An Analysis of Offshore Safety Incidents in the Last 50 years and a look into the current perspectives

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Over the past few decades, the world has seen a number of major offshore incidents that claimed hundreds of lives, damaged the environment critically and caused billions of dollars of property losses. Based on the learnings from the incidents (*e.g*., Sea Gem collapse, Santa Barbara blowout, Piper Alpha disaster, Valdez oil spill), industry came up with new sets of rules, made changes to the processes and devised newer technologies for preventing such catastrophes and minimizing losses. Despite all of these efforts, major incidents kept happening (*e.g.*, Sonrre A blowout, Usumancinta explosion, Montara blowout, Deepwater Horizon blowout). This work analyzed a selection of catastrophic offshore incidents starting from the CP Baker drilling blowout in 1964 to the recent offshore fire incident at Gunashli oilfield in Azerbaijan in 2015. For this study, incidents have been categorized into five different groups – loss of well control events, release/fire/explosion, collision/capsizing, NaTech (Natural hazard triggered technological accidents) and cyber-attacks. Critical learnings and insights from each of the incidents were captured to identify underlying causes and prevalent issues. Based on the findings from past incidents, capabilities of current practices and technologies were assessed. With the growing demand of energy, offshore operations are getting more and more complex as the industry is moving towards the deeper waters to get access to the remote reservoirs. Harsh environment, unconventional resources, complex reservoirs, high pressure high temperature (HPHT) conditions and cyber security are among some of the major safety challenges of the present world. Some of the cutting-edge technologies and advanced systems that have been adopted by the industry to face the current challenges have also been highlighted in this article.

Keywords: Offshore incidents, Lessons learned, Blowouts, Capsizing, Fire and Explosion, Cyber security, NaTech, Well control, Process safety, Incident prevention

Introduction

The very first offshore drilling took place about 120 years ago near the coast of the Pacific Ocean, but the first out of the sight of land offshore well was drilled in 1947 [1] in the US Gulf of Mexico. Offshore operations picked up momentum after that and the industry is growing ever since. By the end of 2017, the total number of offshore oil rigs climbed to 497 worldwide [2]. One of the first major offshore incidents took place in 1964 in the US Gulf of Mexico, when C. P. Baker drilling barge hit a high-pressure gas pocket which resulted in a blowout. Since then the offshore industry experienced many catastrophic incidents all around the world, for example, Ekofisk Bravo blowout (1977), Ixtoc 1 blowout (1979), Alexander L. Kielland capsizing (1980), Piper Alpha fire and explosion (1988), Mumbai High North collision and fire (2005), Deepwater Horizon blowout (2010), Gunashli Oilfield fire (2015) and many more. In Section 2 of this work a selection of major offshore incidents from last 50 years, presented in Figure 1, is analyzed for understanding common underlying causes and capturing lessons for improving process safety performances in the future. For this study, incidents were categorized into five different groups – 1) loss of well control events (*i.e*., blowouts), 2) release/fire/explosion, 3) collision/capsizing, 4) NaTech (Natural hazard triggered technological accidents) and 5) cyber-attacks. Underlying causes of the incidents were analyzed and based on that in Section 3 key lessons were identified, which would help preventing future incidents. In Section 4 challenges and future directions are described, while Section 5 presents conclusions.

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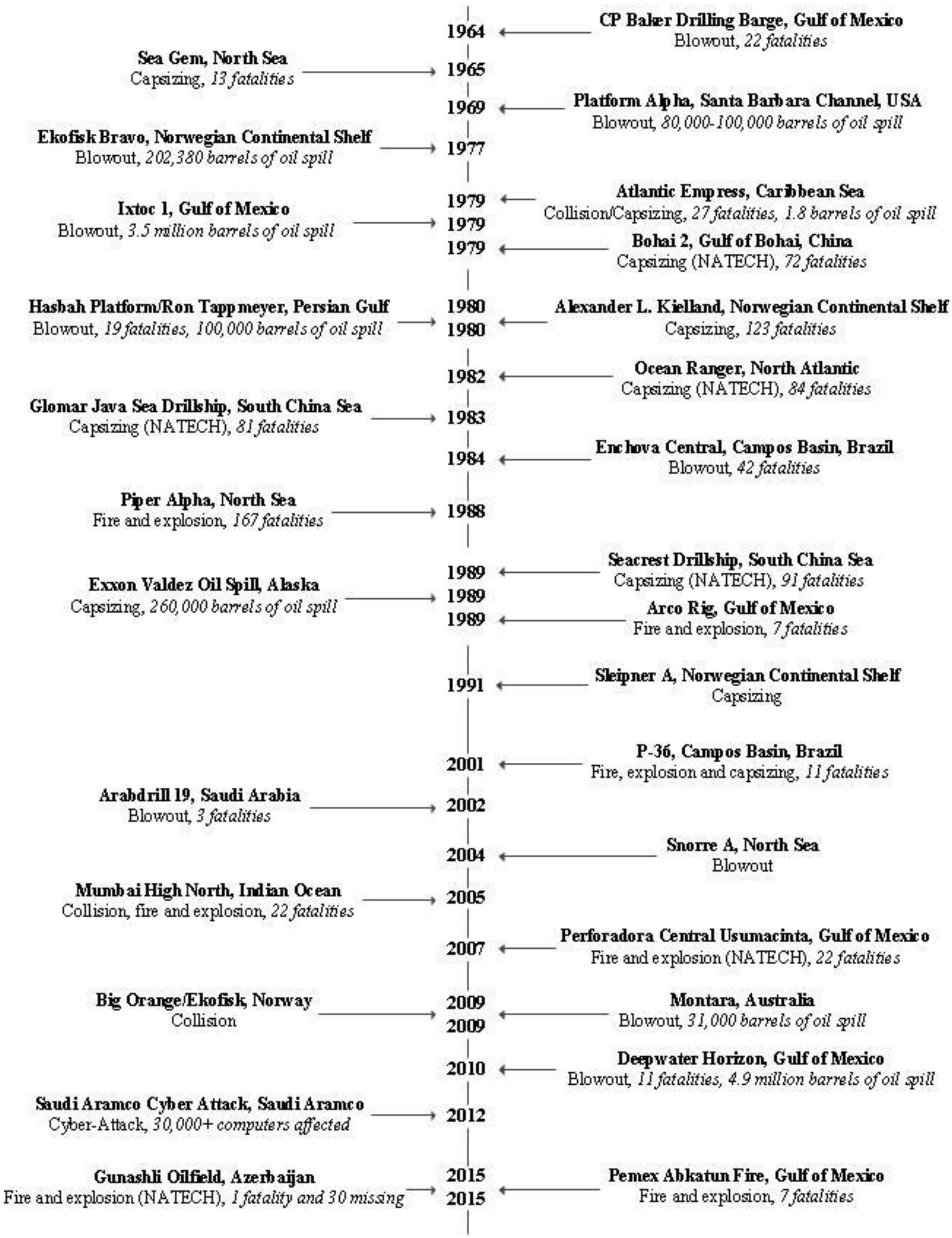

Figure 1 Notable offshore incidents from 1964-present

Incident Analysis

Loss of Well Control

CP Baker Drilling Barge, Gulf of Mexico, 1964

One of the earliest offshore blowouts occurred on June 29, 1964 in the US Gulf of Mexico. The crew of the C.P. Baker was drilling a 10,000 foot well in the Eugene Island Area. While preparing to run the conductor casing, bubble around the vessel was noticed at around 3 am in the morning. Water burst up and engulfed the vessel by entering through open doors at the main deck. Before responding to the emergency, an explosion occurred and the fire encompassed the whole vessel. The boat sank within 30 minutes. Reservoir fluids continued to erupt for the following 13 hours. 8 people died and another 13 went missing, presumed dead, and another 22 people were injured among the 43 crews on board. One crew of M/V Delta Service was also got killed. As per investigation report, drilling hit an unprecedented high-pressure gas pocket and the influx could not be controlled since blowout prevention measures were not in place. [3]

Platform Alpha, Santa Barbara Channel, US, 1969

On January 28, 1969, a blowout occurred at the well number 21 under Platform A, located southeast of Santa Barbara, California. The rig was operated by the Union Oil Company and the incident initiated while drill pipe was being pulled out of the hole for changing the drill bits. It is believed that the well went to underbalance (failure to keep the hole full) causing reservoir fluids to enter the wellbore. An unsuccessful attempt of capping the well caused further increase of the wellbore pressure which ruptured the casing and cracked the seafloor. About 80,000 to 100,000 barrels of crude oil spilled over the next 10-day period. [4]

Ekofisk Bravo, Norwegian Continental Shelf, 1977

On April 22, 1977, an oil and gas blowout in the Norwegian Ekofisk field resulted in the first major oil spill in the North Sea. The blowout occurred during a workover operation while the production tubing was being pulled. The incident initiated due to the failure of the downhole safety valve. The Christmas tree valve assembly was removed prior to the job and the BOP was also not in place to prevent the blowout. However, major catastrophe was avoided by controlling the ignition sources and all of the 112 crew members were managed to evacuate the platform safely. The well was capped in 7 days, but by that time approximately 202,380 barrels of oil was spilled. [5]

Faults in the safety valve installation documents, lack of inspection, inadequate well control planning and misjudgment were believed to be the underlying causes of this incident. [6]

Ixtoc 1, Gulf of Mexico, 1979

On 3 June 1979, IXTOC I exploration well in the Gulf of Mexico experienced a major blowout which released an estimated 3.5 million barrels of oil into the sea. Reservoir fluids entered the wellbore due to a loss of mud circulation while drilling. In attempt to plug the well, drilling assembly was being pulled, but the reservoir fluid flowed to the surface due to insufficient hydrostatic head. The BOP failed to seal the well as it was closed with the thick drill collars inside the assembly, which could not be cut. The oil and gas influx ignited at the surface causing massive explosion and fire. [7]

Hasbah Platform/Ron Tappmeyer, Persian Gulf, 1980

On October 2, 1980, a blowout occurred while drilling an exploratory well in the Hasbah oil field in Gulf of Arabia. The drilling hit a pocket of hydrogen sulphide gas which initiated the blowout event. 19 crew of Ron Tappmeyer Dillship were died and approximately 100,000 barrels of oil was spilled into the ocean. The well control and blowout response got complicated due to release of hydrogen sulphide gas, and it took 8 days to cap the well. [8]

Enchova Central, Campos Basin, Brazil, 1984

Two major incidents occurred at the Enchova Central platform, located in the Campos Basin and operated by Petrobras. On 16 August 1984, a blowout occurred which caused massive explosion and fire. During evacuating the platform, 42 crews were killed. 36 occupants of a lifeboat died due to a failure of lifeboats lowering mechanism. 6 people died while attempting to evacuate the platform by jumping into the sea.

On 24 April 1988, a gas blowout occurred while workover operation which destructed the platform completely. The well was being converted from oil to gas while the blowout occurred and the crews failed to kill the well. Fortunately, no lives were lost. [9]

Arabdrill 19, Saudi Arabia, 2002

Arabdrill 19 was a jack-up rig in Saudi Arabia’s Khafji Field. On 30 September 2002, a leg of the rig buckled while being located over a production platform causing the AD19 to collapse. It is believed that the production tree of the platform was sheared, resulted in a blowout and fire. The blowout caused both the jack-up and the platform to sink and killed 3 people. [10] [11]

Snorre A, North Sea, 2004

On 28 November 2004, an uncontrolled well release occurred during a workover/recovery operation in Well P-31A on the Snorre A facility (SNA) in North Sea. The well was being prepared for drilling a sidetrack, and a swabbing effect while pulling a ‘scabliner’ caused formation fluids to enter the wellbore. The scabliner was in place to cover-up casing damages from previous operations. High pressure gas started to flow through the holes of the damaged casing into the shallow formations and rose to the surface. However, the gas cloud did not ignite due to excellent ignition control and majority of the personnel evacuated the platform. The blowout was killed and the well was stabilized by pumping heavy mud on 29 November 2004. Petroleum Safety Authority (PSA) Norway identified this incident as one of the most serious events to occur on the Norwegian shelf, because of its damaging potential. And also, for a series of comprehensive failure in well control planning and inadequate barrier management. Failure to comply with procedures, lack of risk assessments, violation of well barrier requirements and failure to involve competent personnel in critical decision making were among some of the major root causes of this incident. [12]

Montara, Australia, 2009

On August 21, 2009, H1 well of the Montara Wellhead Platform in the Timor Sea, Australia, experienced a catastrophic blowout during completion process. The well was temporarily shutdown with seemingly three barriers - cemented casing shoe, pressure containing anti-corrosion caps (PCCC) and overbalanced well fluid. But all the barriers failed to stop hydrocarbon influx from the well as they were not properly designed or installed. Pressure containing anti-corrosion caps (PCCC) are not designed to be a well control barrier, but these were considered as independent barriers for preventing influx. Again, pressure test indicated potential failure in cemented casing shoe which was ignored. And the density of the overbalanced fluid was not sufficient for providing enough hydrostatic head to prevent influx. The influx could not be controlled and the blowout resulted in an estimated 31,000 bbl of oil spill [13]. Inadequate barrier management system, failure to follow sensible well control practices, inadequate risk assessment after changes in plan, failure to implement Management of Change (MOC) practices and ineffective inspection program were the major underlying causes of the incident. Also, carefully designed process safety leading indicators program could have identified potential weaknesses in the barrier system, which was absent in this case. [14]

Deepwater Horizon, Gulf of Mexico, 2010

On 20 April 2010, United States experienced one of the most catastrophic blowouts in the history which killed 11 people, injured 17 and spilled approximately 4.9 million barrels of oil spill into the Gulf of Mexico [15]. The blowout occurred during the completion of an exploratory well in the Macondo Prospect in Mississippi Canyon Block 252 of the Gulf of Mexico. The blowout preventer (BOP) failed to prevent the influx due to multiple factors including wiring failure and off-centered drill pipe. The influx initiated from a cement failure which was then escalated to a catastrophic blowout due to a series of technical and operational failures, which can be traced back to failure of several organizational components. As per reports, cement integrity test clearly indicated potential leakage but the results were misinterpreted. Also, a number of other kick indicators were also overlooked, which could have provided valuable time to control the kick and prevent the blowout. Lack of thorough risk assessment after changes in well design and procedures, inadequate cement testing and result interpretation, lack of understanding the physics controlling conditions at the well site, poor operational decision making, lack of training and supervision on critical operations and improper testing of critical equipment and overall lack of organizational safety culture and communication were identified as the major underlying causes of the incident. [16]

Fire and Explosion

Piper Alpha, North Sea, 1988

On July 6, 1988, the Piper Alpha platform located in the North Sea, experienced a series of catastrophic explosions and fires. Light hydrocarbon released and ignited initiating a chain of catastrophic events, when a condensate transfer pump undergoing maintenance was started. The relief valve of the pump was taken out for maintenance and the open flange on the pump side was loosely closed with a blank which failed instantly. Oil lines were ruptured from initial explosion and the fire were continuously fueled by the flow of inter-platform pipelines. A series of explosions destroyed the platform completely and 167 people lost their lives. Poor plant design, inadequate fire and explosion protection system, faulty permit-to-work system, communication failure in all levels, ineffective maintenance management and poor emergency management were identified as the root causes of this catastrophic incident. [17]

Arco Rig, Gulf of Mexico, 1989

On March 19, 1989, a major explosion and fire occurred on ARCO's Platform B in the block South Pass 60 in Gulf of Mexico. Contractors were conducting cold-cutting operations on 18-inch riser pipe to install a pig trap, when fluids started to come out of the riser pipe. Within a few minutes the fluid got ignited and the fire spread to the production and drilling decks. Seven people died and 10 others got injured. The investigation reports suggested that undulations in the pipeline prevented it from completely being flooded with water for removing hydrocarbons. Inadequate job planning and preparation and lack of oversight over contractor activities were believed to be some of the major root causes of the incident. [18]

Pemex Abkatun Fire, Gulf of Mexico, 2015

On April 1, 2015, a serious fire broke out in the Abkatun platform in Gulf of Mexico, operated by PEMEX. The initial explosion was caused due to leak for a rarely used fuel gas line. The gas line was believed to be suffered from microbially induced corrosion, which is often challenging to detect. 4 workers were reported dead immediately, 3 workers went missing and another 16 were injured. [19]

Collisions and Capsizing

Sea Gem, North Sea, 1965

Sea Gem was Britain's first offshore drilling platform which capsized on 27 December 1965 while lowering the rig onto the surface of the water. It is believed that, the rig fell sideways due to potential failure of two of the rig's ten legs due to metal fatigue in part of the suspension system. 13 people lost their lives due to this collapse. Cyclic loading due to environmental forces and vibrations could be the potential causes of metal fatigue that were responsible for failure of suspension system linking the hull to the legs. [24]

Atlantic Empress, 1979

On July 19, 1979, two tankers the Atlantic Empress and the Aegean Captain, carrying about 276,000 tons and 201,000 tons of crude oil, collided in the Caribbean Sea. A series of explosions followed by large fire damaged both of the tankers. The Empress sank into the ocean after burning for about two weeks. 26 crews from the Empress and 1 crew from the Captain lost their lives. Approximately 1.8 million barrels of oil was spilled to the ocean from the Empress. It is believed that the Empress was thrown off course by a heavy thunderstorm which made a path to collision. [20]

Alexander L. Kielland, Norwegian Continental Shelf, 1980

Alexander L. Kielland, an accommodation rig being attached to a drilling platform, capsized on 27th March 1980 on the Ekofisk field in the North Sea. During stormy weather, one of the five legs of the rig separated from the rest of the structure which caused severe listing. Within 20 minutes, the rig capsized completely and 123 people got killed. The failure initiated with a fatigue fracture of one of the leg bracings and due to overloading the remaining 5 bracings connecting the leg with the platform failed in a succession. Incident investigation revealed that the bracing contained cracks probably since the commissioning of the platform, due to poor welding, which developed over time. The emergency response system and evacuation procedure had severe shortcomings and only one lifeboat could be launched successfully. Only 89 people could be saved out of 212 people on-board. [25]

Exxon Valdez oil spill, Alaska, 1989

On March 24, 1989, Exxon Valdez oil tanker struck Bligh Reef in Alaska's Prince William Sound, resulting in a spill of nearly 11 million gallons of crude oil [26]. It is believed that the crews failed to navigate and maneuver the vessel properly due to excessive fatigue. Improper crew resource management, impaired decisions due to fatigue and ineffective vessel traffic system were found to be the major underlying causes of the incident.

Sleipner A, Norwegian Continental Shelf, 1991

The Sleipner A platform was a Condeep type platform with a concrete gravity base structure with four cells elongated to shafts supporting the platform deck. On 23 August 1991, during a controlled ballasting operation a cell wall failed resulting in serious cracks and leakage which caused the platform to sink.

As per incident investigation, the cell wall failed due inaccurate finite element analysis of the linear elastic model of the tricell [27]. Inadequate risk analysis during design stage led to an underestimation of shear stresses by 47% which caused this catastrophic failure. The total economic loss was estimated to be $700 million.

P-36, Campos Basin, Brazil, 2001

On 15 March 2001, The Petrobras Platform 36 (P-36) in the Roncador field, Campos Basin, Brazil, experienced a massive explosion and capsized after 5 days. The drilling platform was supported by two pontoons and four support columns. Volatile fluids passed through a supposedly isolated emergency drain tank (EDT) valve which ignited causing rupture of an adjacent seater service pipe. A subsequent explosion killed 11 crews of the emergency response team. The support column was flooded and situation was made worse due to a failure of a valve in the open position, which allowed uncontrolled flow of water into the column and pontoon. It is believed that closely placed critical equipment and subsystems caused rapid escalation of the events which eventually costed the entire $496 million oil rig. Poor design and placement of critical equipment, alarm flooding, lack of training and communication failure are believed to be the major root causes of this incident [28]. Also, the incident initiated due to a gas leakage from contaminated water which was stored inside emergency drain tanks. Storing large quantity of contaminated water for a long time was not in compliance with the company's procedure.

Mumbai High North, Indian Ocean, 2005

On July 27, 2005, a multi-purpose support vessel collided with the Mumbai High North platform, while attempting to transfer an injured person for medical treatment using a crane lift. Strong waves caused the helideck of MSV to strike gas risers at MHN and severe at least one. Leaked gas got ignited causing explosion and fire. Additional gas risers failed as they were placed very closed to each other without any fire/explosion barriers in between. Within 2 hours the MHN platform got completely destroyed and 22 personnel were reported to be dead. Lack of regulatory oversight, failure to assess risk and inadequate collision avoidance practices were identified as some of the major contributing factors of the incident. [21]

Perforadora Central Usumacinta, Gulf of Mexico, 2007

On October 23rd, 2007, the cantilever deck of a jack-up rig Usumacinta collided with the top of the production valve tree of the nearby Kab-101 platform due to strong wind. The tree valves were damaged causing gas leakage which resulted in two fire events, and 22 people were killed. It is believed that the horizontal motion of the platforms due to heavy wind and wave was misjudged and a delayed evacuation order caused the large number of fatalities. [22]

Big Orange/Ekofisk, Norway, 2009

On June 8th, 2009, Big Orange XVIII, a well stimulation vessel, collided with the Ekofisk water injection platform at the North Sea and caused major damage to the installations. The incident was caused due to major operational failures as the autopilot on Big Orange was not deactivated causing no response to course alterations input to the vessel's control system. On the other hand, Ekofisk radar operators failed to monitor vessel movement in the exclusion zone and did not issue timely warning. Two deficiencies related to the regulatory requirements were reported by PSA investigation – inadequate provisions for monitoring vessels inside exclusion zone and failure to implement recommendations from past incident (Ocean Carrier collision, 2005). The operators also failed to comply with internal policies and requirements. [23]

Natural Hazard Triggering Technological Disasters (NaTech)

Bohai 2, Gulf of Bohai, China, 1979

On 25 November 1979, Bohai number 2 oil rig sank in the Gulf of Bohai between China and Korea resulting 72 deaths. The rig was towed when it encountered a heavy storm. A ventilator pump broke free by heavy waves which hit and punctured a one-meter hole in the deck. The rig became unstable due to excessive flooding, capsized and eventually sank. Failure to secure deck equipment and failure to follow standard tow procedure during inclement weather were the major causes of the incident. Lack of knowledge and training on emergency response was also identified as one of the major causal factors for the fatalities. [29]

Ocean Ranger, North Atlantic, 1982

Ocean Ranger was a semi-submersible mobile drilling unit which sank on 15th of February 1982 in Canadian Waters. During a heavy storm, windows in the ballast control room were shattered by a wave and power to the control panel was lost. Crews suspected spurious operations of the ballast valves and cut electrical power to close the valve to stop influx of seawater. After a few hours power to the console was restored due to unknown reason which allowed the pontoon valves to open causing seawater to flood the ballast tank and platform started to tilt. The crews were not trained enough to deploy necessary techniques to pump water out of the tank. Mis-operation by the crew members caused the valves to be set in the open position causing the rig to tilt further, which eventually capsized by heavy waves. All of the 84 crews apparently evacuated, but could not survive and presumed to be dead [30]. Investigation report identified design flaws, inadequate emergency procedures and lack of training and experience to be the major underlying causes of this incident.

Glomar Java Sea Drillship, South China Sea, 1983

An US drill ship, Glomar Java Sea, capsized in South China sea on 25th of October 1983 during a tropical storm. Shifting of vessel's cargo and loss of vessel's watertight integrity caused the vessel to tilt by losing stability and eventually severe weather conditions led to sinking of the vessel. Failure to respond to the initial tilt due to incompetency was also identified as one of the major causes of the incident. 36 bodies were found and 31 were recovered, and the remaining of 45 personnel were missing and presumed to be dead. [31]

Seacrest Drillship, South China Sea, 1989

On 3rd of November 1989, drillship Seacrest sank due to Typhoon Gay in the south China Sea and 91 crew members were killed. Incident investigation revealed potential erroneous wind overturning moment calculations by the shipbuilder. Also, preparation and response to extreme weather condition were found to be inadequate. [32]

Gunashli Oilfield, Azerbaijan, 2015

On 4 December 2015, a high-pressure subsea gas pipeline in the Gunashli oilfield damaged in a heavy storm resulting in a deadly fire. Fire spread over adjacent oil and gas wells. Initial reports indicated 1 fatality and 30 workers missing after the incident. [33]

Cyber-Attacks

Saudi Aramco Cyber Attack, Saudi Arabia, 2012

On August 15, 2012, Saudi Aramco suffered one of the largest cyber-attacks in the oil and gas industry till date. A computer virus/malware named 'Shamoon' affected over 30,000 computers, disabling several of the Aramco's internal networks for weeks and putting company's ability to produce and supply crude oil at risk [34]. A few weeks later, RasGas of Qatar was also reported to be affected by a similar cyber-attack.

Major Lessons Learned

Improve kick detection and kick control efficiency

Kicks are early indicators of blowouts and early kick detection is undoubtedly one of the most important factors in major incident prevention. Conventionally, kicks are detected with the changes of some real-time process parameters (for example, flow differential, pit volume), which are susceptible to misjudgment due to operational complexity, process disturbances or incompetency. Limitations of the conventional methodologies in kick detection was evident in the Deepwater Horizon blowout incident (2010). Managed pressure drilling (MPD) is a closed-loop pressurized drilling technique which offers better kick detection and control efficiency compared to the conventional process. MPD is gaining popularity due its ability to detect small influxes in both oil-based and water-based drilling muds, but the cost and lack of compatibility of MPD equipment with existing rigs have remained a major challenge. Kick detection efficiency can be improved by using Measurement While Drilling (MWD) techniques where downhole data are transmitted to the surface facility and can be analyzed. Some of the other notable techniques include using smart/wired drill pipe for fast data transmission, use of acoustic sonar to detect influxes, and application of machine learning tools to develop trends of expected mud flow behavior. But commercial implementation of many of these methodologies are still somewhat limited due to increased cost, lack of adaptability and increased complexities.

Focus on process safety leading indicators

Process safety leading indicators can provide critical information on barrier integrity and weaknesses in the risk control system prior to an incident. Tamim *et al.* (2017, 2019) [35] [36] proposed leading indicators framework for drilling and other well intervention operations and analyzed its applicability in predicting and preventing loss of well control events. Deepwater Horizon (2010) and Montara (2009) blowout events were analyzed, which indicated existence of multiple operational and organizational issues prior to the incidents. A robust leading indicators program could have provided crucial information on potential weaknesses in the well control barrier system for both of the incidents.

Conduct thorough job hazard analysis/risk assessment and re-evaluate after changes in plans/procedure

Inadequate risk assessment was identified as one of the major underlying causes for many of the incidents (for example, Platform Alpha oil spill in 1969, Ekofisk Bravo blowout in 1977, Arco rig explosion in 1989, Mumbai High North collision in 2005) analyzed in this article. The risk of sulphide gas release was not evaluated properly in Hasbah blowout in 1980, which complicated the emergency response and evacuation procedure resulting in 19 fatalities. In 2003, a similar hydrogen sulphide containing gas blowout which in 243 deaths, 1242 hospitalizations and 65,000 evacuations in Gaoqiao township, Chongqing, China [37] (this incident was not included in this analysis as the primary focus of the work was on offshore incidents).

Failure to assess hazards and risk after changes in original plan and procedure was found to be critical for Deepwater Horizon (2010), Montara (2009) and Snorre A (2004) blowouts. In the case of Deepwater Horizon, less centralizers were installed than originally planned for. This change potentially contributed towards buckling of the off-centered drill pipe when blowout preventer was activated. In Montara operations, multiple changes were made from the original well completion plan, including installation of the Pressure containing anti-corrosion caps (PCCC) instead of a recognized well control barrier. For Snorre A operations, perforation was done prior to pulling out the scabliner which exposed the damaged casing. Impacts of potential changes in plans were not analyzed for any of the cases. It is essential to incorporate process safety components while designing and drilling a well and manage integrity of well control barriers throughout the life cycle of the wells.

Incorporate process safety practices into engineering design phases

Inadequate or flawed design was identified as one of the major underlying causes for many of the incidents analyzed in this work. For example, in Ixtoc 1 blowout in 1979, the blowout preventer (BOP) failed to seal the well as the shear rams could not cut the heavy drill collar. Absence of blast walls in Piper Alpha platform is considered to be one of the major causes that escalated the event to a catastrophic one [41]. Inaccurate finite element analysis and inadequate risk analysis during design stage are believed to be the major causes of Sleipner A platform failure in 1991. Poor design of the pontoons and support columns of Petrobras's P-36 platform led to a common mode failure resulting in a capsizing in 2002. It is very important to conduct hazard analysis during design phases and make risk-based decisions while designing a plant, platform or process for preventing similar failures in the future. Tamim et al. (2017) [42] discussed approaches of integrating process safety components into engineering design phases effectively for preventing incidents.

Focus on human factors and human-centered design

Human factors were associated with many of the catastrophic incidents in the past. For example, impaired decision-making due to excessive fatigue was identified as one of the major causes of Exxon Valdez oil spill in 1989. Mis-operation in Ocean Ranger drilling unit (1982), lack of inter and intra-platform communication in Piper Alpha incident (1988), failure to monitor and identify collision risk in Big Orange-Ekofisk collision (2009) incident – all these indicate towards the critical need of focusing on human factors and understanding influencing factors that impact human performances. Lack of situational awareness was identified as one of the major causes of higher consequences in Platform Alpha blowout (1969), Ocean Ranger capsizing (1982), Glomar Java Sea Drillship capsizing (1983), P-36 capsizing (2002), Montara blowout (2009) and Deepwater Horizon blowout (2010). Work-related conditions, such as, stress, fatigue time-pressures, are believed to be the major causes of lack of situational awareness [38]. Thus, in risk assessment studies organizations need to review their working conditions and patterns that impact cognitive skills. It is crucial to design systems and processes considering human characteristics, abilities, and limitations for preventing errors or mishaps. Managing a flood of information and alarms for drillers and operators during an emergency is another critical area to be focused on.

Establish robust maintenance and inspection programs

Robust maintenance, effective function tests and quality inspection programs are essential for preventing mechanical and equipment failure. Crack in one of the bracings of Alexander L. Kielland rig's leg went unnoticed which eventually caused the total rig to collapse in 1980. Inadequate function test of the Blowout Preventer (BOP) was identified as one of the major causes of BOP failure in Deepwater Horizon blowout [39]. Lack of corrosion management program led major incidents in the past as well, including hydrocarbon release and fire at Pemex's Abkatun platform in 2015 which was initiated from a piping failure due to microbially induced corrosion. Understanding different corrosion mechanism in marine environments and effectively monitoring remote platforms and the vast networks of pipeline for corrosion have still remained a major challenge in the industry.

Focus on developing process safety competency

Process safety knowledge and competency is essential for designing, constructing, operating, maintaining processes safely and efficiently. It is equally important for minimizing blowout risks while drilling, completing, operating, servicing and abandoning wells. Failure in recognizing hazards and understanding risk were among the major causes of most of the incidents discussed in this article. Contractors play a very crucial role in all of these phases and it is essential for both the operators and contractors to have process safety knowledge and understanding. Owners and contractors need to have a harmonized approach to incorporate process safety practices in every aspects of a project's lifecycle to ensure safer and reliable performance. Lack of oversight in contractors' activity (Arco rig explosion, 1989) and inadequate communication between operators and contractors (Deepwater horizon blowout, 2010) over safety critical issues were some of the underlying causes.

Identify best practices in emergency management and incorporate learnings from the past events

Emergency response and planning can be very challenging in offshore operations due to multiple factors including harsh environments, remoteness, complexity of operations and resource limitations. Different facets of the emergency management system have failed in the past resulting in hundreds of fatalities and millions of dollars of losses. For example – failure to correctly respond to a well release scenario in Platform Alpha (Sant Barbara, 1969) spill, emergency equipment (lifeboat) failure in Enchova Central Platform (1984), inadequate emergency response and evacuation procedure in Alexander L. Kielland capsizing (1980) and Piper Alpha disaster (1988), delayed evacuation in Perforadora Central Usumacinta fire (2007). All these incidents provide great lessons and learnings in designing robust emergency management program for minimizing consequences of major incidents. Over the past couple of decades significant improvements have been made in emergency identification, notification and containment systems. Design of emergency equipment (lifeboats, respirators, survival kits) have also been improved in terms of quicker response and better efficiency.

It is important to learn from the mistakes in emergency response and planning from the past events, identify best practices in emergency preparedness, utilize latest technologies (for example, drone technology) in emergency response and improve competency of the emergency responders for developing a robust emergency management program.

Assess digital vulnerabilities and control cybersecurity risks

Oil and gas industries need to invest in minimizing their digital vulnerabilities and protecting their assets from cyber attacks similar to Saudi Aramco (2012) and RasGas (2012). A cyber attack can disrupt an ongoing operation and can have severe safety and production impacts. Lack of awareness and training, inadequate separation of data networks, use of standard products and software with known vulnerabilities in critical operations, use of outdated control systems in facilities with less security, excessive use of mobile devices and storage units for sensitive information are identified as some of the major vulnerabilities against cyber-attacks [40]. The industry needs to take this issue seriously and identify existing threats and vulnerabilities by conducting cybersecurity risk management. Over the past few years many works have been done to understand and manage the cybersecurity risk, but a continual effort needs to be in place to protect critical infrastructures and assets from increasing cyber threats.

Conduct NaTech risk analysis and vulnerability assessment

Offshore operations and establishments have been catastrophically affected by heavy storms, cyclones, harsh weathers over the past few decades. Inadequate planning, lack of emergency preparedness and training have contributed towards capsizing and loss of Bohai 2 rig (1979), Ocean Ranger platforms (1982), Glomar Java Drillship (1983) and Seacrest Drillship (1989). Inadequate NaTech risk assessment while designing was identified as one of the major root causes of many incidents in the past including Perforadora Central Usumacinta fire and Gunashli Oilfield fire and explosion. Technological advancements have made weather forecasting and monitoring better, allowing more time in emergency planning and response. But consequences of the events are often underestimated in the past, and researchers have suggested that strong surge during storm and wave elevations are underrepresented in engineering studies [43]. Causes and dynamics of NaTech incidents need to be analyzed carefully to develop specific scenarios for better emergency management. Thorough risk assessment needs to be conducted for identifying vulnerabilities and potential failure modes and protective and mitigation systems need to be designed and implemented accordingly.

Challenges and Future Directions

Powered by technological advancements, offshore operations are hitting new frontiers and undertaking newer challenges with the growing demand of energy. Presently, offshore operations are moving towards ultra-deepwater and unconventional resources where high pressure high temperature (HPHT) conditions and complex reservoirs are among some of the major challenges to be handled. For instance, thicker walls for equipment and riser assembly may need to be designed for handling HPHT streams safely, but this would create a new challenge by increasing the total weight of the system. Researchers are working for developing high-strength corrosion-resistant advanced materials suitable to HPHT conditions. Geological uncertainties and structural complexity are some of the major challenges to be overcome for producing hydrocarbons from unconventional resources. Also achieving effective zonal isolation, real-time evaluation of cements, detecting well influxes early are among some of the major areas to be focused on. Subsea operations are also gaining momentum and equipment are being designed and tested for subsea services, which require less maintenance even in extreme conditions. Cutting-edge technologies, for example, drone, augmented reality, are also being considered for improving leak detection capabilities and conducting inspection operations. But, parallel to utilizing high-tech devices and advanced automation techniques, human factors components need to be carefully assessed and integrated with the system for minimizing potential for errors and misjudgment. Thorough studies need to be conducted to fully understand how cognitive skills are impacted by different working conditions for minimizing stress, fatigue and similar factors that can impair awareness and judgement.

Conclusions

Offshore operations are associated with a number of hazards that have caused catastrophic disasters in the past. These hazards can be managed and incidents can be prevented by carefully assessing the jobs and processes, evaluating associated risks, assessing potential emergency scenarios, implementing risk control measures/barriers, maintaining integrity of the barriers, managing changes, providing appropriate training to the workers and learning from near-misses and incidents for continual improvement. A total of ten lessons have been identified which can be learned from different categories of offshore incidents analyzed in this article. Safety performances and emergency management procedures for different offshore operations (for example, exploration, production, transportation) can be significantly improved by incorporating these lessons into existing systems.

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