Elsevier Editorial System(tm) for Journal of Loss Prevention in the Process Industries
Manuscript Draft

Manuscript Number: JLP-D-15-00042R1

Title: MAINTENANCE OF PETROLEUM PROCESS PLANT SYSTEMS AS A SOURCE OF MAJOR ACCIDENTS?

Article Type: Full length article

Keywords: Process safety, preventive maintenance, PSV, hydrocarbon leaks

Corresponding Author: Prof. Jan Erik Vinnem, Ph.D.

Corresponding Author's Institution: University of Stavanger

First Author: Jan Erik Vinnem, Ph.D.

Order of Authors: Jan Erik Vinnem, Ph.D.; Stein Haugen, PhD

Abstract: The prevention of hydrocarbon leaks is of great importance as they are the most critical precursor events that may lead to major accidents on petroleum facilities. Maintenance of process components on offshore and onshore petroleum facilities is therefore of crucial importance in order to avoid major accidents, such as Piper Alpha and Texas City. Maintenance of Pressure Safety Valves (PSVs) is a significant activity because they are usually in quite high number and are recertified regularly. The accident chain that led to Piper Alpha started with maintenance of a PSV. Studies of leak circumstances have shown that, on Norwegian offshore installations, there is approximately one hydrocarbon leak per year resulting from recertification of PSVs due to errors made during isolation and blinding or reinstatement. The preventive maintenance of PSVs thus becomes a source of a leak (and thus, risk) as well as a safety barrier element in order to reduce risk. The paper discusses corrective as well as preventive maintenance of static (not rotating) process equipment in relation to experience with hydrocarbon leaks and identifies cases for optimization of preventive maintenance scheduling for static process equipment.

JLP-D-15-00042

MAINTENANCE OF PETROLEUM PROCESS PLANT SYSTEMS AS A SOURCE OF MAJOR ACCIDENTS?

Comments	Response
Editor Please especially indicate the innovativeness of the paper.	A new para has been inserted in the conclusions in order to emphasise the innovative aspect of the paper.
Reviewer 2 This paper deals with the optimization of preventivemaintenance of static process equipment. The idea is intriguing, and inthis sense the paper is interesting and worth publishing. However, it isdifficult to understand the practical application of the conclusionsreported in the paper. Therefore, several improvements should beimplemented by the Authors before the paper can be considered forpublication. In particular: 1. First of all, the language should becarefully proofed by a mother language since the paper is somewhat hard tounderstand.	English proof reading services have been applied.
2. The meaning and definition of all the symbols 'B1 ,B2,B3,B5,C1,C3' reported in the section 3.3 should be given.	Extra para has been inserted in Sct 3.3 in order to explain the codes B1 – C3.
3.Figure 5 needsunits on the Y-axis.	Figure 5 has been updated with text on Y-axis, and slightly revised numbers in 2014.
4.In page 9, there are 22 cases of preventivemaintenance and 9 cases of corrective maintenance mentioned and why only17 cases of preventive maintenance and 8 cases of corrective maintenanceare disscussed in this section？	Extra para has been inserted in Sct 3.2 in order to explain the difference between 17 & 22 as well as 8 & 9. Please note that late information about one leak has implied that 18 & 23 are the correct numbers, as used in the revised text. (Figure 4 therefore also updated).
5.In page13,' when representative valuesare inserted for the various frequencies and probabilities, the twocontributions may typically be in the same range, if it is considered toincrease the interval between recertification of PSVs.from one year to twoyears'. Could the authors give a more detailed explanation for frequenciesand probabilities?	Some extra text is inserted in order to illustrate the probabilities and frequencies involved.

*Highlights

MAINTENANCE OF PETROLEUM PROCESS PLANT SYSTEMS AS A SOURCE OF MAJOR ACCIDENTS?

Jan Erik Vinnem[1], Dept. of Marine Technology, NTNU/Preventor

Stein Haugen, Dept. of Marine Technology, NTNU

Highlights

- Maintenance of safety valves causes a few leaks each year in oil and gas industry
- Errors made during isolation, blinding or reinstatement are dominating
- Scheduling of preventive maintenance of static process equipment should consider this

[1]Corresponding author, jev@preventor.no

*Manuscript
Click here to view linked References

JLP-D-15-00042

MAINTENANCE OF PETROLEUM PROCESS PLANT SYSTEMS AS A SOURCE OF MAJOR ACCIDENTS?

Jan Erik Vinnem[1], Dept. of Marine Technology, NTNU/Preventor

Stein Haugen, Dept. of Marine Technology, NTNU

Abstract

The prevention of hydrocarbon leaks is of great importance as they are the most critical precursor events that may lead to major accidents on petroleum facilities. Maintenance of process components on offshore and onshore petroleum facilities is therefore of crucial importance in order to avoid major accidents, such as Piper Alpha and Texas City. Maintenance of Pressure Safety Valves (PSVs) is a significant activity because they are usually in quite high number and are recertified regularly. The accident chain that led to Piper Alpha started with maintenance of a PSV. Studies of leak circumstances have shown that, on Norwegian offshore installations, there is approximately one hydrocarbon leak per year resulting from recertification of PSVs due to errors made during isolation and blinding or reinstatement. The preventive maintenance of PSVs thus becomes a source of a leak (and thus, risk) as well as a safety barrier element in order to reduce risk. The paper discusses corrective as well as preventive maintenance of static (not rotating) process equipment in relation to experience with hydrocarbon leaks and identifies cases for optimization of preventive maintenance scheduling for static process equipment.

Keywords: Process safety, preventive maintenance, PSV, hydrocarbon leaks

1. INTRODUCTION

1.1 Background

Preventive maintenance is an important activity in all industrial applications where major accidents may occur. This is certainly the case in offshore and onshore petroleum facilities where fire and/or explosion may put many lives at risk.

---

[1]Corresponding author, jev@preventor.no

Typical preventive maintenance tasks include inspections of components, such as those susceptible to corrosion or erosion, and replacing parts that wear out over time. Another preventive maintenance action is testing safety-critical valves with respect to their ability to isolate flow, including time to close. One such component subjected to preventive maintenance is the Pressure Safety Valve (PSV), which is recertified at regular intervals, usually once per year.

The recertification of PSVs is a case of special importance because the recertification is often done in a workshop, either on or off the plant, by a subcontractor. This implies that a section of the plant is isolated and depressurized prior to the PSV being removed for recertification. The pipe section may be left with temporary seals in some cases; in other cases, the removal of a valve may be followed by immediate installation of a substitute valve that already has been recertified, if there is a pool of identical valves available for rotation in the process plant.

In both cases, the work will involve isolation of the valve from the rest of the process plant, depressurization and gas-freeing of the isolated section, removal of valve, possible installation of temporary seals (while waiting for valve to be returned), installation of a new or a recertified valve, and reinstatement of the section of the plant. The duration of the work will depend on whether a new valve from a pool is installed or the same valve is returned after recertification in the workshop. The event chain that led to the loss of the Piper Alpha installation in 1988 started in a blind flange where a PSV had been removed for preventive maintenance and not returned the same day after recertification.

When a recertified valve is installed, it can be assumed to be ‘as good as new,’ i.e. with a low failure probability. According to prevailing models, assuming failures to be exponentially distributed, the probability of failure on demand (PFD) will increase over time, until the next recertification. Timing of such recertification is therefore an important parameter, since the PFD will increase with longer intervals between recertification.

The recertification interval has traditionally been determined by the maximum allowable failure probability, and this has meant that the interval is limited. No negative effects of the recertification have been considered.

Several studies (Vinnem & Røed, 2014) have shown that hydrocarbon (HC) leaks (i.e. loss of containment [LOC]) are caused in association with maintenance and modifications in the process plant, especially during the isolation and depressurization of the sections of the plant, as well as during reinstatement of the sections. It may be claimed that the most frequent process component to be involved in loss of containment incidents is actually the PSV, probably due to the high number of valves and thus the high number of valve removals and installations.

It is therefore a dilemma that actions aimed at reducing major accident risk are actually increasing risk due to the likelihood that the work itself causes loss of containment during execution of the preventive maintenance work. Okoh and Haugen (2014) have shown that 43% of 184 major accidents occurring in the process industry in the US and Europe during the period 2000–2011 could be related to maintenance causes.

Thomassen and Vinnem (1991) have considered installation of emergency shutdown (ESD), blowdown valve (BDV), and PSV from a fire safety engineering point of view. Hameed and Kahn (2014) have discussed an approach to planning shutdown periods for a processing plant and have also given an overview of different approaches to planning regimes for preventive maintenance of process plants. The main emphasis in this work is on rotating machinery and equipment.

Chien et al. (2009) have discussed a strategy for risk-based inspection of PSVs where the only consequences of failure are those that may occur if the PSV fails to open. Failures during the preventive maintenance activities are not mentioned. This may be reasonable if the fluid in the system is non-hazardous, but not in the case of flammable fluid in the system, which is not addressed by Chien et al. (2009).

Chang et al. (2005) have discussed preventive maintenance of piping systems in a refinery from the risk-based inspection point of view. The risk associated with the inspection work itself is not addressed.

Qingfeng et al. (2011) have discussed the general principles of equipment maintenance and safety integrity management, with the main emphasis on rotating equipment. Reciprocating compressors, screw compressors and centrifugal pumps are named as the highest ranked risk sources. This is not at all consistent with the experience in the Norwegian offshore sector, where PSV is the most frequent equipment involved in the LOC incidents, as will be discussed in Section 3.

Vinnem and Røed (2015) have analyzed loss of containment on offshore petroleum installations and have shown that the most frequent activity carried out at the time of the loss of containment is preventive maintenance of the process plant, followed by corrective maintenance and modification work. As James Reason said, “Maintenance can seriously damage your system” (1997).

Barrier management is addressed by some authors, such as Pitblado (2013), who focuses on analysis of barriers but does not address the management aspect. Statoil’s Technical Condition Safety (TTS) barrier approach is discussed by Ingvarson and Strøm (2009). Barrier management as such is not a topic of this paper.

The purpose of this paper is to illustrate one particular aspect of maintenance planning related to maintenance on HC containing systems. A substantial proportion of the HC leaks in process plants occur in association with preventive maintenance tasks. This does not appear to have been well known and thus not used in planning of such maintenance. The paper aims to discuss in some depth the dilemma between preventive maintenance of process components when such work at the same time is a source of increased risk during preparation, execution and reinstatement, and to propose some recommendations as to achieve an optimum balance between prevention and risk increase.

The purpose of the paper is not to discuss planning of process plant maintenance in general, nor the planning of risk-based inspection or maintenance in general.

Section 2 summarizes the importance of preventive maintenance for the safety of process plants, and Section 3 follows with an overview of how preventive maintenance can be a risk increasing factor, based on available statistics. The challenges are discussed in Section 4, followed by conclusions in Section 5.

2. RISK REDUCTION THROUGH PREVENTIVE MAINTENANCE OF PROCESS PLANT

Preventive maintenance of process plant components and systems is an essential element of safe operation, according to regulations and industry practice, as discussed by Qingfeng et al. (2011). This section discusses the importance of preventive maintenance and the potential for major accidents.

2.1 Preventive maintenance of PSVs

PSV preventive maintenance offers many challenges. PSVs are usually installed in order to protect a vessel from rupturing. For instance, a fire may heat the contents of a vessel and increase the pressure beyond the vessel's integrity. The PSV is installed in order to relieve pressure and thus protect against rupture due to overheating. It is therefore essential that the PSV opens at the prescribed overpressure. The periodic recertification is aimed at assurance that it will open at the right value. There could also be other causes of overpressure, but exposure to heat load is considered to be the most typical cause.

In Norwegian offshore oil and gas installations, the last time a HC leak was ignited was November 1992 (PSA, 2014). This implies that for a period of more than 20 years, there have been no cases where process fire on an installation could have exposed pressure vessels to overheating and protection by PSV could have been required. There have been some fires in utility areas on installations during this period, a couple of which have been extensive fires, but escalation to process areas did not occur.

Therefore, the average demand frequency for PSVs on Norwegian offshore installations is quite low based on occurrence of process fires. On the other hand, there have been seven HC leaks (above 0.1 kg/s leak rate) associated with preventive maintenance of PSVs during the period 2008–2014. This may suggest that the current preventive maintenance scheme is not optimal. An increase of the interval between recertification is likely to increase the unreliability of PSVs. But fewer PSV preventive maintenance tasks is also likely to cause fewer HC leaks.

2.2 Elements of major accident risk associated with maintenance

Maintenance of process systems consists of preventive and corrective maintenance. Preventive maintenance is planned in accordance with overall plans, in order to satisfy authority and other requirements, and shall reflect the requirements according to barrier management (Vinnem et al., 2015). Safety Integrity Level (SIL) requirements may also be part of the basis for the preventive maintenance plans.

Preventive maintenance is used extensively on offshore oil and gas installations for rotating equipment as well as critical barrier elements. The aim is to avoid corrective (or break-down) maintenance and to ensure that there are no undetected failures in safety systems. Optimization of preventive maintenance is usually focused on cost and prevention of breakdowns (Qingfeng et al., 2011). Most of the attention is on rotating equipment, while the present discussion is focused on critical safety barrier elements.

Figure 1 presents the phases of preventive maintenance of process equipment.

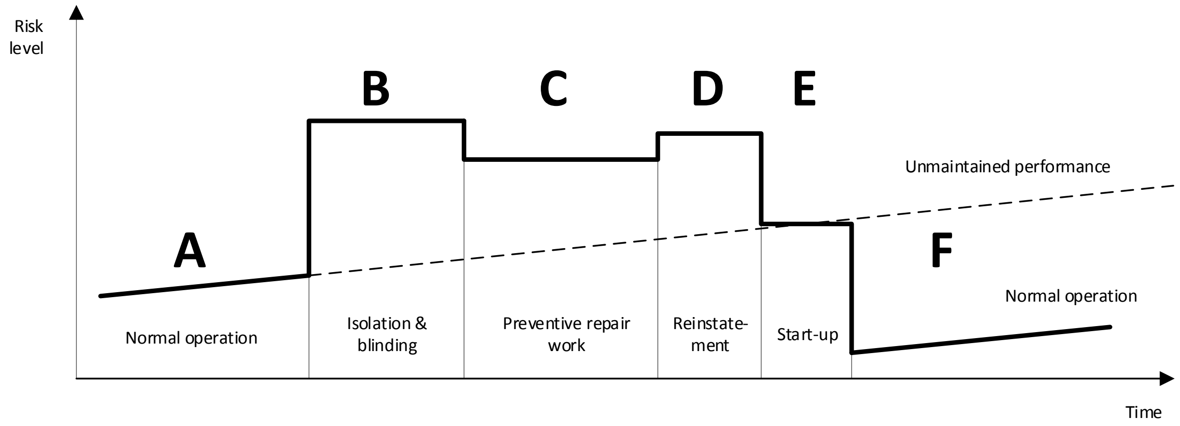

Figure 1. Phases of process equipment preventive maintenance after detection of fault

The diagram illustrates preventive maintenance, e.g. recertification of a PSV. The following phases are illustrated in the diagram in Figure 1 (it should be noted that the risk levels indicated in Figure 1 do not necessarily represent realistic levels or differences between phases):

- Phase A: Normal operation
- Phase B: Isolation, blinding and depressurization
- Phase C: Execution of repair work
- Phase D: Reinstatement
- Phase E: Start-up
- Phase F: Stable operation with restored barrier element

Phase A reflects normal operation. The relevant activities in this phase are planning of the maintenance work (including isolation plan), including delivery of parts to be replaced, etc.

Phase B is the period of preparing for the work: the isolation of sections, insertion of blindings, depressurization and gas freeing, including purging. Experience data show that the risk is significant during this period if failures are made during the implementation of the isolation plan.

Phase C is the execution of the work: taking out the valve, recertifying it and putting it back in place. There are fewer leaks during this period compared to isolation and reinstatement. Work in Phase C is usually the only work covered explicitly by a Work permit (WP).

Phase D is the reinstatement of the process section, including leak test, according to the isolation plan. Some leaks have occurred during this phase.

Phase E is the starting up of the system after maintenance, which is also a period with increased risk. During this period, errors that were not detected by the leak test may materialize.

Phase F is the stable operation with the barrier element back in normal operation. The risk level should be lower than before the maintenance but will principally increase gradually over time until the next testing of the component. There is still a possibility that there are undetected maintenance errors.

Preventive maintenance of process equipment may have the following effects on major hazard risk:

- Increased risk due to degraded performance as a barrier element during stable operation (criticality often as a function of both Health, Environment and Safety [HES] risk and production regularity)

- Possibility for causing LOC during preparation for maintenance (isolation, blinding and depressurization, usually not covered by WP)

- Possibility for causing LOC during actual maintenance task (covered by WP)

- Possibility for causing LOC during reinstatement (including leak test, usually not covered by WP)

- Possibility for causing LOC during start-up (usually not covered by WP).

This list relates to major hazard risk. There is also an aspect of occupational accident risk (not major accident risk) during the execution of the maintenance tasks, but this is not addressed in this paper.

Planning of corrective maintenance is usually limited to consideration of the classification of the equipment, which reflects the effect on barrier performance during stable operation (Phase F in Figure 1), i.e. the first type of influence listed above. It is noteworthy that there are several important effects not covered at all (Phases A–E) during planning of maintenance.

Corrective maintenance is performed when an incident or fault occurs. Sometimes the fault is so serious that the repair needs to be done immediately. The system may be shut down immediately when the fault is discovered and will remain shut down until the repair has been completed. This is exceptional, often the production may continue, possibly with some restrictions, until the repair can be planned and prepared, for instance if spare parts have to be delivered offshore. The required response times are usually based on a criticality classification, which has been prepared in advance. The criticality class shall reflect the importance of the equipment in stable operation in order to prevent major accidents and maintain stable production. Although this is common practice in the industry, it is considered to be too narrow a perspective to reflect all aspects of major hazard risk associated with process equipment.

In principle, the process for corrective maintenance is the same, except that phase A covers the point from when the failure is detected until repair is actually started. As pointed out, in most cases operation can still be continued. An important consideration is whether the risk will be too high in the period until repair has been completed. In many cases, the planning will be quite short, although some corrective maintenance may be postponed for long periods of time (several years in some cases).

The remaining phases are all similar to the description for preventive maintenance.

2.3 Barrier performance data

The Petroleum Safety Authority (PSA) Risk Level Project (Vinnem et al., 2006) annually publishes test data for some essential barrier elements (PSA, 2014) for the following equipment:

- Fire detectors
- Gas detectors
- Riser ESD valves
- Wing and Master valves (Christmas tree valves)
- Downhole Safety Valves (DHSV)
- BDV
- PSV
- Blowout preventer (BOP)
- Deluge valves
- Fire pump (start on-demand).

Figure 2 shows the summary of mean values for the barrier elements averaged for all production installations for the Norwegian Continental Shelf (NCS) in 2013.

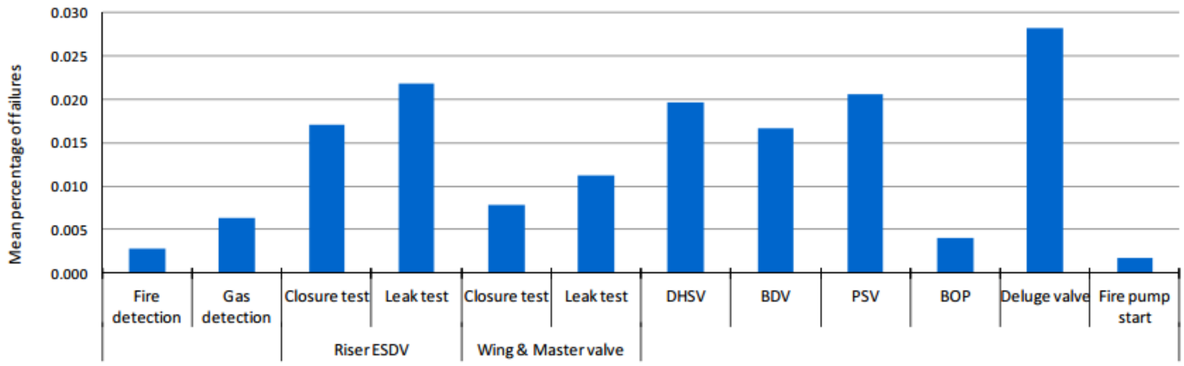

Figure 2. Mean percentage of failures for selected barrier elements, all production installations, NCS, 2013 (Source: PSA, 2014)

For PSV, the fraction of failed test over total number of test is just over 2% as a mean value. The variation between individual installations is shown in Figure 3.

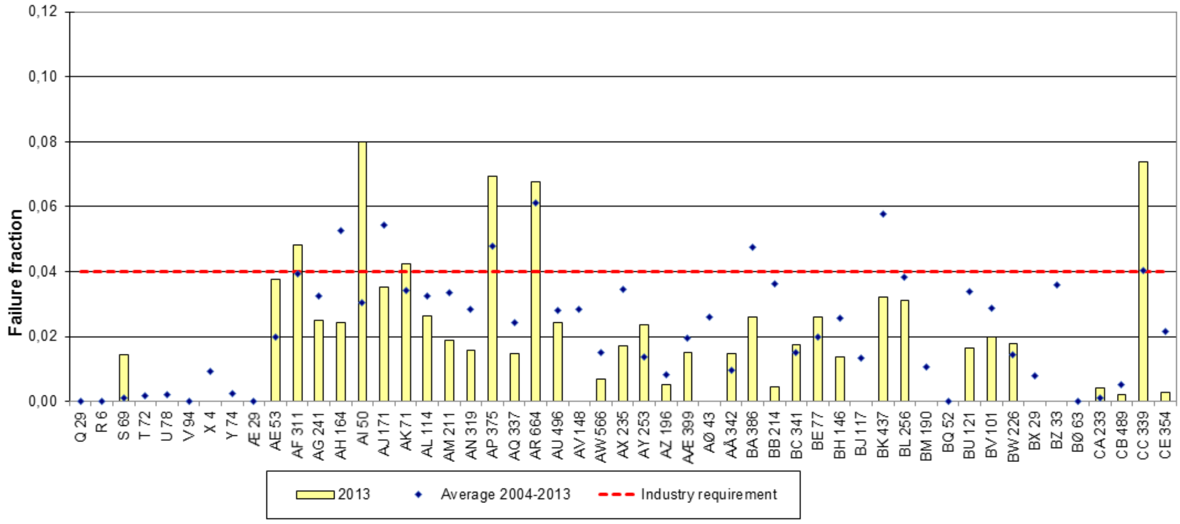

Figure 3. Individual variations for single installations for testing of PSVs, all production installations, NCS, 2013 (Source: PSA, 2014)

Figure 3 shows that there are significant differences between those that have performed many tests (some without failure) and those that have had 6–8% failure. The four installations with the highest fractions in 2013 are installation codes AI, CC, AP and AR, which all have completed well over 100 tests. It is therefore not a case of random statistical variations due to low number of tests. Figure 3 also shows values for the 10 year period 2004–2013. Installations AP and AR are those with the highest values in 2013 as well as in the period 2004–2013.

The test intervals are not known for PSVs on individual installations, therefore possible correlations between test intervals and fraction of faults cannot be established.

The number of tests may be surprising for some of the installations. This is mainly considered to reflect the fact that there may be a few hundred PSVs on large installations, with variable sizes from less than one inch to large valves above 10 inches in diameter. Similar diagrams as Figure 3 are available for all the barrier elements in Figure 2 (PSA, 2014), but these are not addressed here.

3. PREVENTIVE MAINTENANCE AS RISK INCREASING FACTOR

HC leaks represent an important type of precursor event for major hazard risk on offshore petroleum installations. UK Health and Safety has collected release statistics starting in 1992 for the UK sector; similarly, the Norwegian Petroleum Directorate (later taken over by PSA) has collected statistics for the Norwegian sector since 1996. PSA has established a lower threshold for leaks to be reported, 0.1 kg/s (Vinnem et al., 2006), reflecting the lower limit of escalation potential, whereas the UK leaks do not have a lower limit. UK leaks also include processed HC liquids, like diesel oil, hydraulic oil, etc.

The leaks in the Norwegian sector have been analyzed much more thoroughly compared to the UK sector, possibly to some extent because the leaks are more suitable for analysis as they are somewhat more consistent due to the applied threshold.

Another significant difference is that the reporting to UK Health and Safety Executive (HSE) is on a specified form (OIR12), whereas PSA (in the risk level project) has used informal reporting and followed up by asking for investigation (and similar) reports for each and every leak reported. The extent of detailed information is significantly improved when full investigation reports are available.

3.1 Leak statistics

Figure 4 shows the development of leaks above 0.1 kg/s per 100 installation years, 1996–2014. From 2008, the leaks have been split on circumstances during which the leak occurred. The categories that have been used are technical degradation (Category A), manual intervention (Categories B and C, delayed and immediate leak, respectively) and other circumstances (Categories D – process disturbance; E – design error; F – external impact).

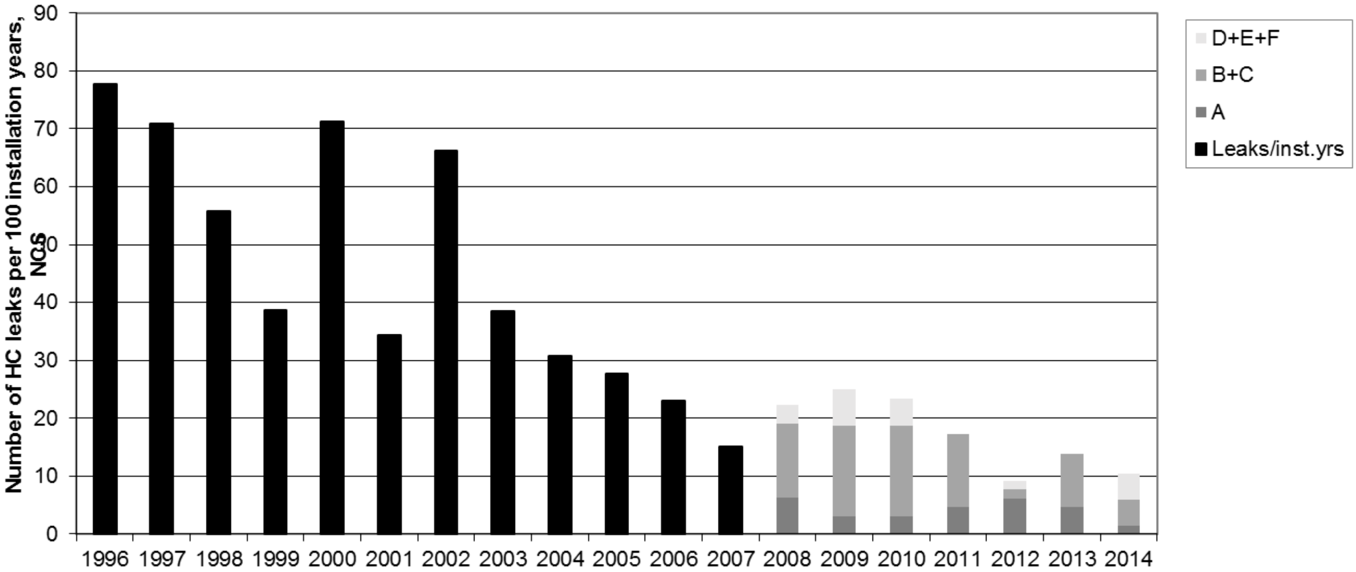

Figure 4. Number of leaks (>0.1 kg/s) per 100 installation years, split on technical degradation, manual intervention and other circumstances, NCS, 1996–2014

Figure 4 shows that manual intervention has been the cause in the majority of the leaks except for 2012 when leaks due to technical degradation were dominating. This has remained virtually unchanged in spite of the reduction that has taken place during the last 10–15 years. If we consider manual intervention during preventive and corrective, this is almost half of all leaks (31 out of 69 leaks 2008–2014). Examples of preventive maintenance tasks that have caused leaks:

- Measure pressure difference across coolers
- Pressure test
- Bolt tightening

- Pump testing
- Periodic biocide injection
- ESD test.

3.2 Leaks during preventive and corrective maintenance

Vinnem and Røed (2015) have demonstrated that the activity with the highest contribution to HC leaks is actually preventive maintenance, followed by modification, corrective maintenance and start-up. It is further shown that the vast majority (75–90%) of all leaks during corrective and preventive maintenance is associated with the manual work carried out. It is further shown that there are some differences between preventive and corrective maintenance:

- Preventive maintenance: 5 immediate leaks, 13 delayed leaks (out of total of 23)

- Corrective maintenance: 6 immediate leaks, 2 delayed leaks (out of total of 9)

The number of leaks during corrective maintenance is too low for this difference to be statistically significant, but it gives some clear indications. With a corrective maintenance task, the equipment may to some extent be isolated due to the failure, thus limiting the isolation phase of the maintenance work. With preventive maintenance, the full isolation work needs to be done as required by the work task itself. This has been shown to be a significant source of faults (Vinnem & Røed, 2015).

It should be noted that immediate and delayed leaks account for 18 leaks out of the 23 leaks associated with preventive maintenance. This implies that five (5) of these leaks are not associated with manual operations. Similarly, there are eight (8) immediate and delayed leaks during corrective maintenance out of a total of nine (9) leaks, implying that one leak is not associated with manual operations. Only leaks associated with manual operations (i.e. the maintenance work – 18/23 leaks for preventive maintenance and 8/9 leaks for corrective maintenance) are discussed further below.

Figure 5 shows the fractions of leaks associated with preventive maintenance, corrective maintenance, modifications and other tasks for the years 2008–2014. Leaks that are not associated with manual tasks are not included. The 'other tasks' category is to some extent dominated by leaks associated with starting up, for instance starting up a well or one case of starting up after an annual shut-down period.

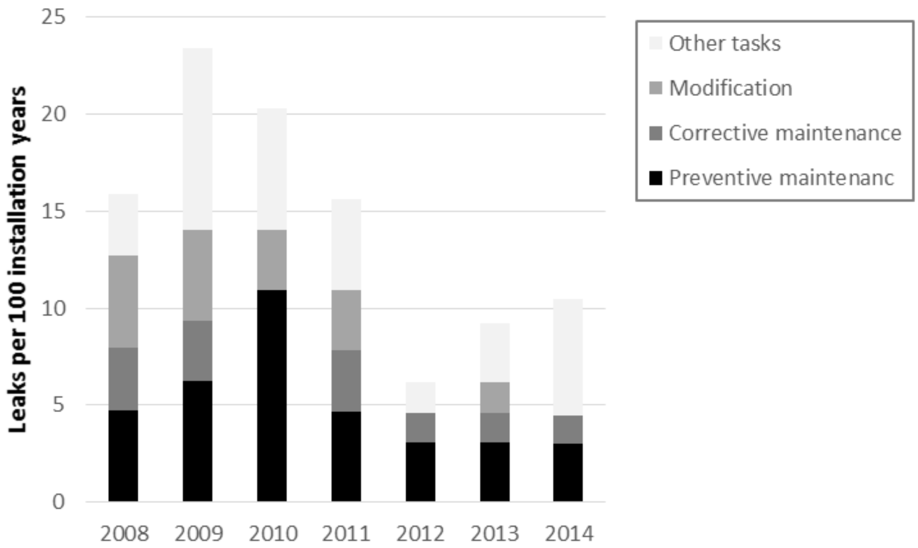

Figure 5. Number of leaks (>0.1 kg/s) per 100 installation years due to preventive and corrective maintenance, modification and other tasks, NCS, 2008–2014

3.3 Cases with PSV failure

Vinnem and Røed (2015) have demonstrated that the most important type of activity within the preventive maintenance category is recertification of PSVs. For the period 2008–2014, seven (7) cases of HC leaks associated with preventive maintenance of PSVs are registered out of a total of 23 leaks associated with preventive maintenance. No other barrier elements are mentioned correspondingly often in the investigation reports for HC leaks.

There are different detailed causes for the seven PSV-associated leaks, although all of the leaks are associated with implementation of the isolation plan. The following are the detailed circumstances of the leaks:

B1. Incorrect blinding/isolation

B2. Incorrect fitting of flanges or bolts during maintenance

B3. Valve(s) in incorrect position after maintenance

B5. Maloperation of valve(s) during manual operation

B6. Maloperation of temporary hoses

C1. Break-down of isolation system during maintenance

C3. Work on equipment not known to be pressurized

The overview of all potential causes (Categories A–E) is presented in Vinnem and Røed (2014). B1, B2, B3, B5 and B6 (with circumstances indicated above) are all subcategories of the category B – Human intervention introducing error which may cause delayed leak. Correspondingly, the Subcategories C1 and C3 belong in the category C – Human intervention introducing error causing immediate leak.

There is not one dominating cause or circumstance; there are unique faults in each case. Three of the cases are associated with verification that was not performed; the other three were related to failure of the verification that was performed to detect the problem at hand. The details of the verification are not known in the last case. There were seven different installations involved in these seven leaks. Thus, there is no common aspect except some kind of verification failure (as is expected) and that recertification of PSV is the task at hand.

4. DISCUSSION

The previous sections have demonstrated that HC leaks have occurred about once a year in association with preventive maintenance on PSVs.

Figure 5 shows that the relative contribution from preventive maintenance to the total may have been somewhat reduced. But there are no reports or incidents where PSV has had a positive effect, i.e. no reports that describe PSVs that have reduced the consequences of an incident.

Figure 4 indicates that the contribution from categories D, E and F (overpressure, design flaws and external impact) has been reduced in the last few years. Closer consideration of the data confirms that this is the case, particularly for leaks caused by overpressure (Vinnem & Røed, 2014).

The leaks caused by overpressure are not associated with pressure vessels or other components that are protected by PSVs. This may reflect the fact that overpressure of process volumes protected with PSVs will usually not occur because the PSVs are fulfilling their intended function and preventing the overpressure from becoming too high.

On the other hand, there are five LOC events associated with preventive maintenance during the last three years: one in relation to testing of a PSV and the other four incidents in association with testing of other types of valves.

All of these tests are associated with what could be classified as static process equipment, which essentially is non-rotating equipment. A closer look at the leaks associated with preventive maintenance reveals that only one incident out of 23 leaks involves rotating equipment, the remaining cases are preventive maintenance of static process equipment, valves, transmitters, etc.

It is therefore interesting to consider optimization of preventive maintenance in the light of the new information about negative effects of preventive maintenance. This is presented in Sections 4.1 and 4.2.

4.1 Optimization of preventive maintenance

The increased insight into risk aspects of preventive maintenance of static process plant equipment calls for a renewed consideration of what is the optimum duration of preventive maintenance intervals, as illustrated in the following.

Determination of preventive maintenance interval often disregards the increased risk during the preventive maintenance task and considers only the reduced risk after preventive maintenance in relation to the costs associated with performing the preventive maintenance. The insight expressed by Figure 1 implies that there are advantages as well as disadvantages to performing preventive maintenance tasks too often and calls for a comparison of these aspects in order to determine the optimum preventive maintenance interval.

Figure 6 presents an idealized comparison of risk increase and risk reduction associated with a short preventive maintenance interval and a prolonged interval, reflecting the phases outlined in Figure 1. It should be noted that the duration of the preventive maintenance work in Figure 6 is exaggerated compared with the length of the maintenance interval. Until the preventive maintenance is carried out, the 'background risk' is increasing due to increase of failure probability with time. If the interval is prolonged, risk will continue to increase for a longer period, but the increased risk associated with carrying out the preventive maintenance work is delayed.

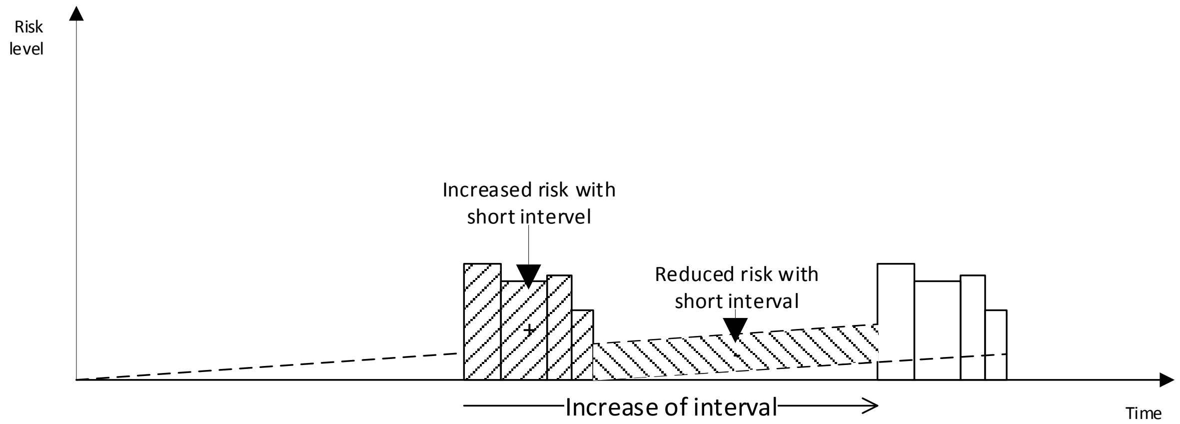

Figure 6. Changes of risk associated with short and prolonged preventive maintenance interval, idealized representation

Figure 6 suggests that the risk increase associated with preventive maintenance may easily be higher than the risk reduction associated with reduced failure frequency, although the illustrations are of a principal nature so the magnitudes of risk contributions are not drawn to scale. The relative magnitudes of the risk contributions will obviously depend on the characteristics of the equipment involved, in addition to other parameters. A general conclusion cannot be drawn; each case has to be considered separately due to differences in hazard potential. The risk potential if a PSV fails on-demand may vary substantially according to pressures, volumes, fluid characteristics, etc. Also the risk due to HC leak during the preventive maintenance (recertification) activity may vary substantially depending on pressures, volumes, fluid characteristics, etc.

When representative values are inserted for the various frequencies and probabilities, the two contributions may typically be in the same range if the interval between recertification of PSVs is increased from one year to two years. This is dependent on the probability that the PSV may be called into service during the prolonged maintenance period. If it fails due to increased unavailability, this may represent a significant increase in risk. There is also the reduced likelihood of experiencing a leak due to the preventive maintenance work, which if ignited also may represent a significant increase in risk.

4.2 Is PSV a unique example or a generic case?

The high number of leaks associated with PSVs means that it is natural to question whether their uniqueness makes it more likely that leaks will occur when they are being maintained. In order to answer this question we need to consider the number of times that PSVs are maintained compared to other valves. We have not looked into these numbers, but it is noted that there is no other way to test these valves than during recertification. This means that there will be a relatively high number of maintenance activities requiring isolation and depressurization for these valves compared to other types of valves. This may be the main explanation for the high number of leaks associated with these valves.

Further, there are other valves that have had leaks during testing. In this way the PSV is not completely unique. The following valves have been involved in leaks associated with preventive maintenance:

- Choke valve
- ESD valve
- Gas lift valve
- Blowdown valve.

The message that planning of periodic testing needs to consider both the possibility of creating a leak during testing and increased reliability as a consequence of the testing is therefore applicable to several types of valves, not only the PSVs. This applies to valves whose testing requires isolations and depressurizations, such as isolation valves that are tested for internal leak rates.

4.3 Optimization of corrective maintenance?

Corrective maintenance is a response to failures that occur, and while it is not about optimization of maintenance, sometimes the delay may be optimized to some extent. Experience has shown that the necessary time should be taken to ensure proper planning of the repair or replacement work. It is then a question of whether production can be continued until the corrective work has been completed or not, as noted earlier. But optimization in the same way as discussed in Section 4.1 is not relevant.

5. CONCLUSIONS

Preventive maintenance of PSVs (i.e. recertification) is a significant maintenance task on offshore and onshore petroleum facilities, mainly due to the high number of such valves and the perceived need for quite frequent recertification. Annual recertification is quite normal, as a standard interval, in order to keep the on-demand failure probability at a low level. This paper has demonstrated that recertification of PSVs is a significant source of LOC-associated risk due to operational errors during isolation, blinding or reinstatement of sections of the plant containing the PSV.

The general message is that testing of valves, instruments, etc., including PSV, is the main source of leaks associated with preventive maintenance of static process components. The negative effect of too frequent maintenance has not been acknowledged in the industry nor by authorities and specialists, and the emphasis on short maintenance intervals may have been too strong.

This is the added insight provided by the present study. Planning of preventive maintenance of PSVs should be extended to cover the leak potential of the work, in addition to the focus on trade-off between maintenance interval and failure probability.

There is a case for optimization of the preventive maintenance of PSVs and other valves in the sense that too frequent maintenance will lead to increased risk during isolation, blinding and reinstatement of the process sections, whereas too infrequent maintenance will lead to increased on-demand failure probability. Maintenance planning therefore needs to consider such optimization on a case-by-case basis. It is not unlikely that prolongation of intervals between recertifications will result, at least for some valves.

Finally, PSVs have been used to illustrate the points in this paper. We don't consider these to be unique in the sense that it is more likely that maintenance will cause leaks compared to other valves or other equipment. The conclusions are therefore considered to be generally valid.

ABBREVIATIONS

BDV	Blowdown Valve
BOP	Blowout Preventer
ESD	Emergency Shutdown
DHSV	Downhole Safety Valve
HC	Hydrocarbon
HES	Health, Environment, Safety
LOC	Loss of Containment

NCS	Norwegian Continental Shelf
NPD	Norwegian Petroleum Directorate
PSA	Petroleum Safety Authority [Norway]
PSV	Pressure Safety Valve
PZV	Process Safety valve
SIL	Safety Integrity Level
TTS	Technical Condition Safety
WP	Work permit

ACKNOWLEDGEMENTS

This paper is related to work performed in the MIRMAP project and the authors wish to acknowledge the Norwegian Research Council for their financial support to the MIRMAP project, no 228237/E30, funded by PETROMAKS2.

REFERENCES

Chang, M-K., Chang, R-R., Shu, C-M., & Lin, K-N. (2005). Application of risk based inspection in refinery and processing piping. *J of Loss Prevention in the Process Industries, 18*, 397–402.

Chien, C-H., Chen, C-H., & Chao, YJ. (2009). A strategy for risk-based inspection of pressure safety valves. *Reliability Engineering and System Safety*, *94*, 810–818.

Hameed, A., & Kahn, F. (2014). A framework to estimate the risk-based shutdown interval for a processing plant. *Journal of Loss Prevention in the Process Industries, 32*, 18–29.

Health & Safety Executive (HSE) Hazardardous Installations Directorate Offshore Division. (2004). *Fire and Explosion Strategy* (Issue 1).

Ingvarson, J., & Strøm, Ø. (2009, September). *Technical safety barrier management in StatoilHydro*. Paper presented at the 2009 Offshore Europe Oil & Gas Conference & Exhibition, Aberdeen, UK.

Okoh, P., & Haugen, S. (2014). A study of maintenance-related major accident cases in the 21st century. *Process Safety and Environmental Protection, 92*, 346–356.

Pitblado, R. (2013, October). *Integrated barrier management approach or offshore developments*. Paper presented at Offshore Technology Conference (OTC) Brazil, Rio de Janeiro, Brazil.

Petroleum Safety Authority (PSA) Norway. (2013) *Principles for barrier management in the petroleum industries*. Retrieved from http://www.ptil.no/getfile.php/PDF/Barrierenotatet%202013%20engelsk%20april.pdf

PSA Norway. (2014). *RNNP Risk level project main report*.

Qingfeng, W., Wenbin, L., Xin, Z, Jianfeng, Y., & Qingbin, Y. (2011). Development and application of equipment maintenance and safety integrity management system. *Journal of Loss Prevention in the Process Industries*, *24*, 321–332.

Reason, J. (1997). *Managing the risks of organizational accidents*. Aldershot, UK: Ashgate.

Thomassen, O., & Vinnem, J. E. (1991). Use of ESD valves in fire safety engineering based on safety assessments. In BHR Group (Eds.), *Management and Engineering of Fire Safety and Loss Prevention*. Abingdon, UK: Taylor & Francis.

Vinnem, J. E., Aven, T., Husebø, T., Seljelid, J., & Tveit, O. (2006). Major hazard risk indicators for monitoring of trends in the Norwegian offshore petroleum sector. *Reliability Engineering & Systems Safety*, *91*(7), 778–791.

Vinnem, J. E., & Røed, W. S. (2014). Norwegian oil and gas industry project to reduce hydrocarbon leaks. *SPE Economics & Management*, *672*, 88–99.

Vinnem, J. E., & Røed, W. S. (2015). *Root causes of HC leaks on offshore petroleum installations*. *Journal of Loss Prevention in the Process Industries*, 36, 54–62