Trends in the Causes of Hydrocarbon Loss of Containment Accidents

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The HSE's Hydrocarbon Release Database (HCRD) has become recognised as the main source of information on accidental process releases. Frequency correlations derived from the HCRD are used in many parts of the world and for risk assessments of onshore sites as well as offshore installations.

The focus of analysis has been on the derivation of leak frequencies for various types of equipment to be used in risk assessments. However, there are many other data fields collected. Among these data fields are the information on the cause of the leak and the operation mode under which it occurred. A study has been carried out to analyse the data from more than 5000 incidents reported in the period October 1992 to December 2019 to investigate various aspects associated with the cause of the leak and the operational mode at the time of the incident.

Three aspects were investigated;

- Proportions of leaks under the various causal and operational mode categories
- Variations in hole size distributions from different causes, and
- Trends over time in the proportion of incidents associated with the design and robustness of process equipment compared with those associated with the way in which it is operated.

Under the first aspect, a series of tables and graphs is presented showing the breakdown of the causes and how they have varied with time.

The results indicate that over the period up to 2005, the frequency of leaks due to issues of design and robustness of equipment were not decreasing at the same rate as those due to operational and procedural issues. However, since 2005 the reduction in frequencies has been largely due to reductions in incidents caused by design/equipment issues rather than operational/procedural.

The analysis also shows that there are significant differences in hole size distribution. Although leaks from operational/procedural failures are less common, they tend to result in larger holes and potentially more severe consequences.

The study also identifies differences in the relative proportions of leaks under different operational modes and that leaks under different modes have different hole size distributions. Larger releases are more likely to occur when the operating mode is other than "Normal Production" (e.g. start-up).

The quality and completeness of reporting and collation of the data has declined since 2015. This has a bearing on uncertainty of relative proportions of events attributed to different causes and operating modes. It will be important that these are addressed.

Keywords

Leak Causes, Operational Modes, Offshore, Hydrocarbon Release Database

Introduction

Following the Cullen enquiry into the Piper Alpha Disaster, the UK offshore industry has been submitting reports of hydrocarbon loss of containment incidents to the UK HSE since October 1992. Guidance on the submission of data is provided in /1/ and /2/.

DNV GL has previously carried out detailed analysis of data from the UK HSE's Hydrocarbon Release Database (HCRD) for a number of purposes;

Derivation of leak frequency correlations for process equipment types /3/, /4/

Derivation of leak frequency correlations for systems /5/

Incident Data Tables /6/, /7/

The first two of the above required examination of a limited number of available data fields, together with population data to develop models, for use in risk assessments. The third produced information on almost all of the data fields in the HCRD but at a high level. The purpose of this study is to look at two groups of data with a view to gain an understanding on the relative occurrence over time and variations in hole size distribution. This may offer some insights into where the offshore industry needs to focus its attention in reducing the frequency of hydrocarbon leaks.

The information available for the leak frequency studies (/3/, /4/) was limited to incidents occurring up until December 2015 and the incident tables (/7/, /6/) on data up to December 2017. Further information was released by the HSE in June 2020 which provided data that enabled the analysis of incidents up until December 2019. This comprised a total of 5101 incidents. While the quality and completeness of the reporting and collation of the data has declined since 2015, it is believed that the incident data for 2016-2019 can provide useful information.

The purpose of the work reported in this paper was to undertake a detailed examination of the relative frequency of the various causes of leaks and to examine interrelationships with severity classification, hole size distribution and variations over the period that the HCRD has been in operation.

Study Basis

The incident data used as a basis is the information contained in spreadsheets available from the HSE statistics web page. The information is contained in two Excel workbooks;

- Workbook obtained through the link “Offshore Hydrocarbon Releases 1992-2016” /8/ which accesses the file “hsr 1992-2014”. This includes data for the period 1992-2015.
- Workbook obtained through the link “Offshore Hydrocarbon Releases 2015-2019” /9/ which accesses the file “hsr 2015-2019”. This includes “final” data for 2016-2018 and provisional data for 2019.

Note that data for 2015 is contained in both data sets but in different formats and that these are not in agreement with each other. In this study the data for 2015 in /9/ has been used.

The combined data sets contain details of 5101 incidents in the UKCS in the period October 1992 to December 2019. These do not reflect all the data in the HCRD. Some fields have been omitted, such as the names of installations and their ID numbers in order to maintain a degree on anonymity. Also, some fields which were made available in the 1992-2015 data set are omitted from the 2016-2019 data set. However, these fields do not significantly affect the analysis carried out in this study although it is likely that the collation process has led to the omission of some data, where there has been more than one cause of release from within one of the four primary categories. In the period from 2016, coinciding with the introduction of the ROGI form, the quality of the data in terms of completeness and adherence to the intended taxonomy has decreased meaning that some judgement is required in assigning categories.

The study also looks at the effect of severity category on the distributions between the causation categories. For some of the more recent incidents the severity category has yet to be determined and these incidents have been discounted in compiling the tables and graphs.

Causal Analysis

ROGI Form Requirements

The information on the causes of accidents is specified in section xi of the ROGI Form /10/. The “short description” section in the form is optional and may not always be completed. In any event, this field is currently withheld from publication by the HSE. The HSE have indicated that it may be made available in future data releases. The primary categories for causes are specified as; Design, Equipment, Operational and Procedural.

Guidance is provided on the categorization in /11/ which defines the categories as follows:

Design: “If there is a suspected design fault in the equipment or related system which contributed to the hydrocarbon release”

This option is intended to include failure to design against anticipated levels of corrosion, erosion, fatigue and wear. However, where the corrosion etc. that caused the leak is greater than anticipated in the design then this shouldn’t be classed as a design failure.”

Equipment: “Failure of equipment is a common contributor to hydrocarbon leaks, and the main categories are listed on the form. If the mode of equipment failure is not included here then tick OTHER and specify the fault.”

Operation: “The main operational failure modes are listed in the form, but if the leak is attributable to one not on the list, then tick OTHER and specify.”

The list includes a large number of options such as “incorrectly fitted”, “improper inspection”, “improper operation”, “dropped object” and “Opened when containing HC”

Procedural: “Any procedural failure should be notified if it contributed to the release of hydrocarbons. Please tick the relevant [most appropriate] box[es], or add details to OTHER if required.”

Any number of categories may be selected recognizing that a given leak may be the result of a combination of factors. However, although the form allows for multiple causes within the same primary category to be ticked, e.g., “Incorrectly fitted” and “Improper Inspection” which are both sub-categories of “Operational”, the HCRD spreadsheet in which the information is collated does not readily allow for this.

Initial Categorisation

The lack of compliance to the taxonomy when recording the cause has led to a large number of causes being specified, some of which do not conform to the standard taxonomy. Some interpretation was applied to reduce the number of categories and A detailed breakdown by severity classification in each of the four main categories is given in the DNV report /12/. However, the main purpose of this study is to look at the overall trends within the four primary categories.

Category Combinations

A given incident may be the result of more than one of the four main categories. Table 1 shows the number of incidents within the 16 combinations of the four primary categories. All combinations are represented including no causes recorded (68 incidents) and all four (39 incidents). Design faults are often associated with equipment faults. Similarly, procedural faults are often found in combination with operational causes.

Table 1: Number of Incidents with Each Combination of Primary Causal Categories

Category Contributing				Severity							
Design	Equipment	Operation	Procedure	Minor		Significant		Major		Total	
				Number	%	Number	%	Number	%	Number	%
No	No	No	No	39	1.5%	18	0.8%	4	1.8%	68	1.3%
No	No	No	Yes	27	1.1%	20	0.9%	0	0.0%	47	0.9%
No	No	Yes	No	491	19.2%	436	19.0%	38	17.0%	973	19.1%
No	No	Yes	Yes	145	5.7%	157	6.9%	15	6.7%	320	6.3%
No	Yes	No	No	1101	43.0%	862	37.6%	64	28.7%	2034	39.9%
No	Yes	No	Yes	24	0.9%	31	1.4%	3	1.3%	58	1.1%
No	Yes	Yes	No	364	14.2%	353	15.4%	33	14.8%	753	14.8%
No	Yes	Yes	Yes	94	3.7%	99	4.3%	13	5.8%	207	4.1%
Yes	No	No	No	11	0.4%	11	0.5%	8	3.6%	30	0.6%
Yes	No	No	Yes	7	0.3%	4	0.2%	0	0.0%	11	0.2%
Yes	No	Yes	No	24	0.9%	34	1.5%	10	4.5%	68	1.3%
Yes	No	Yes	Yes	13	0.5%	28	1.2%	5	2.2%	46	0.9%
Yes	Yes	No	No	154	6.0%	147	6.4%	15	6.7%	316	6.2%
Yes	Yes	No	Yes	2	0.1%	12	0.5%	1	0.4%	15	0.3%
Yes	Yes	Yes	No	53	2.1%	53	2.3%	10	4.5%	116	2.3%
Yes	Yes	Yes	Yes	10	0.4%	25	1.1%	4	1.8%	39	0.8%

Note that the values in the "Total" column may be larger than the sum of the values in the "Minor", "Significant" and "Major" columns since there are 29 incidents which were unclassified at the time of the analysis.

The causes of leaks can be broadly divided into those which are related to the robustness of the equipment itself, i.e. "Design" and "Equipment" or how it is operated on the installation i.e. "Operational" or "Procedural". For the purposes of this study in examining the hole size distribution and trends over time, the incidents can be grouped as follows;

- Those which are the result of Design/Equipment only
- Those which are the result of Design/Equipment as one of the causes
- Those which are the result of Operational/Procedural only
- Those which are the result of Operational/Procedural as one of the causes
- Those which are the result of both Design/Equipment and Operational/Procedural

Note that these sets are not mutually exclusive and can be represented in the Venn diagrams shown in Figure 1

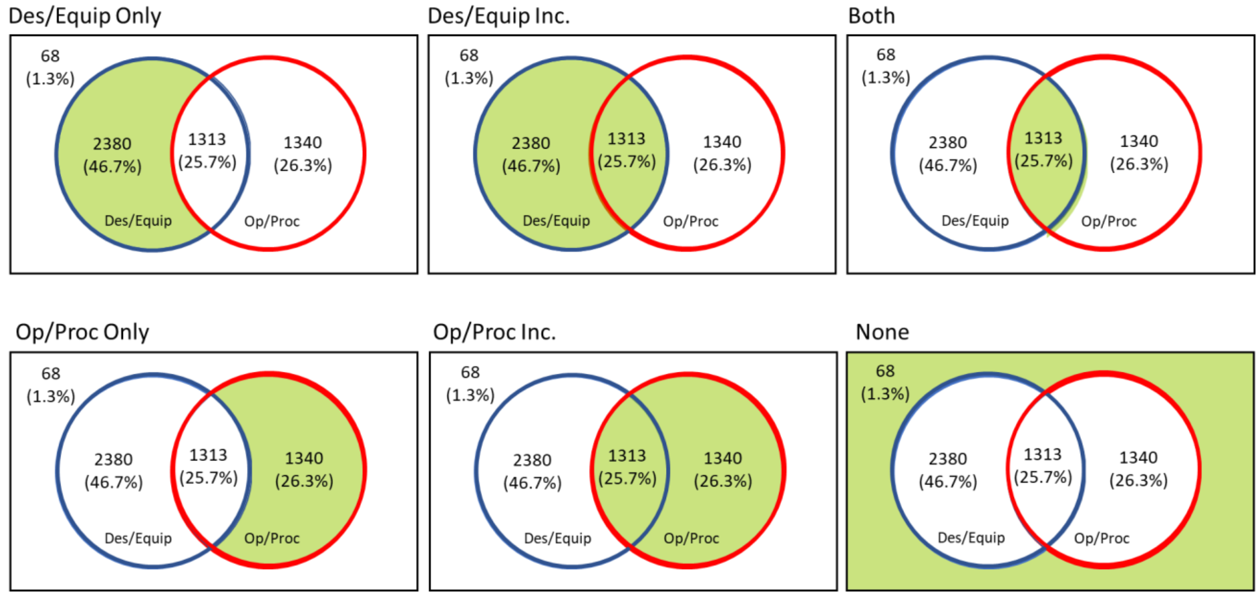

Figure 1: Distribution of Causal Categories

The distribution among the severity classes is shown in Table 2. Note that a given incident will be recorded in one of the first 4 rows but may also be included in the "Des/Equip Included" and /or "Op/Proc Included".

Table 2: Proportion of Causal Groupings By Severity Class

Grouping	Severity							
	Minor		Significant		Major		Total	
	Number	%	Number	%	Number	%	Number	%
None	39	1.5%	18	0.8%	4	1.8%	68	1.3%
Des/Equip Only	1266	49.5%	1020	44.5%	87	39.0%	2380	46.7%
Op/Proc Only	663	25.9%	613	26.8%	53	23.8%	1340	26.3%
Both	591	23.1%	639	27.9%	79	35.4%	1313	25.7%
Des/Equip Included	1857	72.6%	1659	72.4%	166	74.4%	3693	72.4%
Op/Proc Included	1254	49.0%	1252	54.7%	132	59.2%	2653	52.0%

It can be seen that the contribution of incidents attributable to Design/Equipment issues only (Des/Equip Only"), decreases as severity increases. The proportion from Operational/Procedural causes only ("OP/Proc Only") is reasonably constant but the proportion of incidents resulting from a combination of both increases.

Hole Size Distribution

The risk from a loss of containment incident is dependent on the frequency of occurrence but also on the equivalent hole size. Hence, it is important to understand the relative probability within the spectrum of hole sizes and whether the cause of the accident has a bearing on that distribution. The hole size distribution for those incidents for which a hole size has been recorded are given in Figure 2.

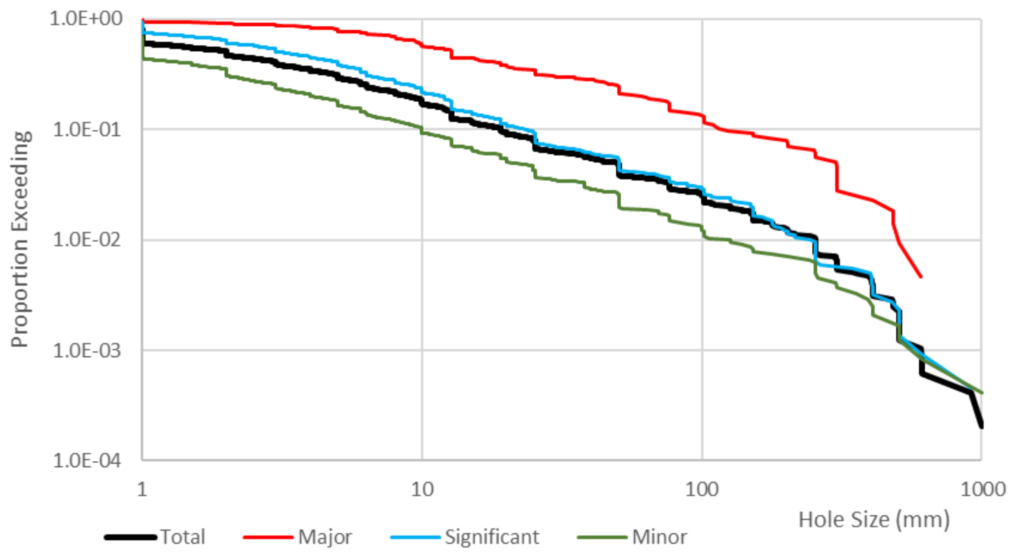

Figure 2: Hole Size Distribution by Severity Category

As would be expected, the proportion of incidents with large hole sizes is greater for those classed as Major than for those classed as Significant, which in turn is greater than those classed as Minor.

It should be noted that the classification is based on both release rate and total inventory released. The release rate is a function of system pressure and type of hydrocarbon being released as well as the hole size. The mass released is a function of the release rate and also the duration of the event which itself is related to inventory of the system and the success or otherwise of isolation and blowdown measures. Hence, it is quite possible for an incident classed as "Minor" to have a hole size greater than one classed as "Significant" or even "Major".

In order to determine whether the cause of the release has an influence on the hole size distribution, plots of probability of exceedance were generated for the five groups identified above. Figure 3 shows the distribution taking all severities into account. Further resolution is provided for the Major, Significant and Minor classifications in Figure 4, Figure 5 and Figure 6 respectively.

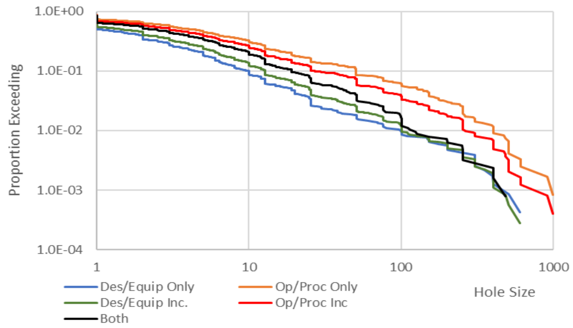

Figure 3: Hole Size Distribution - Overall

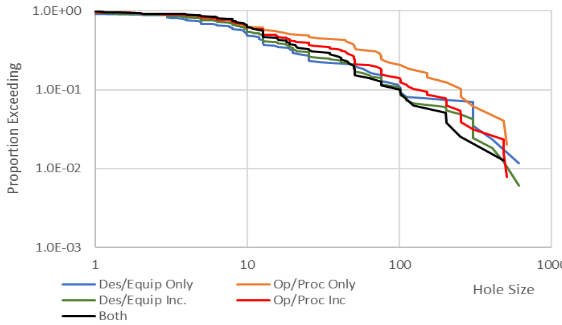

Figure 4: Hole Size Distribution for Major Incidents

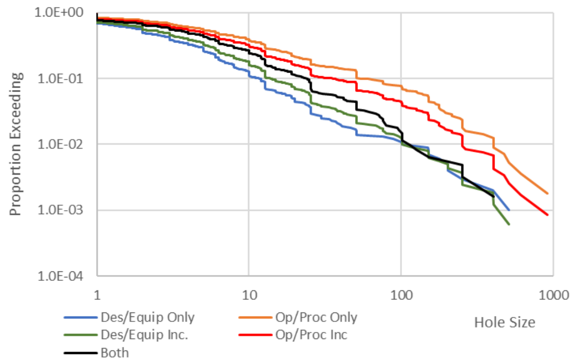

Figure 5: Hole Size Distribution for Significant Incidents

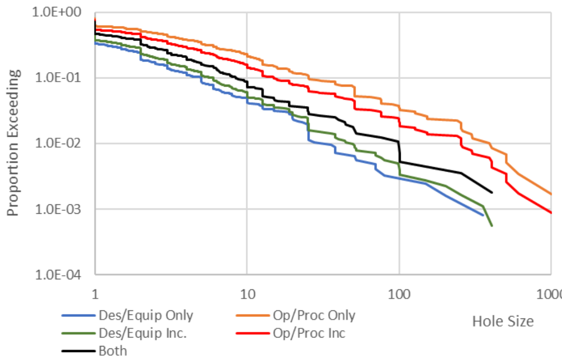

Figure 6: Hole Size Distribution for Minor Incidents

From the above figures it is clear that incidents caused by operational/procedural issues will tend to result in an increased proportion of larger holes compared to Design/Equipment issues and that this differentiation is greater for less severe classifications.

Note that there are a number of incidents where the hole size is very large, potentially a full-bore rupture, but that the equipment was almost fully depressurised resulting in a relatively small release of hydrocarbons, and therefore classed as minor.

Trends Over Time

It is well established that the number of incidents per year has progressively fallen over the time span of the HCRD, albeit it has plateaued in recent years. However, the trends are not the same for different levels of severity, and also are due to different causes. This has been reported in previous studies /13/ and /14/ for the period up to 2015. This study is similar to those analyses but also includes the incidents in the period 2016-2019. To investigate this, the data was analysed to produce 5 year rolling averages of the number of incidents and proportions. The results for the number of incidents are presented in Figure 7 to Figure 12. In these graphs the values on the Year axis are the mid-year of the range, e.g. the values for 1995 are the averages over the period 1993-1997 inclusive.

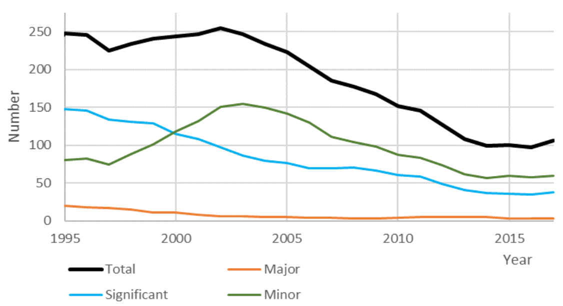

Figure 7: 5-Year Rolling Average – All Incidents

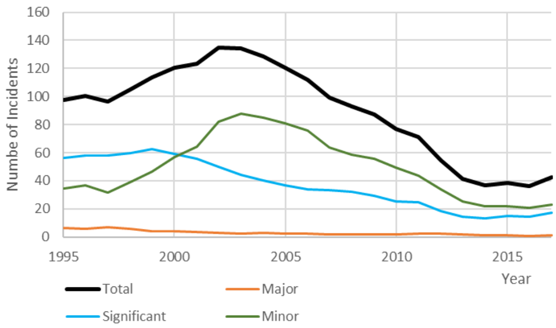

Figure 8: 5-Year Rolling Average for Design/Equipment Only Incidents

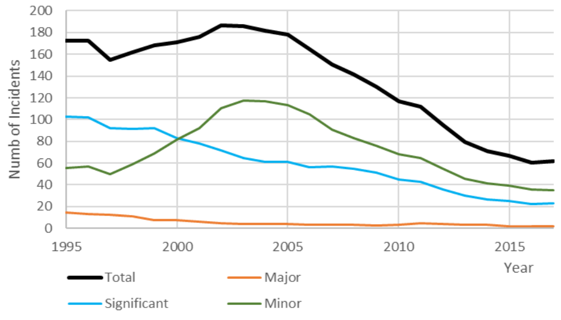

Figure 9: 5-Year Rolling Average for Design/Equipment Included Incidents

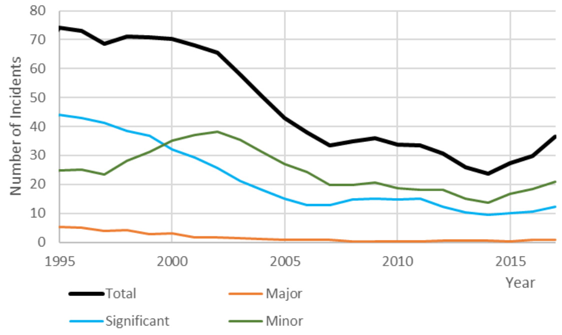

Figure 10: 5-Year Rolling Average for Operational/Procedural Only Incidents

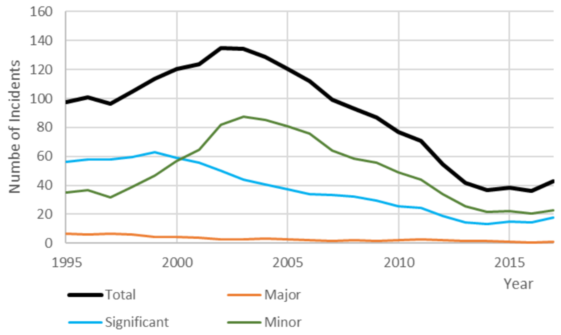

Figure 11: 5-Year Rolling Average for Operational/Procedural Included Incidents

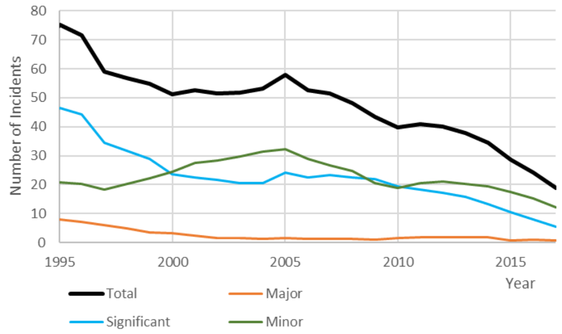

Figure 12: 5-Year Rolling Average for Design/Equipment and Operational/Procedural Combined Incidents

These graphs indicate that the number of incidents has been falling significantly in recent years, following a slight increase in the period leading to 2002, which appears to have been largely driven by incidents caused by Design/Equipment issues. Note that during this period the population of equipment in the UK sector of the North Sea was increasing so these graphs do not necessarily indicate an increase in frequency per equipment item.

Notably, the relative proportions of Minor and Significant incidents change significantly over the period 1992-2005. The reason for this is not clear but could be related to changes in interpretation of the severity criteria.

Graphs of the proportion of incidents covered by the various groups are presented in Figure 13 to Figure 17

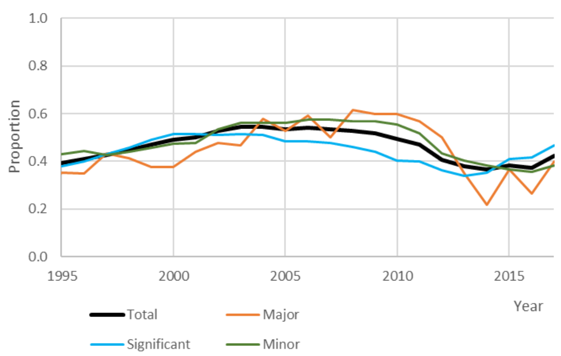

Figure 13: 5-Year Rolling Average for Design/Equipment Only Proportions

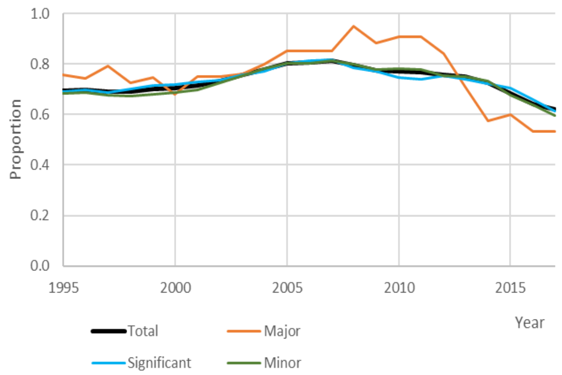

Figure 14: 5-Year Rolling Average for Design/Equipment Included Proportions

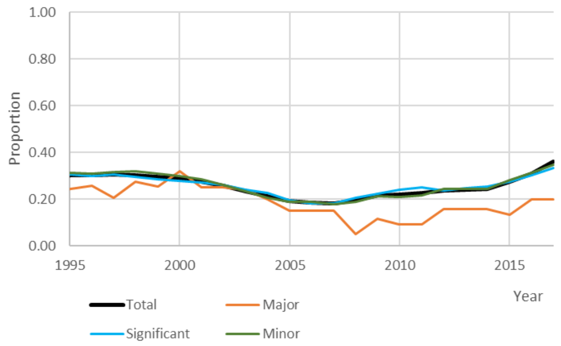

Figure 15: 5-Year Rolling Average for Operational/Procedural Only Proportions

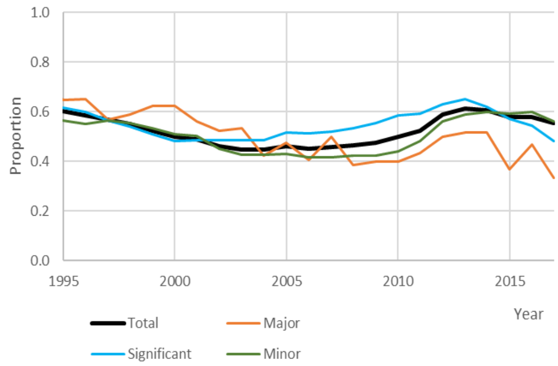

Figure 16: 5-Year Rolling Average for Operational/Procedural Included Proportions

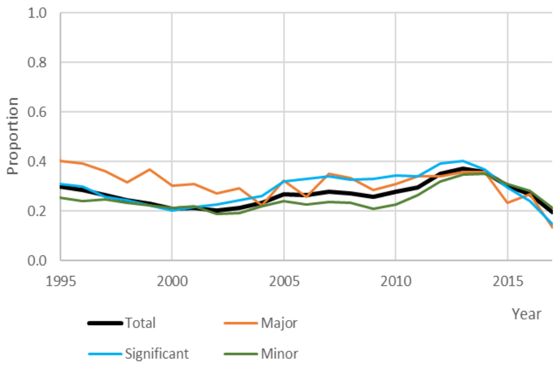

Figure 17: 5-Year Rolling Average for Design/Equipment and Operational/Procedural Combined Proportions

The graphs clearly show two distinct periods and possibly a more recent third. Up until around 2003 the proportion of leaks changed with an increasing proportion being attributed to design/equipment issues. Between then and 2015 the trend reverted, as the reducing number of incidents was mostly due to a decrease in the incidents caused by design/equipment issues. In more recent years the proportion has been relatively constant, although there has been a marked reduction in the number of incidents with both design/equipment and operational/procedural causes.

Corrosion Incidents

It is possible to analyse specific causes in the same manner as given above for hole size distribution and trending over time. Incidents caused by corrosion have been selected as an example to gain insights in how these compare with the overall population of incidents. There are 566 such cases which represents 11% of the total.

Figure 18 shows the hole size distribution for corrosion incidents by severity category. The "Total" distribution can be compared with the distributions for the main Design/Equipment group and the distribution of all causes. This is shown in Figure 19.

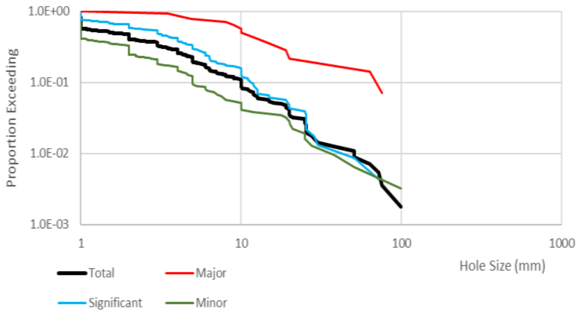

Figure 18: Hole Size Distribution for Corrosion Incidents by Severity Category

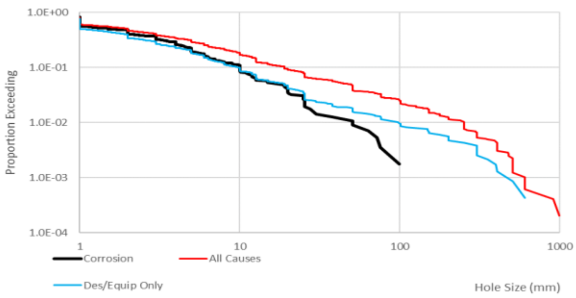

Figure 19: Comparison of Hole Size Distribution With "Des/Equip Only" and Overall

It can be seen from these graphs that the proportion of large holes is less for incidents caused by corrosion, than when a wider range of causes are considered. The largest hole size recorded where corrosion was a factor is 100 mm.

The trend over time for the number and proportion of corrosion incidents is shown in Figure 20 and Figure 21 respectively. These indicate that, as is generally the case with other causes, the number of incidents has been dropping over the period since around 2004. However, the proportion of incidents from corrosion has generally been increasing from around 8% in 1995 to 14% in 2015. There is an indication that this is also now dropping. This is notable since the number of corrosion incidents may be expected to increase as the process equipment ages.

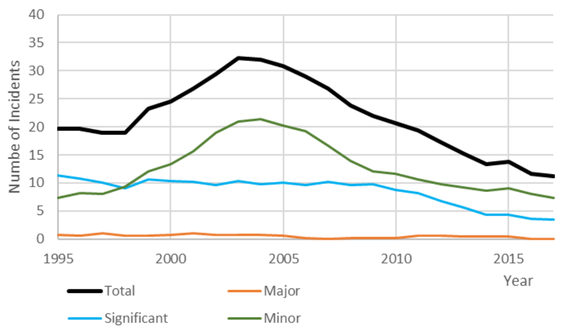

Figure 20: 5-Year Rolling Average for Corrosion Incidents by Severity

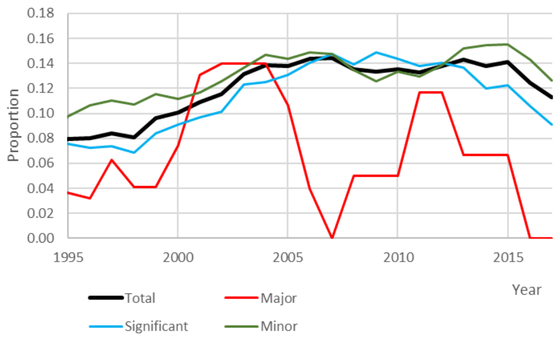

Figure 21: 5-Year Rolling Average for Corrosion Incidents Proportions

Operating Mode Analysis

Categorisation

Similar to the situation with causal data, the lack of compliance to the taxonomy when recording the mode of operation has led to a large number of variations being cited. It is likely that many of these are similar and the number of alternatives should have been reduced during the compilation of the HSE's master spreadsheet.

A detailed breakdown by severity classification into each of the main categories is provided in /12/. These give a breakdown by each unique description. These can be summarised by grouping the modes of operation into their primary classifications as presented in Table 3 and Figure 22.

Table 3: Distribution of Incidents by Operational Mode primary Categories

Main Category	Minor	Significant	Major	Not Determined	Total	Percentage	
						Overall	Excluding. BLANK
NORMAL PRODUCTION	1419	1204	122	11	2756	54.0%	54.7%
SHUTDOWN/STARTUP	518	554	43	1	1116	21.9%	22.1%
MAINTENANCE	189	136	15	4	344	6.7%	6.8%
DRILLING/WELLOPS	182	201	19	0	402	7.9%	8.0%
OTHER	219	179	20	4	422	8.3%	8.4%
BLANK	32	16	4	9	61	1.2%	N/A
Total	2559	2290	223	29	5101	100.0%	100.0%

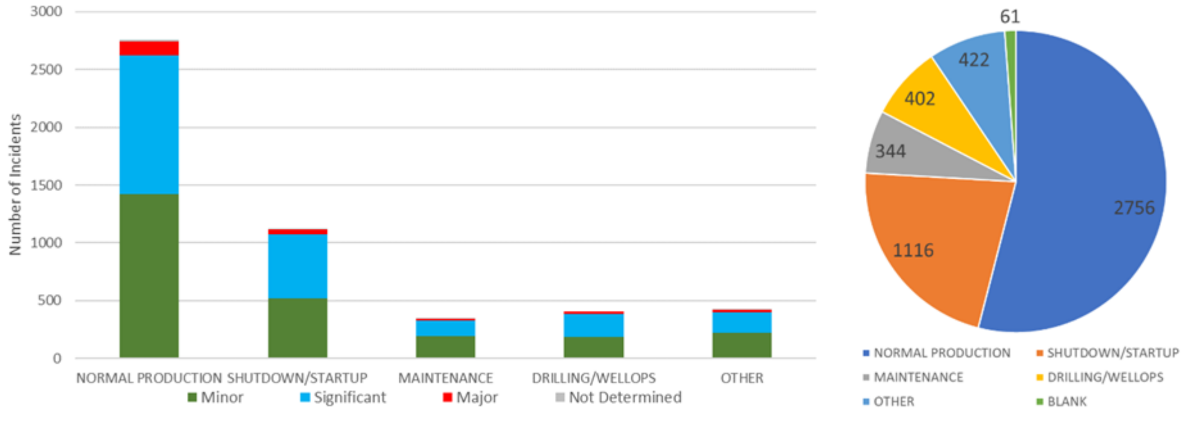

Figure 22: Distribution of Incidents by Primary Category of Operational Mode

As would be expected, the greatest number of incidents occur during normal operations. However, there is a greater proportion of incidents associated with other activities given their short duration relative to "normal operations". This indicates an increase in the leak frequency during those activities. However, the population data for the HCRD does not provide information which would enable this to be quantified.

Hole Size Distribution

Hole size distribution by severity level can be derived for each of the main operational modes. These are presented in Figure 23.

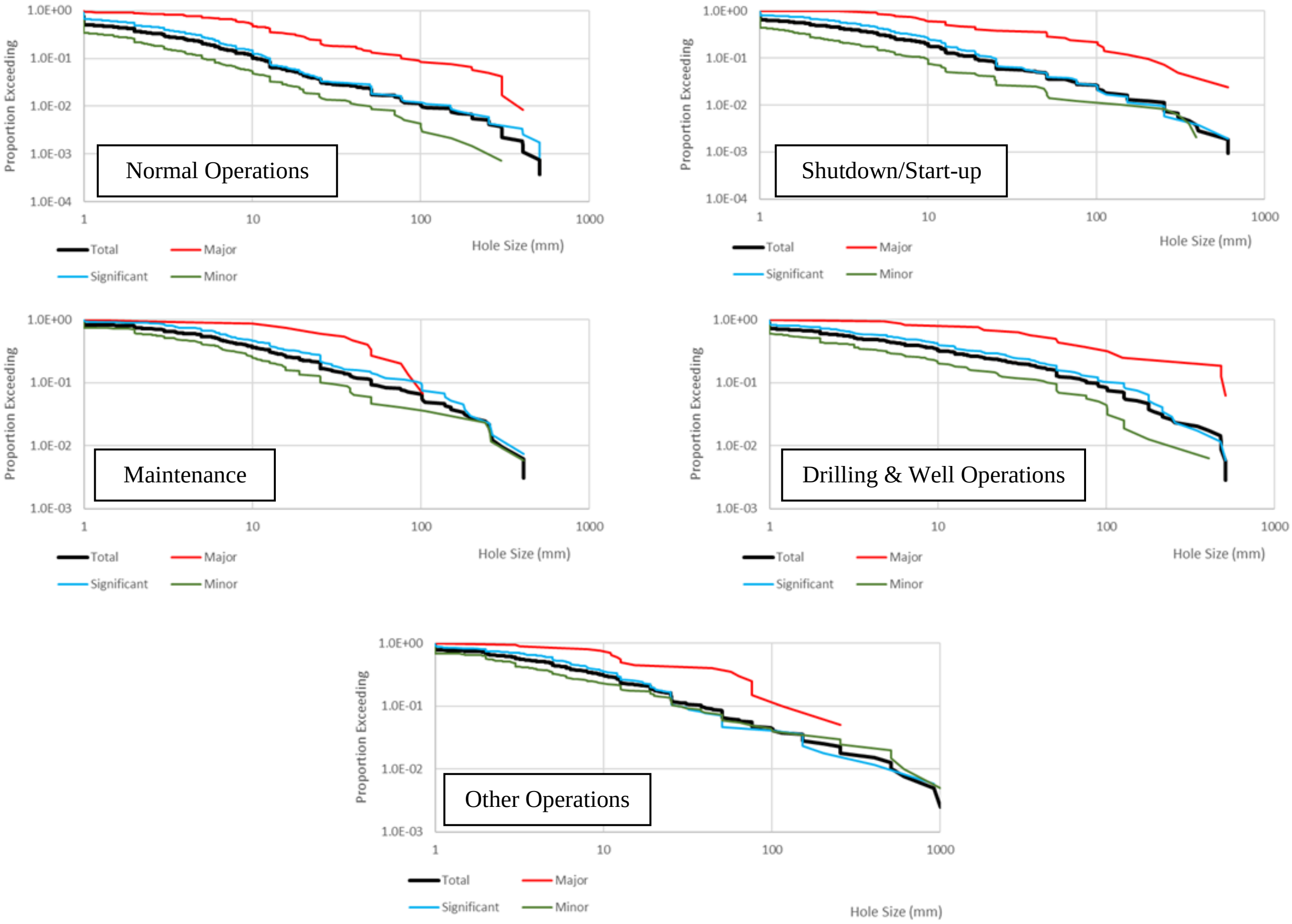

Figure 23: Hole Size Distributions by Operational Mode

The differences in the overall hole size distribution, i.e., irrespective of the severity classification, are more clearly seen in Figure 24.

It can be seen that "Startup" operations (including shutdown) have a higher proportion of large leaks compared with normal operations. There is an even greater difference for "Maintenance", "Drilling & Wellops" and "Other" categories. This difference is more clearly seen in Figure 25 which presents the same data, but for holes greater than 10 mm and using a linear scale on the y–axis.

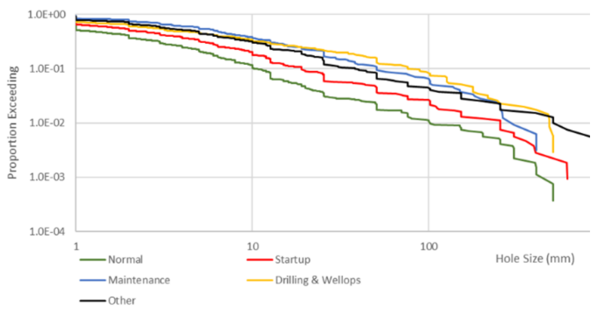

Figure 24: Comparison of Hole Size Distributions by Operational Mode

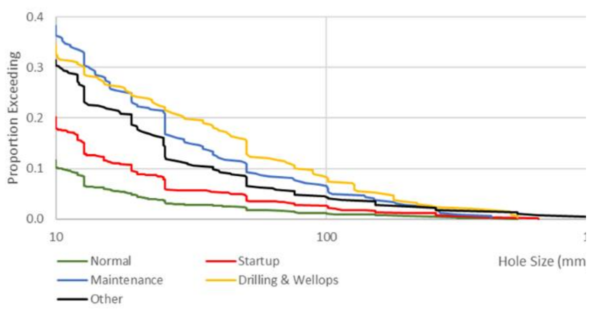

Figure 25: Comparison of Hole Size Distributions by Operational Mode (Alternative Scales)

This indicates, for example, that the proportion of holes in maintenance operations which exceed 10 mm is about 36% compared with 12% for normal production. Similarly, whereas around 1% – 1.5% of leaks from normal operations and start-ups are greater than 100 mm, the figure for the other types of operation are 4%-5%. It should also be noted that when operations other than normal production are being carried out there will be a greater number of workers in the vicinity at the time of the leak. A risk assessment is normally based on the average numbers of workers in the various parts of the installation. This may be underestimating the risk from certain types of operation because;

- the frequency of releases is higher
- the hole sizes, and hence physical consequences, are larger, and
- the exposed population will be greater.

It is known that some leaks, often with large hole sizes, take place during operations where the intention was to depressurise the system prior to breaking containment but where a residual pressure still existed, leading to the release of a small quantity of hydrocarbon. Such low pressure releases have been discounted in the derivation of leak frequency correlations /3/, /4/. However, such incidents have been included in this study and may contribute to the hole size distribution curve. Hence the severity of larger hole size releases during maintenance operations may be generally less than for the same size of hole during normal operations.

Trends Over Time

The Trends over time for the main operational modes are presented in Figure 26.

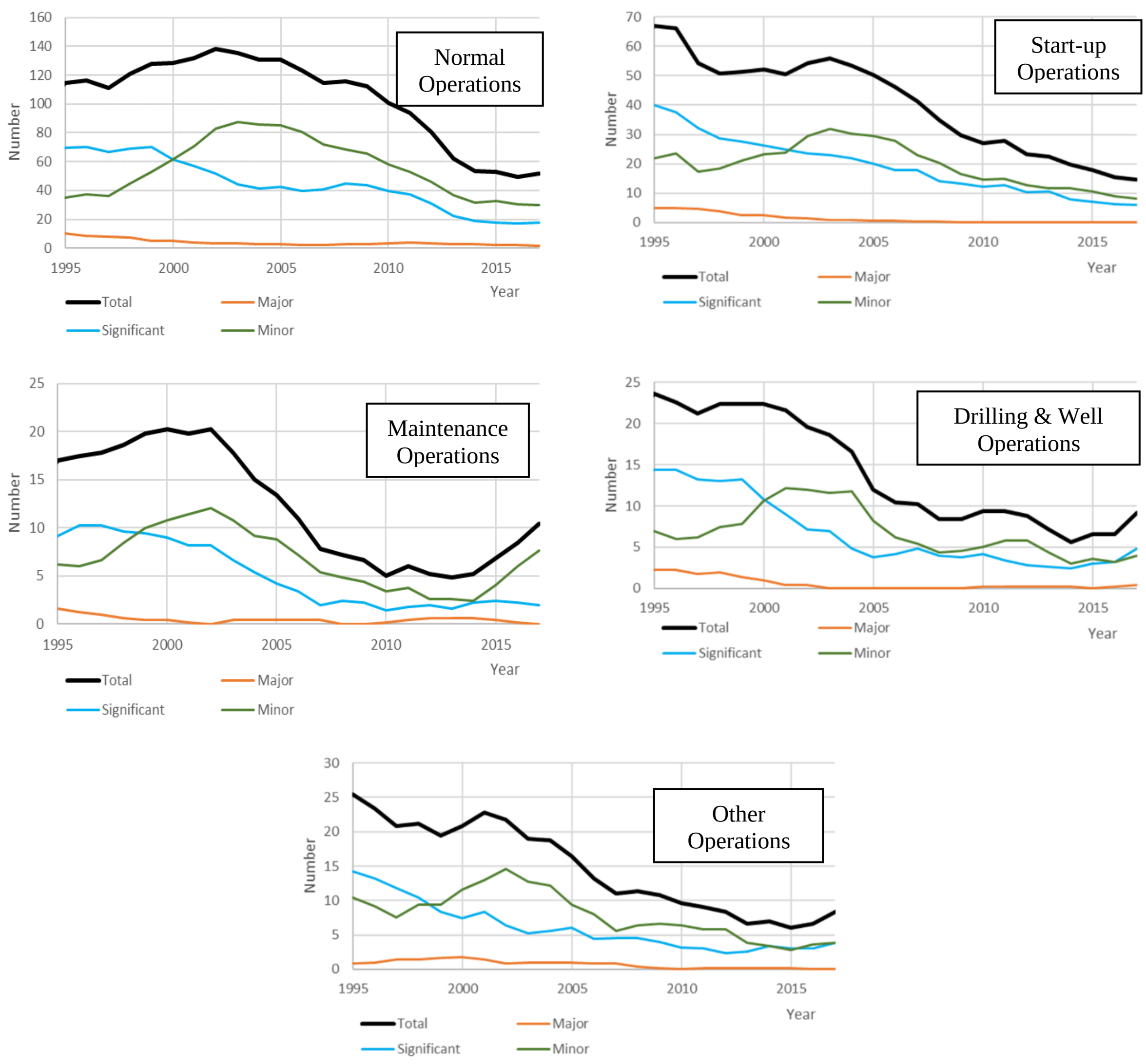

Figure 26: Year Rolling Average For Number of Incidents by Severity for Each Operational Mode

These graphs show a general decline in the number of incidents, although there is an indication that the number during maintenance is rising since 2012. However, the latter are associated with minor incidents and the number for major incidents has fallen to zero. Graphs of proportion of incidents by operational mode are presented in /12/. The proportion may reflect changes in the types of activity being carried out over time. This is most likely to occur with drilling operations.

A comparison on the numbers and proportions of incidents by operational mode are given in Figure 27 and Figure 28 respectively.

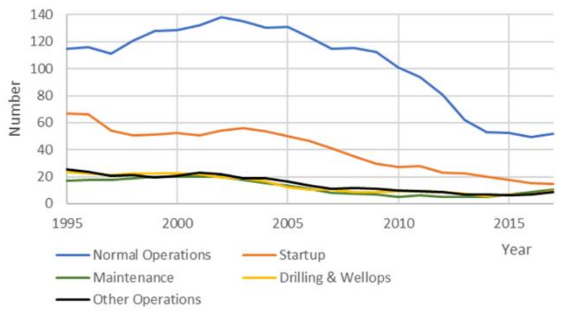

Figure 27: Comparison of Numbers of Incident By Operational Mode

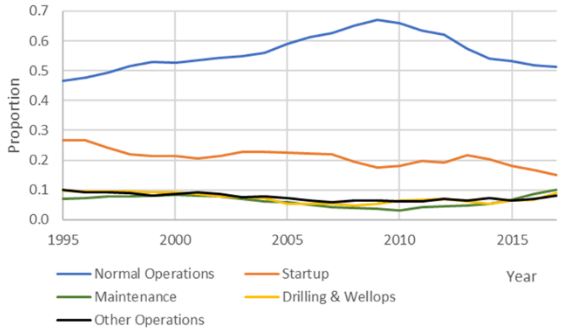

Figure 28: Comparison of Proportion of Incident By Operational Mode

Correlation Between Operational Mode and Cause

Further analysis was carried out to relate the numbers and proportions of operational mode and cause combinations. The results are presented in Table 4 and Table 5 respectively.

Table 4: Number of Incidents by Operational Mode and Causal Category

Operation Mode	Des/Equip Only	Des/Equip Inc.	Op/Proc Only	Op/Proc Inc.	Both	None	Total
NORMAL PRODUCTION	1623	2340	398	1115	717	18	2756
SHUTDOWN/STARTUP	454	752	358	656	298	6	1116
DRILLING/WELLOPS	72	150	187	265	78	7	344
OTHER	99	193	195	289	94	14	402
MAINTENANCE	114	230	186	302	116	6	422
BLANK	18	28	16	26	10	17	61
TOTAL	2362	3665	1324	2627	1303	51	5101

Table 5: Proportion of Incidents by Operational Mode and Causal Category

Operation Mode	Des/Equip Only	Des/Equip Inc.	Op/Proc Only	Op/Proc Inc.	Both
NORMAL PRODUCTION	58.9%	84.9%	14.4%	40.5%	26.0%
SHUTDOWN/STARTUP	40.7%	67.4%	32.1%	58.8%	26.7%
DRILLING/WELLOPS	20.9%	43.6%	54.4%	77.0%	22.7%
OTHER	24.6%	48.0%	48.5%	71.9%	23.4%
MAINTENANCE	27.0%	54.5%	44.1%	71.6%	27.5%

There are clear correlations between the mode of operations and the causes of leaks during those periods. This conforms to expectations with leaks during normal operations being largely due to Design/Equipment causes while maintenance operations are more likely to have leaks due to operational/procedural issues. The other modes of operation have proportions of causes between these two extremes.

Conclusions and Recommendations

The main conclusion from this analysis is that the risks from hydrocarbon releases are increased when undertaking operations which aren't classed as "Normal". This is particularly the case for maintenance operations. There are three factors which result in this increase;

- Although population data isn't available to quantify the increase in frequency during these operations, it is clear that the frequency is greater than during normal operations.
- The hole size distribution is different, because the main causes are due to operational factors, which tend to result in larger hole sizes with more severe consequences.
- These operations will tend to have workers in close attendance who are exposed to the risks.

It is typical to apply generic leak frequencies and hole size distributions to the risk assessment of normally unmanned installations. The same leak frequency is assumed for periods when the platform is manned as for the period when it is unmanned, and this leads to the assumption that a relatively small proportion of leaks will occur during manned periods.

This practice may underestimate the risk to workers since both the likelihood and consequences of leaks will be higher when they are working on the equipment.

Further work on the inter-relationship between different fields may give greater insights into the factors that have a bearing on increased probability of release.

The analysis of the data would have less uncertainties if the information in the HCRD was more complete and less ambiguous. The following recommendations are made.

- All data fields should be reported, e.g. "short description" of the cause on the release.
- The HSE master spreadsheet should be redesigned to allow for the better recording of causes where these come from the same main category. Currently it is incidents where there is more than one causes from the same main group are not collated with all the information.
- Recording of causes in the master spreadsheet should better reflect the taxonomy in order to reduce the number of similar alternatives.

Acknowledgements

This paper has been prepared as part of a joint industry project funded by BP, Chrysaor, Shell, and Energy Institute aimed at analysing and disseminating information on hydrocarbon loss of containment incidents reported by operators of offshore installation in the UKCS.

The work has been carried out in collaboration with the Health and Safety Executive.

DNV GL gratefully acknowledges the support of these organisations.

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