The Deepwater Horizon incident: fire and explosion issues

Prepared by the Health and Safety Executive
The loss of life and serious environmental damage from the blow out incident on the semi-submersible drilling rig Deepwater Horizon in 2010 in the US sector of the Gulf of Mexico has forced a reappraisal of the risks associated with drilling.

HSE commissioned this work in order to consider the lessons to be learned from this international incident. It is important for HSE to stimulate and inform consideration of fire and explosion risks amongst the designers and operators of drilling rigs.

Well control is clearly the first priority but some residual risk of blowout normally remains. This report deals with the minimisation of risks from fire and explosions if blowout does occur and also deals with some issues such as options for ignition frequency reduction and fire and blast mitigation that have not been adequately covered elsewhere.

The report presents findings to inform fire and explosion risk assessment and aid the development of suitable risk control measures. Drilling rig designers and operators should note that some of the changes suggested as a result of the Deepwater Horizon incident can only be implemented at the stage of rig design or major overhaul.

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The Deepwater Horizon incident: fire and explosion issues

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EXECUTIVE SUMMARY

On 20th April 2010 the semi-submersible drilling rig Deepwater Horizon suffered a blowout during completion operations at the Macondo Well in the Gulf of Mexico. Shortly after hydrocarbons reached the surface, there was at least one powerful explosion, followed by a severe fire. The incident claimed the lives of 11 workers and eventually led to the sinking of the rig.

The loss of life and serious environmental damage have forced a reappraisal of the risks associated with drilling. Are these risks as low as reasonably practical (ALARP)? Or are there affordable ways in which Mobile Offshore Drilling Units (MODUs) could be designed or operated that would reduce risk?

Well control is clearly the first priority but some residual risk of blowout normally remains. This report deals with the minimisation of risks from fire and explosions if blowout does occur.

Objectives

Fire and explosion issues divide into two main categories:

1. Arrangements to minimise the risk of ignition in the event of a substantial well release or blowout.

2. Arrangements to mitigate the consequences of fire and explosion should these occur.

The report is divided into three parts:

1. A review of the fire and explosion issues raised by Deepwater Horizon reports. The review covers both the evidence presented about what happened, and recommendations made for change.

2. A brief review of the frequency of blowouts and ignitions in various circumstances: this is significant in judging whether risks are ALARP.

3. A consideration of other options for ignition frequency reduction and fire and blast mitigation that are not covered by existing DWH reports (Sections 5 and 6).

Main Findings

1. The incident illustrates the fact that compliance with conventional zoning codes does not mean that operational risks are necessarily ALARP in the event of blowout.

2. The incident clearly illustrates the high risk associated with ingesting gas into large spaces deep within the rig (e.g. engine rooms) that have no provision for explosion relief. Explosions in such circumstances are very likely to directly threaten the crew and to damage vital rig systems.

3. The incident clearly illustrates the risks associated with reliance on complex manual interventions (e.g. sounding alarms and activating shut-downs) during a fast moving emergency.

4. Two principles are of use in assessing the risk of ignition in the event of blowout:

   a. Blowout releases can normally produce flammable concentrations anywhere on the outer surface of the rig if the release geometry and wind direction are unfavourable.
b. Even at the highest hydrocarbon flow rates it is extremely unusual for a gas cloud to simultaneously affect all parts of the rig; normally the upwind face of the rig is clear.

5. Several options are available for reducing ignition frequency including: Ex Rated equipment (that can operate safely in flammable atmospheres), high level Emergency Shutdown (ESD) on confirmed gas detection and control of ventilation (purged systems). All three options may be appropriate for different systems on a given rig.

6. Ventilation systems with alternative inlets (diverse ventilation systems) are particularly useful for protecting power generation systems in Dynamically Positioned (DP) units. They can greatly reduce the risk of ignition whilst allowing engines to run normally even in blowout conditions.

Conclusions

1. Control of ignition sources across the rig in the event of blowout should be considered in ALARP demonstrations.

2. Manual responses to gas detection are often much less reliable than automatic systems, especially if a rapid response is critical. Substantial reductions in risk can be achieved by improving the reliability of detection systems and simplifying or eliminating reliance on human responses.

3. Preventing the ingestion of gas into large spaces deep within the rig should be a priority. In many cases this can be done by automatic shut-off of fans and the operation of dampers. Active control of ventilation (Section 5.4) should be considered as an option for reducing the risk of ignition, in systems that constitute a high risk of ignition but cannot be immediately switched off in an emergency (e.g. power generation for a DP unit).

4. If there is a residual risk of gas accumulation in internal spaces, the consequences of explosion should be considered. The risks of explosions venting through vulnerable areas of the rig should be minimised; this may involve strengthening some internal partitions and/or providing explosion relief to the outside.
1 INTRODUCTION

On 20\textsuperscript{th} April 2010 the semi-submersible drilling rig Deepwater Horizon (DWH) suffered a blowout during completion operations at the Macondo Well in the Gulf of Mexico. Shortly after hydrocarbons reached the surface, there was at least one powerful explosion followed by a severe fire. The incident claimed the lives of 11 oil workers and eventually led to the sinking of the rig and a substantial flow of oil into the sea which continued for several months; important marine and coastal habitats were badly affected.

The loss of lives and seriousness of the environmental damage have forced a reappraisal of the risks associated with drilling. Are these risks as low as reasonably practical (ALARP)? Or are there affordable ways in which Mobile Offshore Drilling Units (MODUs) could be designed or operated that would reduce risk? A number of important reports describing the incident and/or providing recommendations for change have been published by:

- The Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE)
- US Coast Guard (USCG)
- Republic of the Marshall Islands (RMI – which was the Deepwater Horizon Flag State)
- BP
- Transocean

Drawing on these and other sources of information, HSE’s Deepwater Horizon Review Group has produced interim findings in the areas of: Safety Management of MODU operation; Technical Requirements (design of Blowout Preventers (BOPs), well engineering etc.) and Emergency Response issues. This report extends the scope of the Group’s findings to include Fire and Explosion issues.

There are two key areas of concern:

1. Arrangements to minimise the risk of ignition in the event of a substantial well release or blowout.
2. Arrangements to mitigate the consequences of fire and explosion should these occur.

The report is divided into three parts:

1. A review of the fire and explosion issues raised by Deepwater Horizon reports. The review covers both the evidence presented about what happened (Section 2), and any recommendations made for change (Section 3).
2. A brief review of the frequency of blowouts in various circumstances: this is clearly significant in judging whether risks are ALARP (Section 4).
3. A consideration of other options for ignition frequency reduction and fire and blast mitigation that are not covered by existing DWH reports (Sections 5 and 6).

This final part is supported by a new systematic dispersion study of how the development of gas clouds varies with hydrocarbon mass flow rate, release location, wind speed and direction etc.
Detailed results for the Computational Fluid Dynamics CFD dispersion studies are included as an appendix. Two important principles are illustrated by the work:

1. Blowout releases can normally produce flammable concentrations anywhere on the outer surface of the rig if the release geometry and wind direction are unfavourable.

2. Even at the highest hydrocarbon flow rates, it is extremely unusual for a gas cloud to simultaneously affect all parts of the rig; normally the upwind face of the rig is clear.

The second finding means that a ventilation system with alternative inlets on both sides of a rig could almost always draw in clean air – so long as the downwind inlet exposed to gas was closed off. Such a diverse ventilation system could support the continued operation of power generators and purged motors during blowout. For MODUs with dynamic positioning (DP) this is a key advantage as power generation and some drill handling operations cannot be immediately shut down. Practical issues for such a ventilation system e.g. robustness in the event of spurious detection are discussed in Sections 5 and 6.
Learning appropriate lessons from any incident relies on having detailed and reliable information about the evidence. In the context of fire and explosion issues in the DWH incident, this information would include:

1. How the flow rates of gas and liquids varied with time.
2. How the gas cloud and liquid rainout impacted on the rig.
3. Where and how gas was ignited.
4. What the immediate effects of the explosion and fire were on those onboard.
5. How blast damage may have hampered emergency response.
6. How fire progressed through the rig and how this affected the abandonment of the rig.

Although useful information is available in all of these areas, significant uncertainties remain. The sequence of events leading from blowout, to gas accumulation, to ignition and explosion was rapid. To a large extent investigators were forced to rely on the official testimony of survivors. The recollection of rapid, traumatic events after a substantial delay can reduce the reliability of accounts.

The rig sank in deep water and has not been recovered; very little forensic information is available that might be relevant to the assessment of blast damage or the mechanisms of fire spread.

### 2.1 FLOW RATES OF HYDROCARBONS

BP investigators used a well flow model to simulate flow through the well bore to the surface (BP 2010). The model was calibrated to match the recorded drill pipe pressure, calculated flows from pit volumes and the timing of arrival of gas at the surface. The best estimates of maximum flow rates of gas and oil were respectively 165 mmscfd (68 kg/s) and 20 bpm (44 kg/s). Transocean considered a wide range of different flow rates but these were apparently not derived from detailed physical modelling of flow from the well. Overall there is no significant evidence that the flow of well-fluids exceeded the range typically considered in risk assessments (30 – 200 kg/s).

### 2.2 WEATHER CONDITIONS

The wind speed at the time of the incident was light and variable. The mean speed was around 1.5 m/s with gusts up to 2.6 m/s. Higher wind speeds would have encouraged dilution of the released hydrocarbons and it is possible that this would have delayed or even prevented the ignition. The incident serves as a reminder that fairly calm conditions do occur even offshore and this is typically a worst case as far as dispersion is concerned. It is worth noting that such conditions would be relatively rare in the UK Sector.
2.3 DETECTION OF GAS

Evidence on the detection of gas and delays before ignition comes from the testimony of those involved (USCG 2011). Dynamic Positioning Officers on the bridge reported gas alarms in the shaker house followed by the drill floor at around 21:50. A large number of alarms (~20) subsequently illuminated. Those responsible for receiving the alarms were able to see a release of mud on a video monitor; they also took calls from the drill floor and engine control room.

The general rig emergency alarm – to alert the crew to gas detection - was configured to be manually operated. In the event it was only sounded about 10 minutes after the first explosions. The officer involved testified that she had not been trained to respond to high gas alarms going off in multiple areas of the rig.

The time between the first gas alarms going off and the initial explosions is not known accurately but was of order one minute. Clearly this is a very short time in which to make manual interventions of any complexity.

The release of gas on the deck via the Mud-Gas System was not anticipated by the crew. The incident serves as a reminder that blowouts may occur with little or no warning for those who have to respond.

2.4 LOCATION OF INITIAL EXPLOSIONS

The best evidence for the sequence of events around the time of ignition comes from a crane operator and those in or near the engine control room. The port side crane operator saw drilling mud coming from the Mud-Gas Separator vent followed by the first explosion:

“And it come out of it so strong and so loud that it just filled up the whole back deck with a gassy smoke.....Then something exploded..... And that started the first fire, which was on top of the motor shed and on the starboard side of the derrick.”

Testimony of port side crane operator

The crane operator reported that his first actions were to turn off the air conditioning in his cab as he was concerned about further ignitions – this may suggest that electrical power was still on at the time. Then he reported a more widespread and powerful explosion:

“everything in the back just exploded at one time. It went -- the whole back deck.”

Testimony of port side crane operator

Those in or near the engine control room heard at least one of the two operating engines rev up:

“And right upon that the engines RPM started increasing. I heard them revving up higher and higher and higher. Next I was expecting the engine trips to take over, such as the overspeed and that did not happen. After that the power went out and I was assuming that was our high-frequency trip and we were put in dark, and right on the end of that was the first explosion.”

Testimony of Chief Mechanic – Engine Control Room
Schematic of second deck – showing engine rooms and blast affected areas

“I could hear Engine Number 3 start to rev up, and its normal operating RPM's to way above what I ever heard it run before… As I started to push back from my desk the computer monitor exploded in front of me. All the lights in my shop popped. The light bulbs themselves physically popped. Now I know we're in trouble. I reached down to grab my door, and at the - simultaneously of grabbing the handle, the engine goes to a level that is higher than I can even describe it. It's spinning so fast that it just - It stopped spinning and there's a huge explosion”

Testimony of Chief Electrical Technician – near Engine Control Room

“You could hear the Number 3 engine started revving up. And, as soon as it started revving up, it started a load down change over….there was a big explosion, a loud “Bang,” it got black. The port door on this here side blew in [consistent with an explosion in Engine Room #3]. As soon as it blew in within a matter of seconds the starboard side blew in [consistent with an explosion in Engine Room #6] as soon as you heard the second explosion.”

Testimony of Motorman – Engine Control Room
The Chief Electrical Technician was able to see the blast damage to the side of the rig close to Engine #3 as he evacuated:

“At that point I looked up at the wall, and the exhaust stacks for Engine Number 3, the wall, the handrail, the walkway, all those things were missing. They were completely blown off the back of the rig.”

*Testimony of Chief Electrical Technician – near Engine Control Room*

The engines drew combustion air from the engine rooms which were force ventilated, some with inlets close (<10 m) to the drill floor. Gas alarms did not automatically shut down these ventilation flows so gas would have accumulated in the engine rooms extremely quickly. At the time of the explosion all of the Engine Rooms #1-6 would have been ventilated.

There is clear and unambiguous evidence that gas was in fact ingested by the ventilation fans supplying Engine Room #3 and that a powerful explosion occurred in this space. As well as causing damage to the external wall of the rig, the blast vented into the Engine Control Room and other parts of the rig, despite the intervening A Class bulkheads. It is possible that other engine rooms on the port side also suffered internal explosions but there is no clear testimony to the explosion damage.

Witness evidence also strongly suggests that there was a strong confined explosion in at least one engine room on the starboard side, shortly after that in Engine Room #3. Engine #6 was also operating at this time but there were apparently no witnesses who can confirm that this room suffered external damage that would indicate that an internal explosion had occurred.

The engine rooms were not rated as zoned areas and contained numerous ignition sources that would represent a particularly high risk of ignition in the event of engine over-speed and load change over. The risk would be highest when the engines were operating on load. It is certainly possible that the port side explosion originated in Engine Room #3; however it cannot be ruled out that an explosion started elsewhere and propagated into the Engine Room(s). Similarly it is possible that the explosion on the starboard side corresponded to ignition within Engine Room #6; propagation of explosion into this or one of the other engine rooms cannot be ruled out.

Whatever the location of the initial ignition, the explosion in the Engine Rooms would have been powerful and damaging because these spaces had substantial volumes and were strongly confined. There was no planned provision for explosion venting of the engine room and a strong blast would have propagated through the interior of the rig, displacing internal partitions.

The incident clearly illustrates the high hazard associated with ingesting gas into large spaces deep within the rig that have no provision for explosion relief. Explosions in such circumstances are very likely to directly threaten the crew and to damage vital rig systems.

**2.5 IMMEDIATE EFFECTS OF BLAST ON RIG CREW**

All of those who lost their lives in the incident were working in two areas at the time of the explosions:

1. On (or near) the Drill Floor: Driller’s Shack, Shale Shaker, Starboard Crane Pedestal
2. In the Mud Pump Room.

These areas were affected by the gas cloud and workers exposed to the initial explosion would have had no protection from heat and overpressure.

Most of the injuries to survivors occurred on the second deck in and around the Engine Control Rooms or in accommodation areas. Ceilings and internal partitions were displaced and it appears that this damage was caused by propagation of blast through the rig from explosions in the engine rooms and possibly a high intensity external explosion in the Moon Pool.

2.6 EFFECTS OF BLAST DAMAGE ON EMERGENCY RESPONSE

The explosion knocked out both sets of Engines 1-3 and 4-6. These sets were independent systems, separated in space and were supposed to provide redundancy of supply. However engines in both sets ingested gas and were consequently put out of action by the explosion; the rig was left with a minimal amount of emergency power. After the explosions, the Chief Engineer and other crew made an unsuccessful attempt to start the standby generator in order to bring one of the main generators back on line; main generators were needed to operate the rig fire pumps.

Simultaneously the Sub-Sea Supervisor attempted to activate the Emergency Disconnect System (EDS) to allow the rig to move away from the well and the flow of hydrocarbons. The EDS failed to operate presumably because it had been damaged by the explosions. When it became clear that the EDS had not disconnected the rig from the well and that the flow of hydrocarbons on to the deck would continue, the Master decided to abandon the rig:

“Well, it was pretty straightforward. No -- the fuel to the fire wasn't -- wasn't shut off. We had -- we were dark. We had no fire pumps. There was nothing left else to do but leave the vessel -- abandon.”

Testimony of Master

The Main Stairs and Starboard Stairs as well as some passage ways were blocked with debris, but all of the crew – including several injured - who were not directly exposed to the blast were able to find their way to lifeboats. Two lifeboats were launched around 40 minutes after the explosion carrying the majority of the rig’s crew. Three crew members jumped into the water earlier and were picked up by a fast rescue craft from the DAMON BRANKSTON – a supply vessel that was standing by.

Approximately 11 persons (including the Master) mustered at the forward life-rafts. The launching of these life-rafts was chaotic and several persons ended up in the sea but all survived.

2.7 PROGRESS OF FIRE THROUGH THE RIG

Given the large external fire fuelled by hydrocarbons from the riser and the lack of on-board fire fighting capacity, it was inevitable that the fire would eventually progress into and through the internal decks. It is also likely that many internal bulkheads would have been damaged by the blast. There is a lack of coherent evidence about the rate of internal spread of fire but no clear indications that, in this case, fire spread to and through the rig’s interior hindered attempts to evacuate.

About 35 minutes after the explosion, crew at the lifeboat station saw the travelling equipment and drilling blocks (weight 150,000 lbs) fall from the top of the derrick. This prompted the
launch of Lifeboat #2. Whilst indicating progressive deterioration of the condition of the rig, this failure was clearly caused by the external hydrocarbon fire and is very unlikely to have been significantly delayed by higher fire rating of internal bulk heads e.g. from A-60 to H-60.
3 RECOMMENDATIONS ON FIRE AND EXPLOSION ISSUES IN DWH REPORTS

3.1 US COAST GUARD REPORT AND USCG COMMANDANT’S RESPONSES

The most detailed recommendations in the area of Fire and Explosion issues have been made by the US Coast Guard (USCG). These recommendations were subsequently considered by the USCG Commandant. Both recommendations and responses are reproduced verbatim below to avoid misrepresenting their meaning. The authors do not consider the Commandant’s responses are appropriate to the UK Sector and some additional comments have been made in each case.

All of the recommendations are summarised in Table 1.

Recommendation 1A. It is recommended that Commandant work with the IMO to amend the MODU Code to include clear requirements for the long term labelling and control of all electrical equipment in hazardous areas. In addition, requirements should be established for the continued inspection, repair and maintenance of electrical equipment in hazardous areas in the unit’s safety management system.

Commandant’s Response: I concur with the intent of this recommendation. I agree that preventing ignition of flammable vapors under non-blowout conditions is important. I will evaluate the need to increase oversight to ensure MODUs operating on the U.S. Outer Continental Shelf comply with the International Electro-technical Commission (IEC) standards referenced by the MODU code, and require independent, third party certification to these standards. However, the 2009 MODU Code regulation 6.6 refers to relevant IEC standards for clear labelling, identification, inspection, operation and maintenance of electrical equipment in hazardous areas. Safety management systems on MODUs are required to include compliance with regulatory requirements. The magnitude of the release experienced on the DEEPWATER HORIZON resulted in a large flammable gas cloud that formed well beyond the existing classified hazardous areas. Consequently, ignition of the resulting explosive atmosphere was likely not avoidable.

The implication of the Commandant’s comments is that control of equipment outside existing classified areas to reduce ignition risks is futile and that ignition in the case of blowout is unavoidable. It may well be that in the circumstances of the DWH incident, given the layout of the rig and equipment, that ignition was extremely likely. However not all blowouts ignite; this is covered in Section 3. Overall the rate of ignition is of order 10%. It is difficult to believe that better control of potential ignition sources could not reduce the risk of ignition. This conclusion is supported by modelling of the consequences of blowout and is discussed in more detail in Section 4.

Recommendation 1B. It is recommended that Commandant work with the IMO to amend the MODU Code to provide more detailed guidance for the design and arrangement of fixed automatic gas detection and alarm systems as specified in paragraph 9.8 of the MODU Code (paragraph 9.11). The guidelines should include as a minimum, the recommended type and number of gas detectors, their arrangement, alarm set points, response times, wiring protocols and survivability requirements.

Commandant’s Response: I do not concur with this recommendation. The investigation does not conclude the gas detection system design was inadequate or did not function.
properly. Instead, its description of the incident and actions of those on board portrayed crew members who were not provided with training or procedures necessary to ensure they responded properly. As such, in lieu of the recommended action we will evaluate our inspection and examination policy and procedures to ensure they are sufficient to confirm adequate crew training and proper system function.

The Commandant does not comment on the human factors involved in making complex decisions very rapidly and on the multiplicity of manual responses apparently required of the crew. In general HSE would be unhappy about such a reliance on operator intervention in emergency control.

Recommendation 1C. It is recommended that Commandant work with the IMO to amend the MODU Code to provide more detailed guidance for establishing fire and explosion strategies on board units using dynamic positioning (DP) systems for station keeping. The guidelines should provide a hierarchy of recommend automatic and manual emergency shutdown actions following gas detection in vital areas. The guidelines should also provide accepted approaches for the design and arrangement of the emergency power source necessary for station keeping in the event of a flammable gas release.

Commandant’s Response: I concur with the intent of this recommendation. Upon detection of an explosive or hazardous condition, automatic initiation of Emergency Shutdown (ESD) systems is normally preferred. However, as discussed by section 6.5.2 of the 2009 MODU Code, special consideration should be given to a dynamically positioned MODU engaged in drilling because manual activation of shutdowns may be the most effective method of ensuring the appropriate response and protecting the people and environment. In lieu of the recommended action we will evaluate the need to confirm adequate crew training, procedures and proper system function for manual shutdowns during inspections and examinations.

The Commandant notes that as a general rule automatic response is preferred and by implication endorses this approach for MODU’s that do not rely on DP. There are some important special cases (e.g. during jacking operations), but as a rule MODU’s that do not rely on DP should reduce risk by implementing high level ESD operations automatically in the event of confirmed gas detection.

For MODU’s that do rely on DP, the Commandant refers to and endorses 6.5.2 of the MODU code that allows manual shutdown. The Commandant does not respond to the final suggestion that appropriate emergency systems capable of maintaining station whilst reducing the risk of ignition could be developed and recommended. Such a system would need to have a high resilience in the case of false alarms. This is one advantage of the system of diverse ventilation supply for power generation and purging described in Sections 5 and 6. Closing of one inlet or set of inlets in response to confirmed gas detection would not compromise continued running of the engines and motors necessary for safe operation of the DP MODU.

Recommendation 1D. It is recommended that Commandant work with the IMO to amend the MODU Code to require specific minimum values for explosion design loads to be used in calculating the required blast resistance of structures. In addition, unified guidelines for performing the required blast resistance calculations should be developed.

Commandant’s Response: I concur with the intent of this recommendation. I will evaluate the need for fire and explosion risk analyses to ensure an adequate level of
protection is provided for accommodation spaces, escape paths, embarkation stations, and structures housing vital safety equipment on MODUs operating on the U.S. OCS.

It is not clear in this case whether the analyses are based on blow-out or sub-blowout releases. In the blowout case: a rig that continues to supply engine rooms with flammable vapour risks overpressures that are likely to be beyond practical explosion resistant design.

Recommendation 1E. It is recommended that Commandant work with the IMO to amend the MODU Code to require an explosion risk analysis of the design and layout of each facility. The analysis should use accidental blast loads defined by the Organization, to determine whether the levels of protection for accommodation areas, escape paths and embarkation stations provided by the prescriptive requirements in the Code are adequate.

Commandant’s Response: I concur with the intent of this recommendation. I will evaluate the need for fire and explosion risk analyses to ensure an adequate level of protection is provided for accommodation spaces, escape paths, embarkation stations, and structures housing vital safety equipment on MODUs operating on the U.S. OCS.

Recommendation 1F. It is recommended that Commandant work with the IMO to amend the MODU Code to require ventilation inlets for machinery spaces containing primary and emergency sources of power to be located as far as practicable from hazardous locations.

Commandant’s Response: I concur with the intent of this recommendation. The report of investigation indicates flammable gas may have entered a machinery space via the vent intakes located outside the classified hazardous areas, causing a secondary explosion that resulted in the entire MODU losing primary and emergency power. The magnitude of the release experienced on the DEEPWATER HORIZON resulted in a large flammable gas cloud that formed well beyond the existing classified hazardous areas. Consequently, it is unlikely that any additional distance between the inlets and hazardous areas would have prevented a secondary explosion. Existing sections 6.4 and 9.3 of the 2009 IMO MODU Code already contain several provisions to minimize the risk of explosive or hazardous gases entering machinery spaces via the ventilation inlets. I believe these provisions are sufficient and will confirm actions are taken to ensure compliance with them on MODUs operating on the U.S. OCS.

The Commandant’s assertion that planning for ignition control in the event of blowout is futile is again unsupported by any detailed analysis and appears to conflict with historical experience. In fact Section 6.4 of the MODU code deals with the ventilation of hazardous spaces and is not relevant to Recommendation 1F. Section 9.3 does not address the issue raised in Recommendation 1F either.

Recommendation 1G. It is recommended that Commandant prepare and submit a “lessons learned” information paper to the IMO strongly recommending that existing facilities re-evaluate the placement of supply air intakes for main and emergency power sources, coordinated with the fire and gas detection system logic. The paper should recommend that training, policies and procedures are implemented to shut down ventilation systems and close dampers in the event flammable gas is detected in critical locations.

Commandant’s Response: I do not concur with this recommendation. As noted in my action for recommendation 1F, the magnitude of the release experienced on the DEEPWATER HORIZON resulted in a large flammable gas cloud that formed well
beyond the existing classified hazardous areas. Consequently, it is unlikely that any additional distance between the inlets and hazardous areas would have prevented a secondary explosion. Sections 6.4 and 9.3 of the 2009 IMO MODU Code contain several provisions to minimize the risk of explosive or hazardous gases entering machinery spaces via the ventilation inlets. However, I may take other lessons learned to the IMO after full consideration of the recommendations in this report.

Similar comments apply to the response to Recommendation 1F.

Recommendation 2A. It is recommended that Commandant work with the IMO to amend the MODU Code to require that fire pump systems should be self-contained and depend on no other onboard systems. This should include dedicated fuel supplies for at least 18 hours of operation.

Commandant’s Response: I do not concur with this recommendation. The existing requirements in 46 CFR §108.415 and § 108.421 and Section 9.7 of the 2009 MODU Code provide redundancy by requiring at least two independently driven fire pumps located in different spaces such that both cannot be rendered inoperable by a fire in a single space. I believe these existing requirements are adequate.

Recommendation 2B. It is recommended that Commandant work with the IMO to amend the MODU Code to require H-60 fire separations between the drilling area and adjacent accommodation spaces as well as any spaces housing vital safety equipment.

Commandant’s Response: I concur with the intent of this recommendation. I will evaluate the need for fire and explosion risk analyses for inclusion in Coast Guard regulations to ensure an adequate level of protection is provided for accommodation spaces, escape paths, embarkation stations, and structures housing vital safety equipment on MODUs operating on the U.S. OCS.

There does not appear to be any evidence that this change would have significantly affected the outcome in the DWH incident but it is easy to imagine scenarios in which it could.

Recommendation 2C. It is recommended that Commandant work with the IMO to amend the MODU Code to develop uniform guidelines that can be used as a basis for performing engineering evaluations to ensure that the level of fire protection of the bulkheads and decks separating hazardous areas from adjacent structures and escape routes is adequate for likely drill floor fire scenarios.

Commandant’s Response: I concur with the intent of this recommendation. I will evaluate the need for fire and explosion risk analyses to ensure an adequate level of protection is provided for accommodation spaces, escape paths, embarkation stations, and structures housing vital safety equipment on MODUs operating on the U.S. OCS.

Recommendation 2D. It is recommended that Commandant work with the IMO to amend the MODU Code to require a fixed deluge system or multiple high capacity water monitors for the protection of the drill floor and adjacent areas. Consideration should be given to requiring automatic operation upon gas detection.

Commandant’s Response: I concur with the intent of this recommendation. Fixed deluge systems or multiple high capacity water monitors would provide additional protection in the vicinity of the drill floor. Early employment of a deluge or monitor spray system during a drilling mishap could serve to prevent or delay ignition of an
uncontrolled release of product and/or mitigate the effects of ignition. I will evaluate the need to develop suitable requirements for all MODUs operating on the U.S. OCS.

Recommendation 2E. It is recommended that Commandant work with the IMO to amend the MODU Code to require a fire risk analysis to supplement the prescriptive requirements in the MODU Code. The risk analysis should be a performance-based engineering evaluation that utilizes defined heat flux loads to calculate the necessary levels of protection for structures, equipment and vital systems that could be affected by fires on the drill floor, considering the unique design, arrangement and operation of each MODU.

Commandant’s Response: I concur with the intent of this recommendation. I will evaluate the need for fire and explosion risk analyses to ensure an adequate level of protection is provided for accommodation spaces, escape paths, embarkation stations, and structures housing vital safety equipment on MODUs operating on the U.S. OCS.

Recommendation 3A. It is recommended that Commandant work with the IMO to amend the IMO MODU Code to establish performance standards concerning the maximum allowable radiant heat exposure for personnel at the muster stations and lifesaving appliance lowering stations, along with guidelines for calculating the expected radiant heat exposure for drill floor fire events for each MODU hull type.

Commandant’s Response: I concur with the intent of this recommendation. I will include this issue in my evaluation of the need for fire and explosion risk analyses to ensure an adequate level of protection is provided for accommodation spaces, escape paths, embarkation stations, and structures housing vital safety equipment on MODUs operating on the U.S. OCS.

All of the recommendations 2C to 3A are in line with OSD’s approach to performance based safety engineering.

These recommendations are summarised in Table 1 below.
<table>
<thead>
<tr>
<th>Recommendation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Labelling of rated electrical equipment in hazardous areas.</td>
</tr>
<tr>
<td>1B</td>
<td>Guidance on design of detection and alarm systems.</td>
</tr>
<tr>
<td>1C</td>
<td>Guidance on fire and explosion strategies for units with DP.</td>
</tr>
<tr>
<td>1D</td>
<td>Specification of minimum explosion design loads.</td>
</tr>
<tr>
<td>1E</td>
<td>Explosion risk analysis for each existing facility.</td>
</tr>
<tr>
<td>1F/G</td>
<td>Control of location of ventilation inlets. Shut down of ventilation in the event of gas detection.</td>
</tr>
<tr>
<td>2A</td>
<td>Fire pumps to be self-contained.</td>
</tr>
<tr>
<td>2B</td>
<td>H-60 rated separation between drill floor and adjacent accommodation areas.</td>
</tr>
<tr>
<td>2C</td>
<td>Guidelines on engineering evaluations of fire partitions.</td>
</tr>
<tr>
<td>2D</td>
<td>Fixed deluge or monitors provided for drill floor.</td>
</tr>
<tr>
<td>2E</td>
<td>Fire risk analysis to supplement the prescriptive requirements of the MODU code.</td>
</tr>
<tr>
<td>3A</td>
<td>Standards for maximum radiant heat allowable at muster stations and lifeboat stations.</td>
</tr>
</tbody>
</table>

Table 1: Summary of recommendations in US Coastguard report on Deepwater Horizon.

3.2 BUREAU OF OCEAN ENERGY MANAGEMENT, REGULATION AND ENFORCEMENT (BOEMRE) RECOMMENDATIONS

BOEMRE made only four recommendations in the Fire and Explosion area, all addressing the issue of ignition risk reduction:

1. The Agency should consider including in the Safety Alert discussions on design considerations of existing and planned air intake locations, operating philosophy when conducting design hazard analyses of Mobile Offshore Drilling Units (MODUs), inspection and testing documentation of all safety devices for engine shutdown, and performance of site-specific safety analyses of safety devices to ensure that systems align with operating philosophy.
2. The Agency should consider conducting unannounced inspections of all engine compartment air intake locations for all MODUs operating on the OCS to determine the extent of possible problems.

3. The Agency should perform an audit of mud gas separator venting systems for all MODUs operating on the OCS to ensure that adequate procedures are in place for proper use.

4. The Agency should consider working with the United States Coast Guard to evaluate potential regulatory reforms regarding air intake locations and the inspection and documentation of engine over-speed devices.

These recommendations are for action by BOEMRE and some do not have direct general significance. BOEMRE clearly recognise the significance of ingestion of vapour by engines in the DWH and recommend that this aspect of rig design is worthy of attention (as an inspection issue). BOEMRE Recommendation 1 also presumably refers to the issue of ESD but no definite suggestions about appropriate design philosophies are made.

### 3.3 REPUBLIC OF THE MARSHALL ISLANDS REPORT

The RMI recommendations broadly parallel those made by USCG:

4.7 It is recommended that the Administrator present a submission to the IMO proposing the 2009 MODU Code be amended to add additional criteria for power generating equipment, providing for a greater level of redundancy and availability for those units not equipped with an additional source of emergency electrical power as per section 5.4.5 of the 2009 MODU Code (section 5.3.5 of the 1989 MODU Code).

4.11 It is recommended that the Administrator present a submission to the IMO proposing that consideration be given to amending the 2009 MODU Code to require automatic sounding of the General Alarm system if, after a short time period, the watchstanders at the central control location have not cancelled or manually sounded the General Alarm.

4.12 It is recommended that the Administrator present a submission to the IMO to consider amending the 2009 MODU Code with particular regard to the requirements for the location of ventilation intakes with respect to their proximity to hazardous locations.

4.13 It is recommended that the Administrator present a submission to the IMO to consider amending the 2009 MODU Code to require MODUs to have at least one fire pump capable of being powered independently of a unit’s main and emergency electrical systems.

### 3.4 CHEMICAL SAFETY BOARD (CSB) REPORT

CSB has produced authoritative reports on a number of major incidents and its views on DHW are likely to be of great interest when they are published.
## 4 BLOWOUT FREQUENCIES

### 4.1 OVERALL RISK POSITION

The best data on blowout frequencies come from SINTEF’s blowout database. For well operations in the North Sea and in other areas where equipment is of a North Sea Standard (operation performed with Blowout Preventer (BOP) including shear ram and two barrier principle followed), the SINTEF database has been analysed by SCANDPOWER [Scandpower Risk Management AS, 2006]. The data are recommended by the International Association of Oil and Gas Producers (OGP, 2010).

Some key results from these analyses relevant to drilling are reproduced in Table 2 below:

<table>
<thead>
<tr>
<th>Operation</th>
<th>Average</th>
<th>Gas</th>
<th>Oil</th>
<th>Sub-sea fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exploration Drilling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Shallow gas) Topside blowout</td>
<td></td>
<td>6 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diverted well release</td>
<td></td>
<td>8.3 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well release</td>
<td></td>
<td>9.3 x 10^{-5}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-sea blowout</td>
<td></td>
<td>9.8 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Development Drilling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Shallow gas) Topside blowout</td>
<td></td>
<td>4.7 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diverted well release</td>
<td></td>
<td>6.5 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well release</td>
<td></td>
<td>7.3 x 10^{-5}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-sea blowout</td>
<td></td>
<td>7.4 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Exploration drilling (Deep)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal wells Blowout</td>
<td>3.1 x 10^{-4}</td>
<td>3.1 x 10^{-4}</td>
<td>3.1 x 10^{-4}</td>
<td>0.39</td>
</tr>
<tr>
<td>Well release</td>
<td>2.5 x 10^{-3}</td>
<td>2.5 x 10^{-3}</td>
<td>2.5 x 10^{-3}</td>
<td>0.39</td>
</tr>
<tr>
<td><strong>Exploration drilling (Deep)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTHP* wells Blowout</td>
<td>1.9 x 10^{-3}</td>
<td>1.9 x 10^{-3}</td>
<td>1.9 x 10^{-3}</td>
<td>0.39</td>
</tr>
<tr>
<td>Well release</td>
<td>1.6 x 10^{-2}</td>
<td>1.6 x 10^{-2}</td>
<td>1.6 x 10^{-2}</td>
<td>0.39</td>
</tr>
<tr>
<td><strong>Development drilling (Deep)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal wells Blowout</td>
<td>6 x 10^{-5}</td>
<td>6 x 10^{-5}</td>
<td>6 x 10^{-5}</td>
<td>0.33</td>
</tr>
<tr>
<td>Well release</td>
<td>4.9 x 10^{-4}</td>
<td>4.9 x 10^{-4}</td>
<td>4.9 x 10^{-4}</td>
<td>0.33</td>
</tr>
<tr>
<td><strong>Development drilling (Deep)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HTHP wells Blowout</td>
<td>3.7 x 10^{-4}</td>
<td>3.7 x 10^{-4}</td>
<td>3.7 x 10^{-4}</td>
<td>0.33</td>
</tr>
<tr>
<td>Well release</td>
<td>3 x 10^{-3}</td>
<td>3 x 10^{-3}</td>
<td>3 x 10^{-3}</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Table 2: Blowout frequencies (per well) for drilling operations.

*HPHT wells are 690 bar or above shut in pressure and or bottom hole temperature > 150°C.*
A number of further inputs and assumptions are required to determine the individual risk to those engaged in drilling. These will include:

- The proportion of High Pressure High Temperature (HPHT) wells drilled
- The balance between exploration and development
- Ignition frequencies
- Locations of blowouts i.e. drill floor or lower level or sub-sea and water depth
- Success rate in diverting shallow gas blowouts
- Flow rates in normal blowouts (typically 10 - 35 kg/s)
- Flow rates in HPHT blowouts (typically 50 - 200 kg/s)
- Vulnerability of the Temporary Refuge (TR) in various circumstances
- Effects of well releases – typically assumed not to have sufficient duration to cause TR impairment or evacuation.

A range of drilling Safety Cases and Thorough Safety Case Reviews submitted to HSE has been reviewed. Obviously risks vary depend on the type of off-shore work being undertaken (operational, maintenance or accommodation) but a typical conclusion of risk analysis is that the contribution of blowout scenarios to the individual risk (of death) is of order 3 x 10^{-4} per annum. This generally represents approximately half of total individual risk, with the remainder including transport incidents, falls and a range of other risks.

The individual risk associated with blowouts is below the level of 10^{-3} that would be considered by HSE as normally unacceptable but lies well within the ALARP region (risk >10^{-6}). Reducing the risk associated with blowout and other well releases also makes a significant difference to the total risk.

Fire and explosion issues affect the risk through:

- Ignition frequencies
- Vulnerability of workers in the event of ignition.

### 4.2 IGNITION RISKS

The overall risk analysis suggests that measures to reduce the risk of ignition in the event of blowout should be an important part of an operator’s efforts to ensure that risks are ALARP.

Typical assumptions (based on review of the SINTEF database to 2008) for the frequency and timing of ignition are shown in Table 3.
The risks to workers are dominated by events that ignite early. If the ignition is substantially delayed, there is an opportunity for the crew on the drill floor to escape from within the cloud.

The data indicate that ignition of clouds from blowouts is in fact relatively rare. Most of the time the gas is carried by release momentum and the wind away from the deck, or the gas contacts the rig surface but potential ignition sources are not active or effective.

Experience during large releases on shore reinforces the point that ignition may be considerably delayed. In vapour cloud incidents at Buncefield, Jaipur and the Amuay Refinery (Venezuela), huge vapour clouds covered areas (of order 1 km across) with flammable vapour. The clouds engulfed all kinds of plant, offices, vehicles, factories, housing etc. but in all cases ignition only took place after a very long delay. In the case of Buncefield, several vehicles drove into the cloud (before their engines failed) without causing ignition. Only the starting of a large fire pump finally caused ignition.

The important conclusion is that efforts to control ignition in the event of blowout are not necessarily futile. There is likely to be time to successfully isolate diverse electrical equipment on deck (e.g. ventilation fans) corresponding to a relatively low ignition risk. High current electrical devices represent a high risk but they are finite in number: ways to reduce risk from such equipment are discussed in the next section and if this is done, then the overall risk of ignition can be significantly reduced.

### Table 3: Ignition probabilities and timings

<table>
<thead>
<tr>
<th>Release type</th>
<th>Early Ignition ( &lt;5 minutes )</th>
<th>Delayed ignition ( 5- 60 minutes)</th>
<th>Very delayed ignition ( &gt; 60 minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow gas blowout</td>
<td>0.07</td>
<td>0.11</td>
<td>0.07</td>
</tr>
<tr>
<td>Deep blowout</td>
<td>0.09</td>
<td>-</td>
<td>0.16</td>
</tr>
<tr>
<td>Deep well release</td>
<td>0.03</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
5 OPTIONS FOR REDUCING IGNITION RISK FREQUENCY

The value of measures to control ignition in the event of a substantial gas release depends on:

- Effectiveness in a real emergency (large vapour cloud)
- Risks associated with false alarms.

These factors vary for different rig systems and in general different approaches will provide best value for money for various systems.

Three main approaches to ignition control are available:

1. Ex Rated equipment (that can operate safely in flammable atmospheres)
2. High level Emergency Shutdown (ESD) on confirmed gas detection
3. Control of ventilation (purged or diverse systems).

The first two are familiar and widely used. Purging of motors is widely used to protect them in areas close to potential sources of vapour in normal operation (zoned areas). Air is taken from outside such zoned areas and used to positively pressurise potentially incendive parts of the motors, preventing gas ingress.

The idea could be extended to protect vital systems, such as power generation, against large blowout releases. It is not normally possible to locate a single ventilation inlet on the rig which cannot be affected by gas release in some wind conditions (see Section 6). However it is very unusual for a release to affect opposite sides of the rig simultaneously; normally the upwind side is free of gas. If air for the engines or purge systems is supplied from a duct with inlets on both sides of the rig, there is almost always a potential supply of uncontaminated air available. This arrangement of two inlets is referred to below as a “diverse” ventilation system.

This would be a new technology, developed to avoid a future disaster like the DWH. Currently the crews of MODUs that depend on dynamic positioning face a deadly version of Hobson’s Choice in the event of a blowout. They cannot stop power generation for fear of loss of control of station but to continue to ingest gas at a high rate into unprotected engine rooms runs an extremely high risk of violent internal explosions of the sort that crippled DWH.

A best practice solution for many rigs is likely to involve two or all three of the types of protection listed above. The advantages and disadvantages of each are listed in Table 4.
<table>
<thead>
<tr>
<th><strong>Advantages</strong></th>
<th><strong>Disadvantages</strong></th>
</tr>
</thead>
</table>
| **Ex-Rated Equipment** |  - Low risk in the event of false alarms (equipment continues to operate normally).  
  - Simplicity in design of safe systems.  
  - Cost (capital and maintenance).  
  - Some residual risk (e.g. may be vulnerable to gas jet impingement).  
  - Availability of some types of equipment.  
  - Gas accumulation in internal spaces may continue if systems run as normal. |
| **High Level ESD on confirmed gas detection** |  - Relatively low cost for diverse non-essential equipment.  
  - Low residual risk  
  - Potential risks, disruption and cost associated with false alarms.  
  - Complexity of design of safe systems. Rigorous testing is difficult.  
  - Not appropriate for power generation in rigs dependent on DP.  
  - May not be appropriate in some other circumstances e.g. during jacking, drill handling during BOP operation etc. |
| **Diverse ventilation systems** |  - Key systems (e.g. power generation, drill handling) can continue to operate.  
  - Low risk in the event of false alarms.  
  - Testing and maintenance relatively simple, safe and low cost.  
  - A new untested technology.  
  - Some residual risk of ignition.  
  - Capital cost (especially in refit). |

Table 4: Advantages and disadvantages of different approaches to ignition risk reduction.
5.1 BEST PRACTICE IN RIGS NOT DEPENDENT ON DYNAMIC POSITIONING

A review of safety cases submitted to HSE suggests the following protective systems correspond to best practice in drilling and combined operations:

1. Comprehensive gas monitoring with grouped detectors to allow confirmation of detection by two-out-of-N (2ooN) voting.

2. Isolation of high risk, non-essential systems (e.g. welding sockets) on confirmed (low level) gas detection in zoned areas.

3. Automatic ESD on confirmed (high level) gas detection in zoned or unzoned areas. ESD to include:
   - Surface process (with automatic fail safe blow down sequence)
   - Power generation
   - Ventilation systems (with closure of dampers).

4. Confirmed high level gas detection to inhibit starting of emergency generator sets.

5. Rigorous tests of emergency response systems.

6. Emergency systems supported by battery back-up.

7. All items necessary for use in emergency suitable for use in Zone 1.

8. Top-drive and draw-works suitable for use in Zone 1.

9. Cranes fitted where appropriate with rig savers, ex slip rings and protected equipment in cabin and on boom.

5.2 COMMON DEFICIENCIES IN RIGS NOT DEPENDENT ON DYNAMIC POSITIONING

Based on a review of safety reports submitted to HSE, some installations currently fall short of this standard. The following are common examples of poor practice:

1. Low reliability gas detection vulnerable to false alarms and outages.

2. ESD systems that are heavily reliant on manual intervention. In some cases the actions required (of remotely located operators) depend on whether a release is judged to be “limited” or “unlimited”. The DWH incident illustrates the difficulties operators may face in determining the seriousness of a developing incident and the dire consequences of misjudgements.

3. Air inlets to engine rooms close to areas expected to be immediately contaminated in the event of a blowout, increasing the risk of ignition and a powerful confined explosion.

4. Pumped motors that take air from a few metres outside zoned areas and would be immediately vulnerable in the event of large releases.
5. Drillers’ override on automatic safety systems.

None of these practices are specifically forbidden by current regulations but all may contribute significantly to the risk of a disaster in the event of blowout and may mean that operational risk is not ALARP.

5.3 **BLOWOUT RESPONSE FOR RIGS DEPENDENT ON DYNAMIC POSITIONING**

Currently emergency planning for blowout in rigs dependent on DP involves:

1. Emergency disconnection from the well
2. Moving away from the well.

The DWH incident clearly illustrates the difficulties and the high level of residual risk associated with this approach. In the first place the decision to activate the Emergency Disconnect System (EDS) is invariably a difficult one for an individual crew member. After the initial explosions, the DWH was in an extremely poor state: crew in the Central Control Room (CCR) could see that the DP guidance system was not available and there was no power to the thrusters. The sub-sea supervisor advised the master that he intended “EDSing”. The master replied “No, calm down. We’re not EDSing”. The cost to a drilling company of an unnecessary EDS is high and the willingness of managers to respond promptly and appropriately to a very unusual emergency has to be questioned. Even in the circumstance of the DWH incident, the fear of unnecessary EDS appears to have been a strong deterrent to carrying out the planned response to blowout.

In any case the time required for EDS and moving is large compared with the short time to ignition in a high proportion of blowout cases. The level of residual risk even for a highly trained crew is high. On the other hand an automatic system that activates EDS in the event of confirmed gas detection is almost certainly too risky in the event of false alarms and faults to be appropriate.

A practical alternative is required that allows continued power generation and essential rig operations (related to emergency management) in the event of a blowout. Some options for such a system are discussed in the following sections.

5.4 **CONTROL OF VENTILATION IN THE EVENT OF BLOWOUT**

5.4.1 **Option 1: Shutdown of engine room ventilation**

The ventilation demands of energy generation are substantial: for example each engine room in DWH took in air at a rate of 135,000 - 170,000 m³/hr. Approximately one sixth of the air was used for engine combustion whilst the remainder served to maintain acceptable ambient conditions in the engine rooms.

By separating out the combustion air and shutting down engine room ventilation, the demand for air could be reduced to around 25,000 m³/hr (7 m³/s) per operating engine. Large volumes of flammable gas would not then accumulate in the engine room. Conditions in the engine room would still deteriorate rapidly (high temperatures), but some continued operation would be
possible. In the event of ingestion of flammable gas, an affected engine would over-speed and eventually trip: continued operation of affected engines would be unlikely to be possible whilst the release continued. However if engine inlets were well separated, it is possible that other sets would be ingesting clean air and could be brought on line to replace those that suffered over-speed trips.

Such a system would have important advantages over that the basic arrangement on DWH. The accumulation of flammable gas in the engine rooms would have been prevented and this would have reduced both the risk of ignition and the level of damage to rig systems if ignition occurred. Opportunities for making use of uncontaminated air above different parts of the rig could have been taken albeit in a crude and risky manner. There are a several potentially serious drawbacks:

1. Rapid deterioration in engine room conditions
2. Engine over-speeds, trips and load changing operations at a dangerous time.
3. Significant or complete power outages could be expected.

5.4.2 Option 2: Substitution of external air by stored air

The amounts of air required for power generation make it impractical to substitute ventilation air (drawn from outside) with compressed air from a large tank. This kind of system could however be useful as an alternative supply of air for purged motors or to pressurise other well-sealed enclosures.

5.4.3 Option 3: Diverse ventilation systems

This type of system involves a large ventilation duct with inlets on opposite sides of the rig. (Figure 1). This duct acts somewhat like a ring main in a hydraulic or electrical system.

In normal operation, air would come from both sets of inlets (Figure 2).

Each set of inlets is provided with a set of dampers that are linked to separate polled gas detection at each inlet. If gas is detected at one inlet, then that damper closes (Figure 3).

A high level of damper seal is not required: all that is needed is for the flow of clean air to exceed by a sufficient factor the flow from an inlet where gas is detected. For methane, a ratio of 20 will ensure that even if pure gas is ingested the flow into the engine room will be below the Lower Flammable Limit (5% v/v). In practice, high momentum jets in a blowout situation entrain air very rapidly, so gas ingested by an inlet on the rig periphery is very unlikely to have hydrocarbons in such high concentrations. If external concentrations are in the flammable range 5-15% v/v, much smaller damper sealing efficiencies would still provide a high level of protection: the flow of clean air would only have to be 3 times greater than that from the blocked inlet.

It is extremely unusual for gas to be present at opposite sides of the rig simultaneously. If such a case did arise or there were simultaneous false alarms from detectors in both inlets, it might be appropriate to allow closure of only one set of dampers. However depending on the fan characteristics and duct size it might be possible to close both sets of dampers and run engines on a (planned) level of leakage.
A key advantage of all diverse ventilation systems is that they should not be very vulnerable to mechanical problems or false alarms. If one set of dampers closes for a spurious reason then the engine would continue to run normally and rig operations would not be affected. It should be possible to control the frequency of common mode failures that might affect both sets of dampers.

A second practical advantage is that in moderate winds there is normally a tendency for uncontaminated air to enter the upwind inlet. In fact in windy sites a significant level of risk reduction could be achieved with a passive system (with no dampers) simply by drawing air from an open duct across the rig that would tend to take a flow of uncontaminated air from upwind. This arrangement contrasts with conventional ventilation systems that take air from a single fixed point. If this single inlet happens to be downwind of a source of vapour, trouble cannot be avoided.

Figure 1: Schematic of a diverse ventilation system
Normal operation

Figure 2: Schematic showing operation of a diverse ventilation system in normal conditions
Operation in the case of gas release

Figure 3: Schematic showing operation of a diverse ventilation system in the case of gas contamination near Inlet 2.
6 DISPERSION IN BLOWOUT SCENARIOS

The number of potential blowout scenarios is effectively unlimited; variables include: rig structure, gas and liquid flow rates, release outlet geometry, outlet location, wind conditions, time dependence and so on. The purpose of this section is to propose and justify two important simplifying principles, which can be used to guide safety planning in the event of blowout.

1. **Gas from a blowout can affect any part of a rig** – if the release and wind conditions are unfavourable. The probability of gas affecting a given location is typically in excess of 10%.

2. **Gas from a blowout hardly ever affects both sides of the rig simultaneously.** The probability of this occurring is typically associated with rare flat calm conditions.

It is not possible to prove these propositions by examining all potential blowout scenarios but a systematic investigation of dispersion in a range of conditions gives confidence that they are true generally.

Details of the dispersion source term and dispersion modelling undertaken are included as an appendix to this report. The basic rig geometry chosen is typical of a semi-submersible rig such as DWH. A range of gas densities has been used between those corresponding to methane (lighter than air) and butane (heavier than air). The appropriate density for a blowout is not well defined as the gas fraction is predominantly methane but normally includes variable quantities of higher hydrocarbons. If a blowout includes a significant proportion of liquid this may appear (at high flow rates) as a fine aerosol that moves with the gas and increases the effective density. Witnesses described the release at DWH as being “gassy smoke”.

Recirculation velocities driven by the release momentum and/or the wind are typically large compared with buoyancy induced flows close to the rig. This means that light (methane) releases do not always efficiently lift off the rig surfaces especially in moderate or strong winds.

Figures 4a and 4b shows two views of the same 100 kg/s methane release in the moon pool. This type of release involves a high momentum jet that impinges on a vertical surface within the moon pool; the impinging jet then spreads out in all directions establishing a complex recirculation area within the moon pool. Gas emerges with limited momentum from the large vents in the weather shielded area above, and also downwards out of the moon pool towards the sea.

Substantial areas of the deck downwind of the derrick are contaminated with gas in the flammable range. Flammable gas also affects the downwind side of the rig and the downwind area under the lower deck.

Gas releases in the range 30 to 200 kg/s have been studied and results show that even for the lower flow rates it is appropriate to assume that releases in the moon pool and other locations will contaminate a large area of the deck downwind of the edge of the rig; the downwind side of the rig and downwind parts of the underside of the lower deck will also be contaminated. For most rigs it will be impossible to find a location either on the top, side or lower surface of the rig that will not be affected by gas when the wind is in the wrong direction.

Most of the modelling work has consequently focussed on testing the validity of the second principle – that upstream parts of the rig are almost always free of gas. Then the worst case is a dense release that has a somewhat greater tendency to spread backwards across the deck surface.
against the wind. Most of the modelling has therefore been carried out using a butane release to represent a reasonable worst case.

The higher flow rates (100-200 kg/s) correspond to the high transitory flow rates that may occur in the early stages of a release, as the riser depressurises. Modelled releases start suddenly and continue at a high rate. It is reasonable to assume that if the upstream face stays clear of gas in these circumstances, then this will also be the case for a transitory release of the same magnitude.

Figure 4a: Viewpoint offset 45° from upstream (wind direction shown by arrow)

_Release is from a jet within the Moon Pool - 100 kg/s methane, 5 m/s windspeed._

- Green iso-surface is at 50% LFL
- Yellow iso-surface is at 100% LFL
- Red iso-surface is at 200% LFL

_Large parts of the rig surface downstream of the derrick and drilling floor wind walls are contaminated with gas right to the edge. Substantial parts of the upstream edge of the rig are free of gas._
Figure 4b: Viewpoint offset 45° from downstream (Wind direction shown by arrow)

*Release is from a jet within the Moon Pool - 100 kg/s methane, 5 m/s windspeed.*

*Green iso-surface is at 50% LFL*

*Yellow iso-surface is at 100% LFL*

*Red iso-surface is at 200% LFL*

*Large parts of the rig surface downstream of the derrick and drilling floor wind walls are contaminated with gas right to the edge. Substantial parts of the upstream edge of the rig are free of gas.*

Figure 5 shows the areas of the top surface of the deck affected by a 100 kg/s butane release from the Moon Pool in 5 m/s winds in 8 different directions (0, 45°, 90° etc). Almost all of the top surface of the rig is affected when the wind direction is in one direction or another. When other types of release and other wind speeds are included, there is nowhere on the rig where a single ventilation inlet can be sited without a risk of gas ingestion (Figure 6).

Figure 7 shows some dispersion results for individual wind directions that together make up Figure 5.
Figure 5: Areas of rig’s upper surface affected by a 100 kg/s release (butane) in 5 m/s winds from various directions. Red areas are affected by gas >LFL.

Figure 6: Areas of rig’s upper surface affected by 30 - 200 kg/s releases in a range of locations and wind conditions.
Figure 7: Dispersion results for particular wind directions (shown by arrows).

Areas of the deck that are exposed to flammable concentrations are marked in red.
Figure 8 a-d shows the different release geometries studied.

Figure 8a: Moon pool release – Gas emerges from vents in the wind walls. Gas also issues from the lower opening in the floor of the Moon Pool (not shown here).

Figure 8b: Diverter release
Figure 8c: “Accommodation” source. A horizontal jet from the drill floor (white arrow) impacts on the side of an accommodation block. It is deflected upwards and sideways along channels in the deck.

Figure 8d: Derrick top source. This involves a downward facing jet from the top of the derrick.
The range of dispersion scenarios studied is shown in Table 5. Results for all scenarios are shown in the appendix.

<table>
<thead>
<tr>
<th>DP</th>
<th>Wind Speed</th>
<th>Direction</th>
<th>Release</th>
<th>Flow Rate</th>
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<td>0</td>
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<td>0</td>
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<td>Methane</td>
</tr>
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<td>Butane</td>
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<td>Butane</td>
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<td>Butane</td>
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<td>Butane</td>
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<tr>
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<td>Butane</td>
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<tr>
<td>77-79</td>
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<td>0,22.5,45</td>
<td>Diverter</td>
<td>Butane</td>
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<td>80-82</td>
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<td>Diverter</td>
<td>Butane</td>
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<td>Diverter</td>
<td>Butane</td>
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<td>Medium 5m/s</td>
<td>0,22.5,45</td>
<td>Diverter</td>
<td>Butane</td>
</tr>
</tbody>
</table>

Table 5: Range of dispersion calculations

A number of useful general findings has emerged from the modelling:

1. A flow from the diverter is diluted sufficiently quickly that it does not lead to flammable concentrations at the rig even if the wind blows it directly back. This finding tallies with other modelling and a large amount of practical experience.

2. All other types of release can give flammable concentrations over almost all of the surfaces of the rig if the wind direction is unfavourable. A careful choice of location for ventilation inlets is certainly worthwhile. It is usually a good idea if there is a large solid obstruction between the inlet and drill floor. But if there is only one inlet, there will always be a significant residual risk of ingestion of contaminated gas.

3. Diverse ventilation systems with alternative inlets at opposite sides of the rig substantially reduce the level of risk in almost all cases.

4. A perpendicular jet release into a narrow channel between densely obstructed or solid areas can lead to the jetting of gas sideways in both directions. If channels continue right across the rig, this might lead to high concentrations on both sides of the rig. A diverse ventilation system should not have both inlets lined up with such channels (if a major gas release of this sort into the channel is possible).
6.1 PRACTICAL ISSUES IN DESIGN OF A DIVERSE VENTILATION SYSTEM

1. The ventilation “mains” (i.e. ducts with inlets on both sides of the rig) must be large. If one duct serves three engines of the sort in DWH with similar fans, then the duct must be at least 70% larger (linear dimension) than the conventional ducts used in DWH.

2. Inlets on the vertical sides or underneath of the rig would be preferable but the design needs to control ingress of seawater and allow drainage of liquid from the duct.

3. If dampers leak significantly (which is likely), part of the duct between inlet and fan may accumulate flammable gas. The duct will have one open end but nevertheless it should be routed (at least in part) close to the underside or periphery of the rig and provided with explosion relief.
7 MITIGATING THE EFFECTS OF BLAST

DWH suffered serious internal blast effects with bulk heads, ceilings and partitions being displaced; this led to injuries to the crew and problems in evacuation. The two areas worst affected were both on the second deck: areas around the engine rooms were damaged by confined explosions in the engine rooms and damage was also sustained in the laundry and main accommodation area’s corridors.

There were no reports of gas in these areas prior to the explosion, so it appears that pressurisation was from an explosion at a distance. One possibility is that the damage to the accommodation area was caused by blast effects from a severe external explosion (in the moon pool) that broke through the A-60 bulkheads. However it is also possible that damage to the accommodation areas was caused by the blast from the internal explosion in the engine rooms propagating to a second deck level via the sack room.

7.1 ASSESSMENT OF INTERNAL EXPLOSIONS

A pre-mixed explosion in an internal space without planned venting is particularly dangerous because the expansion of burned gas drives unburned gas into neighbouring spaces. Only a small proportion of the gas that initially accumulated in a room actually burns in that room. Most is driven out of the room, ahead of the advancing flame, and may sustain severe explosions in neighbouring spaces.

The DWH incident highlights the need for careful design of internal spaces where gas might accumulate both in normal and blowout conditions. Strong barriers should be provided to prevent gas and blast propagating into sensitive parts of the rig during an explosion. Such sensitive locations would include: accommodation areas, corridors, escape routes, control areas and any areas housing vital emergency equipment e.g. positioning equipment, fire fighting equipment, control of sub-sea systems etc.

In addition weaker, lightweight panels are required to allow planned venting of any explosion to an external area where its effects are minimised.

Some of the blast assessments that HSE receives are of poor quality in this respect. For example, blast effects from internal explosions are sometimes represented by the rapid decay of pressure from an unconfined explosion using a code like PHAST. This type of approach may seriously underestimate the destructive power and reach of an internal explosion that is channelled through compartments and along corridors between decks.

7.2 ASSESSMENT OF EXTERNAL EXPLOSIONS

Explosion assessments are also required for external explosions. Where pressures in excess of 0.1 bar (10 kPa) are possible near to significant targets, then barriers with planned blast resistance greater than standard A-60 bulkheads will be needed. As before, significant areas would include: accommodation areas, corridors, escape routes, control areas and any areas housing vital emergency equipment e.g. positioning equipment, fire fighting equipment, control of sub-sea systems etc.
8 REFERENCES


US COAST GUARD COMMANDANT (2011) Explosion, Fire, Sinking and loss of eleven crew members aboard the MODU DEEPWATER HORIZON in the Gulf of Mexico, APRIL 20-22, 2010: ACTION BY THE COMMANDANT
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ALARP</td>
<td>As Low As Reasonably Practical</td>
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<tr>
<td>BOP</td>
<td>Blowout Protector</td>
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<tr>
<td>CCR</td>
<td>Central Control Room</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>CFR</td>
<td>Code of Federal Regulations</td>
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<td>DP</td>
<td>Dynamic Positioning</td>
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<tr>
<td>DWH</td>
<td>Deepwater Horizon</td>
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<td>EDS</td>
<td>Emergency Disconnect System</td>
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<td>Emergency Shutdown System</td>
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<td>HSE</td>
<td>Health and Safety Executive</td>
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<tr>
<td>IMO</td>
<td>International Maritime Organisation</td>
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<td>MODU</td>
<td>Mobile Off-shore Drilling Unit</td>
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The Deepwater Horizon incident: fire and explosion issues

The loss of life and serious environmental damage from the blow out incident on the semi-submersible drilling rig Deepwater Horizon in 2010 in the US sector of the Gulf of Mexico has forced a reappraisal of the risks associated with drilling.

HSE commissioned this work in order to consider the lessons to be learned from this international incident. It is important for HSE to stimulate and inform consideration of fire and explosion risks amongst the designers and operators of drilling rigs.

Well control is clearly the first priority but some residual risk of blowout normally remains. This report deals with the minimisation of risks from fire and explosions if blowout does occur and also deals with some issues such as options for ignition frequency reduction and fire and blast mitigation that have not been adequately covered elsewhere.

The report presents findings to inform fire and explosion risk assessment and aid the development of suitable risk control measures. Drilling rig designers and operators should note that some of the changes suggested as a result of the Deepwater Horizon incident can only be implemented at the stage of rig design or major overhaul.

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