CHEMICAL ENGINEERING TRANSACTIONS
VOL. 26, 2012
Guest Editors: Valerio Cozzani, Eddy De Rademaeker

ISBN 978-88-95608-17-4; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1226104

Deepwater Horizon: Lessons learned for the Norwegian Petroleum Industry with focus on Technical Aspects

Stein Hauge*, Knut Øien

SINTEF Technology and Society, NO-7465, Trondheim, Norway
stein.hauge@sintef.no

The Deepwater Horizon accident in the Gulf of Mexico, leading to the largest oil spill in the US history and the death of 11 men, has been thoroughly investigated to avoid a similar catastrophe in the future. In this paper we make a review of the accident including a brief overview of the causes, discuss the relevance of the accident for the Norwegian Petroleum Industry and describe how the Norwegian Petroleum Industry has made an effort to learn from the accident. The conclusion is that the Norwegian Petroleum Industry generally faces the same challenges and the same hazards as in the Gulf of Mexico, and we therefore need to maximise the lessons learned from the Deepwater Horizon accident in order to avoid similar accidents in the Norwegian petroleum activity. However, using two technical systems as examples – kick detection and the blowout preventer – we also show that it is not necessarily straightforward to implement recommendations made for the Gulf of Mexico on the Norwegian Continental Shelf. Additional studies, research and adaptation are in some cases needed.

1. Introduction

On April 20, 2010, an uncontrolled blowout of oil and gas from the Macondo well occurred on the Deepwater Horizon drilling rig, in the Gulf of Mexico off the Louisiana coast. The accident caused the loss of 11 lives and the resulting environmental oil spill has been estimated to almost 5 million barrels.

As a response to the Deepwater Horizon accident, a number of investigations and studies have been carried out. The Petroleum Safety Authority (PSA) Norway also initiated extensive work to learn from the accident, and as part of input to this work, SINTEF prepared a separate report which provided recommendations for the industry in order to reduce the likelihood of a similar accident to occur in the Norwegian petroleum activity (Tinmannsvik et al., 2011).

A common conclusion from many of the Deepwater Horizon investigation reports is that the accident did not happen as a result of one crucial misstep or a single technical failure, but as a result of a series of events, decisions, misjudgements and omissions that reveal a systemic breakdown. Discussing all the aspects of what went wrong and why is however outside the scope of this paper. Rather we want to focus on some of the technical aspects related to the accident. Although it has been thoroughly concluded that organisational and managerial deficiencies were important precursors leading up to the accident, it should also be pointed out that technical failures and system weaknesses played an important part in the causal picture of the accident. The importance of technical causes is discussed on a more general basis by e.g. Kidam et al. (2010).

Please cite this article as: Hauge S. and Oien K., 2012, Deepwater horizon: lessons learned for the norwegian petroleum industry with focus on technical aspects, Chemical Engineering Transactions, 26, 621-626 DOI: 10.3303/CET1226104

2. Main well barriers during drilling operations

During drilling operations it must be ensured that hydrocarbons do not migrate from the reservoir into the well. To maintain well control, barriers to prevent influx are therefore implemented. In addition to the static physical components of the well, such as casing and cement, two main barriers are implemented during drilling; the drilling mud column and the blowout preventer (BOP).

The drilling mud column is a primary barrier during drilling. The purpose of the fluid column is to exert a hydrostatic pressure in the well bore that will prevent well influx/inflow (kick) of formation fluid (NORSOK D-010, 2004). As long as the column of drilling mud inside the well exerts pressure on the formation that exceeds the pore pressure, hydrocarbons should not flow out of the formation and into the well. If mud pressure exceeds pore pressure, the well is said to be *overbalanced*. Vice versa, if the pore pressure exceeds mud pressure, the well is *underbalanced*, meaning that the mud pressure is no longer sufficient on its own to prevent hydrocarbon flow.

In an on-going study of well control incidents on the Norwegian continental shelf it has been found that when studying direct causes of the incidents technical related causes are in majority. In particular, failure or deficiencies of the primary barrier, i.e. the drilling mud column, play an important role. This is often due to insufficient pore pressure predictions and resulting unforeseen conditions in the well during drilling. But insufficient mud weight is also highly dependent on the availability of the mud circulation system. The mud circulation may be considered as (more or less) a continuously running system. A failure while running, for example a pump failure or lack of access to adequate mud quality may also be the underlying cause of a kick.

Upon failure of the mud column barrier (underbalanced well) and subsequent flow of formation fluids into the well (i.e., a "kick"), action must be taken to control the situation. There will be several options for dealing with a kick depending on its size and severity. In a routine kick response scenario, the driller activates an annular preventer or a pipe ram in the so-called Blowout Preventer (BOP) to seal off the annular space in the well around the drill pipe. The driller can then pump heavier mud ("kill mud") into the well to counteract the pore pressure of the rock formation. Because the BOP has sealed off the annular space around the drill pipe, the driller opens the choke line (one of the three separate pipes running from the rig to the BOP) to allow circulating mud to return to the rig. Once the weight of the heavier drilling mud overbalances the hydrocarbon pressure and any hydrocarbons that flowed into the well have been circulated out, the driller can reopen the BOP and resume operations (Chief Counsel, 2011).

If a kick progresses beyond the point where shutting in the annular preventer (or pipe ram) and pumping in heavier mud is sufficient, the last resort will be to activate the BOPs blind shear ram in order to cut the drill string and seal the well.

Consequently, the BOP will constitute a secondary barrier to prevent uncontrolled flow of hydrocarbons to the surface. However, observe that the BOP has a dual function; it is used operationally to control the flow and to circulate mud during a "routine" kick response scenario, but it is also applied in an emergency situation where it is considered necessary to activate the blind shear ram, i.e. to activate the cut and seal function of the BOP.

3. Causes of the Deepwater Horizon accident

Drilling operations in general and operations in ultra-deep-water areas (> 1500 m) in particular require extensive planning and preparations. Further, the complex operations require that the various actors interact effectively. However, there were no conditions at Macondo, related to the underground, water-depth or the environment that were too exceptional to manage. Well qualified and internationally leading companies were involved and had previous experience from similar prospects. Therefore, the drilling and well operations should have been carried out safely. So what went wrong?

3.1 Direct causes leading up to the accident

When considering the direct causes leading up to the Deepwater Horizon accident, some important ones are listed below (Tinmannsvik et al., 2011) – based on (BP, 2010):

- The cement outside the production casing and at the bottom of the well (at the "shoe track") did not prevent influx from the reservoir

- The crew misinterpreted the result of the negative pressure test and considered the well as being properly sealed
- The crew did not respond to the influx of oil and gas before hydrocarbons had entered the riser
- The crew routed the hydrocarbons to the mud gas separator instead of diverting it overboard
- The fire and gas system did not prevent ignition
- The BOP did not isolate the wellbore and the emergency methods available for operating the BOP also failed

In order to avoid collapse of the wellbore and prevent uncontrolled influx of oil and gas, the wellbore is reinforced with pipes of steel – casing – which are anchored with cement on the outside. Cement is also used at the bottom of the well to avoid influx of oil and gas from below. However, the cement outside the production casing and at the bottom of the well (at the "shoe track") did not prevent influx from the reservoir. Oil and gas escaped through the cement and up through the casing. In order to test the integrity of the well including the bottom-hole cement, a "negative pressure test" was conducted by displacing drilling mud, thereby creating under-pressure – negative pressure – in the well. Influx of hydrocarbons would then be an indication of something wrong. However, the crew misinterpreted the result of the negative pressure test. The test indicated influx of oil and gas (i.e. a kick) but the crew considered the well as being properly sealed.

Oil and gas had started flowing into the well, but the crew did not respond to the influx before hydrocarbons were already above the subsea BOP and expanding up through the drilling riser towards the rig. Indications of influx were detectable some 45 min before the crew responded. When finally doing so, they attempted to close the BOP and then routed the hydrocarbons to the mud gas separator instead of diverting it overboard.

However, the mud gas separator had insufficient capacity to handle the large flow from the well, and the gas quickly overwhelmed the separator and escaped through gas vent lines, discharging onto the rig. Here, it encountered a number of potential ignition sources, first on the drill floor and subsequently in the engine rooms. The fire and gas system did not prevent ignition of the flammable gas cloud, partly due to the size of the gas cloud, but also since equipment were bypassed and/or defective. Manual action in terms of closing ventilation inlets to the main engine rooms were not taken, neither from the driller's control panel nor the bridge. The BOP did not isolate the well and the blowout continued. After the explosion the emergency methods available for operating the BOP also failed. The cause of BOP failure is somewhat unclear, but a main theory is that the drill pipe was elastically buckled within the wellbore and was partly outside the shearing blade surfaces of the blind shear ram (DNV, 2011).

3.2 Underlying causes

Some important underlying causes of the Deepwater Horizon accident (Tinmannsvik et al., 2011):

- Ineffective leadership
- Compartmentalisation of information and deficient communication
- Failure to provide timely procedures
- Poor training and supervision of employees
- Ineffective management and oversight of contractors
- Focus on time and costs rather than control of major accident risks
- Failure to appropriately analyse and appreciate risk
- Inadequate use of technology/instrumentation

These causes are discussed in detail in the President Commission report (2011) after the accident and in several other investigation reports and will, except for the latter bullet point, not be the further focus of this paper.

4. Lessons learned for the Norwegian Petroleum Industry

4.1 Could this have happened in the Norwegian petroleum activity?

Every accident is unique, as is also the case for the Macondo blowout. However, many of the causal factors have similarities to previous accidents and incidents. This applies for the Montara accident in

Australia in 2009, the Snorre A incident in 2004 and the Gullfaks C incident in 2010 (Tinmannsvik et al., 2011). The two latter events are of particular interest since they exemplify that things can go wrong also on the Norwegian Continental Shelf, and only narrow margins saved us from major blowouts.

The direct causes of accidents often differ, but many of the underlying causes are identified as recurring problems. Examples of such problems are inadequate planning and preparations, inadequate verification of the well barriers, failure to perform risk evaluation during changes and modifications, and lack of involvement and follow-up by management.

The oil industry is global, and various actors and facilities move between countries, adapting to national regulations if required. However, the design standards very often have a common basis, e.g. represented by the American API-standards. There are however a number of differences, related to for example type of regulatory regime (balance between prescriptive requirements and functional requirements) and regulations. There are also differences between standards since the Norwegian petroleum industry has developed their own NORSOK standards (NORSOK D-010, 2004). Furthermore, there are differences with respect to operational practice and safety culture.

Comprehensive experience from previous accidents has taught us that two events are never identical. It is therefore somewhat futile to question whether the same course of events that took place on Deepwater Horizon could have happened in the Norwegian petroleum activity. We can, however, conclude that our own offshore industry generally faces the same challenges and the same hazards, and we therefore need to maximise lessons learned from the Deepwater Horizon accident in order to avoid similar accidents in the Norwegian petroleum activity.

4.2 Safety recommendations – lessons learned – for the Norwegian petroleum activity

This is what the SINTEF report (Tinmannsvik et al., 2011) contributed to, i.e. to provide recommendations to the Norwegian Petroleum Industry directed towards the oil companies, the rig operators, the service companies and the authorities. Altogether 80 recommendations were put forward based on the identification of 134 recommendations in the various Deepwater Horizon investigation reports. From this, 13 recommendations for the industrial companies and five recommendations for the authorities were particularly highlighted.

It is not always straight-forward to apply the lessons from other petroleum industries, as in this case the Gulf of Mexico, since there may be different practices, different equipment, different regulations, etc. In some cases this has led to further investigations in the Norwegian Petroleum Industry. We will give two examples of this, focusing mainly on kick detection, but also briefly comment on the BOP system.

Upon failure of the primary mud column it is of paramount importance that the hydrocarbons entering the well are detected as soon as possible since early detection may increase the ability of other barriers to respond successfully to the kick.

Kick detection is characterized as a conglomerate of sensor readings and events that must be compared and interpreted by qualified personnel. A single reading may not give a clear indication of whether a kick is under development, and readings from different sensors need to be compared with other events, such as unexplained changes in drill pipe or other pressures, and changes in the weight, temperatures, or electrical resistivity of the drilling mud (Chief Counsel, 2011).

The conventional methods for kick detection during normal drilling operations includes pit volume indicators and/or mud flow indicators designed to detect an increase in the flow of fluid returning from the well compared to what is being circulated by the pump. There are generally two independent measurement systems.

The detailed implementation of kick detection functionality will vary from one installation to the next. Whether automatic alarms are given or not will depend on the set-up of the system and the alarm limits implemented. The reliability of the kick detection systems will also depend on other operations taking place on the rig. Prior to the blowout on Deepwater Horizon, several rig operations were performed in a manner that made kick detection more complicated. Some examples of concurrent rig activities that potentially confounded the kick detection function include (Chief Counsel, 2011):

- Sea water were pumped directly into the well from the sea chest, thereby bypassing the mud pits, creating a non-closed loop system and thus making it harder to monitor and compare the pit gain volume.

- During the latter part of seawater displacement, returns were sent directly overboard bypassing the pits, again making it harder to monitor pit gain.
- Cranes were used, resulting in rig sway which complicates kick detection since background noise in the level data increases.
- Mud pits, sand traps and trip tanks were being emptied during seawater displacement, all complicating kick detection.

The Chief Counsel's report (2011) further points out that the kick detection function on Deepwater Horizon had some technical shortcomings and was highly dependent on human factors;

- No camera to monitor returns sent overboard and no sensor to indicate position of valve sending returns overboard.
- Low accuracy of some instruments, such as sensors for pit volumes.
- Imprecise sensors and sensors sensitive to movements unrelated to state of the well, e.g. during crane operations. This may result in rig personnel discounting the value of the data they receive.
- No automation of simple well monitoring calculations. Non-closed-loop system calculations had to be performed manually but could easily have been automated and displayed for enhanced real-time monitoring.
- The scales of the displays were set up so that fluctuation in data was sometimes hard to see.

Results from the mentioned on-going study on well control incidents on the Norwegian Continental Shelf also show that late kick detection is an important direct cause of such events. Hence, this indicates that the current kick detection systems have an improvement potential. Today's technology makes it possible to instrument a large number of sensors that can be used to detect influx of well fluid, but a safe outcome relies on the human operator to correctly interpret and act on the available information in a timely manner. Even if the monitoring of flow and pit volume has improved, it is still difficult to understand and make decisions based on those reading alone. It is also challenging to get reliable pit volume measurements on floating rigs due to rig movements. Therefore the design of more reliable instruments and more intelligent systems for processing all the various information remains a challenge. In particular, a user friendly monitoring system that can provide operator support during non-standard operations with a minimum of “special setup” could lead to improved kick detection. In the aftermath of the Deepwater Horizon accident it has been questioned how the drilling personnel possibly could fail to react to all the signals of an emerging kick/blowout. It is, however, also tempting to ask: "Given that all these signals were available and reasonably unambiguous, why don't we have kick detection systems that automatically shuts in the well"?

Other important improvement areas for well monitoring / kick detection equipment include more frequent and systematic testing of selected components, setting performance requirements to such equipment and also to improve the personnel's ability to respond to kicks by performing periodic drills. It is however necessary to give due considerations to how such periodic drills can improve the operators ability to identify early kick indications. Due to the unpredictable nature of most kick situations, this also remains a challenge.

Experiences from well control incidents in Norway indicate that many of the technical shortcomings of the kick detection system pointed out for Deepwater Horizon are also relevant here. However, the investigation reports also show that the actual implementation of the kick detection function varies significantly between drilling rigs, as do procedures and routines for setting up the systems prior to operation. Giving general recommendations on how to improve the kick detection systems is therefore not straightforward.

Another barrier (technical system) that failed during the Deepwater Horizon accident was the BOP. The BOP was not able to seal the well for several reasons (see Section 3.1). One contributing cause is assumed to be the loss of communication (electrical and hydraulic signals) due to the explosion on the rig. In the Norwegian Petroleum Industry a back-up activation system based on acoustic signals is implemented. This could have made some difference, which also means that not all of the BOP recommendations from the Gulf of Mexico may be relevant on the Norwegian Continental Shelf.

5. Conclusions

The conclusion is that the Norwegian Petroleum Industry generally faces the same challenges and the same hazards as in the Gulf of Mexico, and we therefore need to maximise the lessons learned from the Deepwater Horizon accident in order to avoid similar accidents in the Norwegian Petroleum Industry. However, it is not necessarily straight-forward to implement recommendations made for the Gulf of Mexico on the Norwegian Continental Shelf. Additional studies, research and adaptation are in some cases needed. This work is still on-going in the Norwegian Petroleum Industry.

Acknowledgements

Thanks to all our colleagues that contributed to the SINTEF (2011) report from where many of the ideas to this paper origin.

References

BP, 2010. Deepwater Horizon, Accident Investigation Report. <www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/incident_response/STAGING/local_assets/downloads_pdfs/Deepwater_Horizon_Accident_Investigation_Report.pdf>, Accessed 10/05/2012.

Chief Counsel, 2011, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling: Macondo the Gulf Oil Disaster. United States <www.oilspillcommission.gov/chief-counsels-report>, Accessed 10/05/2012.

DNV (Det Norske Veritas – USA), 2011, Final Report for United States Department of the Interior. Forensic Examination of Deepwater Horizon Blowout Preventer. Report No. EP030842, Dublin, United States, <www.boemre.gov/pdfs/maps/AddendumFinal.pdf>, Accessed 10/05/2012.

NORSOK Standard D-010, 2004, Rev. 3, Well integrity in Drilling and Well Operations. Standard Norway, Lysaker, Norway <www.standard.no/petroleum>, Accessed 10/05/2012.

President Commission, 2011, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling: Deepwater. The Gulf Oil Disaster and the Future of Offshore Drilling. Report to the President. United States, <www.oilspillcommission.gov/final-report>, Accessed 10/05/2012.

Kidam K., Hurme M., Hassim M.H., 2010, Technical Analysis of Accident in Chemical Process Industry and Lessons Learnt, Chemical Engineering Transactions, 19, 451-456, DOI: 10.3303/CET1019074.

Tinmannsvik R.K., Albrechtsen E., Bråtveit M., Carlsen I.M., Fylling I., Hauge S., Haugen S., Hynne H., Lundteigen M.A., Moen B.E., Okstad E., Onshus T., Sandvik P.C., Øien K., 2011. The Deepwater Horizon accident: Causes, lessons learned and improvement measures for the Norwegian Continental Shelf (In Norwegian). SINTEF Report A19148, ISBN 978-82-14-05088-2, Trondheim, Norway.