1. Introduction

Barriers have great significance in the oil and gas sector as they are intended to minimize the risk and consequence of accidents. Accidents in the oil and gas industry result in human fatalities, asset loss, environmental impacts and reputation loss (Kalantarnia M et al, 2010). Because of the great effects of accidents in the industry, there has been focus in the oil and gas sector on improving safety for people. Because of this focus, occupational safety (personal safety) has shown significant improvement due to occupational safety initiatives aimed at improving safety, as well as improvements due to indirect impact from major hazard regulations. The industry has an overall improvement factor of 8-10 in lost time injury statistics, as per the definition of company

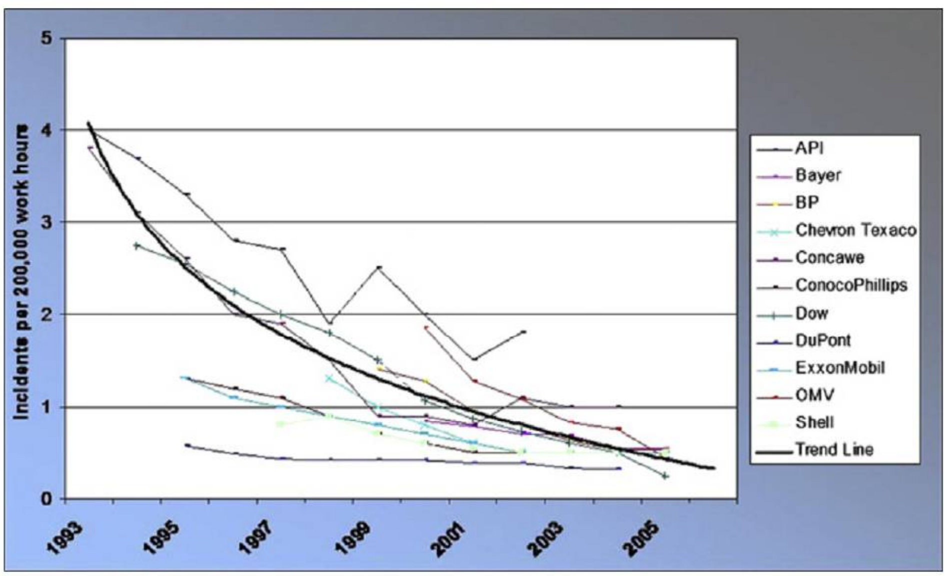

Figure 1.1: Occupational safety performance - company annual reports (Source: Pitblado, R, 2011)

Unfortunately, the improvements are not extending as significantly in the field of MAHs related to process safety. The term "process safety" refers to the collection of safety measures concerned with control of accidents relevant to the process industries (Marshall, VC, 2011). Specifically, in the last decade, a series of major accident events has affected both upstream and downstream industries which have led to great losses. In the upstream industry where drilling and extraction of oil occur, accidents include the P-36 loss in Brazil (2001) and a 250-fatality sour gas well blowout in China (2003) along with a set of near miss accidents. The near miss accidents reported for this decade in upstream include events in the United Kingdom and Norway between 2004 and 2007 from the Rough, Visund and Snorre facilities which had the potential to result in total loss. Meanwhile, the downstream industry where oil is transported, processed and refined also experienced major accidents. Such accidents include Toulouse (2001), Buncefield (2005), Texas City (2005) and several gas pipeline events in Belgium (2004), China and Saudi Arabia (2007) (Pitblado, 2011). For review of the extent at which losses have occurred above average, a trend of process safety losses grouped into 5-year periods is presented in Figure 1.2 (Marsh,

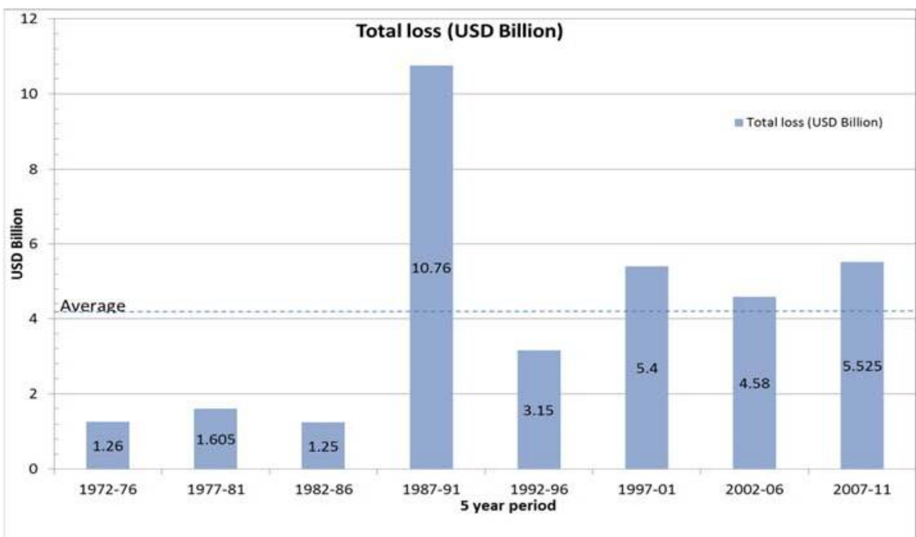

Figure 1.2: Process safety losses – 5-year period (Source: Marsh, 2011)

Based on the chart above, the industry has an average loss $4.2 billion due to process safety incidents per average five (5) year period over the last 40 years. Major accidents related to process safety in Europe and the United States is maintained by MARS and RMP-Star databases respectively. Review of these databases shows that there is no downward trend of accidents in these regions (Pitblado, 2004). Based on review of these databases, it is clear that process safety incidents have been a greater cause of large scale impacts in comparison to occupational safety incidents. Moreover, the process safety incidents which have occurred have resulted in significant human losses as well as financial losses to the associated companies. Clearly, to prevent or reduce impact of such accidents would be beneficial to all negatively impacted parties in such events. Accident prevention and impact reduction are outcomes which can be facilitated by safety barriers, as the next section will elaborate.

"Process safety" refers to the collection of safety measures concerned with control of accidents relevant to the process industries (Marshall, 2001). The term "safety measures" is synonymous with the definition of safety barriers in the context of process safety. Safety barriers are physical and / or non-physical which prevents, controls, or mitigates undesired events or accidents. Barriers may range from a single technical unit, human action or a complex socio-technical system (Sklet, 2006). The concept of safety barriers is closely related to Energy Model which refers to the "barrier" as an intermediary between the hazard and the victim as depict

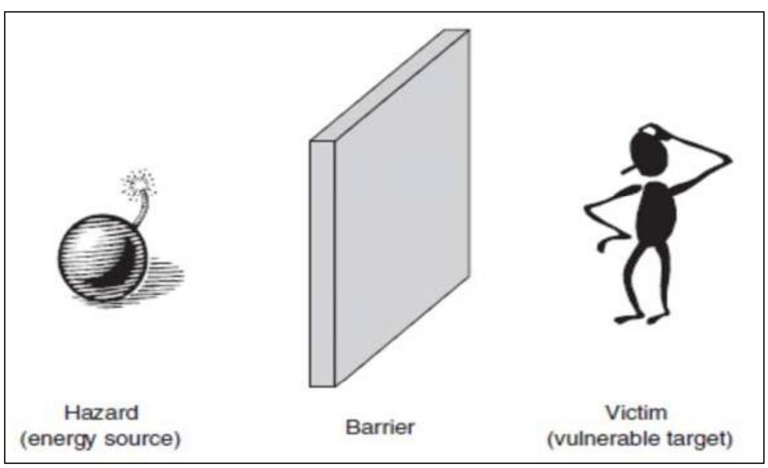

Figure 1.3: Energy Model (Haddon, 1980)

Maintaining the integrity of barriers in terms of preventing the failure or lack of the barriers and controls is a major key component in accident prevention. Trost (et.al, 1995) expressed barrier functionality in the context of prevention, control or minimization. The safety function describes the objective function, by answering "what is" required to assure and / or promote safety. The safety barrier describes the execution of the objective function on "how" to implement safety functions (Andersen et al, 2004). The barrier in this context includes hard and soft barriers. Hard barriers are the equipment or fully automated barriers whereas soft barriers are procedures and systems requiring human intervention for effective implementation (Reason, 1997).

A barrier is a means of preventing a hazard from reaching a potential victim. The potential victim(s) may be human, may be the environment or may be an asset. The focus of this work was on safety barriers that protect humans and assets. The barriers for this discussion pertained to drilling industries in particular. The reason for this focus related to the occurrence of incidents that are due to barrier failure in the industry. The context of this work considered such failures as related to the evaluation techniques for determining appropriate barrier use.

There is a point to note regarding the role of humans and human action being an important aspect of barrier application. Sometimes, humans are labeled as "barriers" when their direct action helps to prevent or minimize a hazardous impact. As recently discussed by McLeod, humans may be more appropriately deemed "safeguards" as opposed to labeling them as barriers, as they are not typically able to meet the full criteria of being considered an effective barrier (McLeod, 2017). This disclaimer also applies to organizational controls, which impact and influence barrier effectiveness, but should only be considered a safeguard in barrier effectiveness.

While it is inappropriate to consider a human to be a barrier, it is important to note that a human still has influence upon barrier effectiveness if a person fails to act properly as safeguard. It has been identified that safety barrier performance relies on human and organizational performance at various levels. It is suggested that weak relationships between personnel in drilling operations and training inadequacies can greatly contribute to the failure of non-human barriers as well as the failure of humans to act correctly as safeguards (Abulhassn, 2016). Now that it is clarified that a barrier may be physical, non-physical, simple, complex, or directly impacted by human action, the importance of maintenance efforts for any barrier type will be briefly mentioned.

There is purposeful intention for focusing on barrier effectiveness for drilling operations as opposed to other energy applications. Examples will be provided demonstrating specific events where there was great consequence as the result of barrier failure in upstream industries including onshore and offshore operations. Such examples will include statistics defining magnitude of implication relating to barrier failure, such as in the case of the onshore Chongqing gas well blowout where $48 million USD and 243 fatal casualties were among the consequences of multiple barrier failures (UNEP, 2004). Blowouts such as these occur more often in onshore operations, further creating reason for focus on barrier effectiveness for onshore drilling operations in particular (Newsmax, 2011). Based on the above information, the current business problem could be stated as follows:

> **"Failure of multiple safety barriers continues to result in catastrophic incidents, contributing to major human, asset and financial losses for the upstream oil and gas industry."**

Hence, there was a need to conduct research on risk evaluation specific to failure of multiple safety barriers in the upstream oil and gas industry.

Sour gas presents a variety of problems. Apart from the intense toxic and flammable hazards of sour gas, it damages drilling equipment and corrodes piping during gas production and transportation. It has been identified that the UAE has the third largest gas reserves in the Middle East (after Iran and Qatar) and fourth largest in the world (after Russia). UAE has 4% of the world's total reserves (Butt, 2001). The International Energy Agency has estimated about 43% of the world's natural gas reserves excluding North America are sour. The Middle East has the highest sour gas reserves in the world contributing to 60% (Huo, 2012). Based on the above information, UAE was considered as a representative sample to evaluate hazards from sour gas drilling operations.

The case for this research was based upon the evaluation of various barrier effectiveness models. Barrier analysis helps to identify missing or inadequately designed barriers and their influence on risk management. The intention of this review was to study the existing developments in barrier analysis techniques and reveal gaps which may form the basis for building future models. Based on the literature review, there were overlapping gaps, two (2) of which were highly critical. It was revealed that the first major gap relates to lack of literature related to the identification of barrier performance parameters specific to onshore sour gas drilling. The second major gap was that there was no literature related to risk assessment considering failure of safety barriers for onshore gas drilling. Based on the review of barrier effectiveness frameworks, it was concluded that no single model completely addressed quantification or qualification of risk considering prevention and mitigation barriers. The barrier models discussed here do not evaluate risk considering the "accident pathway" or the "failure path". In this publication, various barrier analysis techniques and their impact on risk management are elaborated.

The objective of the following was two fold. First, the objective was to identify the various parameters that are essential to define the barrier performance for onshore gas drilling operations in the UAE. The second objective was to develop a predictive barrier-based risk model for assessing the overall human impact & asset loss associated with onshore gas drilling operations in the UAE. The review of various models was undertaken by establishing common themes and using them as a criterion for comparison. The outcome was a recommended method specifically developed for onshore sour gas drilling operations. The implications to these objectives resulted with a list of parameters to measure and control the performance of each barrier protecting a system, and to increase efficiency in managing risks to personnel exposed to onshore sour gas drilling operations. The following outlines a brief explanation of content for each major chapter of this work.

The Literature Review chapter (Chapter-2) examines the definition of what classifies a barrier as being deemed “effective”. An effective barrier meets specific performance parameters in the context of risk assessment. The result of this section will be clarity on the definition of an “effective” barrier.

The next subsection of the Literature Review chapter outlines the evaluation models available to determine the effectiveness of a barrier, specific to the oil and gas industry. Whether or not a barrier is effective and to what degree it is to be effective is qualified by multiple methods. The most common methods were reviewed, and the limitations of each evaluation method have been explained. Due to each barrier evaluation method being limited in some way, one of the purposes of this chapter was to announce the need for further study on where a barrier evaluation method could be developed. The objective of this section was to clarify the problem in available models with the impacted industry base being onshore sour gas drilling operations The Literature Review chapter will then proceed to analyze the theoretical underpinning for this research and finally deduces the research gaps based on the review findings and theoretical underpinning.

After the Literature Review chapter concludes, this study moves on to the Research Design chapter (Chapter-3). The process for conducting survey-based research will be explored. This section explains the research methods carried forth to develop a gap closure via a new solution.

Moving the discussion forward, the Analysis and Results chapter (Chapter-4) reviews and analyzes the findings of the research and study conducted. The purpose of this section is to show the new information learned and by what means it was obtained. This section offers the conditions by which a new barrier evaluation technique was suggested as an outcome of this research to serve as an alternative to the existing options for barrier effectiveness evaluations.

Finally, the Recommendations and Conclusion chapter (Chapter-5) summarizes the findings and suggestions. The final part of this text recommends next steps and will suggests gaps that may need to be further considered beyond this work. The conclusion encompasses description of a hybrid solution for dynamic barrier evaluation which supports risk as it occurs in a live environment that considers human and organizational factors as well as hardware barriers (plant equipment). The proposed solution was realized through the integration of Bayesian Networks, Risk Matrix and consideration of barrier performance factors. Subchapter “Theoretical Contributions of Research” will offer theoretical contribution of knowledge through proposal of a new solution for evaluating barrier effectiveness. The solution will be suggested within the context of how to evaluate optimal barrier choice and performance for onshore sour gas drilling operations. The new method is intended for use in evaluating barriers to prevent MAHs and minimize risk of personnel and asset impacts associated with inadequate barriers.

This ending provides definitive closure regarding next steps that need to be taken to improve barrier evaluating techniques in the oil and gas industry.