

# **FPSO Cidade de São Mateus gas explosion – lessons learned**

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## **Abstract**

The explosion accident in February 2015 on the Floating Production, Storage and Offloading (FPSO) unit Cidade de São Mateus in the Brazilian offshore sector was the most severe offshore petroleum accident since the Macondo blowout in the US in 2010. The paper aims to discuss the critical implications for the safety of such installations and to recommend solutions to improve safety of FPSO vessels. The root causes are discussed and compared with those of the Macondo blowout and gas leaks on offshore installations in the Norwegian sector. Most of the root causes of the Cidade de São Mateus accident are similar to those of the Macondo accident and gas leaks on offshore installations in the Norwegian sector. Two root causes of a technical nature, related to aspects of safe design, were completely neglected in the investigation into the Cidade de São Mateus accident. These safety features are implemented on virtually all Norwegian FPSO vessels: first, replacing the use of a pump room with individual deep well, submerged cargo pumps in order to eliminate the pump room explosion hazard and second, locating living quarters in the bow of the vessel to avoid exposure to fire.

## **Keywords:**

Floating Production Storage & Offloading, Cidade de São Mateus, gas explosion, organizational faults, design weaknesses

## **1. INTRODUCTION**

The explosion accident in the Brazilian offshore sector on the Floating Production, Storage and Offloading (FPSO) unit Cidade de São Mateus (CDSM) on 11<sup>th</sup> February 2015 caused nine fatalities amongst the 74-man crew on board. Petrobras is the operator of the field, whereas the FPSO was operated by the Norwegian company BW Offshore. The death toll was unusually high and not much less than the 11 fatalities in the Macondo blowout in the US Gulf of Mexico (GoM) in 2010 (Skogdalen et al., 2011).

Two investigation reports have been published and it is also reported that the operator of the field, Petrobras, has issued an internal investigation report although this is not in the public domain. The most comprehensive investigation was performed by the Brazilian authorities: National Agency of Petroleum, Natural Gas and Biofuels (ANP) and was published in Portuguese in December 2015 and in English in early 2016 (ANP, 2016). Earlier, the Brazilian Coast Guard (Brazilian Navy, 2015) published a brief report dealing mainly with the

role of the emergency services. The ANP report is the main source of the detailed time-line and root causes discussed in this paper.

The CDSM accident has attracted only a small fraction of the attention paid to the Macondo accident. A Google search for ‘Macondo accident’ returns about 96,000 hits whereas a similar search for the CDSM accident returns just over 9,000 hits. The number of fatalities was very similar; the big difference is the enormous environmental spill in the case of Macondo. The CDSM accident did not cause any spillage although there was substantial damage to the FPSO unit, which had still not been brought to shore for repairs in early February 2016 (Offshoreenergytoday.com, 2016). There was substantial damage to the pump room where the explosion occurred, as well as to the engine room and superstructure containing offices, canteen and nursery.

There have been few severe explosion accidents on offshore installations, and few of these have been investigated thoroughly to allow the international offshore petroleum industry to learn lessons that may be put into effect on other installations. Since 2000 the following accidents on offshore installations have resulted in publicly available investigation reports:

- Rancador, P-36, Brazil, 2001 (ANP, 2001)
- Usumacinta, Mexico, 2007 (Battelle, 2008)
- Macondo, US, 2010 (Graham et al., 2011)
- Cidade de São Mateus FPSO, Brazil, 2015 (ANP, 2016)

P-36 was essentially a flooding accident with fatalities; the flooding was due to open manholes. Usumacinta was a blowout with fatalities that occurred after the evacuation craft were seaborne. Only the last two of the listed accidents involved explosions or fires from which important accident prevention lessons could be learned. The explosion on the Macondo field was so severe that once the gas had ignited the only mitigation possible was emergency evacuation of survivors. In other words, there has been no accident comparable to the CDSM explosion and so it is essential to analyze it to obtain much insight as possible into accident prevention on-board FPSO installations. That is the aim of this paper.

Over the years there have been many gas leaks on offshore installations in the Norwegian sector. Reports of internal investigations are rarely put into the public domain, but reports of all investigations performed by the Petroleum Safety Authority (PSA) are publically available. A handful of PSA investigations have dealt with gas/oil/condensate leaks during the last ten years or so. In none of these cases did the leaked material ignite. The unignited gas leak discussed in this paper (Section 2.5) is one of the few incidents where both the operator’s investigation report (Statoil, 2012) and PSA investigation report are publically available.

The only investigation report from the UK sector which is in the public domain is the report into the Piper Alpha accident in July 1988 (Lord Cullen, 1990), which was somewhat like the Macondo accident in that it was so severe that all mitigating actions failed. Unlike the Macondo accident, however, the Piper Alpha accident could have been halted in the initial stages, even after ignition, if active firefighting equipment had been available. Vinnem (2013a) documented a similar gas leak on the day before the Piper Alpha accident; in this case escalation was avoided through activation of the automatic fire fighting systems.

The above summary makes it clear that there are few publically available reports of investigations into ignited hydrocarbon leaks on offshore installations and few, if any, deal

with accidents like the CDSM accident. It is therefore crucially important to learn from this accident and surprising that international interest in it appears to be so low.

A brief review of papers analyzing investigations in the offshore petroleum industry indicated that, with one exception, major accidents were not the sole topic of the paper. The exception is the Macondo accident, about which quite a number of papers have been published.

Vinnem (2003) listed accidents and incidents involving FPSO or Floating storage Units (FSU) and Shuttle Tanker (ST) during the period 1996–2003. Accidental events were so frequent that both the authorities and the companies started to worry, and realized they had a common interest in reducing the frequency of incidents and accidents. A Joint Industry Project (JIP) to analyze the ST collision risk in detail was launched as a collaboration between the UK, US and Norway, with oil companies, shuttle tanker operators and authorities participating (Vinnem, 2003).

It led to several proposals for risk-reducing measures (Vinnem et al., 2002, 2003), mainly in the organizational and operational fields. The main actions taken by the industry were directed at increasing the competence of workers and involved increasing the amount of training done in simulators. The frequency of incidents and accidents dropped in the years following the project (Chen and Moan, 2005; Chen et al., 2007; Vinnem, 2013; Lundborg, 2014). Vinnem et al. (2015) have proposed on-line risk monitoring as a risk-reducing measure.

The purpose of this paper is to document and discuss the main lessons to be learned from the explosion on the CDSM FPSO and relate them to the lessons of the Macondo accident and some other less severe events. Descriptions of some other accidents are therefore included, in order to demonstrate similarities, with the main emphasis on the Macondo accident and an unignited gas leak on a Norwegian installation (Heimdal). It is important to learn from less severe events as well as major accidents, because there are more of them.

The main comparison is between organizational and operational root causes. The discussion of the contribution of aspects of FPSO design to safety is of equal importance. There has been very little scientific discussion of the principles of FPSO design, although it has been noted that there are fundamental differences between FPSO designs for the Norwegian sector and for other national sectors. The CDSM accident demonstrates the vital importance of two aspects of design (see further discussion in Section 3.2).

Section 2 consists of brief summaries of the Cidade de São Mateus accident, the Macondo accident and some of the gas leaks in the Norwegian offshore sector, amongst which the gas leak on the Heimdal installation may be considered as a typical example. Skrive noe om hvorfor andre ulykker er inkludert. The root causes of these various accidents are discussed and compared in Section 3, which deals with both organizational factors and two technical root causes not identified in the ANP investigation report. Section 4 discusses the findings and conclusions are presented in Section 5.

## **2. CAUSES OF THE CIDADE DE SÃO MATEUS ACCIDENT AND OTHERS**

### **2.1 Causes of the São Mateus accident**

This summary of the accident is based on the ANP investigation report (ANP, 2016). A condensate leak occurred in the pump room at approximately 11:30 on 11<sup>th</sup> February 2015, while the stripping pump was being used to drain liquid waste from central cargo tank no 6. The leak occurred in a flange in the piping system inside the pump room, due to failure of a spade in the flange connection. The spade had probably been fabricated on board and it failed due to a pressure overload caused when the pump was operated against a closed valve. The root causes of the leak are discussed in Section 2.6.

The stripping pump was not designed for shut-off conditions. Such a hazard had been identified in the HAZOP performed during the design stage (ANP, 2016), but it had been resolved by requiring permanent presence of personnel during operation. The FPSO was not operated in compliance with this requirement, because this was not reflected in the operating procedures.

Three fixed gas detectors installed at the bottom of the pump room detected the gas immediately, but the production plant was not stopped automatically. The production was continued for another ten minutes until a management meeting decided to stop production and to send the first team into the pump room. It is not clear from the investigation report (ANP, 2016) when the stripping pump was stopped, but it is assumed that this pump also was kept running for approximately ten minutes, which severely increased the risks. The ventilation system was stopped due to the gas detection. This implied that no dilution of the explosive atmosphere was attempted, which would increase risks for personnel sent to the pump room, as described in the following.

But despite the availability of information that the atmosphere in the pump room was explosive, three different teams were sent to the leakage location at three different times. The first team was sent to the pump room to investigate the reported gas detection. This team spotted identified the source of the leakage as a flange, and the team leader informed the unit's emergency command about the leak. The second team was intended to assess the work required to repair the leak and restore normal operation of the pump room. Whilst this team was in the pump room the portable detector worn by one member recorded 100% of the Lower Explosive Limit (LEL).

The first team reported that the pool of condensate below the leaking flange covered an area of about 2 m<sup>2</sup>. This is the only indication we have of the amount of condensate that leaked out. The size of the spill may have increased further before the explosion, as this observation was made less than 30 minutes after the leak started, and about 45 minutes before the explosion. The leak is described as 'dripping', which suggests that when this observation was made it was not severe.

If the average depth of the pool of condensate were 5 mm, then the amount of condensate in a 2 m<sup>2</sup> pool would be about 15 kg; if the average depth were 10 mm then it would be about 30 kg. This latter amount is of the order of magnitude required to fill the pump room (but not the access shaft) with a stoichiometric LEL concentration. Although this information is rather imprecise, it suggests that the amount of condensate involved in the explosion was quite small.

Once the second team returned from the pump room it was decided that the situation was under control, and the muster status onboard was stood down, allowing people to return to normal operations and prepare for lunch.

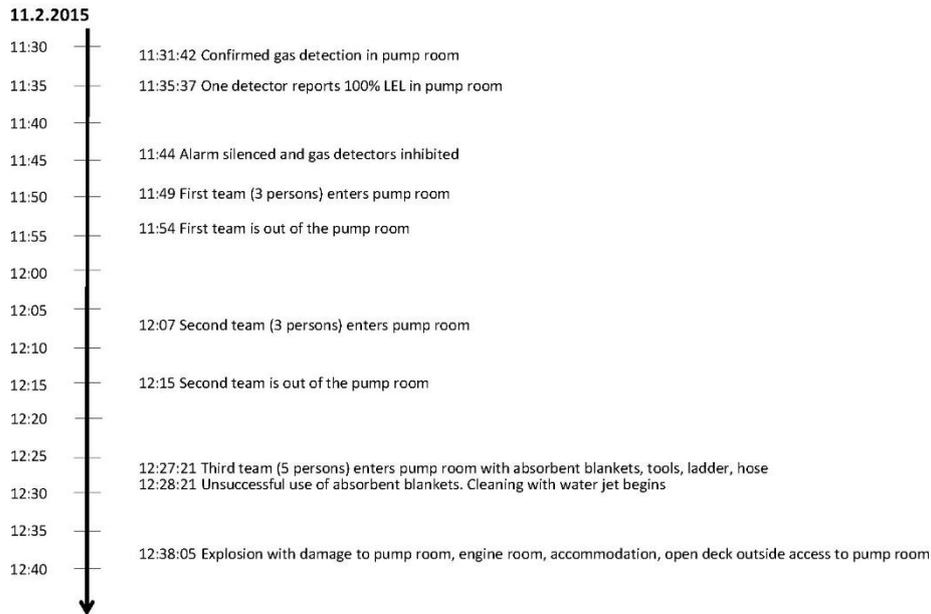
A third team entered the pump room around 12:30, equipped with absorbent blankets, fire hose, ladder and tools, to clear the pool of liquid and tighten the connection screws which appeared to be the source of the leakage. This team went to the site of the leakage, four decks below main deck level. Another team (consisting of members from other emergency teams) was assembled on the main deck, near the entrance to the pump room, to support the third team.

First, the third team attempted, unsuccessfully, to mop up the leaked condensate using absorbent blankets. They also tightened the bolts of the flange connection. Then they used the fire hose to dilute the condensate and remove it to the drain system; a strong explosion occurred at around 12:38, whilst they were doing this. The explosion ruptured the bulkhead between the pump room and the engine room, causing substantial damage to the pump room, access shaft, engine room, the area near the entrance to the access shaft and some accommodation rooms. The report suggests that the likely source of ignition is static electricity from the fire water jet. Ignition occurred when use of the water jet was initiated.

The timeline of the accident is shown in Figure 1, which covers the period, just over an hour long, from the occurrence of the condensate leak until the explosion.

The pressure overload caused the destruction outside of the single access hatch on the top of the pump room, causing the destruction on the main deck level and the immediate death of four members of the emergency teams gathered near the entrance to the pump room. As most of the emergency management personnel were lost in the accident there was little help available to survivors and only limited efforts to search for missing personnel until around 23:30, when external firefighting personnel arrived. It took several days to find all the missing personnel. The final death toll was nine and there were seven cases of serious injury and 19 with light injuries.

The fatalities in this accident were as follows: four of members of the third team sent into the pump room (one survivor only), four persons on the main deck near the entrance to the access shaft for the pump room and one fatality in the engine room muster area (ANP, 2016).



**Figure 1 Overview of immediate causes of leaks (>0.1 kg/s), NCS, 2008–2015 (n=88)**

Attachment provides a complete overview of the causal factors and root causes identified in the ANP investigation. Seven causal factors and 28 root causes were identified. The classification of causal factors into huMan, Technolgy and Organization (MTO) categories (Vinnem, 2013a) is shown in Table 1.

**Table 1 Overview of causal factors and classification in CDSM accident**

Causal factors (ANP)	MTO Classification		
	Human (M)	Techni cal (T)	Organizati onal (O)
1. Inadequate storage of the condensed material			X
2. Operational degradation of cargo system			X
3. Degradation of marine staff			X
4. Operating the stripping pump with the offload sealed	X		X
5. Loss of primary condensed material		X	
6. Exposure of personnel	X		X
7. Ignition of the explosive environment			X

It is clear from Table 1 that the majority of causal factors (and root causes) are in the organizational domain, in common with many other accidents. Root causes are discussed further in Section 2.6.

## 2.2 Performance of mitigation actions

Several of the mitigation actions failed in this incidence. First of all, actions to protect personnel from escalation of the unignited condensate leak into an explosion or fire were inadequate. Figure 1 shows how three different crews were sent into the pump room survey and control the situation. The investigation report shows that actions to protect personnel were significantly inadequate, see Attachment 1, Causal factors No 6 and 7, with the following deficiencies:

- Lack of adequate emergency plans and procedures
- Potential hazards and accident scenarios during the actions to control the incident had not been identified
- Lack of awareness of hazards by management of response crews implied unsafe demobilization stations
- Failure to minimize personnel exposure to the hazards during the emergency response
- Inadequate reviews of emergency response plans implied unnecessary exposure of personnel to hazards
- Failure to recognize the ignition hazard potential implied by the condensate leak.

## 2.3 Design issues not covered by investigation

Table 1 presents a summary of the causal factors identified by ANP; a detailed overview is provided in Attachment 1. Organizational factors made up the majority of root causes (see also Table 2).

The accident had two additional root causes that were completely neglected in the investigation report:

- Reliance on a pump room rather than individual deep well pumps in each storage tank
- Having accommodation located in the vessel's stern rather than her bow.

Most Norwegian FPSO vessels have no pump room, instead having deep well (submerged) pumps in each liquid storage tank. Pump room explosion has long been one of the most important hazards on commercial tankers (Vinnem and Kirwan, 1997). Using submerged deep well pumps for each storage tank completely eliminates the pump room explosion hazard. Individual submerged pumps may be considered an inherently safe design because there is no possibility of explosion and fire when the pump is submerged in hydrocarbons (further discussion in Section 3.2); however it requires significant investment and maintenance is complicated. This underlines the fact that safety improvement sometimes entails a substantial cost penalty.

There are no known previous cases of pump room explosions or fires on FPSO vessels (Vinnem and Kirwan, 1997; Vinnem, 2013a), but there have been several similar incidents on

commercial tankers. In the risk matrix presented by Vinnem and Kirwan (1997), pump room explosion hazard is placed in the highest category, as one out of six scenarios in that category.

The criticality of pump room explosion may be illustrated as follows: If a pump room explosion affects the engine room, as it did in the CDSM accident then it may cause extensive material damage and result in long repair times. This is avoided entirely with deep well pumps.

It should also be noted that on commercial tankers it is standard practice for excess pressure to vent itself on the main deck, as in the CDSM accident, in order to minimize the chance rupture of the hull, which could have catastrophic consequences for the vessel's integrity.

The other root cause neglected in the ANP report into the CDSM accident relates to the location of the accommodation, and is due to the difference between marine and offshore principles. All Norwegian FPSOs, whether purpose-built or converted, have accommodation and the helideck in the bow of the vessel (Vinnem and Kirwan, 1997). This may be considered an inherently safe design, because in a weather-vaning vessel this location accommodation will always be upwind of any source of fire or explosion. This design embodies the offshore principle of siting fire and explosion hazards as far away from the accommodation as possible but although it has been the basis of Norwegian offshore design for more than 30 years, it has not been adopted in many other countries.

Both individual submerged pumps and bow-end accommodation are somewhat specific to the Norwegian sector (Vinnem and Kirwan, 1997). Some of the FPSO vessels in the UK sector have accommodation in the bow, but most have accommodation towards the stern. It has been argued that siting accommodation in the bow means that the helideck on top of the living quarters will be in the part of the vessel subject to the most extensive motion in severe weather conditions, and hence the usability of the helicopter and safety of helicopter operations are more likely to be affected (Vinnem and Kirwan, 1997). Having the helideck in the bow makes landing in severe weather conditions more difficult, but most floating offshore installations in Norway make extensive use of sensors that automatically transmit data on helideck movement to helicopters so that the pilots have a better understanding of conditions before they land.

Having the pump room next to the engine room and in close proximity to the superstructure is unfortunate, as was clearly demonstrated in the CDSM accident. The majority of fatalities occurred on the main deck and in the living quarters. With living quarters in the stern of the vessel, the superstructure will inevitably be close to the pump room and engine room(s), as well as being downwind of any source of fire or explosion in the hydrocarbon process and storage areas. Thus if an explosion occurs in the pump room, the design ensures that excess pressure is vented next to the quarters.

Both the existence of a pump room and the siting of accommodation are fundamental design factors that contributed to the high death toll of the FPSO explosion (9 fatalities). Organizational errors also contributed to the high number of fatalities on the main deck and in the living quarters, but under a different design they would have had less impact. Had the pump room not been next to the engine room, there might not have been an explosion; had the living quarters not been in the stern the number of fatalities would probably have been lower.

## 2.4 Summary of the Macondo accident

A brief description of the Macondo accident has been included in order to enable a discussion of similarities and differences between the two accidents. The failures of risk management in the case of the Macondo blowout have been thoroughly discussed by many authors, including Skogdalen et al. (2010). The following is a very brief excerpt from this source; a longer summary of events may be found in Skogdalen and Vinnem (2012).

In February 2010 Deepwater Horizon started drilling the Macondo exploration well, about 66 km off the southeast coast of Louisiana, USA. The depth of water at this location was around 1500 m, and the plan was to drill to 5500 m below sea level, then plug the well and suspend it for subsequent completion as a subsea producer well. On April 20<sup>th</sup> a well control failure caused explosions and a fire on the rig, which burned until it sank 36 hours later, resulting in 11 fatalities and a massive environmental spill (BP, 2010). According to the National Commission (2010), the root technical cause of the blowout was that the cement BP and Halliburton had pumped to the bottom of the well failed to seal off the hydrocarbons in the formation (Bartlit et al., 2011; Graham et al., 2011).

According to the National Commission (Graham et al., 2011), BP's management process had failed adequately to identify and manage the risks created by late changes to the well design and procedures. BP did not have adequate management controls in place to ensure that key decisions in the months leading up to the blowout were safe and adequate from an engineering perspective. Initial well design decisions are subject to rigorous peer review, and changes to well bore design are normally subject to a management of change (MOC) process. In the case of the Macondo well it appears that BP's Macondo team made changes to the design in an unstructured way, without any formal risk assessment or internal expert review (Graham et al., 2011).

According to the Chief Counsel's Report (Bartlit et al., 2011), several of BP's decisions - not to use drill collars, not to use a mechanical plug, setting the plug in sea water, installing the lock-down sleeve last - might have made sense in isolation, but they also created hazards individually, and particularly in combination with the rest of the temporary abandonment operation. For instance, BP originally planned to install the lock-down sleeve at the beginning of the temporary abandonment. The decision to change the plan and install the lock-down sleeve last triggered a multitude of other decisions that resulted in the well being severely underbalanced and meant that the cement in the bottom hole was the sole physical barrier to leakage during displacement of the riser. There is no evidence that BP conducted any formal risk analysis before making these changes to the original plan, or even of the procedure as a whole (Bartlit et al., 2011). BP's own investigation report acknowledges that there was no risk analysis of the decision to change the plan. BP's management system did not prevent this kind of unstructured decision-making. BP required relatively robust risk analysis and mitigation during the planning phase of a well, but not during the execution phase (Bartlit et al., 2011; BP, 2010). In addition it appears that Transocean's crew neither undertook any risk analysis nor established risk mitigation plans in relation to performance of simultaneous well operations once the cement barrier was judged safe (Bartlit et al., 2011).

In summary, the main root causes of the accident, all in the organizational domain, are as follows (SINTEF, 2011):

- Ineffective leadership

- Compartmentalization of information and deficient communication
- Failure to provide timely procedures
- Poor training and supervision of employees
- Ineffective management and oversight of contractors
- Inadequate use of technology/instrumentation
- Failure to analyze and evaluate risk appropriately
- Focus on time and costs rather than control of major accident risks.

## **2.5 Incidents in the Norwegian sector**

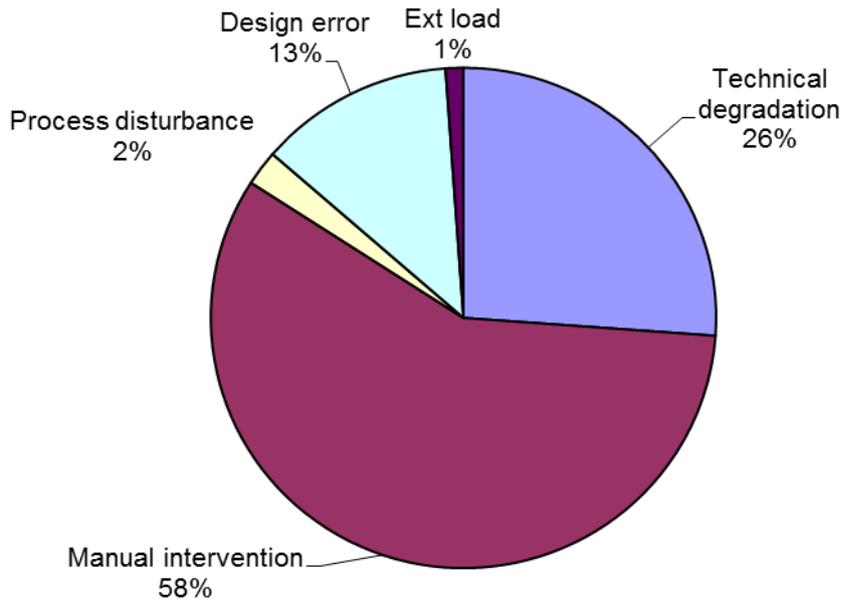
There have been few major accidents involving fire and explosion on FPSO vessels; the most common accidents on these installations have been multiple anchor line failures in severe weather (Vinnem, 2013a). The most relevant comparison to make is therefore not in the technical category (similar incidents), but rather in the human and organizational categories, especially in the latter (different incidents with parallel root causes). Detailed investigation reports on the most serious FPSO accidents are not available, so direct comparison is not possible.

Over the years, there have been several serious incidents on the Norwegian Continental Shelf (NCS), most commonly unignited hydrocarbon leaks, most of which were mainly caused by non-technical faults. These incidents are relevant to a comparison and discussion of operational and organizational root causes of incidents and accidents. These incidents are therefore described in some detail, in order to enable a discussion of similarities and differences. The main emphasis is on one severe unignited gas leak on the Norwegian Heimdal platform in 2012.

Over the period 2008–2015 there have been 88 oil, gas and condensate leaks in the Norwegian sector with an initial leak rate of at least 0.1 kg/s (Norwegian Oil and Gas, 2016; PSA, 2016b). Seven of these occurred on FPSO vessels. As there were six FPSOs operating on the NCS in this period, this corresponds to about one hydrocarbon (HC) leak per FPSO over eight years, a similar frequency to that on other types of offshore production installation.

In the case of HC leaks, leaks from process equipment onboard an FPSO are no different from corresponding leaks on other offshore installations so our statistics are based on all offshore installations in the Norwegian sector. The fact that the installation may not be an FPSO is not considered particularly relevant to the cause of the accident.

Figure 2 shows an overview of the immediate circumstances of all leaks on the NCS with initial HC leak rate of at least 0.1 kg/s.



**Figure 2 Overview of immediate causes of leaks (>0.1 kg/s), NCS, 2008–2015 (n=88)**

More than 50% of the leaks were associated with manual intervention in normally pressurized systems. This percentage has been stable at between 50% and 60% for more than 15 years, and suggests that HC leaks associated with manual intervention in process systems are one of the most significant hazards on offshore oil and gas installations. Based on the description given in Section 2.1, the accident on board CDSM would fall into the same category as about 58% of the leaks on the NCS during the last eight years. Further details of HC leaks in the Norwegian sector may be found in Vinnem and Røed (2015).

One of the relevant incidents during this period is the large gas leak that occurred on 25<sup>th</sup> May 2012 on the Heimdal steel jacket production installation in the Norwegian sector (PSA, 2012). This leak is representative of leaks associated with manual intervention (see Figure 2) and occurred in connection with the testing of two emergency shutdown valves (ESDVs). Before the test, the relevant sections of the production plant were shut down and depressurized for maintenance.

Preparations for testing the ESDVs included the blowdown of a bleed-off pipe section of the flare system. This pipe section included a main control valve (HCV) operated from the central control room, and three manual isolation valves. The HCV has a pressure rating of 180 bar, whilst the final manual isolation valve before the flare had a design pressure of 16 bar. The change of pipe design pressure was just downstream of the HCV. This is not consistent with current industry practice, but was common at the time the installation was designed, more than 30 years ago. The change in pressure rating was well known amongst the experienced operators onboard, but was not universal knowledge.

The last isolation valve, which functioned as the final barrier to the flare, was never operated and remained closed. Once the blowdown had been initiated by opening the HCV, the closed isolation valve was exposed to a pressure of 129 bar. As a result, the gasket ruptured and the insulation and the enclosure around the flange were blown off. Gas leaked out into the local process module and spread over large areas of the upper deck on the installation.

The process operator in charge of the operation was inexperienced, and had not been involved in the planning of the work. The operator who had been involved in the planning (and was aware of the pressure change) was unavailable as he was taking lunch, and the control room personnel were anxious to finish the job during the lunch break to meet a self-imposed deadline.

As soon as the control room was notified of the leak by operator in the process area, the control room operator shut the HCV. The valve finally closed after about four minutes and the leak ceased. Gas was detected in all the process modules, and the gas persisted on the installation for about 30 minutes.

The leak was one of the most serious gas leaks on the NCS in several years. A total of 3,500 kg of gas was released over 252 seconds and the initial leak rate was 16.9 kg/s. The total gas volume in the pipe segment was 53.5 m<sup>3</sup> at 129 bar and 9°C.

The main observations made by PSA in their investigation report (PSA, 2012) were:

- deficient design solution (common practice when the installation was new)
- failure to identify the deficient design solution
- deficient descriptions of how the work was to be done
- weaknesses in the management of documents
- weaknesses in risk assessment during planning
- weaknesses in expertise and risk awareness
- weaknesses in experience transfer and learning from earlier incidents.

An analysis of root causes of HC leaks in the Norwegian sector (Vinnem and Røed, 2015) provides more details and indicates that the gas leak on Heimdal in 2012 is representative of this type of event, sharing the root causes of the majority of HC leaks in the Norwegian sector.

## **2.6 Comparison of root causes**

This section presents a brief comparison of the root causes of the incidents and accidents discussed above, i.e. the CDSM and Macondo accidents, and the Norwegian Heimdal gas leak. The comparison is limited to organizational causes, as the technical and operational causes were incident-specific. The comparison is presented in Table 2, which groups corresponding root causes in the three accidents together in rows.

The reader may note that some of the issues listed under ‘operational root causes’ for the Heimdal gas leak (PSA, 2012) are listed under ‘organizational root causes’ for the CDSM accident. We therefore discuss these operational and organizational root causes together; the operational root causes of the Heimdal gas leak (PSA, 2012) are also included in Table 2.

The summary of root causes of the Macondo accident (Tinnmannsvik et al., 2011) mentions the failure to provide relevant procedures as a root cause. The Heimdal investigation report lists inadequate description of work to be executed, as well as deficiencies in the use of procedures (Table 2). The corresponding root causes for the CDSM accident are outdated/unavailable/inadequate procedures and incomplete operating procedures. Insufficient procedures are certainly a common factor.

The Heimdal investigation report lists inadequate operational risk assessments as a root cause, which corresponds with the lack of a review of hazards and the failure to identify accidental scenarios given in the list of causes of the CDSM accident (Table 2). The numbers in parentheses in the 3<sup>rd</sup> column identify causal factors and root causes as listed in Attachment 1. The numbering of causal factors in Table 2 is also linked to the summary of causal factors presented in Table 1. The corresponding root cause of the Macondo accident was the failure to analyze and evaluate risk appropriately. Failures in the hazard review and operational risk assessment procedures are another common factor.

**Table 2 Comparison of CDSM accident root causes with Macondo accident and Heimdal gas leak (Numbers in brackets in the 3<sup>rd</sup> column refer to causal factors and root causes in Attachment 1)**

Macondo accident	Heimdal gas leak	CDSM accident
<ul style="list-style-type: none"> <li>• Focus on time and costs rather than control of major accident risks.</li> <li>• Failure to analyze and evaluate risk appropriately</li> <li>• Compartmentalization of information and deficient communication</li>   <li>• Ineffective leadership</li> <li>• Poor training and supervision of employees</li> <li>• Failure to provide relevant procedures</li> </ul>	<ul style="list-style-type: none"> <li>• Lack of understanding of system responsibility in management system</li> <li>• Operational risk assessments not adequately executed</li> <li>• Deficiencies in identification and communication of safety critical aspects</li> <li>• Deficient learning from previous leaks</li>   <li>• Inadequate description of work to be executed</li> <li>• Deficiencies in the use of procedures</li>   <li>• Weaknesses in design not identified</li> </ul>	<ul style="list-style-type: none"> <li>• Management of change not performed (1/1)</li> <li>• Lack of hazards review (1/2)</li> <li>• Inadequate communication between shifts (2/4)</li> <li>• Failures in registration and modification of records (2/5)</li> <li>• Lack of marine superintendents (3/7)</li> <li>• Inadequate dimensioning of the training program (3/8)</li> <li>• Lack of supervision (3/9)</li> <li>• Failure to identify training requirements (3/10)</li> <li>• Outdated/unavailable/inadequate procedures (4/12)</li> <li>• Incomplete operating procedure (4/13)</li> <li>• Noncompliance with project criteria (4/15)</li> <li>• Lack of inspections, calibration and tests (5/16)</li> <li>• Failure in the control of spare parts (5/19)</li> <li>• System without space for spades installation (5/20)</li> <li>• Failure to identify accident scenarios (6/23)</li> </ul>

Macondo accident	Heimdal gas leak	CDSM accident
<ul style="list-style-type: none"> <li>• Ineffective management and oversight of contractors</li> <li>• Inadequate use of technology and instrumentation</li> </ul>	<ul style="list-style-type: none"> <li>• Weaknesses in document control</li> <li>• Work not included in Work Permit system</li> <li>• Deficient planning of work task</li> <li>• Access</li> <li>• Verification</li> <li>• Contribution to updating</li> </ul>	<ul style="list-style-type: none"> <li>• Lack of awareness (6/24)</li> <li>• Inadequate mechanisms for the review of emergency response plans (6/27)</li> <li>• Lack of specific instructions for the performance of certain tasks (7/28)</li> </ul>

Failure to learn from previous events is truly a common denominator in a large number of similar incidents on the NCS (Vinnem, 2013b), and is mentioned in the Heimdal investigation report (Table 2). It is not mentioned as a root cause in the CDSM accident investigation, nor in the summary of the root causes of the Macondo accident. As this is a major deficiency in operations on the NCS, it is unlikely that other sectors are not similarly affected, although accident investigation summaries fail to recognize it as a contributing factor. On the other hand, one could possibly argue that the Macondo and CDSM accidents were unique events and that there are no similar events of comparable magnitude with which to compare them.

The Heimdal investigation report lists deficiencies in identification and communication of safety critical aspects of the operation (Table 2) as a root cause. Similarly, the Macondo summary identifies the compartmentalization of information and deficient communication as root causes, alongside ineffective leadership. The CDSM investigation report does not include a corresponding root cause, but it does list root causes such as inadequate communication between shifts, lack of supervision and lack of risk awareness. Lack of awareness is certainly a common factor for these two events.

Weaknesses in document control are listed as a root cause in the Heimdal investigation report (Table 2), whereas the CDSM investigation report lists failures in registration and modification of records. This factor was not listed as one of the main root causes of the Macondo accident (SINTEF, 2011). Failures of document control were thus a root cause common to the Heimdal and CDSM accidents.

An important root cause of the Macondo accident was the focus on time and costs rather than control of major accident risks. This is not listed as a root cause for the Heimdal gas leak, but it is well established that self-imposed time pressure was the reason for starting the operation without experienced personnel present (PSA, 2012). Although not identified as a root cause in the CDSM accident, the long list of deficiencies in Table 2 implies that prioritizing of production over safety may have been a contributing factor.

Finally, lack of compliance is also an important root cause of HC leaks in the Norwegian sector, as discussed in Section 3.1 below.

### 3. DISCUSSION OF LESSONS LEARNED FROM CDSM ACCIDENT

#### 3.1 Human and organizational root causes

There is a saying that ‘If you think accident prevention is expensive, try an accident’. Some companies have recently learnt this the hard way, for instance BP in the case of the Macondo accident. The CDSM accident may also prove quite costly, as the vessel had still not been brought off the field for onshore repairs one year after the date of the accident.

Another lesson is that a full investigation of an incident or accident will always find organizational faults and oversights, and will probably lead to injunctions from the authorities, or more severe consequences.

The common factors in the CDSM and Macondo accidents and the Heimdal gas leak are discussed above in Section 2.6 (lack of adequate procedures and other documentation, inadequate risk assessment, failure to learn from previous events, deficits in communication and awareness and prioritizing of production over safety). They are, as already noted, factors common to many accidents and incidents. The large extent of common root causes is one of the reasons why it is important to investigate incidents and learn lessons that will help to prevent serious accidents. Learning from previous events is discussed in Section **Error! Reference source not found.**

The overview of investigations into root causes of HC leaks in the Norwegian sector in Section **Error! Reference source not found.** demonstrated that the following factors were identified in about 50% of the investigations:

- Failure to follow accepted work practice.
- Failure to comply with steering documentation, such as procedures.
- Failure to perform relevant risk assessments.
- Lack of understanding of risk.

These factors were also relevant to the Macondo, Heimdal and CDSM incidents summarized in Table 2 above. Weak leadership is another root cause commonly identified in accident investigations into oil and gas leaks in the Norwegian sector (Vinnem and Røed, 2015). More than 50% of the oil and gas leaks on the NCS (above 0.1 kg/s initial leak rate) occur during manual intervention in normally pressurized systems (Vinnem and Røed, 2015). The CDSM accident revealed that the same issues affect the BW Offshore organization on the CDSM FPSO. The condensate leak in the CDSM accident also occurred, as described in Section 2.1, during manual intervention in normally pressurized systems. There appears to be considerable similarity between the condensate leak, the initial phase of the CDSM accident and many oil and gas leaks in the Norwegian sector. The Heimdal gas leak was caused by pressurizing a pipe section beyond its capability, as outlined in Section 2.5, which is yet another commonality between these two events.

Experience shows that learning from previous incidents and accidents often is a considerable challenge for organizations. Vinnem (2013b) discussed failures to learn from investigations of HC leaks and some of the most likely causes. When the installation’s own personnel conducted the investigation, few root causes were found (average of 3.4 per investigation).

Nevertheless, it is noteworthy that work practice failures, compliance failures, lack of risk assessment, lack of apprehension of risk and deficient supervision are the most common root causes. These most common root causes should be considered valuable experience from incidents applicable in the Norwegian oil and gas industry, and most likely also for the operator of CDSM.

### **3.2 Design root causes**

One of the issues sometimes discussed in relation to risk management in the Norwegian petroleum sector is the limited scope of accident investigations performed by the supervisory authority itself (Vinnem, 2013b). It is unlikely that an investigation will address weaknesses or deficiencies in regulations if it is carried out by the organization responsible for defining the regulations. A national accident commission, as Norway and several other countries have for the transportation sector (Vinnem, 2013b), that is independent from other authorities, would be more likely to address such deficiencies. The failure of the ANP investigation report (ANP, 2016) to address the two design-related root causes discussed in Section 2.3 may be related to the same type of bias sometimes noted for Norwegian investigations.

The PSA investigation (PSA, 2016a) into the fatal accident on board the mobile installation COSL Innovator 30.12.2015 provides an illustration of the type of bias discussed above. One person was fatally injured in his cabin by a large wave that smashed the cabin window (as well as the windows of several other cabins). The window had not been designed to take wave loading, even though some analyses from the design phase showed that horizontal wave loading on the accommodation block (as part of the box girder) could be expected in design wave conditions. The installation had an Acknowledgement of Compliance (AoC) from the PSA in 2012. The PSA investigation report does not address whether there were oversights or other faults with the compliance assessment carried out by the PSA before it issued that AoC and it also fails to consider what implications such oversights might have had in relation to the accident. One would expect an independent investigation to have considered these issues. The PSA's investigation held the owner of the mobile installation responsible for the accident. The owner replied in the media that the investigation's criticism implied a change in how the regulations are interpreted, which would presumably apply to all similar mobile installations. Similar comments have also been made by an independent expert (Gudmestad, 2016), underlining that there are aspects of legislative principles involved beyond what is discussed in the PSA investigation.

Although the importance of the two design factors discussed in Section 2.3 has been demonstrated through this accident, the CDSM accident is to the best of our knowledge the first practical demonstration - through accidents or incidents involving FPSO vessels - of the importance of these design factors. ANP may be unaware of these important differences (see Section 2.2) between FPSO designs.

Both aspects, deep well pumps and bow-mounted quaters are mentioned by Paik (2007) in a description of how to design FPSO installations, but not recognized as features of inherently safe design, which would have lent them more importance. These design choices may thus be described as established or accepted practice. On the other hand, it is a fact that FPSO vessels are built and operated without paying significant attention to these two aspects of design, implying that outside Norway their importance is to some extent overlooked.

In any case, it is valuable experience feedback from the CDSM accident to note from a Norwegian perspective, and perhaps others may also learn from these events. Many recent international FPSO designs (including designs for newly built vessels) have been quite alarming, apparently paying very little attention to protection against the effects of explosion and fire. For instance in some designs a large deck area on top of the tank sections of the FPSO is taken up by an enormous process plant, perhaps many tens of thousands of cubic meters in volume, and there is no separation of the space into smaller fire and explosion areas. In the worst-case scenario, ignition of a massive gas cloud deep inside such a volume would totally destroy most of the process plant and might even rip the entire vessel into sections, causing it to sink and disappear in just a few minutes. Such designs could be described as violation of established and accepted practice, but it has been seen on several new projects in recent years.

These designs have been implemented in environments where the legislative constraints are very limited and safety is solely in the hands of the industry. Some of these designs appear to reflect a total disregard for the requirements of major accident prevention and to have been driven solely by a desire to minimize costs and maximize production. Lack of legislative constraints do not apply to Brazil and ANP, but it is still noteworthy that the design issues relating to deep well pumps and bow-mounted quarters are not addressed at all. But most likely, ANP has been unaware of these important aspects.

The lack of focus on these design aspects also tends to underline the fundamental challenge of major accident prevention, because of the rare occurrences.

Following the Alexander Kielland accident in the Norwegian sector in 1980 the Norwegian Maritime Directorate introduced new requirements for reserve buoyancy in the deck of floating offshore installations operating in the Norwegian sector (Vinnem, 2013a) but they do not apply outside the NCS. Since these new requirements were introduced the Norwegian sector has not seen any accidents in which reserve buoyancy was important ('multi-compartment filling'). This has meant that from time to time companies are tempted to remove the reserve buoyancy from their new designs to reduce the investment cost; however, some years ago BP learned how important such a capability can be. After Hurricane Dennis swept through the GoM in 2005, personnel returned to the Thunder Horse facility to find it listing at approximately 20°, with the top deck in the water on the port side (MMS, 2005). In the GoM it is common practice to evacuate all personnel from installations in the event of a hurricane, as a precaution, so there were no injuries or fatalities, nor would there have been any had the installation capsized. The listing appears to have been due to installation failures. The facility was preparing for the start of production at the time of the hurricane. The only reason it was possible to salvage the facility and tow it to shore for repairs was that BP had installed reserve buoyancy in the deck (not a requirement in the US) as a safety measure. Had it not been for the buoyancy in the deck, the world's largest (at the time) floating production installation would have been a total loss before it had even started production. This is the only case during the 35 years since this requirement was introduced in the wake of the Kielland accident where it is known that reserve buoyancy in the deck prevented loss of an installation in critical multi-compartment filling.

Because major accidents are rare it is very important that lessons are learned from them, wherever they occur. The importance of safety features and accident prevention should also be identified. This applies to the Thunder Horse incident as well as the CDSM accident.

It is worth noting that design changes may often provide solutions that are termed inherently safe, which, according to Lees (1996), means that hazards have been eliminated. The two design features considered in Section 2.3 are both inherently safe solutions – eliminating risk of living quarters being exposed to fire by locating them upwind of all potential sources of fire and the eliminating the pump room explosion hazard through the installation of submerged pumps in individual tanks. Installing submerged pumps in individual tanks may be easier on new FPSO vessels, but it has also been done on converted tankers.

### **3.3 Emergency response**

Some of the root causes of the CDSM accident were associated with lack of awareness of the hazards posed by condensate and the lack of a review of emergency response plans (Table 2). It is easy to overlook the extreme volatility of condensate liquid, which easily forms a significant gas cloud inside modules and structures. Had awareness of the hazards posed by condensate been greater on board the CDSM FPSO it is unlikely that so many people would have been exposed to the gas explosion hazard, both in the pump room and on deck next to the access shaft for the pump room.

There may be insufficient awareness of hazards to emergency response personnel in Brazilian operations. In the CDSM accident the majority of fatalities occurred amongst the emergency teams and similarly, several of the 11 fatalities in the Roncador P-36 accident were amongst emergency personnel (ANP, 2001).

It is easy for personnel who are not familiar with the characteristics of condensate to overlook hazard potential of condensate. The author vividly remembers a condensate leak incident simulation exercise that took place in Norway about 20 year ago. During the exercise his/her a previous colleague, an experienced Offshore Installation Manager (OIM), exposed 28 persons to the simulated gas explosion hazard whilst attempting to rescue a person with a broken leg from the space in which a gas cloud from the condensate leak was accumulating.

Hazard awareness is also a common factor in many investigations into HC leaks on NCS (Vinnem, 2013b). There are many anecdotal accounts dating from about 30 years ago of persons voluntarily entering spaces so dense with gas that breathing was a challenge, with the sole purpose of closing a manual isolation valve to stop or limit the leak. Today, at least in Norway, hazard awareness is better, particularly in relation to the emergency responses and the need to protect emergency team members from hazards associated with responding to an event.

## **4. CONCLUSIONS AND RECOMMENDATIONS**

The accident on the Cidade de São Mateus FPSO is important in that it has reconfirmed the severe accident potential of HC leaks. The potential severity of the consequences of HC leaks may be well known to risk management specialists, but is too easily forgotten during long periods without ignited HC leaks. The last ignited HC leak (pressurized systems; >0.1 kg/s) in the Norwegian sector occurred in 1992, so maintaining awareness of the ignition potential is a significant challenge.

The CDSM accident has important lessons to be learned in several respects, with respect to design and operation of process plants, mitigation of hazardous scenarios, emergency response management, as well as human and organizational factors in risk control.

The design of the process plant was such that production was not stopped automatically upon confirmed gas detection, but ventilation of the pump room was stopped on gas detection, both factors contributed significantly to the increase of the hazard potential and the high number of fatalities.

Mitigation actions were not carried out with focus on protection of personnel involved in the response actions, which contributed significantly to the high death toll.

Organizational root causes such as inadequate procedures and other documentation, inadequate risk assessment, lack of compliance with steering documentation, failure to learn from previous events, lack of communication and awareness and failure to prioritize safety over production are common to the accidents analyzed in this paper and to many of the unignited HC leaks in the Norwegian sector. It is therefore important to learn from unignited HC leaks rather than waiting for an accident that, like the CDSM accident, with serious consequences.

The accident on the CDSM FPSO is the first case to confirm the importance of two Norwegian principles of safe FPSO design, relating to use of pump room and location of the living quarters.

The CDSM accident has also demonstrated the severe threat that a pump room may pose on an FPSO vessel. It is probable that the hazard posed by an FPSO pump room has often been under-communicated, because only leaks due to technical pump failure are considered. The CDSM accident demonstrates that leaks with operational causes are also a threat and mean that the location of a traditional pump room is critical. Fifty to sixty percent of all HC leaks with an initial leak rate above 0.1 kg/s in the Norwegian sector have operational causes. The combination of conventional pump room location and operational leaks is an extremely dangerous one. To eliminate the pump room explosion hazard it is crucial to install individual deep well submerged cargo pumps instead of a pump room in order.

One of the contributing factors in the CDSM accident was the location of the accommodation unit aft on the vessel, above the engine room, and in the proximity of the pump room. Locating living quarters in the bow of the vessel is also essential because it ensures that they are not exposed to fire and explosion, as in a weather-vaning vessel all the sources will thus be downwind.

Vital lessons should be learned from the CDSM accident with respect to design and operation of the process plant with respect to automatic shut down as well as maintaining of ventilation in case of leaks in enclosed rooms. Important lessons should also be learned with respect to planning of emergency response actions and training of emergency management personnel, as well as for provision of adequate emergency procedures.

It is also important to take lessons regarding hazard potential of gas and condensate leaks in enclosed spaces, which are particularly critical because it can take a very long time for them to be diluted to an unignitable atmosphere, and the need for personnel to be protected throughout this period.

## **ABBREVIATIONS**

ANP	National Agency of Petroleum, Natural Gas and Biofuels
AoC	Acknowledgement of Compliance
CDSM	Cidade de São Mateus
ESDV	emergency shutdown valves
FPSO	Floating Production Storage & Offloading
GoM	Gulf of Mexico
HAZOP	HAZard and OPerability (study)
HC	hydrocarbon
HCV	main control valve
JIP	Joint Industry Project
LEL	Lower Explosive Limit
MOC	Management of Change
MTO	HuMan, Technology & Organizational
NCS	Norwegian Continental Shelf
OIM	Offshore Installation Manager
PSA	Petroleum Safety Authority

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## **Attachment 1**

Causal factors and root causes identified in the ANP investigation (ANP, 2016)

Causal Factor n° 1: Inadequate storage of the condensed material

1. Management of change not performed
2. Lack of hazards review

Causal Factor n° 2: Operational degradation of cargo system of FPSO CDSM

3. Restriction alignments with spades installation/ Management of change not performed
4. Inadequate service crossing / Inadequate communication between shifts
5. Outdated documents / Failure in records registration and modifications
6. Alterations without management of change / Management of change not performed

Causal Factor n° 3: Degradation of marine staff of FPSO CDSM

7. Lack of marine superintendents / Lack of staff management
8. Lack of tutorial / monitoring / Inadequate dimensioning of the training program
9. Lack of supervision / Resources not available
10. Employees with the same attribution performing different functions / Failure to identify training/qualification requirements
11. Lack of training in operational procedures / Failure to identify training/qualification requirements in operational procedures

Causal Factor n° 4: Operating the stripping pump with the offload sealed

12. Outdated/unavailable procedure / Failure to furnish the resources
13. Incomplete operating procedure and lack of proper instructions
14. Incomplete operating procedure and lack of proper instructions /Incomplete procedure
15. Information on pump strokes not available in supervisory system / Noncompliance with project criteria

Causal Factor n° 5: Loss of primary condensed material

16. Lack of inspections, calibration and tests plans to ensure minimum reliability for the safety valve from the stripping pump / Lack of inspections, calibration and tests plans
17. Lack of interlocks in stripping pump / Failure to consider certain aspects which may introduce hazards to the project

18. Lack of the high pressure alarm in the stripping pump offload / Failure to consider certain aspects which may introduce hazards to the project
19. Failure in the control of spare parts / Failure to control information
20. System without space for spades installation / Failure to consider requirements for the project
21. Spades improvisation / Lack of management in changes of projects requirements

Causal Factor n° 6: Exposure of personnel

22. Lack of proper instructions upon emergency procedure / Incomplete / inadequate procedure
23. Accident scenarios in the PRE of installation operator do not include the outcome over the study of Hazards of the Unit / Failure to identify accident scenarios
24. Demobilization of gathering points / Lack of awareness
25. Failure to minimize the personnel's exposure to the hazards during the emergency response / Disregard of reduction of human exposure to the consequences of eventual failures of systems and structures
26. Brigade exposure / Unidentified response resources
27. Exposure of third party detached from the brigade to the explosive environment / Inadequate mechanisms for the review of emergency response plans

Causal Factor n° 7: Ignition of the explosive environment

28. Ignition source introduced triggered by the action of people inside the explosive environment / Lack of proper/specific instructions for performance of tasks