Analysis and Discussion of Deepwater Horizon Accident and Barrier Strategies

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Preface

This report is a mandatory task in the course TMR4555, Applied Risk Analysis. The group members are Nathalie M. de Oliveira and Jeevith Hegde. Both members have worked together in all parts of the project.

The accident assigned to the pair was the Macondo Blowout of April 2010. Even though environmental, economic and reputation losses were hefty in this event, the team chose to focus on issues related to personnel safety. This decision was made in order to keep the work scope manageable.

MTO and energy flow perspectives were used to analyze the accident. Barrier failures were classified based on technical, human and organizational. Barrier failures in the interface between human and organizational aspects amounted to high number and therefore received attention when designing a new barrier strategy.

The new barrier strategy proposed included man, technology and organization barriers and listed their performance requirements. The team hopes to have achieved compliance with PSA's demands on designing barriers and a continuous barrier management process.

The team would like to acknowledge Professor Jan.Erik. Vinnem for his continued assistance and for sharing his knowledge with the class on the subject of *Offshore Risk Assessment*. The image for the title page is credited to [Ideum - ideas + media, 2010].

A famous quote from the character Uncle Ben in the comic *Spiderman* reads, *"With great power comes great responsibility"* . The Macando well would have been one of the deepest offshore wells ever completed, but the stakeholders involved in this accident failed to foresee the fatal accident propagation. As trivial as it may sound, this quote summarizes the lack of top level management focus of the stakeholders on safety.

1 Introduction

1.1 Overview of topics

The list of greatest human engineering accomplishments is long. From building the huge pyramids in ancient Egypt, to sending men to the moon or exploring the depths of the ocean, deeds have been executed by groups of engineers and other professionals that awe us. But oftentimes these mind blowing projects end up costing us much more than we were willing to pay, mainly when consequences are difficult to translate to monetary units, being cashed out on the environment or in lives that are lost.

Nonetheless, we believe most of these unwanted losses can be avoided if a proper barrier management system is implemented. The objective of the barrier management system is to isolate what we hold valuable from potential threats.

Deepwater Horizon, an ultra-deepwater semi-submersible offshore oil drilling rig built in 2001, owned by Transocean and working for BP in its last mission, had an inadequate Barrier Strategy for the Macondo drilling project. The consequence summed up to 11 deaths, 17 major injuries, sinking of the rig and massive environmental damage from estimated 5 million barrels of released hydrocarbons [CSB, 2014]. In the year previous to their accident, Deepwater horizon had drilled down to 10.5 km, the deepest oil and gas well in the world. A great achievement followed by a terrible fall.

But what was inappropriate in Deepwater Horizon's Barrier Strategy? Which barriers failed and what could have been done differently to achieve another outcome? In an accident with the Macondo Blowout magnitude, it is a challenge to answer these questions with the certainty that all possible aspects have been regarded. In this work, the aim is to address some of the most relevant barrier failures, as well as to suggest barriers that could have been implemented to avoid the accident.

We noted that by far the two notions *"Safety Culture must be rooted with top management"* and *"Barrier Management must be a continuous process, keeping pace with changes occurring in the execution phase of the project in opposition to a static safety strategy designed in the planning stage and never updated"*, are the most valuable changes that should be implemented in the organizations involved in this accident and overall over the entire Oil and Gas industry.

1.2 Structure of report

This report analyzes the Macondo accident and the Barrier Strategy that was in place when the accident happened. It also discusses what could have been different in order to minimize the escalation of the outcome or even interrupt the chain of events that caused the blowout.

The report will follow the risk for the people perspective, meaning the more than 80 days of oil spill after the sinking of the rig a, before the definitive shut down of the well, and the environmental damage are outside the scope of this report. We choose to limit the analysis of the accident up to the rescue of personnel not because the 5 million barrels of oil [Vinnem, 2014, The Deepwater Horizon Study Group (DHSG), 2011, CSB, 2014] reported to spill is of small importance, but to keep this work within a feasible outline for the Risk Analysis course, taught by Professor Vinnem. Section 3 starts with a condensed presentation of the accident chronology.

Section 4 starts by presenting barriers which failed and why, from a technical perspective, following the energy flow perspective and MTO perspective. This analysis then evolves to include human and organizational aspects relevant to discussed failures that permitted the accident to escalate to the point where 11 deaths and 17 injuries occurred. This part concludes with comparison of other similar accidents in terms of causes and consequences.

Section 5 proposes specified barrier strategy based on the failure of barrier functions revealed in the previous section. The section 6 concludes the report.

2 Terminology and abbreviations

2.1 Terminology

It is not unusual that different terms are used interchangeably across the oil and gas industry when describing the topic of safety barriers. The definitions of barrier terminologies in this report is refereed from [Sklet, 2006].

Safety barriers- are physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents.

Barrier function- is a function planned to prevent, control, or mitigate undesired events or accidents.

Barrier system- is a system that has been designed and implemented to perform one or more barrier functions.

Barrier element- A barrier element is a component or a subsystem of a barrier system that by itself is not sufficient, to perform a barrier function [Sklet, 2006].

2.2 Abbreviations

ALARP	As Low As Reasonably Practicable
BOP	Blowout Preventer
DHSG	The Deepwater Horizon Study Group
EDS	Emergency Disconnect System
ESD	Emergency Shutdown
HC	Hydrocarbon
LMRP	Lower Marine Riser Package
MTO	Man Technology Organization
NCS	Norwegian Continental Shelf
OIM	Offshore Installation Manager
PSA	Petroleum Safety Authority
SIL	Safety Integrity Level
TD	Total Depth

3 Summary of the Macondo blowout

The Macondo well-blowout accident resulted in 11 personnel fatalities, 17 personnel injuries, an estimated 5 million barrels of oil spilled, and vast environment pollution. [Vinnem, 2014, The Deepwater Horizon Study Group (DHSG), 2011, CSB, 2014]

The accident progression of the Macondo well blowout began in late 2009 when hurricane Ida passed the Mexican gulf damaging the Marinas rig. In January 2010, BP replaced the Marinas rig with the Deepwater Horizon rig from Transocean. When the exploration drilling resumed in February, a leak was identified in the yellow pod of the Blow-Out Preventer (BOP), subsequently the redundant blue pod reduced the leak. However, insufficient charge in the blue pod battery was discovered during investigations. While drilling in depth of 13305 ft, influx of formation fluids were noticed and the drill pipe and well logging tools were stuck. Drilling continued by well sidetracking operation. Two lost circulation incidents occurred in early April at depths of 18260 and 18360 feet. In both instances, the well was stabilized by pumping lost-circulation fluids. At the total depth (TD) of 18360 ft, BP decided to terminate further drilling citing unnecessary jeopardizing of the well bore.

BP chose to use the long string casing completion design and Haliburton was contracted to perform the cementing job. BP requested Halliburton to use 6 centralizers for the cementing job against BP's original plan of using 21 centralizers. The long string casing completion design was installed with 6 centralizers. On April 18th, BP attempted to circulate the well to plug the float collar or the reamer shoe. It took BP nine attempts before the float collar was converted at a pressure of 3142 psi. This high pressure required for the operation, raised concerns about blockages in the reamer shoe, breakdown of surrounding well formations and that the float collar may not have been converted as thought. Due to BP engineers fears of wash-out at the weak formations, BP decided to carry out a partial bottoms-up circulation of the well. Partial bottoms-up circulation meant that any hydrocarbons remaining in the bore could linger in the upper part of the well after cementing.

On 20th April, pressure monitoring observed the floats to be holding and the well in static state. BP planned to start the temporary abandonment procedure consisting of positive pressure test, negative pressure test, displacing drilling mud in the riser, setting cement plug, pressure testing cement plug integrity, performing impression test, and installing lockdown sleeve.

The crew carried out two different positive pressure and negative pressure tests, which were performed less than 48 hours after the cementing job in the bottom of the well. Simultaneous operations (displacing mud, pressure testing, trip tank cleaning, offloading mud to support vessel) meant that the crew was unable to monitor the mud pit levels. This also meant that the crew was unaware as to the amount of mud lost during displacement/flushing operations. There was more backflow than anticipated during the the first negative test and personnel at BP and Transocean had different interpretations of the results, which led to an agreement for a second negative pressure test. The second negative pressure test was accepted even after abnormalities were found in terms of backflow in the drill pipe. The pressure in the drill pipe increased and decreased several times.

The sea water was pushed into the drill derrick which was followed by uncontrolled flow of drilling mud. The crew diverted the hydrocarbon flow to the mud-gas separator, which was not designed to contain huge volumes of gas flowing through the well. Emergency systems failed to perform their function. Due to the latent failure in the BOP control pod's the emergency disconnect system (EDS) was not able to disconnect the Lower Marine Riser Package (LMRP). Two explosions occurred in quick succession and a mayday call was made by the crew. The decision to evacuate the platform was made. Some crew members jumped to sea and others mustered around the lifeboats. The evacuation process was chaotic, but 115 on board managed to be rescued.

For the next 83 days BP and partners made a series of attempts to stop flow of hydrocarbons into the Gulf of Mexico and after 10 different attempts were able to kill and seal the Macondo well.

4 Discussion- failed barriers

4.1 Man Technology Organization (MTO)

A step diagram of the Deepwater Horizon accident was constructed to identify key events and failed barriers leading to the accident. The illustration (Figure 2) depicts the failure in barriers during the accident. Accident causation theories such as, the domino theory, swiss cheese model and energy flow theories can be observed in this accident. To analyze the failure of barriers, an MTO perspective was chosen in combination with the step diagram as seen in Figure 2.

The scope for this analysis was selected to encompass key events leading to the Macondo accident. A color coding system is used to illustrate man, technology, and organizational barriers which failed during the accident progression.

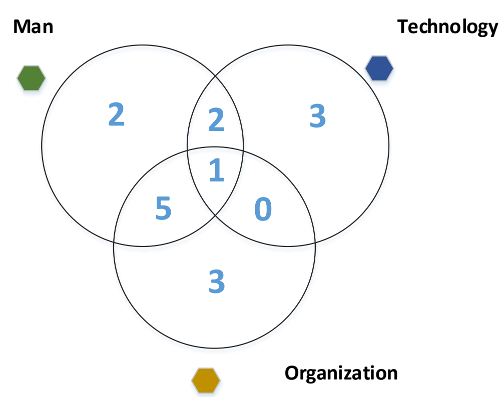


Figure 1: MTO analysis for Macondo Blowout

The results from the step diagram were further incorporated to setup a venn-diagram of MTO failed barriers refer Figure 1. The results show that failures in the intersection of man and organizational barriers are higher in number than other categories. The combination of man and organization resulted in six failed barriers. Choice of long string completion, MMS approval to use single string completion, use of 6 centralizers, incomplete bottoms up operations, early pressure testing, and alarm software disconnected.

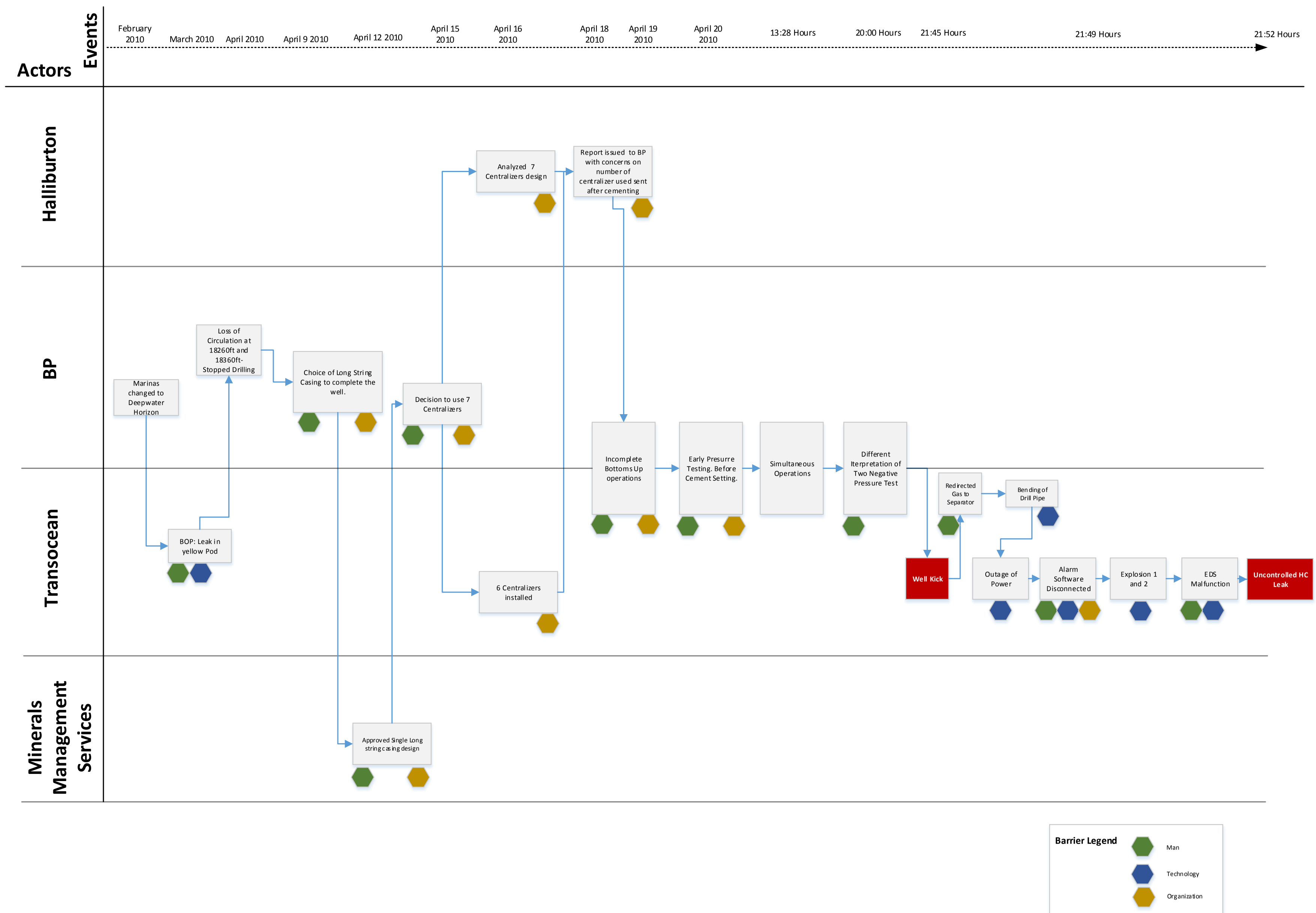


Figure 2: Step diagram with MTO barrier perspective

4.2 Energy flow perspective

The energy flow principle was used to demonstrated the flow of excess energy from the potential source- the reservoir to the vulnerable target- the crew members and topside structure. Together with the energy barrier principle, other accident propagation theories such as the domino theory and the swiss cheese model also provide theoretical background in this analysis.

From Figure 3, it is observed that the accident causation models mentioned above can be illustrated as the failed barriers in the Macondo blowout. The study assumed the Macondo blowout event to be the main accidental event. This event occurred because the physical barriers did not operate as they should have due to man, technology, and organizational factors. Subsequently, the flow of energy progressed from the reservoir to the topside facility. The barriers established to protect the crew and the topside facility were further weakened by failure of additional MTO barriers such as gas detection, fire deluge, and evacuation systems/process.

In majority of failed barriers, organization factors played a vital role in the accident. Choosing the less protective casing design, using less number of centralizers, pressure testing sooner than the cement setting time, inadequate quality in maintenance of equipment- BOP and topside gas detection systems, disabling alarm functions of the fire and gas detection/fighting systems, and chaotic evacuation process all of which contributed to the increased severity of the accident.

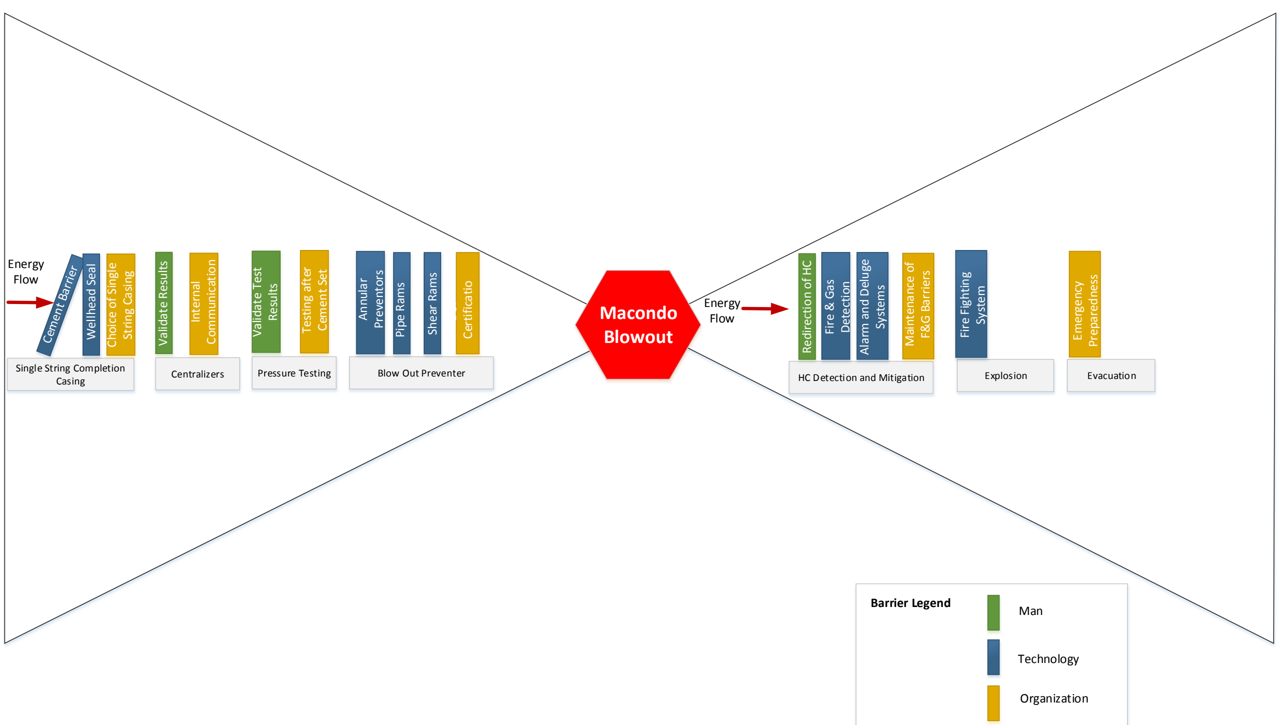


Figure 3: Energy barrier perspective

4.3 Comparison with similar accidents

[Vinnem, 2014] presents a table that compares similar accidents focusing on barrier functions and how/if they worked for each accident. From the presented set of accidents involving blowouts, three had severe consequence for life. Table 1 presents comparison of the Macondo blowout accident with the Usumacinta and Enchova blowout accidents.

Table 1: Comparison of similar accidents

Sl. No.	Facts of Accident	Macondo 2010	Usumacinta 2007	Enchova 1984
1	Initiating event	High pressures in the wellbore and formation	Bad weather	Unknown
2	Accident Progression	During work for abandonment of the well, a kick occurred that escalated to a blowout, with two big explosions, outage of power and sinking of the rig with a leaking well	While finishing to drill a well for a small production platform, a storm approached. The drilling platform was moved and struck the top of a production valve tree on the fixed platform, resulting in leaking of oil and gas. Safety valves were activated but unable to seal completely. Personnel died during evacuation of the platform.	During a drilling activity a gas leak caused a fire to start. This first fire was controlled, and a second fire, from a oil leak, occurred and lasted until the following day. Personnel died during evacuation of the platform.
3	Fatalities	11 of 126 (9%)	22 of 81 (27%)	42 of 249 (17%)

It is interesting to observe that in the previous two blowouts deaths occurred during the evacuation process in the installation, and Macondo's accident investigations lead us to believe that no lives were lost during this process.

One could infer that Transocean had better evacuation procedures than PEMEX (Usumacinta) or Petrobras (Enchova). Even though it was reported that a split chain of command between the Offshore Installation Manger (OIM) and the captain confused some of the crew members during the evacuation in Deepwater Horizon, no fatalities resulted during the evacuation stage [Vinnem, 2014, The Deepwater Horizon Study Group (DHSG), 2011].

4.4 Comparison with the Texas City Refinery accident (2005)

BP's Texas City Refinery explosion claimed 15 lives and injured more than 170 people.

Although this accident and Macondo Blowout aren't strictly similar, a parallel can be draw in the underlying causes of both events. To start, both accidents were considered avoidable if BP had taken appropriate measures (BP was identified as the main responsible). The lack of a safety culture geared towards system safety instead of only focusing to avoid labor accidents was also common to both events. The lack of appropriate maintenance in the level transmitters of the knockout drum and of the slitter tower, leading to malfunction, resembles the inadequate inspection of the BOP pods, previous to its installation in Macondo. Lastly, the refinery operator decision to ignore the high level alarm and continue to fill in the tower with hydrocarbons (BP Texas City Refinery) reminds us of BP's decision to proceed with the well abandonment procedure even though the pressure test result indicated something was amiss in the well (Macondo well). In both cases, there was pressure to complete work as fast as possible, that is, pressure to cut costs [CSB, 2007, The Deepwater Horizon Study Group (DHSG), 2011].

5 Proposed barrier strategies

From the previous sections it is observed that a *barrier strategy management* is vital to avoid risk of major accidents. The barrier strategies can be developed at different levels such as, man, technology, and organization. The Petroleum Safety Authority (PSA) in Norway has in the past focused on developing a framework for building a barrier strategies [PSA, 2013]. Figure 4 is the framework suggested by PSA to develop specific barrier strategies and corresponding performance standards for the barriers.

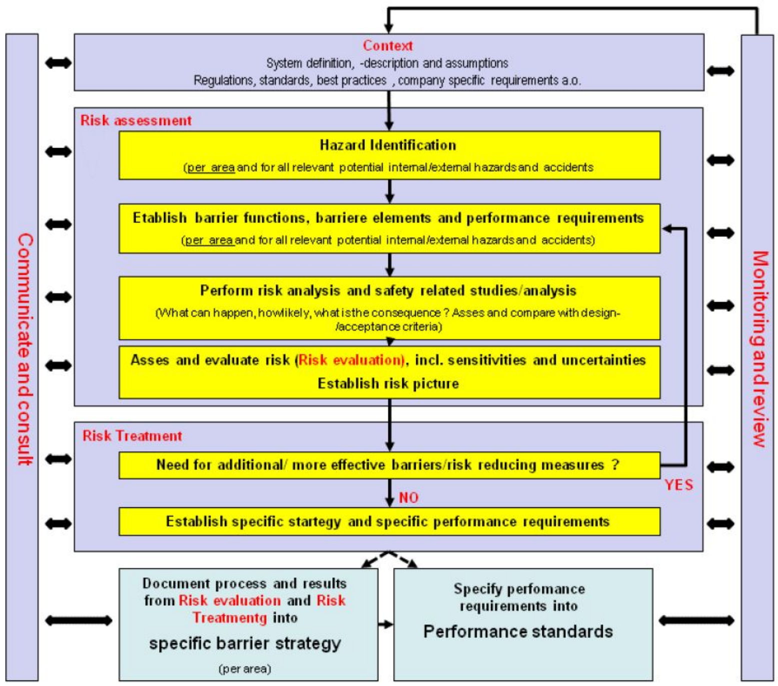


Figure 4: Barrier management in the planning phase [PSA, 2013]

The PSA barrier management framework was utilized in this study to develop barrier strategies. The subsections describe the method in detail.

5.1 Context

In relation to the Macondo blowout, the study was limited to risk of blowout during drilling operations at offshore installations. The study assumed that such an accident can re-occur in the Norwegian Continental Shelf (NCS) and the PSA regulations were referred for requirements on various contexts such as safety functions, fire and explosion protection systems, competence and training, and evacuation process [Petroleum Safety Authority Norway- PSA, 2014].

5.2 Risk assessment

The risk assessment process mentioned in the barrier management framework is a four step process. The first step is to identify hazards in and to the system. The second step is to control the hazards by identifying barrier functions, elements and performance requirements. The third step is to perform a qualitative or quantitative risk analysis of the system. The final step is to asses and evaluate the risks and present a risk picture [PSA, 2013].

5.3 Hazard identification

Hazard identification was carried out through a brainstorming session and by focusing on failed MTO barriers in Macondo blowout. The hazard identification was organized on basis of the checklist provided in [Rausand, 2011](page 67). The identification was limited to a blowout scenario and corresponding fire, explosion, and evacuation related hazards. Table 2 presents the generic hazards identified for the safety case.

Table 2: Hazard identification

SL. No.	Generic Hazard	Hazard
1	Mechanical hazards	High/unstable pressure in the well Stability Degradation of equipment
2	Dangerous materials	Flammable
3	Thermal hazards	Flame Explosion Personnel exposed to high temperature and heat radiation
4	Organizational hazards	Safety culture Less than adequate maintenance Less than adequate competence Crowd control

5.3.1 Preliminary hazard analysis (PHA)

A PHA was carried out with the process as described in [Rausand, 2005]. Barrier functions and elements were introduced as preventive measures to reduce the risk of a blowout. Both existing risk level without proposed barriers and residual risk with proposed barriers were assessed. The preventive actions were utilized to also develop proposed barrier strategy as discussed in Section 5.

Table 3, 4 presents the PHA worksheet with existing risk level and residual risk level. Table 5, 6 present the corresponding initial and residual risk picture.

Table 3: Preliminary hazard analysis

Generic Hazard	Identifier	Hazard	Accident Event	Probable Causes	Initial Risk Probability	Severity	Risk Level	Preventive Actions	Residual Risk Probability	Severity	Risk Level
Mechanical Hazards	1a	High/unstable pressure in the well	Increased reservoir pressure	Fluctuations in formation pressure	4	4	16	Isolate areas with different pressures and fluids.Pressure Testing (Negative and Positive). Bottoms Up.	3	2	6
	1b	Stability	Loss of stability	Ship collision	3	3	9	Collision Avoidance Alarms and Safety Zone Regulations	2	2	4
	1c			Rough weather	4	3	12	Avoid Rig Drift and Drive off	4	2	8
	1d	Degradation of equipment	Leak	Corrosion	2	3	6		2	3	6
Dangerous Materials	2a	Flammable	Hydrocarbon release (topside)	Ignition Source	4	4	16	Isolated hydrocarbons subsea. Reduce Risk of Explosion. Reduce Duration and Size of Leak. Limit Exposure of Personnel at Danger Zones.	2	3	6
Thermal Hazards	3a	Flame	Fire	Hydrocarbon leak (topside)	4	4	16	Isolated hydrocarbons subsea. Reduce Risk of Explosion. Reduce Duration and Size of Leak. Limit Exposure of Personnel at Danger Zones.	2	3	6
	3b	Explosion	Hydrocarbon release (topside)	HC leak (topside)	3	4	12	Isolated hydrocarbons subsea. Reduce risk of explosion. Reduce duration and size of leak. Limit exposure of personnel at danger zones. Personnel evacuation	2	3	6
	3c	Personnel exposed to high temperature and heat radiation	Fire	Improper facility design	4	2	8	Limit Exposure of Personnel at Danger Zones. Facility design based on hazards	3	2	6
Organizational Hazards	4a	Safety Culture	System safety compromised	Lack of top management focus on safety	5	3	15	Management focus on safety through inter/intra company campaigns, Accountability of the company towards safety incidents through industry and national regulations	3	2	6
	4b	Safety Culture	Wrong execution of plans	Communication challenges between stakeholders.	5	3	15	Establishing single point of contacts and analyzing it through social network analysis	4	1	4
	4c	Safety Culture	System safety compromised	Focus on delivery schedule instead of safety	5	3	15	Management focus on safety through inter/intra company campaigns, Accountability of the company towards safety incidents through industry and national regulations	3	2	6

Table 4: Preliminary hazard analysis (continued)

Generic Hazard	Identifier	Hazard	Accident Event	Probable Causes	Initial Risk Probability	Severity	Risk Level	Preventive Actions	Residual Risk Probability	Severity	Risk Level
Organizational Hazards	4d	Safety Culture	Personnel safety compromised	Complacent attitude towards safety	5	2	10	Management focus on safety through inter/intra company campaigns, Establishing continuous improvement safety drive in the company	3	2	6
	4e	Safety Culture	System safety compromised	Overlooking possibility of major accidents	5	3	15	Management focus on safety through inter/intra company campaigns, Accountability of the company towards safety incidents through industry and national regulations	3	2	6
	5a	Less than adequate maintenance	Project delay	Focus on delivery schedule instead of safety	5	3	15	Management focus on safety through inter/intra company campaigns, Accountability of the company towards safety incidents through industry and national regulations	3	2	6
	5b		System safety compromised	Low quality audits (certification)	4	4	16	Accountability of the company towards safety incidents through industry and national regulations	4	2	8
	5c		Project delay, System and personnel safety compromised	Cost cutting in operations	4	2	8	Re-optimize maintenance costs	3	1	3
	5d	Less than adequate competence	Wrong decision making	Lack of training and experience of personnel	4	3	12	Investment in training personnel. Investment in mentoring programmes. Hiring competent personnel. Sharing lessons learned to other companies	2	2	4
	5e		Work overload	Lack of personnel	3	4	12	Hiring competent personnel based on project forecasts. Outsourcing work to consultant companies	3	2	6
	5f	Crowd Control	Man overboard	Critical process/procedure variations	3	3	9	Timely certification and maintenance of safety critical systems, Plans for emergency preparedness based on facility design.	2	2	4
	5g		early launch of life crafts	Improper evacuation procedure	3	4	12	Plans for Emergency Preparedness based on facility design	2	2	4

5.3.2 Risk level picture

From Table 3 and 4 a risk picture was established in a 4 X 5 risk matrix. The risk matrix is based on the ALARP principle along with classification inputs from [Rausand, 2005]. The classification of probability and severity classes are provided in Appendix A of the report. Table 7 provides the color legend for the 4 X 5 risk matrix.

Initial risk matrix- The results from the initial risk matrix show 15 hazards, which fall under the not acceptable limits of the ALARP principle. While 5 hazards fall under the acceptable zone of the ALARP principle.

Table 5: Initial risk matrix

Frequency/ Consequence	1-Very Unlikely	2-Remote	3-Occasional	4-Probable	5-Frequent
4-Catastrophic			3b, 5e, 5g	1a, 2a, 3a, 5b	
3-Critical		1d	1b, 5f	1c, 5d	4b, 4c, 4e, 5a
2-Major				3c, 5c	4a, 4d
1-Minor					

Residual risk matrix- Residual risk matrix demonstrates the risk reduction achieved by introduction of risk reducing measures (preventive actions). In other words, the residual risk is the risk left over after the introduction of risk reducing measures.The results from the residual risk matrix show a reduction in risk level. 16 hazard items fall under the acceptable zone of the ALARP principle, but these risks can further be reduced by introducing additional preventive actions. While 5 hazard items fall under the acceptable zone of the ALARP principle.

Table 6: Residual risk matrix

Frequency/ Consequence	1-Very Unlikely	2-Remote	3-Occasional	4-Probable	5-Frequent
4-Catastrophic					
3-Critical		1d, 2a, 3a, 3b, 5b			
2-Major		1b, 5d, 5g	1a, 3c, 4a, 4c, 4d, 4e, 5a, 5e, 5f	1c	
1-Minor			5c	4b	

Table 7: Risk matrix colour legend

Colour	Legend
	Not Acceptable- Risk reduction required
	Acceptable using ALARP. Consider further risk reduction.
	Acceptable.

5.4 Risk treatment

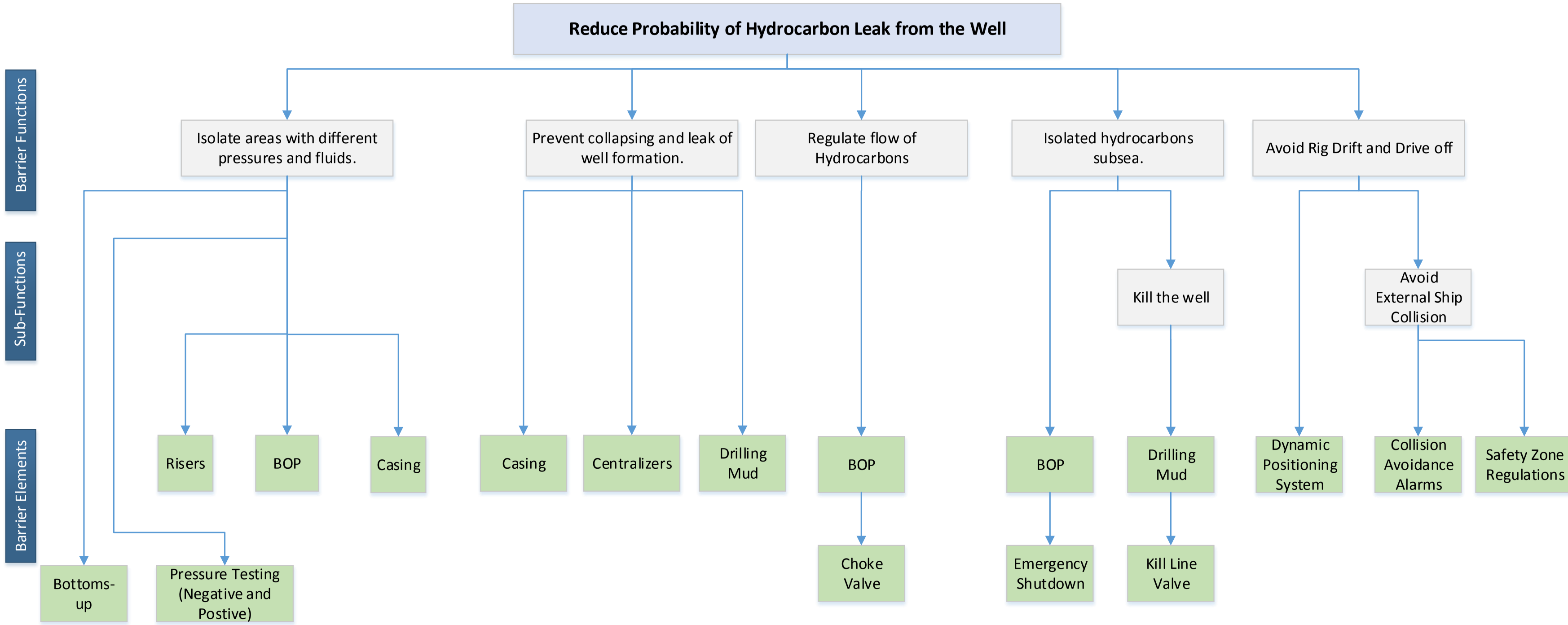
One of the steps in the PSA barrier management framework is to evaluate need for further risk treatment after introducing the preventive actions. In the current study, the residual hazards in the system were as low as reasonably practicable- ALARP. Therefore, the study continued with the next stage- developing specific barrier strategy to avoid recurrence of such accidents in the future. The next subsection describes the barrier functions, sub functions and elements.

5.5 Specific barrier strategy

According to [PSA, 2013], the setup of barrier management for the offshore industry consists of the following steps: the risk picture identifies risks that need reduction; the reduction of these risks is achieved by implementation of barrier functions; barrier functions must be further specified down to barrier elements; to be manageable, these functions or elements need to be measured or evaluated in some way, and the way to do it is do define which requirements they need to fulfill.

In this section we present the selected barrier functions and elements, both to decrease the probability that an accident may occur, in Figure 5 and to decrease the consequence in case an accident occurs, in Figure 6. Later, in section 5.6 performance requirements/standards, the requirements are presented.

Figure 5 can be roughly divided in two parts, one part where a block diagram presents technical barriers, and the second part where a green rectangle presents man and organizational barriers. These barriers are connected to the risk picture presented in tables 3 and 4. The same is valid for Figure 6. While technical barriers presented in both figures were already in place in Deepwater Horizon albeit containing failures, some of the suggested man and organizational barriers were not part of their barrier strategy in the time of the accident.



Organization and Man barriers are included in each barrier element because the selection of the above phyiscal barriers depends on the individual/organization perceptions in form of analysis and design.

- Management focus on safety through campaigns. (Top to bottom and bottom to top)
- Accountability of the company towards safety incidents through industry and national regulations
- Establishing single point of contacts and analysing it through Social Network Analysis tools
- Continuous improvement of safety drive in the company and expansion of each project's Risk Analysis Assessment to keep up with changes made to the original plan during the execution phase - continuous reassessment of the risk picture.
- Periodically re-optimize maintenance costs
- Investment in continuous training of personnel in best available safety practices
- Investment in mentoring programmes
- Hiring competent personnel
- Sharing lessons learnt to other companies
- Timely certificaiton and maintenance of safety critical systems

Figure 5: Proposed barrier management- prevent accidents

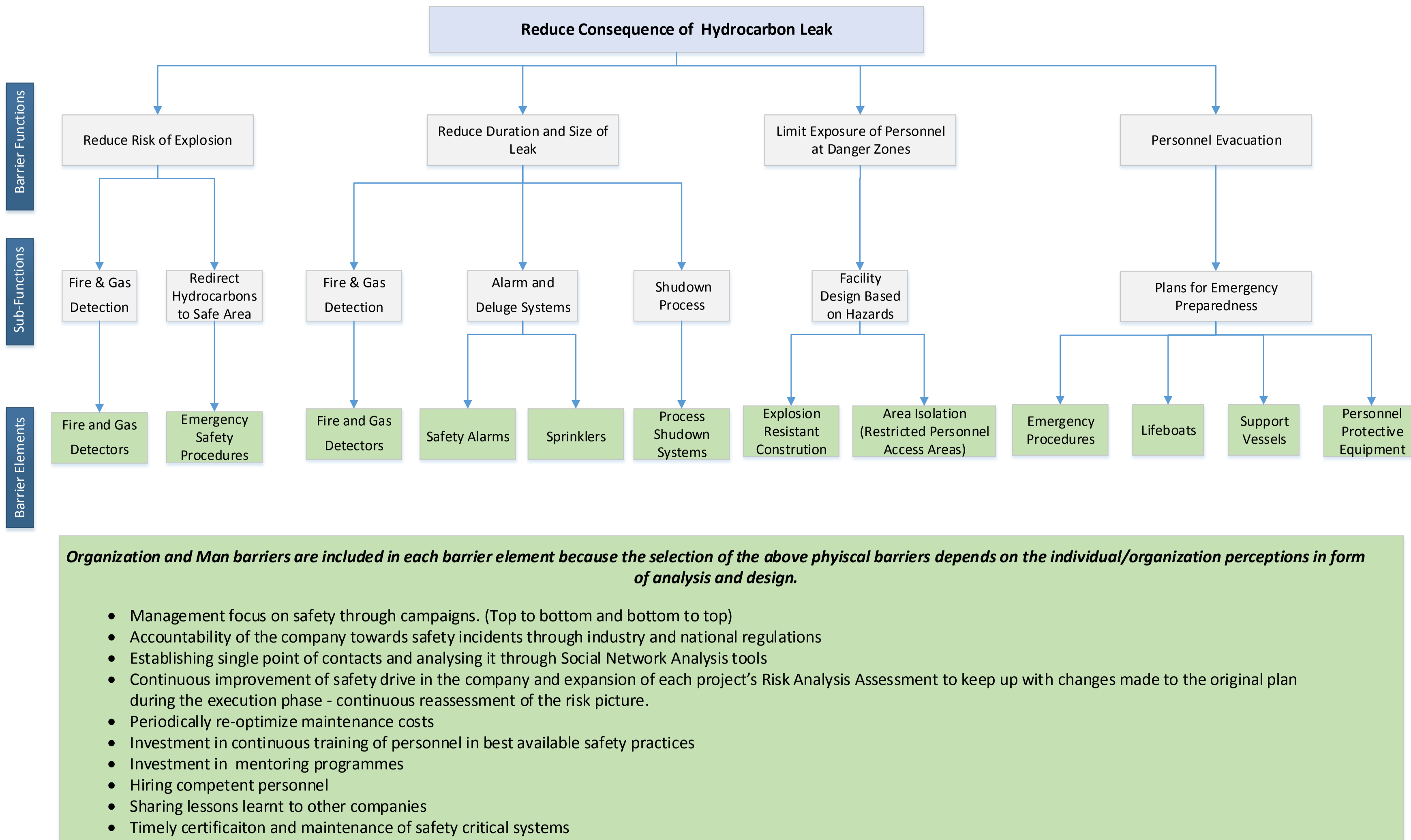


Figure 6: Proposed barrier management- mitigate consequences

5.6 Performance requirements/standards

PSA requires that safety barriers are specified along with their performance requirements in order to ensure effective barrier management [PSA, 2013]. The main goal of this process is to ensure "measurement" of barrier performances to predefined barrier requirements.

Table 8, 9, 10 present requirements for the proposed barrier strategy. The barriers in Table 8 correspond to reducing probability of hydrocarbon leak from the well refer figure 5 while, Table 9 corresponds to reducing the consequence of hydrocarbon leak refer figure 6. Table 10 corresponds to both figures 5 and 6.

Table 8: Barrier performance standard- functional level

Barrier	**Performance Standard** (Functionality, Integrity, Vulnerability)	**Performance Standard**
Isolate areas with different pressures and fluids	Functionality	Established pressure limits in various zones
Prevent collapsing and leak of well formation	Functionality	Loss of drilling mud should not exceed the given limit
Regulate flow of Hydrocarbons	Integrity	Minimum failure rate of BOP through quantitative analysis. Example- SIL analysis
Isolated hydrocarbons subsea	Integrity	Minimum failure rate of BOP through quantitative analysis. Example- SIL analysis
Avoid Rig Drift and Drive off	Functionality	Limits and accuracy dynamic positioning system envelopes

Table 9: Barrier performance standard- element level

Barrier	**Performance Standard** (Functionality, Integrity, Vulnerability)	**Performance Standard**
Fire and Gas Detectors	Integrity	Determine acceptable failure rate of detectors through quantitative analysis. Example- SIL analysis
Emergency Safety Procedures	Functionality	Be aligned with the risk picture
Safety Alarms	Integrity	Determine acceptable failure rate of detectors through quantitative analysis. Example- SIL analysis
Sprinklers	Integrity	Determine acceptable failure rate of FF equipment through quantitative analysis. Example- SIL analysis
Process Shutdown Systems	Integrity	Determine acceptable failure rate of Process Shutdown System through quantitative analysis. Example- SIL analysis
Lifeboats	Functionality	Have sufficient capacity to include all personnel onboard the rig
Support Vessels	Functionality	Response to an emergency call within a given time limit
Restricted Personnel Access Areas	Functionality	Normally manned working stations should be sheltered or out of reach from potential explosions caused by HC release
Personnel Protective Equipment	Vulnerability	Guarantees impact and thermal protection to a stipulated level

Table 10: Barrier performance standard- organization level

Barrier	Performance Standard (Functionality, Integrity, Vulnerability)	Performance Standard
Management focus on safety through campaigns	Functionality	Commit management time to safety activities. Safety walk. Walk-Observe-Feedback.
Accountability of the company towards safety incidents through industry and national regulations	Functionality	Social corporate responsibility drive
Establishing single point of contacts and analyzing it through Social Network Analysis tools	Functionality	Make contact information of single points of contact public and know
Continuous improvement of safety drive in the company and expansion of each project's Risk Analysis Assessment to keep up with changes made to the original plan during the execution phase - continuous re-assessment of the risk picture.	Functionality	Risk Analysis Assessments should be reviewed at fixed intervals during planning phase and whenever a major modification to plan occurs during project execution
Periodically re-optimize maintenance costs	Functionality	At predetermined given time intervals, aiming to cut a given percentage of labor
Investment in continuous training of personnel in best available safety practices	Functionality	Annual evaluation of relevant technical knowledge
Investment in mentoring programmes	Functionality	Ensure mentoring program for new employees
Hiring competent personnel	Functionality	Assessment of technical knowledge and personality
Sharing lessons learnt to other companies	Functionality	Target number of published industry white papers
Timely certification and maintenance of safety critical systems	Integrity	Traceability of equipment and process certificates

6 Conclusions

Through this accident analysis, it is observed that complex systems tag along with complex accident propagation. The consequences in such systems also highlight the need for continued focus on barrier management. However, to understand the nature of faults and failures in such systems a thorough risk analysis is paramount.

Organizational and human barriers and their performance requirements are difficult to define, maintain, and measure. Nonetheless, these barriers are frequently in demand during offshore accident progression. The current study observed that the amount of organization and human barriers that failed in the Macondo blowout increased both the probability of blowout occurrence as well as the consequences associate with the blowout. In instances in this accident, technical barrier failed on account of previous organizational or human barrier failure. For example, the failure to certificate the BOP probably allowed the wiring of the pods to go amiss and the battery on the yellow pod to discharge ahead of time, both technical failures. The same happened in the numerous attempts to control the HC leak to the sea, after the rig had sunk.

This study points on the direction that inadequate human and organizational barrier functions were tightly connected to the development of the Macondo accident. It indicates that there is room for improvement in assessment and treatment of major accidents scenarios, and that system safety should not be neglected in favor of traditional HSE performance indicators.

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A Appendix- PHA Parameters

A.1 Probability Classes

Table 11 presents classification of probability classes as suggested by [Rausand, 2005].

Table 11: Probability classes

Rank	Probability class	Description
1	Very unlikely	Once per 1000 years or more seldom
2	Remote	Once per 100 years
3	Occasional	Once per 10 years
4	Probable	Once per year
5	Frequent	Once per month or more often

A.2 Severity Classes

Table 12 presents classification of severity classes as suggested by [Rausand, 2005].

Table 12: Severity classes

Rank	Severity class	Description
4	Catastrophic	Failure results in major injury or death of personnel.
3	Critical	Failure results in minor injury to personnel, personnel exposure to harmful chemicals or radiation, or fire or a release of chemical to the environment
2	Major	Failure results in a low level of exposure to personnel, or activates facility alarm system.
1	Minor	Failure results in minor system damage but does not cause injury to personnel, allow any kind of exposure to operational or service personnel or allow any release of chemicals into the environment.