RISK-BASED ANALYSIS OF OFFLOADING OPERATIONS WITH FPSO PRODUCTION UNITS

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Abstract. *The offshore operations as for oil and gas production have presented a great increase since the early 80s. The development of new technologies allowed to explore oil field in deepwater increasing the complexity and risk associated with the oil offloading operation between any oil and gas production facility and the tanker, due to severe environmental conditions. The published statistics regarding maritime accidents indicate that, in Europe, those operations present a risk of 0,33 deaths/100 million people-km. That number is four times the estimated value for aerial operations. An analysis of the incidents reported for different maritime transportation industry sectors indicate that approximately 8% of those accidents are consequences of failures in loading and unloading operations with tankers.*

The offshore oil extraction includes activities such as production, pre-processing and production export. To make feasible all those activities in an offshore oil field the production facility and the transportation system must operate in an integrated way. In Brazil offshore oil basin, the transportation system is usually executed with tankers. For Campos Basin, around 82% of the total oil production is transported by shuttle tankers.

This paper, aiming at providing safety for offloading operations in deepwater oil fields, presents the application of risk-based analysis techniques to evaluate offloading operations between a FPSO and a shuttle tanker. The preliminary hazard analysis (PRA) technique is used to identify the most probable initiating events of an accident, considering that loss of performance or control of some critical parameter usually causes those accidents. The cause-consequences relations defined through the PRA analysis allowed to identify the vulnerable tasks and critical equipment, including their potential failure modes and the possible outcomes (consequences) of those failures, as for offloading operation. Applying a qualitative risk analysis based on a risk matrix, the relation between the frequency of occurrence of each hazardous event and its consequence could be classified in low risk, medium risk and high risk. For the most critical hazardous events some recommendations are present aiming at reducing their frequency of occurrence.

Keywords: *Offloading, Risk Analysis, Cause-consequences Analysis*

1. INTRODUCTION

The search for oil fields no longer occurs exclusively onshore, but includes the oceans of the world. This fact, has contributed to the development of platforms for drilling and production offshore in deepwater.

The current method for crude oil export is through pipelines, and pipelines have not yet been deployed in water depths of 3000 meter or more, once there are several technical challenges to overcome. Deepwater field development include concepts as TLPs (Tension Leg Platform), Spar, FSO (Floating Storage and Offloading), FPSO (Floating Production Storage & Offloading) and other technically challenging concepts, however the most popular is FPSO. The FPSO unit normally consists of a ship shaped hull, with an internal or external turret, and production equipment on the deck. The unit is also equipped for crude oil storage. Oil transportation systems required for supporting this infrastructure are pipelines or shuttle tankers. Shuttle tankers are increasingly being accepted as a preferred transportation method for remote and deepwater offshore developments. This acceptance is a result of demonstrated performance with respect to the range of success criteria associated with oil transport from oil fields. The shuttle tanker may have its position controlled with of Dynamic Positioning (DP), computer controlled system to automatically maintain a unit position and heading by using her own propellers and thrusters, avoiding the traditional system using tug boat to keep shuttle heading and position (Cicilia, 2004).

The main shuttle tanker size classes are Aframax, Suezmax, and Very Large Crude Carriers (VLCC). The term Aframax had greater meaning during the 1980s than in the 1990s, although the nomenclature is still alive, however, nowadays, they are generally considered to be tankers between 90000 and 110000 DWT. Suezmax is a naval architecture term for the largest ships capable of transiting the Suez Canal fully loaded, and is almost exclusively used in reference to shuttle tankers, which deadweight (DWT) is between 130000 and 160000 DWT, and VLCC are generally deemed to be tankers above 200000 DWT (Tusiani, 1996).

Offloading operations are an important factor in oil industries. The crude oil transport is determinant in the performance of other operations of the oil production chain, including the processed products distribution. To guarantee successful activities, it is essential the integration of transport and facilities. Shuttle tankers have been growing in importance in tandem with the expansion of the offshore oil industry. In the North Sea, for example, offshore loading systems were used to transport 36 per cent of the crude oil lifted in 1995. Today, offshore loading into shuttle tankers accounts for 47% of the North Sea's total production. This trend is being repeated globally, not only in the waters of Brazil, out also in West Africa and in various locations in Asia. More recently, shuttle tankers have been employed on Canadian fields, while the US stands poised to put such vessels into service to assist with the development of deepwater reserves in the Gulf of Mexico (Tanker Operator, 2003). In 2002, Brazil had 46.0% of the total oil production of Petrobras, located in deepwater (400 to 1,000 m), and 29.9% in ultra-deepwater, with water depth greaten than 1,000 m, (ONIP, 2002). The offshore operations in Brazil represent more than 75% of oil exploration operations and the shuttle tankers have become the main way to distribute the crude oil produced offshore. Nearly 82% of the production of the Campos Basin is transported through shuttle tanker (Reis, 2004).

With an increasing number of FPSOs in use, the number of shuttle tankers performing crude oil offloading from these FPSOs is growing too. Although some FPSOs may offload oil to shuttle tankers indirectly via remote loading buoy connected to the FPSO by a pipeline, the majority of FPSOs currently do rely on direct offloading to shuttle tanker. This direct offloading operation is carried out generally via a tandem. Alongside offloading is another possibility, but a less-adopted configuration in harsh environments. The failure in offloading operations cause accidents of considerable magnitudes thus it is fundamentally important to analyze the involved risk in that operation. Despite the notable effort performed at different levels to achieve a safety level for that operation and the significant growth in use of risk assessment techniques in major hazard industries, in recent years, the occurrence of accidents and incidents at sea is still increasing. The published statistics regarding maritime accidents indicate that, in Europe, those operations present a risk of 0.33 deaths per 100 million person-km, 4 times riskier than the air transport system, that accounts for 0.08 deaths per 100 million person-km. Grounding (32%), striking (24%) and collision (16%) are the most frequent occurrences and they have the highest rate of casualties (Trucco et al., 2008).

The tandem offloading operation is a frequently complex and difficult marine operation. FPSO may weathervane (rotate according to the weather) around its turret located either internally or externally, and it may also have significant low frequency motions in the horizontal plane (surge, sway and yaw) due to waves and wind if in harsh environments. In order to stay connected for loading and at the same time maintain a safe separation distance, shuttle tanker has to position itself according to the FPSO position. Offshore loading by shuttle tankers has been carried out in the North Sea for more than two decades (HSE, 1999). Traditionally, this involves turret mooring or a spread-moored loading buoy. The situation is dramatically changed in the tandem offloading operation in terms of positioning complexity and damage potential, due to the significant amount of mass involved (a 150,000 dwt shuttle tanker, for example) in close distance to an installation (FPSO) for a long period of time (MCGA, 2005). To analyze the nature of the incidents in maritime operations, it is necessary to define a complex relationship among design procedures, equipment, environmental conditions and operations. In order to gain a full understanding and comprehensive awareness of safety in a given situation, it is necessary to use a systemic approach to consider all the aspects that may lead to hazardous events. In complex system safety assessment, a systemic approach means to consider all functional entities that constitute the system as a whole, exploring patterns and inter-relationships within subsystems and seeing undesired events as the products of the working of the system (Beard, 1989). Due to its international character the maritime industry is one of the most regulated activities. These regulations are related to different aspects of vessels operation such as: design, construction, ports in transit, operations, procedures, work crew, environment, and safety of all those involved in its operation, etc.

The safety regulations basically are established by the International Maritime Organization (IMO) and by the classification society such as Det Norske Veritas. The IMO developed a series of studies regarding risk assessment including some applications in different types of ships and safety aspects (IMO, 2004). The (IMO) has recommended a method called formal safety assessment (FSA) for future development of rules and regulations. The FSA application aims to guarantee operational improvements on the design or to help in the forecast and control of hazards situations that could result in incidents. Ruud & Mikkelsen (2008) reports some risk-based rules developments in projects, and describing a pilot research project for development of risk-based rules and functional requirements for systems and components for offshore crane systems.

In the literature, Ren, et al. (2008) and TSB (1995) have reviewed the incidents on vessels causing spill when transporting oil and/or gas and found that during the nineties the occurrence of small oil spill at sea was responsible for 98% of total losses of oil and derivatives. Studies of International Tanker Owners Federation Pollution, in the period from 1974 to 1990, showed that the main causes of oil spills in the world were related to the loading and unloading (70.7%) and with the supply operations (12.5%) and that the period from 1974 to 1998 showed a different percentage: 37% of incidents occur in offloading operations, 20% in other routine operations, 12% due to problems with the hull of the shuttle tanker, 8% by grounding, supply, or collisions and 25% are attributed to other causes not specified, (TSB, 1995) and (IPIECA, 1991 apud CETESB, 2002). Comparing the data between the two periods, considering the ship capacity, the frequency of incidents has reduced significantly, whereas the loading, unloading, and supply are the main causes of oil spill of small and medium size, while grounding and collisions are responsible for the incidents with large spill. Shuttle tanker loss of position in powered condition and subsequently collision with FPSO had been reported a few times, (IMCA, 1999).

Precisely the same way, researches ere developed aiming at analyzing and proposing the technique, models and methodology to risk assessment in complex system. Kontovas and Psaraftins (2009) present a critical review of the FSA methodology and propose ways to improve it; the authors identified possible pitfalls or other deficiencies on all steps of the FSA. Parhizi et al. (2009) proposed accident investigation and risk analysis and used factor analysis to identify effective factors on occurrence of accidents in a petrochemical company. Celik (2008) focuses on examining the potential causes and effects of design-based deficiencies in ship by referring to the outcomes of experimental surveys, ship deficiency reports, and marine accident statistics. They present the relevant deficiencies, especially including failure samples, failures that have an influence on the technical performance and operational efficiency, causing major or catastrophic consequences and which have a huge impact on safety and economy. Hu et al. (2007) discuss quantitative risk assessment and generic risk model, especially frequency and severity criteria in ship navigation, and present a model for risk-assessment approach that takes five factors into account, including detailed information about accident characteristics in China. Vinnenm et al. (2006) develop a method in order to assess trends and status for the risk levels in the Norwegian offshore petroleum industry. The method proposes indicators to illustrate the risk aspect. Lee et al. (2001) using the risk assessment methodology, identify 18 hazardous event and 32 risk control measures are devised to reduce the associated risks to the hatchway watertight integrity of bulk carriers. Soares and Teixeira (2001) present different approaches to quantify the risk in maritime transportation. Based on the discussion of several accident statistics the authors provide a global assessment of the risk levels and its differentiation in ship types and main types of ship losses. Nevertheless, the majority studies found in this area is focused on the FPSO, and not from shuttle tanker point view. Moreover only a few studies consider both FPSO and shuttle as one integrated system for risk analysis.

This paper, aiming at providing safety for offloading operations in deepwater oil fields, considering both FPSO and shuttle as one integrated system, presents the application of risk-based analysis techniques to evaluate offloading operations between a FPSO and a shuttle tanker and to identify the most probable initiating events of an accident. Applying a qualitative risk analysis based on a risk matrix, the relation between the frequency of occurrence of each hazardous event and its consequence could be classified in low risk, medium risk and high risk. For the most critical hazardous events some recommendations are present. The paper is organized as follows: In Section 2 it is presented the methodology. Then in Section 3, aiming at failure consequences mitigation the application of cause-consequences relations to offloading operation is presented, followed by discussion of result in Section 3, and conclusions, in Section 4.

2. METHOD DEVELOMENT

The method is based on the cause-consequences analysis, which is a technique that allows, qualitatively, to assess the consequences of the events of broad impact and to see the vulnerability of the environment, community and facilities to those impacts. The cause-consequences relations requires the identification of one or more physical conditions with the potential to cause damaged, called the hazardous event. After their identification, their characteristics as well as the evidence of their occurrence in the particular stage are established. That is, the procedure is based on the selection of hazardous events, to depict the consequences and to determine their causes (Millan and O'Young, 2000).

This step aims at identifying and generating a list of specific hazards to the problem under review. To determine the hazardous events "brainstorming" technique is used involving experienced personnel, as well the procedures definition for the practice of routine operations using a question–answer technique. Apart from human factors, failures in structural components related to complex system are systematically considered by applying the methodology of failure modes and effects analysis, which usually starts from identifying failure modes of each item composing the whole system. Based on information about the system, interviews and experts opinion, many hazards affecting the system are identified.

In each process stage a preliminary qualitative assessment is executed based on the frequency of occurrence and the consequences of undesirable events that degrade the operation in study, in this case offloading operation.

A given event, with probability of occurrence, may have several causes with different probabilities. Thus, it is necessary to check one or more physical conditions that cause the hazardous event, establish the possibility of occurrence and describe the activities set to maintain the systems operation and reduce the possibility of occurrence of the hazardous event. The frequency of occurrence is classified into five categories: Extremely Remote (A), Remote (B), Less Probable (C), Probable (D), and Frequent (E), which are defined in Tab. 1.

Table 1. Frequency/probability for hazardous events classification

Description		**Definition**	
Extremely Remote	**A**	More than 1 in 100.000 years	Extremely unlikely to occur during an activity, but should not exclude the existence of the hazard
Remote	**B**	More than 1 in 1000 years	Highly unlikely to occur during an activity, but should not exclude the existence of the hazard
Less Probable	**C**	More than 1 in 30 years	Possibly happened once during an activity
Probable	**D**	More than 1 in 10 years	Possibly happened more than once during an activity
Frequent	**E**	More than 1 in 1 year	Frequently happened during an activity

Next, the effects on the system attributable to hazardous event are defined. Moreover, consequence of hazardous events or abnormal incidents on the shuttle tanker and offloading operation are described and explained. Similarly, the recommendations of emergency actions must be listed to prevent or to minimize the consequence propagation aiming at severity reduction. A severity numerical scale is defined for hazardous event classification. This scale was defined for three set: safety of personal, facilities and environment; the first is related to the damages or the lesions that can be caused to the employees and others, the second refer to damages in the equipment or installations in shuttle tanker or FPSO and the third is associated with the damages on fauna, flora and ecosystem. The severity classification criteria are defined in Tab. 2.

Table 2. Relative severity criteria for hazardous events classification

Description		**Set**		
		Personal	Facilities	**Environment**
Insignificant	**I**	No significant harm to people, without removal of staff in the interior of the installation	No significant harm to installation	No significant harm to installation, contamination of environment in minimum concentration
Minor	**II**	Slight harm to people in installation, no significant harm to people outside installation	Minor damage or degradation of the installation, with repair at low cost	Contamination of environment below maximum concentration, though, concentration between minimum and medium
Major	**III**	Serious harm to people in installation and/or slight harm to people outside installation	Major damage or degradation of the installation, with possible repair	Contamination of environment below maximum concentration, though, concentration between medium and maximum
Catastrophic	**IV**	Single fatality or multiple severe harm to people inside and outside of installation	Damage or degradation without possible repair or repair take a long time to do	Contamination of environment above maximum concentration

In the last set of the analysis, a measure to classify the risk was established. This measure is the combination between the five frequency categories and the four severity magnitudes (Kumamoto and Henkey, 1996). Therefore, the Risk Matrix is obtained (Fig. 1), as an efficient method for risk analysis of complex system. Risk matrix can describe the two factors of risks: the frequency and the severity of accidents. The risks according to the estimated outcomes can be classified into three different risk categories, namely "Low Risk", "Medium Risk" and "High Risk".

		FREQUENT				
		A	B	C	D	E
SEVERITY	IV	MEDIUM	MEDIUM	HIGH	HIGH	HIGH
	III	MEDIUM	MEDIUM	MEDIUM	HIGH	HIGH
	II	LOW	LOW	MEDIUM	MEDIUM	MEDIUM
	I	LOW	LOW	LOW	LOW	MEDIUM

Figure 1. Risk Matrix

3. APPLICATION

The method is applied on the analysis of the offloading operation, when the crude oil is transported to shore by shuttle tankers through an offloading arrangement. Two kinds of ships that operate in the Brazilian coast are considered: shuttle tanker with dynamic positioning systems (DP) and conventional shuttle tanker (ST).

From the point of view of the shuttle tanker, tandem offloading operation can in principle be summarized into the following five operational stages (MCGA, 2005): 1. Approach: tanker approaches FPSO and stops at a pre-defined distance; 2. Connection: messenger line, hawser and loading hose are connected; 3. Loading: oil is transferred from FPSO to tanker; 4. Disconnection: manifold is flushed, and loading hose and hawser are disconnected; and 5. Departure: tanker reverses away from FPSO while sending back hawser messenger line, and finally sails away from oil field.

In practice, each FPSO may require its own operational procedures. However, there are generic elements in the operation. A generic example is described bellow (MCGA, 2005). In the first stage, the shuttle tanker approaches FPSO, at a maximum speed of 1.5 knot, this stage finishes when shuttle tanker stood 50 to 100 meter behind the FPSO, distance consider appropriate to begin the connection stage. In the second stage, to physically connect shuttle tanker and FPSO, some activities are executed, for example, the messenger line cross from one ship to the other allowing the mooring hawser, and hose to be connected. The tanker may position itself by its own dynamic positioning system so that the hawser is not tensioned, or in the case of a conventional tanker, a certain ´stern thrust is applied by a tug boat, aiming at controlling hawser tension. In the third stage, tests are realized and the valves in vessels are open and oil is transferred from FPSO to tanker. During this stage, transfer rates are slow initially as the integrity of both vessel systems are checked and gradually increased to a maximum transfer flow. When loading is completed and stopped, the hose is flushed, and, the valves are closed. Finally the hose is dropped and sends to FPSO: hose messenger line, hawser and messenger line, so shuttle tanker moves off away FPSO.

After describing the offloading process sequence, and the routines and procedures associate to offloading operation, the hazards on activities and tasks executed in each offloading stage are established.

In each stage a preliminary hazard analysis is made allowing to identify the vulnerable tasks and critical equipment, including their potential failure modes and the possible outcomes. As results of this application study, 56 hazardous events for DP and 64 hazardous events for ST are identified. The distribution of these hazardous events in each stage is presented in the Tab. 3.

Table 3. Hazardous events Classification on Offloading Operation Stage

STAGE	# of Events		
	DP Ship	ST Ship	Total
APPROACH	8	9	17
CONNECTION	19	23	42
LOADING	9	10	19
DISCONNECTION	14	15	29
DEPARTURE	6	7	13

The connection stage is the phase with the highest number of hazardous event. In fact this stage involves more activities associated with mooring hawser and hose connection, beside the smallest distance between shuttle tanker and FPSO.

3.1 Cause-consequences relations

For all hazardous events, their cause and frequency of occurrence were identified, as well as the activities executed aiming at minimizing the occurrence of these causes (mitigating scenarios). In a similar way, the consequences resulting from the hazardous event are identified and classified according to severity criteria (tab. 2). Furthermore, in each case a set of activities that minimize this effect (contingency scenarios) are described. The information from each hazardous event allows the classification according to risk level (Low, Medium, and High). Fig. 2 shows cause-consequences relations as an example of analysis for one hazardous event: “Auxiliary Engine Failure” in the second stage of offloading operation - connection.

STAGE	HAZARDOUS EVENT	DESCRIPTION	SHUTTLE TANKER KIND	CAUSE			CONSEQUENCE						RISK CLASSIFICATION			
				DESCRIPTION	FREQUENCY	MITIGATING ACTIVITIES	LOCAL (Shuttle Tanker)	OFFLOADING OPERATION	CONTINGENCY ACTIVITIES	PERSONAL	FACILITIES	ENVIRONMENT	PERSONAL	FACILITIES	ENVIRONMENT	OFFLOADING OPERATION
CONNECTION	AUXILIARY ENGINE FAILURE	DIESEL-GENERATOR SYSTEM TRIP	ST	Inappropriate maintenance Lubrication problems Engine Trip	PROBABLE (D)	Used rigorous maintenance task , and check list	Hydraulic Pump Trip Equipment Failure	Operation delay in medium level with possibility of collision if the problem continues	Make maintenance in generator system Execute procedure of disconnection and departure of shuttle tanker moves off away FPSO (if the problem continues)	II	III	II	M	H	M	HIGH RISK
			DP	Inappropriate maintenance Lubrication problems Engine Trip	PROBABLE (D)	Used rigorous maintenance task , and check list	Hydraulic Pump Trip Equipment Failure	Operation delay in medium level with collision possibility	Abort offloading operation Request tug or standby vessel assistance Execute procedure of emergency departure of shuttle tanker moves off away FPSO	III	III	III	H	H	H	HIGH RISK

Figure 2. Example Cause- Consequence Relations for one hazardous event

The outcome cause-consequences relations for all hazardous events are presented in Fig. 3, from which we observe that of the totality of hazardous events 47% are classified as high risk, 38% are classified as medium risk, and only 15% as low risk.

The loading stage presents, of the total hazard events, the highest number of medium risk event and there is no events on low risk. Furthermore this is the only stage where the medium risk events are in a higher ratio than the high risk events. The stages connection and disconnection present, of total events, the highest ratio of high risk events, although it is noteworthy that in the disconnection stage the ratio of high risk events is greater than medium risk and low risk events. The departure stage presents no event on low risk.

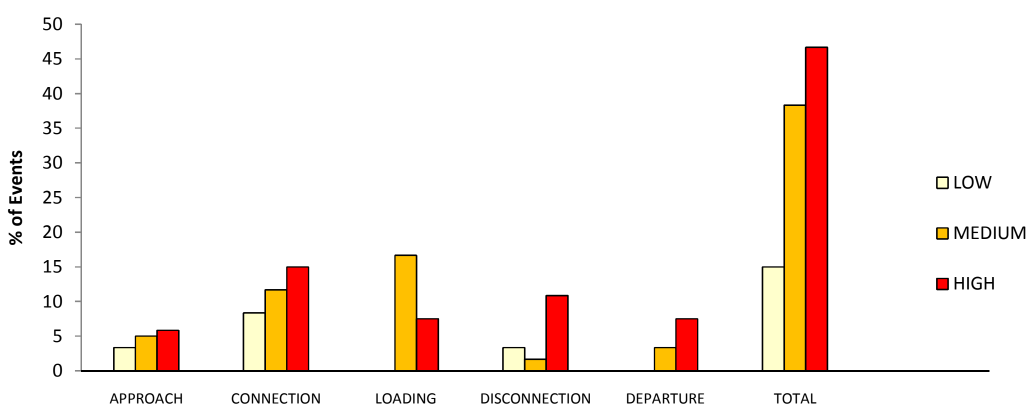

Figure 3. Risk on offloading operations stages

The proportion classified as high risk hazardous events for ST is greater than for DP, in all offloading operation stages. The connection is the stage which the difference between a number of high risk events for ST and DP high risk is significant (Fig. 4).

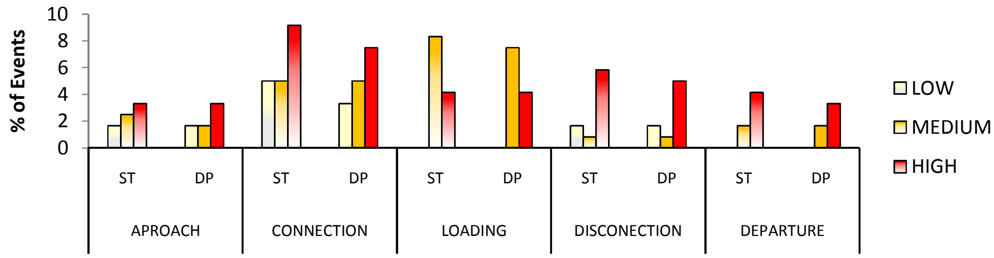

Figure 4. Risk classification on stage and ship kind

3.2 High Risk Events

The hazardous events that cause the highest risks in the process of offloading, according to the combination of the frequency of occurrence and the consequences, have the indication of high risk in the of cause-consequences relations. If the frequency of occurrence of these events is observed (Fig. 5) it is possible to verify that 29% of high risk event are Frequent and 71% of high risk events are Probable. Furthermore, for all the operations with high risk events the hazard happens more than once during an activity. No event with Remote and Less Probable frequency is identified in the analysis.

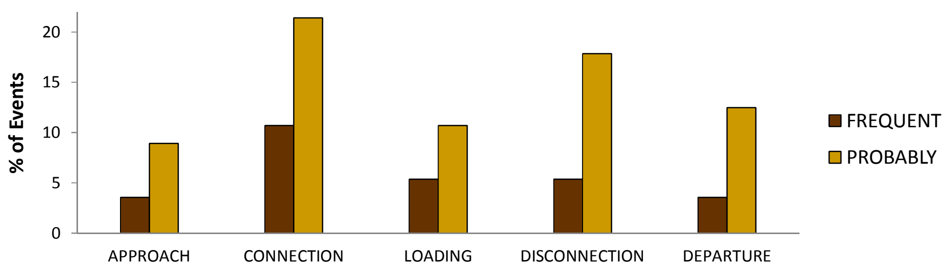

Figure 5. Frequency of High Risk Event on offloading operations stages

Importance must be given to high risk events considered as critical in the 5 offloading operation stages for both vessels ST and DP. Those events are: 1) Auxiliary Engine Failure, 2) Change of environmental conditions, 3) Execution of risky maneuvers, 4) Tug Failure for ST, 5) Dynamic Positioning System Failure for DP, and 6) Towing Cable Failure for ST.

The *Auxiliary Engine Failure* correspond is to a failure in the generator sets that supply electric energy for the vessel systems. The engine loss causes incapacity to transmit electric energy for shuttle tanker systems, including the lubricating oil pumps of the main propulsion engines, thrusters, ventilation, air conditioning, separation equipment, etc; implying in the disconnection of the shuttle tanker (MAN, 2009). The occurrence of this hazardous event would make possible the collision between the shuttle tanker and the FPSO. The severity of this impact will be dependent on the distance of both units, that is, dependent on the offloading operation stage. The *Auxiliary Engine Failure* may be caused by inappropriate maintenance of the generator sets, by problems in the lubricating oil system or some unexpected failure associated to the proper natural ageing of the components of this equipment.

The *Change of environmental conditions* can occur throughout the offloading operation and corresponds to a change process in the conditions of wind, waves and current. It is considered that offloading operation begin with a favorable environmental condition. This event can occur as function of errors in the meteorological forecasts or unexpected changes in the climate conditions. The occurrence of this hazardous event would imply in collision between the shuttle tanker and the FPSO and the severity of this impact will be dependent on the distance of both units, that is, dependent on the offloading operation stage. The way to reduce the frequency of occurrence of this hazardous event is associated with a detailed verification of the meteorological forecast for the period of offloading before the shuttle come into operation field. The contingency measure is to abort offloading operation, through emergency procedures, so shuttle tanker moves off FPSO.

The *Execution of risky maneuver* is the problems associate with the execution of maneuvers of the shuttle tanker throughout offloading operation. Such hazardous event may be caused by programming errors in the automatic system of shuttle tanker or errors of judgment on the maneuverability conditions of the shuttle tanker. In case of occurrence of this hazardous event the shuttle tanker propulsion systems may be overloaded, which will cause a failure, leaving the shuttle tanker with reduced maneuvering capacity. As consequence of this event the collision between the shuttle tanker and the FPSO is possible. Similarly, the severity of this impact will be dependent on the distance of both units, that is, dependent on the offloading operation stage. The contingency recommended involves the request for tug or standby vessel assistance, to correct the position of the shuttle tanker.

Specifically for shuttle tanker ST, the *tug failure*, in any offloading operation stage, also is considered critical, because the shuttle tanker lose the positioning capacity. The *tug failure* may be associated with electric supply failure or hook failure. When the event occurs, a collision between the shuttle tanker and the FPSO is possible and the severity of this impact will be dependent on the distance of both units, that is, dependent on the offloading operation stage. To reduce the possibility of occurrence of this hazardous event the use of procedures of preventive maintenance is recommended. As contingency, offloading operation must be aborted and shuttle tanker reverses away from FPSO.

For the shuttle tanker DP, *dynamic positioning system failure* is considered a failure event similar to the tug failure for shuttle tanker ST, once its occurrence, in any stage offloading operation, will cause lose of the shuttle tanker positioning capacity. This event may result from electric supply problems on the DP, thrusters failure, or control and navigation system failure.

Beyond the events above mentioned, this study allows to identify other hazardous events, however those occur on specific stages of the offloading operation.

For the case of ST, the towing cable failure during the connection, loading, disconnection, and departure, implies in the loss of capacity to keep the position of the shuttle tanker. This failure may be due to the fatigue mechanism or rupture due to overload. Depending on the environment conditions the rolling up of the towing cable in the propeller of the ship can occur, implying in propulsion loss. When at event occurs, a collision between the shuttle tanker and the FPSO is possible and the severity of this impact will be dependent on the distance of both units, that is, dependent on the offloading operation stage. To reduce the possibility of occurrence of this hazardous event the use of procedures of preventive inspection and substitution of the cable are required. As contingency measure in the case of occurrence of at failure, offloading operation is aborted and the shuttle tanker moves off FPSO that maneuver is executed with the aid of the main engine, if possible, or with the aid of another tug.

In the loading stage, for both ST and DP shuttle tanker, a high risk event occurrence due to oil spill of the tanks, caused by improper valve maneuver valves. Once the oil spill has occurred, besides the environment damages where a possibility of fire, causing serious damages to the personal is and the shuttle tanker.

Finally, in the disconnection stage, human errors in the release process of hose and hawser may happen. These errors may cause the fall of these elements in the water, demanding tug or standby vessel assistance contributing to not only operation delay, but also to cause some accident with victims.

4. CONCLUSION

The offshore oil explorations are characterized by complex systems in relation to technology and organization of work. After the initial processing, the oil must travel from the oil field to refinery for further processing. In offshore environment, the crude oil is removed from the field in two ways: by a pipeline laid along the ocean bottom or by shuttle tanker.

The cause-consequences relations analysis is a tool of risk analysis that supports in great measure the identification of critical hazardous events during offloading operations. It allows looking at the event in two directions simultaneously, so, it allows visualizing mitigating scenarios for the causes of hazardous events and contingency scenarios for the consequences of hazardous events.

When each stage of a complex operation is analyzed, as the offloading operation, the cause-consequence relations are used to find the vulnerable points and to establish the causes of hazardous events and, in a similar way, to determine their consequences.

The tandem offloading operation is a complex and difficult marine operation. It may range from once every 3 to 5 days, depending on the production rate, storage capacity of FPSO, and shuttle tanker size. The duration of the operation takes about 24 hours based on FPSO storage capacity and oil transfer rate. Meanwhile, a suitable environmental condition is required. Shuttle tanker loss of position in powered condition and subsequently collision with FPSO is the most significant risk.

Some hazardous events were identified and characterized as high risk events for 5 offloading operation stages. These events are: Auxiliary Engine Failure, Change of environmental conditions and Execution of risky maneuvers. In particular, shuttle tanker ST also presents high risk events associated with the tug boat failure and the towing cable failure. For the shuttle tanker DP stands out as high risk event the Dynamic Positioning System failure.

The cause-consequence relation is a proactive methodology to prevent accidents through risk assessment. It is possible to apply this methodology in complex system aiming at obtaining an effective way to identify and to depict a system, in order to reduce failures and to minimize consequences of the hazardous events.

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