Deepwater Horizon – Summary of Critical Events, Human Factors Issues and Implications

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human
reliability

Specialists in
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1 Introduction

This article is intended to provide a summary of the BP Deepwater Horizon incident and a commentary on the causes from a human factors perspective. It is taken from the BP accident investigation that was published on 8 Sept 2010 and can be downloaded from their site at http://www.bp.com/sectiongenericarticle.do?categoryId=9034902&contentId=7064891. The BP report acknowledges that this is not a definitive investigation, as they were limited to by lack of access to certain witnesses and the unavailability of important physical evidence. This article is based on that report and the accompanying video overview. Where appropriate, we have given our own insights from a human factors perspective.

Some terms explained

The Deepwater Horizon drilling rig was stationed in the Gulf of Mexico for exploratory drilling on the Macondo well. The drilling rig is a mobile, temporary rig that drills the well, identifies that there is a viable reservoir of hydrocarbons, and then makes it safe and ready for a more permanent production rig. This involves drilling a deep bore hole in stages and filling the casing with cement. Figure 1 gives a picture of the Macondo Well taken from the accident report. This shows the cement barrier which failed and allowed hydrocarbons and mud from the reservoir to escape through the drill pipe (the main pipe through the middle section). The accident report describes test procedures that the crew were carrying out. These involve the kill and fill lines which can be seen as the small pipes that join the drill pipe at the blow out preventer. The blow out preventer (BOP) is a shut-down device that can cut off liquid flow using either the annular preventer, which can slow or stop the flow, or the blind shear ram, which shuts it off completely.

The well is said to be in an overbalanced state when the pressure on the drill side is higher than the pressure from the reservoir. It is an underbalanced state when there is more pressure on the reservoir side, and in this state the hydrocarbons will flow out of the well.

The accident sequence is complex and shows how several barriers were breached. To understand the complexity it is useful to clarify some of the roles and responsibilities of different companies involved in the operation. BP was the well owner, and was also responsible for the design of the well and for leasing the rig; Transocean were the owners and operators of the rig; providing the rig crew (for example the tool pushers and drillers) and Halliburton were responsible for the cement operations.

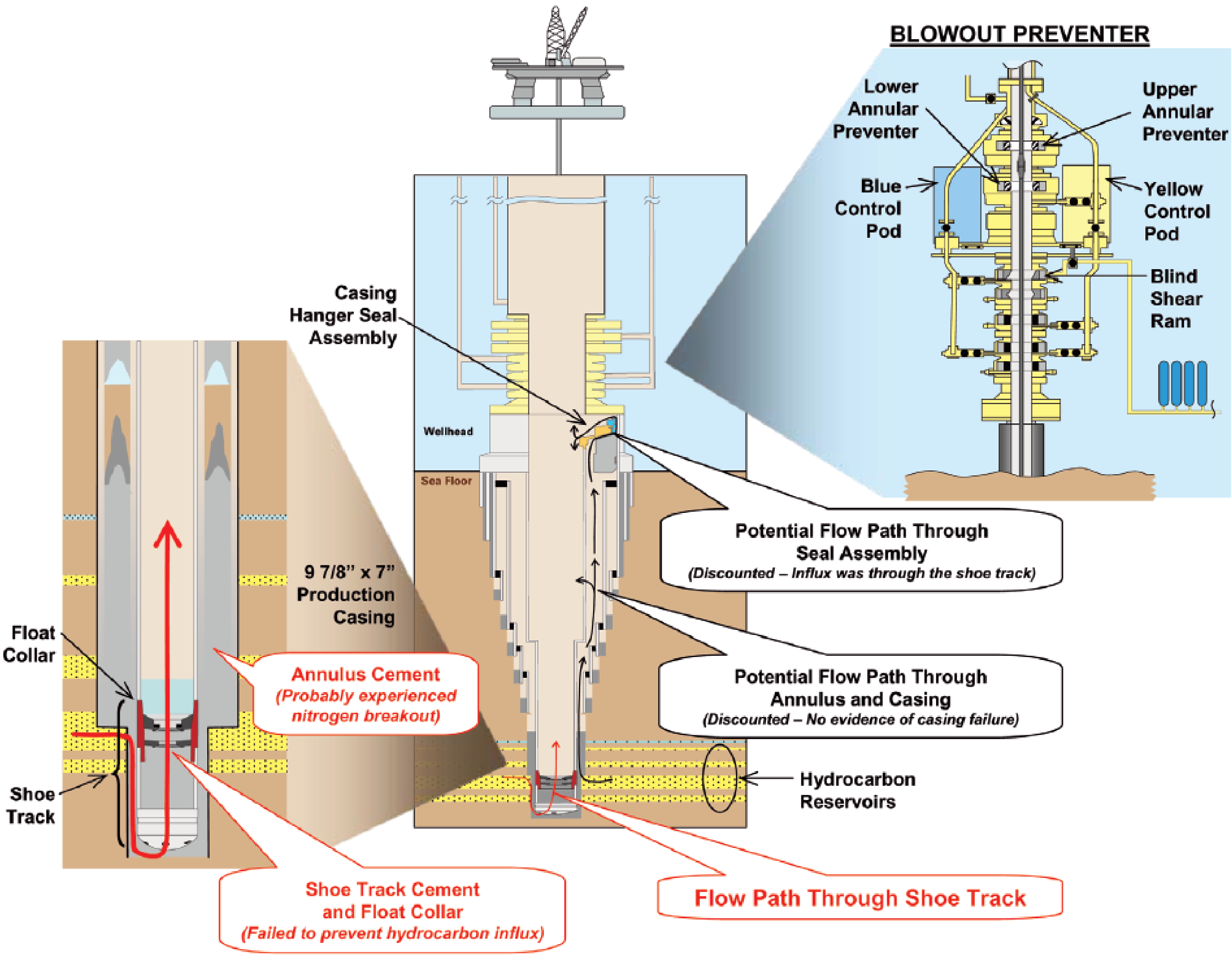


Figure 1: The Macondo Well

2 Accident Chronology

This is a much simplified version of the chronology and aims to give an overview of the events that is accessible to non-specialists, for the purpose of understanding the accident and how safety barriers were breached.

April 9th	The final section of the well is drilled
April 10th	The cement job is started to seal the well bore from the reservoir sands
April 20th	Integrity Test of well carried out: -positive pressure test (successful) -negative pressure test (results interpreted as successful). This test places the well in a controlled underbalanced state to test the integrity of the mechanical barriers.
17:35	Whilst carrying out the negative pressure test, the BP team leader realises that the rig crew are using a process for negative testing that is not the BP preferred method. Operations are reconfigured to meet the requirements of the permit (a permit is a safety system which only allows work to progress when authorised persons have set out the way the work will be carried out, and defines roles and responsibilities and how risks are being controlled).
18.42 – 20.00	Sea water is pumped into the kill line to confirm that it is full, the fill line is routed to the mini trip tank and flow stops. The line is monitored for 30 minutes and shows no flow. They notice that the drill line pressure is still high and discuss, but this is attributed to the 'Bladder effect'. The crew assume that the negative pressure test is successful.
20.00 – 21.01	The crew start normal activities for temporary abandonment of the well (as it is deemed commercially viable for production drilling) – this involves returning it to the normal 'overbalanced' position. However, during the process, at approximately 20.52, the well goes into an underbalanced position – this means that the pressure on drill side is less than in the reservoir and therefore hydrocarbons start to flow. During this time the crew were emptying the trip tank – which may have masked the indication of flow. Drill pipe pressure increases – this should have alerted crew, but it was not noticed.
21.08	The team is busy carrying out a test to check if fluids can be displaced overboard. As part of this test the pumps are shut down.
21.31 approx	The differential pressure is discussed – indicating that the drill pipe pressure has been noticed and acknowledged as something that was not expected.
21.40	Mud overflows onto the rig floor. The crew diverts the mud flow to the mud gas separator. Crew close the annular preventer and drill pipe pressure steadily increases. Mud and hydrocarbons discharge onto the rig and overboard
21.45	Assistant driller calls senior toolpusher to report '*the well is blowing out.[the toolpusher] is shutting it in now*'.
21.47	Gas alarms sound. There is a rapid increase in pressure in the drill pipe.
21.48	Gas probably enters the engine room air intake and explosions shake the rig. Extensive damage ensues, possibly damaging the cables which allow the communication of emergency shut-down system to communicate with the Blow Out Preventer.
	Emergency shutdown activation is unsuccessful – the BOP is unable to seal the well – hydrocarbons continue to feed the fire and explosions.
22.00	Order given to abandon the ship. 11 people were determined to be missing and the search and rescue activities commenced: no-one was found.

3 Key Events and Critical Factors:

As shown in Figure 2, the accident analysis revealed 8 interlinked factors that contributed to the incident.

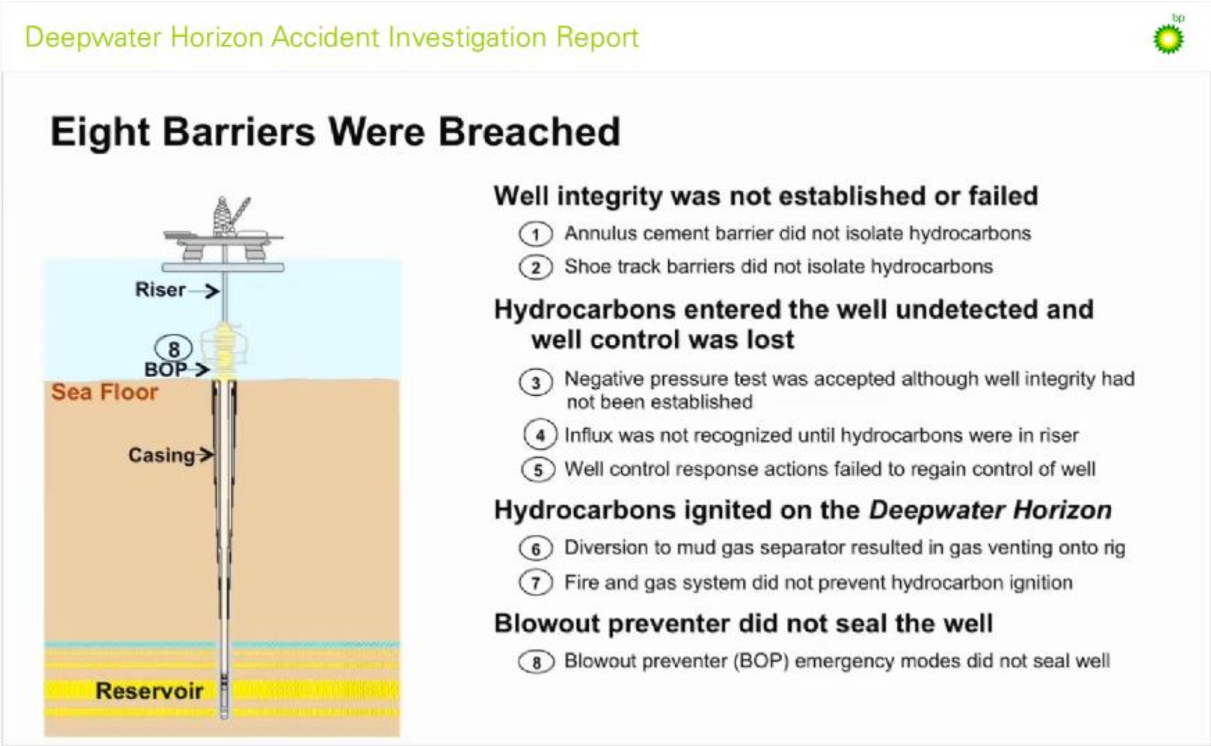


Figure 2: Key factors in accident sequence (from BP video presentation bp.com)

Well integrity was not established or failed:

Barrier 1 Annulus cement barrier did not isolate the hydrocarbons

- Cement slurry design:

This was critical because of the pore pressure and fracture gradient – however the technical review of the slurry design gave heavy emphasis to preventing lost returns ('lost returns' have cost and production implications). The report concludes that there was little focus on other important aspects of design, for example, foam stability, contamination effects and fluid loss potential were not considered.

Lab tests carried out as part of the investigation suggest that the slurry was unstable at drilling depth pressures and temperatures and there was likely to be nitrogen breakout. The slurry was not fully tested before use.

Our comment

Focus on production pressures at the expense of safety is an insidious threat for all hazardous operations. The safety requirements for the slurry design, the risks associated with not meeting them should have been explicitly recognised and communicated between Halliburton and BP.

Most industries face challenges in achieving production targets. It is not mentioned in the incident report, but the rig was 41 days over schedule. Each day over schedule cost the company approx $500,000. It would be interesting to understand how these pressures translated into the decisions at different levels of the organisation and between BP and Halliburton that impacted upon the incident process.

For interesting insights see Hollnagel's latest book which describes the conflicting pressures as the Efficiency-Thoroughness Trade Off.

- Cement placement:

  The equipment supplied (casing string) came with 7 centralisers. Halliburton had identified on the placement model that 21 centralisers would be needed and sent a further 15 centralisers over to Deepwater Horizon. The BP Macondo team thought they had been sent the wrong centralisers and did not use them (they thought they were introducing another risk).

Our comment; The accident analysis concludes that not using the centralisers probably did not contribute directly to the accident, however it indicates that different people held different mental models of the design and operational aspects of the well. There are two likely issues here; the management of people's understanding and knowledge when design and operational parameters change and poor communication between team members leading to different understandings, perception of risk and possibly different goals.

- Confirmation of placement

  The exploratory drilling was determined as a commercially viable well – it was therefore to be temporarily abandoned and a permanent well instated for production. As part of making the well safe to be temporarily abandoned, the process involves pumping in expected volumes of mud to test the integrity of the cement. The BP Macondo team used final lift pressure and returns to confirm successful cement placement and decided no further evaluation was needed. However this was not in line with procedures which state that more rigorous evaluation is required in some circumstances (in this case).

Our comment

It is not clear why the well team did not follow the guidance in BP's Engineering Technical Practice (ETP) – they did discuss the situation and developed decision trees to decide that no further evaluation was required. This suggests that they did not have clear guidance regarding the appropriate strategies for different conditions. Possible reasons for not following the BP ETP include:

- ***it was viewed as guidance only,***
- ***it was difficult to use,***
- ***it was thought not to be relevant to these circumstances,***

- ***it did not clearly state the conditions in which it was/not to be applied.***

Barrier 2 The shoe track barriers did not isolate the hydrocarbons

After the annulus cement failed to effectively isolate the reservoir, a mechanical barrier failed and enabled hydrocarbon ingress into the wellbore. The accident investigation did not feel able to determine whether this was attributable to the design of the cement, contamination of the cement with mud, effects of nitrogen breakout or a combination of factors.

Hydrocarbons entered the well undetected

Barrier 3 The negative pressure test was accepted even though well integrity had not been established

A positive pressure test was carried out successfully, followed by a negative pressure test. The objective of the negative pressure test is to test the ability of mechanical barriers to withstand the pressure differentials during subsequent operations; the reduction of hydrostatic head to seawater and disconnection of the Blow Out Preventer (BOP) and riser.

During the negative testing the BP Macondo team did not recognise the significance of some events e.g. high fluid returns (15 bbls taken rather than 3.5 that the analysis team felt should have been expected). This excess flow through the drill pipe should have indicated to the rig crew that there was a flow path to the reservoir through failed barriers. The accident investigation states that:

- There were 'broad operational guidelines' for the test.
- The rig crew and well site leader were 'expected to know' how to perform the test.

However witnesses state that the (Transocean) rig crew's 'preferred method' was different to the written procedure provided by the BP Macondo well team, in that they monitored the drill pipe line rather than the kill line. The well site leader noticed the discrepancy and they proceeded with the BP Macondo method. The the rig crew were therefore likely to be unfamiliar with the procedure they were now using, and both their ability to carry out the operation successfully and to correctly interpret the information sources was likely to have been severely compromised.

During the test the rig crew and the well site leaders both misinterpreted the drill line pressure of 1400psi. Witnesses state that the toolpusher (rig crew) suggested that the pressure on the drill pipe was due to a phenomenon they (toolpusher and driller) had seen before called 'annular compression' or the 'bladder effect'. The well site leaders and rig crew accepted this and carried on.

Our comment;

- ***the rig crew were familiar with a different procedure for the negative pressure test. Generally we would recommend that procedures are more detailed for operations that are more complex and carried out infrequently to compensate for unfamiliarity. There was a high reliance on leadership and know-how of the crew. However, the procedures that were available were guidelines only and did not provide enough detail, for instance they did not specify bleed volumes or give success/failure criteria.***
- ***The information that was available may have been difficult to interpret and this was exacerbated by the crew's unfamiliarity with the procedure and its lack of detail.***

- ***There appears to have been a failure to explore other options that would explain why flow did not exit the kill line and a reliance on the explanation of 'Bladder effect' without considering whether there were other scenarios or risks. Poor decision making is often linked to 'fuzzy' symptoms, inadequate information provision, and poor feedback of the consequences when a course of action is taken. This may be due to a combination of other factors that are not explored in the report. Common problems are: time pressure and the pressure to achieve production goals (their immediate goal was to make good the temporary abandonment of the well,), ambiguity of roles and responsibilities, and possibly poor communications between team members.***

Barrier 4 Influx not recognised until hydrocarbons were in the riser

At 20.52 the well became underbalanced again and hydrocarbon influx resumed, however this was not detected by the crew. Flow increase from the well was discernable from real time data from 20.58.

The report suggests that end–of–well activities such as setting a cement plug in the casing, bleeding off the riser tensioners, and transferring mud to the supply vessel may have distracted the rig crew and mudloggers from monitoring the well.

At 21.08 the spacer reached the top and the crew had to perform a sheen test. This is a test to ensure that the spacer can be discharged into the sea (probably for environmental reasons). There are two implications here – the crew were focused on the test and not monitoring the drill pipe pressure, and the test involved routing flow in such a way that fluid flow could no longer be monitored at the mudlogger's console. Drill pipe pressure, which gives an indication that there is an influx of hydrocarbon, would still be available on the driller's console.

At 21.31 the mud pumps were shut down. Witness accounts state that at this point there was a discussion on the rig floor between the driller and toolpusher about 'differential pressure'. The pressure on the drill pipe increased by approximately 560psi between 21.31 and 21.34. These data suggest that hydrocarbons entered the riser at 21.38 and the crew started well control actions at 21.41.

The well should have been monitored continuously – however, procedures did not specify how this should be achieved during activities such as in-flow testing, cleaning or other end-of-well activities.

Our comment

In our experience in control rooms, operations are sometimes assumed to be continuously monitored. However this is an assumption sometimes used in the design of plant and subsequent risk assessments without proper consideration of its practicality in the production environment. It appears that as the crew were busy with other activities, monitoring drill pipe pressure may not have taken priority and there was nothing to alert them to the unanticipated drill pipe pressure. Again, drill pipe pressure was not indicative of a known problem, and the crew had difficulty assessing the situation and understanding its significance.

Appropriate training and job aids would have increased both the speed and accuracy of identification that there was an influx of hydrocarbons and enhanced the probability of appropriate well control actions.

Barrier 5 Well control response activities fail to gain control

At 21.40 mud flowed uncontrolled on to the floor of the rig. The rig crew attempted to gain control by:

- Closing the annular preventer. However, this did not seal properly and was too late as hydrocarbons were already in the riser.
- Diverting hydrocarbons to the mud gas separator (MGS). The alternative of dumping it overboard through 14in pipe was not chosen. This would (probably) have diverted it safely overboard.

Real time data was lost at this point – there were fires and explosions.

When the supervisor tried to initiate the Emergency Shut Down (ESD) system the sequence did not activate (probably due to damaged cables -see below).

Our comment

- ***It is not clear why the decision to divert through the HGS was taken, but it indicates lack of situational awareness of the suitability of the MGS for large volumes of hydrocarbons and of the risks involved. It may have been motivated by good, but misguided intentions, for instance reducing the impact on pollution of dumping mud overboard with high hydrocarbon content.***
- ***Speed of response was crucial. Diverting the flow overboard would have given the crew more time to respond. The accident report concludes that Transocean's protocols did not fully address responding to high flow emergency situations after well control is lost. Their actions suggest they were not adequately prepared to manage an escalating well control situation.***
- ***The crew had very little time to respond to the influx of hydrocarbons in a rapidly escalating situation. Key members should have been trained and competent. However, the accident report does not give details of the emergency training for the crew.***

Hydrocarbons ignited

Barrier 6 Fire and Gas system did not prevent hydrocarbon ignition

The high pressure hydrocarbon was diverted through the MGS which was designed for low pressure only – there were several vent points that released the gas onto the rig and into potentially confined spaces.

The design of the MGS allowed high pressure carbons to be diverted into the system even though it was outside the design specification and there were vent points onto the rig.

Our comment

This suggests that inadvertent operation by operator was not considered in the HAZOP studies of the MGS.

Blow out preventer (BOP) did not seal the well

Barrier 7 The BOP emergency modes did not seal the well

There were three different routes to activate the BOP emergency mode.

1. The fire is likely to have damaged the cables which provide electronic communication to the pods - prevented the ESD from initiating the Blind Shear Ram (BSR).
2. Automatic Mode Function (AMF) – two independent control pods on the BOP should activate the BSR if certain conditions were met. Subsequent analysis of the control pods showed they were not functioning properly; one had a failed solenoid valve and the other had insufficient battery charge – this would have failed to complete the AMF sequence.

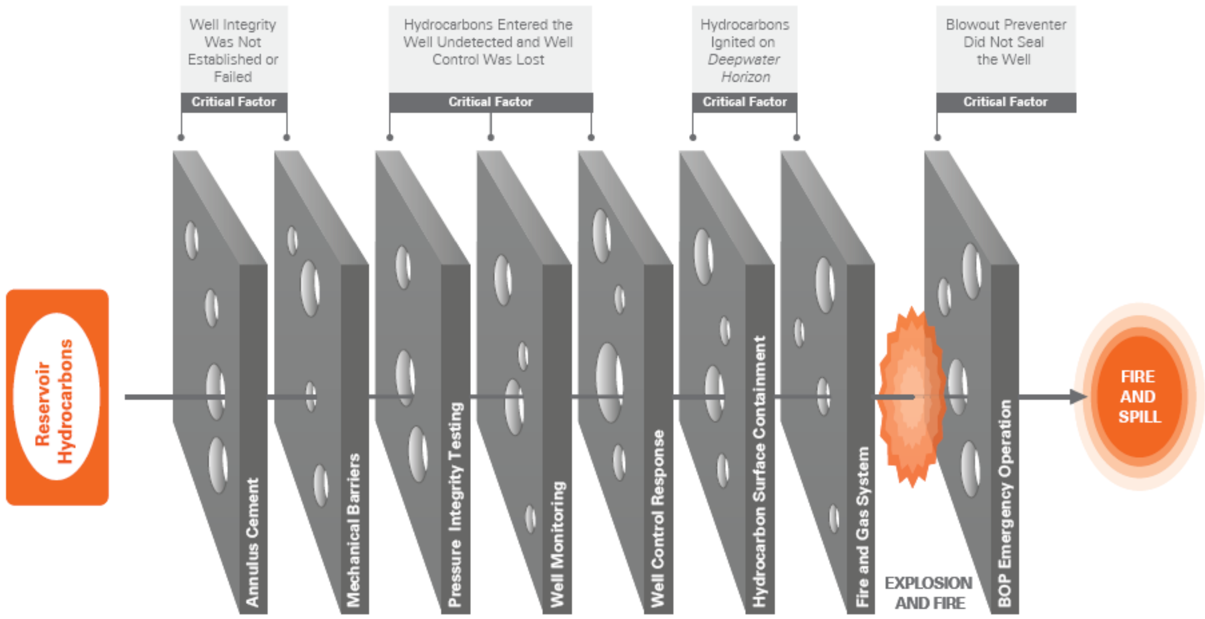
   Our comment

   This indicates poor maintenance management system for the pods, possibly linked to a lack of identification of critical components.

3. Intervention by remote operated vehicle. It is thought that this did activate the blind shear rams, however they failed to seal the well and hydrocarbons continued to flow.

4 Summary

The accident report concludes that no single action caused the incident – it was a culmination of a complex interaction of mechanical failures, human judgements, engineering design, operational implementation and team communication. They use the Reason's familiar Swiss Cheese metaphor to illustrate the barriers that were breached.



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

The recommendations in the report focus on areas very familiar to human factors specialists such as procedure development, training, and proactive risk assessment. Specifically they include; improvements to procedures, competence assurance, Process Safety Performance Management (PSPM), which also extends to monitoring the contractors' PSPM systems, well control practices, rig process safety, and lastly BOP engineering design and assurance.

Similar recommendations have emerged from the analysis of the causes of many high profile medical incidents. While the report answers questions to a certain level, as a human factors specialist I am still left wanting to know more, particularly about the latent conditions that were prevalent before the incident. After a quick read through these were my burning questions that the report leaves unanswered:

- Why were procedures not used – is this typical?
- What was the effect on decision making and on practice of the pressure to get the well tested and capped?
- Is there a safety management system in place that includes slurry design? Why was the slurry design not subject to a HAZOP?
- Why were the changes to centralisers not part of a process that manages the changed specification – if so, why were there communication breakdowns between Halliburton and BP?
- Why did the crew use the mud gas separator rather than pipework that would have discharged the mud more quickly?
- What emergency training did the team have? Did they have training or job support to help them identify and respond to escalating situations?