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A guide to the equipment, methods and procedures for the prevention of risks, emergency response and mitigation of the consequences of accidents: Part I

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Foreword

This report is the first part of a dilogy which aims to be a compendium for regulators without a specific background in risk and safety assessment. It describes the state-of-the-art of the safety-related equipment, methods, procedures and projects available nowadays for the prevention of risks, the emergency response and the mitigation of the consequences of accidents.

While the present report addresses the above topics from a generic perspective, the second part, currently in preparation, focuses on the particular challenges of the Nordic Seas.

The review is based on the retrieval and analysis of a large number of open source information, along with personal contacts with Authorities and HSE representatives of several major oil and gas operators. This helps the reader go into further details and better appreciate the latest technological advancements in offshore safety as a consequence of the lessons learnt from the Macondo Accident.

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1 Introduction

After the Deepwater Horizon blowout (DHB) on 20th April 2010, which represents one of the major environmental disasters in the offshore history, stakeholders globally raised awareness of safety in offshore drilling and production activities.

On 15th June 2010, President Obama said: "One of the lessons we've learned from this spill is that we need better regulations, better safety standards, and better enforcement when it comes to offshore drilling."

In many countries, several organisations performed detailed analyses of the causes of the DHB incident, resulting in the recognition of the need to improve the legislation as well as to adopt sophisticated approaches for risks analysis and management of offshore activities.

Several activities with oil and gas industries took place worldwide to enhance the safety in offshore jobs and to improve the emergency response, restoration plans and technologies.

In 2013, the European Parliament and the Council of Ministries adopted the Directive 2013/30/EU on the "Safety on offshore oil and gas operations". This Directive is the main initiative taken in EU after the DHB accident.

An interesting study, carried out at the JRC, describes the state of the art as of 2013 in the report "Best Technologies and Safest Practices in the Offshore Oil Gas Sector; an overview of developments and advancements following the Macondo Accident (2014)". The aim of the Authors is to keep this report up-to-date to maintain the JRC at the forefront of knowledge in the field of safety and risk assessment in the oil and gas industry.

In the US, a new legislation and more detailed guidelines were approved, and new organisations were created to address offshore safety and marine environmental protection.

These initiatives are briefly summarised, e.g., in the API report (2013) "Improvements to offshore safety by industry and government" and in the BSEE report entitled "best available and safest technologies for offshore oil and gas operations. Options for implementation (2013)"

- http://www.api.org/~/media/Files/Oil-and-Natural-Gas/Exploration/Offshore/Improvements-to-Offshore-Safety-Report.pdf,
- https://www.nap.edu/read/18545/chapter/1#viii

What happened afterward? What is the current state of the art? This report tries to answer those questions, thanks to a thorough investigation, mostly based on open source information as well as contacts with some oil companies, and provides an overview on the state of the art so far (after the Macondo accident) on innovative safety systems, technologies and procedures (prevention, mitigation, and emergency response) in the case of accidents occurred during offshore activities of exploration and production of hydrocarbons.

In order to proceed in a systematic way, a generic accident is described qualitatively using a Bow-Tie Diagram (BTD). The Bow-Tie methodology is being used in several engineering domains as a tool to describe, for each identified hazard or random hazardous situation, safety control measures (prevention and mitigation) to protect people, assets and the environment from the consequences of an accident.

Bow-Tie methodology has also proved to be a good technique for communicating safety issues inside a company and among stakeholders.

The Bow-Tie approach is outlined in the next section with the aim of introducing the proper terminology as well as the technical and organisational elements characterizing accident scenarios.

Special attention is addressed to those elements that contributed to the DHB disaster: safety management aspects, capping and BOP new developments, emergency response, and environmental recovery.

Although this study represents the first step towards a deeper knowledge acquisition about safety issues in the offshore industry, it required an extensive and protracted research process.

Each covered subject can be further expanded on the basis of the examined documentation, which is available at in-line web links and from the references listed in Appendix.

2 Representation of accident scenarios: the bow-tie diagram

The Bow-tie methodology is currently applied by several industries (e.g., the chemical, aeronautical, food, and oil and gas industry) to synthetically and clearly represent all the causes of a particular event that may have the potential to lead to a major accident. It is also being used as a technique for communicating safety issues and safety control measures. A rich literature on bow-tie is available. Some interesting documents are provided in the Appendix.

Figure 1 represents a generic bow-tie diagram and shows its main elements, from the root causes to the set of possible consequences.

Each hazardous plant condition that analysts consider significant for risk quantification should be represented by a bow-tie diagram.

The central element of a bow-tie is an undesirable event with the potential to cause harm, whose causes (on the left-hand side) and consequences (on the right-hand side) are determined. In the scientific literature this element is named in different ways, e.g., Critical event, Initiating event, Hazardous event, Top event. In this report, the generic term of Undesirable Event (UE) is adopted.

UEs are particular plant conditions describing an accidental situation in which the integrity of the installation is threatened. They are identified as a result of the application of hazard analysis techniques. In the offshore domain, a typical UE considered is the Loss Of Containment (LOC), leading to the release of oil and gas from different points of the plant (e.g., process, well, flexible riser), causing fires, explosions, and environmental pollution.

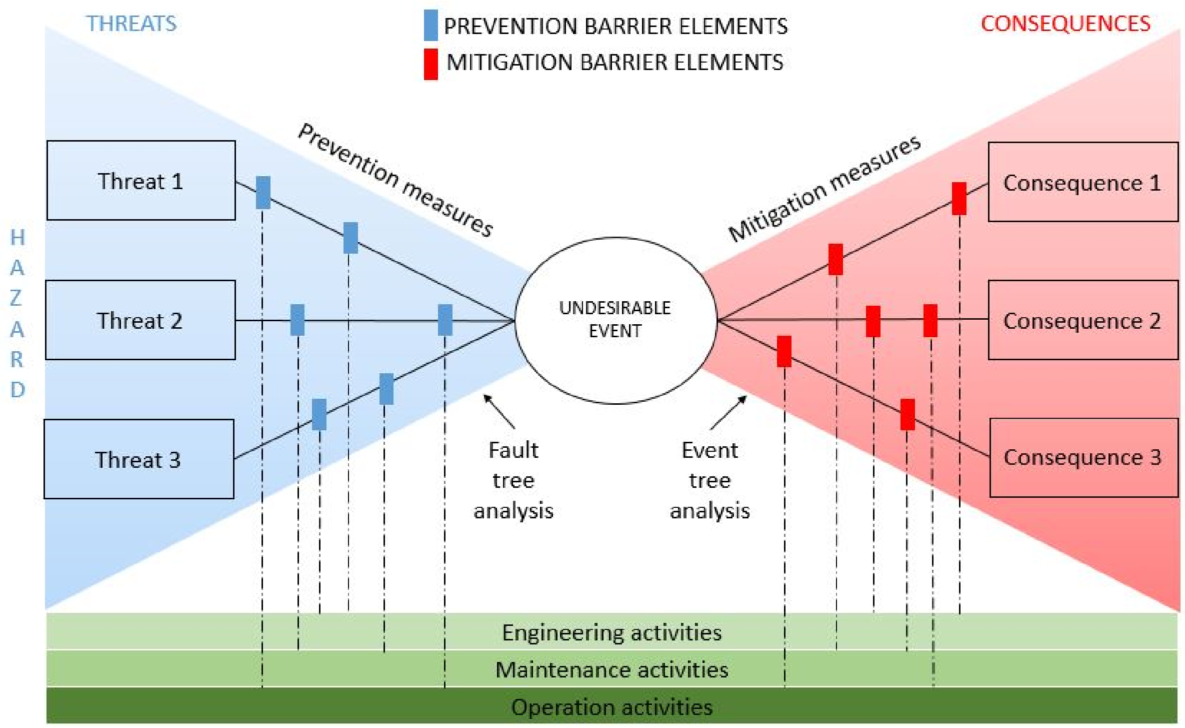

Figure 1: Generic Bow-Tie Diagram

The causes of an undesirable event are referred to as "*threats*" or "*triggering events*". They may be single or in combination with other threats. Threats are represented at the far left-hand side of the diagram. They can be of natural or anthropogenic origin. The occurrence of a threat may directly lead to the occurrence of the UE in case of failure of all related prevention barriers.

Prevention barriers are physical systems (e.g., emergency shut-down, BOP) and/or safety-related manual procedures (e.g., maintenance, operator intervention) planned to prevent the UE from occurring (i.e. to reduce its frequency) and to lower its damage potential.

In quantitative risk analysis, it is necessary to determine the occurrence frequency of the undesirable event by combining the frequency of the threats with the failure probability of independent or dependent barriers. To this aim, a simple way to proceed is to describe the logical relationships between UE and threats using a fault tree, in which the top event is the undesirable event and threats are the basic events. The fault tree is a deductive and highly systematic technique applied for logically describing all causes of a given event. The scientific literature on fault tree is very rich. A complete description of the fault tree methodology can be found at the following address:

http://www.nrc.gov/docs/ML1007/ML100780465.pdf.

The probabilistic quantification of a fault tree allows determining the frequency of the occurrence of the UE, given the occurrence frequencies associated with all threats and the failure probability of components making up the preventive barriers; moreover, importance and sensitivity analysis allows improving the safety of the installation on rational and cost-effective basis.

In essence, the left part of the bow-tie shows how many safety barriers are available to prevent, control or reduce the accident potential of the undesirable event, as well as the type of these barriers and their effectiveness.

The right-hand side of a bow-tie describes the potential negative effects of the occurrence of the UE. Indeed, the UE may develop into the worst consequence in case of failure of all mitigation barriers (also referred to as protection measures). Generally, several mitigation barriers are foreseen with the aim to reduce as much as possible the damage to sensible targets i.e. personnel, assets, and environment.

Examples of mitigation barriers are gas detectors, fire suppression, water spray, dikes, fire walls, disk rupture, emergency responders, and all other means that may be adopted to reduce the potential consequences, i.e. the magnitude of the possible damages depends on the performance of such barriers.

The logical relationships between the UE and the final consequences can be represented using an event tree (ET), in which different branches are generated considering the state (working, failed), of mitigation barriers. An ET can be probabilistically quantified in terms of occurrence frequency of each consequence on the basis of the UE frequency and the failure probability of the mitigation barriers. Also on event trees, the literature is very rich. A first clear presentation, which suits well with the application in the oil, gas and chemical domains, can be found at:

http://frigg.ivt.ntnu.no/ross/slides/eta.pdf.

Being barriers both physical systems and manual procedures, their performance depends on the quality of engineering, maintenance, and operation activities as well as on the safety culture of the company's management.

In the bow-tie in *Figure 1*, the restoration activities, intended as actions performed to restore the polluted environment to its normal conditions, are not represented; however, they will be also dealt with in this report.

For both prevention and mitigation measures, more barriers are generally in place to reduce the probability of having an accident with given potential damage. Certainly, the number of physical barriers should be commensurate with the importance of the consequences.

The Bow-Tie Diagram construction procedure is made up by the following steps:

1. Definition of the undesirable event;

2. Identification of the threat(s) as cause(s) of the undesirable event;
3. Identification of the barriers to prevent the occurrence of the undesirable event, or to reduce its frequency; description of the failure model of barriers (fault trees), which may compromise their effectiveness;
4. Identification of mitigation barriers to reduce the effects of the occurrence of the undesirable event;
5. Identification of the range of possible consequences as resulting from the occurrence of the undesirable event (event trees).

A generic path "threat→undesirable event→ consequence" identifies an accident scenario.

The consequence of a given undesirable event may be the threat of another undesirable event and so on, giving rise to a chain of bow-ties. For instance, this occurs in domino effects.

Chains of bow-ties can also be produced when different contractors are involved in a complex hazardous activity, e.g., made of a sequence of hazardous jobs. Each contractor is charged with a job, which is part of the activity and performs the related risk study using a bow-tie for each undesirable event. Since the different jobs are sequential, the Consequences on one bow-tie must be linked as threats to one or more downstream bow-ties. These relationships help increase confidence in the completeness of the risk analysis of the whole activity.

In *Figure 2* the simplified example of an offshore semi-sub rig hit by a strong gale is provided. It can be represented as a chain of bow-ties. The extreme weather conditions can be considered as the triggering event of the MODU's instability, which will lead to a mooring failure, if not properly managed.

In this case, mooring failure will be the effect, and the extreme weather conditions the cause. However, if the failure is not managed and mitigated, it might lead to an uncontrolled rig shift, which could bend the piping system. The extension of the bending effect depends on the possibility of mitigating it. Again, the mooring failure turns from effect into a cause.

In fact, it could be supposed that the pipe bending may cause the rupture of a valve, and thus the loss of containment on the rig, with subsequent release of the geological under pressure fluid into the environment. Therefore, if not promptly managed, the release will lead to various scenarios: a fire/explosion (if ignited), an oil spill and/or a gas release.

However, the bending of the drilling string (or production piping system) will probably threaten the whole well control system, leading to a pressure loss of the well and a final blowout, and causing major fires, explosions, and environmental pollution.

In all cases, the final consequences may be life loss, asset damage, and environmental pollution.

It is worth to underline that the bow-tie diagram is a qualitative method for representing a complete picture of accident scenarios in a simple way. Indeed, the probabilistic quantification requires the application of the classical fault tree and event tree methods, whereas the determination of consequences (fire, explosions, release of toxic substances) is obtained using suitable numerical or simulation models. For instance, concerning explosions, the following link gives an example of the use of a model based on Computational Fluid Dynamic (CFD):

https://www.icheme.org/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/XXII/XXII-Paper-04.pdf

The description of a CFD tool for gas explosion hazard analysis, called AutoReaGas, can be found at:

https://hal.archives-ouvertes.fr/ineris-00971910

A software tool for bow-tie diagram construction can be found at:

http://www.bowtiepro.com/

In accordance with the bow-tie scheme, the following elements constitute the various sections of the report:

- Hazard;
- Major accidents;
- Triggering events (or threats);
- Safety-related barriers;
- SEMS;
- Consequences;
- Emergency response and environment restoration.

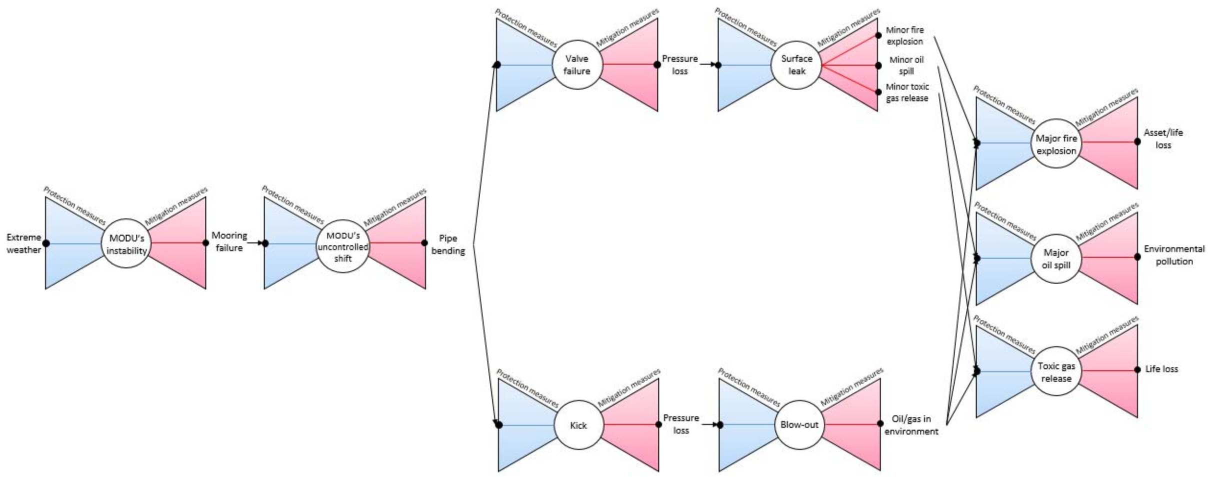

Figure 2: example of an event chain in which a threat (the cause) leads to an accident (effect) which can be itself the cause of another effect and so on. The gravity of the consequences increases as the accident sequence progresses

3 Hazards

A hazard is defined as an intrinsic property of anything with the potential to cause harm. The origin of hazards can be natural or man-induced; they are often parts of normal activities and cannot be removed, such as the presence of a hazardous substance. Particular hazards can also be generated in a plant in a particular situation and may last for short periods of time, e.g., an overpressure in a vessel or a run-away reaction.

A hazard can lead to one or more accidents depending on the threat and on the state (working/failed) of the related prevention and mitigation systems, i.e. safety barriers. Generally, the magnitude of damages caused by accidents (accident gravity) is directly related to the number and type of safety barriers that fail.

It is very important to identify all hazards and their threats through the application of hazard identification methods, [1] since not identified hazards remain hidden, and the plant unprotected until an accident occurs.

Offshore activities are subject to several hazards, which can be subdivided into two main groups depending on their origin: natural or anthropogenic. Here is a non-exhaustive list of: [2], [3]

Natural hazard

- Hydrocarbons;
- Toxic material;
- Extreme Weather;
- Shallow gas;
- Geological/seismic hazards.

Anthropogenic hazards

- Platform structure;
- Shipping activities;
- Helicopter use;
- Lifting operations, i.e.:
    - Crane operations;
    - Derrick lifting operations;
    - Pipe handling;
- Diving and underwater operations;
- Ballasting;
- Well testing and flaring;
- Hot work in hazardous location.

4 Major accidents

According to the European offshore Directive 2013/30/EU, a major accident (incident with negative consequences) is defined as an event causing major damage to people, assets and the environment, i.e.:

a) an incident involving an explosion, fire, loss of well control, or release of oil, gas or dangerous substances involving, or with a significant potential to cause, fatalities or serious personal injury;

b) an incident leading to serious damage to the installation or connected infrastructure involving, or with a significant potential to cause, fatalities or serious personal injury;

c) any other incident leading to fatalities or serious injury to five or more persons who are on the offshore installation where the source of danger occurs or who are engaged in an offshore oil and gas operation in connection with the installation or connected infrastructure; or

d) any major environmental incident resulting from incidents referred to in points (a), (b) and (c).

The offshore domain has already witnessed a long list of major accidents. An interesting collection of offshore oil and gas drilling related accidents, with details and photographs of the drilling rigs involved, are listed below.

The following website is a repository of a significant set of major accidents occurred in the oil and gas offshore field. Each case history is clearly described; original sources of information are provided together with photos:

http://www.oilrigdisasters.co.uk/

Similarly, the following link leads to a set of the world's worst offshore oil rig disasters, more precisely to a subset of the previous one:

http://www.offshore-technology.com/features/feature-the-worlds-deadliest-offshore-oil-rig-disasters-4149812/

BSEE Database on accident for statistical analysis occurred in the Gulf of Mexico, Pacific, and Alaska:

https://www.bsee.gov/stats-facts/offshore-incident-statistics/incident-stats-and-summaries

Examples of major accident types in offshore drilling and production:

- Loss of containment from production riser and from process components;
- Blowout (which can trigger the accidents below);
- Fire on board;
- Explosion on board;
- Toxic gas release (CO, H_2S, HF, etc.);
- Oil spilling in the environment (water, shore);
- Hydrocarbon release from Cargo Handling System;
- Impact from Dropped Object/ Swinging Load;
- Helicopter Crash;
- Vessel Collision;
- Structural Failure or Loss of Stability of FPSO (Floating Production Storage and Offloading);
- Capsizing.

Any occurred major accident is worth to be deeply investigated to identify the root causes, trace out its evolution, learn the lessons and, eventually, provide useful feedbacks to technical services for continuously increasing the safety level of the installation.

In the chain of events described in *Figure 2*, it is not easy to define what is the cause (triggering event) and what is the consequence.

Therefore, to clarify which among the different accidents should be considered the major accident and which should be the triggering event or the consequence, in this report we describe as a major accident only the following accidents:

- Blowout (which can trigger all the other accidents below);
- Fire on board;
- Explosion on board;
- Toxic gas release (CO, H2S, HF, etc.);
- Oil spilling in the environment (water, land).

On the other hand, all the other accidents will be treated as possible triggering events.

Several accident databases are available in the World. A useful source of information on accidents repositories and analysis, together with a review of the lessons learnt, can be found in the following JRC report "Safety of offshore oil and gas operations: Lessons from past accident analysis":

http://publications.jrc.ec.europa.eu/repository/bitstream/JRC77767/offshore-accident-analysis-draft-final-report-dec-2012-rev6-online.pdf

Besides the accident databases listed in the above JRC report, additional sites of interest are:

- In 2010 OGP published the Risk Assessment Data Directory, report No. 434-17, containing the list of major accident occurred in onshore and offshore plants, on the basis of which occurrence frequencies have been estimated:

    http://www.ogp.org.uk/pubs/434-17.pdf

- Accident statistics (UK):

    http://www.hse.gov.uk/offshore/statistics.htm

- BSEE Database on accident for statistical analysis occurred in the Gulf of Mexico, Pacific and Alaska:

  https://www.bsee.gov/stats-facts/offshore-incident-statistics/incident-stats-and-summaries

5 Triggering events or treats

A threat is an event (simple or complex) which is able to cause the occurrence of an UE when all preventive measures fail, i.e. these events are the root causes or initiators of accident scenarios.

Examples of simple threats: valve rupture; human error; mud pump failure; etc.

Examples of complex threats: well kick; riser failure; drilling into shallow gas pockets; etc.

Complex threats can be further decomposed into a set of simpler threats up to their root causes (e.g., by fault tree analysis).

A non-exhaustive list of main triggering events in offshore activities can be subdivided according to their origin as follows: [2]

Natural triggering events

- Extreme weather conditions (e.g., hurricane, high wind load, temperature extreme);
- Earthquake;
- Shallow gas;
- Entrained gas within the mud system;
- Geological seabed instability.

Anthropogenic human/mechanical technical causes

- Mooring failure;
- Loss of dynamic positioning;
- Main generator room ignition;
- Loss of well control
- Process system integrity failure (valves, flanges, seals, other);
- Process control software (SCADA);
- Cyber-security systems;
- Vessel collision;
- Structural/platform failure (rig stability);
- Ballast failure/error;
- Dropped objects.

These events refer to a loss of functions, and they can be subdivided into their primary causes, such as failures of system components, and external events.

An important role is also played by human errors during design, inspection, test, maintenance, and operations.

The term *threat* also suggests that a major accident may be maliciously caused. A brief search on open sources allowed finding some interesting information.

The following DNV GL article deals with the cyber-security threats for oil and gas industry:

http://www.offshoreenergytoday.com/top-10-cyber-security-threats-for-oil-and-gas-industry/

In this article from Journal of Energy Security, threats are grouped into eight categories according to the type of activity:

http://ensec.org/index.php?option=com_content&view=article&id=453:protecting-offshore-oil-and-gas-installations-security-threats-and-countervailing-measures&catid=137:issue-content&Itemid=422

An interesting Honeywell paper on security problems and proposed solutions can be found at:

http://www.automation.com/pdf_articles/honeywellps/Maritime_Security_WhitePaper.pdf

Security management system, OGP Report 512, 2014:

http://www.iogp.org/pubs/512.pdf

6 Safety-related (prevention and migration) barriers

Hazardous plants are installations in which the perturbation of one or more process variables (caused by components failure, human errors or external events) may lead, if not promptly arrested, to undesirable events that have the potential to cause major accidents. Hence, systems and/or safety related emergency procedures are designed to prevent, control or mitigate the consequences of hazardous plant states.

Prevention means avoiding the presence of the Undesirable Events or to reduce their occurrence frequency. Control means limiting as much as possible the extent and/or the duration of UEs, and mitigation means reducing the magnitude of damages when event evolve into accidents. All these safety-related systems and procedures are referred to as Safety Barriers. **[4]**

Safety barriers can be defined and classified in different ways. For instance, the International Association of Oil and Gas Producers (IOGP) published the report 544 (April 2016), concerning the standardization of barriers definitions, which are classified as physical systems and human-based barriers. Physical systems are grouped into eight categories, each one subdivided into subcategories, whereas human-based barriers are subdivided into six categories. For details, see:

http://www.iogp.org/Reports/Type/544/ID/812 .

Moreover, Management System Elements are defined to check and maintain physical barriers and to support human barriers. Indeed, an important point is to maintain the safety-related barriers in optimum conditions, since they must be available at all time. Most of them intervene automatically without any manual activation, so they need to be periodically tested/inspected and maintained. **[5]**

The performance of safety barriers can be characterised using the attributes mentioned in the Snorre Sklet's Doctoral Thesis "Safety Barriers on Oil and Gas Platforms"**[6]** **:**

a) *functionality/effectiveness* is the ability to perform the specified function under given technical, environmental, and operational conditions;

b) *availability/reliability* is the ability to perform the intended function on demand and to work properly for the time needed;

c) *response time* is the time interval from the demand to the intervention;

d) *robustness* is the ability to resist to the accidental load;

e) *triggering event* (or *condition)* means what triggers the activation of a barrier.

The performance of barriers over time is controlled by means of key performance indicators. A report from IOGP (Rep. 556, July 2016, a supplement to rep. 456) deals with this subject. **[7]**. The key indicators are:

- number of fatalities;
- fatal accident rate;
- fatal incident rate;
- total recordable injury rate;
- lost time injury frequency;
- number of lost work day cases and number of lost work days;
- number of restricted duty cases and restricted duty days;
- number of medical treatment cases.

All barriers are safety-critical elements, i.e. they are components or systems whose failure may cause or substantially contribute to a major accident, with consequences on people, assets and the environment. Within the hydrocarbon industry they are also referred as Safety and Environmental Critical Element (SECE).

Non-exhaustive list of mechanical and procedural preventions SECEs: [8], [2], [9]

- Ignition control system/ATEX procedure;
- Cement slurry control procedure (chemical and physical characteristics);
- Software update procedure;
- Control of the drilling mud characteristics procedure;
- External and internal communications procedures;
- function test procedure;
- Hydrocarbon containment system;
- Risers and pipelines system;
- Blowdown, pressure relief and flare system;
- Automatic and manual emergency shut-down systems;
- Blowout Preventer;
- GPS and backup systems;
- Collision avoidance systems;
- Mooring, riser monitoring systems;
- Emergency electrical power supply system;
- Emergency shut-down system;
- Ballast control system;
- Fire, gas and smoke detection systems;
- Well control system;
- Dead-man system;
- acoustic system;
- auto-shear system.

As already shown above, there are several mechanical prevention barriers available on the market. However, all these barriers should not be taken into consideration at the same time because redundancy is not always the key to safety. On the other hand, it is important to select the available technology that best fits each situation.

In this report, the Blowout Preventer (BOP) is considered in more detail, since its failure in the Deepwater Horizon accident pushed many authorities and industries to study new and more reliable designs.

6.1 Possible blowout causes [9]

Depending on the well phase, a blowout can be originated by different causes:

- During the **drilling and completion phase**, a blowout is usually triggered by a loss of hydrostatic pressure in the well due to drilling mud containment failure. The alarm signs can be either an abrupt variation of the level of mud (brine, in the case of completion phase) or an unforeseen presence of geological fluids mixed with the mud (brine), which will quickly raise the mud level.

- In a **production installation**, the mechanical failure (or sabotage) of either the bottom-hole or the wellhead equipment is considered the main cause of blowouts. In this case, the alarm sign is the uncontrolled rise of the fluid flow.

6.2 Blowout preventer [9]

Nowadays, in order to control an unwanted kick, which could lead to a blowout, every rig adopts two prevention barriers:

a) The first and most important barrier will always be the perfect management of the drilling mud as well as the knowledge of its characteristics in accordance with the geological conditions of the reservoir formation. A well-calibrated density of drilling mud will contrast and balance-out the hydrostatic pressure of the compressed geological fluids in the reservoir, which otherwise will quickly rise towards the surface (kick) and trigger a blowout.

b) If for any reason (e.g., mechanical failure, human error, and geological unforeseen conditions), there is a drilling-mud pressure loss in the well, and the sensors detect a fluid rise, then a second blowout barrier is the Blowout Preventer.

As described above, the blowout may be originated by different causes depending on the phase (drilling or production).

BOPs are compulsory, complex, sturdy but also delicate mechanical devices to be installed on every rig. Due to the often complicated wells characteristic, each BOP design must be adequate to each different situation.

To be effective it must be properly designed and tailored for each single installation according to its technical and physical parameters and geological conditions of the reservoir.

In order to offer the best protection, BOPs are both automatically and manually controlled by qualified personnel.

On the market there are different types of BOPs.

6.2.1 External annular BOP

It is a rubber doughnut-shaped valve placed around the drilling string or pipe, on top of the BOP stack. It can be mechanically squeezed inward to seal on the pipe or the open hole (if placed inside it). Most blowout preventer (BOP) stacks contain at least one annular BOP at the top of the BOP stack and one or more ram-type preventers below. While not considered as reliable in sealing over the open hole as round tubulars, API specifications require the elastomeric sealing doughnut to seal adequately over the open hole as part of its certification process.[10]

6.2.2 External ram BOP (Shaped, Blind and Shear)

A ram blowout preventer consists of two halves of a cover for the well that are split down the middle. Large-diameter hydraulic cylinders, normally retracted, force the two halves of the cover together in the middle to seal the wellbore. The halves of the cover, formally called ram blocks, are available in a variety of configurations depending on the well design.

Other ram blocks are fitted with a steel-cutting surface tool to enable the ram BOPs to shear through the drill pipe, hang the remaining drill string on the ram blocks, and seal the wellbore. Obviously, such an action limits future options, and it is employed only as a last resort to regain pressure control of the wellbore. The various ram blocks can be changed in the ram preventers, enabling the well team to optimize BOP configuration for the particular hole selection or the operation in progress. [10]

Among the different types of rams, the Blind Shear Ram (BSR) is designed to be the actual emergency sealing ram, being the only one designed to cut the pipe and seal the BOP system and hence the well. Sealing off the BOP system after slicing the drill pipe is a technical challenge, but it is within the capabilities of current technology.

If the BRS works and seal, the enormous force caused by the pressure differential above and below the BSR (thousands of pounds per square inch) requires high structural integrity, carefully engineered seals, and adequate testing under extreme conditions. [11]

Annulars and pipe rams are mainly used for closing the bore, when it is necessary to circulate out through the drill string, choke and kill. Pipe rams can also be used to hang off the pipe below the ram on a tool joint or hang-off tool.

6.2.3 Inside BOP

Inside BOP is a one-way valve placed inside the drilling string in order to avoid the rise of the fluid.

In a production installation, the primary BOP systems are the packers installed inside the casing. The secondary Blowout Preventers are the bottom-hole and wellhead safety valves which should block out the sudden increasing of the geological fluid flow.

6.2.4 Advancement in BOP technology

After the Deepwater Horizon disaster, the recommendations made by various committees included the study of new and more reliable BOP equipment.

The following website contains a good description of both the BOP functions and the areas of investigation in terms of design, operation, maintenance and lessons learnt from the Deepwater Horizon disaster.

For details see:

https://www.nap.edu/read/13273/chapter/6#62

The Offshore magazine reports information and articles about new tools and technologies (hardware and software) for the offshore industry. It is a good source of information on offshore applied research.

For details, see:

http://www.offshore-mag.com/articles/print/volume-76/issue-11/equipment-engineering/new-tools-and-technology-for-the-offshore-industry.html

BOP Technologies announces the "Failsafe Design for Blowout Preventers" project, a new approach to allow a BOP to work even if the drilling rig loses power or hydraulic pressure (CIRBOP, Circular Intensified Ram Blowout Preventer). For details, see:

http://boptechnologies.com/news/

http://www.businesswire.com/news/home/20151209006576/en/

However, in the following website, it is stated that BOP Technologies is seeking funds to build the new CIRBOP. For details, see:

http://www.rigzone.com/news/oil_gas/a/147197/New_BOP_Targets_Prevention_of_Future_Deepwater_Horizon_Incidents

At the web address https://www.nap.edu/read/13273/chapter/1 the book "Macondo Well Deepwater Horizon Blowout" can be accessed. It reports the outcomes of the Committee on the Analysis of Causes of the *Deepwater Horizon* disaster and identifies the measures to prevent similar accidents in the future.

Concerning mitigations measures, the following is a not-exhaustive list of critical elements (SECE): [2][8][9]

- Confinement of the accident effects;
- Alarm system and Emergency Shut-Down (ESD);
- Fire and smoke detection systems;
- Fire protection systems (active and passive);
- Portable fire-fighting equipment;
- Ventilation and Air Conditioning (HVAC);
- Air instrument and nitrogen system;
- Emergency electrical power supply system;
- Emergency electric power shut down system;
- External and internal communications;
- Responsible, Accountable, Consulted, Informed (RACI applied to emergency situations);
- Personal Protective Equipment (PPE);
- Emergency planning and response (temporary refuge and evacuation: three tiers);
- Access, escape and evacuation routes;
- Escape lighting;
- Emergency plan and useful contact list updated and immediately available.

The above list of prevention and mitigation SECE elements shows that some barriers may act as either prevention or mitigation devices depending on the threat and the resulting undesirable event. As an example, if the undesirable event is the "loss of well control" then both the mud system and the BOP would be located on the left-hand side of the bow-tie.

If, on the other hand, the undesirable event is the "loss of primary control" then the mud system would be located on the left-hand side of the bow-tie whereas the BOP on the right-hand side. [Error! Bookmark not defined.]

The emergency electric power system, the air instrument system and the internal communication systems are other examples of SECE elements that are utilities of both prevention and mitigation barriers.

CBS (the U.S. Chemical Safety Board), the Federal Agency in charge of the investigation of accidents in the chemical industry, completed the analysis of the Deepwater Horizon disaster. Conclusions and recommendations concerning barriers are described in four reports. In particular, volume 2 deals with barriers and SECE. For details, see:

http://www.csb.gov/macondo-blowout-and-explosion/

Many safety barriers are fail safe systems based on electrical, electronic and programmable logic elements. The main standard encompassing the whole life cycle of such systems is the IEC 61511, which is derived from the basic IEC 61508 and applied to the oil and gas field. For details, see http://www.iec.ch/

From the following website, it is possible to download an interesting scheme showing major accidents that can affect personnel on drilling and production offshore installations, together with the related physical barriers. For details, see http://shephardpost.com/

7 Safety and environmental management system

Prevention and mitigation barriers include technical systems and human operational procedures. There are several operations of primary importance for the successful intervention of safety-related barriers. They include tests/inspections and maintenance.

Poor maintenance or erroneous tests may compromise the availability/reliability of fundamental systems, like emergency generators, air compressors, fire and gas detection systems, etc. Therefore, it is fundamental to train the operators on how to perform routine tasks and behave in emergency situations.

This is not sufficient to ensure the appropriate level of safety, as the management is also required to thoroughly oversee the maintenance of the safety barriers throughout the whole life of the installation.

This implies, e.g., the constant training of the staff that must be commensurate with the hazard level of their tasks, the systematic use of operational procedures along with a competent supervision, the systematic analysis of risk, the accident investigations, etc.

The Safety Management System (SMS) or the U.S. Safety and Environmental Management System (SEMS) encompasses all activities aiming at analysing and controlling the risk in order to maintain a high safety standard during the whole life of the installation. In what follows, the acronym SEMS will be used.

SEMS describes the operator’s policy on safety and environmental protection and covers organizational aspects, chains of responsibilities, personnel training and expertise, which are necessary to demonstrate that the risks related to different activities are well known and adequately reduced to acceptable values.

Note on the U.S. SEMS

From 2004 to 2010 the safety was performed, on a voluntary base, according to the American Petroleum Institute RP-75 (API RP-75) Recommended Practice for Development of a Safety and Environmental Management Program (SEMP) for Offshore Operations and Facilities.

After the Macondo accident, in 2010 the U.S. Code of Federal Regulations (Title 30 Part 250) included the subpart S, known as Safety and Environmental Management System (SEMS). The original SEMS rules made also mandatory the previously voluntary practices in the American Petroleum Institute's (API) Recommended Practice 75 (RP 75). In 2013, the Bureau of Safety and Environmental Enforcement (BSEE) released the Safety and Environmental Management Systems (SEMS) II final rule. SEMS II revises and adds several new requirements to the existing SEMS, including a Centre for Offshore Safety (COS).

SEMS aspects can be enforced or updated via audits or inspections. They support the physical barriers effectiveness, through:

- High safety culture level;
- Hazard analysis;
- Job safety analysis for operational tasks;
- Safety and risk analysis;
- Operating procedures;
- Management of change;
- Competent supervision;
- High level well integrity standards and practices;
- Constant training of personnel (for the normal work and in emergency situations);
- Application of state-of-the-art technology and recognised best practices;

- Assurance of Quality and Mechanical Integrity (MI) of Critical Equipment;
- Operational activities (Test, Inspection, and Maintenance) carried out following established procedures and checklists;
- Pre-start up review;
- Investigation of Incidents;
- Audits;
- Record and documentation.

A methodology that helps defining the responsibility in decision making, which is currently applied by offshore operators, is the RACI matrix (Responsible, Accountable, Consulted, and Informed). [12], [13]

The description of the RACI methodology can be found at:

https://project-management.com/understanding-responsibility-assignment-matrix-raci-matrix/

RACI methodology also helps avoid the main causes of unproductive work and project failure, since it identifies roles and responsibilities of each participant, avoiding role confusion and duplication of efforts, removing ambiguities, enhancing communication and coordination between the participants, resolving the conflicts arisen in the project and during the process, and improving the efficiency and effectiveness of the team.

For each task, RACI identifies the following roles:

- Responsible (who takes action);
- Accountable Authority (who has the authority to approve the final decision);
- Consulted (the experts providing information before the responsible takes action);

Informed (who needs to be kept informed).

<u>Other sources of information about SEMS published after the Macondo disaster.</u>

Since the safety management aspects have been recognized to be a contribution factor of the Deepwater Horizon disaster, many countries devoted a lot of effort to improve the effectiveness of their SEMS.

The following links address to documents dealing with the organizational issues in the industry of different countries:

The U.S. Chemical Safety Board (CBS), which is the Federal Agency in charge of the investigation of accidents in the chemical industry, completed the analysis of the Deepwater Horizon disaster, and in 2016 published four reports plus a summary report containing conclusions and recommendations. In particular, the forth volume deals with the safety and environmental management system. Key issues are human factors, organizational learning, safety performance indicators, risk management practices, corporate governance, and safety culture. The report can be found at:

http://www.csb.gov/assets/1/7/Macondo_Vol4_Final_staff_report.pdf

The mission of the US BSEE (Bureau of Safety and Environmental Enforcement) is to promote safety, protect the environment, and conserve the offshore resources. About SEMS provisions, see:

https://www.bsee.gov/site-page/fact-sheet

In 2015 the American Petroleum Institute (API) issued a report titled "How industry and government are improving the safety of offshore energy development in the post-Macondo era". For details, see:

http://www.api.org/~/media/files/ehs/clean_water/oil_spill_prevention/after-macondo-report-april-2015.pdf

SCOR Technical Newsletter describes improvements after Macondo (2014).

For details, see:

https://www.scor.com/images/stories/pdf/library/newsletter/pc_nl_macondo_mel-07-04.pdf

SPE-143718-PP Consequences of Macondo: A Summary of Recently Proposed and Enacted Changes to U.S. Offshore Drilling Safety and Environmental Regulation 2011. For details, see:

http://www.jsg.utexas.edu/news/files/mcandrews_spe_143718-pp.pdf

SEMS Background Summary, 2012, describes the activities that came out with the SEMS regulation issued by BSEE in 2010. For details, see:

http://www.ourenergypolicy.org/wp-content/uploads/2012/05/SEMSWhitePaper4-17-12byAcutech.pdf

COS (Centre for Offshore Safety) is an industry sponsored group focused exclusively on offshore safety in the U.S. Outer Continental Shelf (OCS). One of the activities of COS is the development of good practice documents in the areas of Safety and Environmental Management Systems (SEMS). For details, see:

http://www.centerforoffshoresafety.org/

<u>All activities in the petroleum industry are based on International and European Standards (IES):</u>

In Norway, the NORSOK standards complement IES, because of the Norwegian safety framework and climate conditions. For details, see

http://www.standard.no/no/fagomrader/energi-og-klima/petroleum/

A map of NORSOK Standards for use in the oil and gas industries can be found at

http://www.standard.no/Global/PDF/Petroleum/NORSOK%20standards%20plansje%20A2%20-%20november%202015%20utskrift.pdf

<u>NORSOK standards of particular interest are:</u>

- NORSOK Z-013 Edition 3, October 2010; Risk and emergency preparedness assessment. The content of this standard can be downloaded from

  http://www.standard.no/en/PDF/FileDownload/?redir=true&filetype=Pdf&preview=true&item=459004&category=5

- NORSOK D-010 Well integrity in drilling and well operations, Rev 4, June 2013

  http://www.standard.no/en/PDF/FileDownload/?redir=true&filetype=Pdf&preview=true&item=644901&category=5

Other public bodies dealing with safety issues are:

- PSA (PTIL) Petroleum Safety Authority Norway, Norwegian Environment Agency, and Norwegian Directorate of Health published the guidelines regarding the management regulations, which is kept updated http://www.psa.no/management/category401.html#_Toc377975494

  The last update (18 December 2015) can be found at

  http://www.psa.no/getfile.php/Regelverket/Styringsforskriften_veiledning_e.pdf

- The Norwegian Maritime Authority issued the Regulations No. 1191 of 5 September 2014 concerning the safety management system for Norwegian ships and mobile offshore units. For details, see:

  https://www.sjofartsdir.no/contentassets/ff94712f5077403aaf5f0acf295d18e4/5-september-2014-no.-1191-safety-management-system-for-norwegian-ships-and-mobile-offshore-units.pdf

- The UK Health and Safety Executive (HSE) documents on SEMS are available at:

http://www.hse.gov.uk/offshore/managementsystems.htm.

  This page contains accesses to information on the various SEMS elements, e.g.:

  - permit to work (PTW): http://www.hse.gov.uk/humanfactors/topics/ptw.htm

  - supervision: http://www.hse.gov.uk/humanfactors/topics/supervision.htm

  - competence: http://www.hse.gov.uk/humanfactors/topics/competence.htm

  - effective safety leadership:

  Leadership for the major hazard industries: http://www.hse.gov.uk/pubns/indg277.htm

  Organisational change and major accident hazards: http://www.hse.gov.uk/pubns/chis7.pdf

- The Protection of the Arctic Marine Environment Working Group prepared the report "Systems safety management and safety culture in the Arctic offshore oil and gas operations" (March 2014) on behalf of IADC (International Association of Drilling Contractors) and PAME (Protection of Arctic Marine Environment). The report describes the regulatory regimes, standards, guidance tools and approaches for improving safety culture and safety management systems. Details can be found in IADC "Enhancing operational integrity by ensuring a competent workforce". For details, see:

  http://www.iadc.org/wp-content/uploads/2014/02/PAME-Systems-Safety-Management-and-Safety-Culture-Report-Mar-2014.pdf [2]

  http://www.iadc.org/accreditation/

  The Safety Alert service is offered to its members by IADC. Each alert included in the database, coming from a company, describes the incident or the near-miss that occurred, its root causes, and corrective actions taken. This continuous "learning from experience" process helps increase awareness of the personnel on safety aspects of their activities, while improving the safety level of the installation at the same time. For details, see: http://www.iadc.org/safety-alerts/

- OGP REP. 476, August 2016, on "Recommendations for enhancements to well control training, examination, and certification". For details, see:

  http://www.ogp.org.uk/pubs/476.pdf

- OGP REP 501, April 2014, on "Crew Resource Management for Well Operations teams". For details, see: http://www.iogp.org/pubs/501.pdf

- ISO 17777:2000(E), Guidelines on tools and techniques for hazard identification and risk assessment. For details, see:

  http://www.standard.no/en/PDF/FileDownload/?redir=true&filetype=Pdf&preview=true&item=129929&category=5

- ISO 14004:2016, Environmental Management System - General Guidelines on principle, systems and support techniques. This standard provides organizations with guidance on how to establish, implement, maintain or improve an environmental management system. For details, see:

  http://www.iso.org/iso/catalogue_detail?csnumber=60856

- The following ISO standard 14001 helps organizations improve their environmental performance policy. For details, see:

  http://www.iso.org/iso/introduction_to_iso_14001.pdf

- ISO/TS 17969:2015 deals with the Guidelines on competency for personnel of Petroleum, petrochemical and natural gas industries. For details, see:

  https://www.iso.org/standard/61167.html

- NOPSEMA, National Offshore Petroleum Safety and Environmental Management Authority. Guidance note on safety Management Systems, 2015. For details, see:

  https://www.nopsema.gov.au/assets/Guidance-notes/N-04300-GN-1052-Safety-Management-Systems-Rev-1-Aug-2015.pdf

8 Consequences

For each major accident, consequences are the final elements of a bow-tie and describe the different damages depending on the performance and preparedness of the mitigation. Consequences of a major accident can be referred to different areas: people, assets, and environment.

8.1 Consequences on people

Personnel is the main, most critical and vulnerable element in every risk analysis. The first part of each emergency plan should always aim to protect offshore operators and mitigate the negative consequences of every accident.

The **thermal dose** $(radiation\,intensity \cdot exposure\,time)$ produced by a fire may cause different skin burns to a human being (first, second and third degrees burns) up to the lethal consequence.

The effects of the **pressure wave** generated by an explosion can be subdivided into direct and indirect. The direct effects are related to the compression of the most sensible organs: lungs and eardrum. The indirect effects of the pressure wave are related to the translation of the body towards a rigid surface, and the impact with fragments of the exploded equipment.

In the case of release of **toxic substances** (e.g., H_2S), the routes of absorption by the human body are by inhalation and by direct contact with skin or eyes. The actual effects depend on the absorbed dose.

In all cases, the prompt availability of personal protective equipment is of paramount importance.

Even if this report restricts attention to accidents leading to major loss and/or multiple casualties, in risk analysis, it is necessary to consider the single casualty or injury due to work accidents.

As an example, hereafter is a non-exhaustive list of major short-term consequences on people:

- major injuries to the whole body parts;
- burns;
- respiratory problems;
- eyes problems;
- death.

8.2 Consequences on assets

Assets mean money. Although human life is important, major assets-care often lead major decisions.

Fortunately, major assets are less vulnerable than people and, therefore, are less threatened by triggering events. Referring to the chain of events in *Figure 2*, each triggering event will cause an accident, which eventually could lead to an asset loss. As long as it is a minor asset and there are no further consequences, it can be considered as a minor loss and somehow included in the budget (e.g., bended pipe or broken tool). However, when the entire installation is at stake the consequence must be avoided at all costs. Fortunately, the triggering events that directly lead to major asset loss are rare and normally easily detected with anticipation, such as major structural failure or major fire.

As an example, hereafter is a non-exhaustive list of major short-term consequences on assets:

- partial or total installation burn/explosion/melt;
- partial or total installation temporary impracticability;
- installation sink;
- major equipment loss;
- data and documentation loss.

8.3 Consequences on the environment

The most common environmental consequence of an offshore installation failure is the oil spilling into water. Oil will thin down into a few micron-thick films, which will quickly spread over several squared kilometres, blocking the light through the water surface and the oxygen exchange and polluting the ecosystem. If the oil reaches the coast, it will deeply and steadily pollute the shore and the whole shore ecosystem as well. Unfortunately, it is a well-known and grimly well-experienced scenario that must be avoided at all cost in the future. However, as explained later on in this report, the emergency response to this consequence cannot have always the time-priority.

As an example, hereafter a non-exhaustive list of major short term consequences on environment:

- water body pollution;
- coastal ecosystem pollution;
- marine and coastal ecosystem endanger.

In risk analysis and platform design, it is important to know models and data about human vulnerability to fires, explosions and releases of toxic substances. Regulations in each Country establish the maximum dose thresholds that should not be exceeded. Some publications are listed below.

HSE (UK) Methods of approximation and determination of human vulnerability for offshore major accident hazard assessment can be found at:

http://www.hse.gov.uk/foi/internalops/hid_circs/technical_osd/spc_tech_osd_30/spctecosd30.pdf

TNO (NL) Methods for the determination of possible damage to people resulting from release of hazardous materials (Green book) can be found at:

https://www.scribd.com/doc/61170131/Green-Book-Methods-for-the-Determination-of-Possible-Damage-CPR-16E .

It also contains data for evaluating the vulnerability of platform structures.

The International Association of oil and gas producers (OGP) published in 2010 the Risk Assessment Data Directory Report No. 434 – 14 containing the threshold limiting values for human vulnerability indoor and outdoor. For details, see:

http://www.ogp.org.uk/pubs/434-14.pdf

9 Emergency response and environment restoration

For each accident, mitigation systems aim at reducing the magnitude of the damages (consequences) to the personnel, the assets, and the environment. The emergency response plan is the ultimate measure of mitigation.

Requirements of an emergency response plan: [2]

- Cooperation with contractors, authorities, and communication of the respective information available.
- Capping systems (different techniques).
- RACI matrix to define tasks and responsibilities.
- Temporary refuge details.
- Details of evacuation and escape equipment.
- Means of recovery to a place of safety.

The above response plan should:

- be readily available in case of emergency.
- clearly identify the hierarchy of the emergency command structure for both the onshore and offshore bits and ensure a prior identification of competent and acknowledged personnel (RACI matrix).
- include the details of the emergency control room facilities and all the existing equipment and documentation.
- include the periodical verification of the whole communication system.
- verify that the key personnel have the proper knowledge and experience to make the communication system working.

The Open Source offers a huge amount of documents dealing with the problem of emergency planning and response. The following websites have been selected with the aim of giving a clear picture of the issue:

- The ISO 15544:2000(E) on "Offshore production installations — Requirements and guidelines for emergency response":

  http://www.standard.no/en/PDF/FileDownload/?redir=true&filetype=Pdf&preview=true&item=129709&category=5
- The UK guidelines on emergency response:
  - http://oilandgasuk.co.uk/emergencyresponse.cfm
  - Guidelines for the Management of Competence and Training in Emergency Response for Offshore Installations
  - Guidelines for the Management of Emergency Response for Offshore Installations
  - https://www.gov.uk/guidance/oil-and-gas-offshore-emergency-response-legislation
- The UK Health Safety Executive "Prevention of fire and explosion, and emergency response on offshore installations", 3rd edition, 2016:

  http://www.hse.gov.uk/pUbns/priced/l65.pdf
- The Australian NOPSEMA "Guidance note on emergency planning", 2016:

  https://www.nopsema.gov.au/assets/Guidance-notes/A313116.pdf
- The API "Guidelines for Offshore Oil Spill Response Plans - Technical report 1145", September 2013:

http://www.oilspillprevention.org/~/media/oil-spill-prevention/spillprevention/r-and-d/spill-response-planning/1145-e1-final.pdf

- The Italian Civil Protection Dept. National Emergency Response Plan against pollution by oil spills or other toxic material caused by marine accidents, 2010:

  http://www.protezionecivile.gov.it/resources/cms/documents/piano_nazionale_antinquinamento_marino_ENGLISH.pdf

- The UK Emergency Preparedness Offshore Liaison Group (EPOL) "Integrated offshore emergency response", 2013:

  http://www.epolgroup.co.uk/files/4213/8598/1778/IOER_-_v1.1_-_15.09.2013_Final_EPOL.PDF

- As an example of emergency response plan, see:

  http://www.sjofartsverket.se/pages/24800/Baltico%20Meeting%202012/Nord%20Stream%20emergency%20plan.pdf

9.1 Tier preparedness [9],[14], [15]

The so called "tiered preparedness" was developed by the oil industry in the 1980s to primarily face marine shipping spills, which represented a mobile threat, although of a finite size. it means that the entire volume of oil carried by a vessel as fuel or cargo is known in advance. therefore the mitigation intervention kit can be properly sized. With oil drilling industry development, a different type of exposure scenario has been developed, i.e. the potential spill of an indeterminate amount of oil during drilling or production activities. To face this new and much more extensive scenario, it is now clear that well-designed well intervention equipment (e.g. source control, BOP, capping system, etc.) became an important tool for the industry to demonstrate its ability to contain an incident.

Nowadays, it is imperative to provide '*the right resources, in the right place at the right time*' and enable a proper response to an oil spill of any magnitude everywhere in the world, by integrating regional and global response resources and coordinating with the International Convention on Oil Pollution Preparedness, Response and Co-operation, 1990 (OPRC Convention).

The Tiered preparedness is divided into three different levels (tiers).

Tier 1: it refers to the capability of resources that the operator locally holds and uses to mitigate spills, typically operational in nature, occurring in the facility or nearby.

An example of Tier 1 emergency response is the failure of a Christmas tree valve, leading to a localized oil spill. A prompt and knowledge intervention by technicians on board can fix the problem without any external intervention.

When the accident is larger or propagates in the environment so much that the sole effort of the equipment and personnel of the rig does not provide for a complete mitigation of the problem, the Competent Authority of the local Nation will be alerted, and the emergency rises to Tier 2.

Tier 2: it provides national or regional extra resources to Tier 1 capabilities to increase response capacity or to introduce more specialist technical expertise. Tier 2 response capabilities can be achieved throughout different ways of cooperation between local facility and State, such as mutual aid agreements, industry-led cooperatives, and government-led cooperatives.

In order to face a tier 2 emergency, every emergency operative base should be ready to ship proper equipment together with trained personnel. Hereafter is a non-exhaustive list of necessary components for mitigating a localized spill of oil in the environment [9]:

- anti-pollution kit including absorbent material bags, absorbent floating barriers, absorbent sheets and proper disposal containers;

- several hundred meters of pneumatic floating boom;
- a few mechanical skimmers to skim the floating oil from the water surface;
- Adequate quantity of proper and known chemical dispersant.

An Example of Tier 2 is when a major structural failure occurs on an offshore installation, and the installation itself is so compromised to be unable to work out a solution itself. Therefore, the on-board personnel needs a readily available specialized help from the vicinity, usually the same country.

Where the sole effort of the local Nation is not enough, the Tier 3 is called in.

Tier 3: in the past 30 years, a network of oil industry positioned several response facilities in different strategic locations around the world, in order to respond to the increasing perceived risks. Such facility network was called Tier 3. Therefore, wherever Tier 2 cannot accomplish with its duties, a more global response will be called in. It is the Tier 3 that provides with globally available capabilities and resources that further supplement Tiers 1 and 2.

The Tier 3 evolution continued with industry-funded groups working collaboratively through mechanisms such as the Global Response Network (GRN) and through the consolidation of some other response cooperatives to provide more effective and efficient management processes.

Tier 3 is called out when the installation failure is so difficult to deal with that only a few emergency kits, placed in a few strategic areas around the Globe, can mitigate the ongoing disastrous consequences. Examples of Tier 3's are written in the history of the oil & gas major accidents.

9.2 Emergency Response Plan [2], [15],[16]

The emergency response plan can be articulated into three chronologically consequent phases, which will ensure the correct result of the entire operation.

9.2.1 First phase (secure people and installation)

This phase is worked out within the very first moments of the accident. The outcome of the entire operation depends on it. Hence, this is the most delicate and anxiety-bearing phase of the whole emergency response plan. Due to the required fast response, this phase is normally accomplished only by the rig personnel, which therefore must be highly qualified and specifically trained. The presence of an experienced Emergency Manager in command is essential to the positive result of the operation.

The first phase includes:

- Isolation of personnel to safe areas from hazardous processes and materials, and possible hazard mitigation (tier 1 only)

It is the very first action to be ensured after the alarm has risen. All non-injured personnel should be able to accomplish with this operation autonomously thanks to periodic and specific emergency drills.

During emergencies, a Temporary Refuge (TR) is an area with all the necessary emergency means (e.g., firewalls, ventilation system, smoke and gas detection system, evacuation routes, emergency secondary lighting, etc.), and where sufficient quantities of specific Personal Protection Equipment (PPE) are allocated. Moreover, TR should be equipped to act as a temporary emergency command centre from which the main plant equipment (BOP, control panel, ballast, etc.) can be controlled. The emergency plan should also contain instructions about alternate actions and mustering areas in the event of an accident, which impairs the TR.

- Search and rescue phase (tier 1 only)

While all the non-injured personnel is secured within a safe area (e.g., TR), specifically trained personnel proceeds to search and rescue of all the injured personnel into safe areas. Search and rescue phase is usually carried out together with the fire-extinguishing phase.

– Evacuation phase (tier 1 and tier 2)

After or while the personnel is relatively and temporarily safe, its evacuation from the installation will ensure the complete and final safety state of all personnel.

To ensure suitable evacuation-and-escape facilities on the installation, it is necessary to provide a solid and proved evac-plan and sufficient equipment, such as floating devices and lifeboats. Also a periodical escape drill is strongly suggested to ensure a correct evaluation of the actual and updated evac-time and for the effectiveness of the equipment itself. To ensure the accomplishment of the final phase of the evac-procedures, external personnel and equipment might be employed such as rescue vessels or helicopters.

– Fire-Extinguishing actions (tier 1 and tier 2)

Fire-fighting actions can be automatically or manually triggered. In both cases they should be deployed during the earliest stage of the emergency.

It is important that the fire-fighting reaction be proportional to the fire action, otherwise the reaction can lead to problems often greater than the fire itself. In other words, an automatic general fire-fighting system should go off only when required. To ensure the accomplishment of the final phase of the fire-extinguishing operation, external personnel and equipment might be employed, such as fire-fighting vessels, fire-fighting airplanes, etc.

– Securing the (offshore) installation (tier 2)

Once all personnel is safely evacuated, and the eventual fire is extinguished, if the installation is still in position, it is vital to reduce the possible consequent structural and mechanical failures of the installation, which could worsen an existing leakage or lead to a blowout or to other major accidents. To ensure such a technically difficult and delicate task, external specific personnel and equipment might be called in.

The positive and prompt outcome of the securing operations will greatly help with the second phase of the Emergency Response Plan: to stop the environmentally damaging consequences as soon as possible.

9.2.2 Second phase (stopping the environmentally damaging consequences) (tier 2 or 3) [9],[17]

As soon as all the staff is safe and sound, and the installation is secured, the second phase can start. It is the initial mitigation of the environmentally damaging consequences caused by the major accident. Among all, the most common and durable consequence is the oil spilling into the water. As described above, it represents a major environmental consequence for both marine and shore ecosystems. For this reason, the source of this threat should be handled with all the necessary technical means as fast as possible.

The following website reports the quantity of oil spilled into the sea in U.S. water in the period 1990-98 (Marine Safety Management System). For details, see:

http://www.allcountries.org/uscensus/390_oil_spills_in_u_s_water.html

Sources of oil spilling are the rupture or failure of the oil piping system or drilling string, which lead to the uncontrolled leakage of the drilled oil reservoir into the water body through the well. Therefore, a prompt action of well containment must be worked out throughout two main different methods:

- Well capping;
- Drilling a relief well.

For both methods, a brief description is provided with particular emphasis on new developments.

Well capping

A capping stack is a device that has the purpose to stop or redirect the flow of hydrocarbons in order to have time to seal the well permanently. It is used when the Blowout Preventer fails stopping the escape of hydrocarbons from the wellhead. The capping stack valves can be closed either to seal the well or to redirect the hydrocarbons to the vessels on the surface through flexible pipes.

The capping stack can be attached to the well in three ways:

- Attached to the top of the Blowout Preventer (BOP);
- Attached directly to the wellhead;
- Attached to the Low Marine Riser Package (LMRP).

Following the Deepwater Horizon accident, in which the oil continued to flow for 87 days before capping, there was the need to develop the capping technology and organization. Several projects were set up to develop new solutions and tools to stop the flow of hydrocarbons rapidly. The results obtained so far are provided below as links to websites of interest:

1) An important project under development is based in Norway. It is the Subsea Well Response Project (SWRP) aiming at enhancing the international subsea well incident intervention capabilities. Four capping systems were developed to be used in different situations. They are located in different regions in order to reduce the intervention time. For details, see: http://subseawellresponse.com/

2) After the Macondo accident, ExxonMobil, Chevron, ConocoPhillips and Shell committed to the Marine Well Containment Company (MWCC) the design and construction of a new capping device. The pre-deployment testing of the new equipment took place in 2012. The MWCC website contains information, photos, and videos about the new capping device. For details, see:

   http://www.marinewellcontainment.com/mwcc-capping-stack-demonstration/

3) After the Macondo disaster, Helix Well Containment Group (HWCG), which is a consortium created by 16 companies that operate in the Gulf of Mexico, was committed to develop a rapid deep-water containment response system. For details, see:

   http://www.hwcg.org/

   http://www.mtshouston.org/pdfs/2014/nobleenergyhwcgjanuary2014.pdf

4) The Oil Spill Prevention and Response Advisory Group (OSPRAG) was established by the UK oil and gas industry to review the UK regulations and to implement recommendations after the Macondo accident. British Petroleum (BP) acted as project manager for the design and construction of the new capping device, with the support from the engineering company Wood Group Kenny. For details, see:

   http://oilandgasuk.co.uk/wp-content/uploads/2015/05/EN021.pdf

5) Wild Well Control (WWC) assists operators in the prevention, preparation, response and recovery from a deep-water well control event. Equipment is located in Aberdeen, Scotland, and can be rapidly deployed. For details, see:

   http://www.wildwell.com/

6) On July 2014, the American Petroleum Institute published new guidelines for the design, manufacture and use of subsea capping stacks. For details, see:

   http://www.api.org/news-policy-and-issues/news/2014/07/29/api-publishes-new-industry-standard-fo

7) The international association oil gas producers (OGP), formed the Global Industry Response Group (GIRG) in 2010 aiming at adopting all necessary measure to successfully face accidents like that of Deepwater Horizon. OGP formed three teams of experts to address the problems of "Well engineering design and equipment/operating procedures", "Capping and Containment" and "Oil spills response". Conclusions and recommendation of these teams are described in the following documents:

- Well engineering design and procedures can be found at:

  http://www.ogp.org.uk/pubs/463.pdf

- Capping and Containment can be found at: http://www.ogp.org.uk/pubs/464.pdf
- Oil spill response can be found at: http://www.ogp.org.uk/pubs/465.pdf

8) Wild Well Control Inc. (WWCI, Houston, Texas) is a provider of emergency fire-fighting, well control and related engineering services for onshore, inland water, offshore and deep-water operations. The following document describes different methods for stopping the release of hydrocarbon when the well control is loss. For details, see:

   https://docs.neb-one.gc.ca/ll-eng/llisapi.dll/fetch/2000/90463/589151/594086/594088/600443/609664/C-05-6D_-_Appendix_B_Same_Season_Relief_Well_Capability_Review_-_A1S2V9_.pdf?nodeid=609515&vernum=-2

9) The DIFIS system. Soon after the Prestige accident (https://en.wikipedia.org/wiki/Prestige_oil_spill) the JRC conceived the DIFIS (Double Inverted Funnel for the Intervention on Shipwrecks) project, which was performed by a consortium of companies (CYBERNETIX, SENER, CONSULTRANS) and research institutes (IFREMER, CEA, SIRENA, ISI) from France, Spain and Greece, coordinated by the Dutch Institute MARIN.

   DIFIS is a system for a prompt underwater intervention on deep shipwrecks. It consists of a large fabric dome which captures the escaping oil and collects it, through a large riser tube, into a large bell-shaped reservoir placed some 30-50 m below the sea surface (so as to make it insensitive to adverse surface weather conditions), which is then periodically emptied by a shutter tanker .

   The Consortium performed extended calculations, simulations and scale tests that proved the validity of the concept and provided detailed design, deployment procedures, and economic feasibility studies.

   From the DIFIS project websites, it is possible to access to papers and video that describe the system in detail: http://www.marin.nl/web/show/id=88561

Drilling a relief well

Drilling relief wells in response to a blowout is a standard tactic in the oil and gas industry. This technique is intended to provide an alternative conduit for injecting dense mud and cement into the out-of-control primary well, thereby plugging it.

Drilling a relief well requires a rather sophisticated technology and some careful calculations, in particular for drilling correctly to the small target many kilometres underground. In fact, at the depth of the target intersection point, the location of the well is roughly known, so the drilling operations are supported by some form of geophysical sounding and electromagnetic sensing [18] to ensure a good connection between the relief and the target well.

The mud density must also be very carefully decided to avoid a possible well-fracturing and a consequent mud leakage into the formation around the relief well [19].

Since a relief well may take many months to be completed, it is considered the ultimate solution for regaining control of a well, also because it introduces additional environmental challenges due to the long duration of the blowout. In addition to that, it is also necessary to keep the relief well under control to prevent a possible blowout.[20] A good example of a relief well plan can be found at the following link:

http://www.jwco.com/relief_well_plan_cratered_well.htm [21]

9.2.3 Third phase (environmental restoration) (tier 2 or 3) [22], [16], [23]

Once the well leakage is under control or even while a team of technicians is working on it, a second team will start the mitigation of the environmentally damaging consequence, which should lead to a complete recovery of the pre-existing environment. Unfortunately, such a goal normally takes years to be completed, and it mostly depends on what already done during phases 1 and 2. Moreover, restoring the environment to the status prior to the accident (**c**leaning up oil) requires the highest level of technology available on the market.

List of existing available techniques for environmental restoration:

Spill Containment

Oil booms are used to contain oil spill in the sea. Available types of oil booms are:

- Pollution Control Floating Dam: polymers that absorb the spillage of hydrocarbons;
- Single point Inflatable: it is suitable for use in a variety of conditions from sheltered water to open ocean waves;
- Sheltered Waters Floating Oil Boom: these oil booms help control spillage in sheltered water as well as in those areas where the water level is relatively shallow;
- Intertidal Floating Oil Boom: it makes use of the tide as a ballast to make sure that the oil spill doesn't go unrestricted;
- Floating Oil Boom: it is appropriate for any kind of water surface;
- Absorbents: are placed on the water so that they can continuously absorb the oil and hydrocarbons;

Further information can be found at:

http://www.marineinsight.com/environment/different-types-of-floating-oil-booms/

http://www.itopf.com/knowledge-resources/documents-guides/response-techniques/containment-recovery/

Dispersant

Dispersants remove surface oil, which could harm wildlife, and keep oil from spreading to the shoreline, enhancing its natural biodegradation and reducing its vapours on the water surface. They accelerate and improve the separation of particles. They are a chemical mixture of surface-active substances added to colloids.

There are two types of dispersant:

- Conventional type: a mixture of non-aromatic hydrocarbons solvents. These dispersants are used undiluted at the time of application, and their quantity is kept between 30-100% of the oil spill quantity.
- Concentrate type: a mixture of oxygenates like glycol and non-aromatic hydrocarbon. They are used after diluting, and the dosage is reduced to 5-15 % of dispersant over oil quantity.

The amount of dispersant depends on several factors, e.g.:

- Type and quantity of oil in the spilled surface;

- Weather condition;
- Distance from the shore;
- Marine environments and marine organism in the area of the oil spill.

Further information can be found at the following links:

http://www.marineinsight.com/environment/different-types-of-dispersants-used-in-an-oil-spill/

http://www.itopf.com/knowledge-resources/documents-guides/clean-up-techniques/dispersants/

http://response.restoration.noaa.gov/about/media/what-have-we-learned-about-using-dispersants-during-next-big-oil-spill.html

Mechanical Recovery

In this case, the oil is removed with minimal environmental impact. There are two types of mechanical recovery: dynamic and stationary.

The Dynamic Oil Recovery does not generally remove all the oil from the water surface when continuous spreading of the oil slick and turbulence at the water surface are of concern.

The success or failure of Stationary Oil Recovery depends on the speed at which skimmers and booms are launched and to what degree the spreading of the oil can be controlled.

The type of skimmer that can be used effectively depends on some factors, such as:

- Spill quantities;
- The properties of the oil;
- The local conditions, water depth, current;
- The weather and sea state.

Mechanical recovery can be inefficient, resource-intensive, and limited by water conditions. Indeed, most skimmers are best suited for calm water, since their effectiveness is sharply reduced by wave action.

Further information can be found at the following link:

http://www.npcarcticpotentialreport.org/pdf/tp/8-6_Mechanical_Recovery-Current_Practice-Operational_and_Technology_Constraints_and_Opportunities.pdf

The BSEE site describes on-going researches on new and improvements of existing technologies.

For details, see: https://www.bsee.gov/site-page/mechanical-containment-and-recovery

Controlled In-Situ Burning

In-situ burning is recognised as a viable alternative for cleaning up oil spills on land and water, as it can rapidly reduce the volume of spilled oil and eliminates the need to collect, store, transport, and dispose of recovered oil.

Ignition is easy for volatile oils but is more difficult for heavier oils. Containment of the oil on water may be necessary to carry out in-situ burning as the oil must be thick enough to quantitatively burn.

The residue from burning oil is largely unburned oil with some lighter or more volatile products removed.

Safety in burning is of prime concern since emissions are, e.g., particulate matter/soot, Polycyclic Aromatic Hydrocarbons (PAHs), Volatile Organic Compounds (VOC), Gases, etc.

The following document describes advantages extensively as well as limitations and problems of in-situ burning:

http://www.wcss.ab.ca/Draft%20Burn%20Manual%20-%20Merv%20Fingas.pdf

At the US API web site, the following report (2015) on in-situ burning gives an insight on this technology:

http://www.oilspillprevention.org/~/media/oil-spill-prevention/spillprevention/r-and-d/in-situ-burning/guide-for-isb-of-on-water-spills.pdf

The following IOGP-IPIECA report is a guideline for the selection of in-situ burning equipment:

http://www.oilspillresponseproject.org/wp-content/uploads/2016/02/JIP-5-ISB-equipment.pdf

The Arctic Response Technology published, in 2014, a state of the art report on In-Situ Burning in Ice-affected waters:

http://www.arcticresponsetechnology.org/wp-content/uploads/2012/11/2014-IOSC_In-Situ-Burn.pdf

Physical Recovery

This method is applied to clean up shorelines by wiping with sorbent materials and pressure washing equipment. Raking and bulldozing can be used to assist natural processes. For details, see

https://www.epa.gov/emergency-response/epas-response-techniques

Natural Processes

Natural processes tend to reduce the severity of an oil spill and accelerate the decomposition of spilled oil.

There are different kinds of natural processes, such as: [24]

- Weathering;
- Evaporation;
- Oxidation;
- Biodegradation;
- Emulsification.

For details on Biodegradation, see:

http://www.oilandgastechnology.net/health-safety-environment-news/oil-natural-gas-eating-bacteria-clear-spills.

Further information on natural processes can be found at:

https://archive.epa.gov/emergencies/content/learning/web/html/oilfate.html]

In the case of an oil spill, satellite and aerial remote sensing represent a very useful technology supporting emergency response. An idea about this technology can be found at

http://eijournal.com/print/articles/technology-advances-support-emergency-responses-in-extreme-environments

9.3 Some considerations about the definition of a methodological approach for emergency planning and response

This section presents some ocnsiderations about the definition of a methodological approach for emergency management, by looking also at the use of emergency management principles and methodologies already developed for chemical plants falling under the application of the European Directive on major hazards (82/501/CEE, amended as 2003/105/CE and 2012/18/UE), also referred to as Seveso Directive.

To this aim, first of all it is necessary to describe the main differences between a (complex) Seveso establishment and an offshore (drilling, production) installation from the risk assessment point of view, since the Emergency plan is based on the results of risk analysis and it must be included in the safety report.

9.3.1 Risk analysis considerations [25]

Risk analysis is a complex procedure, which answers the following questions:

- What can go wrong?
- What are the causes?
- What are the consequences?
- How likely is it?

These questions are obviously applicable to any system, even though the models and data may differ, due to the different characteristics of the systems.

Table 1 provides the main differences in risk analysis for chemical and offshore installations. The following aspects are considered:

- Installation complexity;
- Location and orography;
- Environmental conditions;
- Risk indexes for screening purposes;
- Hazard identification;
- Modelling accident frequencies;
- Modelling accident consequences;
- Risk calculation and representation;
- Safety management system;
- Information to the public;
- Domino effects;
- Land use planning;
- Emergency planning.

As can be seen from the content of *Table 1*, the risk quantification procedures are based on similar models. Indeed, common methodologies concern the identification of hazards, selection of hazardous scenarios of interest, and determination of their occurrence frequency. For consequence assessment, more sophisticated models are used in offshore due to the high density of components, which imply that:

- In case of explosion, due to the high density of components, a deflagration may become a detonation, with heavier consequences;
- Domino effects among components are very probable;

– The application of more sophisticated models based on Computational Fluid Dynamics (CFD) is necessary (more complex models require more data).

	Seveso establishment	**Offshore installation**
Installation complexity	Different units of the plant are displaced horizontally. The density of components is very high only within a single unit.	Different units of the plant are displaced vertically. The density of components is very high on various floors.
Location and orography	On land, with natural or man-made obstacles, and generally close to inhabited areas.	On see water (i.e. flat area), very far from inhabited areas.
Environmental conditions	May be extreme, including flooding.	May be extreme.
Risk indexes for screening purposes	For each plant unit risk indexes are used to decide the level of detail of risk analysis to be applied.	Not applied.
Hazard identification	HAZID, HAZOP, FMEA, etc. Accidents databases.	Same.
Modelling accident frequencies	Fault tree, Event tree, and other reliability methodologies, including human factors. Reliability databases.	Same.
Modelling accident consequences	Fire, explosion (empirical/analytical models), environmental pollution due to dispersion of toxic substances in atmosphere, land, water courses.	Fire, explosion (complex CFD models), dispersion of toxic substances on atmosphere, sea water oil pollution models.
Risk calculation and representation	Risk indexes; Risk contours; societal risk (F-N curves).	Risk indexes.
Safety management system	Yes.	Yes, very similar.
Information to the public on how to behave in accidental situations	Yes, very important. Different information diffusion methods at different distances from the plant.	Not necessary.
Domino effects	Between adjacent units/plants.	Between adjacent components.
Land use planning	Yes, very important	Not Applicable
Emergency planning and response.	Internal plan, external plan involving local and regional authorities.	Tiered preparedness concept. Tiers 1, 2, and 3.

Evacuation	Very critical to evacuate (informed) population at risk.	Limited to trained staff.

Table 1: Main differences of risk analysis between chemical/petrochemical and offshore installations

Safety and environmental management systems (SEMS) are also very similar, whereas the risk representation methods are different due to the different situation about the population distribution. It goes without saying that the information to the public and the land use planning problems exist only for chemical plants.

Due to the use of CFD models, and the need for domino effects and human error studies, it can be stated that the risk analysis of offshore platforms (especially MODUs) may be more complex than that for chemical plants.

On the other hand, opposite conclusions can be drawn as far as the emergency planning and response is concerned.

9.3.2 Methodological approaches for Emergency planning and response

The last two rows of *Table 1* mention the main differences in emergency planning and response between chemical and offshore facilities. In both cases, the occurrence of an accident triggers the internal emergency plan, i.e. the emergency is faced with internal resources only. When this is not sufficient, the external plan is activated.

The organisation and the necessary resources to resolve the internal emergency situation may differ too, being dimensioned according to the time required for the external resources to arrive on site, which is normally longer for platforms, as it depends on the distance from the coast and weather conditions.

Guidelines for emergency planning are available in both fields (chemical and offshore). Although the aim and basic principles are the same (to save human life, minimise environmental and assets damages), the plan organisation is different, as it depends on the type and characteristics of the plant, and its correct application requires the periodic training of all the personnel.

During an emergency, the time needed to take decisions is usually very short, and work conditions very stressful, so it is imperative to provide all the necessary information to come up with the correct decisions.

For chemical and petrochemical establishments a strong interest in researches aiming at developing support tools for external emergency planning and response started in the ’80s. Several support tools are now available at emergency control centres, based on Geographical Information System (GIS) architectures, and interfaced with multi criteria decision models, knowledge bases and expert systems.

GIS is the main user interface that allows working with several layers of geographical information and related databases: plant layout with location of risk sources; networks of road, rail, rivers, pipelines; location of resources for emergency (fire brigade, police, transport means for evacuation); technological networks; population distribution (residents, tourists, workers and their movement during the day); etc.

These systems contain several models e.g. accident consequences, road and rail traffic, population distribution change, evacuation, etc.

The literature on this topic is very reach. See for instance [26], [27], [28], [29].

The development of such tools is very useful, since they not only help in taking correct decisions in real emergency situations, but they can also be profitably used for training decision makers, by simulating situations of emergency and studying the effects of different decisions.

In the case of offshore oil and gas installations, the search of open source decision support tools on emergency planning and response did not return any useful result. The question is: why?

A clear explanation is that people involved in an emergency situation are well informed and trained on how to behave. So, decisions are based on the different status of the installation (process, safety and mitigation systems, evacuation means, etc.) during the development of the emergency. The same situation occurs in a chemical plant when the internal emergency plan is activated; the staff is aware of what to do, i.e. people don’t need a decision support tool, but simply to know the plant state evolution.

10 Conclusions

Universally considered as a dark milestone in the oil & gas world Industry due to the disastrous consequences, the 2010 Macondo accident forced the entire worldwide oil & gas community to change the way of thinking and acting. For this purpose, several documents (e.g., Directive 2013/30/EU) and guidelines (e.g., IADC guideline) have been issued [30], in addition to the new set of best practices published after the accident.

After six years of studies on the Deep Horizon BOP failure, finally, oil & gas drilling industries seem to have started upgrading their technology.

This report has been conceived as an overview of the latest generation of equipment designed to prevent major offshore accidents and reduce the consequences on people and the environment.

The bow-tie diagram has been selected as the main guideline of the report (Figure 1), being able to outline in a clear way how a major accident (here called "undesirable event") is related to a set of causes (threats) and a set of consequences.

A single bow-tie may act as a single ring in a long chain of events, where each event is simultaneously the cause (the trigger) of the following event and the consequence of the previous one (Figure 2).

In a bow-tie chain, some major elements have been highlighted:

- <u>The Hazard,</u> which is a threat that only exists while working in an offshore installation.
- <u>The major accident,</u> considered as the negative consequence of a series of events leading to a major loss.
- <u>The triggering event (or threat),</u> which includes all those situations, locations or pieces of equipment that may cause an accident, if not controlled.
- <u>The safety-related barriers,</u> meant as all those equipment, situations and operational procedure (SEMS) that prevent the threat from turning into an accident, and that mitigate and contain the accident, avoiding worse consequences on people, assets and the environment (being respectively short, medium and long-term consequences).

Last but not least,

- The emergency response, which includes the environmental restoration as a second stage (medium or long term) response plan.

Regarding the here mentioned major accidents, main concerns were over the consequences of blowouts and oil spills, such as life loss, equipment loss, and environmental damages. In fact, besides possibly being the worst scenario in the case of a well-control-loss, a blowout can trigger fire/explosion on board and, in a second stage, an oil spill into seawater. Therefore, this report pointed out to the main actions to undertake and the most suitable equipment for preventing and mitigating such a scenario.

As a prevention method, the Blowout-Preventer (BOP) is the most common and widely used equipment in the oil industry. However, it is also worth stressing that its failure may contribute to the accident.

As a mitigation method, the relief-side-well is possibly the most common technique adopted globally.

The list of web pages and links provided in this report helps the reader go into further detail on these techniques and better appreciate the latest technological advancements in offshore safety, as a consequence of the lessons learned from the Macondo Accident.

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Figure 1: Generic Bow-Tie Diagram 5

Figure 2: example of an event chain in which a threat (the cause) leads to an accident (effect) which can be itself the cause of another effect and so on. The gravity of the consequences increases as the accident sequence progresses 8

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Table 1: Main differences of risk analysis between chemical/petrochemical and offshore installations.. 38

Glossary

API: American Petroleum Institute

BOP: Blowout Preventer

BP: British Petroleum

BSEE: Bureau of Safety and Environmental Enforcement

BTD: Bow-Tie Diagram

CBS: Chemical Safety Board

CFD: Computational Fluid Dynamic

CIRBOP: Circular Intensified Ram Blowout Preventer

COS: Centre for Offshore Safety

DHB: Deepwater Horizon Blowout

DNV GL: Det Norske Veritas Germanischer Lloyd

EPOL: Emergency Preparedness Offshore Liaison group

ESD: Emergency Shut-Down

ET: Event Tree

FPSO: Floating Production Storage and Offloading

FT: Fault Tree

GIRG: Global Industry Response Group

GRN: Global Response Network

HVAC: Ventilation and Air Conditioning

HWCG: Helix Well Containment Group

IADC: International Association of Drilling Contractors

IOGP: International Association of Oil and Gas Producers

LMRP: Low Marine Riser Package

LOC: Loss Of Containment / Loss Of Control

MI: Mechanical Integrity

MODU: Mobile Offshore Drilling Unit

MWCC: Marine Well Containment Company

OCS: Outer Continental Shelf

OPRC: Oil Pollution Preparedness, Response and Co-operation

OSPRAG: Oil Spill Prevention and Response Advisory Group

PAME: Protection of Arctic Marine Environment

PPE: Personal Protective Equipment

PTW: Permit To Work

RACI: Responsible, Accountable, Consulted, Informed

SCADA: supervisory control and data acquisition

SECE: Safety and Environmental Critical Element

SEMP: Safety and Environmental Management Program

SEMS: Safety and Environmental Management System

SMS: Safety Management System

SWRP: Subsea Well Response Project

TR: Temporary Refuge

UE: Undesirable Event

WCC: Wild Well Control

WWCI: Wild Well Control Inc.

DIFIS: Double Inverted Funnel for the Intervention on Ship wrecks

PAHs: Polycyclic Aromatic Hydrocarbons

VOC: Volatile Organic Compounds

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