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Loss of containment of toxic and flammable inventories from process plant is associated with a long history of major accidents including fires, explosions and toxic releases. Such accidents affect both workers and the offsite public. These issues are often associated with the onshore process industries which incorporate a very wide range of segments including pharmaceutical manufacture, tank storage, downstream oil & gas, fine and speciality chemical manufacture as well as many others. What may be less well appreciated is that while the Civil Nuclear sector has a key focus on containment of radiological materials, it also maintains significant inventories of flammable and toxic materials, which it terms ‘chemotoxic’ hazards. It follows that a very broad range of industries have a desire to prevent and mitigate the potential for loss of containment events which release chemotoxic materials. Existing sources of loss of containment intelligence include the Health & Safety Executive (HSE) and other databases which can be interrogated to glean process safety insights. Such systems incorporate some limited coding of data, but often feature much greater detail within unstructured free text. Systematic interrogation of such free text fields could yield greater detail within process safety insights as well as a potentially larger number of records with which to draw insight. The Discovering Safety Programme is a multidisciplinary initiative funded by the Lloyd’s Register Foundation. The programme aims to improve plateaued safety performance through better insight via data analysis tools including text mining and natural language processing. This paper describes the early stages of a project within the Discovering Safety Programme to obtain process safety insights from HSE’s regulatory database. This work includes analysis of coded information, proposals to extract intelligence from unstructured free text and also exploration of whether process safety intelligence can be extracted from a subset of occupational safety incidents. The paper describes the findings from industry consultation, including the civil nuclear sector.

Keywords	LOSS OF CONTAINMENT, PROCESS SAFETY, CHEMOTOXIC, NUCLEAR, PROCESS INDUSTRY, PROCESS ENGINEERING, PROCESS INTEGRITY, DATA ANALYTICS
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Understanding Loss of Containment of Non-radiological Chemotoxic Materials in the Civil Nuclear and Process Industries

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Abstract

Loss of containment of toxic and flammable inventories from process plant is associated with a long history of major accidents including fires, explosions and toxic releases. Such accidents affect both workers and the offsite public. These issues are often associated with the onshore process industries which incorporate a very wide range of segments including pharmaceutical manufacture, tank storage, downstream oil & gas, fine and speciality chemical manufacture as well as many others. What may be less well appreciated is that while the Civil Nuclear sector has a key focus on containment of radiological materials, it also maintains significant inventories of flammable and toxic materials, which it terms 'chemotoxic' hazards. It follows that a very broad range of industries have a desire to prevent and mitigate the potential for loss of containment events which release chemotoxic materials.

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1. Introduction

The Thomas Ashton Institute, a collaboration between the University of Manchester and the Health & Safety Executive (HSE), launched in early 2018. The Institute carries out interdisciplinary research in the field of safety and health, covering both occupational safety issues and major accident hazards, including process safety management.

The Lloyd's Register Foundation (LRF) is a charity[1] with a mission to protect the safety of life and property, and to advance engineering education and research. LRF have provided funding for the *Discovering Safety Programme*, which aims to improve safety by generating insights from data, in particular large, under-utilised datasets.

The authors would like to thank the Foundation for providing funding and guidance for this important programme. The remainder of this paper describes the *Loss of Containment* project, which is a set of process safety focused activities with an initial focus on the onshore process industries within Great Britain.

The work described in this paper focuses upon process safety the main goal of which is to prevent and mitigate high-consequence, low-frequency events such as fires, explosions and toxic releases. Occupational Safety (referred to as Conventional Safety in the nuclear sector) refers to the management of issues which largely affect individual workers such as slips, trips, falls from height and vehicle hazards. Clearly, it is important to manage both process safety and occupational safety well, but it is generally acknowledged that they require different approaches to their management.

Figure 1 shows a Venn diagram with Occupational Safety and process safety shown separately but with an overlap displayed in yellow. The authors are keen to explore whether this area exists, its extent and whether there are any features within the overlap which could lead to bias if intelligence derived from this area were used to inform process safety management. The

[1] www.lrfoundation.org.uk

rationale for doing this is that HSE's existing datasets contain a large number of Occupational Safety events because these have a significantly higher frequency than process safety events.

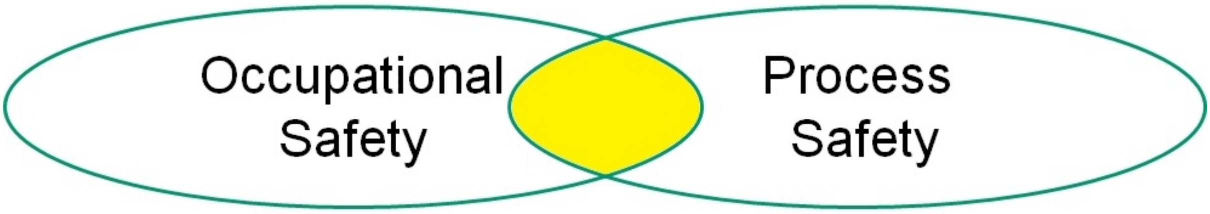

Figure 1 - Occupational & Process Safety Overlap

The overlap between Occupational Safety and Process Safety is cautiously explored with examples and an early consideration of limitations later in this paper.

2. Loss of non-radioactive containment in the nuclear sector

Gale and Clay conducted an exploratory study to investigate the nature and extent of loss of containment events (LoC) of non-radioactive materials in the nuclear sector. Loss of containment in this study was based partly on the definition of the International Association of Oil and Gas Producers (IOGP) Report No 456 Version 2 [1] and can be understood as:

Unplanned or uncontrolled release of any material, fire, explosion and toxic hazards. In this study, radioactive materials are excluded. LoC is a type of event. An unplanned or uncontrolled release is a LoC, irrespective of whether the material is released into the environment, or into secondary containment, or into other primary containment, not intended to contain the material released under normal operating conditions.

3. Nuclear study methodology

Qualitative data were gathered using an inductive research investigative approach. The global population for this study comprised the UK nuclear sector, excluding defence. The working population was synonymous with the global population. Sampling adopted the convenience method, which in this case was appropriate because those approached were either the most senior executives in representative entities of the nuclear sector, or similar.

The nuclear sector was stratified; organisations and individuals were approached through the investigator's network. The nuclear defence sector was not included. The first contacts were made, normally at Chief Executive and Executive Director levels, or equivalent. These individuals then identified suitable respondents who were all engineers, scientists or specialists with significant knowledge and experience. Collectively, notwithstanding the small sample size, they accounted for a comprehensive overview of the nuclear sector in the UK. Generally speaking, the senior people contacted went to great lengths to ensure that appropriate experts were identified for this study and the authors are very grateful for this.

The nuclear sector stratification was determined in relation to functional aspects; this took account of the nuclear industry structure [2], based on the hypothesis that loss of containment may be differentially problematic across subsectors of the nuclear sector. The identified subsectors are:

- Decommissioning;
- Nuclear Energy Generation;
- Research and Development;
- Nuclear Waste;
- Nuclear Transportation – land, rail, sea; and
- Security.

The risks on a decommissioning site may be significantly different from those on an energy generation site or in transportation. At least one entity was approached in each subsector. In total, 14 key people from 9 organisations were approached, yielding 9 respondents (one per organisation). The backgrounds and substantive experience of the respondents covered all subsectors listed, notwithstanding that not all subsectors were represented as the current employing organisations of the respondents. Regulatory and inspection experience was represented well in the sample interviewed.

An inductive approach was adopted, using open ended questions gathered in a telephone/ Skype interview survey. Under each question a number of further, steering and prompting questions and / or hypotheses were tested.

The data gathered were in the form of utterances. No recordings were made of the interviews, but *verbatim* notes were taken and destroyed at the end of the work for reasons of confidentiality.

Data were processed manually using a five stage qualitative data analytical technique, based on McCraken's methodology [3].

4. Data analysis methodology

4.1. The role of data in preventing engineering catastrophe

High Reliability Organisation (HRO) theory emphasises the importance of paying attention to ‘weak signals’ which in aggregate demonstrate that control of hazardous processes is being lost [4]. In the UK, the Control of Major Accident Hazards (COMAH) Regulations [5] and associated guidance prompt operators to review a range of process safety ‘intelligence’ from around the world that could impact on the understanding of hazards, risks and the effectiveness of control measures. Process safety intelligence may include lessons learnt from past accidents in similar industries or using similar hazardous materials, relevant good practice and technological developments. There is also the need to use reliable data to inform formal hazard identification and risk assessment studies. In some of these study types, qualitative intelligence is useful to augment the study team’s own knowledge; for example, Hazard and Operability (HAZOP) studies often do not incorporate any frequency estimations. Other techniques require quantification to estimate the likelihood of hazardous event scenarios, or to estimate the probability of various prevention and mitigation barriers operating as intended. Examples of quantitative techniques include Failure Mode and Effects Diagnostic Analysis (FMEDA), and Layer of Protection Analysis (LOPA). Also, a Quantified Risk Assessment (QRA) is a numerical methodology that combines the likelihood and severity for each hazardous event scenario to obtain the overall risk for an industrial site.

Many operators draw on a family of datasets known collectively as Reliability, Availability, Maintainability and Safety (RAMS) sources to use in their formal risk assessment processes. However, these sources have declined in number over time with limited exceptions:

“Data collection activities were at their peak in the 1980s but, sadly, they declined during the 1990s and the majority of published sources have not been updated since that time.” [6]

The decline in the availability of RAMS sources means that in some cases questionable alternatives are used, which led a HSE research report [7] examining LOPA studies to conclude:

“The degree of rigour applied to LOPA studies, and in particular the data values used, vary widely. Some LOPAs were reliant on standards and other published sources of generic data for their initiating event and protection layer data values. While others used analytical methods such as fault trees and human reliability studies to synthesise more appropriate data for the site in question, many drew on inappropriate generic data or referenced inappropriate examples.”

Some texts provide means to ameliorate generic data by tabulating ‘stress factors’ – multipliers to adjust generic data based on environmental or duty conditions [8]; however, it is difficult to assess the rigour of the evidence underpinning these approaches. As an example one of these approaches indicates that a stress factor in a railway environment should be double that of a ship in exposed waters.

It is clear therefore that operators managing major hazards have an ongoing need for a range of process safety intelligence. At the same time, the experience of the authors suggests that setting up elaborate new cross-industry data collection initiatives are likely to fail. It appears therefore that there is merit in better use of existing, disparate datasets around the world, including those not directly set up with process safety intelligence in mind.

4.2. HSE’s existing datasets

HSE is the health and safety regulator covering Great Britain founded under the Health & Safety at Work etc. Act 1974. Within this remit HSE collects a wide range of data, including information which is required to be provided by law by employers. This includes incidents required to be reported under the Reporting of Injuries, Diseases and Dangerous Occurrences (RIDDOR) Regulations 2013 [9]. Many of the events reported under RIDDOR are related to occupational safety outcomes, such as injury accidents resulting from slips, trips and falls. Others are highly relevant to process safety, such as loss of containment of specified quantities of flammable materials.

The authors are also mindful of the other datasets and data driven projects which have been developed, including the eMARS database – the Major Accident Reporting System which records relevant major accident events which are required to be reported by European Union (EU) member states and other nations on a voluntary basis.

4.2.1. COIN database

HSE also records information about regulatory interventions, such as inspections and investigations undertaken by its inspectors. HSE has a database called the Corporate Operational Information System (COIN) in which these interventions are recorded in some detail. COIN was put in place primarily to record a site-based history so that inspectors visiting can review previous interventions and site performance. The system has some reporting and analysis tools built in, but these are limited in scope. Key dimensions for the whole of the COIN database are provided in

Table 1.

Table 1 - COIN Database Dimensions

Metric	Approximate Value
Company Records	3,000
Sites	11,000
Cases / Service Orders	350,000
Database Size (Data only)	430 GB
Document Attachments Size = 1350 GB (1.35 TB)	1.4 TB
Data Retention Period	7 years from last related intervention

The COIN database contains three different types of data:

- Coded data – fields which hold either numerical / date data or a range of pre-determined options.
- 'Free text' – narrative added by HSE staff with limited or no structure.
- Document attachments – various PDF, MS Word, PowerPoint and similar documents which may originate from HSE or may be collected from employers – e.g. internal investigation reports.

A challenge with the database is that currently a seven-year data retention period is in place, which results in the deletion of records seven years after the last linked intervention. As an example, if an accident occurred that resulted in an enforcement notice then the seven-year period would not begin with the date of the accident but the last recorded information updated in respect of the notice – for example description of when / how the notice was complied with. In the future, the project team intend to retain anonymised data for a much longer period for analysis purposes. Some data is also retained in other systems for longer periods depending on its type, but not within the COIN database.

A key object within the COIN database is a case or service order. A single case is created for each regulatory intervention, for example an injury accident which is investigated will have a single case with a unique serial number assigned. In some instances, a slightly different object called a service order is used but for practical purposes amounts to the same object. Each case will have its own coded data, free text and document attachments. The detail available and where it is stored depends on the type of intervention. It is important to note that the majority of data is recorded in free text fields or document attachments, which means that the Discovering Safety team are exploring text mining techniques to extract insight as part of this and other projects.

4.2.2 Loss of Containment Taxonomy

Following the Buncefield explosion and fire in 2005, a recommendation was made by the Buncefield Major Incident Investigation Board [10] that HSE and others should improve the collection of incident data on high potential incidents including overfilling, equipment failure spills and alarm defects within the major hazard sectors. Following this, several pieces of work were undertaken, including changes made within the COIN database to increase the coding available for loss of containment events.

Figure 2 shows a screen within COIN which requires users to input coded mandatory fields in some instances. While the screen is completed for many events (e.g. personal injury accidents), completion of all fields is only required for loss of containment events which are themselves a subset of RIDDOR Dangerous Occurrences (DOs).

Case	Customer	Contact	Status	Summary	Site
[redacted]				Escape of flamma...	[redacted]

Underlying Causes
Underlying Causes
Maintenance Procedures

Safety Management System Failing
Safety Mgt Systems Failing
Organising - Communication

Nature of Substance	
Substance	Area Affected(Extent/Severity)
Flammable	Potent serious damage to prop

Activity at Time of Release
Activity
Maintenance Planned

Site of Release
Site
Valve open end

Direct Cause of Incident
Cause of Incident
Human Error: Violations

Mitigating Defence Against Escalation
Defence
Contained within second cont

Secondary and/or tertiary containment failure causes
Secondary Containment Failure
Not Applicable

Figure 2 - Redacted Coded Fields Screen

RIDDOR requires the reporting of DOs where no injury occurs across all industry sectors; many of these DOs may be unrelated to process safety, for example collapse of scaffolding on a construction site. There is no specific requirement to report all loss of containment events; there are instead several DO categories which are likely to represent some of them. Those DO categories which are considered likely to be loss of containment events and therefore force the mandatory completion of the full analysis screen in COIN by HSE staff are:

- Pressure system explosion, collapse, or bursting;
- Electrical short circuit resulting in fire and explosion;
- Process explosion, or fire resulting in 24-hour disruption;
- Escape of defined quantities of flammable substances;
- Escape of substance in quantities sufficient to cause death, major injury or any other damage to the health of any person (e.g. toxic substances); and
- Various adverse events in pipeline systems.

It should be noted that the above list is a simplified summary and full details of the reporting criteria are provided in the RIDDOR regulations.

It is also important to note that the definition of DOs in RIDDOR is much narrower than the range of near miss events that many in the process industry would want to record as part of a robust safety management system. Furthermore, it is known that RIDDOR is subject to underreporting, despite the legal requirement to do so. The level of underreporting varies by industry sector and is estimated from separate employee survey data in respect of injury accident events and not DOs. HSE's most recent estimate for average RIDDOR reporting levels for non-fatal injury accidents is around 50% [11]. Dangerous Occurrence reporting levels have not been estimated.

The current recording system is relatively detailed, for example, the 'Direct Cause of Incident' field contains 35 options to select from. Many of these are hardware related - such as 'Corrosion under lagging'. In terms of Human Factors, there are four explicit selections that can be made, these are:

- Human Error: Slips;
- Human Error: Lapses;
- Human Error: Mistakes; and
- Human Error: Violations.

However, there are also many other selections which could potentially involve human factors issues. Some examples include:

- Drive away;
- Impact / dropped object;
- Incorrect installation;
- Incorrect isolation;
- Inadequate procedures;
- None / faulty indicator; and
- No level alarm / trip.

There are also several selections which appear to involve hardware issues, but which are likely to link in some way to human performance – for example human factors in the design process.

More generally, the key challenge to gaining new human factors insights from large data sets will be the quality of information and the underlying investigation of root or underlying causes. Human factors-related information is often overlooked, even by seasoned investigators, if they have not been specifically trained to identify such data. Similarly, if a human factors element is not overlooked entirely, it is oversimplified. Often, investigations will point to generic 'human error' or 'human factors' as the single cause of adverse events, rather than looking for the underlying performance influencing factors[2] that shape human behaviour.

Although the accuracy of data and analysis is important, tolerance of uncertainty will be crucial. Better use of data analytics will provide both human factors and safety specialists with new and rich ways of collecting and analysing patterns of human behaviour. New computational methods will allow us to derive meaningful, actionable cause-effect relationships, which have not been previously described, and support decision-making in these areas.

5. Data analysis results

5.1. Early analysis

The Loss of Containment project and the wider Discovering Safety Programme has been designed to be iterative – to deliver early value and demonstrate capabilities at concept stage before refinining. In addition, the intention is to use existing GB data held by HSE to develop approaches which can later be augmented with other international datasets from a wide variety of public and private sector organisations. Accordingly, the team have recently completed some basic analysis of the coded data relevant to Loss of Containment events (LoC) reported as RIDDOR dangerous occurences (DOs).

A HSE SQL[3] database specialist created a replica of the live COIN database to provide an electronic resource for all of the Discovering Safety projects. Coded data was converted into comma separated value (CSV) files and free text entries were provided as plain text. Document attachments in various formats (e.g. PDF, Word, Excel) were also converted to plain text. All records were linked together as in the live database by a case serial number. Therefore, for each case separate files exist for coded data, free text and multiple document attachments as text files with images and metadata removed.

The open-source data analysis package 'R Studio' was then used to perform some basic analysis on the coded records associated with DOs considered as loss of containment events. In order to do this the wider DOs dataset was filtered by DO type and all those entries not relevant to LoC events were deleted based on the criteria described in section 2.2. The dataset was then subject to processing to improve confidence in data quality. As an example, some entries were removed as they had no associated information around causation, in most cases because they were open investigations within the live database. This processing resulted in a dataset size of 464 DO records which were all incidents occuring prior to May 2018.

[2]http://www.hse.gov.uk/humanfactors/topics/pifs.pdf

[3] Structured Query Language – a programming language used with databases where there are relations between several different data fields.

Firstly, the coded field 'underlying causes' was simply extracted and plotted as a histogram (Figure 3). This shows that issues with Hazard Analysis or Risk Assessment were recorded as the principal underlying cause within the dataset. This basic exploratory analysis has only considered the first underlying cause recorded in the database, although the system allows additional underlying causes to be added for each incident. There are a small number of incidents where a cause could not be established due to uncertainty during the investigation (recorded as "Unknown") or where "Not Applicable" was recorded; this would include incidents where the measures in place had reduced the risk to tolerable levels but the incident had occurred due to residual risk. Figure 3 shows the number of events on the y-axis, not a percentage.

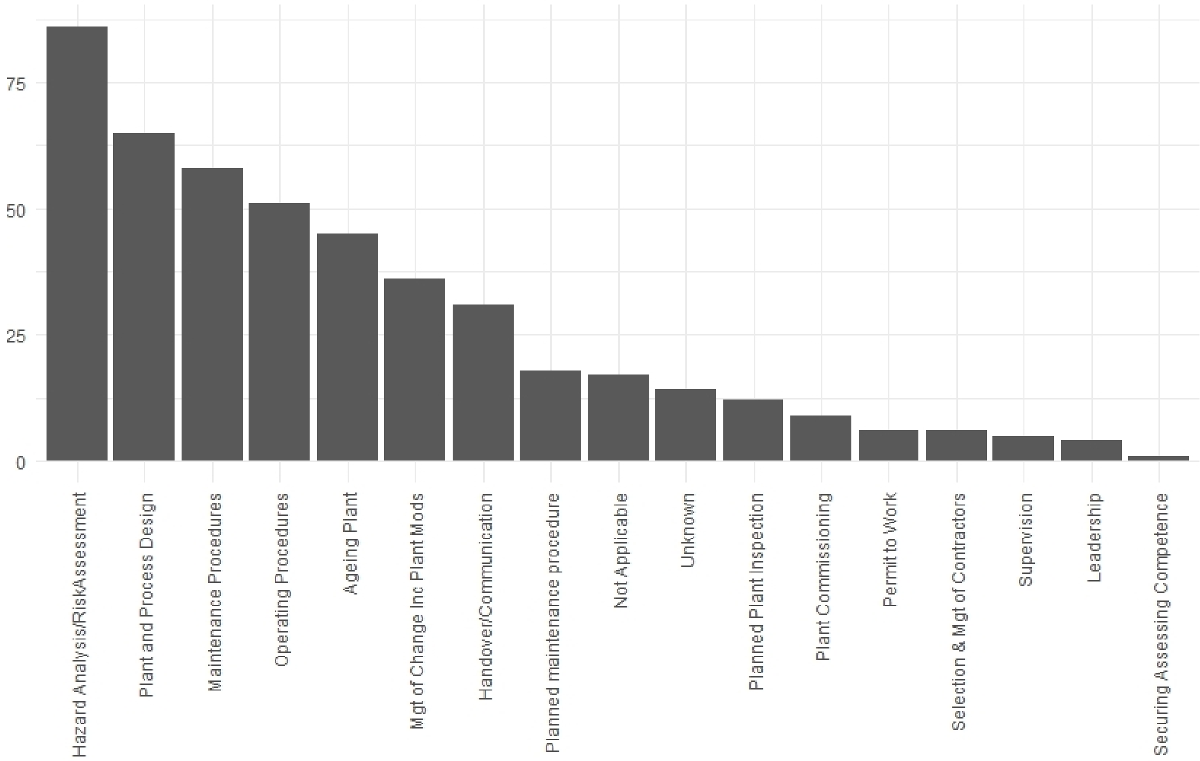

Figure 3 - Recorded Underlying Causes

Please see important caveats and limitations around this data described in the body of the paper

From the recorded underlying causes, one was selected for further analysis at this proof-of-concept stage. Given the project team's experience of Ageing and Life Extension (ALE) issues, it was decided to focus the analysis on the subset (N=45) of these 'Ageing Plant' cases and assess another field linked to these. The coding system is particularly helpful, in that, a detailed plant item list exists for the 'Site of release' field, right down to individual process plant items. R Studio code was written to extract all instances of the plant item involved in the release for the ageing plant cases and this was also plotted as a histogram (Figure 4). Again, the y-axis shows number of events, not a percentage. Whilst the potential value in undertaking this analysis can be seen from the output, it is also apparent that there are a number of drawbacks. Firstly, there is a large proportion of 'not applicable' entries and secondly, the relatively low size of the original events dataset and even smaller subset means that for many plant items there are only single instances, which reduces the confidence that wider lessons can be extracted from such analysis.

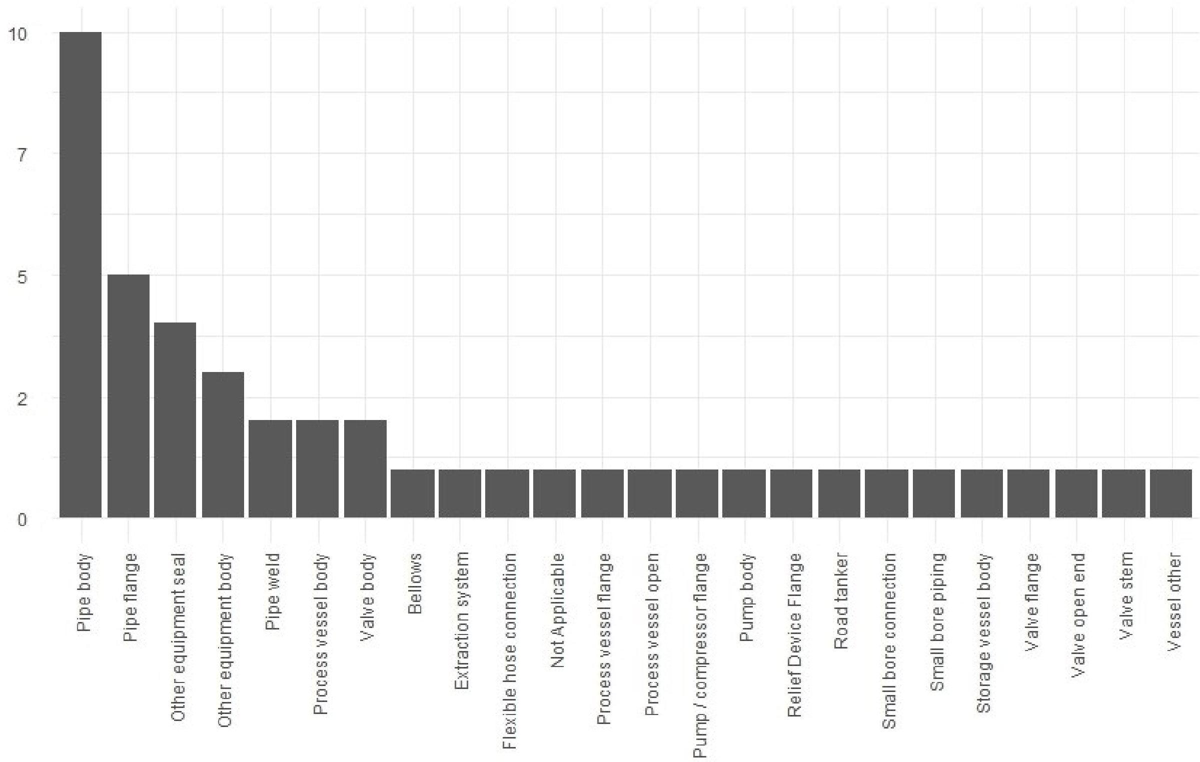

Figure 4 - Recorded Site of Release for Ageing Plant Cases

Please see important caveats and limitations around this data described in the body of the paper

The high proportion of ageing plant cases involving ‘pipe body’ is perhaps surprising. The expectation prior to analysis was that plant items which provide an interface or have moving parts would be more likely to fail and therefore be causative of more LoC DOs. Further analysis is planned to better understand this since the current analysis does not allow any robust conclusions to be drawn as to why this is the case. Some possibilities HSE specialists are keen to test are:

- These cases involve Corrosion Under Insulation (CUI) issues which has conventionally been an industry issue and been more complex to resolve through inspection than exposed pipework.
- Poorly performing organisations neglect the fundamentals of asset integrity but replace less costly interface and moving part items for production reasons.

There are also likely to be other possibilities which are only possible to discover through more detailed analysis and increasing the number of records under consideration.

5.2 Limitations of the existing analysis

At this early stage in the project, the existing analysis has been done to prove the concept that some value can be extracted from the dataset. In addition, the preparatory data extraction and conversion has been completed to make future work more efficient and not dependent upon running multiple bespoke queries on the live database. It was also intended to highlight early on any drawbacks in the existing data, so that the team could develop approaches to ameliorate this, in consultation with process safety professionals working in industry.

The main challenge highlighted by the existing analysis is that the number of records in the database with detailed coded fields completed is very small when compared to the size of the database overall. Whilst some high-level findings to inform other work are valuable, it is likely that the greatest value to the process industry would be to develop a multi-factor analysis that better explains detailed causation. In the case of loss of containment events with ageing plant as an underlying cause, it would be useful to know in more detail whether, for example:

- There was a total absence of an asset integrity programme, or flaws in an existing one?
- The cause of failure was due to a backlog of safety critical maintenance which would have detected and rectified the degradation process if correctly carried out?
- The failure was associated with degradation, or instead parts obsolescence (lack of replacement parts available in the market for older plant) associated with ageing plant?

A further challenge is that the COIN dataset covers Great Britain (England, Scotland and Wales) only, whereas it would be more powerful to be able to compare events across and within other countries. The short data retention period (7 years) is also challenging when attempting to carry out time-series analysis.

The underreporting in RIDDOR may introduce an element of bias, in that, there may be different findings within those operators with poor compliance with RIDDOR. It is also not possible from the current analysis to distinguish between subsets within the process industry, for example, whether there would be different profiles within the tank storage sector when compared with fine chemical manufacturers.

The use of a coding taxonomy is helpful, but also poorly covers the links between causation. For example, high workload leading to a backlog in planned plant inspection, leading to a failure to take action to mitigate the effects of ageing mechanisms.

Further bias may be introduced in that the dangerous occurrences reported are, by definition, cases where mitigation may have prevented injury to workers and / or the public. These may not be as reliable as other precursors to major accidents, which are not required to be reported under RIDDOR.

5.3 Personal injury accidents relevant to process safety

There are clear differences between occupational and process safety which have been well documented, including most notably after the Texas City Refinery explosion in 2005 [12]. At a site level a focus on injury accidents as a metric of process safety performance is clearly a flawed approach.

However, at a GB level, personal injury accidents dominate the events which are formally reported and recorded by HSE. The experience of the project team suggested that a proportion of those personal injury accidents occurring in the process industry may have had relevance to process safety. In particular, there are known to be injury accidents resulting in relatively minor reversible injuries to workers resulting in an absence from work or normal duties for over seven days, where good fortune resulted in an outcome which could have been much more severe. In relation to loss of containment events, small leaks of harmful substances may lead to minor injuries (e.g. superficial burns), but have had the potential, under slightly different circumstances, to lead to the release of greater quantities with the consequent potential for onsite and offsite process safety implications.

The team manually searched the COIN database for some examples of such events and two examples are provided overleaf.

Example 1

One employee sustained burns to their ankles when a high temperature and caustic liquid mixture flowed over their chemical resistant shoes and came into contact with their ankles. This resulted in several weeks off work, but the individual is expected to make a full recovery. The incident was reported to HSE as a RIDDOR over seven-day injury accident.

The incident occurred during a post-reaction cleaning operation on a chemical reactor when the vessel was being filled with a caustic cleaning solution whilst agitation and heating were applied. The intention was to heat the solution to approximately 65°C and to fill the vessel to 90% capacity. Level control was due to be achieved by manual dipping. Temperature control was also monitored manually, as the vessel had no instrumentation and no high-level alarms fitted. There was some confusion as to whether the vessel needed to be filled to 100% capacity to clean the upper levels of the vessel and fittings.

The incident occurred when either level control was lost and the vessel was overfilled onto the upper reactor floor, or when temperature control was lost and boiling occurred. In addition to the lack of instrumentation, there was also no written operating procedure for reactor cleaning operations at the time of the incident.

This injury accident, whilst only briefly outlined here, clearly provides process safety insight in respect of process plant design as well as operational procedures. Failure to achieve level and temperature control in the process industry has been associated with many major accidents causing on and off-site implications.

Example 2

One employee sustained superficial burns to their face following a short duration flash fire resulting in approximately two weeks off work on medical advice. This was reported to HSE as a RIDDOR over seven-day injury. Had no injury occurred this incident would not have needed to be reported as a DO since it would not meet the criteria for a process fire as it did not result in 24-hour plant stoppage.

The incident occurred when the employee was adding a powder to a reactor which already contained significant quantities of the solvent Methyl Ethyl Ketone (MEK) which had recently been 'splash filled' into the reactor contrary to company recognised good practice. The powder was dispensed directly from the polymer bag it was supplied in and it is believed this may have created a static spark which ignited the solvent vapours present in the reactor following the splash loading of solvent. The area around the reactor port was designated an explosive atmospheres (ATEX) zone 1 area and there is no evidence of any unsuitable equipment having been brought into this zoned area prior to the ignition. The process operator filling the vessel was wearing anti-static footwear. Once ignition occurred, a flash fire resulted at the reactor port causing superficial burns to the operator who was standing upright decanting the powder. The fire was rapidly and completely extinguished by a second process operator closing the reactor lid shut.

Clearly, this is another injury accident with the potential to have escalated into a large-scale process safety event given the large amount of solvent present in the reactor and the presence of other adjacent processes and employees.

It is clear from this brief manual review that there is data recorded in the COIN system categorised on an occupational safety basis, which could generate insight for process safety professionals. The challenge in extracting this information is that whilst there is some basic coding of RIDDOR accidents, much of the detailed description exists in free-text fields or in associated document attachments. In order to successfully extract relevant process safety events, the team will need to develop text mining algorithms that can analyse large volumes of data with minimal manual intervention, whilst generating sufficiently low numbers of false-positives. Some of the other challenges anticipated are:

- It is possible that bias could be introduced, as process industry events resulting in personal injury may differ in some key ways from events that do not result in any personal injury but have the potential for escalation. Indeed, it may be the case that as in Example 2 above, employees who are present may prevent escalation and the potential for off-site effects, but suffer injuries whilst doing so.
- There is significant underreporting of RIDDOR accidents, this is known to vary widely across sectors and is likely to vary between operators within the same sector. It is possible that underreporting is inversely correlated with process safety performance such that extracting lessons learned from such events would underrepresent the nature of failings in poorly performing organisations.
- The level of detail available in incident investigations recorded in COIN varies according to the nature of the incident and its outcome. The information may be held within different attachments – for example where detailed forensic engineering is carried out this is likely to be recorded in a separate attachment from an investigation summary.

In spite of these, and other considerations, it is suggested that there is value in the project team exploring the value in text mining of process safety events from personal injury data; subject to regular review to understand the limitations of the approach.

6. Nuclear study results

6.1. Most prevalent non-radioactive loss of containment in the nuclear sector

Participants reported that typical containment where losses might occur are: concrete and steel tankage, vessels, pipework and associated mechanical plant, equipment, valves, seals and joints (e.g. flange joints). Bulk storage and distribution was mentioned (e.g. for nitric acid). Silos were mentioned as well in relation to fugitive emissions during purging with inert gas, for example argon.

There is discrete or non-system containment, falling into two categories: in older facilities, of steel drums and containers containing known and unknown contents which leak, corrode or are in danger of leaking, exploding or catching fire. Secondly, there are unmarked containers, made from various materials, which may be leaking, fragile or in danger of leaking, located in unused spaces. In some cases, particularly in much older buildings (built in the 1940s and 1950s) some inventories in containers were reported to have been found within the structure of buildings (e.g. wall cavities).

Materials being lost from containment or representing a real danger of loss of containment include unknown and uncharacterised substances. Numerous hazardous substances; mainly in liquid form, but gases and gaseous forms were included (e.g. nitric acid mist, hydrogen, and inert gases: argon and nitrogen). Hazardous substances include, but are not limited to: nitric acid, hydrazine, uranium hexafluoride, hexafluorosilicic acid, polychlorinated biphenyls (PCBs), sodium hydroxide (caustic soda), other acids, alkalis, corrosive substances and fuels (mainly diesel). Argon, in particular, is used in high volumes and concentrations for purging.

There is evidence of concern for loss of containment hazards in relation to chemicals, substances and materials associated with cryogenic facilities. Oil and fuel storage can be an issue in relation to, loss of containment, usually minor,, although serious incidents do occur in relation to overfilling incidents and leaks from vehicles. Other relevant losses of containment may include: sewage, process steam, water supply, surface water and compressed air. Compatibility reactions can be a source of release amounting to loss of containment. This can be an issue in storage, use and handling. An example is the acidification of sodium nitrite bearing streams (with nitric acid), which can cause the evolution of large amounts of NOx fumes.

In all parts of the nuclear sector, to a greater of lesser extent, the loss of containment of water supply abstracted from, boreholes, rivers and reservoirs is considered very serious for a number of reasons. There is an increasing need to conserve water. A significant loss of containment of water supply means that there can be a serious impact on business continuity and indirectly, safety, due to the reduced capacity to provide cooling water and / or produce process steam, necessary for process plant integrity, requiring shutting down sections of plant. This underpins the concept of *"safety critical steam"*. This is particularly important on decommissioning sites. The majority of water supply pipework systems in the nuclear sector tend to have been installed in the 1950s. Pollution of ground water and watercourses is a real concern for the nuclear sector. This applies across the sector and is particularly important in relation to waste repository functions.

Respondents reported that process fires resulting from loss of containment have featured to varying degrees of scale.

6.2. Common root causes of loss of non-radioactive loss of containment in events in the nuclear sector

The following is a classification of loss of containment derived from the study. The causes listed are not mutually exclusive.

- Deterioration related causes
  - corrosion under insulation
  - corroded pipework, vessels and tanks
  - containment materials failure (e.g. mild steel)
  - sea water and coastal environment corrosion
  - corrosion and erosion of reinforced concrete containment bunds
  - seal and gasket failures
  - leaks from equipment and mechanical plant
  - leaks from valves and flanges
- Maintenance related causes
  - poor inspection
  - poor maintenance practice
- Design, methodology and procedural causes
  - problems arising from design decisions
  - overflows due to level sensor failure
  - syphoning during filling
  - problems arising from inadequate or inappropriate safety cases
- Education and training
  - operators and managers not understanding the physics and chemistry principles which underpin procedures (a lack of hazard awareness).

6.3. Deterioration related causes

From the survey, the most common deterioration of containment is caused by ageing plant. Plant life extension, whilst not a primary root cause, is a strategic root cause. The root causes are exacerbated, potentially, by the decision for plant and facilities to be used for longer than had been intended originally.

Corrosion under insulation is by definition an unseen problem. It is difficult and costly to inspect for this, particularly adjacent to structures and vessels, as well as in congested plant configurations.

Corrosion of pipework, vessels and tanks, from both outside and inside, is a major cause. Containment materials failure may occur due to various mechanisms (e.g. stress). Sometimes, the selection of containment materials can be considered inappropriate or ill conceived. In coastal locations, seawater corrosion is a frequent cause of loss of containment, either directly applied or from salt in the atmosphere.

Corrosion and erosion of reinforced concrete is a known problem. An example of this is a containment bund for nitric acid bulk storage that had deteriorated, due to hose leakage following the end of refills eroding the concrete bund and the reinforcing steel. The leak was discovered when high levels of iron salts were reported in ground water tested in the vicinity and found to be caused by the acid corroding steel reinforcement in the bund.

Seal and gasket failures appear to be a common loss of containment root cause. However, it may be more important to understand why the seal has failed. An example of this was the case of a correctly executed purging procedure, following the delivery of nitric acid for bulk storage. The connecting lines were being purged. The necessary vacuum could not be produced and maintained and instead of the usual trickle of acid following the purging process, a large volume of acid was released due to a vacuum seal failure, which explained the inability to obtain a vacuum. This occurred in an impounding bund and operators were fully clad in personal protective equipment. Arguably the procedure was flawed and / or the lack of understanding of the physics, underpinning the correctly followed procedure, led to a significant loss of containment. The root cause was not a seal failure in this case, because that failure came about because the operators did not realise the context in which failure occurred.

Leaks at equipment, mechanical plant, valves and flanges were said to be common causes of problems.

6.4. Maintenance related causes

In some cases maintenance had not been undertaken in the past and this was a fundamental underlying problem leading to the risk of loss of containment. Nuclear generating plant was transferred, in 1996, from the Central Electricity Generating Board (CEGB), to a holding company, British Energy, with two operating subsidiary companies: Nuclear Electric and Scottish Nuclear Ltd; these were privatised in the same year. The ageing Magnox reactors were part of generating capacity. Respondents stated that the condition of the privatised plants was poor at the time of transfer and inadequate maintenance was evident in 1996.

Respondents reported that key issues associated with loss of containment emerged following inspections, repairs, or corrosion treatments to pipes. In some cases, pipe wall material was inadequate for ongoing service conditions, particularly in ageing plant.

6.5. Design, methodology and procedures design causes

The question of design decisions in relation to the ultimate root cause of loss of containment is important. An example is loss of containment through overfilling. In order to avoid the specification and installation of instruments in a radio-active environment, engineers specify “numerators” or level tube devices; when blocked these can lead to overfilling. There is a design culture that believes that a “failsafe” outcome can be delivered through specifying traditionally approved methods. However, these do not necessarily function as well over time and become a risk when inspection and maintenance is poor. More modern instrumentation could be specified, but there is often resistance to this, due to the prevalent design culture rather than sound engineering reasons. Other problems in design are prioritising the reduction in capital cost through design. This can lead to, for example, mild steel being specified where stainless would have been better but more expensive, given the expected design life. Life extension of plant then increases the risk of loss of containment due to corrosion.

Safety cases that do not consider all eventualities build in risks and could in some cases be argued to be the ultimate cause of a loss of containment. Designing a safety case to the request: *“this is what we want to do”* is different from a safety case for the request: *“what are the limiting parameters for this situation”*.

6.6. Education and training

Operators and managers not understanding the physics and / or chemistry principles underpinning procedures (a lack of hazard awareness) can lead to loss of containment events. Safety cases require that operators and managers have a clear and deep enough understanding of the principles. It could be argued that inadequate levels of understanding can be considered as a potential root cause of loss of containment in certain circumstances.

6.7. Human behaviour contributing to non-radioactive LoC in the nuclear sector

Human behaviour appears to be at the heart of many unplanned events, including loss of containment. Human performance includes the extent to which procedures are followed. Deviations were reported to be due to tiredness, malicious intent, lack of knowledge and understanding and mistakes. All of these can lead to a loss of containment.

Lack of knowledge and understanding can be considered an important factor underpinning human behaviour, which can contribute to loss of containment.

Some respondents said that historically some examples of poor practice resulting in disciplinary action for individuals had occurred following documentation irregularities. It was not possible to determine how common this had been and whether specific historical decades were more associated with this experience.

6.8. Other considerations with respect to non-radioactive loss of containment

Flooding risk in nuclear facilities, in relation to the potential for loss of containment is seen as a low probability, very high impact problem, in relation to a specific plant. The Zoning of Plant Regulations have changed recently. Both the above issues are seen to be connected with lessons learned from the Fukushima Daiichi event in 2011.

Some respondents claimed that as soon as operators and managers in the nuclear sector were made aware of issues and factors relating to unplanned events and safety issues, such as loss of containment, they were much more open than in other sectors to learn lessons and take action as a result. This study has not investigated whether this is supported by objective evidence.

Confined spaces are considered by some as particularly problematic in relation to threats from loss of containment. Risk assessments and safety case development are important in relation to managing these threats.

There is strong evidence in the nuclear sector of culture and willingness of sharing knowledge and understanding internationally. This is seen as a strong and positive feature of the nuclear sector culture. This could be built upon with respect to the implementation of initiatives associated with improving understanding and practice in relation to loss of containment.

Rail transportation does not appear to suffer significantly from loss of containment events and respondents claimed that non-nuclear sector rail transport learns more from nuclear than *vice versa*.

The survey found that there is a growing importance attached to promoting and valuing a constructive relationship between the operator and the regulator. Indeed, regulations and regulators are often cited in relation to improvements in practice.

The appointment of engineers from other sectors, to the nuclear sector, is said to have a beneficial influence on raising awareness of *"conventional safety and loss of containment issues"*.

7. Previous work

A comprehensive piece of work was previously undertaken by the Health & Safety Executive [13] to analyse 975 loss of containment events using the software tool "Storybuilder". This involved detailed coding of incidents which had occurred between 1991 and 2009. This work was particularly powerful given that this analysis preceded the detailed coding of data within the COIN database and so provides further assurance that text mining techniques from narrative records can produce great value. Since this work was undertaken, the tools and culture within data science have progressed enormously. As a result, it is the project team's aspiration to move to an almost 'real-time' data repository available to industry professionals with the ability for queries to be developed in a bespoke manner by users and the ability to refresh analyses as new data accumulates rather than having to await periodic publication.

8. Conclusions

It is clear that appropriately developed techniques for extracting valuable process industry insights from uncoded free text data, commencing with HSE's own COIN data could unlock a previously underutilised source of intelligence. The experience of applying these techniques on GB data will enable a better roadmap to be developed to augment the GB data with worldwide sources. Engineers, managers, operators and regulators are 'time poor' – creating elaborate data collection regimes will result in failure. Letting software do the 'heavy lifting' on data which already exists, but is poorly structured, is a pragmatic way forward.

Moving forward, the plan is to conduct further analysis on the coded data but also commence text-mining techniques with the personal injury accidents as described earlier. However, it is most important that these and other projects incorporate feedback from industry to develop and refine approaches which are most helpful to industry.

Based on the study undertaken in the nuclear sector, the subsectors of the nuclear industry sector in which there is most relevance and need for understanding, education and training in relation to loss of containment of non-radioactive materials, are decommissioning and generation. In the latter, the focus is on existing plant, rather than new build. The type of loss of containment is associated with ageing plant, particularly in relation to maintenance and corrosion under insulation.

In the case of decommissioning sites, ageing plant is a major concern, particularly with respect to maintenance, corrosion under insulation and seawater and coastal corrosion. The life extension of plant creates challenges.

Design considerations have an impact on loss of containment. Arguably, the design culture is conservative and there appears a resistance to explore the use of instrumentation in radio-active areas. There is some evidence of a poor understanding of materials incompatibility. Better evidence would help ameliorate this.

Chemotoxic materials are a cause for concern within the nuclear sector and there is therefore a strong interest in risk assessment and safety case development.

Interestingly, the loss of containment of water supply is a serious issue. This leads to environmental, business continuity and disruption in cooling and process steam generation, required for process integrity and safety.

Poor maintenance, as a result of a poor maintenance regime, poor inspection, remediation and repair were issues identified in relation to the risk of loss of containment.

Lack of understanding, education and training, in some cases, in the scientific and engineering principles underpinning procedures and processes was found to be an issue.

The nuclear sector shares learning internationally and is open to learning from lessons arising from incidents. The nuclear sector has a strong reporting culture and there is evidence that unplanned and abnormal events, however small, are reported as a matter of routine. However, the large amount of data generated may prove difficult to interrogate and for trends to be identified quickly and effectively.

In the past, there may have been less interest or awareness in what some called "conventional" health and safety and loss of containment of chemotoxic materials, but this appears to be changing. Improvements have been noticeable in the last ten years, due to significant events and changes in ownership, organisation and management of some components of the nuclear sector.

5. Feedback & engagement

The project team are keen to engage with the global process industry and nuclear communities to receive feedback and suggestions to further develop the project over the coming months and years. The team can be contacted via discoveringsafety@hse.gov.uk and would welcome all feedback but would particularly welcome comments on the following topics:

- Signposts to global sources of process safety intelligence which could augment our GB data sources in the longer term, particularly any which exist holding data for process industries in the developing world and / or unstructured / underutilised datasets. It would be particularly useful to focus on onshore data since this does not benefit from global initiatives that exist in the offshore oil & gas sector.
- Challenges previously experienced in-company or across-sector which arose in respect of data collection, analysis and sharing of process safety learning.
- Types of insights which would be most valuable to emerge from the work – for example what process safety questions would users most want answered from robust analysis?
- What type of model would enable the sharing of intelligence on a sustainable and user-friendly basis?

Whilst the project is at a relatively early stage at present the team are keen to explore the possibilities for collaborating to create a searchable resource which would assist end users with duties under COMAH to review learning from worldwide process safety events. Ideally, this resource would allow the segmentation of the process industry such that, for example, an operator of a tank storage facility could filter intelligence in a different way to a batch manufacturer of fine chemicals. Such an approach would make it easier for users to ask questions tailored to their sector, for example:

- What proportion of loss of containment events in the tank storage industry result from overfilling?
- Which plant items are particularly vulnerable to management of change issues?
- How is plant start up / shutdown related incidents changing over time?

As with the earlier questions, the project team are keen to seek detailed feedback from users as to how such a resource could work in practice to best assist those wishing to improve process safety performance for the benefit of us all.

6. Disclaimer

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