

ROOT CAUSES OF HYDROCARBON LEAKS ON OFFSHORE PETROLEUM INSTALLATIONS

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ABSTRACT

Hydrocarbon leaks on offshore installations may result in severe consequences to personnel, to the environment and to assets. In order to prevent such leaks, it is crucial to understand their root causes. The objective of this paper is to study the circumstances of hydrocarbon leaks on the Norwegian continental shelf (NCS). In the study, all reported hydrocarbon leaks from process inventories on all offshore installations on the NCS, with an initial leak rate higher than 0.1 kg/s in the period 2008–2014, have been considered. This includes 78 hydrocarbon leaks, of which about 60 % have occurred during manual intervention on normally pressurized systems. The dominating activity when leaks occur is preventive maintenance. A significant fraction of the leaks occur during the preparation for maintenance; such a preparation is typically carried out during the night shift. About half of the leaks are associated with wellhead area and manifolds, separation and compression systems. A substantial fraction of the leaks can be associated with verification faults, dominated by the failure to comply with procedural requirements that are needed to carry out independent verification.

Keywords:

Hydrocarbon leak, major accident, root cause, Norwegian continental shelf

1. INTRODUCTION

The prevention of hydrocarbon (HC) leaks is crucial; they are one of the most critical precursor events that may lead to major accidents in the oil and gas industry, resulting in severe consequences to personnel, to the environment and to assets. Major accident examples are Deepwater Horizon (Presidential Commission, 2011), Piper Alpha (Cullen, 1990), Texas City (CSB, 2007), and Longford (Hopkins, 2000).

It has been demonstrated extensively over the last decade that the personnel involved in process system interventions are involved in the causation of more than half of the leaks from process plants on offshore installations residing on the NCS (114 out of 208, in the period

2001–2014) (Vinnem, 2010). The leaks are those with an escalation potential caused by a mix of gas, condensate and crude oil leaks. Competence, attitudes, motivation, and other relevant factors, would therefore influence the performance of interventions and the associated probability of leaks. This is discussed in some depth by Vinnem et al. (2010).

Accidents with more than two fatalities are often referred to as major accidents, and such accidents are rare in offshore operations. The last major accident with fatalities in offshore operations on the NCS occurred in 1985. Even precursor events are quite rare and have been reduced considerably during the last ten years. Based upon the PSA risk level project there is now, on average, less than one precursor incident every second year (PSA, 2015). The low frequency is good news, but gives at the same time, a challenge for safe operations. It is crucially important to maintain motivation and awareness, in order to prevent as far as possible, the occurrence of such precursor events. The next precursor event may be the next major accident if the battery of mitigation barriers on offshore installations has a substantial failure.

There are many types of major hazard precursor events, such as vessels on a collision course, structural defects, the temporary loss of well control, the failure of subsea installations, as well as HC leaks. Kongsvik et al. (2011) has explored the extent to which a safety climate measure, from a survey of working conditions used in an oil and gas offshore operating company, can be used as an indicator in relation to HC leaks on offshore installations. It was found that the safety climate measure was positively correlated with the frequency of hydrocarbon leaks, based on the empirical evidence in the study. Other aspects of the circumstances of leaks have been discussed by Vinnem (2012a, 2012b, 2012c, 2013), Røed et al. (2012), and Vinnem & Røed (2013, 2014).

When it comes to the details of the circumstances of such leaks, we find that only to a limited extent has such information been published. The UK Health and Safety Executive (HSE) has published annual reports on the hydrocarbon leaks reported from the UK offshore industry, but it has not focused on the detailed circumstances of the leaks. The Petroleum Safety Authority (PSA) in Norway has also published annual statistics (PSA, 2015).

Edmondson (2004) has published the experiences of the HSE and its campaign to reduce the number of leaks by 50%. Edmondson notes that the causes are not associated with any great technical complexity, but often, in the failure of basic controls and procedures. This is in line with previous findings and is the main message of this present paper. A recent study of leaks reported to the HSE by Li (2011) confirms the previous analysis. The most recent overview was presented at a Step Change in Safety Conference (Wright, 2014) and was based on statistics collected from Step Change in Safety noted in the Safety Alert Database and Information Exchange (SADIE).

The objective of this paper is to study the circumstances of HC leaks, and in particular, the immediate and root causes for such leaks due to technical as well as operational issues. All leaks exceeding 0.1 kg/s in the process area for the period 2008–2014 on offshore installations residing on the NCS are included in the study. In total, 78 leaks have been studied, with:

- 14 leaks in 2008
- 16 leaks in 2009
- 15 leaks in 2010
- 11 leaks in 2011

- 6 leaks in 2012
- 9 leaks in 2013
- 7 leaks in 2014

Normalised figures with regard to the annual number of installation years on the NCS are presented in Vinnem and Røed (2012) and in the annual RNNP report. The most updated results were presented in April 2015 (PSA, 2015). However, since the number of installation years has not changed to any great extent during the past 10 years, and for the sake of simplicity, only absolute figures are to be presented in this paper.

It is the authors' view that the present paper documents the root causes to a deeper level than has been presented in the literature so far. The studies are based upon accident investigation reports to the extent possible (more than 90% of the incidents). We consider that a categorisation based only upon accident reporting systems (e.g. Synergi as introduced by Høivik et al, 2009) is a too arbitrary approach that should be considered with care. A consequence of this is that information about hydrocarbon leaks without an accident investigation should only be deliberated upon to provide preliminary and limited information.

Chapter 2 gives a brief overview of hydrocarbon leaks and data sources. Chapter 3 presents an analysis of the leaks with an emphasis on the immediate and root causes. Chapter 4 discusses the findings of the study and their relevance and their applicability. The conclusions are presented in Chapter 5.

2. AN OVERVIEW OF HC LEAKS AND DATA SOURCES

The PSA started collecting data about HC leaks in 2000, with the first reporting period including 1996–2000. The data from the first period was established without the prior knowledge of what would be needed. It is, therefore, often considered that the data from the initial period is somewhat uncertain.

2.1 Period 1996–2007

In the period 1996–2007, 312 hydrocarbon leaks, with an initial leak rate >0.1 kg/s, were reported to have occurred on the NCS. But few, if any, studies have been carried out considering the root causes of these leaks. The most comprehensive study available is the RNNP project (PSA, 2008) covering causal aspects and this only explores the state of affairs to a limited extent. Also, Haugen et al. (2011) and Vinnem et al. (2007) have considered this period, but they have not focused on the root causes.

Another source of information is a project that has scrutinised 42 accident investigation reports from the period 2002–2010. This data was based upon the input from various research communities, consultancies and authorities. The findings were presented by Lootz et al. (2012). The main focus of this article was to reveal to what extent such hydrocarbon leaks could be explained in terms of a poor design.

Since there is a limited number of studies considering the root causes of HC leaks in this period, and since they are, in any case, not representative of today's situation, the leaks before 2008 are not elaborated on in this paper.

2.2 Period 2008–2014

In the period 2008–2014, 78 hydrocarbon leaks >0.1 kg/s were reported. For these leaks, comprehensive studies have been carried out as part of the Norwegian Hydrocarbon Release Reduction Project. Reference is made to Røed et al. (2012), Vinnem & Røed (2013, 2014), and to the present paper. Other relevant sources of information were the RNNP project (PSA, 2015), as well as a study analysing causal factors that related to hydrocarbon leaks, lifting incidents, and fire in electrical installations, on the NCS (Mostue et al., 2014).

3. IMMEDIATE AND ROOT CAUSES

This section is based on a detailed analysis of each individual leak case during the period 2008–2014. Investigation reports submitted by the companies have been used in order to obtain an in-depth understanding of the work processes that have, in most cases, been ongoing at the time of the leak, including possible faults and errors that may have occurred. The results are presented in an anonymous manner.

The categorisation is based upon the BORA project (Haugen et al., 2007 and Vinnem et al. 2007) with the following categories:

- Technical degradation of system (Category A)
- Human intervention
 - introducing latent error (delayed release) (Category B)
 - causing immediate release (Category C)
- Process disturbance (Category D)
- Inherent design errors (Category E)
- External events (Category F)

3.1 Immediate Causes of Leaks

The approach used in the analysis of leaks is documented in Røed et al. (2012) and in Vinnem and Røed (2014).

This section does not address the issue on who should be responsible for making improvements, but tries to reveal, as much as possible, about the root causes of the leaks that have occurred, mainly during the period 2008–2014. The technical degradation of equipment, as well as operational faults during manual intervention on normally pressurised equipment, is focused upon. Figure 1 presents the distribution of immediate causes for the period 2001–2010, as well as for the most recent periods of 2008–2010 and 2011–2014.

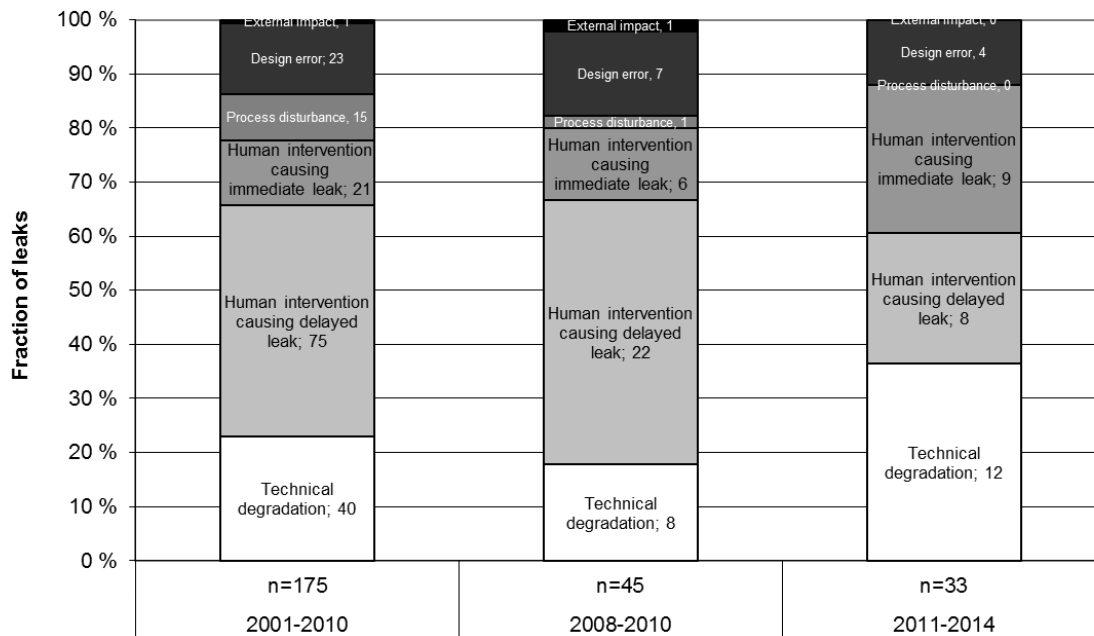


Figure 1. Distribution of Immediate Causes for HC Leaks > 0.1 kg/s, 2001–2014 (n=208)

The contribution from technical degradation has increased during the period 2011–2014; this is mainly due to an abnormal year in 2012, with more than 60% of the leaks due to technical degradation. The contribution from manual intervention in normally pressurised systems (Categories B & C) is in the range of 50%–60%, irrespective of the period considered.

3.2 Technical Faults

The distribution of equipment types that has been involved is of interest when it comes to technical faults. Figure 2 presents a summary of the equipment types and subcategories for the immediate causes for technical degradation (Category A) and design errors (Category E).

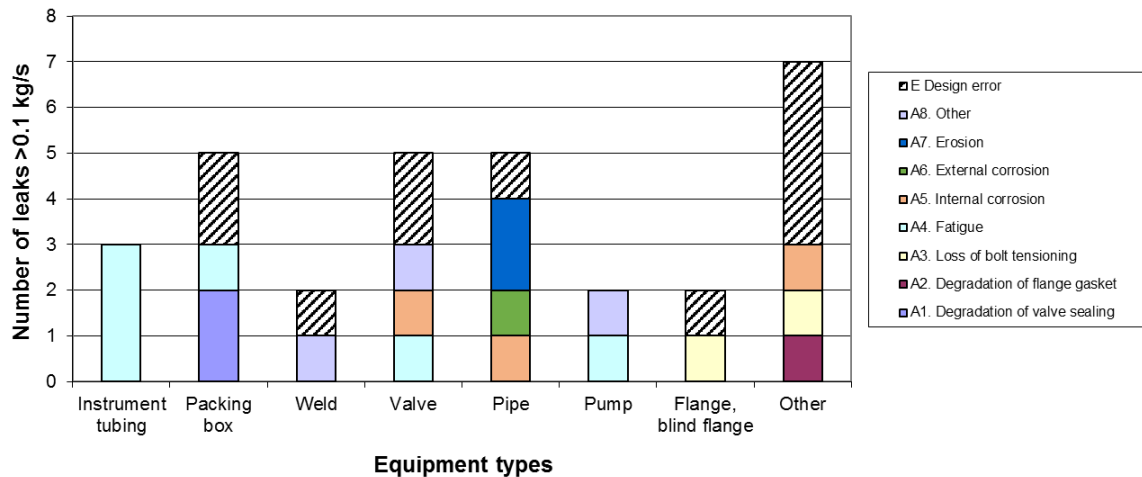


Figure 2. Distribution of Immediate Causes and the Type of Equipment for Cause Categories A and E, 2008–2014, n=31

The relative contributions are worthwhile to be considered in some detail. It can be seen from Figure 2 that all tubing failures are due to fatigue (degradation A4), which would be expected. There are three categories with 5 faults (neglecting ‘other’); packing box, valve and pipe. For the first of these categories, wear-out (degradation A1) and design errors dominate, and where one leak is due to fatigue. For valves, 2 out of 5 leaks are due to design errors, and with one case due to internal corrosion (degradation A5) and one case due to fatigue. All of the failures of pipes are due to corrosion (degradation A5 and A6) or erosion (degradation A7) except one case categorised as design error.

When considering the subcategories of Technical degradation (Category A), fatigue was the source of six leaks, followed by corrosion (internal and external) that was the source of four leaks and erosion (two leaks). The degradation of valve sealing and the loss of bolt tensioning also contributed with two leaks each in the period.

Vibration was a root cause in approximately six out of the 20 leaks in the A category (the exact number is uncertain, since it was not specified in all of the accident investigation reports - and whether or not it was stated that vibration was a root cause). This means that vibration was a significant factor, but not a dominating root cause for technical degradation leaks in the period, representing approximately 30% of the leaks.

Eleven of the leaks in Figure 2 were in category E - design failure. Out of these, five leaks were related to errors on valves or on the poor choice of valve type (including actuators). Two leaks were related to supporting structures. The last four leaks were related to the wrong design of a spade, to poor well design, to a sand cyclone not properly designed for erosion, and a high level switch based on an outdated technology.

Figure 3 presents a size distribution for technical faults involving equipment where a diameter is a relevant parameter, i.e. welds, valves, pipes, instrument tubing and flanges, including blind flanges.

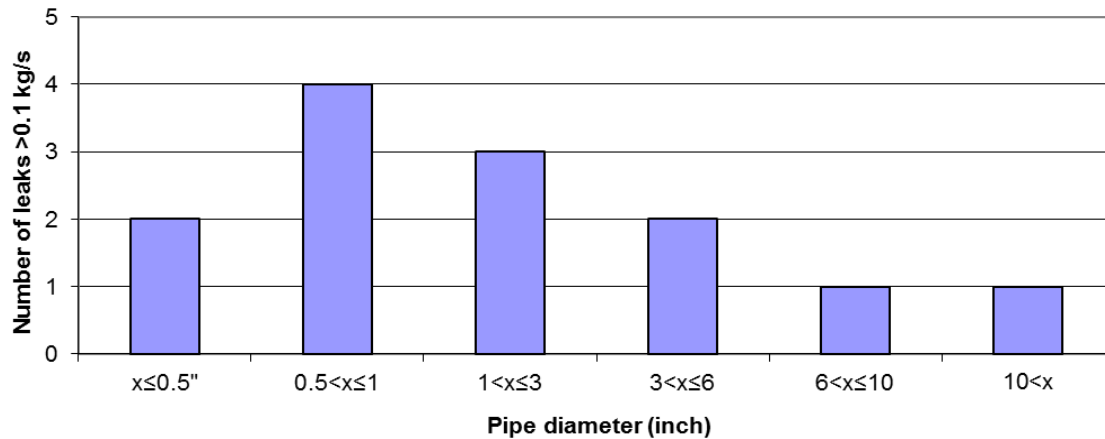


Figure 3. Distribution of the Pipe Diameters of Leaks involving Welds, Valves, Pipes, Instrument Tubing and Flanges, for Cause Categories A and E, 2008–2014, n=13 (4 leaks in Figure 2 where diameter is unknown)

According to Figure 3, any equipment with a diameter of between 0.5 and 1 inch is the most frequent of the failures, which is not at all surprising since there is a substantial amount of equipment in this group on most installations all of the instrument tubing failures (three), as well as one of the weld leaks, one pipe failure, and one blind flange leak, fall into this category. Otherwise the distribution is quite flat. It could be added that the six leaks less than or equal to 1 inch correspond to 1.33 leaks per 100 installation years.

3.3 The Type of Activities Involved in the Leaks

The leaks that occurred during the period 2008–2014 have been categorised according to which type of activity the leak was associated with, and to the extent that this was documented in the available documentation. In fact, there were few cases where this was unknown. The leaks occurred, in some few cases, after the activity had been completed, such as that when a latent condition would cause a delayed leak during, or after, start-up. Still, the leak was associated with that activity that caused the latent condition. The distribution is shown in Figure 4.

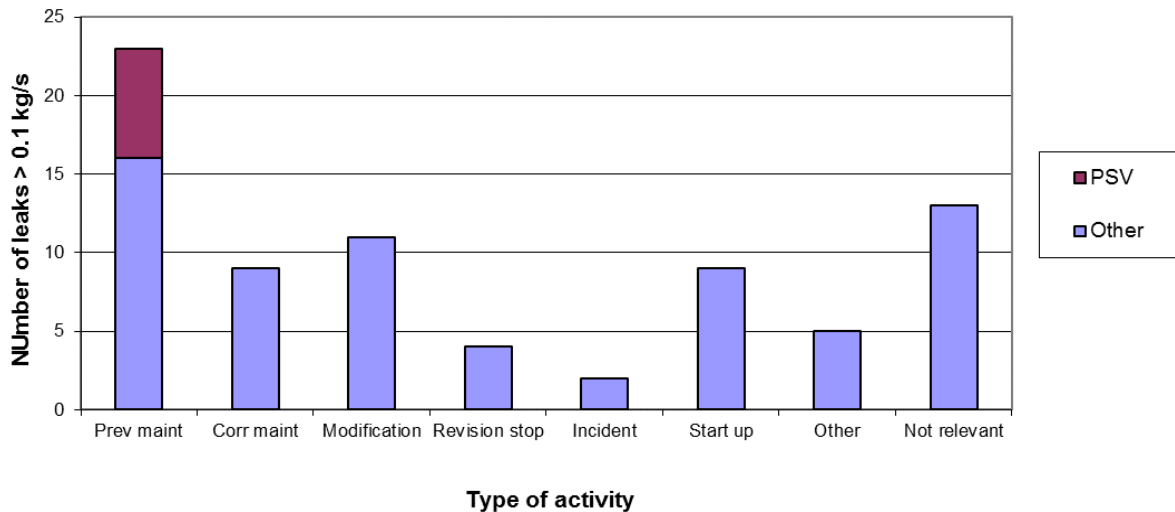


Figure 4. Distribution of the Type of Activities involved in Leaks, 2008–2014, n=76 (2 leaks with unknown activity)

Figure 4 shows that almost one third of the leaks occurred in an association with preventive maintenance, testing, inspection, and/or cleaning, etc. One special case within the preventive maintenance category is the recertification of Pressure Safety Valves (PSVs). This is quite a substantial contribution within the preventive maintenance category, with seven leaks out of a total of 23 leaks (30%). It should be noted that preventive maintenance is carried out as a risk reducing measure; so this is a measure that is intended to reduce risk, when multiple times, it has in fact introduced risk. ‘Incident’ implies that the leak occurred in response to some unwanted event occurring, such as tripping of a compressor.

The category ‘Modifications’ was the second highest contribution, with 11 leaks (neglecting the ‘not relevant’ category). The third highest contributions were corrective maintenance and ‘Start-up’ with nine leaks each. The latter category was in a couple of cases the starting up after the annual shutdown; the majority, however, were the starting up of wells and other equipment. We also see that few leaks are associated with annual shutdowns; ‘Revision stops’. The ‘not relevant’ cases are mainly of the cases in Category A – technical degradation, where the leaks are not associated with any operation. Figure 5 shows the distribution of the circumstances for preventive and corrective maintenance, as well as for modifications.

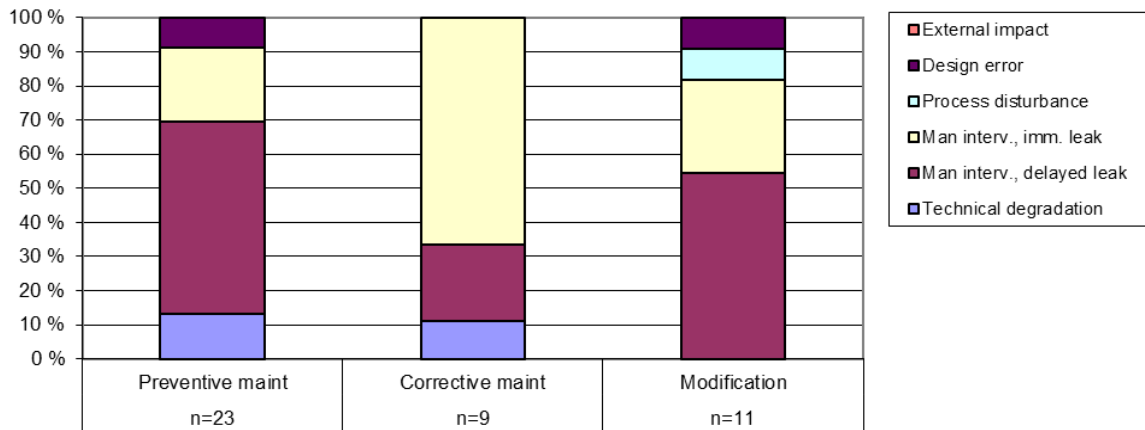


Figure 5. Distribution of the Circumstances when Leaks occurred in respect of Preventive, Corrective Maintenance, and Modifications, 2008–2014, n=43

The overall distribution of the circumstances for all of the types of activities shows that immediate and delayed leaks contributed to 55%–60% of all leaks. The three activities as shown in Figure 5 had contributions of manual intervention equal to 79%, 89% and 82%, respectively. This implies that the vast majority of leaks associated with maintenance and modification were due to a manual intervention.

3.4 The Type of Systems Involved in the Leaks

The systems that were involved in the leaks are presented in Figure 6. The three highest contributions were from gas compression, wells and separation. Metering, oil exports, fuel gas systems, manifolds and gas exports, also had significant contributions, whereas gas injection, water treatment, gas lift, and riser/flowlines, had quite low contributions.

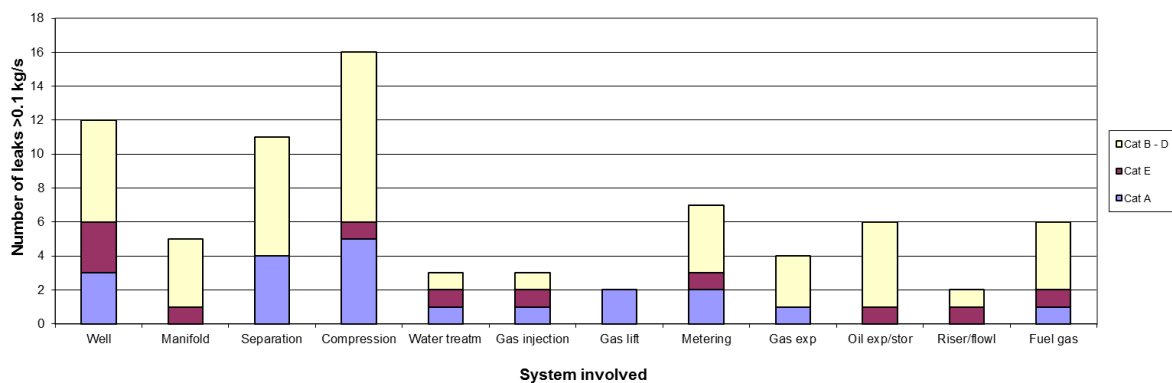


Figure 6. Distribution of the Type of Systems Involved in the Leaks, 2008–2014, n=77 (1 unknown leak)

In this figure, technical failures (Cat. A) and design failures (Cat. E) have been highlighted, since for these fault categories, there may be a strong relationship between the fault and the system involved.

The number of leaks is highest for the wellhead, manifold, separation and compression areas. This reflects to some extent that the number of instruments, fittings, bypass piping, etc. are distinctly highest in these areas, and the extent of maintenance operations will also be highest.

When considering technical failures, the most prevailing system is compression with five leaks. This is not surprising, since this system involves rotating equipment and high pressure. The second and third highest contributions are from separation and well with four and three leaks, respectively.

3.5 Details of the Leaks during the Night Shift

Røed et al. (2012) have shown that a substantial fraction of the leaks have occurred during the night shift, which is particularly critical. The times considered are the actual times of occurrence of the leaks. It could be argued that the times the errors were made would be more interesting, but for many of the leaks, this is not recorded in the data basis of the study. It should further be noted that leaks during the night shift have been increasing during the last five years; whereas it was decreasing in the period 2008–2010. Considering the entire period 2008 – 2014, we cannot conclude with any significant trend.

The leaks in the second part of the night shift (i.e. midnight until the start of the dayshift) are of particular importance. The average number of leaks in the second part of the night shift was 2.7 leaks/hour versus 1.7 leaks/hour in the first part of the night shift and versus 3.7 leaks/hour during the day shift. The leaks during the night shift, especially during the second part of the night shift have, therefore, been considered more closely. Figure 7 presents the distribution of the phases when the errors were made and is applicable to the leaks between midnight and the start of the day shift.

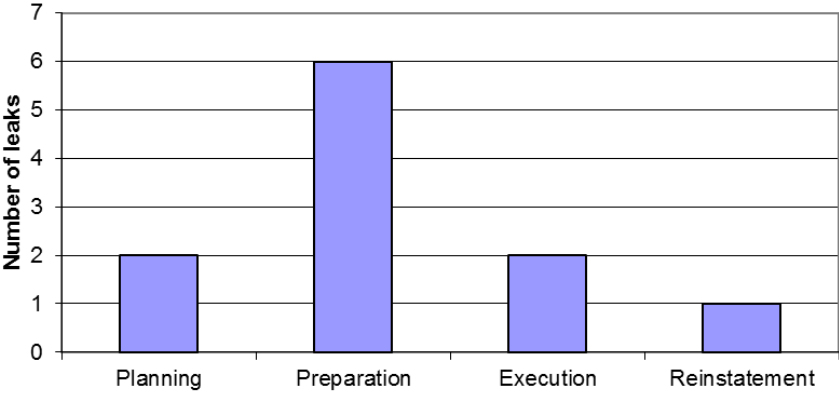


Figure 7. The Distribution of the Phase Errors are made for Leaks between Midnight and the Start of the Day Shift, 2008–2014, n=11

Figure 7 shows that nine out of the 11 leaks were associated with planning, preparation, and reinstatement, and only two of the leaks were associated with the work task itself.

Verification may be a challenge when isolation work is performed during the night shift, especially if there is only one process operator on duty during the night shift. Figure 8 presents the distribution of the types of verification failure during the night shift. Five cases out of the eight cases concerning a failure to perform verification (omission failure) have occurred during the period. The failure of the performed verification, to detect the problem, occurred in three cases during the period 2008–2014.

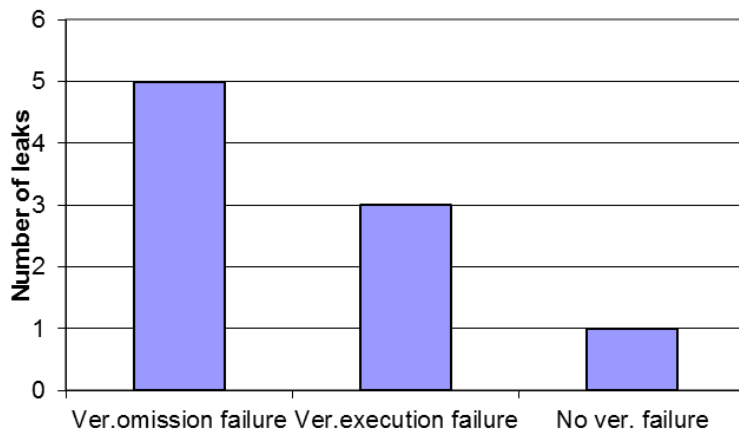


Figure 8. The Distribution of Verification Errors for Leaks between Midnight and the Start of the Day Shift, 2008–2014, n=9 (2 unknown leaks)

There were eight leaks with a verification failure in the period between midnight and the start of the day shift, according to Figure 8. These eight cases have been considered in some detail with respect to the circumstances of the verification failures. The following is a summary of the failures to perform verification:

- Performance according to personal evaluation, which replaced compliance with the controlling documentation, without following procedures for deviating.
- Bad weather implied that the work force was demobilised and then mobilised the day after; but key personnel were not present then. This may have contributed to the verification process being forgotten.
- No work permit, no isolation plan, no verification.
- Several non-compliances with the controlling documentation, including the failure to perform independent verification in the field.
- Valve position was not verified before opening.

The following is a summary of the failures of performed verifications that were instigated to detect the problems that verification was supposed to reveal:

- Isolation plan verified by the supervisor, but without noting that the bleed was not in accordance with the controlling documentation.
- Verification was performed by a person in the field who had not been involved in the planning and was not fully aware of the valve status. This was not according to best practice.
- The isolation plan implemented by the night shift was left to the day shift for verification. The valve closing was not according to the revised instructions and, therefore, was not effective; thus it was not detected by verification.

When the investigation reports are scrutinised, there is one factor which is common for all cases; a lack of compliance with the controlling documentation. Several of the investigations express either explicitly, or implicitly, that there were so-called ‘silent deviations’; i.e. practices had been established informally and that it was quite alright to systematically avoid compliance with procedures, instructions, and standards.

The limitation of having only one process technician on the night shift is also mentioned in some of the investigations.

3.6 Differences between Installations

There were large differences between individual installations, as is documented in the Risk Level Project (PSA, 2015). Figure 9 shows a more detailed illustration of the differences between individual installations, with a focus on those installations with the most frequent leaks and with verification faults.

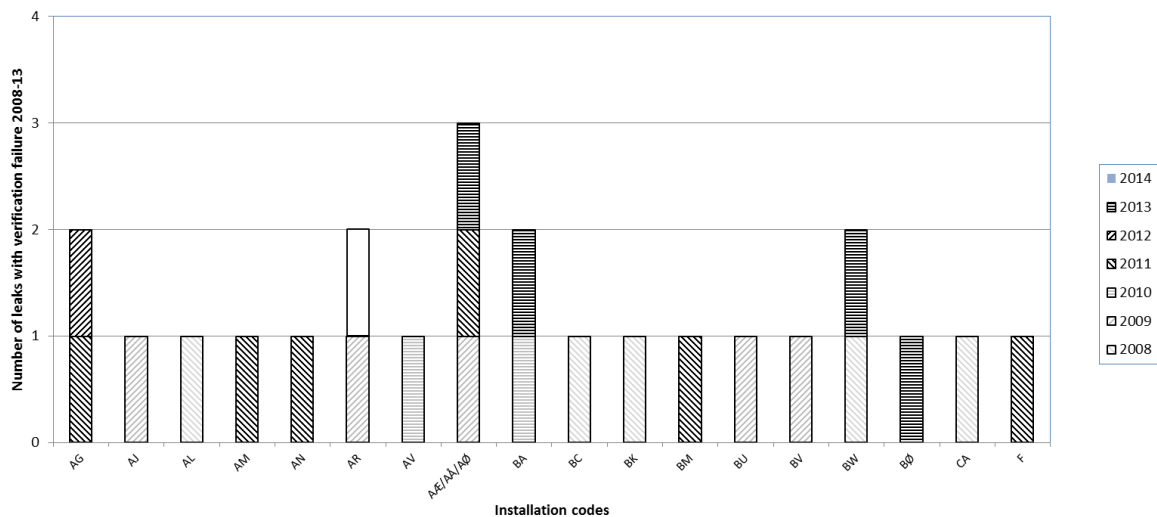


Figure 9. Anonymised Installations with Verification Faults, 2008–2014, n=24

Figure 9 shows that one installation had three leaks involving verification faults during the seven year period; there are four installations that had two leaks involving verification faults during the seven year period; and there were 14 installations that had one leak involving a verification fault. It could also be noted that the installation(s) with the highest values in

Figure 9, has in the same period, had four additional leaks associated with manual intervention on normally pressurised systems, but without a verification error.

The five installations with more than one leak involving verification faults are as follows:

- One installation having had only a few years in operation
- Two installations with around 20 years in operation
- Two installations with almost 30 years in operation

This does not suggest that age is an important factor, but it cannot be disregarded completely. On the other hand, there were several installations that had been in operation for more than 30 years that are not on the list and they had had leaks that were due to verification faults.

Three of the five installations with more than one leak involving verification faults had experienced such leaks with only a few years in between. In fact installation 'AÆ' had such leaks in 2009, 2011 and 2013. This may be taken to indicate that a learning process from these incidents was and is weak. This weakness has also been argued by the PSA in their accident investigation reports that were in relation to some of the recent incidents that displayed a major hazard potential. It could further be mentioned that four out of the five installations, with more than one leak involving verification faults, have also registered leaks during the period between midnight and the start of the day shift; i.e. those installations are included in the data basis for Figure 7.

3.7 Leak Rate vs Leak Category

A quantitative risk analysis has focus on leak rates as well as on leak frequencies. Figure 10 presents the distributions for each cause category, expressed as per 100 installation years, and the initial leak rate category.

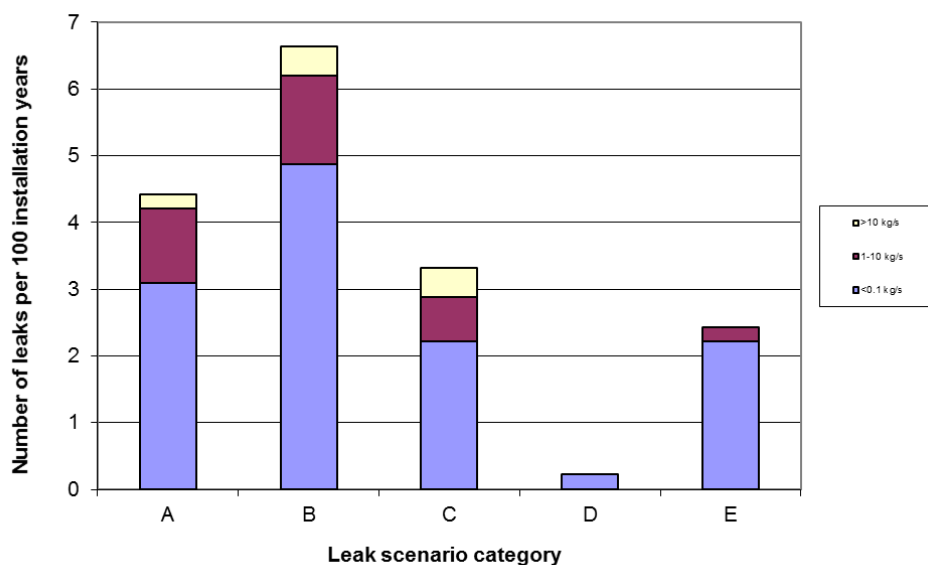


Figure 10. Number of Leaks in Leak Rate Categories for Immediate Cause Categories, NCS, 2008–2014, n=77 (1 leak in category F not included)

Figure 10 shows that the frequency of technical degradation (A) is 4.4 leaks per 100 installation years, the frequency of categories B or C is 10.0 leaks per 100 installation years, and the frequency for all of the categories taken together is 16.6 leaks per 100 installation years.

The fraction of leaks in the lowest category (0.1–1 kg/s) is fairly constant (around 70%) for the categories A, B & C. The fraction is higher, 90% for Category E, but this difference is not significant, due to the low number of leaks in this category.

4. DISCUSSION OF RELEVANCE AND APPLICABILITY

This section discusses the validity of the findings as presented in the paper and discusses some of the main issues relating to technical faults, operational errors.

4.1 Validity

The results are based upon a study of all of the reported hydrocarbon leaks in the process area of installations on the NCS with a flow rate >0.1 kg/s in the period 2008–2014. Since all hydrocarbon leaks are included in this study, the results are per definition representative. This is obviously only valid if we can assume that all leaks >0.1 kg/s have been reported. The PSA has on several occasions evaluated the completeness of the reporting and has conducted special surveys in order to establish if any reportable leak incident could be missing. They have never detected any such occurrence. Also Vinnem et al. (2006) discussed the question of possible missing reports several years ago. They concluded that in the period 1996-2000 there could have been some reports missing for the category 0.1-1 kg/s, since the reporting regime

was rather new at that time. However, for the time period considered in this present paper, this cannot be claimed. Therefore, we also consider the underreporting of hydrocarbon leaks since 2008 as being unlikely for the category 0.1-1 kg/s. There have, on the other hand, been a few cases where the leak was initially reported as an external release to sea or as an occupational injury. These cases have had combined effects and there has been a misunderstanding about how they should be reported.

The data shows stability over time when it comes to the fraction of leaks in each category A-E. Even though the number of leaks was reduced during the period, the fraction of leaks in each category remained stable. By considering individual years, the amount of data is limited, with 6–16 leaks per year in the period 2008–2014. With such low numbers, we cannot be certain that the distribution for each separate year represents an underlying trend, or has occurred by coincidence. Because of this, we should be careful when applying the results for individual years separately.

All of the studies presented are based upon the best available information; i.e. with only a few exceptions, the accident investigation reports have been our basis for this study. Based on these reports, the authors have carried out all of the categorisation of the results given in the paper. This has ensured consistency among the leaks being studied. But for sure, there are cases where a different categorisation could have been possible. In any study that is considering causes, in general, the results will always be more uncertain the deeper the root causes are considered. This is also the case for the present paper. Although some of the results in the paper are based upon a limited number of observations, the paper gives a useful insight that may be used in research to prevent hydrocarbon leaks in the future.

4.2 Relevance of System Focus

The main focus of leak statistics is often on involved systems and equipment, and the causes are often attributed to technical aspects such as fatigue or corrosion. We may consider if this is a relevant classification of circumstances and causes, based on the characteristics discussed in Section 3 above.

The focus on systems, equipment, and technical causes, are relevant for two of the categories discussed in this paper: Category A – technical degradation as well as in Category E – design errors. For these types of failure, the information in Figure 6 should give a valuable insight into which systems are involved in leak incidents. In contrast, Figure 2 and Figure 3 give other details about leak incidents in these categories.

When it comes to the other categories where manual intervention was the dominating factor, the system, the equipment, and technical causes, are not as similarly relevant as they are for Categories A and E. This applies in particular to the Categories B and C where immediate and delayed leak was associated with manual intervention in the process systems. Category D focuses on process disturbance and is mainly related to the manual intervention by control room operators. Firstly, this is a very different manual intervention, and secondly, these leak incidents are few in number, especially after the year 2010; see Figure 1. The technical system focus is, in any case, not relevant for this category either.

The most relevant focus for Categories B and C is obviously to consider the different types of operations and the steps of such operations where errors were made, causing immediate or delayed leaks, such as in Figure 4, Figure 6, and in Figure 7 – Figure 8.

4.3 Compliance with Procedures, Instructions and Standards

Vinnem and Røed (2014) have shown that verification failure during manual intervention is one of the key aspects contributing to HC leaks. The majority of failures (16 out of 23 cases) were due to the failure of complying with the requirements to carry out an independent verification as presented by the instruction for the work and in the form of an isolation plan. Such failures point to compliance issues. The seven remaining failures that were associated with verification failure are cases where verification was carried out, but was unable to identify the error made. Some of these cases are also associated with compliance issues, when there may have been a requirement to perform the verification ‘in the field’; i.e. to go out and physically inspect the isolations and blindings in the process plant. In some of the verification failure cases, the verification was performed as a ‘paper exercise’ in the office, without any physical inspection. Thus, these events are also compliance related. Figure 8 demonstrates that verification is also a focus aspect for the leaks that occurred during the night shift.

Dahl & Olsen (2013) have investigated the relationship between compliance and leadership on offshore installations. They have found that strong leadership has a direct positive influence as well as indirect influence on compliance with steering documentation. It is not unlikely that a significant extent of compliance failure has had some connection to a lack of leadership. The study by Dahl & Olsen (2013) also focused on workplace accidents. However, there is no proof that the results are applicable to major accident precursors. The compliance with safety precautions in relation to workplace accidents is quite similar to complying with the instructions and the procedures that relate to how to perform isolation and blinding work. Thus, it could possibly be expected that the influence of leadership is similar.

It should be noted that the respondents to the survey in the work by Dahl & Olsen (2013) were all employees of the operator company and were not subcontractors. That also fits in well with the present context. The data in Vinnem & Røed (2014), as well as in Figure 7 above, all suggests that the majority of failures occurred in association with operations by personnel employed by the operator company (i.e. in the phases of planning, isolation, and reinstatement). The fewest errors were made in the execution phase, where the involvement of subcontractor personnel was at the highest level.

Another issue is to what extent there was a correlation between compliance and the way procedures and instructions were formulated. This is a relevant issue to consider. One of the operator companies had a practice which was very different from the other companies when it came to the application of procedures. This company had few HC leaks, and additionally, they were considerably fewer than some of the other operators. Because of low numbers (few leaks) we are however not able to demonstrate that the difference is statistical significant.

Antonsen, Almklov & Fenstad (2008) have investigated the correlation between compliance and procedures and they have found that simplicity and employee participation are important aspects in relation to compliance with procedures. Data collection in this study was for

onshore bases for the offshore petroleum industry, implying that the case study was, at least, partly relevant.

5. CONCLUSIONS

In this paper, the root causes of hydrocarbon leaks on the NCS are presented. All of the reported leaks, with an initial leak rate >0.1 kg/s, from process inventories in the period 2008–2014, by all of the operating companies on the NCS, have been studied. The key observations are:

- Equipment types that were involved in leaks: Packing boxes, valves, and pipe and instrument tubing, were the most dominating equipment types.
- Systems involved in the leaks: Compression, separation, and the well itself, were the dominating systems.
- The smallest of equipment was dominant: Almost half of the leaks were caused by technical faults, where the diameter was a relevant parameter (i.e. welds, valves, pipes, instrument tubing and flanges, they were all related to small diameters that were $<1''$).
- The dominating activity type was preventive maintenance: almost one third of the leaks occurred in association with this activity.
- For the leaks associated with manual interventions, the prevailing causes were the incorrect fitting of flanges and bolts during maintenance, together with valves in an incorrect position after maintenance. When considering a shorter period of time, say 2011–2013, the dominating causes were the maloperation of valves during manual intervention and a break-down of isolation systems during maintenance.
- A substantial fraction of the leaks can be associated with verification faults. The prevailing cause was that verification had not been performed at all. In particular, verification may be a challenge when isolation work is performed during the night shift, especially if there is only one process operator on duty during the shift.
- There were considerable differences between individual installations when it came to verification faults. Five installations had several leaks in the period 2008–2013 that were associated with verification faults, while most of the installations had no such leaks at all.

ABBREVIATIONS

HC Hydrocarbon

HSE Health and Safety Executive

NCS	Norwegian Continental Shelf
PSA	Petroleum Safety Authority [Norway]

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