Deepwater Horizon Incident
Evaluation of the Breached Barriers

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1. OBJECTIVE

This report assesses how automation within the well control system could have prevented, or significantly reduced, the outcome and impact of the Deepwater Horizon incident that unfolded on 20 April 2010 in the Gulf of Mexico. The process utilized a barrier analysis of the breached barriers identified within the BP Deepwater Horizon Accident Investigation Report (BP 2010) and whether automation, and other identified key assurance measures, could have maintained the barriers and prevented or mitigated the incident.

2. EXECUTIVE SUMMARY

On 20 April 2010, while drilling at the BP Macondo Prospect, a blowout caused an explosion on the Deepwater Horizon rig. This resulted in 11 tragic fatalities, 15 personnel injuries, the total loss of the rig and largest reported marine oil spill in history.

The resultant oil spill continued until 15 July 2010 when it was closed by cap. Relief wells were used to permanently seal the well, which was declared "effectively dead" on 19 September 2010.

On 8 September 2010, BP released an accident investigation report. The report identified eight key findings.

Safe Influx has reviewed the eight key findings of the report. The review assessed the impact of a number of assurance measures against the failed barriers. The assurance measures included automated well control and four other measures.

The conclusions are that automation within the well control system would potentially have eliminated six of the eight breached barriers and, more importantly, prevented the incident from escalating. The measures already instigated by the industry did not fully address the failed barriers and the identified underlying causes.

There is a high potential that more blowout events will happen within the upstream oil and gas industry unless further risk reducing measure are considered.

Implementation of automation within the well control envelope is paramount to the next step change in well operations safety and integrity. Automation of processes enables the influence of Human Factors to be better controlled and almost eliminated.

3. DEEPWATER HORIZON RIG & MACONDO WELL INCIDENT

3.1 Deepwater Horizon Rig Information

The Deepwater Horizon was a fifth-generation, ultra-deepwater, RBS-8D design, dynamically positioned, column-stabilized, semi-submersible mobile offshore drilling unit owned by Transocean. The rig was completed in 2001 in South Korea by Hyundai Heavy Industries and commissioned by R&B Falcon a later asset of Transocean. The rig was registered in Majuro and under contract to BP at the time of the incident.

In 2002, the rig was upgraded with "e-drill", a monitoring system whereby technical personnel based in Houston, Texas, received real-time drilling data from the rig and transmitted maintenance and troubleshooting information.

Advanced systems played a key role in the rig's operation. The OptiCem cement modelling system, used by Halliburton in April 2010, played a crucial part in cement slurry mix and decisions. These decisions became a focus for investigations into the explosion.

3.2 Deepwater Horizon Incident: Loss of Lives, Environmental Impact & Loss of Rig

On 20 April 2010, while drilling at the Macondo Prospect, a blowout caused an explosion on the rig that resulted in 11 tragic fatalities and 15 personnel injuries. The fire was inextinguishable and, two days later, on 22 April 2010, the Deepwater Horizon sank. The uncontrolled release of oil at the seabed caused the largest marine oil spill in history. The remains of the rig were located on the seafloor at a depth of approximately 1,500 m deep, and about 400 m northwest of the well.

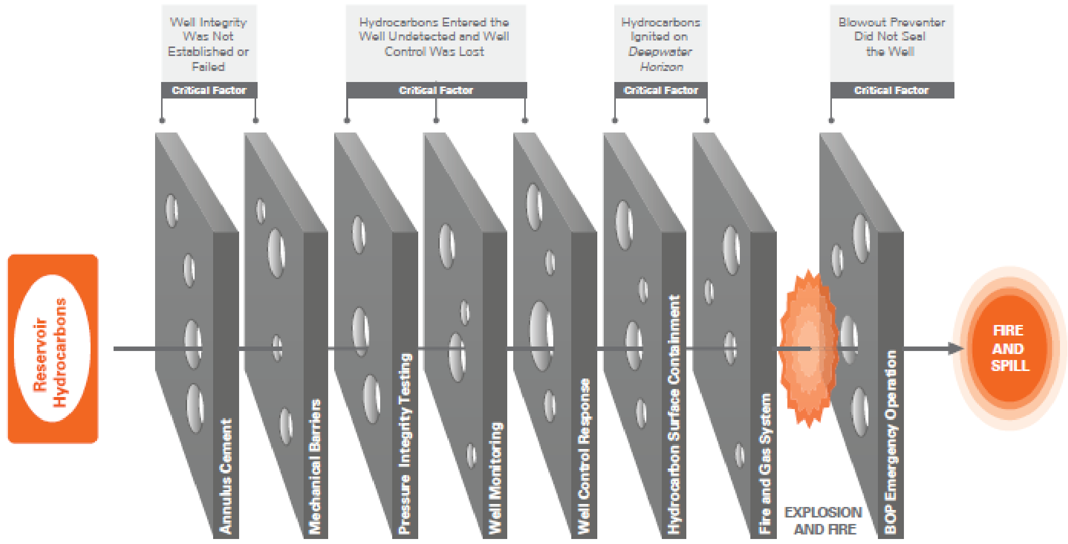
The resultant oil spill continued until 15 July 2010 when it was closed by subsea cap. Relief wells were used to permanently seal the well, which was declared "effectively dead" on 19 September 2010.

4. INCIDENT INVESTIGATION & REPORT

The Deepwater Horizon incident was investigated by various bodies. These included reports by National Incident Commander Thad Allen, United States Coast Guard, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, Bureau of Ocean Energy Management, National Academy of Engineering, National Research Council, U.S. Government Accountability Office, National Oil Spill Commission, and the United States Chemical Safety and Hazard Investigation Board.

On 8 September 2010, BP released an accident investigation report. The report identified eight key findings with respect to the cause of the accident. Refer to **Figure 1** and **Figure 2** below.

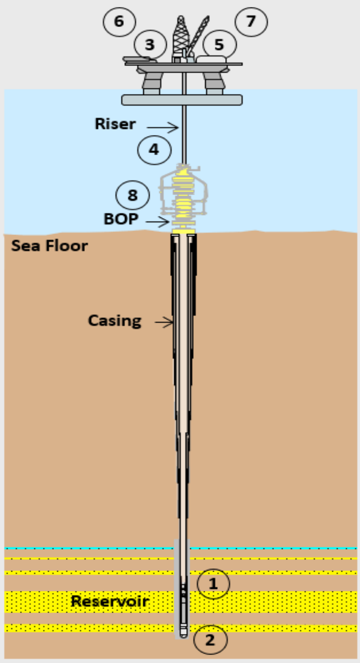
In *Figure 1*, the eight blocks represent the defensive physical or operational barriers that were in place to eliminate or mitigate hazards. The holes represent failures or vulnerabilities in the defensive barriers. The eight key findings are represented by the holes that lined up to enable the accident to occur.



Adapted from James Reason (Hampshire: Ashgate Publishing Limited, 1997).

Figure 1 - Barriers Breached and the relationship of Barriers to the critical Factors (BP 2010)

Eight Barriers Were Breached under Four Headings



A. Well integrity was not established or failed

1. Annulus cement barrier did not isolate hydrocarbons
2. Shoe track barriers did not isolate hydrocarbons

B. Hydrocarbons entered the well undetected and well control was lost

3. Negative pressure test was accepted although well integrity had not been established
4. Influx was not recognized until hydrocarbons were in riser
5. Well control response actions failed to regain control of well

C. Hydrocarbons ignited on the *Deepwater Horizon*

6. Diversion to mud gas separator resulted in gas venting onto rig
7. Fire and gas system did not prevent hydrocarbon ignition

D. Blowout preventer did not seal the well

8. Blowout preventer (BOP) emergency modes did not seal well

Deepwater Horizon Accident Investigation

Figure 2 - Breached Barriers Summary (BP 2010)

The eight key findings are summarized below:

1) **Annulus Cement Barrier** - The day before the accident, cement had been pumped down the production casing and up into the wellbore annulus to prevent hydrocarbons from entering the wellbore from the reservoir. This annulus cement probably experienced nitrogen breakout and migration, allowing hydrocarbons to enter the wellbore annulus.

2) **Shoe Track Barrier** - Hydrocarbons then entered the production casing through the shoe track. Hydrocarbons entered the casing rather than the annulus suggesting that both barriers in the shoe track must have failed (first barrier – cement shoe track, second barrier – float collar).

3) **Negative Pressure Test** - Prior to the temporary abandonment of the well, a negative pressure test was conducted to verify the integrity of the mechanical barriers (shoe track, production casing and casing hanger seal assembly). In retrospect, pressure readings and volume bled at the time of the test were indications of flow-path communication with the reservoir, signifying that the integrity of these barriers had not been achieved.

4) **Influx not Recognized** - With the negative pressure test having been accepted, the well was returned to an overbalanced condition, preventing further influx into the wellbore. Later, as part of the temporary abandonment program, mud was replaced with seawater, putting the well in an underbalanced condition. Over time, this allowed hydrocarbons to flow up through the production casing and pass the blowout preventer (BOP). Indication of an influx with an increase in drill pipe pressure are discernable in real-time data from approximately 40 minutes before the crew took action to control the well.

5) **Well Control Response Actions** - The first well control action was to close the BOP and diverter, routing the fluids exiting the riser to the mud gas separator (MGS) rather than the overboard diverter line.

6) **Diversion to MGS** - Once diverted to the MGS, hydrocarbons vented directly onto the rig through the derrick vent and other flow paths connected to the MGS (the MGS was overwhelmed due to the high flow condition).

7) **Fire and Gas Detection System** - Hydrocarbons migrated beyond areas on the Deepwater Horizon that were electrically classified to areas where the potential for ignition was higher.

8) **BOP Emergency Mode** - The three methods for operating the BOP in the emergency mode were unsuccessful.

   - The explosion and fire likely disabled the emergency disconnect sequence,
   - Condition of critical components in the yellow and blue control pods likely prevented activation of the automatic mode function (AMF),
   - the autoshear function initiated by a remote operated vehicle, likely resulted in the BOP blind/shear ram (BSR) closing, but the BSR failed to seal the well.

“There was a high level of reliance on the manual/human intervention in the activation of Deepwater Horizon safety systems, which included well control response. The reliability of the systems was therefore limited by the capability of individuals to respond in a stressed environment.” (BP 2010)

5. CURRENT SAFE INFLUX AUTOMATED WELL CONTROL SYSTEM

Safe Influx’s Automated Well Control technology, in its current form, detects a kick, takes control of the rig equipment to space out, shuts down the mud pumps and top drive, and then shuts-in the BOP. It has significant potential and application in the industry to manage/reduce well control risks & associated impacts.

It is currently designed for the drilling phase which also covers early tripping off bottom and back-reaming. Further modules are being developed to take due consideration of the different phases in drilling, workover and abandonment of oil and gas related wells. A non-comprehensive list of some of these additional modules that are of particular relevance to the Deepwater Horizon Incident is provided in Section 6 below.

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6. FUTURE SAFE INFLUX AUTOMATED WELL CONTROL MODULES

Table 1 below shows conceptual Safe Influx software modules which are of relevance to this report. Had they been in place on the Deepwater Horizon, six of the eight barriers may not have been breached. The impact of the Deepwater Horizon incident would have been greatly reduced or prevented entirely.

SAFE INFLUX FUTURE MODULES

MODULE	DESCRIPTION
DRILLING PHASE	
Safe DIVERTOR	Automated closure of the diverter when very high flow rates are detected. Automated wind direction and valve selection.
Safe BLOWOUT	Immediate automated annular shut-in for sudden high intensity flowrate without automated space out.
Safe INFLOW	Automated well control protection during inflow test through monitoring of pressure and volume.
Safe CIRC	Automated well control protection during circulating through monitoring of flow rate and volume.
EMERGENCY SITUATIONS	
Safe AMF	HMI Push Button that will initiate the automated disconnect sequence from the driller's chair
Safe GASCLOUD	Gas detection to trigger AMF and, if needed, initiate an engine air intake and engine shut down sequence
WELL CONTROL EQUIPMENT & MONITORING	
Safe BOP	BOP fault finding identification and automatic selection of alternative control.
Safe MONITOR	Health monitoring of BOP control system and subsequent fault indication on HMI.
Safe LOCKOUT	Prevents operations continuing if well control equipment is defective.
MODULE IDEAS FOR CONSIDERATION	
Safe BOPRAM	Applies to every BOP closure, auto switch to TT. If level increasing, send warning and auto close alternative barrier.
Safe MGS	Protection mechanism for over-pressure in MGS by activating a different flow path.

Table 1 - Planned Future Safe Influx Modules relevant to Deepwater Horizon

Note: All modules presented in Table 1 are conceptual and currently not commercially available. With sufficient resources, these modules can be developed in a short time frame to add to the existing Automated Well Control system.

7. BARRIER ANALYSIS

Table 2 below provides a summary of the barrier analysis that was performed and what the impact would be on the event with additional assurance measures in place.

Barrier	Barrier Description	Additional Assurance Measures				
		Automated Well Control (Future Modules)	BOP: Explosive shear ram	BOP: Extra BSR	BOP: Condition / Health Monitoring	Revised regulatory framework.
1	Annulus cement barrier did not isolate hydrocarbons.	NO	NO	NO	NO	NO
2	Shoe track barriers did not isolate hydrocarbons.	NO	NO	NO	NO	NO
3	Negative pressure test was accepted although well integrity had not been established.	YES Safe INFLOW	NO	NO	NO	NO
4	Influx was not recognized until hydrocarbons were in riser.	YES Safe CIRC	NO	NO	NO	NO
5	Well control response actions failed to regain control of well.	YES Safe CIRC Safe DIVERTOR	NO (1)	NO (2)	NO	NO
6	Diversion to MGS resulted in gas venting onto rig	YES Safe MGS	NO	NO	NO	NO
7	Fire and gas system did not prevent hydrocarbon ignition.	YES Safe GASCLOUD	NO	NO	NO	NO (3)
8	BOP emergency modes did not seal well.	YES Safe BOP Safe MONITOR Safe AMF Safe LOCKOUT	NO (1)	NO	NO (4)	NO

Table 2 - Assessment Summary

Notes from Table 2.

(1) NO, an Explosive Shear Ram would not have regained control of the well or allowed BOP emergency modes to seal to prevent the fatalities and injuries.

- Reason: The rig team did NOT attempt to close the BSR prior to the explosion. Therefore, a human activated explosive shear rams would not have prevented the explosion, subsequent fatalities and injured personnel.
- However, an explosive shear ram, activated after the explosion, may have significantly reduced the size of the oil spill.

(2) NO, an additional BSR would not have regained control of the well.

- Reason: The rig team did NOT attempt to close the BSR prior to the explosion. Therefore, a human activated additional BSR would not have prevented the explosion, subsequent fatalities and injured personnel.

(3) NO, the existing changes to the regulatory framework would not have prevented ignition, explosion and subsequent loss of life and injuries. It may, however, prevent a long-term spill.

- Reason: No functional changes to the regulations were enforced to prevent the ignition of the gas. There has, however, been a functional change to the enforcement that stipulate the availability of a capping device that would minimize the environmental impact.

Useful Information:

- Deepwater Horizon was completed in 2001 to MODU code 2001.
- Only the Deepwater Horizon had dynamic positioning, the other rigs being moored. MODU code 2001 did not include the important addition for DP rigs with regards to shutdown requirements of machinery and equipment as described below. Later MODU code 2009 included the below requirement. If the Deepwater Horizon had such an automated system, it is likely, given the gas cloud, that all engines would have shutdown. There would have been a “Deadship” situation, and the risk of explosion would have been dramatically reduced and, potentially, eliminated. Full control of BOP would have still been available to accommodate a shut in, shear, disconnect and even maintain ability to start engines again once the gas cloud had dispersed.

“In the case of units using Dynamic positioning systems, disconnection or shutdown of machinery and equipment necessary for maintaining the operability of the dynamic positioning system should be based on a shutdown logic system designed to preserve the capability to maintain operational integrity of the well and station keeping ability. Shutdown of generators and related power supply equipment needed for the operation of the dynamic positioning system should be divided into independent groups to allow response to gas detection alarms while maintaining position keeping.”

(4) NO. Industry “BOP: Condition/Health Monitoring” would not have prevented ignition, explosion and subsequent loss of life and injuries. It may, prevent a long-term spill.

- Reason: The rig team did NOT attempt to close the BSR prior to the explosion. Therefore, additional BOP: Condition/Health Monitoring would not have prevented the explosion, subsequent fatalities and injured personnel.
- However, additional BOP: Condition/Health Monitoring, may have significantly reduced the size of the oil spill.

8. HUMAN FACTORS AND AUTOMATION

The Deepwater Horizon incident did not happen because of one crucial misstep or a single technical failure, but was caused by a chain of events, decisions, misjudgements, and omissions. Eight key findings/breached barriers were identified as an immediate cause of the Deepwater Horizon incident (reference Section 4). However, multiple underlying causes have been attributed to the cause of the breached barriers mostly around Human Factors (Tinmannsvik et al 2011). These underlying causes were further underpinned by the National Commission report to President (2011).

- Failure of management and communication.
- Failure to provide timely procedures, poor training, and supervision of the team.
- Ineffective management and oversight of contractors.
- Inadequate use of the technology and instrumentation.
- Failure to appropriately analyse and appreciate risk.
- Focus on time and cost rather than major accident risk.

The above clearly identifies the human element and influence on decision making and, ultimately, the impact on a safe and efficient operation.

Data from the Deepwater Horizon event showed that the rig crew failed to identify the early warning signs of a kick and did not shut in the well over 40 minutes after the initial indication of a kick (BP 2010). The decision cycle steps and barriers for well control were assessed in a case study with respect the Deepwater Horizon event. (St. John 2016). It was concluded that all the decision cycle steps and barriers (reference Table 3) were absent for the Deepwater Horizon event.

Decision Cycle Steps and Barriers	**Absent / Present**
Detect	
Driller is vigilant and not over-confident in barriers	Absent
Company man is vigilant and not over-confident in barriers	Absent
Indication of a reservoir influx is detected early	Absent
Interpret	
Appropriate consideration given to the possibility of influx by any drilling crew member early	Absent
Appropriate consideration given to the possibility of influx by any drilling crew member late	Absent
Decide	
The team had correct confidence in barriers and behaves accordingly	Absent
Any frontline team member raised issue early	Absent
Act	
Driller shut in the well prior to discussion with others	Absent
Team member checked flow early	Absent
Team member conducted pressure tests early	Absent
Team member investigated the situation by any method early	Absent
Well shut in early	Absent
Well shut in late	Absent
Blowout prevented	Absent

Table 3 - Decision cycle steps and barriers – Deepwater Horizon (St. John 2016)

Humans design as well as operate, i.e., the system we are involved with are man-made and run, therefore, human factors always lie in the workplace and cannot be fully eliminated (Reason 1990). Automation of processes are not affected by human physical and psychological factors such as stress, fatigue, and momentarily inattention.

This is further underpinned by a study conducted in 2020 comparing the influence of Human Factor of traditional well control versus automated well control. (Marex 2020). This study shows a reduction in probability of human error by 94% for blowout events when implementing automated well control. Automation of processes enables the influence of Human Factors to be better controlled and almost eliminated, greatly improving the overall safety and efficiency of drilling operations.

Assisting the well construction industry is experience from other industries (i.e., aviation, nuclear, automotive) where safety and operational performance have seen dramatic improvements through the careful and considered implementation of automation. A methodological approach to the implementation of automation is critical to the success of such change and must consider the capacities and abilities of both humans and machinery. Such change is best implemented through a stepped automation level approach using e.g., the Sheridan-Verplank Scale. (Sheridan & Verplank 1978).

9. CONCLUSIONS

The review of the Deepwater Horizon incident (BP 2010) has highlighted the dependence and influence of Human Factors on operations within the Oil & Gas Industry, and the drilling sector in particular. In up to 67% of blowouts, Human Factors (i.e., Driller's loss of level 1 Situational Awareness) played a key role in the impairment of barriers and subsequent blowout events. (OESI 2016; Holand 2017). Other studies, comparing the influence of Human Factor of traditional well control versus automated well control, shows a reduction in probability of human error by 94% for blowout events. (Marex 2020).

There is a high potential that more blowout events may happen within the upstream oil and gas industry unless further risk reducing measure are implemented.

Automation of processes enables the influence of Human Factors to be better controlled and almost eliminated. Careful and considered implementation of automation within the well control envelope is paramount to the next step change in well operations safety and integrity.

Implementation of automation must consider the capacities and abilities of both humans and machinery. Such change is best implemented through a stepped automation level approach. (Sheridan & Verplank 1978).

- Automation within the well control system would potentially have eliminated six of the eight breached barriers and, more importantly, prevented the incident from escalating.

- There has been no automation of the BOP function since the Deepwater Horizon incident. Even after significant changes to well control training was introduced in 2012 (IOGP 2012) and subsequent revisions in 2016 and 2019 (IOGP 2019), analysis of more recent data indicates that Human Factor influences still constitute a major hurdle in effective well control. It is reasonable to expect that we will encounter the effects and impacts of future blowouts:

- The decision for not closing the primary BSR was driven by Human Factor influences. As such, it can be concluded that an extra BSR would not have resulted in a different outcome.

- Explosive shear ram technology would not have addressed the initial explosion and subsequent fatalities and injuries. This technology may have minimized the asset damage and reduced the environmental impact of the event.

- A more elaborate condition monitoring system would not have addressed the initial explosion and subsequent fatalities and injuries. This technology may have minimized the asset damage and reduced the environmental impact of the event.

- Changes have occurred within the US Regulatory framework after the Deepwater Horizon event, such as the separation of responsibilities and creation of the Bureau for Safety and Environmental Enforcement. Statutory changes might prevent a long-term spill, but would not have prevented the explosion, fatalities, and injuries.

10. RECOMMENDATIONS

- Continue investing in research and development of automation within the well control envelope.

- The oil and gas industry should continue to support the use of automation to improve the safety and efficiency of their operations.

11. NOMENCLATURES

AMF = automatic mode function
BOP = blowout preventer
BSR = blind/shear ram
MGS= mud gas separation

12. ACKNOWLEDGEMENTS

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