inefficiency. The following will review the context, execution, and limitations of the ARAMIS method.

Context

Andersen et al (2004) analyzed barrier strength based on three parameters. The ARAMIS framework (Andersen et al, 2004) was developed as result of joint research under SEVESO II directive. The parameters in analyzing safety barrier strength are defined as follows:

- Level of confidence (LC)
- Levels of efficiency
- Response time for the safety barrier

The benefit of this approach is linking of the safety management system to the barrier system in order to provide a more comprehensive future estimate of the safety barrier effectiveness (Hourtolou & Salvi, 2003). LC has been correlated to the probability of failure on demand of the safety function. The probability of failure on demand is well defined for Safety Instrumented Systems, which are systems requiring activation by an outside source such as personnel action, and has been extended in concept to all types of barriers (Chaumette et al, 2007).

The approach recommends the LC criteria to be applied at the highest safety system level which encompasses all subsequent systems. This is a scientific approach for safety instrumented systems (IEC 61511, 2002). However, considering this scientific approach for barriers such as management systems and human factors / manual work processes may result in higher levels of subjectivity than intended. Personnel and procedural guidelines may have specific safety objective functions which can influence the LC rating and overall ARAMIS score.

The efficiency of the technical barrier in the ARAMIS method is defined by the ability of the barrier to perform the safety function for a specified duration in a non-degraded mode. The response time of the safety barrier is defined as the duration between initiation and fulfillment of the safety function.

Consider an analogy in the drilling function; a High Integrity Pressure Protection System (HIPPS) response time shall be defined as the time duration between the initiation of the systems and shutting of the well. Similarly, efficiency and response time are hardware related safety barriers, and it is difficult to quantify these values for soft barriers. It is often difficult to derive these values from an operational perspective even for hardware barriers. In general practice, these values are recommended by manufacturers, technical guides and data sheets.

Execution

The ARAMIS evaluation technique stipulates criteria for the identification of safety barriers. The following are the 2 critical criterions:

i. Safety barriers must be independent. This does not account for redundant safety barriers such as 2-o-o-3 or 1-o-o-2 fire / gas detectors. The logical extension of this statement defines that barriers shall not account for common cause failures attributed to the criteria of independency.
ii. The identified barriers must be proven in concept. This means that only modeled safety barriers can be accounted in the evaluation. In the current era of technological evolution, this is a constraint for un-established or unproven barriers.

The methodology of defining the effectiveness of a barrier under the ARAMIS model relies upon quantifiable metrics. Specifically, it relies upon the Probability of Failure on Demand (PFD) metric, which is an equivalent for the Level of Confidence (LC) parameter. The PFD applies to passive, active and human intervention barrier types.

This approach introduces a key factor in the evaluation of a barriers' LC rating; the efficiency of safety management personnel is also part of the evaluation for barrier effectiveness (Hourtolou & Salvi, 2003). The efficiency of safety management personnel at an organizational level is related to maintenance protocol, adequacy and relevance of procedures with respect to regulation, as well as training and safety culture (Andersen, Duijm, et al; 2004). The objective of this process is to evaluate the Safety Management Efficiency Index. The index considers ten (10) structural factors. The needed maintenance of these factors corresponds to a rating for measuring the confidence for lifecycle management of the safety barriers. The structural factors on the index ensure the effective safety function of the barrier across its lifecycle as illustrated in Figure 2.7.

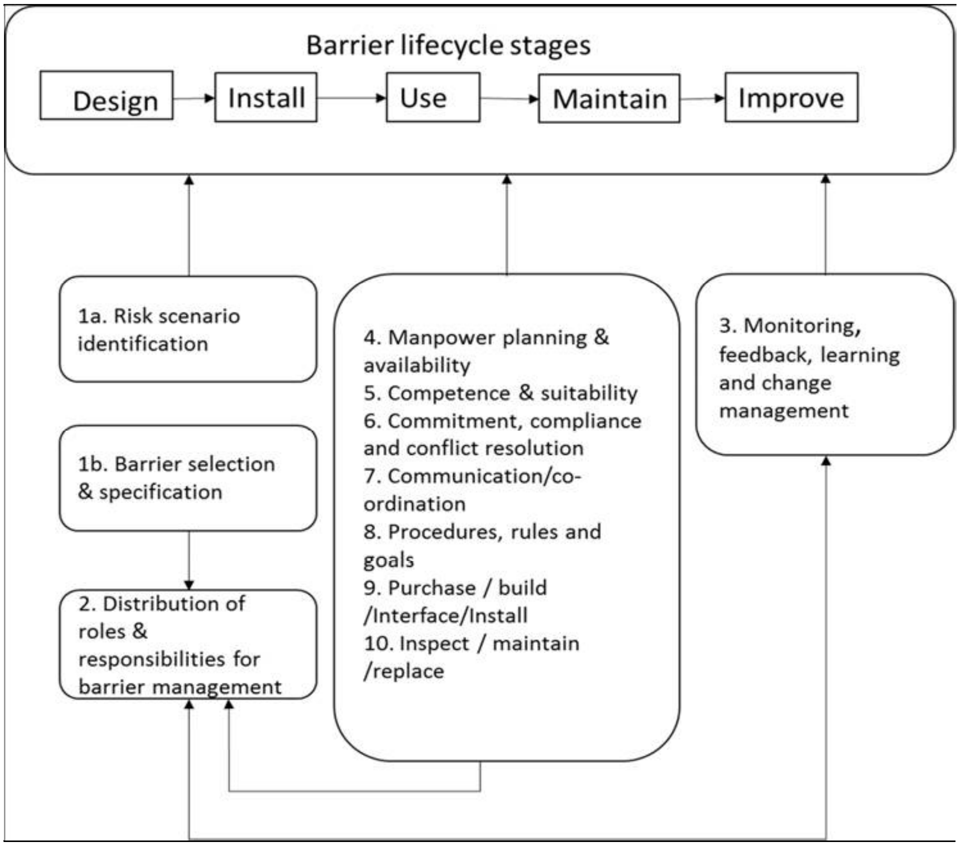


Figure 2.7: Structural elements of the safety management organization across the barrier lifecycle (Andersen et al, 2004)

The model acknowledges the contribution of safety culture in the evaluation of safety management. Therefore, the ten (10) structural elements of organizational safety are evaluated against eight (8) cultural factors which define the safety culture of the organisation. The cultural factors are listed below:

i. Learning and willingness to report
ii. Safety prioritization, rules and compliance
iii. Leadership involvement and commitment
iv. Risk and human performance limitation perception
v. Safety responsibility and factor
vi. Bi-directional trust between management and employees
vii. Work team atmosphere and support
viii. Motivation, influence and involvement

The evaluation of the ten (10) structural elements is performed through an audit and the safety culture factors are estimated through a questionnaire based investigation technique.

Surveys from relevant technical experts are conducted to evaluate the effect of safety management efficiency to predict the future state of the safety barriers. Based on these inputs, a quantitative rating is determined for safety culture and structural elements of the safety management organization. These two ratings are further combined into an LC for the identified safety barrier.

Limitations

Due to the comprehensive nature of this survey and rating exercise, it may require enormous efforts to complete this exercise for all the barriers identified in a Bow-Tie exercise. The process prescribes for this approach to a list of representative barriers only, although it is important to note that evaluating only for a representative set of barriers does not give an accurate estimate of the risk. Additionally, the ARAMIS method lacks consideration for interdependent barriers and is applicable for barriers that have historical presence which omits application for new barrier technologies. Next, the following barrier evaluation method to consider is titled Advanced Safety Barrier Management, a method which considers barriers individually and also considers personnel factors, albeit without a survey approach.

2.4.3 Advanced Safety Barrier Management – human & organizational aspects

The advanced safety barrier management approach considers human and organizational aspects of barrier performance. This method evaluates barriers on an individual level, and it combines attributes of the Bow-Tie Model with the "success pathways" approach (Pitblado, Nelson; 2013). Considering success pathways is an approach used in the high-risk nuclear industry. This combination allows one to consider the ways persons and business operations impact barriers simultaneously with baseline barrier effectiveness. The Advanced Safety Barrier Management approach does not support single fail point analysis and requires barriers with historical fail data, omitting its applicability to novel applications. The following will review the context, execution, and limitations of the Advanced Safety Barrier Management evaluation method.

Context

The Bow-Tie framework considers only independent barriers. In a practical context, this assumption may be invalid. For example, consider a management directive that does not allow or accept schedule delays or cost overruns. This can cause degrading effects on implementing barriers if proper time is not allowed for barrier maintenance or if enough personnel are not dedicated to barrier operation; this can impact subsequent barrier functionality. Therefore, the Bow-Tie Model may depict a complete system with multiple barriers, but in reality may be less effective than the visual depicts. This is why a modified approach is considered appropriate.

Pitblado & Nelson (2013) have proposed a innovative approach to barrier assessment considering human and organisational factors by combining the Bow-Tie risk model with success pathways. The combined approach provides a framework to consider human factors and organisational factors in barrier assessments. The execution of the advanced safety barrier management approach incorporates a safety objective tree along with the traditional Bow-Tie approach.

Execution

Organizational and human factors are to be considered as overarching elements while evaluating the effectiveness of any barrier. Despite the level of influece and impact, organisational factors tend to be absent or under-represented in Bow-Tie diagrams. This limitation can be overcome by incorporating safety objective trees. The tree structure provides insight to the plant personnel on available options to prevent the accident path.

Safety objective trees consist of a five (5) level hierarchial tree structure. The top level refers to the “safety objectives”, which in Bow-Tie terminology could be referred to as “prevention of the top event occurrence” such as preventing loss of containment. The second level relates to practical realisation of the safety objective through a safety function such as maintaining pressure limits. The following level refers to the challenges to the safety function such as pressure build up due to line blockage. The fourth level refers to those strategies and / or mechanisms that are disabled which may impair the safety function. The final level provides solutions in the form of mitigating strategies to protect the safety function challenges. A typical safety objective tree developed for the nuclear industry is listed below in Figure 2.8.

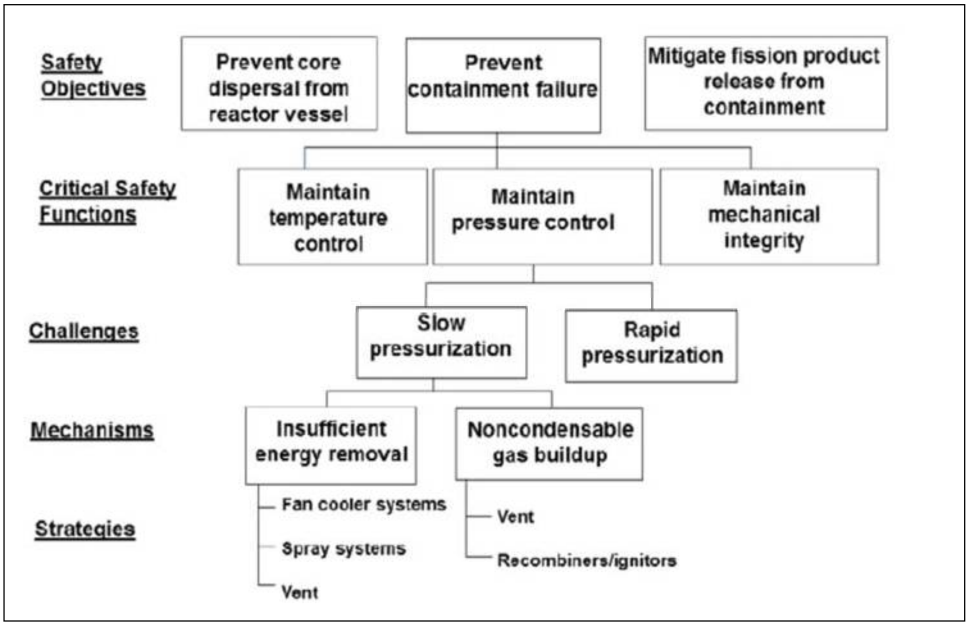


Figure 2.8: Example safety objective tree (Pitblado & Nelson, 2013)

Using a hybrid approach of Bow-Tie risk assessment along with safety objective trees assist in integrating the barrier approach with an event-based assessment approach. The Bow-Tie framework as a standalone evaluation method does not provide enough information to properly consider barrier effectiveness. Human intervention may be required to prevent event progression towards the accident path. Corrective actions which may include critical decision making makes Bow-Tie integration with the safety objective tree a more holistic evaluation method.

There are four inputs which are required to enable the critical decision making process (Pitblado & Nelson, 2013):

i. Current process state (achieved by determining process condition and plant equipment status)

ii. Health of barriers

iii. Health of critical functions

iv. Available success pathways for the accident

The status of any barrier is typically captured through results arising from audits and inspections. These are used to observe anomalies related to physical damage and visual clues. These do not include or consider overarching organisational and human factors contributing to the barrier failure, such as recent reorganiztaion or oboarding new personnel with lacking experience. The Barrier Systematic Cause Analysis Technique (BSCAT) (Pitblado & Fisher, 2010) is an investigation process that has an increased focus on barrier failure and the associated root cause contributing to the failure. Using this process, a full operations Bow-Tie can be converted into an incident Bow-Tie as in Figure 2.9. By excluding branches of the operations Bow-Tie, focus can be applied to incident pathways through the incident Bow-Tie.

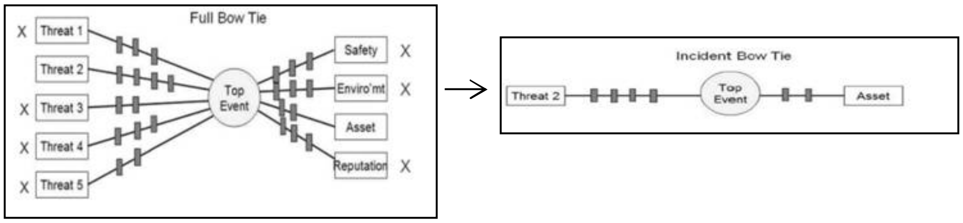


Figure 2.9: Conversion of operation to an incident Bow-Tie (Pitblado & Fisher, 2010)

This investigation approach assesses the barrier failures and recommends new values for barrier effectiveness and reliability. The updated risk assessment incident management considers a reactive approach to risk assessment based on the incident findings and their impact on barrier effectiveness and reliability.

Through the BSCAT method, the performance of each barrier is evaluated and documented. In case of failure, root cause failure of each barrier is identified in Figure 2.10. The failed barriers are further investigated to identify immediate causes, basic causes and suggested improvement actions. By this method, barrier effectiveness is evaluated and provides early warning signs of potential major accidents in the future.

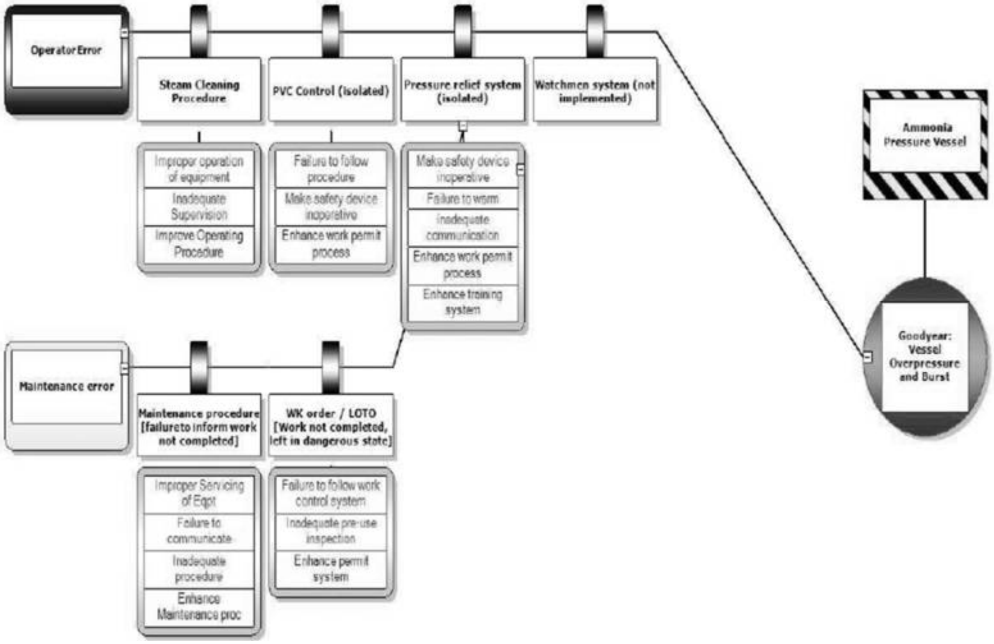


Figure 2.10: Barrier Analysis - DNV BSCAT method (Pitblado & Fisher, 2010)

Limitations

The limitation of this method is that it does not provide a structured framework or algorithm to update the risk based on the failed barriers identified during the investigation process. This is crucial as any barrier interdependancy may result in underrepresentation of weaknesses across barriers due to a single fail point. This method is also limiting in its requirement to have historical fail data, leaving the evaluation to be dependant upon previously-failed barriers. The following method also considers a fault tree in its analysis, and has emphasis on multi-barrier interdependance.

2.4.4 Bayesian Belief Network (BBN) in Risk Modeling

The Bayesian Belief Network (BBN) is a model used to evaluate barrier effectiveness with strong consideration to multi-barrier interdependence. This model leverages fault tree mapping and does account for human and organizational influences. Additionally, the BBN considers time as an influencing factor to evaluating barrier effectiveness. It is lacking, however, in that it does not extend consideration to post-top event barriers. The following will review the context, execution, and limitations of the BBN risk model.

Context

The (BBN) is a dynamic integrated model (Ale et al, 2014) for risk in a real time environment, inclusive of considerations for human and organisational factors. It is used to define the variables and the related inter-dependencies which may not be captured in linear and deterministic models, and as a dynamic model, it supports ongoing changes and updates (Hudson, 2010). This approach is used to test whether different risk contributing elements can be integrated into a

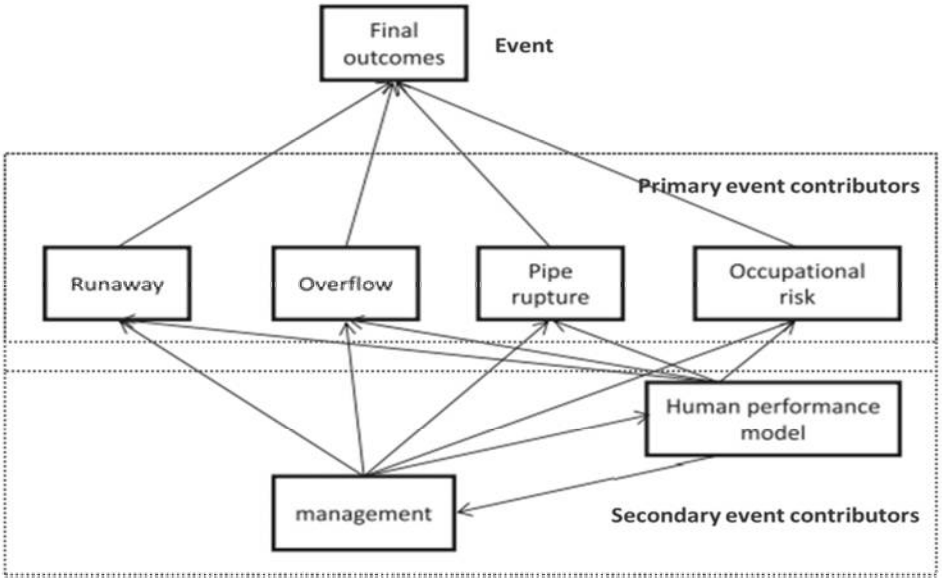


Figure 2.11: Schematic BBN Model (Adaptation) (Ale et al, 2014)

Execution

The discrete BBN model identifies the inter-dependencies between primary and secondary event contributors, as well as mutually exclusive primary events that impact barrier performance (Kabir et al, 2015). This is the transformation of fault trees into Bayesian Based Networks through identification of functional nodes. The boolean variables from the fault tree (failure / no failure) are replaced by the probability of failure, and the probability of top event are computed using normal arithmetic. The logical relationship of a fault tree can very well be transformed into a BBN model. This, in principle, means that only the threats and the prevention barriers in the Bow-Tie framework are accounted in this approach.

Another key feature of this model is the time-dependant factor as depicted in the dynamic risk model (Figure 2.12). Time is a variable considered in evaluating the barrier effectiveness considering human and mangement influences. Conditional distribution of human factors / influences were evaluated against the variable money spent to improve safety. At each time step, the distribution of initial money is kept as a constant. In addition to the initial money, extra money is added towards the total pool of money spe

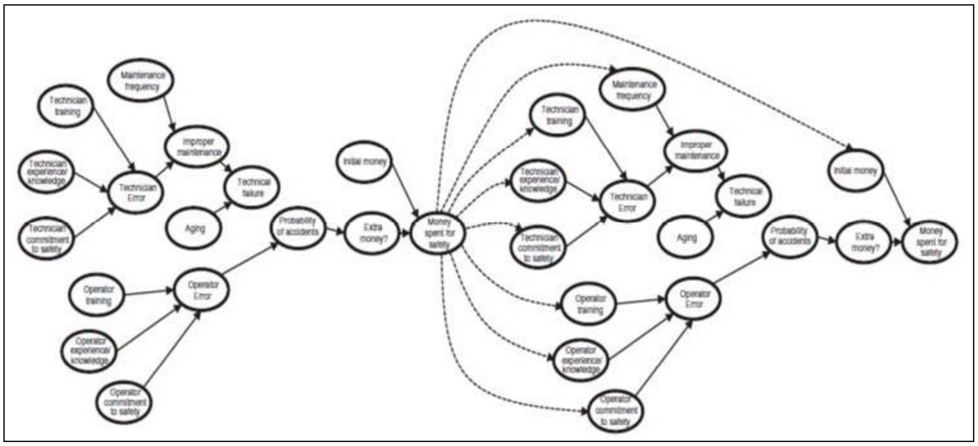


Figure 2.12: Two time intervals of the dynamic risk model

The conclusions of this model have confirmed the real time experience, which shows costs increased continuously in an effort to influence a lower accident probability. There is benefit to this model in that the nodes can be updated continuously as new factors are disovered, making this a model that supports dynamic application (Wooldridge, 2003).

One way to execute this model is by using an online application to frame the components for evaluation. AgenaRisk is an example of a risk tool that is software based and supports risk analysis and decision making. This tool helps to model expected and unexpected losses in operational contexts (Neil et al, 2004). AgenaRisk uses Bayesian Network methodology and is targeted for industries such as aerospace, defense, and energy. The tool is a great consideration for upstream industry use in the context as described in AgenaRisk white paper published in 2004 titled: "Using Bayesian Networks to Model Expected and Unexpected Operational Losses". Leveraging the effectiveness of Bayesian Network within the convenience of a software-based system would be one way to maximize the utilization of Bayesian Networks in upstream operations.

Limitations

There are limitations for the BBN model, a few of which will be mentioned here. The first limitation of this model is that the consequence and the impact of mitigation barriers (e.g. functional interdependencies between the top event and the consequence being realised) are not accounted. The event frequency considers only the threat barriers influences and inter-dependencies. The second limitation is that the money spent for safety accounts only for personnel expenses, which can be deemed elementary. In reality, safety budget is split between technical system upgrades and human influences. Another limitation is regarding the conclusions drawn through this model; they were not derived or verified against real data. Therefore, the result of this BBN model should not be interpreted in its absolute context. While the BBN method is meant to apply to a range of barrier types and purposes, the next barrier for consideration is designed for a particular barrier application.

2.4.5 Barrier and Operational Risk Analysis (BORA)

The Barrier and Operational Risk Analysis (BORA) is an assessment of barriers to prevent and / or mitigate hydrocarbon release, which is a critical hazard consideration in the oil and gas industry. BORA leverages a fault tree to evaluate the technical aspects of a barrier and it's effectiveness. It leverages an eight (8) step approach that relies upon data and audit results to focus on the causes leading to what would be considered a "top event" in the Bow-Tie framework. This model does not evaluate barrier interdependancy and fails to account for mitigation barriers subsequent to the occurance of the top event. The following will review the context, execution, and limitations of the BORA risk model.

Context

The BORA method focuses on the effect of safety barriers on the overall hydrocarbon release frequency while considering the technical, human and organisational factors impacting the barrier performance (Aven et al., 2005). These impacting factors are considered "risk influencing factors" (RIFs), which influence barrier failure or malfunction (Rausand, 2013). These RIFs are given quantitative values and are used in a risk assessment for barrier reliability based on risk factors. The eight (8) execution of the BORA method is described in the following section.

Execution

The BORA method is developed based on the following steps, which will be elaborated in the succeeding section:

i. Develop a barrier based model depicting risk occurrence through hydrocarbon release
ii. Evaluate performance of the safety barriers assigned to prevent hydrocarbon release
iii. Quantify risk based upon barrier performance data
iv. Create risk diagrams
v. Assign a score to the factors identified in the diagrams from Step 4
vi. Quantify the risk influence factors
vii. Modify the generic input data
viii. Re

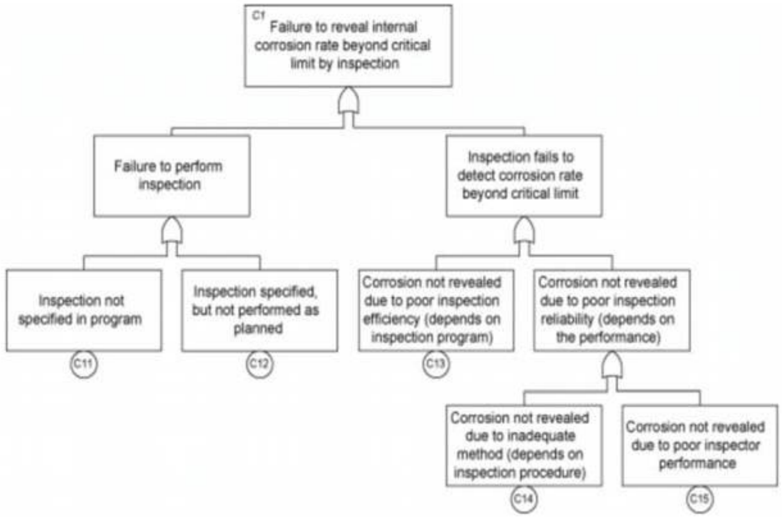


Figure 2.13: Fault Tree for a selected safety barrier (Sklet et al., 2006)

Steps 1 & 2: 1)Develop a barrier based model depicting risk occurance through hydrocarbon release & 2) evaluate performance of the safety barriers assigned to prevent hydrocarbon release - The BORA-release approach combines block diagrams, event trees and fault trees to provide a clear and consistent representation of the various barrier systems in a way that visually leads towards preventing the release of hydrocarbons. An example is shown in **Error! Reference source not found.** from pipeline applications. Even though a barrier block diagram may be considered generic, the framework enables sufficient detailed analysis of the individual barriers.

Step 3: Quantify risk based upon barrier performance data - The BORA model initially considers a broad range of barriers. However, the performance of individual safety barriers needs to be analyzed. The fault tree approach is undertaken to evaluate the barrier effectiveness of technical barriers. Generic input data are collated from a range of sources. These include generic databases related to equipment failure, surveillance of operational activities and testing of technical systems. For some of the technical systems which require human intervention for successful functioning, reliability data may not be available. In this event, human reliability data can be sourced by means of expert judgement sessions.

Step 4: Create risk diagrams – A hybrid approach of top-down and bottom-up depiction is undertaken to develop risk influence diagrams. A top-down approach ensures that a common framework for risk interacting factors is developed. The bottom-up approach enables specific RIFs pertaining to the plant / facilty under observation to be properly identified and assessed. A constraint of six (6) RIFs per basic event were established in this scenario to avoid unmanagable RIFs from a facility perspective. This adapted framework consists of personnel characteristics, tasks, technical systems, administrative controls and organisational factors (Kim, 2003).

Step 5: Assign a score to the factors identified in the diagrams from step 4 - Three approaches to RIF scoring were proposed. The first approach requires individual audit of the RIF based on the risk influence diagrams developed for the basic event. The second approach relates to a six (6) point performance criteria and does not account for the industry average values. The third approach uses survey and accident investigation information for arriving at the scoring values.

Step 6: Quantify the risk influence factor - Weighting of risk factors are specific to the facility under consideration. Therefore, expert judgement has been proposed. The weightage input related to the risk factor is to be provided by operation personnel.

Step 7: Modify the generic input data - In this step, probabilities are adjusted as a sum of products of the scores, are normalised by the weight of the RIF (inputs considered from the previous 2 steps) and are then multiplied with the genric input data. The resulting values are benchmarked against a range (P_{high} and P_{low}). This range may be defined by expert judgement or by use of generic equipment reliability database (e.g, OREDA)

Step 8: Recalculate the risk - The revised hydrocarbon release frequency is calculated considering technical, human and organisational risk interacting factors. Moreover, the final frequency considers the actual performance of the safety barriers.

The approach was validated by its implementation in a case study by Sklet, Vinnem, & Aven titled "Barrier and operational risk analysis of hydrocarbon releases (BORA-Release): Part II: Results" in 2006. Feedback from the personnel included positive response regarding knowledge about the safety barriers to prevent hydrocarbon releases and RIFs impacting the barrier performance.

Limitations

The steps within the BORA model indicate the term "risk" at various stages. This terminology should be interpreted as "frequency" as the barriers accounted in the model and their inter-relationship is related to the preventive barriers towards the hazard realisation. The BORA model is heavily dependant upon personnel opinions and requires expert inputs. The method also focuses on hydrocarbon release at the exclusion of other risk types. Additionally, the BORA model does not account for the mitigation barriers usually depicted in the "right" of the Bow-Tie. The next barrier evaluation technique is also a quantifying approach, and it expands beyond hydrcarbon application.

2.4.6 LOPA Based Methodology (Quantification of Safety Barrier Performance)

The Layer of Protection Approach (LOPA) is a three (3) step process that is meant to identify barriers and identify how layered barriers may prevent or delay a hazard. It is an approach that involves categorizing barriers and considers barrier interdependance. While it does introduce quantified measures for understanding barrier effectiveness, it is not a dynamic approach and is not feasible for life-cycle barrier evaluation. The LOPA ratio is l

$$\text{LOPA ratio} = \frac{\text{Tolerance risk frequency}}{\text{Scenario frequency}}$$

Figure 2.14: LOPA ratio (Harbawi et al, 2010)

Purpose

The LOPA safety barrier performance assessment is specifically aimed at understanding the escalation potential of a hazard, also referred to as a fired domino scenario (Landucci et al., 2015). Customisation in evaluating barriers in a layered scenario is conducted as passive barriers and procedural barriers can not be considered as independent since they may fail by a common cause such as fire (NFPA, 2009) (Dowell et al., 2002). Therefore, the evaluation of safety barrier performance for escalation framework is aimed at quantifying availability and effectiveness via a ratio derived from these variables, as visualied in Figure 2.15. In the context of escalation prevention, it is considered that several safety barriers tend to delay the event while still contributing to

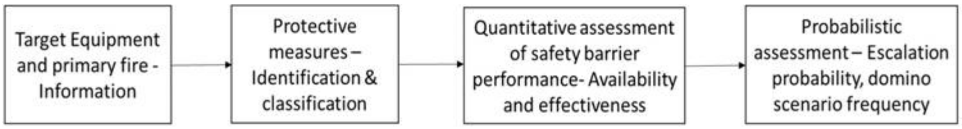


Figure 2.15: 4 staged process - characterization of barrier performance (Landucci et al.,2015)

Based on the above concepts of availability and effectiveness, escalation probability is the eventual consequence of a primary event. As a potential alternate to LOPA, Bayesian Belief Networks (BBN) can also be a fit for purpose tool in similar applications. Within the framework of a conventional quantitative risk assessment approach, the modified event tree analysis is considered a simplistic tool to appropriately evaluate barrier performance based on effectiveness criteria. 2.15 illustrates the main steps to integrate safety barrier performance in the escalation probability assessment.

Execution

The authors (Landucci, Argenti, Tugnoli, & Cozzani, 2015) list the methodology to assess the availaibility and effectiveness of the safety barriers triggered by fire event based on a three (3) stage process.

Step 1: Data repository – Reference target equipment and reference installations
Step 2: Safety barriers performance data – Active / Passive protection systems, procedural measures
Step 3: Reference data for escalation assessment

For the selection of data repository action for step 1, it is important to consider the site features and equipment under analysis. Therefore, two macro categories of Reference Target Equipment (RTE) and Reference Installations (RI) are introduced. RI are installation categories where common standards are applicable to the selection and design of fire protection measures. RTE are equipment which are more critical to domino effect.

Safety barrier performance data would be based on the analysis of specific technical documentation based on NFPA and API standards applicable to the corresponding equipment. Due to the complexity of fire protection systems, the evaluation of Probability to Fail on Demand and System Availability would be achieved through fault tree analysis. The activation of fire protection systems does not ensure the prevention of escalation. The effectiveness would be calculated through relevant literature review specific to water deluge systems to protect LPG storage vessels.

Limitations

LOPA is a solution that results in outcomes that could alter the fundamental operational process of a system. Because it is data-intensive, it should be conducted at the beginning of engineering activity for drilling operations for optimal pivot response to negative data results that may be identified (Lassen, 2008). Having organizational dedication to maintain regular LOPA evaluations at interval points during operation may be something organizations are reluctant to consider, especially if there are personnel constraints for conducting the analysis correctly. Because the approach is intensive, its' lack of simplicity can lead to underuse. Additionally, the LOPA approach is best suited for static systems, so application for dynamic situations is not ideal. Moving forward to the final method for consideration, the following six (6) step process is aimed at identification of barriers for ongoing monitoring to evaluate effectiveness.

2.4.7 Six Step KPI Method – evaluation based KPI methodology

The Six Step Key Process Indicator (KPI) method is an evaluation-based approach meant to assist in identifying and classifying barriers for KPI monitoring. It is a method that requires certain criteria for each barrier to be monitored on an ongoing basis to identify negative changes, anomalies or risks. This approach leads to ongoing barrier effectiveness management and proactive assessments to prevent failure through early detection. Limitations for this approach include the dependency of a baseline for the barrier performance, which automatically omits new barrier technology from being ideal to evaluate with this method, and it does not evaluate barrier interdependency.

Purpose

In a multi-barrier hazard prevention scenario, it is essential to be able to identify the most critical barriers for evaluation and ongoing monitoring. This is a six (6) step process that is recommended by OGP and was developed by the National Research Council (2011) is listed in Figure 2.16. The purpose of this approach is to identify critical barriers and develop a systematic method to measure KPIs (The International Association of Oil and Gas Producers, 2011). Monitoring and measuring KPIs on specific barriers can lead to clearer paths of

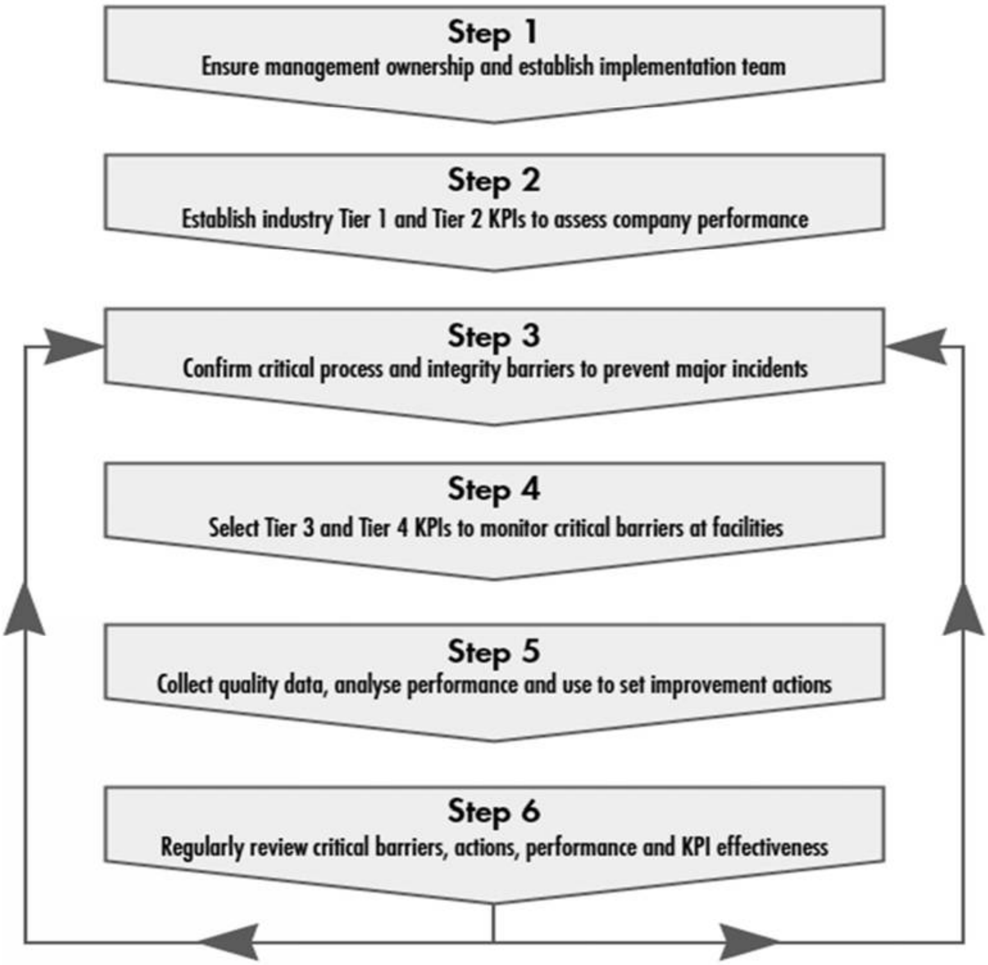


Figure 2.16: The Six Step Process (The International Association of Oil and Gas Producers, 2011)

Execution

The 6 step process begins and ends with proactive personnel activity. The steps will now be reviewed. Following the outline of the steps, limitations will be listed.

Step 1: Identify the responsible team members - The first step in the process is to identify the appropriate leadership and personnel to hold responsibility for process implementation and ongoing evaluation (The International Association of Oil and Gas Producers, 2011). This will improve the odds of meaningful execution and will help clarify lines of accountability for corrective action when issues are identified.

Step 2: Establish relevant company-specific KPIs - The second step in the process is to select key performance indicators that are measurable and significant. These factors will relate to the performance of a company, such as response time required to mitigate a hazard when barriers fail. This will be used to benchmark the company's existing performance for comparison against future solutions to improve the KPI in the future.

Step 3: Identify the critical barriers pertaining to hazard prevention - The third step is to identify the barriers that are believed to be the most critical and determine their potential weakness. Barriers that have failed to prevent hazard in the past and barriers that have not responded to hazard occurrence as expected in the past should be considered critical by default as their inaction or malfunction historically should be cause for future monitoring and analysis to identify reliability.

Step 4: Establish relevant barrier-specific KPIs - Step 4 entails a preventative and metric-based approach to identifying KPIs that pertain to the specific barriers identified as "critical". Such KPIs will be tailored to each barrier and its' dependency; for instance, if a critical barrier is dependent upon personnel activation, then a KPI may be the number or percentage of personnel trained at a site to engage the barrier, and may include accomplishment of annual refresher trainings (National Research Council, 2011).

Step 5: Data collection - The fifth step requires active data collection of KPI reports from Steps 2 & 4. For example, reviewing the KPI reports from company response time in step 2 and reports on number of trained employees for barrier activation in step 4 may reveal a correlation of slower response time with fewer trained employees. This correlation may lead management to take action in the next step.

Step 6: Review and refine - The process concludes with Step 6, which is a step of reflection and corrective action. If KPI reports from step 5 reveal a correlation with failed barriers, slow company response time, and low training statistics then the company may decide to correct this via a more robust training program. Conversely, the company may find that the barrier is best implemented by automated systems that may be more reliable, and this may lead to investment into a new barrier solution altogether.

Limitations

This 6-stage process assumes that the barriers have already yielded historical results and can be improved upon. This leads to limitation of the approach to new barriers which have no historical points for consideration, which may require a hazard to occur before this approach is useful to the drilling industry. Because of this, the 6 step approach is most appropriate for barriers which have been implemented, are generally deemed useful, but seemingly have improvement needs based on past failures.

Conclusion of literature review

The above listed barrier evaluation approaches were compared under the following themes to derive meaningful outcomes and identify gaps to serve as basis for building comprehensive models in the future:

i. Barrier effectiveness criteria
ii. Barrier coverage in the analysis (preventative and mitigating)
iii. Barrier interdependency factors
iv. Approach benefits / limitations

While each barrier has benefits, each also has limitations. This chapter evaluated various barrier effectiveness models. The models have been analyzed in the context of risk management. Based on the review of existing barrier evaluation approaches, some common gaps were identified. Each approach reviewed concluded with applicable limitations, many of which were overlapping. These overlapping gaps include the following:

i. Lack of a comprehensive evaluation considering preventive and mitigation barriers
ii. Lack of a simple risk framework considering the barrier effectiveness
iii. Consideration of common cause failures and aligning the accident pathway

Future scope and area of research should focus on barrier effectiveness framework considering a holistic evaluation of risk to determine the impact of a malfunction or deterioration in operation of a safety barrier. Risk acceptance criteria should also be appropriately defined for such evaluations as current criteria focusses predominantly on facility wide risks and not process specific risks.

Inferences and gaps from literature review

A detailed literature review has been conducted in the following six (6) segments:

i. Process safety & major accident hazard
ii. Barrier performance parameters
iii. Barrier failure and risk impact

iv. Barrier based risk framework (qualitative and quantitative)
v. Drilling and H_2S related risk assessments
vi. Dynamic risk assessment models

The purpose of this review is to clearly itemize the barrier evaluation option and the limitations of each in isolation. Gaps that are present for qualitative, quantitative, and the balance of methods in the work are listed in Appendix 1.

Based on the detailed literature review, the following are the key inferences and conclusions:

Inferences:

i. Barrier performance parameters are not studied for onshore sour gas drilling operations
ii. Failure or weakening of barriers are currently not considered in risk assessments
iii. Risk analysis is static and does not consider barrier failures

In addition to clarifying the gaps and needs in the industry as related to barrier analysis, there are facts which are present regarding the intent and importance of barrier discussions. These facts are:

i. **Process safety barriers are the measures of control** that help to solve or prevent a potential accident
ii. To meet **increasing energy demands**, **more sour gas wells** will need to be drilled in the future

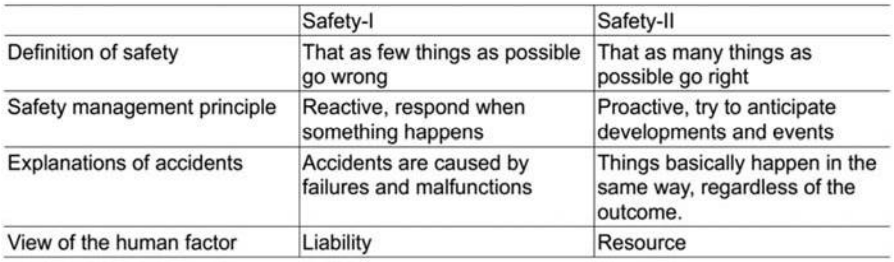
Considering the gaps presented and the facts which highlight the context for barrier discussions, it is clear that room for improvement in the area of evaluating barrier effectiveness specific to onshore drilling operations. As information is limited and subjective and complete information is not fully modeled, such as where qualitative and quantitative methods lack full modeling of inter-dependencies between barriers, it seems a semi-quantitative model may bridge the gaps that any of the previous models pose in isolation. As the industry will continue operating for the foreseeable future, it would benefit the industry to focus research in this area with the goal of reducing risk of barrier failure through employing effectiveness evaluation techniques that are designed specifically for onshore drilling.

After this literature review, the hypothesis that a semi-quantitative model may be an appropriate solution was elaborated and explored. Research and analysis was conducted to test the hypothesis with the aim of meeting two (2) objectives which will be announced in the next chapter. The following section will move forward to examine the research methodology that was executed for the current study in understanding the aforementioned gaps in barrier evaluation techniques and how such gaps may be addressed with a new hybrid solution.

2.5 Theoretical Underpinning

Safety definition transition (Safety I to Safety II theories)- from ‘avoiding that something goes wrong’ (Safety -1) to ‘ensuring that everything goes right’ (Safety-II)– or more precisely the ability to succeed under varying conditions, so that the number of intended and acceptable outcomes (in other words, everyday activities) is as high as possible. This can be called Safety-II. The basis for safety and safety management now becomes an understanding of why things go right, which means an understanding of everyday activities (Hollnagel E. , 2014) .

Safety I and Safety II theories and their key elements have been juxtaposed next to each other in Figure 2.17.



	Safety-I	Safety-II
Definition of safety	That as few things as possible go wrong	That as many things as possible go right
Safety management principle	Reactive, respond when something happens	Proactive, try to anticipate developments and events
Explanations of accidents	Accidents are caused by failures and malfunctions	Things basically happen in the same way, regardless of the outcome.
View of the human factor	Liability	Resource

Figure 2.17: Comparison of Safety I and II theories along with the key elements

Various risk models and methods have been developed since 2001 onwards supporting Safety II theory (2001 – Risk matrix based method, 2005 – ARAMIS technique, 2006 – Barrier and Operational Risk Analysis and 2015 – Layer of Protection Approach)

The Table 2.4 shows the models and techniques evolved supporting Safety II theory.

Table 2.4: Model / techniques (Barrier evaluation techniques and risk models) evolved based on Safety II theory

Model (year) – Authors	**Features**	**Gaps**
Risk Matrix based method (2001) – Middleton & Franks	Risk Matrix enables combinations of likelihood and consequences of major accidents to be combined in a single diagram	It **does not consider barrier performance** while evaluating Risk
Accidental Risk Assessment Methodology for Industries - ARAMIS (2005) - Salvi & Debray	The Accidental Risk Assessment Methodology for Industries (ARAMIS) is a barrier evaluation technique that relies upon quantifying Level of Confidence (LC), efficiency, and response time associated with a barrier	It is **only a barrier evaluation technique** and does not evaluate risk
Barrier and Operational Risk Analysis – BORA (2006) – Aven et al	• A method for qualitative and quantitative risk analysis of the platform specific hydrocarbon release frequency • Evaluates the effect on the hydrocarbon release frequency of safety barriers introduced to	It does not include the analysis of consequence barriers**, it only estimates frequency**, therefore it is not a complete risk model

Model (year) – Authors	**Features**	**Gaps**
	prevent release, and how platform specific conditions of technical, human, operational, and organizational Risk Influencing Factors (RIFs) influence the barrier performance	
The Layer of Protection Approach - LOPA (2015) – Landucci et al	Layer of Protection Approach (LOPA) is a three (3) step process that is meant to identify barriers and identify how layered barriers may prevent or delay a hazard	• It is a **barrier evaluation technique** and does not incorporate risk interpretation • LOPA approach is **best suited for static systems**, so application for dynamic situations is not ideal

Based on the review of existing models based on Safety II theory, it has been identified that the current models do not have an **integrated approach** for

dynamically evaluating risk (Combination of Frequency and Consequence) of MAHs considering barrier factors.

Two key research gaps were deduced from Literature Review and theoretical underpinning based on the review of models from Safety II theory:

- Barrier performance parameters specific to onshore sour gas drilling is not identified.
- Dynamic Risk assessment of MAHs which consider the failure of safety barriers for onshore sour gas drilling has not been carried out.