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THE EFFECT OF MACONDO BLOWOUT ON RISK ANALYSIS AND RISK MANAGEMENT

Master Thesis by
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ABSTRACT

On April 20th, 2010 the offshore petroleum industry was hit by a severe accident. The undetected entry of high pressure – high temperature, highly charged hydrocarbons out from the Macondo exploration well to the rig and the ignition of hydrocarbon caused a blowout and a catastrophic explosion. The accident took place during the temporary abandonment. It killed 11 platform workers while 17 others were seriously injured.

The Macondo blowout was followed by extensive investigations, studies and researches with an aim at strengthening safety and reducing risk during drilling in complex offshore environment.

In this Master thesis, a thorough analysis is conducted to evaluate the recent development of risk analysis and risk management in oil and gas industry. A focus will be on Macondo accident and its effect on organizational factors, effects on standard and regulations, impacts on regulatory bodies and associations. Based on risk analysis techniques, measures will be proposed to improve barriers performance and safety during drilling and wells completion in the Deepwater environment.

The basis of this work will be the literature review, the study of existing investigations reports as well as interviews with professionals and experts within the oil and gas industry with the aim at finding how the Macondo accident has impacted the safety culture when it comes to the concept, the design and the drilling operations.

Keywords: *HPHT, Risk Analysis, Risk Management, Barriers performance, Risk communication*

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ABBREVIATIONS

APB	Annular Pressure Buildup
BAT	Best Available Technology
BHP	Bottom Hole Pressure
BP	British Petroleum
BOEM	The Bureau of Ocean Energy Management
BOP	Blow out Preventer
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BSR	Blind Shear Ram
BSEE	The Bureau of Safety and Environmental Enforcement
CCD	Cause Consequence Diagrams
CNSOPB	The Canada - Nova Scotia Offshore Petroleum Board
CSE	Concept Safety Evaluation
DHIRG	Deepwater Horizon Incident Review Group
DwH	Deep water Horizon
ECD	Equivalent Circulation density
EDS	Emergency Disconnect System
EER	Escape, Evacuation, and Rescue
ESD	Emergency Shut Down
ESV	Emergency Shutdown Valve
FTA	Fault Tree Analysis
HES	Health, Environment and Safety
HPHT	High Pressure High Temperature
HSE	Health and Safety Executive (UK)
IADC	International Association of Drilling Contractors

IRF	International Regulators Forum
LWD	Logging While Drilling
MODU	Mobile Offshore Drilling Unit
NCS	Norwegian Continental Shelf
NMD	Norwegian Maritime Directorate
NOFO	Norwegian Clean Seas Association for Operating Companies
NSOAF	The North Sea Offshore Authorities Forum
OCS	Outer Continental Shelf
OGP	International Association of Oil and Gas Producer
OLF	Norwegian Oil Industry Association
ONRR	Office of Natural Resources Revenue
OSD	Offshore Division
OSPRAG	Oil Spill Prevention and Response Advisory Group
PSA	Petroleum Safety Authority
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
QRA	Quantitative Risk Analysis (Assessment)
REWI	Resilience Early Warning Indicator
SEMS	Safety and Environmental Management Systems
SINTEF	The Foundation for Technical and Scientific Research at NTNU
TRA	Total Risk Analysis
UKCS	United Kingdom Continental Shelf
WLCPF	Well Life Cycle Practices Forum

1. INTRODUCTION

1.1. Background

Although major accidents are generally a dark spot in the history of humanity, they are at the same time, a source of inspiration and a challenge for scientists and engineers in their efforts for creating measures to prevent accidents of its kind in the future.

The Macondo blowout that took place nearly 3 years ago continues to be a subject of in-depth investigations, studies and researches with a purpose that lessons learned could serve for safe drilling operation in new oil and gas fields located in complex Deepwater offshore environments and in the Arctic.

This tragic accident has called for profound transformation; new technologies have been introduced, new bodies and entities created while various policies, regulations and standards have been revised. On the other hand, commissions have been created and the experience obtained from Macondo accident is being used to improve safety and emergency preparedness in relation to drilling and well operations.

In the aftermath of Macondo accident, several reports and publications were devoted on the event exhaustive review and therefore they reported on precautions and technologies that should be required to improve the safety of oil and gas exploration and production operations (US Department of the Interior, May 27, 2010). Others dealt with the facts surrounding the accident and thus analysed available information to identify possible causes and made recommendations to prevent similar accidents in the future (BP Investigation Team, September 8, 2010, Petroleum Safety Authority, 2011a, Transocean, 2011). While the remaining category, though not exhaustive in this study report, were made with an expectation that lessons learned from Macondo blowout bring new emphasis on practical risk analysis and risk management in the industry (Skogdalen and Vinnem, 2011, Vandenbussche et al., 2012, Ulveseter and Vasset, Sept 15th 2012 , Øien and Nielsen, 2012, John et al., 2013).

This master thesis will mainly examine the recent development of risk analysis and risk management following the Macondo accident. A special attention will be the investigation of hazards linked to subsurface formation, drilling technology as well as the organizational and human decisions. It will suggest the needed improvements to avoid the occurrence of blowouts during drilling and/or wells completion in complex Deepwater environment.

1.2. Purpose

The purpose of this Master thesis is primary to evaluate the impacts of the Macondo accident on risk analysis and risk management, in particular changes related to regulatory bodies, organizational factors, standards and regulations.

In addition, the aim of the thesis is to provide new insights on hazards/risks associated to organizational factors, subsurface geological conditions and the well design in order to avoid blowout and/or well loss problems during drilling operations in HPHT conditions.

1.3. Content

The master thesis is divided into 4 chapters, including this introduction chapter which provides a background for the work, the purpose, the content and the study methodology.

The second chapter provides an exhaustive literature review of risk analysis and risk management studies followed by the Macondo blowout. It gives a comprehensive understanding of risk associated with deepwater drilling and completion from subsurface characterization and geohazards analysis, drilling technique and well design, operational barriers (human and organizational factors) as well as risk methods and tools used to analyse hazards during drilling operations. This chapter also discloses in detail the Macondo accident failure path by systematically revisiting the performance of primary and secondary barriers as well as flaws observed during the well control and response when the hydrocarbon was observed on the rig floor.

The third chapter reflects on the effects of Macondo accident on policy, regulations and organizations. It underlines changes occurred in USA, from the institutional reform to the introduction of the new offshore drilling regulation including the Drilling Safety Rule, the Workplace Safety Rule, and the requirement of the performance – based regulations for all operators in the OCS to implement a Safety and Environmental Management System. Here, the master thesis basically highlights revisions made with respects to the API recommended practices: API RP 53, API RP 65–2, API RP 75 and API RP 96. Also highlighted is Norway, with the need of the industry to give a high priority the development of a more integrated and uniform approach to barrier management as well as specific changes occurred with Norsok D-001, D-002, D-010 and Z-013. In addition, also discussed is the UK, with a sensible reinforcement of peer review of well design assessments and rigorous auditing approach of Safety Case acceptance for MODUs.

The last chapter of the present study discusses barriers performance requirements as part of improvement in risk analysis and risk management. The chapter considers that technical, operational and organizational barrier elements must display characteristics such as: capacity, functionality, effectiveness, integrity, robustness and availability. The discussion held in this chapter emphasizes on barriers performance compared to recent improvement in policy, regulations and standards, the understanding of sub surface characterizations, the risk and technology development as well as the safety management perspective.

In the conclusion, the master thesis finds that extraordinary improvements have been made in term of revised policy, regulations and standards. Other decisive efforts are also observed within technology development for a safe drilling operation in more difficult environment of Deepwater and in the Arctic. However, the study points out that the risk perception and risk communication remain crucial for an overall improved safety culture in the oil and gas industry.

1.4. The basis and study methodology

The master thesis will be based on primary, secondary and tertiary sources:

(1) Primary sources used in this study are standards, rules and regulations, the US President Commission investigation report known as the Salazar report as well as interviews with experts and professional in oil and gas industry.

(2) Secondary sources include (i) the Deepwater Horizon Accident Investigation Report (2010) by BP Incident Investigation Team; (ii) the Final Report on the Investigation of the Macondo Well Blowout (2011) by Deepwater Horizon Study Group (DHSG); and (iii) The Macondo Well Incident: Transocean Investigation Report. Volume June 2011; while

(3) Tertiary sources are textbooks and publications that describe and analyse the accident. Other readings about drilling operation will be also used with a focus on risk analysis and risk management.

2. MACONDO BLOWOUT: THE ACCIDENT AND THE FAILURE PATH

Macondo[1] is an oil field prospect located in Mississippi Canyon Block 252 of the Gulf of Mexico approximately 68 km southeast from the nearest shorelines in Louisiana. The prospect was purchased by British Petroleum (BP) for the mineral rights to drill for oil at the Minerals Management Service's lease sale in March 2008 (Bureau of Ocean Energy Management Regulation and Enforcement (BOEMRE), 2008).

The prospect may have held 50 million barrels (7.9×10^6 m^3) producible reserves of oil (Edward, May 13, 2010). On October 7th, 2009 the Transocean Marianas semi-submersible rig commenced drilling, but operations were halted November 29th, 2009 at 4,023 feet (1,226 m) below the sea floor, when the rig was damaged by Hurricane Ida (Spear, May 23, 2010). The Transocean Deepwater Horizon rig resumed drilling operations in February 2010 (www.subseaiq.com, Jan 20, 2012).

On April 20th, 2010 the failure of well integrity followed by the undetected influx and the ignition of hydrocarbons caused a blowout and a catastrophic explosion on the Deepwater Horizon offshore oil drilling platform. To understand the Macondo accident, the contributing factors as well as risks associated to the blowout, the current study report has found necessary to review the subsurface characterizations and geo hazard analysis in addition to others complex relationship such as well design, human and organisational factors that made the Macondo disaster to happen. Based on existing investigation reports (BP Investigation Team, September 8, 2010, Chief Counsel's Report, 2011, Transocean, 2011, The Deepwater Horizon Study Group (DHSG), March 1, 2011), the following section systematically revisit barriers performance and raisons that have caused their defection during Macondo well completion. It also provides in brief the design, engineering, logistical, and operational challenges related to Macondo.

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[1] Macondo- the prospect name given by BP, after the fictional town in Gabriel Garcia Marquez's 1970 novel: "*One Hundred Years of Solitude*".

2.1. A review of risk analysis and management studies related to the Macondo blowout

Nearly three years have passed since the Macondo blowout. The accident happened April 20th, 2010 due to the loss of well control as all the system's barriers failed to contain the hydrocarbon kick. The undetected entry of high pressure – high temperature, highly charged hydrocarbons out from the Macondo exploration well to the rig and its subsequent ignition caused a blowout and a catastrophic explosion. The accident killed 11 and severely injured 17 platform crew workers. A severe fire fed by the hydrocarbons from the well continued for 36 hours and caused the MODU sank. For almost three months, a large offshore oil spill followed causing a huge environmental damage in the Gulf of Mexico.

Extensive investigations, studies and researches followed this accident. In the response to the US president's directive, the Salazar report on May 27, 2010, conveyed an exhaustive review of the Macondo event and reports on precautions and technologies that should be required to improve the safety of oil and gas exploration and production operations on the Outer Continental Shelf (US Department of the Interior, May 27, 2010). The report underlines that drilling activities in the Deepwater environment create increased risks and challenges. And there is a need to re-evaluate whether the best practices for safe drilling operations developed over the years need to be bolstered to account for the unique challenges of drilling in deep-water (US Department of the Interior, May 27, 2010). The Salazar report highlights immediate as well as short term actions to enhance the safety of future OCS drilling activities. Those recommendations cover specifically the following categories:

- *Blowout Preventer Equipment and Emergency Systems*
- *Procedures to Ensure Adequate Physical Barriers and Well Control Systems are in Place to Prevent Oil and Gas from Escaping into the Environment*
- *Organizational and Safety Management*

The BP and the Transocean investigation reports gathered the facts surrounding the accident, analysed available information to identify possible causes and made recommendations to enable prevention of similar accidents in the future (BP Investigation Team, September 8, 2010, Transocean, 2011).

The BP's accident investigation team used fault tree analysis [see Appendices A] to define and consider various scenarios, failures modes and possible outcomes. Based on analysed information, the team found that the accident was due to a complex and interlinked series of mechanical failures, human judgements, engineering design, operational implementation and team interfaces in a circumstance of multiple companies and work teams involved over time (BP Investigation Team, September 8, 2010).

The Transocean investigation report, through an extensive interview of witnesses, the review of available information regarding well design and execution, as well as the examination of real-time well monitoring data; they found that the Macondo incident was the result of a succession of interrelated well design, construction and temporary abandonment decisions that compromised the integrity of the well and compounded the risk of its failure. At Macondo, the window for safe drilling between the fracture gradient and the pore-pressure gradient became increasingly narrow and to maintain the appropriate Equivalent Circulating Density (ECD) became difficult (Transocean, 2011). And this was experienced through several kicks and losses of fluid to the formation, during the drilling operation.

Many independent reports focused mainly on root causes, other analysed results from investigations reports and/or re-evaluated barriers performance to document the failure of Deepwater Horizon. Barrier is defined as measure which reduces the probability of realizing a hazard's potential for harm and which reduces its consequence (International Standard Organisations, 2000). Barriers may be passive or active, physical, technical, or human/operational systems (Norsk, Feb. 2008). For the case of Macondo accident, barriers cover complex causal relationships such as human factors, the field subsurface characterizations and technology used during drilling operation. May 7th, 2010 the PSA established a project team to systematize and assess experience from Macondo incident and thus from the learning, draw recommendations that can contribute to the improvement of safety and emergency preparedness in relation to drilling and well operations on the NCS. Based on produced investigation reports as well as on a number of assessments by various professional bodies and various national and international processes, the PSA team found that the accident underlying causes were the same as those identified for the Montara blowout happened 8 months early in shallow water of the Timor Sea. According to the PSA, the DwH accident must be seen as a wake-up call to the Norwegian petroleum sector, that it must lead to a big improvement in managing major accident risk, and that the conclusion that the safety culture needs developing throughout the industry must also be considered relevant for Norway's petroleum activity (Petroleum Safety Authority, 2011a). Among other requirements of high priority, the PSA report suggests the improvement in barriers management and to improve the well integrity problems.

More than thirty Working Papers by DHSG highlight lessons learned from Macondo's failure. The papers' findings recognize that oil and gas exploration and production has embarked in extreme environments such as in the ultra-deep waters and in the arctic that resource developments will require new strategies to reduce the future likelihoods of major failures such as uncontrolled blowouts, production operations explosions and fires (The Deepwater Horizon Study Group (DHSG), December 5, 2010).

Several scientific papers, literature studies through textbooks and publications were made with an expectation that lessons learned from Macondo blowout bring new emphasis on practical risk analysis and risk management in the industry. Some focused on qualitative risks analysis(Januarilham, 2012), while others used quantitative risk analysis (Skogdalen and Vinnem, 2011, Bea, 2011).

Qualitative risk analysis uses the knowledge of risk from experts through brainstorming and group discussion to present a simplified risk picture in a descriptive categories or coarse scale (i.e. high, medium, low) (Aven, 2008). Through qualitative risk analysis and the use of tools such as reliability block diagram, FMECA (Januarilham, 2012) found five critical components in a BOP that give the highest value of safety performance starting from (i) shuttle valve (blind shear ram function), (ii) blind shear ram (ram piston), (iii) flange (BOP stack), (iv) gasket (BOP stack) and (v) annular preventer (rubber housing) respectively. Thus the shuttle valve for blind shear ram function and the blind shear ram are the most critical components in the BOP.

The quantitative risk analysis (QRA) also known as Probabilistic Risk Assessment (PRA), Probabilistic Safety Assessment (PSA), Concept Safety Evaluation (CSE) and Total Risk Analysis (TRA) (Skogdalen and Vinnem, 2011) uses the knowledge of risk from model-based risk such as Event Tree Analysis, Fault Tree Analysis and other tools to represent the risk picture (Aven, 2008). Quantitative risk analysis studies (Andersen et al., 1996) showed that a logical event tree model based on Fault Tree Analysis (FTA) and Cause Consequence Diagrams (CCDs) may provide an adequate modelling procedure on an overall level in the blowout model. Fault Trees typically give a static picture of the subject for analysis whilst CCDs allow a proper modelling of the dynamic conditions (Andersen et al., 1996). These modelling tools contribute to visualizing the cause and event sequences leading to kick and blowout and thus constitute suitable means for communicating risk aspects regarding kick and blowout to drilling and safety personnel. A computer model BlowFAM (Blowout Frequency Assessment Model) capable to handle 300 risk elements and thus predict Blowout risk for a given site is described in (Dervo and Blom-Jensen, 2004). Today, BlowFAM development focuses on the risk contribution at coiled tubing and snubbing and incorporation of issues like underbalanced drilling. BlowFAM was developed using SINTEF Offshore Blowout Database. According to this database, risks (e.g. blowouts) due to unexpected overpressures, narrow pressure margin contribute to 60%. The contribution from operational aspects (e.g. tripping) is circa 8% while issues related to rig, riser and well (e.g. cementing, crew experience, equipment failure) amounts to 32% (Vandenbussche et al., 2012). BlowFAM model has shown positive advantages compared to traditional kick frequency/BOP reliability approach such the kick detection at the surface measured by mean of delta flow at the rig floor (Ocean Energy Safety Advisory Committee, August 29, 2012).

Kristen Ulveseter and Peder Andreas Vasset, in the article “The Next Generation Safety Approach Post Macondo”, provide some insights into on-going work on Well Control Philosophy. DNV is currently in the process of evaluating how the human operator may best be supported in a well control event in order to ensure that correct actions are taken in time. Automated drilling operations are expected to increase drastically over the coming years and DNV is committed to further enhance safety and the use automation of the BOP system (Ulveseter and Vasset, Sept 15th 2012) whereby its efficiency will rely on early and accurate kick detection. To control the high-level pressure for marginal formation-pressure limits, an efficient and reliable kick-detection system is especially important. The quality and processing of the information flow will also be imperative and the automated functions will depend on the scenario, i.e. on-going operations, mud-balance system, well-control system configuration, drill-string configuration, etc., (Ulveseter and Vasset, Sept 15th 2012). A more recent program "Accident Sequence Precursor (ASP)" is being developed by ABS and Safetec Nordic AS to assess the well integrity. Through ASP, engineers have developed a risk model for a well kick, including all of the relevant precursors, along with a preliminary set of risk-influencing factors – such as competence, time pressure, the cement program, etc – and how these factors influence the probability of the precursor event (John et al., 2013).

A persisting challenge in the aftermath of Macondo blowout consists of oil spill and the huge environmental damage caused by the accident. Substantial effort through hundreds of different assessments, thousands of samples across the Gulf in various forms have been underway in the attempt to restore the Gulf's health and productivity. The interview with Jeffrey Brown and Garret Graves at PBS News Hour, reveal various anomalies seen in different areas (PBS News Hour, April 20th, 2012). The same media acknowledges that drawing conclusions in terms of grading the overall health of the Gulf will be premature at the current stage (PBS News Hour, April 20th, 2012).

Special interest has been the use of Macondo spill as an evaluation case to establish proactive safety indicators for monitoring of risk of oil spills in the Artic area. Øien and Nielsen used the Resilience Early Warning Indicator (REWI) method to provide early warnings to prevent major accidents. REWI is a set of self- assessment measures that provide information to senior managers and safety professionals within an organization about fundamental attributes of organizational safety and performance in the long run (Øien and Nielsen, 2012). Based on flow chart, the fundamentals attributes of resilience covered by REWI method called Contributing Success Factors (CSFs) are: risk understanding, anticipation, attention, response, robustness, resourcefulness/rapidity, decisions support and redundancy (Øien and Nielsen, 2012).

Macondo blowout is studied in this master thesis as an example of severe major accident in the offshore petroleum industry. A ‘‘major accident’’ in the oil and gas industry is as any event arising from a work activity involving death or serious personal injury to five or more persons on the installation or engaged in an activity in connection with it (HSE, 2006). Major accident analysis is an important subject for offshore exploration and production facility. According to Vinnem, the main contributor to a major accident in the offshore platform can be: blowout, leakage due to process integrity, riser failure, fires in utility and accommodation, and marine accident (Vinnem, 2007).

Although improvement in facility design, technology, and implementation of safety management system are already made, catastrophe accident is still on (Serrano and Foo, 2008). Nowadays, major accident prevention has led more focused attention on barrier management, stringent regulation, growing research on process safety area. And it is ultimate that systematic hazard identification has to be assessed to ensure protective measures are in place.

2.2. Understanding risks associated with Deepwater drilling and completion. The case of Macondo field.

In very recent days, the petroleum world business focuses on surveying and the exploration of news oil and gas resources located in complex extreme environments such as Deepwater, oil sands, shale plays and the arctic. For the case of Deepwater, four major Deepwater basins are identified in the world: USA 1.5 million b/d; Brazil 1.7 million b/d, Angola 1.4 million b/d; and Nigeria 1.2 million b/d, along with other miscellaneous basins at 0.7 million b/d (Powers, 2012). Such reservoirs are more complex, more technology – intensive and they constitute a challenge to the current risk and risk management practices. The experience with the BP Macondo oil spill illustrates a noteworthy task in containing a blowout in Deepwater.

2.2.1. Subsurface characterization and geohazards analysis

A key objective of a site survey is to assess geo hazards, and to enable the risk posed to drilling operations by the seabed and geological conditions to be managed and reduced. According to (Nadeau, 2011a), the Gulf of Mexico (GoM) is characterized mainly by extremely high rates of sedimentation and burial, having predominantly very young Neogene Tertiary reservoirs with exception of a few isolated unaffected by uplift and erosion occurrences such as certain reservoirs in the Perdido fold belt. In the GoM and the area of Macondo prospect, the Golden Zone across the basin is controlled mainly by the geothermal gradients and the sedimentary burial from the Mississippi River system. The Golden Zone (GZ) is a concept used by (Buller et al., 2005, Nadeau, 2011a) to characterize the probabilities of hydrocarbons zones locations based on geothermal gradient. The basal zone, which is bounded by the 200ºC and 120ºC isotherms, is where most hydrocarbons are generated from source rocks. The zone is therefore named the expulsion zone, and is characterized by low permeability and (hence) high pore pressure capable of hydraulically fracturing the rock (Buller et al., 2005). Here only a minor percentage of the oil and gas is entrapped while a grand statistical average shows that the highest volume concentrations of hydrocarbons corresponds to the 90ºC isotherm (Nadeau, 2011b).

Analysed GoM data by (Buller et al., 2005, Nadeau, 2011a) show that, despite the extreme rates of porosity loss in the compaction zone, the median, P50, reservoir pressure probability is for normal or near hydrostatic pressures to occur at temperatures <60ºC. At temperatures >60ºC, the probability of overpressure begins first to increase gradually and later at temperatures >120ºC, the P50 increases exponentially. Here, the subsea environmental conditions reflects reservoirs of High Pressure High Temperature (HPHT) (Nadeau, 2011a). The HPHT are defined as those with temperature >120ºC and >1.4 times hydrostatic pressure gradients (i.e. >1.4 g/cm3 specific gravity (SG) gradient or about >12 pounds per gallon (ppg) drilling mud weights (Buller et al., 2005, Nadeau, 2011a). According to Paul H. Nadeau those HPHT drilling conditions are more rigorous indicator of overpressure risks rather than the >1.7 g/cm^3 (or ~15 pounds per gallon drilling mud weights) and >149ºC (300ºF) values currently used in the petroleum industry (Nadeau, 2011a).

The above findings are in agreement with the paper of Close et al., 2008, which indicates that the area of GoM has a unique combination of Risk Influence Factors (RIFs) compared to Deepwater wells in other parts of the world [cited in (Skogdalen and Vinnem, 2011)]. The same paper points out that in water depths of over 3000 m, shut-in pressures are more than 690 bars; bottom hole temperatures are higher than 195ºC. It also is observed problematic formations with salt zones and tar zones. At Macondo prospect, the total depth was reached at 18,360 ft (5,596 meters). Reservoirs sand contained hydrocarbons at pressures approximately 11,850 psi (817 bars) (Transocean, 2011). In order words, deep reservoirs - located in more than 9000 m true vertical depth and tight sandstone reservoirs (>10 mD) display extreme flow assurance issues.

As shown, the GZ concept presents a predictive power with respect to its ability to quantify exploration risks, particularly for overpressure development and for HPHT environments. Understanding the geological processes responsible for the occurrence of HPHT reservoirs is vital in order to properly assess these risks as well as increase exploration efficiency. Paul H. Nadeau has demonstrated that 79% or about four out of five GZ reservoirs (i.e. between 60ºC and 120ºC) are NPNT, as compared to 64% HPHT or about two out of three reservoirs in the expulsion zone. This means that the risk of high-pressure reservoirs increases by a factor of three, or 300%, at temperatures >120ºC (Nadeau, 2011b).

In order to improve safety and lower environmental risks, both for exploration and production drilling operations, it is stressed in advance to use geothermal gradients and approximately calculate pore pressure curves before the drilling. A recommended practice in new areas is to identify the depth at which the 60ºC isotherm is likely to occur and design drilling programmes accordingly (Nadeau, 2011b). Drillers must be well prepared to manage the increased probability by penetrating over pressured hydrocarbon-bearing sandstones, and therefore diminish the potential of dangerous pressure ‘kicks’ (or blowouts).

To understand the risk associated with drilling in Deepwater, one should not limit only on the studying of the thermal gradient but also on others hazards such as leak off pressure (LOP), fracture initiation, minimum stress, etc. For each hazard identified, hazard potential should be stated in terms of the likelihood that the particular condition exists at a specific locality. The Technical Notes provide interpretation guidelines for the assessment of some key geohazards that may be identified during site survey (International Association of Oil & Gas Producers, April 2011). Table 1 illustrates some of the potential problems to be assessed during drilling operations.

Table 1: List of issues that should be subjected to risk assessment while planning drilling in Deepwater

Organization factors	Well drilling design	Subsurface conditions
Management Manning/organization Personnel competence/ experience Well planning Communication Training Work practice Work environment Testing/Maintenance Documentation Work schedule aspects Operational procedures	Top drive, Riser, Kill and choke system, Casing, centralizers Well head Equipment Blowout preventer (BOP), Drillistring/down hole equipment Cement job, Drilling fluid (Mud weight), Swabbing, Stinger seal and/or packer seal Power generation and emergency power supply Gas lift valve, Short shoe track, Uncertainty regarding float conversion, Wireline, Heave Compensator, Coiled tubing, ROV system Drilling into neighboring well, Drilling direction, Drilling control, Maturity of new technology	Top-hole geology Sedimentary sequences/ Stratigraphy: (Sand, Mud, Clay, Swelling, Clays or Gumbo, Marl, Carbonates, Salt, etc. Abnormal and High pressure/fracture gradient High temperatures Uncertainty of seismology $H_2S/CO_2/H_2S_4$environment Hydrate environment Shallow water flows Tight hole and loss of circulation Dip angle

2.2.2. Drilling technique and well design

Researches have revealed that drilling in Deepwater is complex (Mohr Engineering Division, October 31, 2008). The drilling window is narrow, and the narrower the window, the more difficult to execute drilling operations. In this situation, the industry needs to assess risks and monitor well operations in all life cycle.

Deepwater reservoirs have generally such narrow drilling windows between the pore pressure and the fraction gradient. Resolving one problem often creates another and the well control becomes detrimental (Mohr Engineering Division, October 31, 2008). The paper by (Ziegler, 2012) shows that the moment the previous shoe is drilled out, ECD (Equivalent Circulation density) is too high to drill a single foot of formation.

Drilling technique for narrow windows: The drilling work for narrow windows involves two factors; the equivalent static density (ESD) as well as the equivalent circulating density (ECD). The Chief Counsel Report, 2011 defines ESD as the pressure exerted by a column of fluid in the wellbore in static condition while ECD refers to the total pressure that the same fluid column exerts when it is circulating (Chief Counsel's Report, 2011).

When circulating, ECD exceeds ESD because the force required to circulate the fluids exerts additional pressure on the wellbore. This implies losses, and statically the overpressure exerted by the mud is too small to hold back formation contents, and a kick is the result. Such a well then is considered undrillable without the use of Managed Pressure Drilling (MPD) equipment to remove the ECD effect (Ziegler, 2012).

A Managed Pressure Drilling technique makes designing a Deepwater well simple (IADC, 2013). Retrofit Dual Gradient drilling system is one of the simple and low complex introduced technology. The technique uses two or more pressure gradients within selected sections to manage the well pressure profile and removes the drilling window constraints because of too little pressure increase per ft drilled. One of the biggest advantages of the pumped riser dual gradient system is that the empty part of the riser becomes a giant expansion chamber and therefore a perfect mud-gas separator (Ziegler, 2012).

Well design: According to Pritchard and Lacy, the drilling industry needs to recognise where serious risks exist in complex well development, and to design wells, which deal with the uncertainties in geological risk. They claim that in some categories of complex wells, wellbore stability events are as high as 10% of the total Deepwater well time, and well control incidents over four times those of normal wells [cited in (Skogdalen and Vinnem, 2011)]. Basically, the well design must ensure that the drilling fluids and casing strings work together to balance and contain pore pressures in the rock formation without fracturing the rock.

Depending on oil or gas future plan production, in addition to the learning of the subsurface geology, the design process involves in addition the study of the environmental and mechanical stresses over the design lifetime. To rank drilling complexity, industry has developed a risk index/standard point of reference called the Mechanical Risk Index (MRI). The MRI also called Dodson Mechanical Risk Index divides wells into five complexity levels, and the later categorization is based on how difficult will be to drill e.g. depth of water, total well depth, number of casing strings and salt penetration (Skogdalen and Vinnem, 2011).

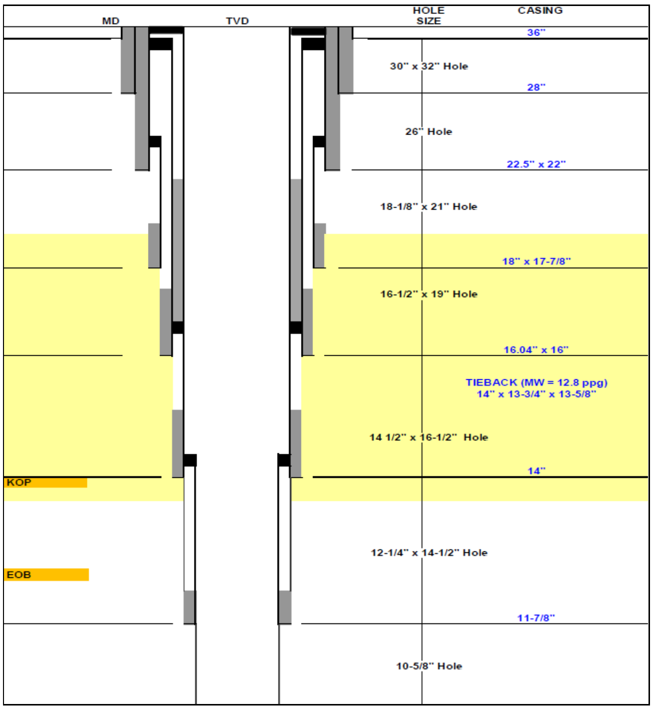
For deepwater conditions well design, special attention is paid to the annular pressure buildup (APB). This occurs when the high temperature hydrocarbons travel up and heat up the well. In some cases, the pressure can become high enough to collapse casing strings. A number of design features to manage annular pressures or mitigate the risks of casing collapse exist. These include rupture disks, compressible fluids in the annular space, and insulated production tubing. (Chief Counsel's Report, 2011).

In the original plan for the Macondo well, BP specified the use of a long-string casing. After experiencing lost-circulation problems between the section 17,168 and 18,360 ft, BP considered using a liner to minimize the downhole pressure exerted during installation and cementing. Industry data in Mississippi Canyon Block 252 area indicates that approximately 57% of the wells used long strings while approximately 36% used liners or liners with tiebacks (BP Investigation Team, September 8, 2010). During temporary abandonment, the top of the long string would be sealed at the casing hanger in the wellhead for later production, while the liner would be sealed at the downhole liner hanger with the installation of a tieback at a later date before production start (BP Investigation Team, September 8, 2010).

The paper of Ziegler points out that drilling riserless top hole to control shallow water and gas, i.e. having kill mud in the actual wellbore may be considered as a major safety improvement (Ziegler, 2012).

However, to attain a minimum economic size for a production string or allow the use of modern logging/testing tools in the case of explorations/appraisal wells, multiple large and heavy casings are used.

On the sea floor beneath, a blowout preventer (BOP) is used, capable to seal off the well with a number of hydraulic systems, including one designed to slice right through the whole stack. The Macondo well used a BOP, rated to operate at a maximum pressure of 15,000 psi and in water depths greater than 9,000 ft (BP Investigation Team, September 8, 2010). The fig. 1 below illustrates an example of well design.



- Burst (typically changes to upper half of well)
  - Tieback (14", 13-3/4", 13-5/8")
  - Use 16.04", 16.15" instead of 16"
  - Higher rating (submudline) hangers
  - Or resolve with Cap & Flow
- Collapse (typically changes to lower half of well)Use heavier 16.04", 16.15" instead of 16"
  - Use heavier 14" instead of 13-5/8"
  - Higher rating 14" hanger systems
  - Use long string to control APB (weight limited)
  - Lower liners collapse (11-7/8" and smaller)
- Formation strength (broaching)Move mechanical failure point deeper
  - Change casing setting depths to take advantage of strong formation (e.g., salt) or weak/thief zones
  - Or resolve with Cap & Flow
- Using existing pre-NTL10 wells may be challenging
  - More complicated solutions, e.g., scab liners

Figure 1: An example of a well design [source (JITF and API 96/97, 2010)].

2.2.3. Operational barrier (Human and organizational factors)

Many cases of incidents take place because previous antecedent events had either been ignored and/or the organisation had failed to identify the root causes and implement the necessary operational barrier.

The Macondo blowout occurred at time of 38 days behind the schedule and at an estimated $58 million above budget. (Walker, March10th, 2011) has ascertained that decisions have been largely the contributing factors of the accidents and hence the failure of management. Below it is revealed that warning signs in the coming weeks prior to the incident were ignored to save time and money. This was the basis of (CSB, July 2012), affirmation that Macondo accident failed to learn from the previous accidents.

In North Sea a few months prior to Macondo, Sedco 711 has registered a near miss, with the mud and hydrocarbons reaching the rig floor after a delayed response to kick indicators. Though Transocean was the drilling contractor, the experience of the incident was not shared with BP. Unlike Macondo, the BOP of Sedco 711 well sealed and subsequently the ignition, the loss of life and the spill were avoided.

Prior Macondo accident, various incidents, that took place were resolved by the shut in the well, or raising the mud weight and/or by sidetracked well. March 8th, 2010, the well kicked at 13,305 feet. The incident was followed by BP investigation from a geological perspective. A decision approved by MMS was communicated to reduce lost drilling time (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (OSC), January 2011b) and a new drilling liner and the change of the production casing in long string from 9 7/8’’ to 7’’ were implemented (BP Investigation Team, September 8, 2010). Regarding this incident it was found that informal and verbal discussions held with Transocean however there is no evidence indicating that the event was investigated to draw lessons learned. Others similar incidents have been reported in (Chief Counsel's Report, 2011); i.e the well kicked at 8,970 feet on October 26th, 2009, and the ballooning, or “loss/gain,” event on March 25th.

The issue of human factors in offshore drilling and well completion is particularly important as offshore well control programs currently rely to a large extent on manual control, procedures and human intervention to control hazards. In the view of CSB Investigator Cheryl MacKenzie; “*There are no human factors standards or regulations in U.S. offshore drilling that focus on major accident prevention*”. Giving an example, she points out that Transocean’s rig workers, originally were working 14-day shifts, but they were required to go to 21-day shifts on board. From this change CSB is confronting to the question whether this decision was assessed for its impact on safe operations and/or whether fatigue was a factor in this accident (CBS, Apr 19, 2012).

Khorsandi et al., 2013 have highlighted the need for better risk analysis methods, particularly for the operational phase through accounting for human and organizational factors, as well as taking account of platform specific characteristics such as specific work operations and the analysis of barriers (Khorsandi et al., 2013). A human factor is a wide-ranging discipline. It is concerned with both the human interactions with the technical components of the system (e.g. operating, monitoring maintaining) and the wider human activities required to sustain the system (e.g. training, work organisation) (Widdowson and Carr, 2002). Among organizational factors common for industries and engineering systems (Paté-Cornell, 1993) pointed out:

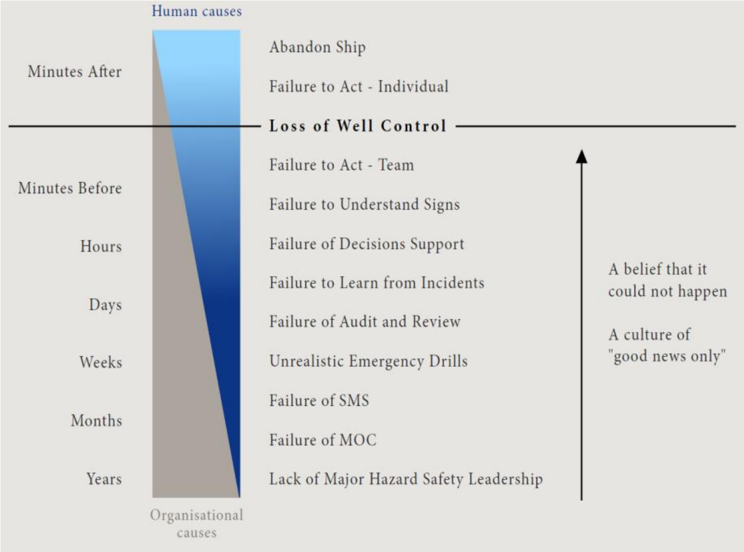


Figure 2 : Time scale in relation to potential failures due to human belief. Source OGP cited in (OLF et al., 2012)

- *flaws in the design guidelines and design practices (e.g., tight physical couplings or insufficient redundancies),*
- *misguided priorities in the management of the tradeoff between productivity and safety,*
- *mistakes in the management of the personnel on board, and*
- *errors of judgment in the process by which financial pressures are applied on the production sector (i.e., the oil companies' definition of profit centers) resulting in deficiencies in inspection and maintenance operations*

This analytical approach allows identification of risk management measures that go beyond technical solutions (e.g., add redundancies to a safety system) in addition to management practices improvements. It is obvious that through risk analysis, it will be possible to find which human decision and actions that influenced the occurrence of the basic events, and then identifies the organizational roots of these decisions and actions. Fig. 2 shows a time scale in relation to potential failures due to human belief during the drilling operation management. The illustration demonstrates that the response time is an important aspect of concern to avoid accidents. Some decisions embedded in organizational aspects have to be implemented years to avoid accidents and those are undoubtedly the Safety Leadership. In other term the following summarises the underlying causes of an accident: (i) Ineffective leadership; (ii) Compartmentalisation of information and deficient communication; (iii) Failure to provide timely procedures; (iv) Poor training and supervision of employees, (v) Ineffective management and oversight of contractors; (vi) Inadequate use of technology/instrumentation; (vii) Failure to appropriately analyse and appreciate risk; (viii) Focus on time and costs rather than control of major accident risks.

Table 2: HOFs that influence major hazard risks. By Sklet et al., 2010 Source cited in (Skogdalen and Vinnem, 2011)

Work practice	The complexity of the given task how easy it is to make mistakes, best practice/normal practice, checklists and procedures, silent deviations and control activities.
Competence	Training, education, both general and specific courses, system knowledge, etc. Communication between stakeholders in the process of plan, act, check, and do.
Management	Labour management, supervision, dedication to safety, clear and precise delegation of responsibilities and roles, change management.
Documentation	Data-based support systems, accessibility and quality of technical information, work permit system, safety job analysis, procedures (quality and accessibility).
Work schedule aspects	Time pressure, work load, stress, working environment, exhaustion (shift work), tools and spare parts, complexity of processes, man-machine-interface, ergonomics.

According to (Mohr Engineering Division, October 31, 2008), human error can be expressed as follows:

$$Human\ error\ probability = \frac{\text{Number of error}}{\text{Number of opportunities for error}}$$

$$Human\ error\ rates = \frac{\text{Number of error}}{\text{Total task duration}}$$

A useful check on whether all HF activities are being addressed, is illustrated in Table 2. The relevance of these domains for a system or piece of equipment shows the nature of the issues in each domain which may vary from project to project.

2.2.4. Risk methods and tool to analyses hazard during drilling operations

a) *Overview of risk analysis*

According to T. Aven, 2011, risk definition has changed throughout the history. Basically, risk analysis has two objectives: (i) to accurately estimate the risk, that is the probabilities P_x – a concept that has been pioneered by Kaplan, S. (1988), Parry, G.W. (1988), Singpurwalla, N. (2006) etc. cited in (Aven, Revised version 24 April 2012), and (ii) to describe the uncertainties about the world (Aven, 2011). T. Aven, 2011, points out that the probability should be restricted only to a tool that describes/measures uncertainties rather than the definition of risk.

With regard to Macondo accident, risk analysis is used as a basic analytical tool to identify the “failure path” or accident sequence such as : (i)initiating events, (ii) intermediate developments and direct consequences of these initiating events, (iii) final systems’ states, and (iv) consequences (i.e. losses).

Typically, there are two approaches for risk analysis: qualitative and quantitative risk analysis (Malloy and McDonald, Oct. 31, 2008). Qualitative risk analysis uses the knowledge of risk from experts through brainstorming and group discussion to present a simplified risk picture in a descriptive categories or coarse scale, i.e. high, medium, low, etc.; While quantitative risk analysis (QRA) uses the knowledge of risk from model-based risk such as Event Tree Analysis, Fault Tree Analysis and other tools to represent the risk picture (e.g. specific events that may occur and the magnitude of their consequences) in more detail (Aven, 2008). The obtained risk picture will be evaluated against the risk acceptance criteria and when applicable compared to alternative. Risk reducing measures is presented and generally cost benefit analysis is followed as part of decision making. Quantitative risk analysis requires quantified data to assess risk; usually those are combined with the expert judgment.

Depending on the intention of the analysis and result, criticality and reliability are tools used to support the risk analysis process. Those tools are particularly important for the design of components or machineries in the production and safety systems and/or when it is needed determine the system robustness and redundancy in order to give the highest value of production and safety assurance.

The most effective way to improve risk analysis is to improve the quality and the quantity of the data, and to quantify the uncertainties. The uncertainties for the case of drilling in Deepwater may be related to (i) variability of the earth, random by nature and inherent to the geological process that can not resolved even with additional data (ii) uncertainties characterized as epistemic due to incomplete knowledge of geological process, which can be reduced through R&D projects, and in particular, model uncertainty that reflects the inability of a simulation model to represent precisely the true physical behaviour of the process (iii) uncertainties due to a lack of available/accurate data, and/or poor resolution. Such uncertainties include accuracy and precision of field data (measurement errors, limited, non-representative or unavailable data, data handling errors).

In addition to these geo mechanical parameters, uncertainties related to the remote sensing acquisition method (geophysical acquisition and processing parameters, spatial and vertical resolution) and the site specific measurements (geotechnical and Logging While Drilling (LWD) quality and interpretation) should be considered.

On the Norwegian sector, the risk from blowout are studied from safety and the environmental perspective, through Quantitative Risk Assessments and Environmental Risk Analyses respectively with input parameters: the blowout probability, the flow rates and duration. For the assessment of blowout risks, the developed methodology by DNV uses the field specific reservoir challenges, best available technology (BAT) and best operational practices to generate a more field and operation specific risk exposure.

b) Risk Management

Risk management utilizes multiple approaches and strategies with aim at minimizing both likelihoods and consequences of failure. Prevention, remediation – emergency response, and control – crisis management are employed in continuous coordinated interactive processes intended to achieve acceptable risks throughout the life-cycle of a system (Bea, 2011). Three general categories of risk management approaches are employed: (i) proactive (before activities are carried out), (ii) reactive (after activities are carried out), and (iii) interactive (during performance of activities).

An offshore safety regime based on prescriptive/proactive regulation has the advantage of being relatively easy and simple to implement and follow up however its weakness can be found in not preventing new types of accidents that may appear in the future. The regime may also limit operators' dedication and understanding of responsibility as well as proactive initiatives to increase the safety level beyond compliance. This is particularly important in the Deepwater offshore where new technologies and techniques to improve production and safety and also reduce costs are being constantly developed, but by their nature may introduce potential new risks.

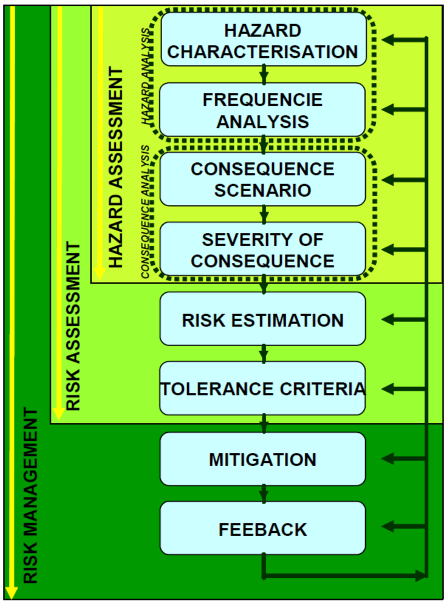


Figure 3: Risk Management Flow chart (source Eric Cauquil: Risk Matrix for Non Recurrent Geological Process: Application to the Gas Hydrate Hazard OTC, 2009 Houston Texas, May 4-9, 2009)

As per fig. 3, classical risk management includes three main phases: (i) a hazard assessment including a hazard analysis (hazard characterization and frequency analysis) and a consequences analysis (consequence scenario and severity of consequences) (ii) a risk assessment (risk estimation and tolerance criteria and (iii) a proper risk management plan through mitigation and feedback. Those phases must be sequential but also iterative. The hazard assessment gathers, organizes and summarizes all data relevant to risk assessment and management.

c) *Environmental risk management*

In this section, discussion will only be limited to a short introduction of the environmental risk management for drilling operations in Deepwater. In absence of the EIA study baseline on Macondo, it has not been possible to go in depth of the topic.

Generally, the environmental QRA is confined to “incidental” or “acute” hazardous events (International Standard Organisations, 2000). Facilities for Deepwater hydrocarbons exploration and production are in many cases sufficiently remote that considerations of this type of risk to the public do not dominate. In downstream activities, risk to the public is often the main concern.

Following Macondo accident, immense amounts of toxic reservoir fluids and gases from the Macondo well were able to escape into the open waters of the Gulf of Mexico. Some of these fluids and gases reached the surface. For mitigation measures, a large amount of dispersants were introduced into the well flow stream near the seafloor prevented a large amount of the otherwise buoyant oil from reaching the surface and thereby reduced the surface impacts on nearby wetlands, wildlife, beaches, and communities. This dispersed oil and other toxic fluids from the Macondo well reservoir were transported by strong surface and subsea currents to many parts of the Gulf of Mexico.

Currently, the impact of Macondo environmental disaster is being evaluated in terms of the costs associated with immediate and direct injuries to human lives, property, and productivity. Traditionally, the cost is extended to short and long term effect on the publics, their industries and commerce. And today, it may become difficult to accurately assess the environment impact.

The US government Commission has found that information from the leasing and permitting processes, obtained by MMS followed in the Gulf of Mexico before the Deepwater Horizon incident, diverged with the environmental review process for OCS activities and that, the Interior’s approach to the application of NEPA requirements in the offshore oil and gas context needs significant revision (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (OSC), January 2011a). The US government commission has found the need to revise and strengthen NEPA Policies and Practices in the Offshore Drilling context.

d) Risk analysis and risk management during drilling operations

Drilling operation in Deepwater has revealed to be of large uncertainty due to well pressure drops below the formation pore pressure that may occur during drilling. In the book "Misconceptions of Risk" by Terje Aven, too high a well pressure may results in a low drilling speed, differential sticking problems and, in the worst case, fracturing of the formation.

Prior drilling operation, a risk assessment is conducted that consist of a risk model identifying first all possible consequences/major hazards such as blowout, fire/explosion, structural failure, etc. as well as related accident sequences. In the second stage all safeguards/barriers in place are identified. The fig. 4 below illustrates steps followed to determine appropriate risk assessment.

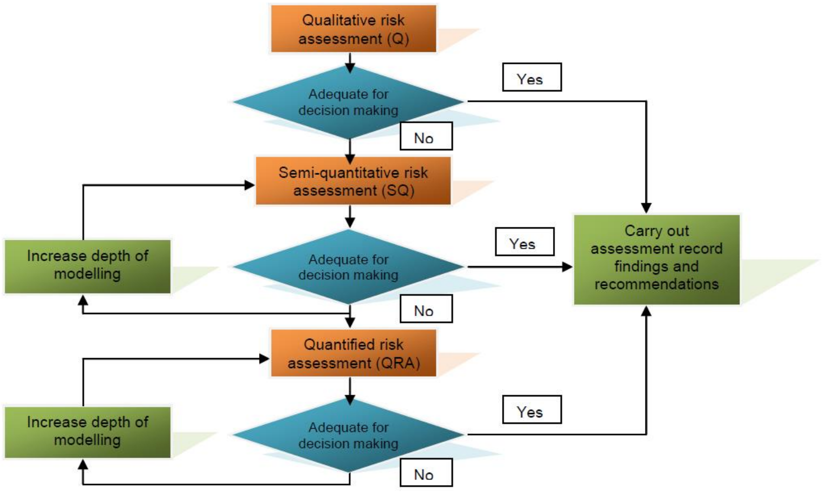


Figure 4 : Step to determine appropriate risk assessment source (Bea, 2011)

A comprehensive literature review specifically for risk analysis application on Gas and Oil well drilling operations can be found in (Cunha et al., 2005). This master has grouped the development of risk analysis methods in drilling activities into three categories:

(a) The 1st group covers simple models developed to examine possible outcomes and compare different options for investment with different levels of risk and uncertainties. Those models can be found in: (i) Newendorp and Root, 1968, 1969. (ii) Newendorp, 1983, reflected a more sophisticated model accounting for uncertainties in both geologic data and economic uncertainties; (iii) Cowan, 1969, combined the probabilistic geological engineering and economic data to produce possible distribution functions related to potential outcomes of exploiting new reserves; (iv) Turley,1976, used Monte Carlo Simulation Technique to show that expected costs and all the decisions in drilling situations are ultimately linked to the formations pressure; (v) Virine and Rapley, 2003, used the risk analysis toolsets in economic evaluation applications for the oil and gas industry; (vi) when McIntosh, 2004, used the probabilistic modeling/process to manage the most critical and unexpected events, the "non-productive time" and the determination of whether the minimum cost while drilling is attained.

(b) The 2nd group is referred to the application of risk analysis in the areas of reliability and availability analysis, safety management techniques and human and organizational factors. This group can also be linked to a wide use of QRA for offshore operations following the Pipe Alpha accident in 1988. First such works are discussed in Ostebo et al, 1991; In the same category, the work by (Andersen et al., 1996) suggested an approach to blowout risk modeling based upon physical causal mechanisms and expert judgments (a subjectively assessed probability) combined with hard data rather than worldwide blowout statistics. Those models are found in Kårstad, 1980, Tørhaug et al., 1980, Dahl et al. 1983, NPD, 1985, Nilsen, 1992; Ottesen et al., 1999 used quantitative risk analysis (QRA) and proposed a wellbore stability analysis method capable of quantifying the risks associated with the operational failure which enables the engineer to choose the appropriate mud density to avoid wellbore instability problems; the work by Thorogood et al., 1991, used the mathematical analysis of the probability of collision combined with a decision tree to describe the consequence; In Coopersmith et al., 2001, is used project parameters such as reservoir size, production rates, number of wells and drilling schedule to describe applications of decision tree analysis in the oil and gas industry; In Liang, 2002, by means of probabilistic distribution functions, it is demonstrated that risks associated to kick or loss of circulation can be minimized or controlled by changing some of the drilling parameters such as mud weight, mud rheological properties, flow rate, tripping speed, penetration rate

(c) The 3rd group refers to risk analysis methods that wide use digital technology e.g. real time well monitoring and Model Updating during drilling activities. Those new concepts called Integrated Operations are also referred as: the digital Oil field, Intelligent Field, eField or iField. The use of such technology has enabled the decision makers in the O&G industry to access to remarkable new technologies to acquire huge amount of data at unprecedented speed such data obtained from sensors to measure drilling operational and reservoir parameters.

Reference of digital technology in drilling operation can be found in (Rajaieyamchee and Bratvold, 2009). Here the influence diagrams known as Bayesian Decision Networks are used to frame, analyze and support real time drilling decisions. Such influence diagrams have been built and tested for optimal placement of casing (CSG) shoe, such to solve wellbore stability problems such Lost Circulation (LC), Stuck Pipe (SP), and kick during drilling a Deepwater well.

For every foot drilled, the operator considers cost in determining whether the CSG needs to be set- to case off most of the pressure transition zone and maximize the formation fracture resistance at the shoe for subsequent sections, or to take one of the following actions (i) drill ahead, (ii) increase MW&drill ahead, or (iii) abandon the well or stop and circulate, (iv) set CSG or (v) plug-back. The decision- maker has some control over the downhole conditions by reading information provided by relevant sensors. Those read the pore pressure, the equivalent circulation density (ECD) also known as Equivalent Mud Weight (EMW), the MW and the true vertical depth of the hole (TVDhole).

With an upgrade of an object-Oriented Influence Diagram (OOID), the decision problem is split into sub-problems to enhance the computational tractability and comprehensibility of influence diagram models. The OOID model allows to have a the potential for fostering multi-level decisions by giving the operator a confidence in strategic decision for CSG setting as well as enable drilling engineers to discuss the process at different levels to reduce information overload, thereby minimizing the potential of secondary consequences being overlooked.

Another example of the use the digital technology in drilling operation can serve the developed expert system by Texas A&M University. The system which was developed first by Al-Yami et al., 2010, uses an artificial Bayesian Intelligence as a systematic approach for optimum selection and execution of cementing operations (Al-Yami and Schubert, 2012). The developed expert system is more flexible than using flow charts. According to Shadravan et al 2010, the design of drilling fluid expert system depends mainly on previous experience and knowledge, effective communication, as well as a good coordination between the engineer, the service company and the rig foreman. Recent development shows that Bayesian updates can be used to combine the generic and rig data on barrier reliability.

Beside BlowFAM indicated in section 2.1., a dedicated flow modelling software e.g OLGA from SPT Group can define the range of potential blowout flow rates from the studied well. On the Norwegian market scenario modelling is typically carried out by specialized companies and provided as part of blowout and kill studies (Vandenbussche et al., 2012).

According to the Underbalanced Operations and Managed Pressure Drilling Committee of the International Association of Drilling Contractors, the Managed Pressure Drilling is defined as (Mohr Engineering Division, October 31, 2008):

"An adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. The intention of MPD is to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process"

MPD has the capability to control the back pressure, fluid density, fluid rheology, annular fluid level, circulating friction, and hole geometry, or combinations.

Therefore, the MPD requires a certain minimum amount of equipment, technology, and know-how. Among equipment and tools for the MPD are: Rotating Control Device installed above the Annular Preventer augmented with a drilling choke manifold (separate from the rig choke manifold), Non-return Valves (NRV) in the drill string, and a "what-to-do-if" guideline for those operating the equipment.

To demonstrate how potential hazardous aspects, operations and procedures related to the application of MPD can be; a typical HAZID + HAZOP or a What-if+Checklist are performed in the planning stages. Checklists and 'what-if analysis,' can be used early in the system lifecycle when little detailed information is available. HAZOP as well as FMEA require more details of the drilling machinery system but produce more comprehensive information on the hazards.

HAZID (Hazard Identification Studies) is designed to identify all potential hazards, which could result from operation of a facility or from carrying out an activity. A comprehensive and successful HAZID should be based on conceptual well-design schematics, conceptual layout drawings showing the UnderBalanced drilling operation (UB) or Managed Pressure Drilling (MPD) equipment, the rig and equipment, the hazardous areas/zones and the escape routes, and conceptual procedures. By (IADC, 2012), examples of hazards introduced by a UB/MPD operation include, but not limited:

(a) Change in barrier philosophy
(b) Drilling fluid medium
(c) New equipment
(d) New or modified procedures
    a. Well control
    b. Normal operating
(e) High pressure lines at surface
(f) Personnel training and competence

Figure 5: HAZOP process

The Hazard and Operability Study (HAZOP Study) is defined as a standard hazard analysis technique used in the preliminary safety assessment to determine what would happen if that component were to operate outside its normal design mode. The HAZOP process is illustrated in Fig. 5.

A HAZOP study involves an 'examination session' in which a multi-disciplinary team. It systematically uses a series of guide words/terms to examine how a deviation from the design intent may occur and to identify the potential consequences.

For drilling operations, the examination in HAZOPs is carried out with guide words/terms (*see IEC 61882*) such as 'TOO FAR', 'NOT FAR ENOUGH', 'TOO SLOW', 'TOO FAST', 'RELEASED' ,'NOT RELEASED'. Sometimes a serious hazard may involve the interaction between several parts of a system. In such cases there may be a need for more detailed study using techniques such as Fault Tree and Event Tree Analysis. As with any hazard identification technique there can be no guarantee that HAZOP by itself will identify all potential hazards or operability problems.

What If Analysis and Checklist are designed to review process systems and operating procedures to confirm whether they will operate and be operable as intended, without having introduced any avoidable hazards. Combination of What If Analysis and Checklist are forerunner to HAZOP method. This implies to the technique of quantitative assessment of particular risks, the likelihood or frequency of the event and the severity of the consequence using key words. This is often combined with the analysis of proposed risk reduction (or protection) measures to provide a risk assessment report.

While conducting a baseline risk assessment, it is most important to narrow the scope of the drilling operation to hazards of a particular interest, or specific process, or impact area. In the case of this master thesis the scope of work is the Deepwater environment. If risk is defined as energy sources that can get out of control, we then assume that as a baseline the energy sources described are normally and initially under control. To maintain organization during the assessment, every hazard should be considered for each step in the process under normal, abnormal, and emergency conditions.

Once the baseline has been established and consequences identified, a risk model representing all of the accident sequences can be developed using an Event Tree (ETA) with linked Fault Trees (FTA), Bow-tie or Influence Diagrams.

2.3. Macondo Accident pathway

Traditionally to ensure the well integrity, we need at least two barriers. Primary barrier are about the mud, cement, drilling riser, casing, etc. while the secondary barriers suggested by Offshore Standard DNV-OS-E101, October 2009 comprise the Blowout Preventer, the choke and kill system, the diverter system, etc.

For Macondo prospect, the primary barriers were to prevent undesirable hydrocarbon flowing into the wellbore while secondary barriers controlled the influx hydrocarbon if primary barriers had become unsuccessful (Skogdalen et al., 2010). None of these barriers worked to prevent Macondo accident and in (Chief Counsel's Report, 2011), the investigation team identified a complex interplay of mechanical failures, human judgments, engineering design, operational implementation and team interfaces that initiated and escalated the accident . Barrier failure analysis for Macondo accident is as follow:

2.3.1. Final casing

The Macondo well design consisted of 8 casing (see fig. 6). BP engineers decided to retain the original design of a long-string production casing – a single length of 9-7/8-in. x 7-in. casing extending from the subsea wellhead to 13,237 ft. below the seabed (18,304 ft. total depth) (BP Investigation Team, September 8, 2010). BP’s decision to run a long string rather than a liner and tieback reduced the number of barriers to annular flow to only two, the cement and the seal assembly.

BP used dril Quip’s SS-15® BigBoreTM Subsea Wellhead System (18 ¾ in., 15,000 psi) (PetroWiki, 2012). Subsea wellheads use a casing hanger system to suspend the casing in the pressure housing located at the sea floor. A seal assembly (or pack off) located between the casing hanger and the high pressure housing, is designed to prevent hydrocarbons from entering the wellbore. Any wrong installation of the casing or the breach of the annulus cement barrier could have allowed hydrocarbons to enter the casing.

Lowering the casing string into the well with the float equipment installed pushes drilling fluid ahead of it and can create surge pressures that can fracture the formation, leading to loss of drilling fluids and damage of the hydrocarbon production zones. BP incorporated a surge reduction system including an auto-fill type of float collar and reamer shoe to reduce surge pressure and protect the formation.

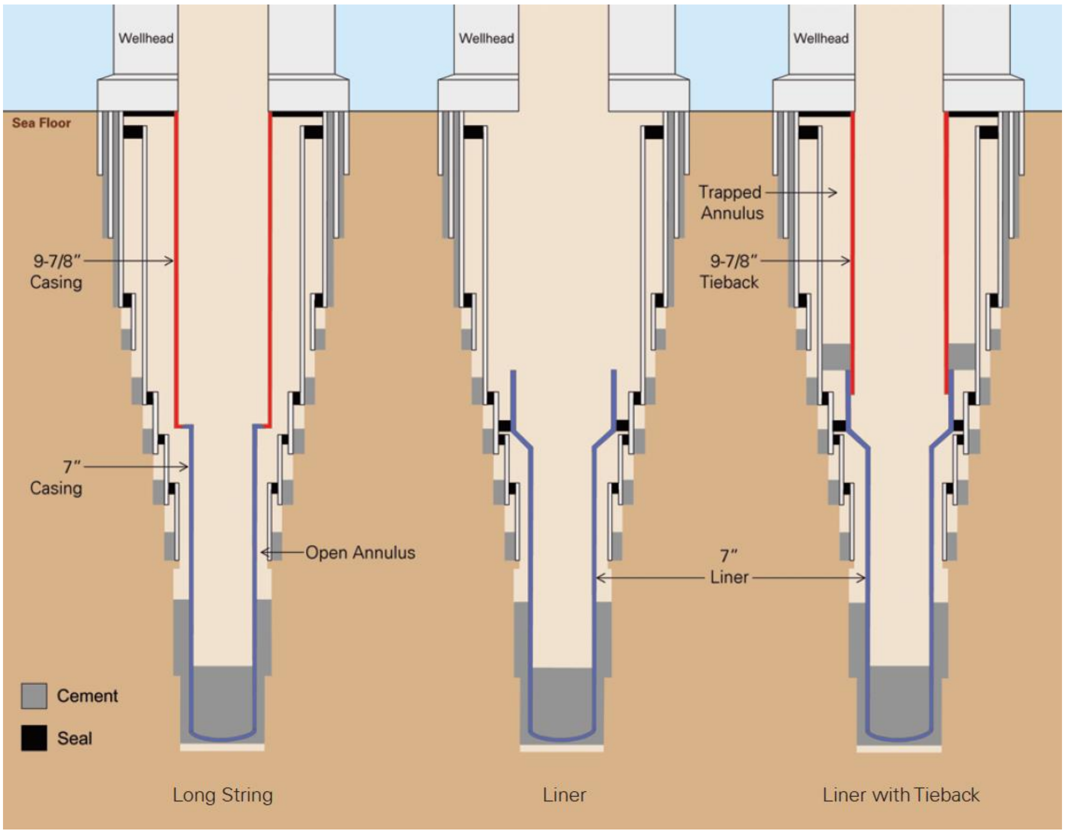


Figure 6 : Long string, liner and liner with Tieback (BP Investigation Team, September 8, 2010)

During the running of the production casing, six centralizers were pre-installed on the lower 7-in. interval of the production casing string. Halliburton cementing models specified the use of 21 centralizers to prevent high risk of cement channelling and subsequent gas flow channelling. Though the BP investigation team didn’t found any indication that the use of 6 centralizers was behind inadequate integrity of cement as barrier, Halliburton found that the decision to use an inadequate number of centralizers remains relevant because cement channelling can provide a flow path of hydrocarbons into the wellbore (Halliburton, 2010).

2.3.2. Cementing job

Primary cementing is the process of placing cement in the annulus between the casing and the formations exposed in the wellbore and therefore to achieve zonal isolation. Casing is typically installed with two sets of cementing check valves that constitute the mechanical barrier: the float shoe, located on the very bottom of the casing string; and the float collar, usually installed from two to six casing lengths (joints) above the bottom. Root cause of the cementing job failure could be due to high load condition, insufficient flow rate during the conversion of float collar, or float collar valve failure (The Deepwater Horizon Study Group (DHSG), March 1, 2011):

Converting the Float Collar: A BP’s production casing design for the Macondo well called for only one cementing check device: a double valve, auto-fill float collar (Transocean, 2011). The float collar used at Macondo contained two flapper check valves that are held open during installation by an auto-fill tube. While open, these valves allow mud to pass through the float collar and up into the casing.

Before cementing, the float collar is “converted” or closed. Specifically, the auto-fill tube is forced out of the float collar so that the flapper valves close and prevent mud and cement slurry from flowing back up into the casing. BP’s procedure to convert the float collar called for slowly increasing fluid circulation rates to 5–8 barrels per minute (bpm) and applying 500–700 pounds per square inch (psi) of differential pressure, consistent with manufacturer guidelines (BP Investigation Team, September 8, 2010). At a flow rate of 1 bpm needed to convert the float collar, the drilling fluid did not flow through the float assembly, and pressure began to build, indicating that something was blocking circulation (Transocean, 2011). The drilling fluid started to circulate after nine attempts and ramping pressure up to 3,142 psi, which far exceeded the manufacturer guidelines and BP’s own procedures for this operation. After the break in pressure, BP directed the drill crew to continue circulating mud and to monitor the pressure. The observed circulating pressure was 137 psi instead of the expected 370 psi at 1 bpm, and 350 psi instead of the expected 570 psi at 4 bpm. With anomalous conversion pressure (3,142 psi), low flow rates (less than 5 bpm), and low circulating pressure (less than modelled after conversion), no definitive evidence existed that the float valves had converted. Public testimony has revealed that BP personnel on the rig were concerned with the high amount of pressure needed to convert the float collar and that the float collar and/or the casing could have been damaged in that process (Halliburton, 2010). However the post-accident float collar testing has shown that 10,155 psi was required to cause damage to the internal float flapper assembly and it is believed that the ball may have been ejected from the ball seat without converting the float collar (Transocean, 2011).

Debris removal before cementing: Before cementing, clean drilling mud is pumped down and through the well to push debris out of the casing to ensure nothing will impede the circulation of cement. Circulating a full “bottoms-up” using the full volume of mud from bottom to surface is considered a best practice prior to cementing. Volumes of the drill pipe and casing plus a safety factor are considered to be the absolute minimum mud volume. At Macondo, the original BP well plan called for circulation of 1,315 bbl, which was 1.5 times the casing volume (Transocean, 2011). This was later modified on the updated casing program. BP performed only a limited circulation of 111 bbl. The total volume circulated, including circulation after float conversion, was 346 bbl, significantly less than the 1,315 bbl required in the original drilling program and the 2,750 bbl required for a full bottoms-up circulation.

Cementing jobs: Mud contamination is a major cause of cement plug failure as it affects the compressive strength of the cement significantly. As foamed cements are compressible, the cement quality will change through the process of circulation. In severe pressure variations, expected values would see a 1,000 psi pressure decreasing when flowing down the casing where pressures may exceed 10,000 psi.

Given its knowledge of the narrow window for safe drilling, BP selected a technically complex cement program that minimized the pressure exerted on the formation. The key features of the cement program included:

- Using a lower density nitrified slurry cement
- Using a small volume of cement

- Pumping the cement into the well at a low rate

The nitrogen foam slurry formulation used by Halliburton for cementing operations consisted of an amount of retarder of 9 gallons per 100 sacks of cement. Though the Transcocean investigation team claims that a foam stability test was only conducted on a slurry formulation with an amount of retarder of eight gallon per 100 sacks of cement (Transocean, 2011); Halliburton reacted that other tests such as thickening time and compressive strength were also performed on the nine gallon slurry formulation and were shared with BP before the cementing job had begun (Halliburton, 2010). However there is no indication from BP that a risk assessment was made prior the commencement of cementation.

After the cement was in place, the seal assembly was set and tested, and the BP well team and shore based drilling engineer, who was on board, notified their onshore counterparts that the cement job had gone as planned (Transocean, 2011). Afterward, the Halliburton cementer pumped 21.9 bbl of spacer into the well using the cement unit, followed by 132 bbl of mud for displacement at a rate of 4 bpm (Transocean, 2011). This volume was sufficient to launch the top cement wiper plug from the subsea running tool at the wellhead.

2.3.3. Run positive and negative pressure test

Because it may be anticipated that a particular cement job may be faulty the oil industry has developed tests, such as the negative pressure test, the cement evaluation logs and the segmented or radial bond log, etc. to evaluate the integrity of the cement (Halliburton, 2010), and in a case of cement failure, remedial actions are also provided.

Although, the appropriate personnel and equipment were on the rig and available to run a cement bond log test, BP personnel have publicly testified they intended to conduct the cement bond log test at a later date (BP Investigation Team, September 8, 2010).

The negative test was conducted. The test confirms the integrity of barriers in the well (such as cement barriers, mechanical barriers, casing, and seal assembly) by simulating the reduction in hydrostatic pressure that occurs when heavy mud is displaced with lighter seawater, and when the BOP stack and the riser are removed.

According to the Transocean investigation report, the design and interpretation of a negative pressure test was the responsibility of the operator in this case BP. The test design may vary from well to well, as there was no established industry standard or MMS procedure for performing a negative pressure test (Transocean, 2011).

From data logs between 15th and 20th April 2010 as well as the information from the hydraulic analysis of Macondo #252 well prior to accident, the pressure was bled off three separate times in an attempt to reduce the drill pipe pressure to 0 psi so that the well could be monitored (Transocean, 2011).

The negative pressure test was conducted by monitoring for flow via the kill line as specified in the MMS-approved April 16th temporary abandonment plan (BP Investigation Team, September 8, 2010).

In the “Genesis of the Deepwater Horizon blowout”, Phil Rea gives a view of the inexplicable pressure and flow anomalies during the negative test. This view which differs from the BP investigation team report, explains that during the pumping and displacement of this heavyweight spacer, a breach in pressure integrity at the casing shoe resulted in the undetected loss of about 80 barrels of drilling mud into the probably uncemented annulus (Rae, 2010). Thus the undetected loss of mud resulted in under-displacement of the heavyweight spacer and led to otherwise inexplicable pressure and flow anomalies during the negative test (Rae, 2010).

The BP Investigation Report revealed that the negative tests were not successful and tests’ results, were misinterpreted by its own and Transocean’s employees on the rig (BP Investigation Team, September 8, 2010) and crew was not aware the differential pressure of 1400 psi was likely due to block of viscous spacer in the kill line. Meanwhile, Halliburton’s comments on National Commission cement testing released on Oct. 28th, 2010; well logs and rig personnel confirm that the well was not flowing after the cement job. The same report points out that if the negative tests had been accurately interpreted, necessary remedial action would have been possible.

2.3.4. Well monitoring and simultaneous operations

Temporary Abandonment Plan: Temporary abandonment takes place when the cement is approved and the well is secure to let the operator to safely leave the well. This process requires displacing the drilling mud with seawater and sealing the well with a cement plug and/or mechanical plug.

BP engineers generated at least five different temporary abandonment plans for the Macondo well between April 12 and April 20, 2010. The procedures varied considerably, calling for different sequences of activity, different depths at which to set the surface cement plug, different displacements, and different negative pressure test procedures (BP Investigation Team, September 8, 2010).

On April 20, 2010, when the temporary abandonment was underway, BP shore-based engineers sent their final amended temporary abandonment plan to the rig. The displacement procedure which was developed by M-I SWACO and approved by BP, incorporated a large amount (425 bbl) of 16-pounds-per-gallon (ppg) spacer (i.e. more than double the average volume used in previous displacements) to complete the displacement (Transocean, 2011). Instead of using normal spacer material, BP mixed two viscous lost-circulation materials, or “pills,” left over from prior rig operations. Combining these water-based pills into one spacer would mean that they could legally be discharged overboard rather taken to shore for costly. The same procedure called for displacement of the weighted drilling fluid with seawater before setting a secondary cement barrier. It also directed the drill crew to displace to 3,300 ft. below the mudline with seawater in order to set the surface cement plug in water. However, the plan still maintained monitoring the negative pressure test on the kill line, as specified in BP’s MMS-approved temporary abandonment plan.

Despite questions that remained regarding the integrity of the production cement and the float collar conversion (Transocean, 2011), and following the misinterpreted negative tests conducted after the cement job, BP instructed proceeded with mud displacement in the production casing and riser with lighter seawater, and this have allowed the well to flow (Halliburton, 2010). It has appeared that BP never subjected the procedural changes to a formal risk assessment for the final temporary abandonment plan (The Deepwater Horizon Study Group (DHSG), March 1, 2011).

Final Displacement: Upon completion of the cement program, the drill crew set up and ran into the well a 6-5/8-in. x 5-1/2-in. x 3-1/2- in. tapered drill string. While at 4,817 ft., with the drill string just above the blowout preventer (BOP) stack, the blind shear ram (BSR) was closed to perform a positive casing test. The positive casing test confirmed the casing was competent and that the BSR had sealed.

As the drilling mud was displaced, the investigation found that the well became underbalanced to one or more of the formations sometime between 8:38 p.m. and 8:52 p.m., but there was no clear indication of an influx at that time (Transocean, 2011).

Sheen Test: A sheen test is conducted to verify that the displacement of synthetic oil-based mud was complete and that it was appropriate to discharge the remaining water-based fluids in the riser overboard into the sea. Although the compliance engineer concluded the sheen test was successful, analysis by (Transocean, 2011) indicates that the spacer had not reached the surface. Post-incident analysis revealed that the volume of seawater pumped was inadequate to accomplish that, resulting in a portion of the spacer remaining below the BOP stack. Between 21:09 and 21:13, during the four-minute interval that the sheen test was conducted, drill pipe pressure increased from 1,013 psi to 1,202 psi. Based on post-incident analysis, this pressure increase was a result of hydrocarbons flowing into the well (Transocean, 2011)

2.3.5. Well control and response

Post-accident analysis indicates that the first indications of flow from the well (control problem) could be been seen in real time data after (at approximately) 20:58. The rig crew and the mud loggers either did not recognized indications of flow into the well until the hydrocarbons entered into the riser at approximately 21:38 hours. The first well control response likely took place at 21:41 hours when the drill crew attempted to close the annular preventer of the BOP.

Based on hydrostatic pressure calculations, OLGA® well flow modelling and analysis of data from Macondo well static kill on August 4th, 2010; they have found evidence that hydrocarbons entered the casing through the shoe track. Therefore, the shoe track cement and the float collar must have failed to prevent this ingress. However the report could not established an understanding of the causation of the accident in term of float collar failure (Transocean, 2011).

Activation of the BOP: BOP has very serious implication on the overall success of drilling. Zeigler estimates that 40% of Deepwater well control problem events leading to total loss of wellbore are due to BOP failure. The first raison is due to risk of formation hydrates when gas mixes with free water while the second raison is connected to the narrow margin in between fracture gradient & pore pressure (Ziegler, 2012), i.e. when the formation is not able to support the backpressure created by the choke line friction. Even if the BOP is close in time on an inflow, it is still challenging as the kick is still contained below the BOP, and there is no established drilling method to circulate out this kick (Ziegler, 2012). The current generation of subsea BOP's, still in its functioning closely related to the original patented in 1929, but today very large, complex and heavy (355 tons) devices that require an enormous amount of maintenance and testing (Ziegler, 2012).When the hydrocarbons started to flow on the rig, there was already a large amount of hydrocarbons in the riser of which the BOP should have held back.

Upon recognizing an influx, the drill crew took well-control actions including activating the upper annular BOP, diverting the flow of hydrocarbons from then riser into the mud-gas separator (MGS), and closing both of the variable bore rams (VBRs). Post-accident analysis revealed that the MGS was overwhelmed by the flow. MGS has function as separator to handle hydrocarbon release, mud, or fluid from the well. Mud and hydrocarbons began to pour out of the MGS vents and other piping, and gas spread rapidly across the aft deck and into the nearby internal spaces, setting off alarms as it spread (Transocean, 2011). MGS is not able to handle the high flow, hydrocarbon with hydrate formation and H_2S content potential. It took only 4 min between time 9:45; when the team advised about the well control situation and 9:49; the time for the two explosions and the loss of the main power of the rig and subsequent the end of data transmission to shore (Transocean, 2011). The BP investigation report agrees that if fluids have diverted overboard rather than to the

MGS, there may have been more time to respond, and the consequences of the accident may have been reduced.

Fire and explosion: On the Deepwater Horizon, the secondary level of protective systems included a fire and gas system as well as the electrical classification of the certain areas of the rig (BP Investigation Team, September 8, 2010). The explosion and the fire likely damaged the MUX cables. With the loss of the electrical power, the AMF activated automatically the high-pressure shear circuit to close the blind shear rams (BSRs). The BSR are designed to cut the drill pipe in the BOP stack, seal the well, and close the ST Locks to mechanically hold the BOP rams closed against pressure from the well. However the blind shear rams closed, a portion of the drill pipe became trapped, preventing the rams from completely shearing, closing, and sealing, thereby allowing fluids to continue to flow up the well bore. According to BP Investigation team report, the AMF sequence could not have been completed by either control pod, due to failed solenoid valve 103 in the yellow pod and an insufficient charge on the 27 Volt AMF battery bank in the blue pod (BP Investigation Team, September 8, 2010). Moreover, the Transocean Investigation Report pointed out that the high-velocity flow of material eroded the rubber of the sealing element and the metal of the drill pipe and prevented the annular BOP from sealing.

All three operating methods of the BOP i.e. the emergency disconnect sequence (EDS), the automatic mode function (AMF) and the auto shear function operated by remotely operated Vehicle (ROV) failed to seal the well. The review of the rig audit findings and maintenance records by the BP investigation team has revealed indications of potential weakness in testing regime and maintenance management system for the BOP (BP Investigation Team, September 8, 2010).

Initial Emergency Response, Muster, and Evacuation: The explosions caused also significant damage in the drilling areas and engine rooms and left debris in some sections of the accommodations area, including the internal muster areas. With the loss of electric power and in the absence of adequate redundancy, the emergency system failed to start. A few batter-activated systems functioned for a while. The emergency lighting functioned briefly, and then failed.

At approximately 9:56 p.m., an attempt to use the BOP control panel to activate the emergency disconnect system (EDS) failed. The BOP control panel lights were on, indicating that it had power, but post-incident investigation confirmed that the EDS did not activate to separate the rig from the BOP.

From the intense heat of the fires and damage from the explosions, it was quickly apparent to the bridge team that it was impossible to regain control of the well or to fight the fires. Instructions were given to abandon the rig, and personnel left the bridge to muster at the forward lifeboats. Many people were evacuated using lifeboats, others jumped from the forward end of the rig into the sea. Of 126 crew workers on board, 115 survived the accident. The BP investigations team indicates that so the Transocean rig crew was not sufficiently prepared to manage an escalating well control situation.

3. EFFECTS OF MACONDO ACCIDENT ON POLICY, REGULATIONS AND ORGANIZATIONS

Every major accident from maritime oil spill at sea to offshore oil and gas accidents has been followed by new regulations. The loss of the Ocean Ranger semi-submersible rig off Newfoundland in 1982 enabled the CNSOPB’s legislation amendment in 1992 to require a series of inspections and certifications (Kelm, 2011). The explosion and fire on Piper Alpha platform in the North Sea in 1988 where, 167 workers died prompted fundamental overhauls of offshore safety systems in 1993. The same is the case in the chemical process industry such as accidents in Bhopal, Seveso and the fire at the Texas City refinery in the USA during 2005, those led to new US and EU regulations. Accidents such as the Exxon Valdez oil spill in the coast of Alaska in 1989, the sinking of the oil tanker Erika off the coast of France in 1999, the sinking of the Prestige followed by oil spill in Spanish waters in 2002, as well as the Alexander Kielland disaster in 1980 with 123 fatalities, all were followed by the enacting of provisions applied to operational safety.

With regard to Deepwater Horizon, and shortly after the accident, the Department of the Interior enacted in October 2010, new offshore drilling regulation including the Drilling Safety Rule and the Workplace Safety Rule. Performance-based regulations that require all operators in the OCS to implement a Safety and Environmental Management System that has become law (McAndrews, 2011). New prescriptive rules for Deepwater drilling will have a significant impact on drilling engineering, operations, and costs.

After completing its investigation, the US President Commission provided a number of recommendations in January 2011 with an aim on how the government can prevent and mitigate the impact of future offshore spills.

The US presidential commission 2011 report proposes the creation of an industry-operated self-regulating organisation (on the model of such bodies as the Institute of Nuclear Power Operations - Inpo) which can contribute to the development and implementation of high safety standards as well as providing evaluation of and advice on company operations, management, performance and behaviour. This type of solution functioned well in the nuclear power industry, and Inpo has a good deal of positive experience which could also be useful for further development of government regulation and the petroleum industry in Norway (BP Investigation Team, September 8, 2010).

The US presidential commission gets across well that the route to improved management of major accident risk in the petroleum industry goes through strong and competent players. Measures which could be relevant include:

- *government assessment of the financial capacity of the companies as a safety factor in player qualification and licence award processes*
- *government contributions, including through player qualification and licence award processes, to making company safety performance an important condition for securing access to business opportunities*
- *Industry reviews of processes and criteria for qualifying suppliers of goods and services in light of experience from the DwH incident and earlier major accidents in order to assess whether management of major accident risk is taken sufficiently into account.*

As other many regulations enacted in post-accident situation, one must caution the potential weakness they present when they relate on issues of the moment rather than long term sound policy that extend on other possible future hazards.

3.1. United State of America

Until the Macondo accident, the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly the Minerals Management Service (MMS) was the United states Department of the Interior institution responsible for leasing, safety, environmental compliance, and royalty collection on the Outer Continental Shelf (OCS). Following the report to the President by the National Commission on the BP Deeepwater Horizon Oil Spill and the Offshore Drilling, September 14th, 2011, the BOEMRE proposed additional SEMS regulations that authorize unannounced rig inspections and third party audits. On October 1st, 2011, as part of a major reorganization, BOEMRE was split into 3 institutions: The Bureau of Ocean Energy

Management (BOEM) – with a mandate to regulate offshore exploration plans, the Bureau of Safety and Environmental Enforcement (BSEE) – to inspect oil rigs and enforce safety, and the Office of Natural Resources Revenue (ONRR)(National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (OSC), January 2011b). In section 21(b) of the OCS Lands act, the BOEMRE on behalf of the Secretary of Interior requires the use of best available and safest technologies in offshore drilling and production operations. The BOEMRE has the responsibility of determining the best available and safest technologies, and ensuring that they are applied to offshore drilling and production operations. BOEMRE regulations are largely prescriptive, and many of the regulations are based on the use of safe equipment which can meet the BAT requirement.

The institution responsible for industry safety issues is now the Bureau of Safety and Environmental Enforcement (BSEE), which has responsibility for ensuring regulatory compliance within the industry with key functions: the Offshore Regulatory Program, the Oil Spill Response and the Environmental Compliance.

The BSEE with headquarter in Washington DC. It manages national programs, policy and budget. BSEE through its several regional offices is responsible for reviewing applications for permits to drill to ensure that all the recently implemented enhanced safety requirements are met. Those offices conduct inspections of drilling rigs and production platforms, and investigate accidents and incidents. BSEE operates also a National Training Centre.

Based on certain recommendations in the May 27th, 2010, report from the Secretary of the Interior to the US President Barack Obama (US Department of the Interior, May 27, 2010), a new Regulation Identifier Number (RIN) 1014–AA02 under the authority of BSEE replaced the former RIN 1010–AD68 which was published October 14th, 2010.

The Final Rule (RIN) 1014–AA02 that became effective on October 22, 2012 (Bureau of Safety and Environmental Enforcement, 2012b, Bureau of Safety and Environmental Enforcement, 2012a):

- Updates the incorporation by reference to the second edition of API Standard 65-part 2, which was issued December 2010. This standard outlines the process for isolating potential flow zones during well construction. The new Standard 65-part 2 *enhances the description and classification of well-control barriers, and defines testing requirements for cement to be considered as a barrier*.
- Revises requirements from the Internal Final Rule (IFR) on the installation of dual mechanical barriers in addition to cement for the final casing string (or liner if it is the final string), to prevent flow in the event of a failure in the cement. The Final Rule provides *that, for the final casing string (or liner if it is the final string), an operator must install one mechanical barrier in addition to cement, to prevent flow in the event of a failure in the cement. The final rule also clarifies that float valves are not mechanical barriers.*
- Revises § 250.423© to require the operator *to perform a negative pressure test only on wells that use a subsea blowout preventer (BOP) stack or wells with a mudline suspension system instead of on all wells, as was provided in the Interim Final Rule.*
- Adds new § 250.451(j) stating *that an operator must have two barriers in place before removing the BOP, and that the BSEE District Manager may require additional barriers.*
- Extends *the requirements for BOPs and well-control fluids to well-completion, well-workover, and decommissioning operations under Subpart E – Oil and Gas Well-Completion Operations, Subpart F – Oil and Gas Well-Workover Operations, and Subpart Q –Decommissioning Activities to promote consistency in the regulations.*

Following Macondo accident, API created 4 Joint Industry Task Forces (JITF) in the areas of Prevention, Intervention and Spill Response. The work made resulted in major effort to revise key existing standards and several new API standards. Usually API standards are reviewed and revised or withdrawn every five years. Many OGP members (mainly US based) have contributed actively to the revision and development of the API standards. In the following section selected API are discussed:

(a) **API Std 53 :** Based on a day-long forum at the Interior Department May 22nd, 2012 whereby Frank Gallander, Chairman of API Std 53, Chevron (Gallander, May 22, 2012) gave a public presentation on new developments related to API Std 53;After the Macondo accident, the API Std 53 was changed into a standard. The standard API Std 53 is an industry document for the operation and maintenance of drilling BOP equipment. Primary it contained 21 sections. As other documents were in direct conflict with it, through a kind of a clean cut API Std 53 was narrowed down to seven sections. The first five sections, common to both, surface and subsea BOP, the Section 6 is assigned to surface BOP and control systems and how it is operated and maintained, while the Section 7 is more in-depth in the subsea side of it.

In the new standard, it was incorporated some of the effects of negative pressure on subsequent BOP's. And it was identified the condition-based maintenance as an alternative to schedule-based maintenance. Greater emphasis is on the communications route for the manufacturer and equipment owner.

There's some prescriptive points in the document, specifically the drawdown test, which refers back to specification 16-d and that's for the design, manufacturing, and testing of BOP control systems or 16-c, which is choke and kill systems. With regards to 16-d, lines hydrocarbons can be introduced and permeate through the line structure, while for 16-c hoses for control systems must fulfil fire testing requirements.

Regarding the failure of shear rams to seal, the API Standard 53 "Blowout Prevention Equipment Systems for Drilling Wells" proposes the use of dual shear rams as a base case for subsea BOPs (OLF et al., 2012).

Based on the joint task force (JTF) equipment recommendations the ROV interface standardization has also been adopted into an industry standard. Minimum functions required to hold the ROV interface configuration were adopted.

(b) **API RP 75 :** As per the BOEMRE Office of Public Affairs, the Fact Sheet on Safety and Environmental Management Systems (SEMS) makes mandatory 13 elements of RP 75 that the Workplace Safety Rule must follow:

- General provisions: *for implementation, planning and management review and approval of the SEMS program.*
- Safety and environmental information: *safety and environmental information needed for any facility, e.g. design data; facility process such as flow diagrams; mechanical components such as piping and instrument diagrams; etc.*
- Hazards analysis: *a facility-level risk assessment.*
- Management of change: *program for addressing any facility or operational changes including management changes, shift changes, contractor changes, etc.*
- Operating procedures: *evaluation of operations and written procedures.*
- Safe work practices: *manuals, standards, rules of conduct, etc.*
- Training: *safe work practices, technical training – includes contractors.*
- Mechanical integrity: *preventive maintenance programs, quality control.*
- Pre-start up review*: review of all systems.*
- Emergency response and control: *emergency evacuation plans, oil spill contingency plans, etc.; in place and validated by drills.*
- Investigation of Incidents: *procedures for investigating incidents, corrective action and follow-up.*
- Audits: *rule strengthens RP 75 provisions by requiring an audit every 4 years, to an initial 2–year re-evaluation; and then subsequent 3-year audit intervals.*
- Records and documentation: *documentation required that describes all elements of the SEMS program.*

(c) **API RP 96:** API announced on April 1st, 2013 the publication of two new oil and natural gas industry standards for well design and drilling operations.

The first, Deepwater Well Design and Construction, API Recommended Practice 96, provides engineers a system-wide reference for onshore well design, drilling and completion operations using subsea blowout preventers (IADC, 04 April 2013). It covers the range of considerations that must be taken into account when planning for Deepwater drilling operations. Those include:

- *Appropriate barrier and load case consideration to maintain well control.*
- *Guidance supplementing API 65-2, December 2010 on barrier philosophy and management (Isolation Potential Flow Zones during Well Construction) of API 90 on annular pressure buildup.*
- *Risk assessment and mitigation practices for casing and equipment installation operations.*

Through various API among them the API RP 96 as well as others documents that use BOP in industry, a new definition of a BOP was proposed. The API RP 96 is a guiding document for the design and construction of Deepwater subsea wells. Here BOP is defined and classified with regard to well-control equipment with some relationship given to the pressure. BOP is therefore defined based on MASP [*Maximum Anticipated Surface Pressure*] as a design load that represents the maximum pressure that may occur at the surface during well construction or production. And as part of the subsea well – the MAWHP [*Maximum Anticipated Wellhead Pressure*] is considered as the highest pressure predicted to be encountered at the wellhead in a subsea well. Another definition is the Maximum Speculative Wellhead Shear Pressure [MSWSP], which means the expected pressure at the wellhead for a given hole section, a specific shear pressure requirement, specific operating piston design, the drill pipe material specifications, to achieve shearing at MASP, MAWHP, or whatever other limiting design pressure for the well.

According to IADC, it is the responsibility of each organisation involved in UBO/MPD Operations to ensure that all relevant documents in their specific working environment or region are consulted for applicability. The second, Protocol for Verification and Validation of High-Pressure High-Temperature Equipment, API Technical Report 1PER15K-1, establishes a process or evaluating equipment used in high-pressure and/or high-temperature (HPHT) environments both on and offshore.

3.2. Norway

An exhaustive historical development of the oil and gas regulatory regime in Norway and the use of risk assessment in the NCS, is well covered in the paper (Khorsandi et al., 2013). For the last 40 years, the regulation regime has evolved from the establishment of the Norwegian Petroleum Directorate (NPD) in 1973 and the initiation of a simple technically oriented and prescription based rules to the creation of PSA in 2004 with the use five regulations i.e (i) Framework HSE Regulations, (ii) Management Regulations, (iii) Facilities Regulations (iv) Activities Regulations and (v) Technical and Operational Regulations. The current regulations administered by the PSA for governing offshore activities are a mixture of performance based and prescriptive requirements which largely refer to the NORSOK standards (Khorsandi et al., 2013). According to the DNV, performance based regulation gives the industry a relatively high degree of freedom to selecting the right solutions that will fulfil regulatory requirements. More information, content and the overall principle of each regulation stated above are given in (Khorsandi, 2010). We should recall that in 1999/2000, the Trend in Risk Level Project (RNNP) was initiated. Managed by PSA, the RNNP establishes a description of the risk level the parties in the industry could agree upon.

Following the Deepwater Horizon drilling rig disaster in the Gulf of Mexico, the Petroleum Safety Authority Norway (PSA) established May 7th, 2010 a project team. The work conducted by the team was to develop the best possible basis for the authority’s supervision and other measures which could improve health, safety and the environment (HSE) on the Norwegian continental shelf (NCS) (PSA, 2011). As a result of the work, PSA has recognized that the Deepwater Horizon accident cannot be confined to incident affecting only BP, Transocean and Halliburton, Deepwater drilling, blowouts and/or the Gulf of Mexico. They recognized that the disaster affected all types of activity and all players in the national and international petroleum sector. It has been stressed that the accident must lead to improvements in the industry as a whole.

The PSA has already identified three key areas in a need of improvement to help reduce major accident risk on the NCS (Petroleum Safety Authority, 2012, Petroleum Safety Authority, 2011b):

a) **Barrier management**: In the PSA’s view, the industry must give a high priority the development of a more integrated and uniform approach to barrier management.

   i. <u>Capping and containment</u>

      • Work has been launched to develop effective capping and containment solutions which can halt and/or divert the wellstream as quickly as possible in the event of a blowout. These efforts must be given high priority and closely monitored by the authorities, including the PSA.

      • The PSA is monitoring the development of equipment, plans, proposals for standards, and evaluating necessary adjustments to the regulations – such as requirements for consent applications, emergency preparedness and well control.

      • In connection with capping and containment, the PSA is in a dialogue with the OLF and the Subsea Well Response Project Group established by the International Association of Oil and Gas Producers (OGP) after the Deepwater Horizon accident.

   ii. <u>Blowout preventers (BOPs)</u>

      • Experience from the Deepwater Horizon incident reinforces the importance of applying modern barrier principles in order to integrate safety in BOP designs for both fixed installations and mobile units.

      • BOP integrity and operational issues presented by well control are being followed up through the PSA’s participation in the International Regulators’ Forum (IRF), the OGP and the International Association of Drilling Contractors (IADC).

b) **Risk management**: The PSA sees the need to pursue ambitious studies and developments to secure better management tools. A particular requirement exists to be able to analyse, assess and understand change-related risk in every phase of an operation. That covers everything from extensive organizational and structural reshaping to variations from plans for implementing individual activities.

c) **Organization and management**: This is reflected in decision making and prioritization processes, management of expertise and operational changes which aim at reducing major accident risk. Emphasis should be on communication and information sharing within companies and between operator and contractors, and management rather than the focus on short-term financial gain.

PSA recognises that Regulations and standardisation in Norway must have both national and international perspectives – and be seen in relation to existing work on regulatory development (Petroleum Safety Authority, 2011b). A total of 45 recommendations have been made to the Norwegian petroleum industry in the OLF's report. Most of these are preventive in character, but they include capping and collection, oil-spill clean-up, standards and industry practice. The OLF believes that this issue of blowout preventers (BOPs) is best handled by the expert committee on wells of the International Association of Oil & Gas Producers (OGP) (Petroleum Safety Authority, 16.08.2012).

As a result of Macondo accident and following other near miss recently occurred in the NCS; those include the Gullfaks B hydrocarbon leak December 4th, 2010, and the gas leak on Heimdal main platform May 26th, 2012 see (Petroleum Safety Authority, 2013), the Norsok D-001 and D-010 standards review became evident. Both standards provide the norms for drilling and well requirements on the Norwegian continental shelf (NCS). Information provided below are based (OLF et al., 2012):

(a) **Norsok D-001:** The standard is about the "*drilling facilities*". The Norsok revision work has been on-going since spring 2011. OLF considers it the responsibility of each individual operator and drilling contractor to review, evaluate and, if necessary, revise its internal management system and steering documentation to take account of these recommendations:

- *To reduce the risk of a gas cloud over the rig, Norsok D-001 will specify that the mud gas separator (MGS) should no longer be connected directly to the diverter system. The diverter system itself should be upgraded to a "safety system" designed to divert any gas in the riser to the overboard lines and safely away from the rig.*
- In Norway, explosion risks are already significantly reduced by the Norwegian Maritime Directorate (NMD) requirement for automatic closure of air intakes and automatic shutdown of non-explosion (non-Ex) equipment upon gas detection. There is also NMD *requirements in-place for fully independent power supplies for "re-lighting" and dynamic positioning* (DP).

- Norsok D-001 and D-010 include more explicit *requirements for primary and back-up BOP control systems, their ability to perform in emergencies and testing of them*.

(b) Norsok D-010 rev.4: The standard is about "*well integrity in drilling and well operations*". In Macondo, the first cause was the failure of the cement to isolate hydrocarbons behind the casing. Sintef study recommended the update of NORSOK D-010 rev.4 "Well integrity in drilling and well operations" with respect to the cement as a primary barrier, and the use of new technology (Tinmannsvik et al., May 2011). Based on existing new technologies, NORSOK D-010 rev.4 has been updated in terms of improved procedures for planning, mixing, pumping and qualification of cement as a primary barrier:

Cement jobs: Norsok D-010 rev.4 finds "critical" cement jobs. It requires that cement and casing design for slurries placed across hydrocarbon zones be verified in cementing company labs prior the use. For critical slurry designs, such as those containing foam cement or gas block additives, the slurry design, slurry properties, waiting on cement times and cementing plan should be independently verified. This verification can be performed by either an independent in-house department or an external third party.

The standard also expects that all displacement to a lighter underbalanced fluid should be done with a closed BOP and through the choke and kill lines.

Inflow (negative) pressure testing: Norsok D-010 rev.4 has been updated to define the requirements related to inflow (negative) pressure testing clearly. Under Norwegian rules, putting a well in an unbalanced condition prior to establishing well integrity is not accepted. For Macondo case, barrier verification should have taken place before circulating the well to an underbalanced condition. Well programmes should provide a detailed procedure and acceptance criteria for all inflow tests. Inflow tests should be conducted in a controlled manner with detailed procedures which have been approved by an authorized person, and accompanied by a demonstrated risk analysis.

BOP: Many reports including that from DNV, identified deficiencies in control systems, maintenance requirements and failure of the shear rams. *Norwegian regulations require five year overhaul and recertification of all BOP components, a back-up control system and regular testing. And Norsok D-010 rev.4 further proposes improvement and the strengthening of testing procedures of the BOP, its control and emergency back-up systems.*

Norsk D-010 anticipates the operators to conduct a risk assessment to determine the optimum BOP configuration for each well, utilising the latest BOP reliability, performance and assessment data, the design of the well to be drilled, and the rig in use. The findings should be recorded in the well control bridging document. A risk analysis shall be performed to decide upon the best BOP configuration for the location in question.

Regarding the BOP, we should mention that though, the American Petroleum Institute (API) Standard 53 proposes the use of dual shear rams as a base case for subsea BOPs. The OLF has found that this may not always be the safest option. Due to the variability of rig and drilling environments in the NCS, *all ram configurations should, as part of well planning, be subject to comprehensive well specific risk and engineering analysis, using the latest BOP reliability and performance data*.

Casing, well control emergencies: Norsok D-010 rev.4 updates requirements for routine well control exercises, specifically in the areas of:

- spacing out and centralizing pipe prior to shearing and disconnecting
- diverter line-up to overboard lines
- well control exercises to be conducted (scope, frequency, acceptance, etc.)

The Norsk D-010 rev.4 finds that a MOC procedure covering the well life cycle should be included in the operator’s management system steering documentation. A proposed change shall be supported by a justification that should address the following:

a) *reason for change*
b) *description of the new proposed solution*
c) *possible consequences and uncertainties*

d) updated risk assessment in line with the proposed change

(c) Norsok Z-013: Revision 3 of NORSOK Z-013 is related to "*Risk and emergency preparedness assessment*". In its cf. sf. § 17, the standard requires that *the quantitative analysis will be significantly more suitable to establish and/or tone required performance standards for all relevant barriers*. According to "Principles for barrier management in the petroleum industry"; by (PSA, 2013) a barrier management can be defined as coordinated activities to establish and maintain barriers to ensure that they maintain their function at any time.

(d) Norsok D-002: is about "*well intervention*". The system requirements well intervention equipment whereby primary barriers are harmonized with the Norsok D-010, while the secondary barriers have been expanded to reflect the expectation of the current industry development.

3.3. United Kingdom

In UK, the offshore regulation went into a revolution following the Alpha pipe accident in 1988. A systematic and thorough consideration of safety and communication was introduced into UK legislation. An Offshore Installations (Safety Case) Regulations (OSCR) came into effect May 31st, 1993 and replaced the former safety standard that was often based on prescriptive codes. Since then QRAs was introduced into UK legislation as a part of the safety cases for both existing and new installations (e.g. drilling, production or accommodation rig). A Safety Case "*is a comprehensive and structured set of safety document that demonstrates that all major hazards have been identified and assessed, that the proper measures are in place to manage those hazards, and that the risks have been reduced to ALARP*"(HSE, 2006). The revised OSCR in 2005 intended to relieve unnecessary burdens on duty holders and on HSE, to enhance the safety case's value to the duty holder and to provide a greater stimulus for continuous improvement.

Reference to Vinnem 2000, the offshore regulation for the Norwegian industry as well as for the UK is mainly goal based, with functional safety requirements stated by the regulations, thus giving the industry extensive flexibility with respect to how to reach the stipulated goals. Today many countries have endorsed similar legislations.

At the time of Macondo blowout, a new Government in UK led by David Cameron was being created while the parliament was in recess. The accident quickly developed attention in Britain media not only because the operator on Macondo – BP was a British company in USA, but also due to the waking up of public awareness following the huge oil spill threatening marine life. Particular interest was the public/press realisation of Deepwater drilling in UK West of Shetland and what will be the potential impacts of a moratorium on Deepwater drilling posed by the US Government.

Shortly after the Macondo, and in view of the early Montana blowout in 2009, the Offshore Division (OSD) set up its internal Deepwater Horizon Incident Review Group (DHIRG) to provide a forum to assess the implication of those incidents for the UKCS. Today DHIRG final report is not yet published as the final reports (e.g. CBS reports on Macondo) are not received from the US investigations.

From the published investigations reports on Macondo, the HSE initiated and performed a quick review of safety regulatory regime to gain an insight into the UK sector's asset integrity key performance indicators; part of arrangements for monitoring and measuring major accident risk contributors with an aim at checking if the existing systems around the safety case regime were working properly. It followed a sensible reinforcement of peer review of well design assessments and rigorous auditing approach of Safety Case acceptance for MODUs with specific actions being undertaken:

- *Multiple layers of regulatory protection*
- *Established Safety Case regime for MODUs*
- *Wells notification to HSE*
- *Independent wells examiner*
- *Independent verification of safety critical elements (e.g. BOPs)*
- *Duty Holder focused intervention by HSE wells specialists and other offshore HSE inspectors*

- *Weekly drilling operations reports to HSE*
- *Mature, goal setting safety regime*
- *Safety culture/work force involvement in North Sea*

Table 3: A summary of changes in policies, regulations and standards following Macondo blowout

Country	**Majors Changes**			
	Changes registered	**Discussed standards in this study, as revised after Macondo blowout**	**Early edition**	**New edition**
USA	- New offshore drilling regulation including the Drilling Safety Rule, the Workplace Safety Rule, and the requirement of the performance – based regulations for all operators in the OCS - BOEMRE split into 3 institutions: BOEM, BSEE and ONRR - SEMS regulations that authorize unannounced rig inspections and third party audits	API Spec 16A “Drill through equipment (BOPs)”	2004	Dec. 2012
		API Spec 16C “*Choke and kill systems*”	1993	May 2013
		API Spec 16D Control systems for drilling well control equipment and diverter systems	2004	Jan. 2013
		API Std 53 *“Recommended Practices for Blowout Prevention Equipment Systems for Drilling Wells”*	1997	Jan.2012
		API RP 65-part2 “*Isolating potential flow zones during well construction”*	2002	Dec. 2010
		API RP 75 “*Recommended Practices for a development of safety and environmental management for OCS operations and facilities*”	2004	Under revision
		API RP 96 “*Deepwater well design Considerations*”	New	Ed.1, Mar. 2013
Norway	- PSA established a project team to follow the DwH accident - Supervision and other measures which could improve health, safety and the environment (HSE) on the Norwegian continental shelf (NCS) - Specification in Norsk D-001 that the mud gas separator (MGS) should no longer be connected directly to the diverter system. - a “safety system” designed to divert any gas in the riser to the overboard lines and safely away from the rig - improved procedures in Norsok D-010 for planning, mixing, pumping and qualification of cement as a primary barrier - MOC procedure covering the well life cycle should be included in the operator’s management system steering documentation - Requirement in Norsok D-Z013 of a quantitative analysis to establish and/or tone required performance standards for all relevant barriers	Norsok D-001 “*drilling facilities*”.	1998	Ed 3, Dec. 2012
		Norsok D-002 *“well intervention”*	2000	Applicable for all wells after Jan 1st, 2014
		Norsok D-010 “*well integrity in drilling and well operations*”	2004	Rev4, 2013
		Norsok Z-013 “*Risk and emergency preparedness assessment*”	2010	Ed.3, Oct. 2010
UK	- The creation of the DHIRG, OSPRAG and WLCPF - peer review reinforcement of well design assessments and rigorous auditing for MODUs - adoption of minimum, prescriptive safety standards for fail-safe devices such as the blowout preventer	-	-	-
ISO	- Several ISO standards are being updated, and mostly are - To adopt the outcome of the API work and Norsok standards.	ISO/TC 67 “*Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*”	The latest update 2009	-

With regards to oil spill and its impact on the environment, the UK established in addition, the Oil Spill Prevention and Response Advisory Group (OSPRAG), which later formed the Well Life Cycle Practices Forum (WLCPF) as a group to provide a permanent platform for industry to share and build good practices around well design, construction and completion. Under the WLCPL, five sub teams were created with the following responsibilities: (i) the BOP Issues, (ii) Relief Well Planning Requirements, (iii) Well Life Cycle Integrity Guidelines, (iv) Competency/Behaviours/human Factors and (v) Well examination/verification. By the time of the present Master thesis report, the Forum report was not yet published.

The Department of Energy and Climate Change (DECC), as initial response on environmental issues anticipated the review of environmental and pollution response regulatory regime once clear lessons emerge from GoM. In addition, DECC together with HSE inspectors doubled number of MODU environmental inspections and all E&A wells and in particular Deepwater wells (>300 metres) were being reviewed and consented on a case by case basis.

In general, Macondo accident was discussed in the Chief Executive's Report to the Board, 2011. The report refers to 25 conclusions and recommendations relating to safety, environmental protection, oil spill response and liability to avoid problems such as the Macondo and Montara accidents. Those recommendations cover a number of issues and they are about: improving industry planning for high-consequence, the Government should adopt minimum prescriptive safety standards for fail-safe devices such as the blowout preventers, ensuring that the UK offshore inspection regime does not allow simple failures to go unchecked, and that measures to improve safety culture are undertaken (Health and Safety Executive Board, 2011). Very recently, new online guidance was introduced to makes easier the understanding of the health surveillance.

Beside efforts in the UK, the European Commission envisaged future amendments to Offshore Oil and Gas Directives – including Directive 92/91/EEC which covers the minimum requirements for improving the safety and health of workers in the mineral-extracting industries through drilling. The document which was published in Summer 2011, outlined the EC's ideas to ensure that a disaster similar to the one in the Gulf of Mexico will never happen in the waters around the EU and that the best practices existing in Europe should become the standard throughout the area (Health and Safety Executive Board, 2011).

In general, this master thesis has observed that a robust and a high offshore regulatory standards exemplified by HSE's Safety Case regime is led by the Step Change in Safety Leadership Team. The Team comprises industry, regulators, trade unions and the workforce.

3.4. International Standard Organization

The following section is based on recent industry action plan events by the ISO/TC 67 Management Committee Ad-hoc Group (AHG) prepared in response to the Montara and Macondo. It is suggested that a number of the high priority subjects are already being addressed in API, and the proposed ISO/TC 67 activity for these subjects is generally to adopt the outcome of the API work into ISO (ISO/TC 67 Management Committee AHG Industry Events (ISO/TC 67 MC N088), March 1st, 2011).

The Norwegian Electrotechnical Committee and Standards Online AS, states that most of the international standardization activities are organized in ISO/TC 67 "*Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*". By third quarter 2011, 154 standards were published of which 52 were in revision and 43 new work items were proposed. A total of 60 countries participate/observe the activities. Norway takes part in all 6 sub-committees in ISO/TC 67, and contributes with experts in most of the working groups. The Norwegian petroleum industry participates also in many of other international standardization committees, see [http://www.standard.no/en/sectors/Petroleum/].

Some of these proposals will seek to merge several existing industry standards, bring useful national standards into the international arena for broad industry consensus agreement and make the resulting ISO standards readily available for global adoption in Europe, Gulf States, Russia, US and many other regions around the globe.

Normally, the ISO revision is pre-scheduled to be revised every 10 years. The last ISO update happened in 2009. It is therefore seen that with Macondo experience, the industry and many ISO users will still have to rely on changes that were discussed in the previous sections with API and Norsok standards.

4. DISCUSSIONS

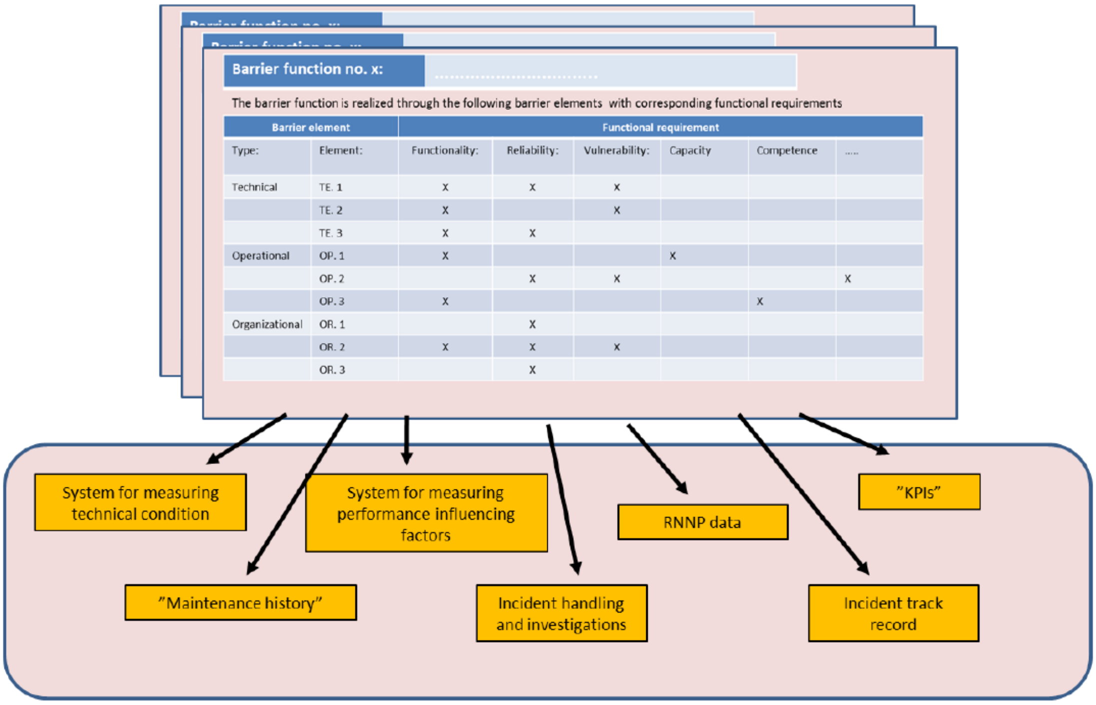
4.1. Barriers performance and safety management during wells completion in Deepwater

Barriers performance and what will be the requirements to ensure safe drilling in Deepwater? Barrier performance is a topic discussed first by Vinnem, 2000 in his paper “Risk Monitoring for Major Hazards”. He finds necessary a universal effort to report the barrier performance though he recognized the difficult to design such reporting scheme given its complex data and parameters aggregation. This master thesis recognized that the trends in risk level in the petroleum activity (RNNP) adopted by the PSA, mostly emphasis the gathering and reporting information on incidents such as oil spills, fire, explosion, blowout, etc. Those accidents and incidents may take place because barriers failure to prevent and/or to limit hazards or accidents from occurring. It is clear that the reporting of incident will remain incomplete as far as the experience with barriers performance is not reported/or not known.

PSA requires that functionality of barrier should be maintained during facility lifetime by establishing various barrier strategies (Kristensen, September 12, 2012). Barrier act as prevention measure (prior accident happened) and mitigation measures (after accident happened, to mitigate and limit disastrous consequence).

A substantive progress has been made by the PSA through its reports “Principles for barrier management in the petroleum industry”, 2013. The experience acquired by the PSA through its supervision has shown that working in a structured and purposeful manner to minimize risk at an early stage provides a significantly better chance of implementing good solutions without incurring substantial costs or facing major challenges (PSA, 2013).

PSA has established the governing principles as well as indicators/activities/measures employed in the industry today to verify the performance requirements for a number of barrier elements as it is illustrated in figure 7.



Barrier function no. x: ……………………………

The barrier function is realized through the following barrier elements with corresponding functional requirements

Barrier element		Functional requirement					
Type:	Element:	Functionality:	Reliability:	Vulnerability:	Capacity	Competence	…..
Technical	TE. 1	X	X	X			
	TE. 2	X		X			
	TE. 3	X	X				
Operational	OP. 1	X			X		
	OP. 2		X	X			X
	OP. 3	X				X	
Organizational	OR. 1		X				
	OR. 2	X	X	X			
	OR. 3		X				

Figure 7 Performance verification of barrier functions and associated barrier elements source (PSA, 2013)

Based on ISO 31000, it is required that non-functioning or impaired barriers must be identified. This is achieved through one or more iteration processes by risk assessments, identification of uncertainties, and – as a consequence of additional details in the project's development/planning phase – reassessment and optimization of performance requirements with an aim at making sure barriers functions and associated barrier elements have the intended properties.

In the figure 7, PSA has categorized barriers based on their requirements for technical, operational and organizational barrier elements. Therefore, they often display characteristics such as: capacity, functionality, effectiveness, integrity, robustness and availability.

For the case of drilling operation, an example of technical barrier elements provided by the barrier function is to secure an adequate fluid column during drilling operations. In this respect, the monitoring operation and the initiation of necessary countermeasures to prevent and/or to deal with a kick will depend on predefined routines/procedures in addition to equipment such as mud pumps and blowout preventers (BOPs) that must function efficiently. The performance requirements for operational and organisation barrier elements could include personal expertise in doing the work as well as criteria for action, response time, notification to the central control room, number of personnel and availability.

In the Norsok D-010 rev.4, the well integrity requirement needs to be ensured to prevent influx hydrocarbon during drilling activity. Norwegian regulations require that personnel must be capable of handling hazards and accidents, and that provision must be made so that personnel with control and monitoring functions are able to acquire and respond to information efficiently at all times. The following shows an example of bow tie diagram to visualize causes and consequences while drilling with the new technology of Managed Pressure Drilling method.

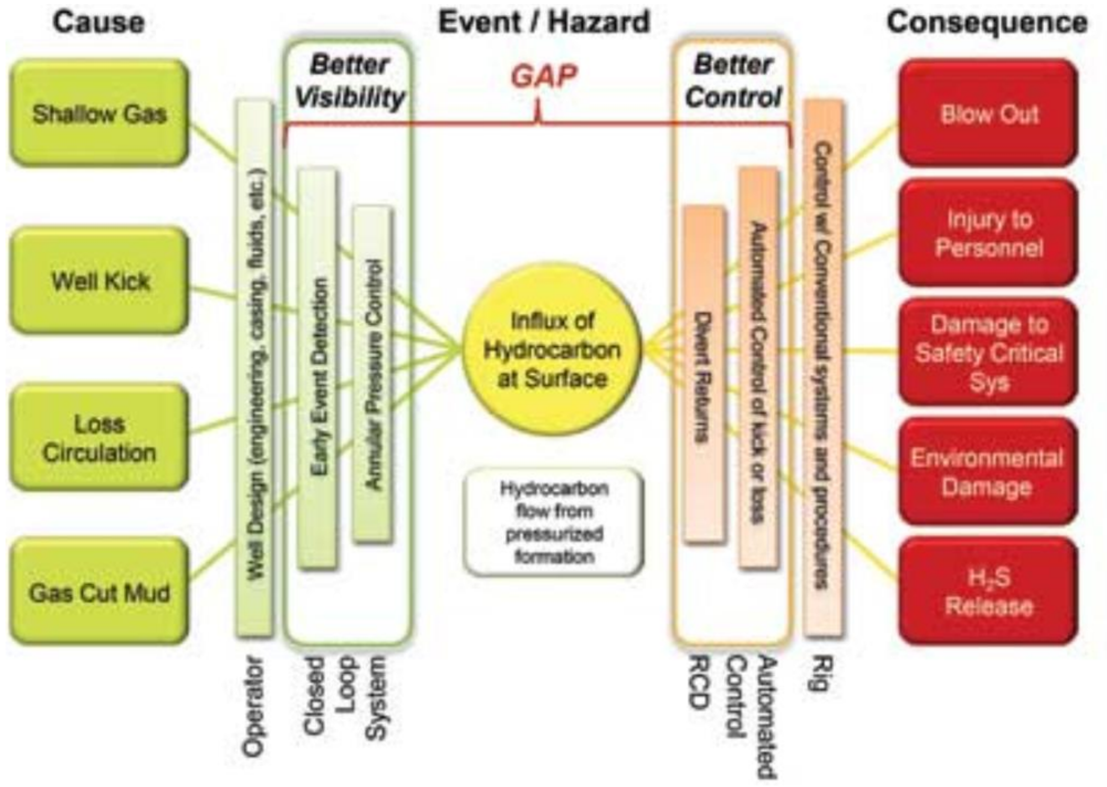


Figure 8: A bowtie risk diagram models the causes and consequences of an influx of Hydrocarbons into the well, and shows how MPD adds layers of well control and mitigation source(Sammat, 2013)

In the [Appendices B], it is provided a summary of the Macondo barrier failure with MTO approach. Different barriers can be of a technical, operational or organizational nature, or a combination. A complete set of indicators for managing Major Accident Risk must cover the Man, Technology and Organization (MTO) perspective

Issues related to policy, regulations and standards: Since the end of 19th century, the oil and gas industry has been registered a tremendous change and improvement in policies, regulations and standards by ensuring that the G&O exploration and production are conducted safely. As other major accidents such the Pipe Alpha, Texas City Refinery, etc., the Macondo accident has been also a precursor of substantial change in policy, regulations and standards.

Changes have mainly been recorded in USA and Norway but also the other worldwide community has been following Macondo with special interest. Most changes has particularly been seen through the revised Norsok and API Recommended practices as well as the institutional reform with an aim at improving safety during drilling operation in Deepwater environment. In USA, the Macondo Accident has led to significant reform of the US Department of the Interior's offshore safety and environmental regulator. The dual roles MMS as a leasing agent and regulator, early strongly criticized (Brown, 2012) has been restructured with the creation of new bodies as reflected in section 3.1. It has been stressed that the new created regulators bodies should be properly resourced and not subject to undue political and industry pressure.

Some changes in decision risk management have recommended the US offshore regulatory regime, to adopt a proactive, risk-based performance approach similar to the UK safety case approach in the North Sea.

Sub surface characterizations: From personal communication with P.Nadeau and as it is also reflected in the appendix E, a setup of an adequate barrier in a situation of HPHT environment call for a sound understanding of the subsurface geologic environment. For an exceptional case such the Macondo prospect of the Gulf of Mexico (GoM), even an experienced scientist, geologist can make easily a mistake when care is not well taken to analyse the anomalously low leak off pressure (LOP) without properly considering the sub-surface stress regimes.

With the subsurface generally limited in total stratigraphic extent, it results in a rapid departure from more hydrostatic pressure condition, to very high degrees of overpressure, often approaching lithostatic gradients, and near the Leak Off Pressure limit of the formations (Nadeau, 2011a). As it has been revealed by P. Nadeau, the risks can be compounded if the operator fails to realize that “LOP” test results could in fact be FPPs (Fracture Propagation Pressures, normally close to the minimum stress) (Nadeau, 2011b).

The master thesis has found that the combination with Goldon Zone (GZ) geological processes, the stress regimes (e.g. a careful analysis of Formation Break-down Pressure (FBP) and the Fracture Propagation Pressure (FPP)) as well as the Leak off Pressure (LOP) will be an important step for significant improvement in risk analysis and risk management for adequate well completion/casing and cementing design. This is equally important for the risk analysis process as it will provide the correct hydrostatic pressure gradient which is necessary for a proper drilling mud weights design that will allow excellent cement distribution and bonding during cement displacement in the situation of HPHT conditions.

Risk and technology development: The drilling of Macondo well used the Best Available Technology (BAT), a 5th generation MODU. According to the technical specification, the Deepwater Horizon was equipped with Dynamic Position type DP3, a device with redundancy in technical design and with an independent joystick back-up. The back-up dynamic positioning control system must enable the MODU to automatically disconnect in a case of emergency.

Other equipment, instruments and monitoring system of the Deepwater Horizon were of the highest quality: “e-drill” – a drill monitoring system whereby real-time drilling data from the rig was received for maintenance and troubleshooting information, the BOP of 15000 psi –as the last critical component designed to contain the hydrocarbon in a case of kick. Other characteristics included the pressure and drill monitoring technology, to automated shutoff systems. The OptiCem cement modelling system, used by Halliburton in April 2010 for BP's Gulf of Mexico drill, played a crucial part in cement slurry mix and support decisions.

Beside the above mentioned perfections, one can never be sure that possible incidents were all identified and that risks and uncertainties have been adequately identified, if alternatives have been assessed at the right time and that they were sufficiently consistent with the identified risk picture.

Today, the Macondo accident has created the possibility of new technology testing and implementation. A MPD approach is currently wide used for a BHP control during Deepwater drilling. In the contrast of the mud weight designed to hydrostatically overbalance exposed formation pressures, the Norsok D-010 rev.4 has strengthen the primary well barrier with the MPD equipment and in addition to mud column in the well. The MPD equipment is used to adapt and control the annular hydraulic pressure profile within the exposed formation pressure limits. Though the primary and secondary well barriers remain independent, the MPD still maintain the same function for the secondary well barrier as well as for the primary well barrier. We should recall that the Norsok D-010 rev.4 has maintained the same definition for the secondary well barrier found in the conventional drilling which consists of an envelope of several well barrier elements, e.g. casing or liner strings, casing or liner cement, casing or liner packers, plugs wellhead and BOP. The tertiary well control consists of the last barrier for well integrity. It includes the pumping substance i.e. heavy slug into the wellbore to stop uncontrolled flow in the well. Following the Norsk D-10 rev.4, revision, a new crossflow well barrier is suggested to prevent flow between formations (i.e. where crossflow is not acceptable). The crossflow well barrier may also function as primary well barrier for the reservoir.

One of many cases of the recent technological development referred to in this Master thesis, consists of new aqueous-based version: “the SandWedge® conductivity enhancement system” announced by Halliburton following the Macondo disaster. The new version delivers proprietary conductivity enhancement technology with more operational efficiency, versatility and reliability. The aqueous-based system also enables important applications in remedial fracture treatments (Halliburton, 2012).

Safety management perspective: The empirical literature accounts some consistent associations between specific leadership styles and safety outcomes [see table 4]. The reader is advised to consult the HSE Research Report by (Lekka, 2012) for more on effective leadership behaviours for safety.

According to Hollnagel et al., 2008, the modern research into workplace accidents has identified that missing the side effects of change is the most common form of failure for individuals and organizations cited in (Smith, 2011). During well design, a rigorous peer-review process takes place, however when changes such as drilling procedures or well design occur in the weeks and days and/or during drilling operations it may become unrealistic to conduct a thorough peer-review and subsequently adopt a management of change (MOC) process. A passive leadership at Macondo, seems to have guided some decisions that made possible the accident.

Table 4:   Leadership styles and their safety outcomes adapted from (Bea, 2011)

leadership styles	**Safety outcomes**
Transformational leadership (e.g. acting as a role model, inspiring and motivating employees to work safely and showing concern for employees' welfare, It enhances employees' levels safety consciousness (i.e. knowledge).)	• Fostering perceptions of a positive safety climate, • Promoting higher levels of employee participation in safety activities, • Compliance with safety rules and procedures and safety citizenship behaviors (e.g. participation in safety committees, looking out for workmate's safety)
Transactional (contingent reward) leadership (e.g. clarifying performance expectations, monitoring and rewarding performance; It enhances employee safety performance such as safety citizenship behaviors.)	• perceptions of a positive safety climate, • positive safety behaviors and reduced accident rates
Passive leadership (i.e. turning a blind eye to safety)	• Negative perceptions of safety climate and an increase in safety-related events and injuries.

Several publications (Smith, 2011, Kelm, 2011) as well as the investigations reports have revealed that safety-related processes, policies, and procedures (e.g. the adequate review by the Minerals Management Service and/or whether commercial pressures led to breaches of legally approved practice) and the ad hoc lack of formal risk analysis or internal expert review that in some cases caused catastrophic consequences during Macondo well abandonment plan.

The rig operations continued despite flaws observed along the drilling activities on Macondo: e.g. the extraordinary pressure necessary to convert the float collar, the cement job on the production casing without making sure that the selection of only six centralizers on the casing string would not lead to channelling of the cement in the annulus and the casing shoe track, the inadequate negative pressure test. All those decisions [see table 5] compromised the well integrity.

It is obvious that an understanding of different types of leadership and behaviours in complex organizations, that promote error detection and prevention, is extremely crucial in order to avoid small margins of errors given that they will lead to very serious consequences.

Table 5: Examples of Decisions that increased Risk at Macondo while saving time (Hair and Narvaez, 2011)

Decisions	**Was there A less risky alternative available?**	**Less time than alternative?**	**Decision-maker**
Not waiting for more centralizers of preferred design	Yes	Saved time	BP on shore
Not waiting for foam Stability Test Results and/or Redesigning Slurry	Yes	Saved time	Halliburton and (perhaps BP) on shore
Not Running Cement Evaluation Log	Yes	Saved time	BP on shore
Using Spacer Made form Combined lost Circulation Materials to Avoid Disposal issues	Yes	Saved time	BP on shore
Displacing Mud from Riser Before Setting Surface Cement Plug	Yes	Unclear	BP on shore
Setting Surface Cement Plug 3000 Feet Below Mud line in Seawater	Yes	Unclear	BP on shore (Approved by MMS)
Not installing Additional Physical Barriers During Temporary Abandonment Procedure	Yes	Saved time	BP on shore
Not Performing Further well integrity Diagnostics in light of troubling and Unexplained Negative Pressure Test Results	Yes	Saved time	BP (and perhaps Transocean) on Rig
Bypassing Pits and conducting Other simultaneous Operations During Displacement	Yes	Saved time	Transocean (and perhaps BP) on Rig

Taking Halliburton example reported in the Corporate Sustainability Report (Halliburton, 2011), many incidents continue to happen due to employees do not proper follow procedures. The same report shows that the near misses and high-potential incidents reporting has enabled the company to identify and fix behavioural, process or equipment issues before they result in incidents. Though the overall reporting rate declined by 6%, the near-miss reporting increased by 11% year-over-year and high-potential incident reporting also increased slightly.

One of the most popular safety management approaches consists of the occupational health and a safety measure which is limited to report measures on near misses, accident involvement and injuries. In Norway, the use of the RNNP, to illustrate contributors in incident as well as the comparison between incidents reported, shows that over the last 40 years the risk exposure with regards to both major accidents and occupational accidents have considerably reduced. The same situation is also observed in UK since the introduction of the Safety Case. In USA, SEMS regulations have now authorized unannounced rig inspections and third party audits of SEMS programs. Recent drilling contracts for work in the US Gulf of Mexico often address new post-Macondo regulatory requirements relating to BOP certification and testing. Provisions obligating the contractor to act in accordance with the operator's Safety and Environmental Management System "SEMS" requirements are also frequently proposed by operators along with more stringent terms addressing maintenance, testing and certification of BOP, rig crew training, etc…..The proposals would like lessees also to systematically identify risks, establish procedures to address those risks, authorize any employee on an offshore facility to stop work, delineate authority for operational safety and establish guidelines for reporting unsafe conditions (Moomjian, 2012).

The above picture shows that the promotion of ZERO, or near-ZERO, HSE results and Safety Quality (SQ) performance information require extensive involvement of company in addition to training, networking within the industry. On the other hand, the master thesis finds that the effectiveness study of leadership in high hazard contexts calls for development of specific indicators (similar to RNNP) to measure the leadership behaviours in view to guarantee high levels of safety.

Various studies (Austnes-Underhaug et al., 2011) have shown that the safety management system is often hampered by the continuous interior restructuring and integration process in companies. This situation creates significantly stresses in the security management and environmental protection. Since 1998, BP has known such transformation with the extensions of its operation by continuous merger and reorganization. Though the company asset increased considerably, the management may remain difficult to success due to the culture difference.

The same observation has been seen with in relation to Gullfaks C incident in May 2010. The study by (Austnes-Underhaug et al., 2011) showed that among several underlying causes of the incident, the merge of Statoil and Hydro in one company in 2007. In this context, the full integration of all activities, resources and management documentation created too many topics in documents procedures with the group's system of governing documents (DocMap) largely copied into the system's governing documents (APOS). This created a challenging situation to differentiate between processes, requirements and methods. This also connects to non-compliance.

Issues related to governance documentation and compliance may thus have served as underlying causes of the incident on Gullfaks C. Similar observations were mare with regards to Snorre A in 2004 (Austnes-Underhaug et al., 2011). Procedures perceived as cumbersome and difficult to deal with, and can sometimes also be difficult to follow because there are conflicting claims to the same operation.

Furthermore,(Austnes-Underhaug et al., 2011) points out that the staffing change Autumn 2009 - Spring 2010 has had an impact on management and decision-making on Gullfaks C. Much of the leadership of the Gullfaks C was replaced, and it is pointed out a lack of lessons learned in this process.

When a new management system such as ARIS[2] and/or a new technology such as MPD are introduced in a system, it follows normally several conflicting requirements of the systems. It is therefore important that more detailed risk assessment, risk management plan and issues such as “organizational context”, “management and decision-making” and “compliance” are well analysed. This is a concern especially for rotation, experience transfer and management documentation. An example related to organizational context can serve that employees may be less willing to summarize

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[2] ARIS (Work process oriented management) is Statoil's management system describing roles, work flow, requirements and methods for the various activities. ARIS replaced APOS since 2010

and systematize the knowledge they possess and share this, or a feeling of loss of ownership, power and importance of the organization, as well as fear of being fired. Lack of motivation may for example result in deferral, hesitation, sabotage or rejection of the implementation and application of new knowledge.

4.2. Dilemma in risk communication

By recalling findings of the investigations team's reports, some problems of Macondo go beyond the Code of Professional Conduct. In various situations, decisions were taken without any formal risk analysis: e.g. the cement design as part of the primary well barrier, the casing with in short supply of centralizers as part of the secondary well barrier. Other flaws during the well completion were recorded: e.g. the use of excessive pressure to convert the float collar, the misinterpretation of the negative pressure test, the use of spacer made form combined lost circulation materials to avoid disposal issues, the decision not to install additional physical barriers during temporary abandonment procedure, etc. The tertiary well control/barrier recommends the use of heavy slug into the wellbore to control the flow in the well. This could not happen because the excessive pressure and the damage caused to others equipment's among them the BOP.

Though some decisions were criticized by certain contractors and the fact that information on hazards was not shared among all the stakeholders involved in the well completion, this master thesis report has raised concerns on the effectiveness of risk analysis and/or risk management used on Macondo. For some decisions, the acceptable state of art of the use of risk analysis and risk management was just ignored. As the operator and contractors failed adequately to implement the needed risk analysis there was nothing left to proceed with risk communication? On the other hand, few occasions when risk was understood there is no indication that those occasions of risk were subject to communication or consultation as it is recommended by ISO 31000. The BP culture of communication during the drilling the Macondo well drilling has to be questioned. Some attitudes and behaviours which are neither ethical nor professional have been also discovered in the post Macondo time. One BP former employee on the name of Kurt Mix, who resigned in 2012 purposely deleted oil flow estimates i.e. around 200 messages and emails that made difficult the investigation to reconstruct some situations of the accident.

Findings of the investigations teams have shown that Macondo accident took place because mainly human and organizational errors. Those extend to working practice, competence, communication, procedures and management (Skogdalen and Vinnem, 2011). This master thesis goes beyond this simplified statement and confirms that act of negligence/irresponsibility and the circumstance of not performing risk analysis and risk management as required by acceptable standards and rules are among the challenges scientists, engineers and the leadership will have to improve. Meanwhile, Sintef, 2011 recognizes the extremely difficult or even the impossible circumstances to access the information related to human errors e.g. the organizational safety culture, the organization management, and personal experience.

In the Fig. 9, it is shown the basis of regulatory requirements, [ISO 31000 Risk management – principles and guidelines and ISO standards for management and leadership]. The fig. 9 has been used by (PSA, 2013) as a starting point to describe a barrier model which specifies principles for barrier management.

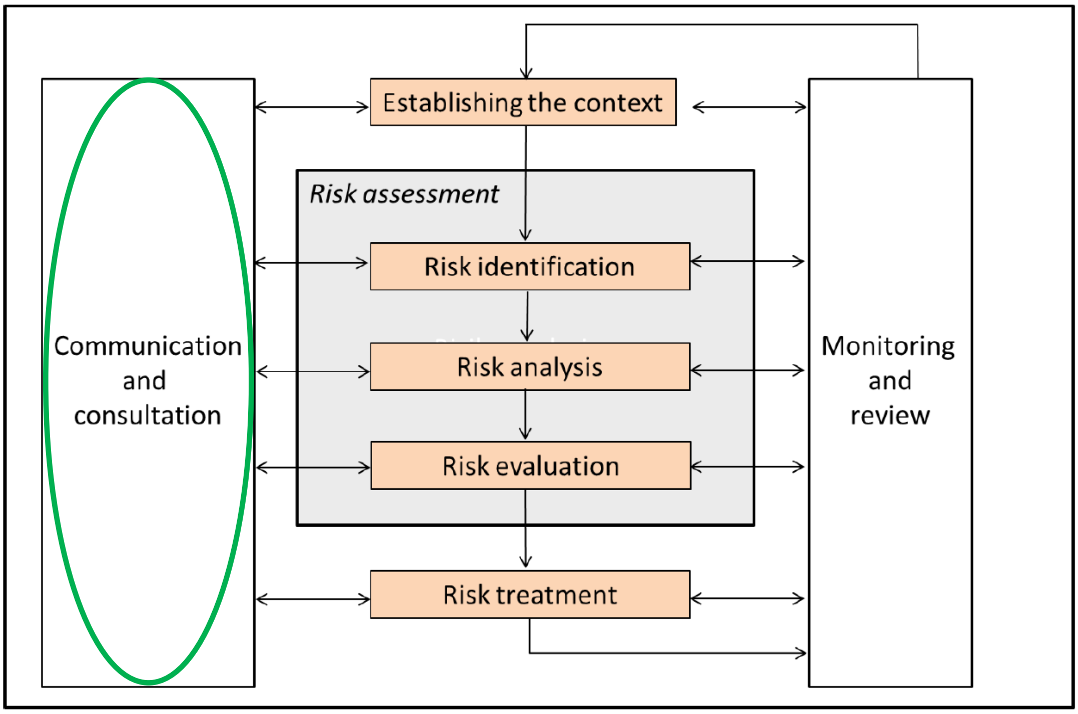

Figure 9: Process for risk management in ISO 31000

From the above risk management model, the responsible party must ensure (and demonstrate) that communication and consultation with both internal and external stakeholders are appropriate throughout the barrier management process. This is intended in part to ensure:

- *good quality – by drawing on relevant expertise and experience throughout the process, including when establishing the context, when conducting risk assessments and management, and for supervising and monitoring at all times*
- *participation by and a sense of ownership among stakeholders who will be affected by decisions in every phase*
- *understanding of the background to decisions*
- *that risk analyses are communicated in such a way that target audiences obtain a nuanced and coherent presentation of the analysis and its results*
- *that documentation of the barrier strategy(ies) is actively used to provide those involved with a common understanding of the basis for the requirements specified for the various barriers.*

Communication and consultation are not to be regarded as an independent activity, but as one which will pervade the whole barrier management process in every phase.

In the aftermath of the 2010 BP Gulf of Mexico spill, former Shell president, John Hofmeister said that in order for BP to truly make changes to its HSE management practices and procedures, the changes must be fully integrated into the company. He said BP must “penetrate the minds and hearts of people who implement these procedures, and that takes times and education and communication” (Souder, June 20, 2010). In other meaning companies that fail to dedicate an appropriate amount of time, education and communication to ensure practices are in line with their values and policies, they will continue to experience high costs due to social risk and missed opportunities for cost savings, reputational capital and strategic business opportunities.

In particular, the followings should be highlighted for better success in risk analysis and risk management: (i) *the use of rigorous and structured method for risks identificat*ion, (ii) *the management has ownership and understanding of risks*, (iii) *the* *access of experienced rig crews and service personnel,* (iv) *the review and discussion of risk management on a daily basis during the operation,* (v) *the use of purpose designed software for capturing, reporting and tracking actions in the risk management,* (vi) *the mitigation measures are fully understood by the rig team at the time of execution* , (vii) *clear responsibilities of the various people in the team in relation to the identification and management of risk*, (viii) *the external validation of the project during the peer review process,* (ix) *enables a formal link to the wider organizational experience to be made through access to Lessons Learned databases*.

In this era, the use of digital oil field technology offers its advantage to the industry with a possibility to access huge amounts of information that help to make high-quality decisions and the ability to share information at unprecedented speeds and quantities. If safety communication (e.g. open and trusting channels for sharing safety-related information) and hazard awareness and management (e.g. including an organisations' use of audits and risk assessments to identify problems and put the necessary control measures in place) will be part of the routine of risk assessment, this will bring an improvement in safety.

As demonstrated, systematic risk assessment as detailed by ISO 31000 is one of the key tools for successful project management of drilling operations. A single consistent approach is taken to the identification, evaluation, mitigation and management of risk throughout the whole process. It links the identified risks to uncertainties in the project cost and connects the rig team with those risks at the point of execution of the job. Time response remain crucial in making decisions, thus one will avoid surprises by conducting an in-depth risk analysis before the project starts and make sure all risk have been identified and understood.

In the overall objective, it is stressed that the development process must focus on "Human Centred." This should adhere to the principles of ISO 9241-210:2010 "Ergonomics of human-system interaction—Part 210: Human-centred design for interactive" in which both hardware and software components of interactive systems can enhance human–system interaction. Today, many companies require employees to conduct regular behaviour-based safety (BBS) observations as a way to increase awareness and improve safety behaviours.

5. CONCLUSIONS

A quote by George Bernard Shaw says “a life spent on mistakes is not led only more honourable but more useful than a life spent doing nothing”. It is part of human nature that experience teaches at the cost of mistakes. Investigations reports analysed in this master thesis as well as various used publications have confirmed that Macondo accident was due to human errors, the failure in organization culture, in particular the wrong decisions, personnel deficiencies, oil platform design flaws and technical problems. In Appendices F, it summarizes what author finds, are the major contribution by this Master thesis.

By adopting the complacency attitude and the lack of oversight, the Macondo operator and contractors appear never to have undertaken any risk analysis nor to have established mitigation plans regarding their performance of simultaneous operations after the cement barrier was judged being safe.

It has been seen that the recent risk analysis and risk management development is being strongly impacted by Macondo accident. Extraordinary improvements are recorded in term of revised policy, regulations and standards. In addition, decisive efforts are observed within technology development for a safe drilling operation in more difficult environment of Deepwater and the Arctic. This study has confirmed that no matter that a risk analysis is made, the risk communication remain crucial to avoid major accidents.

For the case of Deepwater drilling activities, the understanding the subsurface geology, rock mechanics will be the basic primary guarantee for a safe design system. We have seen a need to develop indicators that will deal with barriers performance evaluation both during the design and the operation in deeper HPHT wells. This is should be part of the improvement of risk analysis techniques in an attempt to show which factors from subsurface formation, drilling technology and human decisions will have more influence on the occurrence of a blowout.

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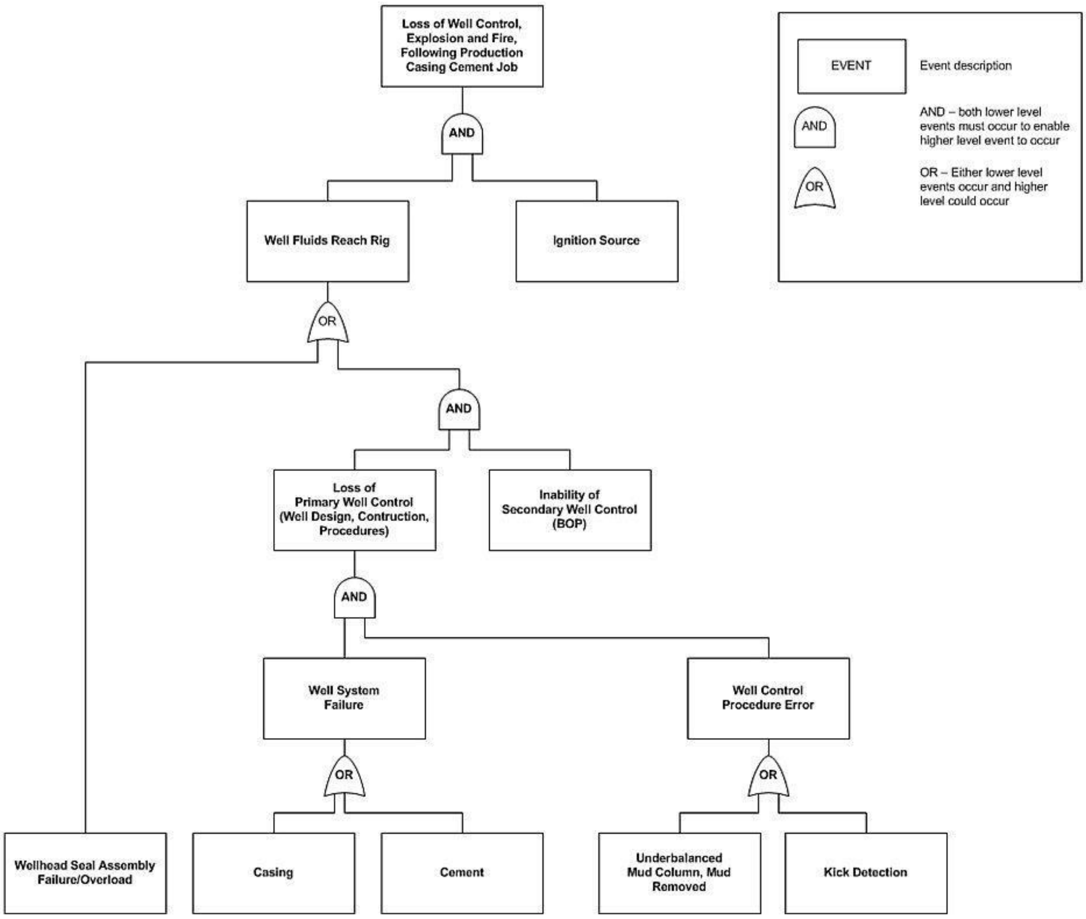
A. Appendices: Fault Tree Analysis Used in Investigation of Macondo Well Explosion sources(Hair and Narvaez, 2011)

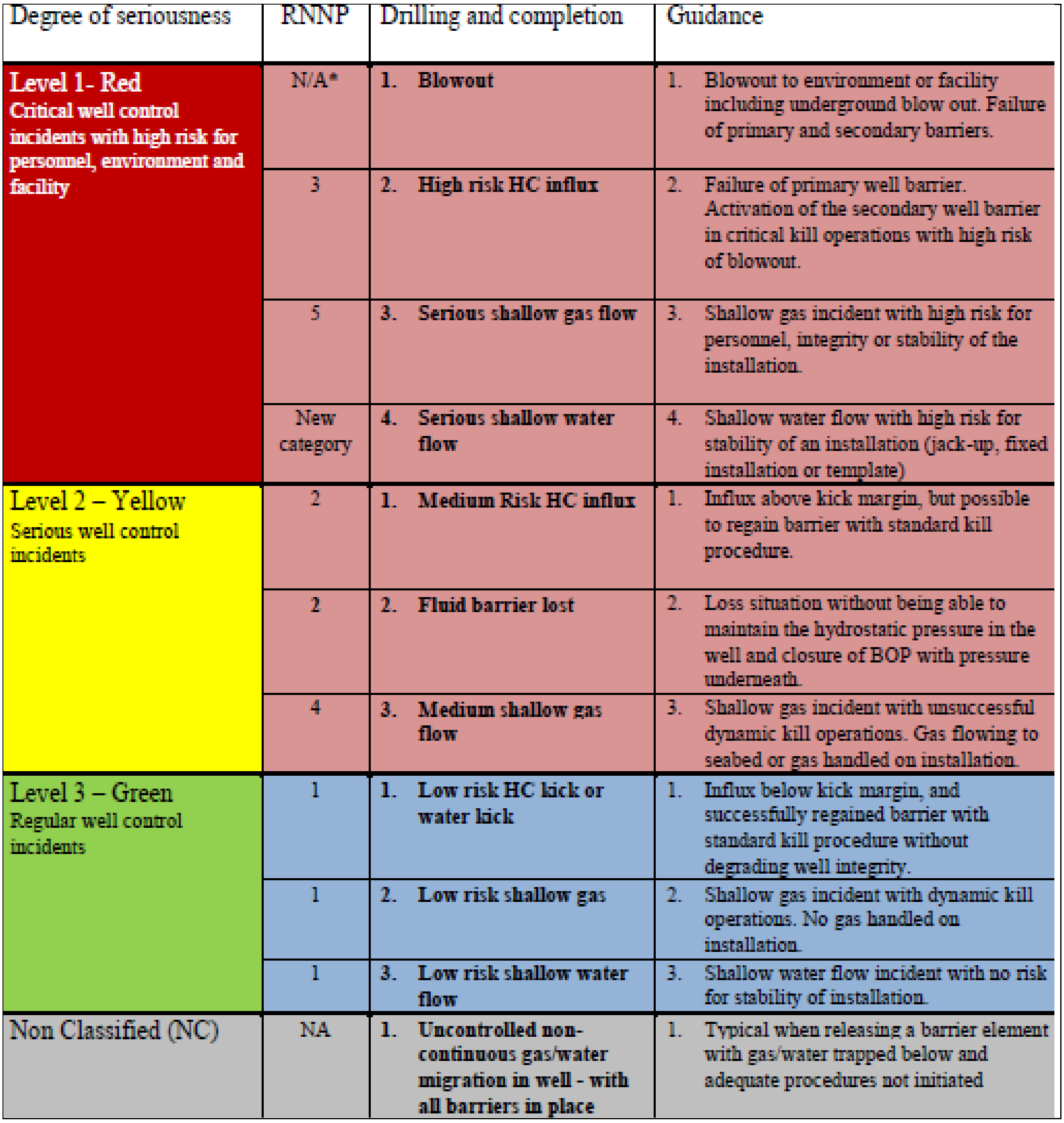


B. APPENDICES: PROPOSED BARRIER STRATEGY FOR DRILLING AREA (SUMMARY OF THE MACONDO BARRIER FAILURE WITH MTO APPROACH)

Barriers	**Performance Standard**	**Human**	**Technology**	**Organization**
Containment Barrier	- Containment Function - Drilling and Well Barrier	- Personnel involved in cement job should be competent - The consequence for any modification should be assessed properly by performed personnel	- Well integrity should be ensured from good cement mixture. - Improved well design for wells with high flow potential - Location of float collar at the bottom shoe to create overbalanced and prevent poor integrity of shoe track - Adequate centralizer should be installed to prevent channeling	- Audit on cementing technical activity should be conducted regularly. - Comprehensive cement lab test is available - Management of change should be clear - Regulation and industry accepted recommended practices must be followed. - Effective quality assurance/audit should be performed to ensure good contractor performance.
Barrier to Limit Spill Size/Cloud	- Gas Detection System - Ignition Source Control	- Personnel should assess any multiple and simultaneous operation to prevent distraction and loss of focus for major work - Personnel should be competent in technical to identify signal in hydrocarbon release	- ESD must be initiated automatically with the activation of fire and gas detector. - Use of more accurate kick detection devices	- Availability joint document or procedures between company and contractor to handle well control. - Specific regulation from authority and company for negative pressure test should be developed with clear minimum standard acceptance. - Competency and training system should ensure personnel to have required competency in well control
Barriers to Prevent Ignition	- ESD System - Process Safety System	- Personnel should be competent to act in the event of abnormalities.	- Fire and gas detector must be able detect gas to form flammable volume - HVAC engine room is designed to shut off upon gas detection - Location of any venting system outlet is designed to have adequate distance with ignition sources. - Engine room must be classified - Emergency shutdown system must be initiated automatically in the course of gas detector is activated.	- Automatic activation of safety system on the rig. - Regular audit system on the rig to identify hazard on the rig. - Training system for personnel to react in the event of emergency. - Clear procedure in rig to determine the time to use diverter or MGS should be available

Barriers	**Performance Standard**	**Human**	**Technology**	**Organization**
Barriers to Prevent Escalation	- Natural Ventilation & HVAC - Fire Detection System - Active Fire Fighting - Passive Fire Protection - Explosion Barrier	- Personnel must assess manual operation for firefighting, EER, and safety instrumented system - Personnel should continuously monitor well performance during critical activity - Personnel must competent to take any proper action in case of emergency situation occur	- MUX cable should be protected from explosion and fire. - Control pod and batteries should be designed with redundancy and longer life time - OEM electrical connector should be used and installed at solenoid valve - Pump at the ROV should be reliable to initiate any emergency action to close BOP	- Company should have proper safety management system on critical equipment. - Audit finding for critical equipment should be closed immediately and appropriately. - Rig contractor must follow and confirm with regulation and vendor policy for critical equipment - BOP diagnostic practices should cover all critical components of the control system (e.g., AMF batteries).
Barrier to Prevent Fatalities	- Escape and Evacuation - PA and Alarm	- Personnel should aware consequence of safety critical Equipment, such as alarm, inhibition.	- General alarm must be designed to automatically sound in case of hydrocarbon released detected from fire and gas detector	- Company should give high attention of process safety rather than personal safety. - Lesson learned from near misses or precursor event should be distributed to all employee and contractor. - Proper emergency training system should be in place - Inhibition of critical equipment should be treated critical.

C. APPENDICES: MATRIX FOR CATEGORIZATION AND CLASSIFICATION FOR WELL CONTROL INCIDENT. DRILLING AND COMPLETION OPERATIONS

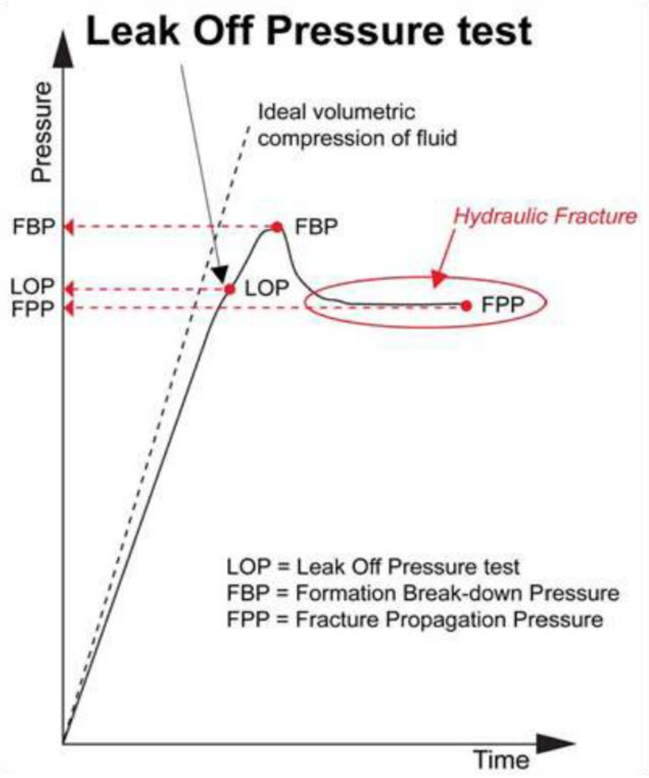


Degree of seriousness	RNNP	Drilling and completion	Guidance
Level 1- Red **Critical well control incidents with high risk for personnel, environment and facility**	N/A*	1. **Blowout**	1. Blowout to environment or facility including underground blow out. Failure of primary and secondary barriers.
	3	2. **High risk HC influx**	2. Failure of primary well barrier. Activation of the secondary well barrier in critical kill operations with high risk of blowout.
	5	3. **Serious shallow gas flow**	3. Shallow gas incident with high risk for personnel, integrity or stability of the installation.
	New category	4. **Serious shallow water flow**	4. Shallow water flow with high risk for stability of an installation (jack-up, fixed installation or template)
Level 2 – Yellow Serious well control incidents	2	1. **Medium Risk HC influx**	1. Influx above kick margin, but possible to regain barrier with standard kill procedure.
	2	2. **Fluid barrier lost**	2. Loss situation without being able to maintain the hydrostatic pressure in the well and closure of BOP with pressure underneath.
	4	3. **Medium shallow gas flow**	3. Shallow gas incident with unsuccessful dynamic kill operations. Gas flowing to seabed or gas handled on installation.
Level 3 – Green Regular well control incidents	1	1. **Low risk HC kick or water kick**	1. Influx below kick margin, and successfully regained barrier with standard kill procedure without degrading well integrity.
	1	2. **Low risk shallow gas**	2. Shallow gas incident with dynamic kill operations. No gas handled on installation.
	1	3. **Low risk shallow water flow**	3. Shallow water flow incident with no risk for stability of installation.
Non Classified (NC)	NA	1. **Uncontrolled non-continuous gas/water migration in well - with all barriers in place**	1. Typical when releasing a barrier element with gas/water trapped below and adequate procedures not initiated

Pink: alert to PSA according to management regulation § 29

Blue: notification to PSA according to management regulation § 29

D. APPENDICES: LEAK OFF PRESSURE TEST ILLUSTRATION SOURCE (NADEAU, 2011B)



Global Leak Off Pressure (LOP) pressure trend and that of anomalously low observation from offshore Louisiana, deeper than 3km below sea floor. Values with less than 1.7 g/cm^3 equivalent mud weight gradients are a particular concern for drilling operations.

A Leak Off Pressure (LOP) test vs. time plot for mud pressure in a well borehole. The test is performed by pumping drilling mud at a constant rate into the borehole. Normally the test is only performed until the mud starts to leak into the formation (LOP). The Formation Break-down Pressure (FBP) is typically ~10% greater than the LOP. After the formation has broken down, a hydraulic fracture is propagated at the Fracture Propagation Pressure (FPP). Note that the LOP and FPP can have similar pressure values

E. Standards for drilling, well construction and well operations, relevant to the Macondo accidents. Adapted from (ISO/TC 67 Management Committee AHG Industry Events (ISO/TC 67 MC N088), March 1st, 2011, OGP International Assocations of Oil &Gas Producers, November 2012)

I. Engineering design, systems & equipment related documents:

API TR 6AF *Capabilities of API flanges under combinations of load*

API Spec 16A /ISO 13533 *Drill through equipment (BOPs)* (Revised)

API Spec 16C Choke and kill systems (Revised)

API Spec 16D/ISO 22830 *Control systems for drilling well control equipment and diverter equipment* (Revised)

API Spec 16RCD *Drill through equipment rotating control devices*

API RP 49 Recommended practice for *drilling and well servicing operations involving hydrogen sulfide*

API Std 53 BOP *equipment systems for drilling wells* (Revised)

API RP 59 *Well control operations*

API RP 64 *Diverter systems equipment and operations*

API RP 65-1 *Cementing shallow water flow zones in deep water wells* (Revised)

API RP 65-2 *Isolating potential flow zones during well construction* (Revised)

API RP 90 *Annular casing pressure management for offshore wells* (under revision)

API RP 90-1 (formerly RP 90) *annular casing pressure management for offshore* wells (under revision)

APPEA *Australia offshore oil and gas title holder self-audit checklist*

DNV OS-C101 *Drilling plant*

EI Guidelines for routine and non-routine subsea operations from floating vessels

EI Model code of safe practice, Part 17 Volume 1: High pressure and high temperature well planning

EI Model code of safe practice, Part 17 Volume 2: Well control during the drilling and testing of high pressure, high temp offshore wells

EI Model code of safe practice, Part 17 Volume 3: High pressure and high temperature well completions and interventions

IMO MODU (Mobile Offshore Drilling Units) Code

ISO TR 10400/API TR 5C3 *Equations and calculations for the properties of casing, tubing drill pipe and line pipe used as casing or tubing*

ISO 10405 *Care and use of casing and tubing*

ISO 10423/API Spec 6A *Wellhead and Christmas tree equipment*

ISO 10426-1/API Spec 10A *Cements and materials for well cementing*

ISO 10426-2/API Spec 10B-2 *Testing of well cements* (under revision)

ISO 10426-3/API Spec 10B-3 *Testing of deepwater well cement formulations*

ISO 10426-4/API Spec 10B-4 *Preparation and testing of foamed cement slurries at atmospheric pressure* (under revision)

ISO 10426-5/API Spec 10B-5 *Determination of shrinkage and expansion of well cement formations at atmospheric pressure*

ISO 10426-6/API Spec 10B-6 *Methods of determining the static gel strength of cement formulations*

ISO 10427-3/API RP 10F *Performance testing of cementing float equipment*

ISO 11960/API Spec 5CT *Casing and tubing for wells* (under revision)

ISO 11961/API Spec 5D Steel drill pipe

ISO 13354 *Shallow gas diverter equipment*

ISO 13624-1/API RP 16Q *Design, selection and operation of marine drilling riser systems*

ISO 13625/API 16R *Marine drilling riser couplings*

ISO 13628-1/API RP 17A *Design and operation of subsea production systems* (Revised)

ISO 13628-2/API Spec 17J *Unbonded flexible pipe systems for subsea and marine applications*

ISO 13628-4/API Spec 17D Subsea wellhead and tree equipment

ISO 13628-5/API Spec 17E *Subsea umbilicals* (Revised)

ISO 13628-6/API Spec 17F *Subsea production control systems* (Revised)

ISO 13628-7/API RP 17G *Completion/ workover riser systems* (under revision)

IEC 61892-7 *Mobile and fixed offshore units-Hazardous areas*

ISO 13628-8/API RP 17H *Remotely operated tools and interfaces on subsea production systems* (under revision)

ISO 13628-11/API RP 17B *Flexible pipe systems for subsea and marine applications*

ISO 13679/API RP 5C5 *Procedures for testing of casing and tubing connections* (under revision)

ISO 13680/API Spec 5CRA CRA casing and tubing

ISO 14224/API Std 689 Collection and exchange of reliability and maintenance data for equipment

ISO 14310/API Spec 11D1 Packers and bridge plugs

ISO 15156/NACE MR 0175 *Materials for use in H2S-containing environments in oil and gas production*

ISO 19901-6/API RP 2MOP *Marine operations*

ISO 19901-7 Stationkeeping systems for floating offshore structures and mobile offshore units (under revision)

ISO 19904-1 *Floating offshore structures—Monohulls, semi-submersibles and spars*

ISO 20815 *Production assurance and reliability management*

ISO 23251/API Std 521 *Pressure relieving and depressuring systems* (under revision)

ISO 28300/API Std 2000 *Venting of atmospheric and low-pressure storage tanks* (under revision)

ISO 28781 *Subsurface barrier valves and related equipment*

NORSOK D-001 *Drilling facilities* (Revised)

NORSOK D-002 *System requirements well intervention equipment* (Revised)

NORSOK D-SR-007 *Well testing system* (under revision)

NORSOK D-010 *Well integrity in drilling and well operations* (Revised —considered in API 96 and ISO 16530)

Norwegian Oil and Gas 117 *Well integrity guideline*

II. Management related documents:

API Bull E3 *Environmental guidance document: Well abandonment and inactive well practices for U.S. exploration and production operations*

API RP 75 *Development of a safety and environmental management program for offshore operations and facilities*

IADC HSE *Case guidelines for mobile offshore drilling units*

IADC *Deepwater well control guidelines*

ISO 13702 *Control and mitigation of fires and explosions on offshore production installations* (under revision)

ISO 15544 *Requirements and guidelines for emergency response*

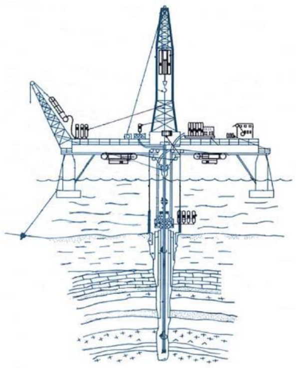
ISO 17776 *Guidelines on tools and techniques for hazard identification and risk assessment* (under revision)

NORSOK Z-013 *Risk and emergency preparedness analysis*

OGP 210 HSE *Guidelines for the development and application of HSE management systems* (under revision)

OGP 415 *Asset integrity - the key to managing major incident risks*

OGP 435 *A guide to selecting appropriate tools to improve HSE culture*



OGP 476 *Recommendations for enhancements to well control training, examination and certification*

OGUK OP006 *Guidance on suspension and abandonment of wells* (under revision)

OGUK OP064 *Guidelines on relief well planning — subsea wells*

OGUK OP065 *Guidelines on competency for wells personnel including example*

OGUK OP069 *Well integrity guidelines*

OGUK OP070 *Guidelines on subsea BOP systems*

OGUK OP071 *Guidelines for the suspension and abandonment of wells including guidelines on qualification of materials for the suspension and abandonment of wells*

OGUK SC033 *Guidelines for well operators on well examination and competency of well-examiners*

III. Documents in development

API TR PER15K-1 HPHT *Protocol for equipment rated greater than 15K PSI*

API Std 16AR (New) *Repair and remanufacture of drill-through equipment (working title*)

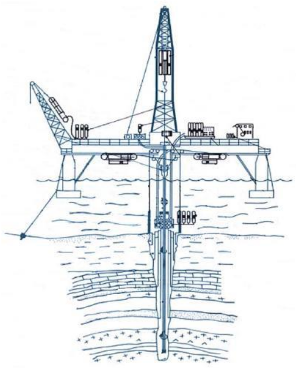
API Spec 17W – *Subsea capping stacks*

API RP 90-2 *Annular casing pressure management for onshore wells*

API RP 96 Deepwater well design considerations (New)

API Bull 97/IADC *Well construction interface document*

ISO TR 12489 *Reliability modelling and calculation of safety systems*



ISO 13628-16/API Spec 17L1 *Petroleum and natural gas industries — Design and operation of subsea production systems — Specification for flexible pipe ancillary equipment*

ISO 13628-17/API Spec 17L2 *Petroleum and natural gas industries — Design and operation of subsea production systems — Guidelines for flexible pipe ancillary equipment*

ISO 14998 *Completion accessories*

ISO 17969 Guidelines on competency for wells personnel

ISO 16339 *Well control equipment for HPHT (High Pressure High Temperature) drilling operations*

ISO 16530 *Well integrity in the operational phase*

F. THE CONTRIBUTION BY THE MASTER THESIS:

1. Has grouped the development of risk analysis methods in drilling activities into three categories:
   - The 1st group covers simple models developed to examine possible outcomes and compare different options for investment with different levels of risk and uncertainties
   - The 2nd group is referred to the application of risk analysis in the areas of reliability and availability analysis, safety management techniques and human and organizational factors.
2. The 3rd group refers to risk analysis methods that wide use digital technology e.g. real time well monitoring and Model Updating during drilling activities. Has found that the combination with Goldon Zone (GZ) geological processes, the stress regimes (e.g. a careful analysis of Formation Break-down Pressure (FBP) and the Fracture Propagation Pressure (FPP)) as well as the Leak off Pressure (LOP) will be an important step for significant improvement in risk analysis and risk management for adequate well completion/casing and cementing design. This is equally important for the risk analysis process as it will provide the correct hydrostatic pressure gradient which is necessary for a proper drilling mud weights design that will allow excellent cement distribution and bonding during cement displacement in the situation of HPHT conditions.

3. Finds that the effectiveness study of leadership in high hazard contexts calls for development of specific indicators (similar to RNNP) to measure the leadership behaviours in view to guarantee high levels of safety

4. Goes beyond this simplified statement and confirms that act of negligence/irresponsibility and the circumstance of not performing risk analysis and risk management as required by acceptable standards and rules are among the challenges scientists, engineers and the leadership will have to improve

5. Has confirmed that no matter that a risk analysis is made, the risk communication remain crucial to avoid major accidents

Stavanger, June 2013