

STRETCH IN TECHNOLOGY AND KEEPING THE FOCUS ON PROCESS SAFETY FOR EXPLORATION AND PRODUCTION IN THE 21st CENTURY

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Oil and gas are contributing enormously to the quality of our life into the 21st century, just as they were throughout the 20th century. With the economy developing forward, more and more energy sources are required by our society, and in the last several decades people have switched to offshore deepwater hydrocarbon reservoirs. Besides politics, current exploration and production are limited by the technology, which may lie in deeper wells, higher pressure reservoirs, or crudes which are difficult to recover because of higher viscosity.

Innovative offshore technology needs to be developed to carry out deepwater production and operations. At the same time, these hazardous operations (*i.e.*, deeper wells and higher pressure reservoirs) are creating new and unique hazards. Along with the current attention from Transocean Deepwater Horizon Incident and Oil Spill in Gulf of Mexico, the development of advanced technologies to ensure the process safety and operational reliability of offshore facilities is becoming extremely important.

Currently, we face the challenge of how to prevent or control hazards of deepwater exploration and production. Process safety is always an essential part of the oil and gas industry and a core value that needs continual improvement. In this work, a variety of ideas, including inherent safety design and human factor, are proposed to improve offshore process safety, protect workers and the environment. Regulations should be dynamic and ready to be modified based on occurring industrial issues. Accordingly, the government and offshore operators should develop comprehensive management programs to assess process safety and environmental hazards.

INTRODUCTION

Most recently, more and more energy sources are required by our society and people have relied much on offshore deepwater hydrocarbon reservoirs. Deepwater reserves are estimated to amount to around 65 Gbbl of oil equivalent worldwide. Besides politics, current exploration and production are limited by the technology, which may lie in deeper wells, higher pressure reservoirs, or crudes which are difficult to recover because of higher viscosity. The hazardous operations (*i.e.*, deeper wells and higher pressure reservoirs) are creating new and unique hazards, which make the offshore process safety and operational reliability of offshore facilities extremely important. In recent years companies have realized that achieving operational goals safely depends on both technology developments and research.

It is well known that offshore operations have a very special environment, involving drilling, production, transport, as well as emergency response to incidents. Offshore employees are faced with many different factors that increase their exposure to injury, such as poor weather conditions, high pressure operations, chemicals, and confined space. Due to these dangerous natures of offshore operations, employees typically have very demanding work schedules. A thorough risk assessment and HAZOP have to be conducted for each offshore facility. However, with deeper wells and higher pressure reservoirs, more unique hazards are present with offshore facilities. Therefore, some measurements have to be proposed or considered to make sure all offshore workers are safe during exploration and production activities. The three most important concepts are summarized in this work, including inherently safer design, human factor, and regulation improvement. Also much needed are research and technology development for operation in deep waters and high pressure reservoirs. In this paper, we will focus on these issues and elucidate how to integrate them more effectively into offshore process safety.

HAZARDS IN OFFSHORE OPERATIONS

In the past few decades, more and more offshore plants have been built to meet the quickly increased energy demand. However, due to the complexity in exploration, drilling and production for deep-water plants, unique hazards may occur in these processes.

Hazard identification (HAZID) is the first step of HAZOP analysis. Complete HAZID results will facilitate the LOPA and bow-tie analysis for offshore plants. The risks in offshore operations are mainly focused in blowout, riser and pipeline leakage, process system leakage, structural corrosion and failure, fire and explosion, collision, extreme environment factors, human and other factors.

1. Blowout
   a. BOP failure
   b. Oil nuzzle/hose rapture

   c. Failure of diverter
   d. Failure of riser adapter
   e. Washout of valve
2. Leakage (riser and pipeline)
   a. Slurry vessel
   b. Slurry metric vessel
   c. Liquid seal of slurry metric vessel
   d. BOP
   e. Hose of hydraulic pressure system
   f. Valve, oil nuzzle, riser pipe
   g. High hydraulic pressure system
3. Leakage (process system)
   a. Gas handling process
4. Fire or explosion
   a. Pool fire (on the platform or in sea, crude oil or crude product)
   b. Jet fire (leakage of high pressure equipment, gas, liquid or aerosol)
   c. Flash fire
   d. Vapour explosion
5. Structural failure
   a. Failure/fall-off
   b. Structural fatigue due to long-term service
   c. Vibration fatigue of pipeline
6. Collision
   a. Lift/down of BOP
   b. Lift/down of diverter
   c. Movement of deck cover
   d. Collision of oil tanker, supply ship, fishing ship, warship(submarine) and other ships or supply helicopter with the platform
7. Corrosion
8. Environment factor
   a. Extreme weather such as strong wave, cyclone
   b. Earthquake
9. Human factor
   a. Fall-off/slip-up/trip-over
   b. Human error
10. Other factors
   a. Vibration of slurry pump
   b. High voltage of electric switches
11. Transportation
   a. Fire
   b. Leakage
      i. crude oil/LNG leak into void
   c. Structural failure
      i. failure of bulkheads and venting
      ii. structural failure to center cargo tank support
      iii. collapse/displacement of center cargo tank
      iv. failure of center cargo tank
   d. Collision
      i. supply ship, fishing ship, submarine and other ships
      ii. helicopter
   e. Bad weather
      i. Sinking

There are other hazards with regard to control systems for drilling and the process of drilling liquid (slurry) preparation. The pressure control for drilling slurry is very important to safe production. So the stability of the control system may be important. Moreover, the quality of the drilling liquid is critical to production, however the process of drilling liquid preparation is complex, usually including much rotary equipment, *e.g.*, liquid-gas separator, vibrating screen, desander, hydrocyclone, mixer, jet slurry pump, slurry pump.

OFFSHORE INHERENT SAFETY

The idea of reducing rather than controlling hazards was firstly proposed by Kletz[1] in the late 70's and expanded in a book titled, "Cheaper, Safer Plants or Wealth and Safety at Work: Notes on Inherently Safer and Simpler Plants".[2] The concept of inherent safety is particularly used in the chemical process industries and was officially developed in 1991 with slightly different words from those of Kletz.[3] Inherent safety design includes four main methods to reduce hazards in the process: minimize, substitute, moderate, and simplify.[4] Inherent safety has been recognized as a desirable principle by several authorities, including the US Nuclear Regulatory Commission and the UK Health and Safety Executive (HSE) and adopted by industries. The idea of inherent safety can be incorporated at any stage of design and operation; however, its application at the earliest possible stages of process design (such as process selection and conceptual design) yields the best results, which is consistent with the idea of safety through design.[5] There is extensive literature regarding inherent safety from Kletz,[1] Hendershot,[6] Mansfield,[7] Medonos and so on.[8]

Recently, the inherent safety approach has been proposed as one of the options for risk management in offshore oil and gas activities.[9] However, unlike methods of HAZOP and quantitative risk assessment, inherent safety is only applied to some parts of offshore process design and operations so far. The objective in achieving inherent safety in offshore operations is to eliminate hazards caused by high pressure operations with oil and gas. Elimination of hazards on an offshore facility is difficult because most of the hazards are directly related to the function of the facility.[8] Previous research have shown that process and structural failure incidents account for almost 70% of incidents in offshore facilities.[10]

The application of inherent safety of offshore operation could focus on following parts. First, according to the concept, the most promising idea is to reduce the fire/explosion hazards presented during oil and gas separations. Therefore, advanced subsea multiphase pumping systems might be developed and transport the oils and gases directly to onshore, rather than separating them on the offshore platform and then transport pure oil to onshore. This idea can eliminate lots of hazards using better process design and separation of the mixtures onshore. Second, keeping the process and drilling equipment simple could save more space and weight of the platform based on the concept of minimization. Third, more stable and resistant structures could be designed to adjust to poor environmental conditions. Stable structure can reduce the damage from severe weather conditions, such as hurricane. Fourth, the location of accommodation modules with good design of egress can provide better emergency responses.

A 1999 report from the government's Minerals Management Service (MMS), leaked by Democratic Senator Maria Cantwell of Washington, found that there were 117 BOP failures in a two-year period in the late 1990s. Finally, with deeper well reservoir and higher pressure during drilling process, more reliable blowout preventer (BOP) or the backup system for pressure control could reduce the potential hazards of fire and explosions. These are some ideas proposed based on the principles of inherent safety but there are still lots of thoughts not covered in this section. For example, in the last decades a remotely operated vehicle (ROV) was designed and used commonly in deepwater exploration and production. The using of ROV could significantly reduce the hazards especially in deepwater environment where it is hard for humans to approach.

Currently the main problem is the lack of awareness and understanding of inherent safety by designers and project leaders. If project leaders or managers can apply inherent safety at the very beginning stage of the project, this approach is worthwhile pursuing.

HUMAN FACTORS IN OFFSHORE SAFETY

It has been indicated that human factors have significant influence on offshore process safety. Detailed analyses of the causes of incidents involving offshore structures indicates clearly that only a small percentage of the incidents are caused by failures of the structures, which means most incidents (~80%) are actually caused by unanticipated actions of human during installations, operations, and maintenance.[11] Therefore, integrating explicit considerations of human factors into design of new systems or operation of existing systems is very critical in offshore installation and production.

There are several ideas related with human factor studies in the offshore safety. It is well known that there is a wealth of existing case histories, technologies, and experience. The challenge is how we can learn and understand these incidents and then to apply the knowledge wisely to future offshore operations. Also, studies of human behavior in complex systems might be able to get major improvements in the process safety and reliability of offshore platforms.

It is very important to recognize that by some estimates human errors are a contributing factor in more than 80% of offshore incidents.[10] It is also important to be able to execute an effective emergency response plan when incidents do occur. If the situation can be quickly and correctly identified, there will be more opportunity and time to bring it under control.[12] In addition, selection and training of personnel are critically important in building effective process safety systems.[13]

OFFSHORE REGULATIONS AND STANDARDS

Offshore exploration and production are very impacted by a significant body of laws, regulations, and standards. Laws are usually created through an act of congress and provide broad goals and objectives. Regulations are created by federal or state agencies as a method of providing guidelines for complying with a law. Standards are normally developed through professional organizations to improve the individual quality of a product or system. There are several agencies that cover regulations and safety standards related with hazardous operations including OSHA, EPA, and API and so on. Here we summarize some regulations, standards, and codes and their relevance with regard to offshore safety.

The Process Safety Management (PSM) standard (29 CFR 1910.119) was promulgated by the Occupational Health and Safety Administration in 1992.[14] Process Safety Management is a holistic program aimed at preventing releases of any substance defined as a "Highly Hazardous Chemicals". However, oil and gas well drilling and servicing operations and operations in the Outer Continental Shelf are exempt from the process safety management standard. Beyond the extraction of water, any processing involving 10,000 pounds or greater amounts of flammable liquids or gases at an offshore facility is covered. Either the federal PSM standard or a State's PSM standard would be enforced when applicable at these offshore production facilities. The U.S. Coast Guard, the Department of the Interior (Minerals Management Service), and OSHA are responsible to promulgate regulations to address hazardous working conditions with respect to offshore oil and gas operations.

The rules of Oil Pollution Prevention by EPA are under the Clean Water Act for transportation related onshore and offshore facilities.[15] This requirement applies to all offshore facilities and any onshore facility that, "because of its location, could reasonably be expected to cause substantial harm to the environment by discharging into or on the navigable waters, adjoining shorelines, or the exclusive economic zone."

API developed a series of recommended practices especially covering safety and fire protection in offshore exploration and production.[16] For instance, RP 49, Recommended Practice for Drilling and Well Servicing Operations Involving Hydrogen Sulfide; RP 54, Occupational Safety for Oil and Gas Well Drilling and Servicing Operations; RP 75, Development of a Safety and Environmental Management Program for Offshore Operations and Facilities; RP 76, Contractor Safety Management for Oil and Gas Drilling and Production Operations. Especially RP 75 could be applied to assist in development of a management program designed to promote safety and environmental protection during the performance of offshore operations.

There are two types of regulations: prescriptive and performance-based. Prescriptive regulations specify rules that must be explicitly followed, while performance-based regulations specify objectives but allow flexibility in the technology and approaches used to meet these objectives. Current US regulations are a combination of both measures. However, some countries, such as UK and Norway, are moving toward more performance-based regulations. The systematic studies on these regulations could help to find the possible gaps. It is recommended that modification or revision of those regulations could help to develop better systems for continuous improvement of safety and environmental practices.

Regulations and standards are dynamic and need to be improved regularly according to the industry performance. For example, following the Deepwater Horizon oil rig incident, questions have arisen over the Mineral Management Service regulations regarding reliable back-up systems for BOP to cap underwater wells. Oil-drilling safety equipment may not function in a deep-water environment. Currently, Norway and Brazil require the devices, so-called "acoustic switches", but the United States does not. Therefore, the modification of regulations on backup systems of BOP would be recommended.

RESEARCH NEEDS

There are significant challenges and technology gaps with regard to offshore operations that require immediate attention. There is a need to develop theories, analytical techniques, and technology to improve the current offshore infrastructures from all sources of failure including, design, operations, management, natural disasters, and intentional acts such as terrorism. The research should focus upon developing theories and techniques that apply to many types of process safety issues faced by the offshore industries such as structural integrity, layers of protection, off-gas handling, drilling, risk assessment and consequence analysis, human error and safety culture. Test beds may include processing facilities and complex structures within the offshore infrastructure, transportation vehicles (*e.g.*, ship, helicopter), and the marine environment.

The goals of this research include integration of the concepts of process safety into the design and operation of offshore platforms and use this to improve their safety performance such that the unit/process is not vulnerable to certain failures. Another goal is to investigate the potential consequences of particular failures and mitigation of the consequences by proposing/identifying engineering solutions to improve safety performance. Also, by identifying aspects of the system that are vulnerable (not resilient), the speed and efficiency of response to failures could be improved. Some relevant areas of research include:

- **Structural integrity of risers/pipelines.** Risers and pipelines are subjected to different types of corrosion due to continuous loadings (fatigues) and their exposure to the marine environment. Research is needed to study the corrosion behavior underneath the coating layer to assess the integrity of particular structures and develop coating/corrosion assessment criteria for service under extreme conditions.
- **Pressure control.** As we know poor pressure control can cause major safety, quality, and productivity problems. High pressure inside a sealed system may cause a physical explosion or chemical release which will cause potential fires and explosions. As we mentioned before, in offshore exploration and production, now we face deeper wells and higher pressure reservoirs. Hence, it is highly desirable to keep pressure in good control and maintained within its safety limits. More research from pressure control, pressure reducing, pressure regulating, and pressure relief valves should be conducted.
- **Layers of protection.** Many US offshore rigs are equipped with blowout preventer (BOP) casing shear rams to seal off an oil or natural gas well being drilled or worked on. However, the BOP is currently the only layer of protection within the system and vulnerable to single-point failure. Research efforts are needed for developing/identifying multiple layers of protection, developing a comprehensive database that captures the operational performance of offshore rigs (through the collaboration with industry members), and risk-based inspection planning to minimize losses.
- **Risk assessment and consequence analysis using CFD.** Computational Fluid Dynamics (CFD) has gained widespread recognition as a powerful tool for risk assessment and consequence analysis. The very nature of infrequent and highly diverse disasters can make prediction of the likelihood and consequences of such events very difficult. The multitude of systems and structures involved requires a very broad multidisciplinary team to understand, evaluate, compare, and plan for disastrous failures. Research is needed with regard to fluid-structure interaction (vibrations of risers, motions of floating platforms), flow around vessel hulls in the presence of current and wind forces, wave loads (slam and impact), tank sloshing, BOP (impact) facility siting.
- **Recovery of H_2S.** H_2S (hydrogen sulphide) is corrosive for carbon steels used in offshore structures and can lead to nervous disorders and acid rain. To remove H_2S from the system, a process called gas sweetening and amine sweetening has been used for onshore processing facilities. This process removes H_2S from the feed stream and redirects it to other processes in the plant, where it is converted into elemental sulphur or sulphuric acid. However, the current process is limited by the operating conditions and requires additional units to be built, which makes it insufficient for the offshore facilities. Given the compact size of the offshore structures, there is a need to optimize the current gas recovery process for offshore processing facilities.
- **Resilient operation of deep-water drilling.** During drilling, all materials drilled out need to be removed,

i.e., transported to the surface, a process which is referred to as hole cleaning. Often, some of the material remains in the well. Due to the number of parameters influencing hole cleaning and the complex mechanisms involved, the phenomenon has not yet been fully understood. Integration of the concept of resilience to the drilling and whole cleaning processes is needed. This understanding will facilitate the development of methods to identify weaknesses of the current procedures.

- **Human error and safety culture.** Both human error and safety culture have been identified as contributing causes in industrial accidents, including offshore facilities. Assessment of the safety culture in every aspect of work in the organization and development of a systematic approach to apply safety culture in the organization will lead to reduction of human errors.
- **Clean-up spills.** Mechanical containment should be the primary line of defense against oil spills. Mechanical containment should be used to capture and store the spilled oil until it can be disposed of properly. However, this method is not effective in clearing a large spill area. Chemical and biological methods can be used in conjunction with mechanical means for containing and cleaning up oil spills. Dispersing agents are the most useful in helping to keep oil from reaching shorelines and other sensitive habitats. Biological agents have the potential to assist recovery in sensitive areas such as shorelines, marshes, and wetlands. In this regard research for new dispersants including nano-surfactant technologies to improve the oil spill cleanup is needed. Also needed are advanced technologies for the speedy recovery of oil spills that are mechanically contained.

SUMMARY

Deeper wells, higher pressure reservoirs, and crudes with higher viscosity have introduced hazardous operations in offshore facilities and hence creating new and unique hazards. The aim of introducing inherent safety concept and human factor is to encourage designers to integrate process safety with design and to tackle safety problems at the earliest and retrofit stages. Moreover, based on case studies and current incidents, regulations and standards should also be modified by government and provide better safety culture for exploration and production in the 21st century.

Efforts should be made to expanding the current focal point from that of drilling and utilization of BOPs to include a more encompassing proactive prevention program requirement for all offshore operations. There are numerous possible ways in which disasters equal or greater than Deepwater Horizon could occur in offshore operations. As such comprehensive programs that include inherent safety considerations, multiple layers of protection, consideration of human factors, analysis of worst-case scenarios and emergency response planning is needed. Finally, major efforts are needed to explore new technology developments in various areas.

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