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A Thorough Analysis of the Engineering Solutions Deployed to Stop the Oil Spill Following the Deepwater Horizon Disaster

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The Deepwater Horizon drilling accident that occurred on 20 April 2010 was a two-fold catastrophe. The initial total loss of the drilling rig was followed by one of the worst environmental disasters in recent history. The four million barrels of oil that were released into the Gulf of Mexico continue to impact human activities in the area. The Macondo well incident (Mississippi Canyon 252-1, leased by BP as the primary operator) was the first deep subsea blowout in the history of the oil and gas industry, and both the United States' government and the private sector were unprepared to deal with it. All of the safety system's lines of defence failed and the response required multiple courses of actions to be taken to address an unprecedented situation. It was imperative to deliver the best engineering solutions under intense and ongoing pressure in a very harsh and highly stressful operational environment. In this paper we review the engineering solutions considered by the response teams.

The first part of the paper gives a brief presentation of our approach to the case study. The second reviews post-blowout events, the initial organizational response and the discovery of leaks. The final part presents how the statement of the problem was developed by the organization and how the response was structured. We then analyse the engineering solutions and finally, show how the organization implemented these solutions to control the source of the spill, recover the effluent and seal the well. In conclusion, we provide an overview of the engineering work that was carried out and preview our forthcoming work.

We assume that the response to the Deepwater Horizon oil spill was efficient from an operational point of view. Therefore, our findings will be used to develop a new approach to the analysis of major accidents and ultimately shape the design of a new set of disaster management guidelines.

1. The approach

Our approach to the case study consists of two main steps: an initial assessment of the documentation that is used to build a database of sources, and a qualitative deep search within the documentation.

1.1 Documentation and quality assessment

The study of an accident can be compared to a police investigation. There are multiple sources of information that are provided by different organizations, which are re-processed by the media, "highlighted" with expert opinions, commented on by the public, etc. However, unlike papers published in academic peer-reviewed journals, the quality of most of this information is not evaluated. Therefore the reliability of even official reports needs to be assessed, as for example in the selected bibliography prepared by Fiolek et al. (2010). Consequently, our initial task was to assess the selected documentation based on a quality matrix. This matrix takes four parameters: pertinence, reliability, "distance" from the raw data and accessibility. The results of the evaluation are used to build a database of documents.

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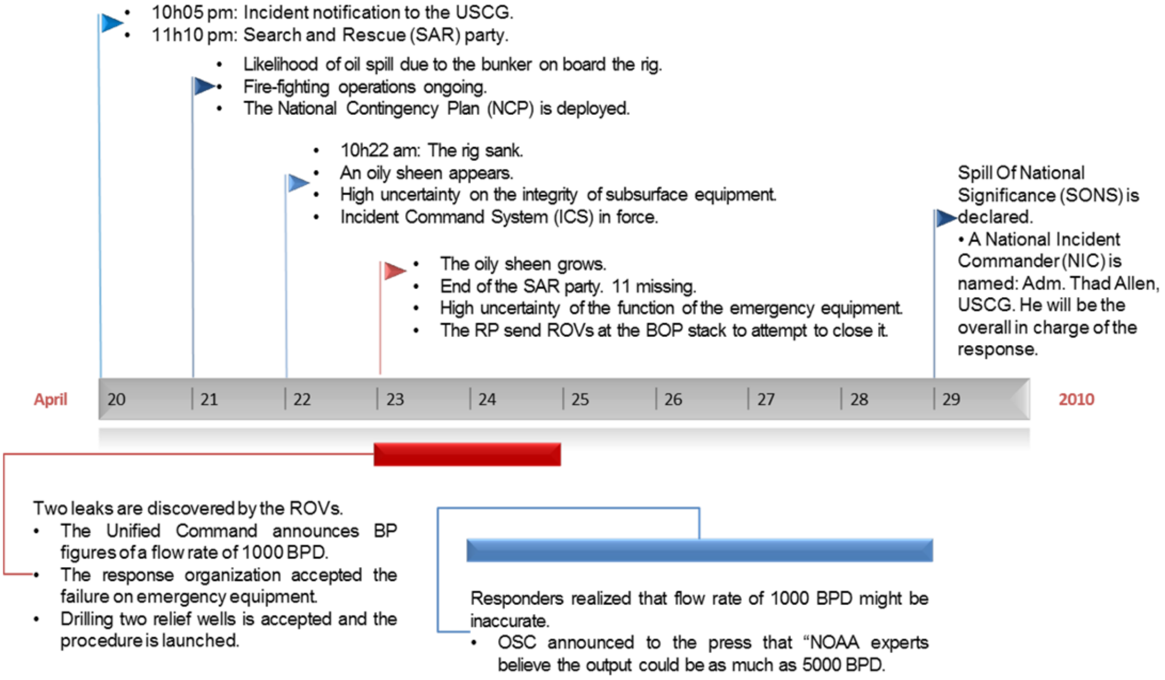
1.2 Qualitative search

Once the database was compiled, we explored the documentation. To do this, we used qualitative search software (Nvivo10©, Qualitative Data Analysis Software | Mixed Methods Research | NVivo, n.d.). This tool provides a deep text and context search within large and multiple documents. All of the relevant information from different sources on a specific topic can be aggregated. This aggregated information (called a Node) can then be analysed. As an example, the “Deepwater Horizon disaster” node is composed of approximately one hundred sources, and almost 10,000 references representing more than 10,000 pages. The advantages of Nvivo10© are that it is a user-friendly tool that can be used to create ad-hoc databases for socio-technical studies. Furthermore, it offers powerful text mining tools that can accurately pinpoint terms and concepts.

2. From the blowout to the discovery of leaks

In this section we present a timeline of the early stages of the response. This is derived mainly from reports by the United States National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011) and the United States Coast Guard (2011a). In less than ten days, responders would completely change their disaster management paradigm – shifting from a search and rescue operation following the rig explosion, to an unprecedented confrontation with a wild well 5,000ft below sea level.

2.1 Timeline of the early stages of the response (20–29 April)



- 10h05 pm: Incident notification to the USCG.
- 11h10 pm: Search and Rescue (SAR) party.

- Likelihood of oil spill due to the bunker on board the rig.
- Fire-fighting operations ongoing.
- The National Contingency Plan (NCP) is deployed.

- 10h22 am: The rig sank.
- An oily sheen appears.
- High uncertainty on the integrity of subsurface equipment.
- Incident Command System (ICS) in force.

- The oily sheen grows.
- End of the SAR party. 11 missing.
- High uncertainty of the function of the emergency equipment.
- The RP send ROVs at the BOP stack to attempt to close it.

Spill Of National Significance (SONS) is declared.

- A National Incident Commander (NIC) is named: Adm. Thad Allen, USCG. He will be the overall in charge of the response.

Two leaks are discovered by the ROVs.

- The Unified Command announces BP figures of a flow rate of 1000 BPD.
- The response organization accepted the failure on emergency equipment.
- Drilling two relief wells is accepted and the procedure is launched.

Responders realized that flow rate of 1000 BPD might be inaccurate.

- OSC announced to the press that “NOAA experts believe the output could be as much as 5000 BPD.

Figure 1: Initial response milestones

The National Contingency Plan (NCP) was deployed and the response was organized within hours of the notification of the incident. It was led by the United States Coast Guard (USCG) as the designated Federal On-Scene Coordinator (FOSC). BP was named as the Responsible Party (RP) – the company in charge of (and liable for) treating the problem it had caused (Code of Federal Regulations, 2011).

2.2 Leaks

Two main leaks were discovered within a week of the blowout; one at the end of the broken riser and the other in a kink at the top of the blowout preventer (BOP) stack.

Responders initially attempted to seal the leak at the end of the broken riser and then focused their efforts on the leak in the kink at the top of the BOP stack. A third leak that was discovered later did not have a significant impact on the overall flow rate.

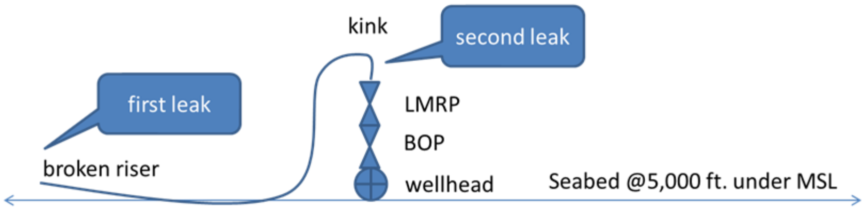


Figure 2: Simplified drawing of the seabed on 24 April

2.3 The flow rate

Establishing the flow rate was critical and extremely difficult due to the need to obtain good estimates and problem of obtaining them. The information was needed for product (solution) sizing, production optimization, cost (and time) savings, future anticipation (well shut-in pressure) and simply to help the public to understand the scale of the crisis (McNutt et al., 2012a). It was estimated as 62,000 barrels per day (BPD) on day 1 of the disaster, and decreased slightly to 53,000 BPD when the well was capped on day 86 (McNutt et al., 2012a). However, these values could be not established until the Flow Rate Technical Group (FRTG) provided figures on 19 May. Before that date, the responders working on solutions lacked significant information. Nevertheless, they were obliged to develop engineering solutions to the problem.

3. How did concurrent, cooperative and additional solutions solve the problem?

3.1 Problem statement

The responders faced a source control problem in conditions that had never been encountered before: a deep subsea well blowout that led to the total loss of a rig, followed by the subsea release of hydrocarbons from two openings on the seabed, at a depth of 1,500 metres and a pressure of 150 bar, with no natural light and no human access. A further problem was the proximity of the United States' coast, a very dense field of oil and gas exploration, a very fragile coastal environment, ocean currents and the threat of hurricanes, all under the global scrutiny of civil society (McNutt et al., 2012b).

3.2 Research angle and limitations

Here we present a shortened version of our work on engineering solutions. Specifically, we do not include "off the shelf" solutions and established procedures or equipment used to tackle an oil spill. For example, we do not include the drilling of relief wells (and the following hydrostatic and bottom kill), BOP emergency controls, or the top kill/ junk shot procedure. We also do not discuss sea surface treatments such as the use of dispersants (at the surface and subsea) or shoreline clean-up operations, as there have been no significant changes in past decades in this aspect of oil spill management (United States and National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, 2011). All of the solutions presented here were specifically designed to address the particular situation.

3.3 Engineering approach

Solutions were developed by the responsible party's (RP) engineers under the oversight of the Incident Command and were implemented by various teams designated as "Containment Task Forces". Their mission was to find short- and longer-term solutions that would contain the oil at source or cap the well. Any engineering solutions had to respect the following principles, "To avoid solutions that might result in a worse situation; That time was of essence; That reaching a solution would require redundancy and contingency; and That resources would be provided as needed to staff the teams and to develop solutions". (United States Coast Guard, 2011)

Once a solution was designed by a team, it was submitted for review to both sides of the organization (the Incident Command and RP senior management) who ranked it, and it was finally approved by the National Incident Commander (NIC). The Unified Command approved the implementation of the procedure provided by the engineering team *in situ*. Here we present these solutions in chronological order in order to show how the actual response unfolded and the decision-making processes involved (including feedback from the response teams).

3.4 The cofferdam

The first engineering solution was a cofferdam (containment dome). This no-seal collection system had been used to collect oil from leaks from subsea wells damaged during the Katrina and Rita hurricanes.

Applied to the Deepwater Horizon situation, the response team expected to be able to collect oil from the main leak at the damaged riser (rather than over the BOP stack). The cofferdam consisted of a huge steel container that was set above the leak to guide effluent and some seawater (the cofferdam is not sealed to the leak) to a surface vessel via a collection line. Engineers were faced with a new challenge as the cofferdam had to be modified to the situation. The equipment had been designed to work in a shallow water environment. In the deep sea environment, effluent (a mix of oil and gas) produces methane hydrates, a solid organic compound that risked clogging the line. Engineers were aware of the phenomenon and planned to circulate warm water inside the cofferdam once it was installed over the leak, and to inject methanol into the effluent once the line was connected to the surface ship.

On 8 May the cofferdam became clogged by methane hydrates and oil recovery was compromised. The failed operation was abandoned. However, the failure led to an NIC request for the creation of the Flow Rate Technical Group (FRTG). This ad-hoc team of top scientists had to quickly provide engineers with an estimate of the flow rate, the oil budget and the total volume of oil released.

Collection period: 0 days; Quantity: 0 barrels (bbl).

3.5 The Riser Insertion Tube Tool (RITT)

Following the failure of the cofferdam, engineers proposed another solution to collect the flowing oil. This took the form of a Riser Insertion Tube Tool (RITT). This solution was implemented from 8–25 May.

The RITT was a small flexible tube that was inserted at the broken end of the riser and made it possible to collect the effluent. It was four inches in diameter and fitted with a soft sealing ring that improved the tightness of the connection with the damaged 21-inch riser in order to collect as much effluent as possible. Nitrogen was injected inside the riser to assist the lift of the effluent through it. The insertion of this smaller flexible tube into the end of the riser (like a surgical catheter) made it possible to collect the effluent closer to the source. This avoided contact with seawater and prevented the formation of methane hydrates. According to BP engineers, the equipment was designed to collect up to 12,000 BPD. The FRTG logged an instantaneous value of 8,000 BPD. Three RITTs were developed and ready to use and one was successfully deployed.

Collection period: 10 days (15–25 May); Quantity: approx. 22,000 bbl.

3.6 The Containment and Disposal Project

The Containment and Disposal Project (CDP) was a large-scale project designed to improve recovery capacity using the existing lines of the blowout preventer (BOP) and Lower Marine Riser Package (LMRP) of the wellhead stack (Luckins, 2010). This project was expected to be in place for at least six months while other teams focused on short-term solutions. The BOP and the LMRP were fitted with lines to perform well control operations such as kill (mud injection) or choke (bleeding the well). Although the top kill operation failed, it established that the lines were in good condition and could be used in other ways. A thermal survey of the lines was carried out on 28 April in preparation for the top kill operation. A subsea system composed of manifolds and Free Standing Risers (FSR) was designed to connect the LMRP and BOP lines to surface vessels that processed the effluent. The mobile rig Q4000 was fitted with a burner that allowed effluent to be flared and made it unnecessary to store oil. This unit was connected through a riser to the choke line of the BOP stack. Helix Producer 1 was connected to the kill line of the BOP through FSR1.

Q4000: Collection period: 29 days (16 June – 14 July); Flaring of approx.10,000 BPD.
Helix Producer 1: Collection period: 3 days (12–14 July); Quantity 20,000 bbl.

3.7 Top Hat 4

At all stages of the response various options were explored in parallel in order to either seal the well or capture the leaking oil. The concept of a collection device to be fitted over the LMRP of the BOP stack was developed at the end of May, following the failure of the top kill operation (not discussed here).

Ten top hats were developed, 8 were constructed, and 2 were shipped to the site (first 5, then 4). Top Hat 4 was actually deployed. This soft-seal collection device was fitted, via a transition spool, to the LMRP of the BOP stack. Following the lessons that had been learned from the cofferdam failure, the drill pipe was fitted with a nitrogen injection capabilities designed to blow away sea water while the hat was lowered. A permanent injection of methanol inhibited the formation of hydrates inside the hat when it was connected to the LMRP, and hot water was continuously circulated through the riser (above the hat) when it began to capture oil. The top hat was connected to the Discoverer Enterprise, the vessel responsible for processing the oil.

Collection period: 26 days (3–26 June); Rate: around 17,000 BPD; Quantity approx. 500,000 bbl.

3.8 The 3-ram capping stack

This equipment was the only device designed to sequentially (but permanently) seal the well and definitively cut the flow. Several options were considered, in particular a BOP-on-BOP option, before the decision was taken to build a 3-ram capping stack. The capping stack allowed responders to control the flow and consequently to “cap and flow” the well, or simply to cap it. It was composed of a set of stacked rams and fitted with lines to recover oil, via a connected riser, diverted by the rams. The main concern in capping a well is the build-up of pressure once it is sealed. Therefore, scientists had to model the geological reservoir and estimate the shut-in pressure value before capping. This value was critical in order to understand the behaviour of both the geological area and the well. A value that exceeded the estimated range (as was the case) created uncertainties regarding well integrity, potential fluid loss through the surrounding materials, and the worst-case scenario of a subterranean blowout.

On 15 July the capping stack was used to seal the well. Well integrity tests were performed until 17 July; during this period, pressure was closely monitored to ensure that there was no loss of well integrity (Hickman et al., 2012). On 19 September, the well was declared to have been successfully killed following intersection by the first relief well. This marked the end of the huge response to this unprecedented accident.

4. Conclusion and forthcoming work

4.1 Response workflow, 20 April–19 September

The response became the largest ever undertaken in United States’ peacetime history. At its peak, up to 48,000 people and 6,500 vessels were mobilized, and more than 41,000 km of booms were deployed to protect the shoreline.

The response lasted five months and teams were forced to develop innovative engineering solutions to capture the oil and stop the uncontrolled flow. These solutions were designed and deployed in parallel with the drilling of relief wells. Official BP figures claim that 810,000 bbl. of the 4 million bbl. released from the well were recovered, representing approximately 20% of the total amount of oil released (United States District Court For The Eastern District Of Louisiana, 2015). Other estimates are questionable.

4.2 Conclusion of current work

The following Gantt diagram is used as a retrospective tool overview of the solutions that were deployed. It shows engineering works and oil collection time for each solution. The period for engineering works is composed of the classical design, procurement, installation and commissioning phases. It represents the time needed to develop the solution before making it operational.

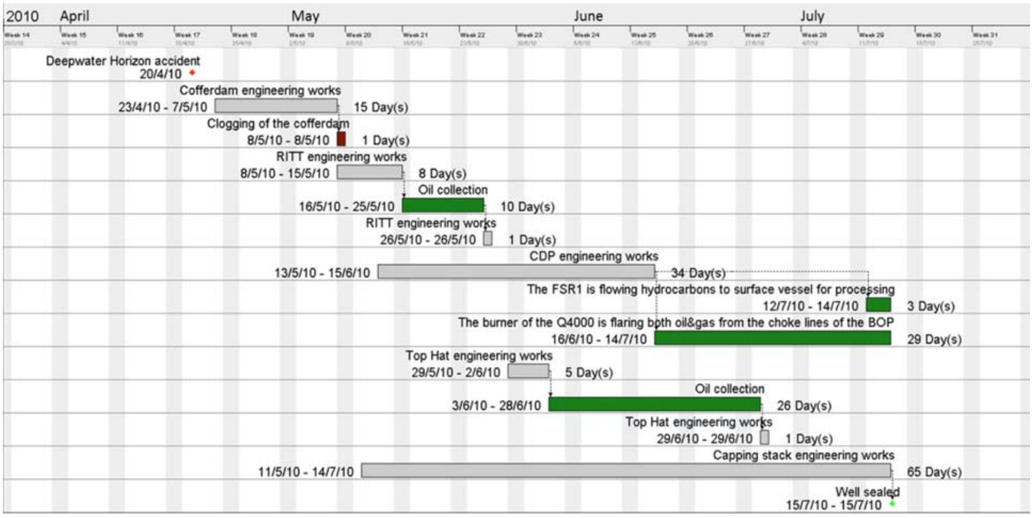


Figure 3 : Gantt diagram of engineering solutions

Apart from the cofferdam, all of the engineering solutions were successful. Most effluent was captured by the Top Hat 4. Flaring (with the Q4000 burner) was another efficient alternative. It took 87 days for well shut-in procedures to be implemented and 153 days to kill it (not shown). Cumulative collection time was 68 days; this represents 78% of the response time (until the well was capped). The cumulative time for engineering works was 129 days.

This paper presents the initial part of our work; here, engineering solutions are the subject of our research. These findings will form the basis for future work on the producers of these solutions: engineers.

4.3 Future work

Our future work will focus on engineers; specifically, engineering teams. Our aim is to understand how teams were able to work in such difficult circumstances and how they were able to produce solutions to huge problems. We will mobilize a new conceptual framework called “engineering thinking in extreme situations” (Guarnieri and Travadel, 2014), who define the conceptual framework as, engineering activities that are significantly difficult to manage due to a lack of resources in the face of a societal emergency.

According to Guarnieri and Travadel (op. cit.) there are three constraints that govern the work of engineers:

They don’t know the full extent of the situation.

They fact a critical lack of resources, especially technical knowledge and practical know-how. If the environment becomes hostile (in the context of a disaster, for instance), this only gets worse.

Society expects a lot from them. Deadlines must be met, and solutions must be found.

In an industrial disaster, the success of the response largely depends on the initiatives taken by workers. Their ability to undertake collective action is a key factor in transitioning into resilience, and managers need to take the intrinsic characteristics of such action into account. This emerging concept has been applied to the study of the Fukushima Dai-Chi nuclear accident. In our future work we will use the Deepwater Horizon case study as a proof-of-concept in another industrial sector. By providing another example of the use of the concept, we hope to trigger a fundamental rethink of the response of organisations to major and unprecedented accidents.

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