5 Conclusions, Recommendations, Theoretical Contribution and Future Work

5.1 Conclusions

Through the analysis conducted in this work, key factors or themes were established which could be critical for evaluating safety barrier performance. The factors have been successfully tested for Content, Criterion and Construct Validities. Seven (7) factors were identified which influence barrier performance for onshore gas drilling operations based on Factor Analysis. The factors are Performance, Defense, Trust, Limit, Perception, Dependency and Robustness. These factors and the underlying 25 variables shall form the basis for building future risk models or barrier analysis methods.

Additionally, the factors were validated by 10 representatives from the drilling industry ranging from Senior Drilling Engineer, Asset Integrity Engineers, Process Safety Engineers, Drilling HSE Manager, HSE System Manager, Vice-President HSE and Safety Regulator. An overall score of 4.8 / 5 was obtained based on the feedback from the representatives. Through the evaluation of these factors for individual safety barriers, it could assist in the overall re-assurance of process safety (by evaluating safety barrier performance) in onshore gas drilling operations.

The research has presented an active risk monitoring method which evaluates barriers and transforms the existing Bow-Ties to a Bayesian Risk Model considering an onshore gas drilling environment. The driver for this research was due to lack of linkage in any of the existing risk frameworks between barrier performance and the associated risk impacts. MAHs put personnel, production, capital investment and corporate reputations at risk.

A review of MAH was conducted for three (3) onshore sour gas drilling operations within the region of the United Arab Emirates (UAE). The review was conducted to compare the various MAH along with the number of threats and consequences identified for each of the drilling operations. Based on the review, Asset-C was selected as the asset for application of the transformed Bow-Tie and Bayesian Risk model due to the comprehensive listing of the MAH and the associated safety barriers. Based on the identified MAHs for Asset-C, only six (6) out the eleven hazards were related to core drilling operations.

The Major Accident Hazards were further decomposed into thirteen (13) threats and six (6) consequences. The consequences considered for this research were focused on personnel and asset impacts. The Major Accident Hazards comprised of twenty eight (28) threat barriers and eighteen (18) recovery measures. It was observed that majority of the threat barriers and recovery measure barriers were associated with plant hardware or fully automated equipment. The drilling Major Accident Hazard Bow-Ties were transformed into potential accident pathways. Since, Risk is a combination of threats and consequences, it was decided to split the accident pathways into Threat and Consequence event pathways respectively.

In the next stage, Drilling and HSE personnel from the specific asset under consideration were required to rate each of the safety barriers using the identified factors. The ratings were carried on a five (5) point scale, where one (1) relates to Very Low (ineffective) and five (5) relates to Very High (effective). The average scores from all the participants were normalized by conversion of the rating scale from 1-5 to a normalized scale of 0-1 for usage as an input in the Bayesian Networks. The Bayesian Network for this analysis was developed using AgenaRisk Version 6.0 software. This software has been in use from 2005 and is widely used in defense, transport, banking, telecommunications and safety engineering companies owning safety critical systems for which quantitative risk assessment is required (Fenton & Neil, 2014).

Each of the safety barriers were modeled using the ranked nodes. Ranked nodes represent discrete variables whose states are expressed on an ordinal scale that can be mapped onto a bounded numerical scale that is continuous and monotonically ordered (Fenton et al., 2007). Ranked nodes have been defined on an underlying unit interval [0-1] scale. A five-point scale such as {very low, low, average, high, very high}, is chosen to model the individual safety barriers in the Bayesian Network. The interval width for each state is 0.2. Thus, "very low" is associated with the interval [0 - 0.2], "low" is associated with the interval [0.2 - 0.4], and so forth. Ranked nodes enable the Bayesian Network construction and editing task much simpler than is otherwise possible. Through this method, each of the threats and consequences were transformed into a dynamic Bayesian Network diagram.

Threat barriers and consequence barriers were evaluated using the constructed Bayesian Networks – an overall barrier performance is thereby evaluated for each of the thirteen (13) threats and six (6) consequences associated with all six (6) major accident hazard events. From the analysis of overall barrier performance, it was observed that the threat barrier effectiveness ranged from 68% (Induced well control and plugging pilot hole threats) to 78% (related to core drilling operations). This signifies barrier controls require more focus for induced well control and plugging of pilot hole operations in relative comparison to other threats. Similarly, consequence barrier effectiveness ranged from 70% on controls related to mitigate on- field impacts (Fire, explosion and toxic) to 75% on controls related to off- site and public impacts. In the next stage, IR and MR were referred from existing Risk Ranking Reports.

IR is evaluated as a criterion for MAH identification considering "NO" safety barriers. MR is ranked considering Safety barriers are perfectly functional (100%). IR and MR were ranked using ADNOC 5 X 5 Semi-quantitative Risk

Matrix (ADNOC, 2014). Meanwhile, risk control is built on the reduction of the frequency of occurrence of the major dangerous phenomena, taking into account the safety barriers' performance so that the dangerous phenomena are defined with an acceptable couple, i.e. gravity of the event (consequence) -frequency of occurrence (Dianous & Cecile, 2006). In reality, the AR exposure was correlated with safety barriers' performance.

It is observed that the AR for personnel is very close to the High Risk region and the risk is in the higher ALARP [2]region in comparison to the MR. For the Asset related risk, the AR is around the lower ALARP region in comparison to the MR which is in the Low Risk region.

Therefore, comparing the Personnel and Asset Risk, the AR exposure of personnel risk is slightly higher. The barrier based risk model & results were validated through a workshop consisting of mixed group comprising of HSE Manager, Process Safety Engineers, Senior Drilling Engineers, Senior Well Integrity and Regulators (Safety Department Manager). The validation parameters included were overall conceptual framework (barrier performance factors), relevance of data, models / techniques, interpretation of risk and overall applied value of the risk model (Abbas & Routray, 2013). The respondents have given a score of 4.8 to overall conceptual framework and models/ techniques, 4.6 overall applied value of the risk model, 4.5 for the interpretation of the results and 4.3 for the relevance of the data. The average of all the components was 4.62 which means that the model is highly reliable.

In conclusion, the respondents found value for the model application in real life. The risk assessment model allows for real analysis of barrier effectiveness in an onshore gas drilling application. The risk model presents the Actual Risk Exposure to the Drilling operations which will assist the decision making of the Management in a Drilling organization to identify the progressive deterioration of barriers and initiate corrective actions proactively.

[2] ALARP – As Low As Reasonably Practicable

This research has been conducted with structure, method, and attention to depth. However, there were noted limitations in the process of conducting this research. It is recommended that future researchers take note of the following limitations related to this study, and consider the implications for future work in this area of barrier analysis.

5.2 Limitations

The research was carried out with a certain limitation. Three (3) assets were considered for evaluating the risk for onshore gas drilling operations. However, in future studies, more fields could be considered and benchmarking of risk between the assets could be considered.

5.3 Recommendations

Based on the above conclusions, it is recommended that the concerned drilling organization needs to focus on personnel risk since the AR exposure of personnel risk is slightly higher in comparison to asset risks. Similarly, the company needs to re-visit and strengthen the threat safety controls specific to plugging of pilot hole and induced well control threats. For the consequence safety controls, there is a need to focus on controls mitigating on field release impacts to personnel.

Currently, the models have been developed and risk has been evaluated using Bayesian Networks. It is recommended that future studies could consider other Dynamic Risk models such as Petri nets and Markov models to evaluate the risk. It would be useful to compare the risk results using various models.

5.4 Theoretical Contributions of Research

Objective 1

Through the last decades, progress has been respectfully noted on the subject of barriers related to hazard prevention and mitigation. For objective one (1), there is now clarity on specific barrier performance factors for onshore gas drilling operations. This contribution belongs chronologically with predecessor contributions as follows:

1995 – Hollnagel lists the aspects that define barrier quality. The aspects include efficiency/adequacy, resources required, robustness, delay in implementation, applicability to safety critical tasks, availability and evaluation and dependence on humans (Hollnagel E. , 1995).

2002 – PSA defined that performance of barriers may relate capacity, reliability, availability, efficiency, ability to withstand loads, integrity and robustness (PSA, 2002).

2002 – PSA/ RNNS subscribed to oil companies that performance of safety barriers comprises of three components namely functionality/efficiency, availability/ reliability and robustness (PSA/ RNNS, 2002).

2004 – As part of ARAMIS project, evaluation of safety barriers is performed based on three (3) criteria. The criteria included effectiveness, response time and level of confidence (Andersen, et al., 2004).

2006 - Sklet has identified 5 attributes to characterize the performance of safety barriers. The identified attributes were functionality / effectiveness, reliability / availability, response time, robustness and triggering event / condition (Sklet, 2006).

Addition based on current research:

2017 - Through research, seven (7) factors have been identified to evaluate barrier performance. The factors include: performance, defense, trust, limit, perception, dependency and robustness.

The grouped variables under each of the factors are listed below:

i. Factor 1 – Performance factor

- Availability
- Validity
- Lagging indicators
- Effectiveness
- Barrier test simulation
- Safety critical tasks

ii. Factor 2 – Defense factor

- Adequacy

- Redundancy
- Impact of safety critical tasks
- Survivability

iii. Factor 3 – Trust factor

- Reliability
- Response time
- Integrity

iv. Factor 4 – Limit factor

- Triggering event
- Capacity
- Maintainability

v. Factor 5 – Perception factor

- Level of confidence during operations
- Error promptness
- Operational complexity
- Barrier reputation

vi. Factor 6 – Dependency factor

- Human dependence

i. Barrier inter-dependence

- Factor 7 – Robustness factor

i. Robustness

Objective 2

Since the turn of the century, progress has been respectfully noted on the subject of evaluating hazard risk and impact. For objective two (2), there is now clarity on an effective barrier evaluation technique that can be employed for onshore gas drilling operations. This contribution belongs chronologically with predecessor contributions as follows:

2001 - A Risk Matrix-based method can bridge the gap between purely qualitative and fully quantitative approaches. The Risk Matrix enables combinations of likelihood and consequences of major accidents to be combined in a single diagram (Carter et al, 2003). When all significant events are plotted on the same diagram safety critical events can be recognized and some indication of cumulative risks can be obtained (Middleton & Franks, 2001).

2006 - Barrier and Operational Risk Analysis (BORA) of hydrocarbon releases presented a method for qualitative and quantitative risk analysis of the platform specific hydrocarbon release frequency. This method analyzes the effect on the hydrocarbon release frequency of safety barriers introduced to prevent release, and how platform specific conditions of technical, human, operational, and organizational Risk Influencing Factors (RIFs) influence the barrier performance. Moreover, the BORA method does not include the analysis of consequence barriers, it only estimates frequency (Aven et al, 2006).

2005 - 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 (Salvi & Debray, 2005).

2015 - 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 interdependence. 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. Additionally, the LOPA approach is best suited for static systems, so application for dynamic situations is not ideal (Landucci et al, 2015).

Addition based on current research:

2017 - Based on the current effort, it can be concluded that the research has proposed a Dynamic Barrier based Risk Model. A Bayesian Based Network (BBN) is used to connect all the safety barriers and evaluate the frequency and consequence of a major accident event, thereby evaluating risk of major accident event. A barrier score is assigned considering various barrier performance factors to evaluate Operational Risk using a Risk Matrix approach. Through this method, risk is evaluated through the integration of Bayesian Networks, Risk Matrix and consideration of barrier performance factors. Moreover, The Bayesian Belief Network (BBN) is a dynamic integrated model (Ale, et al., 2014) for risk in a real time environment, inclusive of considerations for human and organizational factors. Bayesian Networks have been used to define the variables and the related inter-dependencies which are not be captured in linear and deterministic models (Hudson, 2010).

5.5 Implications for Future Work

There are a few points to regard relating to implications for future research. To begin, it is recommended to get a wider range of experts based on the comments in the previous section regarding limitations to this research. Also for future reference, other hybrid Bayesian Networks may be extended as model(s) to consider for this research to expand consideration for new risk evaluation solutions. One such consideration may include a hybrid Bayesian Network that accounts for multiple variables as contributors to overall barrier system reliability (Neil, Tailor, Marquez, et. al.; 2008). This would have positive impact on the breadth of future work. Another such consideration is to expand the discussion of risk assessments into other domains within the oil and gas industry. Other areas that share relevant application include downstream activities in gas processing within refineries, and in midstream activities where oil is primarily transported via pipeline migration.

In this study, focus has been given on individual safety barrier performance. It is imperative to understand the performance of safety barriers from the implementation perspective. Some of the safety barriers can result in a domino event (Landucci *et al*, 2016) which needs to be credited for their importance from a hazard management perspective. It would be critical to study specific aspects related to escalation in future studies.

Regarding the results for the first objective study, there are still two (2) aspects which needs to be detailed as further research is undertaken in this domain area. These factors identified through the listed variables should relate in some form of quantification to evaluate individual safety barrier performance as a standalone variable group. Secondly, further research needs to be carried out to evaluate several safety barriers and define an inter-linkage for risk definition especially for MAH scenarios specifically for drilling applications.

The following are the additional potential opportunities as an extension on this research in the future:

1. Currently, this study has focused on safety barriers in process safety. Similar study could be initiated in the field of personnel safety and relevant comparisons could be drawn

2. Risk model currently developed for onshore drilling applications could be further extended and evaluated for other application within the Oil and Gas industry (Such as Offshore facilities, Gas plant, refineries and distribution).

3. The developed risk model could be further applied and checked for validity in various business domains such as Enterprise Risk, Financial Risk and Environmental Risk applications

4. Considering barriers in other oil and gas domains will be beneficial, as well as considering how to optimize barrier performance in addition to evaluating barrier effectiveness.

Finally, it should be noted that this study focuses on barrier evaluation. Future research should consider optimizing safety barrier performance as progression on this topic. Considering barriers in other oil and gas domains will be beneficial, as will considering how to optimize barrier performance in addition to evaluating barrier effectiveness. With these considerations, future work will surely benefit from this sharing of research and conclusions and will be stronger for considering these implications.