Learning from Dangerous Occurrences in the Chemical Industries

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It is important to learn lessons to continuously improve safety in the major hazards industries. Dangerous occurrences reported to the Health and Safety Executive (HSE) through RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) provide an opportunity for such lessons to be learned. The Health and Safety Laboratory (HSL) have been analysing dangerous occurrences on behalf of the COMAH Competent Authority. Some dangerous occurrences (incidents) are the precursors to major accidents, and because of the greater numbers of dangerous occurrences compared to major accidents it allows for a greater number of events to be studied. The aims of the work are to provide the Competent Authority and industry with a detailed insight into the issues that affect the sectors performance in managing major accident risk.

The most common sites of dangerous occurrences were found to be pipes, valves and storage vessels. These were associated with direct causes of defective and degraded equipment, front line operator failures, system failures, reactions and overpressures, and corrosion. There was a human or organisational direct cause in approximately 30% of the incidents studied. Some of the direct causes were subject to further study.

The underlying causes of dangerous occurrences were found to be hazard analysis / risk assessment, maintenance procedures, plant and process design, and operating procedures.

Over 50% of "occupational" accidents at COMAH establishments had direct causes related to human or organisational failings, and these were associated with underlying causes of operating procedures and hazard analysis / risk assessment. More accidents happened in circumstances other than normal operating conditions compared to dangerous occurrences.

1. Introduction

It is important to learn lessons to continuously improve safety in the major hazards industries. Dangerous occurrences reported to the Health and Safety Executive (HSE) through RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) provide an opportunity for such lessons to be learned. The Health and Safety Laboratory (HSL) have been analysing dangerous occurrences on behalf of the COMAH Competent Authority. Some dangerous occurrences (incidents) have been identified as potential precursors to major accidents, and because of the relatively greater numbers of dangerous occurrences compared to major accidents it allows for a greater number of events to be studied. The aims of the work are to provide the Competent Authority and industry with a detailed insight into the issues that affect the sectors performance in managing major accident risk.

This work presents information on when dangerous occurrences occur, what these dangerous occurrences are, the sources of the dangerous occurrences and their direct and underlying causes. As well as giving an overview of the patterns behind all dangerous occurrences, trends that have emerged over time are discussed. There are also specific studies on dangerous occurrences related to corrosion, human factors and runaway reactions/overpressures. Finally, patterns in accidents (reportable injuries) are compared to those for dangerous occurrences.

2. Results and Discussion

Six years of relevant dangerous occurrence data on chemical sites are compared between 2007 and 2013 with the aid of bar chart graphs.

For the work on all incidents, and the corrosion incidents, the first three years of data (coloured blue in the graphs) are based on HSL's causal analysis of the incident, using the incident investigation material available on COIN (HSE's incident and inspection IT recording system). The second three years of data (coloured red in the graphs) are based on HSE inspectors' causal analysis, which has been directly entered into COIN. The analysis presented is in terms of the reporting categories that are available to inspectors within COIN. No attempt has made to check the validity of the categories chosen by inspectors.

The work on human factors incidents, runaway and overpressure incidents and accidents uses information from the causal analysis of incidents entered into COIN by HSE inspectors between 2007 and 2013. Between 2007 and 2010 causal information was entered for some incidents, but was not compulsory. The work on runaway and overpressure incidents was supplemented by HSL's causal analysis between 2007 and 2010.

In the graphs which follow, incidents can have more than one entry per category so the totals will add up to more than the number of incidents. If the particular causal field was left blank by the HSE inspector then this is shown as "Details not given", and if the particular causal field set to N/A then this is shown as "Not applicable".

2.1 All Incidents

This section studies both the predominant causes of incidents over the past seven years and if any trends are emerging over that period. The number of incidents is listed in Table 1.

Table 1: The number of incidents of the seven dangerous occurrences related to chemical sites.

	Incidents per year		**Incidents in a three year period**
2007-08	99		
2008-09	90	2007-10	256
2009-10	67		
2010-11	138		
2011-12	106	2010-13	301
2012-13	57		

Most incidents occurred during normal operation, which is the most common mode for chemical plants; also dangerous occurrences tend to occur when the plant is live. Most incidents only have onsite effects.

Pipes are the most common release site (see Figure 1). Storage vessels and valves are also frequent release sites, but the number of releases here, seems to be decreasing. Other equipment / vessels are also common release sites, but the category covers a large range of equipment. Process vessels, pumps and compressors and relief devices do not have many incidents; maybe the risks associated with these release sites are well understood and standards are typically followed. Releases from flexible hoses are infrequent, but seem to be increasing.

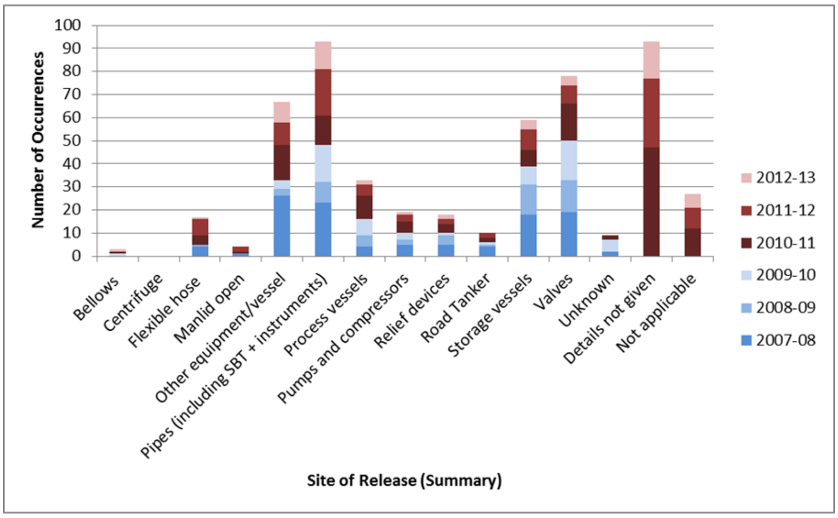

Figure 1: The site of release summarised into groups.

The most significant direct causes of incidents are front line operator failures, defective and degraded equipment, system failures, corrosion and erosion, and runaways and overpressures (Figure 2). The number of front line operator failures seems to be decreasing over recent years, and while it is tempting to attribute this to a genuine reduction in human failure, it is just as likely to be due to an under reporting of such failure. Defective and degraded equipment, as a direct cause, is associated with the underlying causes of maintenance procedures and plant and process design.

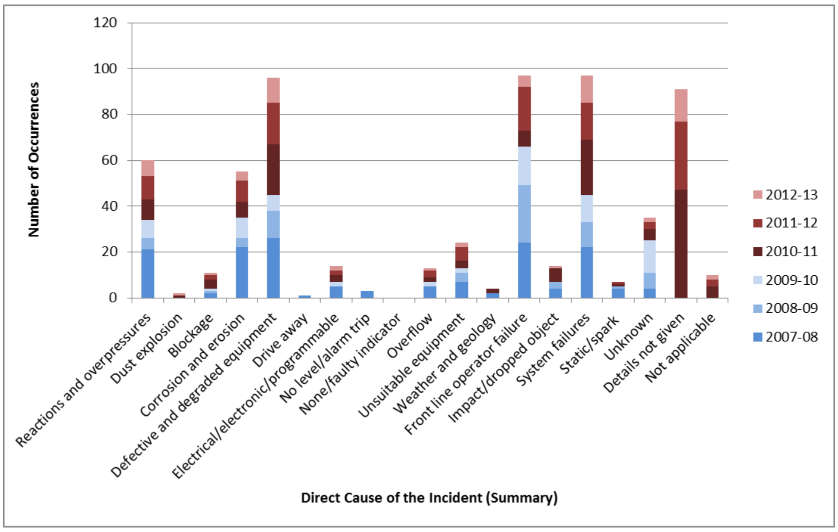

Figure 2: The direct causes of COMAH relevant dangerous occurrences summarised into groups.

The most common underlying causes are planned maintenance procedures, plant and process design, hazard analysis / risk assessment and operating procedures (Figure 3). There may be a human failure link between these underlying causes; as illustrated by the HSE Human Factors Roadmap for the Management of Major Accident Hazards (Jackson, 2010) (see Figure 4, the underlying causes found in this study are shown on the Human Factors Roadmap in red). The roadmap provides a practical approach for linking major accident hazards to assured performance of humans engaged on safety critical tasks. For instance clear reliable procedures are based upon the solid foundation of major hazard scenarios identification, from which safety critical tasks are identified, followed by a robust task analysis (together with human error analysis). Performance influencing factors include plant and process design and have an impact on human behaviour (including failure), so are therefore included as part of the human error analysis.

There is a link between planned inspection and planned maintenance. If no planned inspection is done then maintenance will tend to be reactive i.e. "fix on fault". Ageing plant, which was introduced as an underlying cause in 2010, was shown to be a significant cause. The introduction of an ageing plant national inspection topic would likely increase recording of ageing plant problems. Ageing plant is to some respect a direct cause, rather than an underlying cause, involving a time related failure mechanism. High work load, leadership and Process Safety Performance Indicators (PSPI) were also introduced as underlying causes in 2010, but have been cited less than ageing plant.

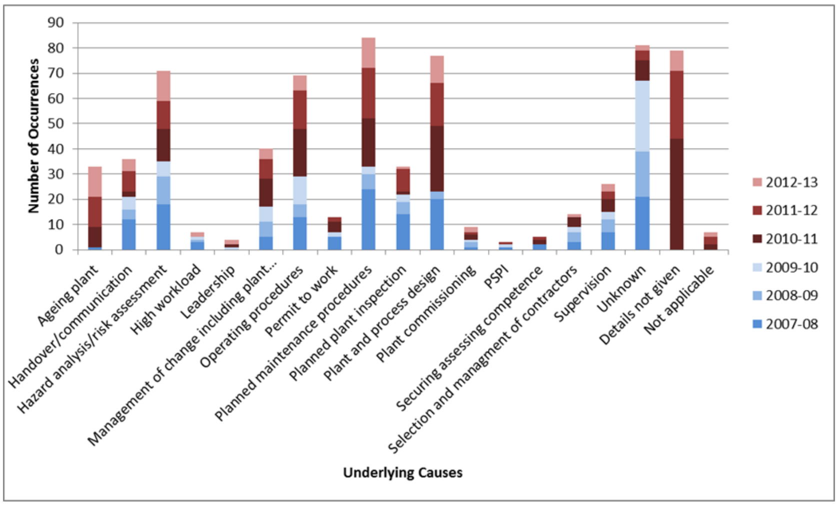

Figure 3: The underlying causes of COMAH relevant dangerous occurrences.

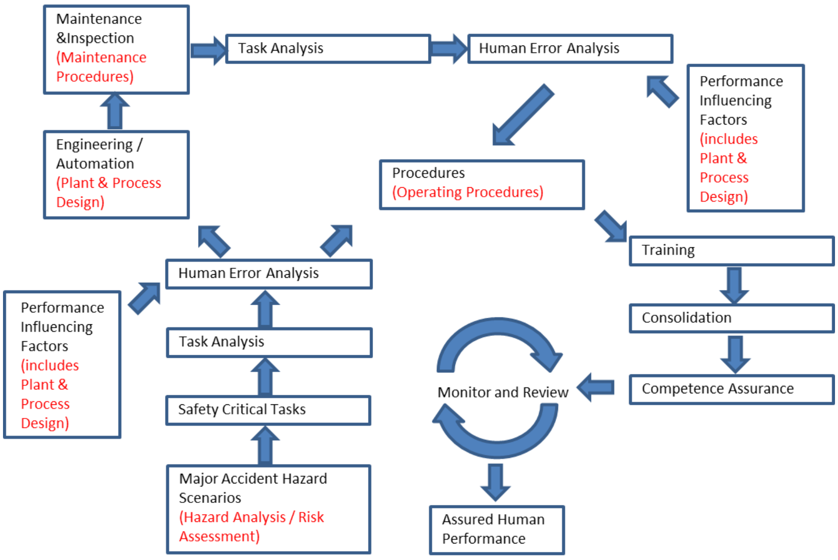

Figure 4: The HSE Human Factors Roadmap for the Management of Major Accident Hazards (Jackson, 2010), the underlying causes found in this study are shown on the Human Factors Roadmap in red.

A comparison can be made with a HSL study based on incident data between 1991 and 2002 (Collins, 2003). The 'nature of substance' data is broadly consistent with recent data. Most incidents occurred during normal operation, but the proportion of incidents during maintenance is higher than in the last 6 years. Pipes, valves and storage vessels were important release sites before 2002 and have remained high risk. Higher numbers of incidents for process vessels and flexible hoses occurred before 2002 compared with the present. A possible explanation is that perhaps process vessel design is improving and guidance for use of flexible hoses is being followed.

Corrosion has grown as a direct cause since 1991-2002 whilst incidents due to blockages and overflows have reduced. In the case of corrosion, it would be expected that this would become a more common occurrence as plants and equipment age. On blockages and overflows, it may be the case that operating procedures and process control are improving. Plant and process design, maintenance and operating procedures remain important underlying causes. Hazard analysis / risk assessment has been recognised as important in recent incidents.

A comparison can also be made with 500 pipework incidents occurring before 1990 (Hurst, 1991). The most significant direct causes were operating error, overpressure and corrosion. The most significant underlying causes were maintenance and design. Possible preventative mechanisms were also studied including human factors reviews, hazard studies and task checking. Very few incidents were found not to have been preventable.

2.2 Corrosion Incidents

Corrosion incidents are strongly linked to the release of flammables, both as a dangerous occurrence type and 'nature of substance'. The number of corrosion incidents seems to be decreasing over recent years. Pipe bodies are the major site of releases that are caused by corrosion incidents.

Internal corrosion (27 incidents) is more often reported than external corrosion (17 incidents) as a direct cause (seven incidents were due to corrosion under insulation and in two incidents the type of corrosion was unknown). There will be more variation in internal corrosion mechanisms than external corrosion; also external corrosion should be easier to identify, except where there is insulation. The most common underlying causes are failures in planned plant inspection and planned maintenance procedures (Figure 5). Plant and process design and ageing plant are also important underlying causes. Ageing plant was introduced as a category in 2010, so is likely to be under reported. Since 2010, approximately 50% of corrosion incidents have been attributed to ageing plant. Most incidents occurred in the refining and petroleum industries, which perhaps is associated with the link to releases of flammable liquids.

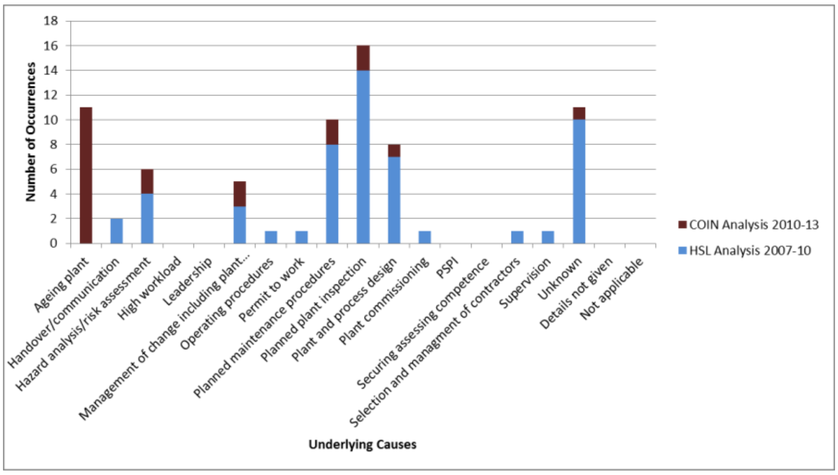

Figure 5: The underlying causes of COMAH relevant corrosion related dangerous occurrences.

This analysis should be viewed in conjunction with the EC JRC Report on Corrosion Related Accidents in the Petroleum Industries (Wood, 2003). It was found that the nature of the substance contributed to 46% of corrosion incidents. The most significant process related substances were sulphur / sulphur compounds, water and hydrogen sulphide. The process units with the most corrosion failures were hydro-treatment and distillation. The units with very high severity consequences were hydro-treatment, distillation, pipeline transfer and storage. It was found that 50% of incidents originated in pipework. The most significant vulnerabilities in the pipework being elbow joints, anti-corrosion protection failure, inadequate materials and external environment.

It was found that a variety of conditions appeared to contribute to accelerated corrosion rates leading to equipment failure, including:

- A corrosive agent formed by a reaction between process fluids,
- Process conditions causing decomposition of the corrosion inhibitor,
- Sulphur and sulphur compounds inducing corrosion,
- Corrosion induced by the presence of hydrogen or hydrogen sulphide,
- Corrosion accelerated through corrosive agents in the process water.

2.3 Runaway and Overpressure Incidents

Various direct causes and pressure relief system mitigation, of interest to the process safety discipline, are considered in this section (see Table 2).

Table 2: The different types of process safety incidents studied in this section.

		Number of incidents
Direct Causes	Auto Ignition / Spontaneous Combustion	32
	Incompatible Substances	15
	Runaway/ Chemical Reactions	21
	Overpressure	41
Mitigation Against Escalation	Pressure Relief System	24

The results of the causal analysis are shown in Tables 3 and 4. There was a relatively small data set for incompatible substances, so the patterns that emerged from this analysis were not very strong. For runaway / chemical reactions, hazard analysis / risk assessment was a significant underlying cause; this is possibly due to the specialist experimental studies that would be required to complete an accurate risk assessment. It was found that the most common dangerous occurrence types and natures of substances were consistent with each other, and those expected for their direct cause.

Table 3: Causal analysis of incidents with a process safety direct cause.

Direct Cause	**Most Common Dangerous Occurrence Type**	**Most Common 'Nature of Substance(s)'**	**Most Common Underlying Cause(s)**
Auto ignitions / spontaneous combustions	Explosion / fire	Explosive Flammable (various)	Hazard analysis / risk assessment.
Incompatible substances	Release of substance (toxics)	Toxic and very toxic Oxidising	Hazard analysis / risk assessment Operating procedures
Runaway / chemical reactions	Release of substance (toxic)	Toxic and very toxic	Hazard analysis / risk assessment Operating procedures Plant and process design
Overpressure	Release of substance (toxic) Release of flammable liquid	Flammable (various)	Operating procedures Plant and process design Hazard analysis / risk assessment

Table 4: Causal analysis of incidents with a process safety related mitigation against escalation.

Mitigation Against Escalation	**Most Common Dangerous Occurrence Type**	**Most Common 'Nature of Substance'(s)**	**Most Release Site(s)**	**Most Common Direct Cause(s)**	**Most Common Underlying Cause(s)**
Pressure relief	Release of flammable liquid Release of substance (toxic) Explosion / fire	Flammable (various)	Process vessel vent Relief device bursting disc	Overpressure System failure	Plant and process design Hazard Analysis / risk assessment

Figure 6 shows the combined underlying causes for the four runaway and overpressure direct causes, the three most significant being hazard analysis / risk assessment, operating procedures, and plant and process design.

The conclusions of the runaway and overpressure incidents work were:

- Process vessels are more important for runaways and overpressures than for other incidents.
- The major direct causes of the incidents considered were auto ignition/spontaneous combustion and overpressure.
- The major underlying causes are hazard analysis / risk assessment, plant and process design, operating procedures.

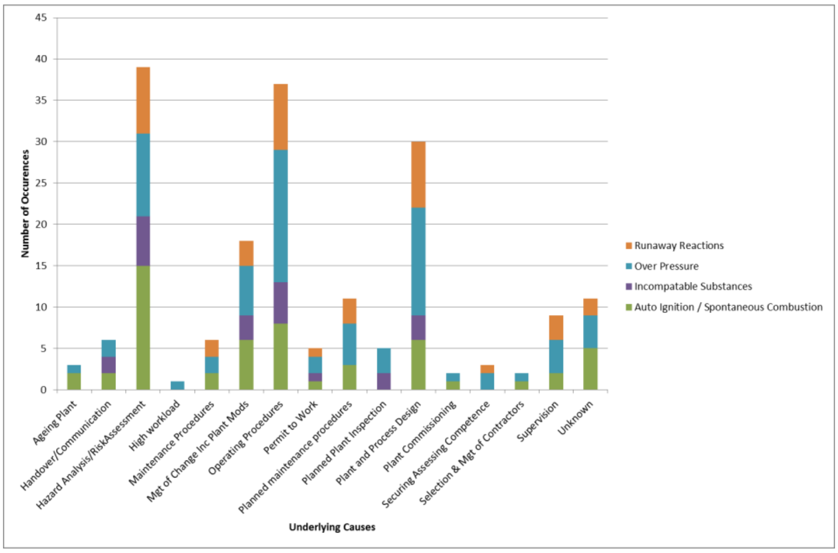

Figure 6: The underlying causes of runaway and overpressure dangerous occurrences.

Two previous pieces of work on runaway reaction incidents are considered below:

1. UK Incidents (Barton, 1989)

The sample was 189 batch reactor runaways between 1962 and 1987. For the chemical process involved in the runaway; polymerization was by far the most important reaction type. The industry in which the runaway occurred was typically fine and intermediate organics and plastics, rubbers and resins. There were a variety of associated direct and underlying causes including reaction chemistry / thermochemistry, temperature control and mischarging of reactants or catalysts. There were human factors failures due to both front line operators and systems. HSE developed guidance for industry following this review but the decrease in incidence rate of runaway events since then may also be due to a reduction in the number of companies operating such processes.

2. US Incidents (US Chemical Safety and Hazard Investigation Board, 2002)

The sample was 162 reactive incidents available to CSB between 1980 and 2001. The most important consequence categories were fire / explosion and toxic gas release. The industry involved was mainly chemical manufacturing and a smaller quantity of bulk storage / handling. Acid was the most important chemical class and decomposition was the most important reaction type. The equipment type was mainly reactors, storage equipment and other process equipment. The reaction hazard was mainly chemical incompatibility and runaway reaction. The root cause was generally hazard evaluation and storage / handling procedures.

The main conclusions from these two pieces of work therefore were that:

- Reactions were mainly decompositions and polymerisations.
- Underlying causes were mainly hazard evaluation and procedures.
- The site of release included reactors, storage vessels and other process equipment.

2.4 Human Factors Incidents

The various front line operator failures (human errors: lapses, slips, mistakes and violations, including procedural violations) and system failures (inadequate procedures, inadequate isolation, inadequate control and incorrect installation) are considered in this section.

Table 5: The numbers of human factors incidents studied in this section.

Type of failure	**Number of incidents**
Front line operator failures	135
System Failures	189
• Inadequate control	64
• Inadequate isolation	29
• Inadequate procedures	78
• Incorrect installation	41

Figure 7 shows the underlying causes of front line operator failures were operating procedures, hazard analysis / risk assessment, plant and process design, supervision and maintenance procedures (including planned maintenance procedures).

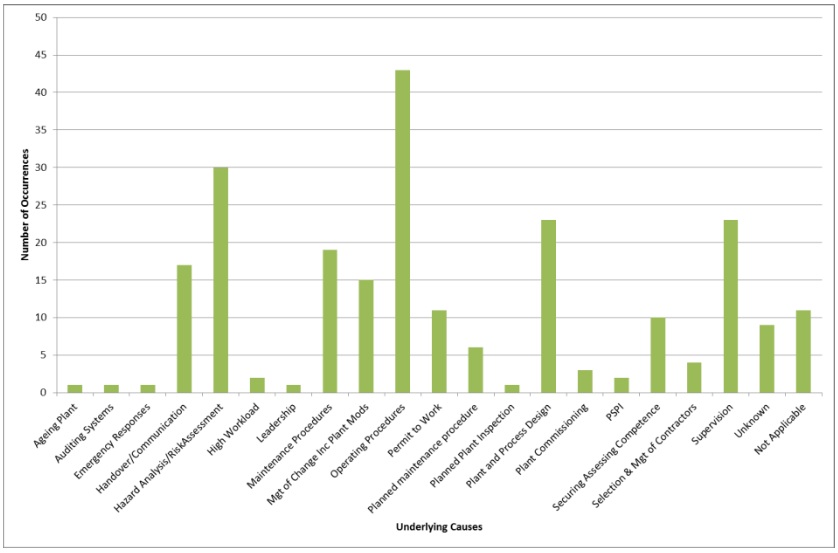

Figure 7: The underlying causes of front line operator failure.

Figure 8 shows that the most common underlying causes for system failures were operating procedures, hazard analysis / risk assessment, plant and process design and maintenance procedures (including planned maintenance procedures). The importance of the plant and process design is shown as a significant underlying cause. As with Figure 3 (and Figure 6), the evidence represented by Figure 7 and 8 highlights the link between major hazard identification, procedures and performance influencing factors (e.g. plant and process design).

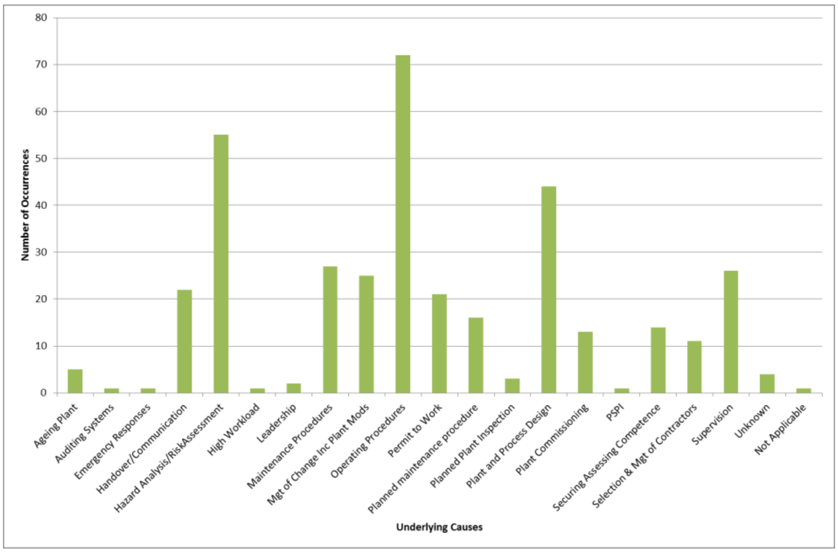

Figure 8: The underlying causes of system failures.

The conclusions of the incidents work were:

- The most significant direct cause was human failure.
- The most common dangerous occurrence type was release of flammable liquid.
- The typical sites of releases were valves and pipes (typically open end), for both front line operator and system failures
- The most common 'nature of substance' was flammable (various)
- Typical underlying causes were operating procedures, hazard analysis / risk assessment; but plant and process design was also important for system failures.

2.5 Accidents

In this section accidents at chemical sites are studied, and these are reportable fatalities (25 cases) and reportable injuries (1574 over three day injuries, 49 over seven day injuries and 590 specified major injuries such as amputations, eye injuries and burns), rather than dangerous occurrences (incidents). However, only 347 of the accidents have causal information available. Of the direct causes, front line operator failures and system failures are the most frequent (56% of accidents were due to human or organisational failings). Operating procedures and hazard analysis / risk assessment are the most common underlying causes (Figure 9). In terms of the 'nature of substance', most accidents involved non-COMAH substances; possibly the risks associated with COMAH substances are better understood.

A smaller proportion of accidents occur during normal operations compared with dangerous occurrences (33% of incidents that have relevant causal information), with a relatively large number of accidents occurring during maintenance work (20%). Fortunately COMAH dangerous occurrences do not often result in reportable fatalities or injuries, but reportable "occupational" injuries do occur on COMAH establishments, as in other industries. These "occupational" injuries will tend to be in human factors intense activities such as maintenance, with procedures once again being a notable underlying cause, and the link with hazard analysis and performance influencing factors (e.g. plant / process design and supervision) being evident (i.e. as outlined by the HSE Human Factors Roadmap (Jackson, 2010)).

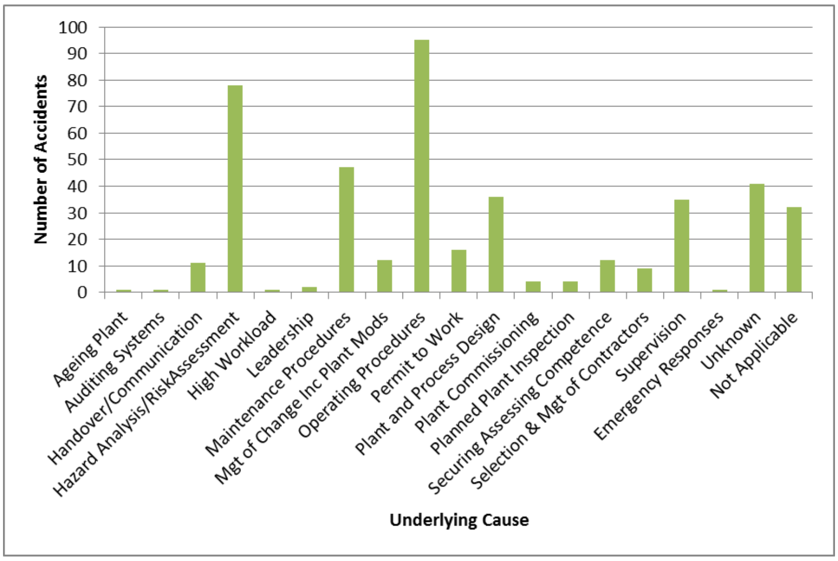

Figure 9: The underlying causes of accidents.

3. Conclusions

The most common sites of dangerous occurrences were found to be pipes, valves and storage vessels. These were associated with direct causes of defective and degraded equipment, front line operator failures, system failures, reactions and overpressures, and corrosion. There was a human or organisational direct cause in approximately 30% of the incidents studied. Some of the direct causes were subject to further study.

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4. Acknowledgements

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