Perceptions of Process safety

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Abstract

This paper examines empirically how safe operation of high hazard technology ('process safety') is understood by people at the operational end of organizations operating such plant in the oil & gas and chemical industry. Such organizations tend to be hierarchical, with a reliance on rule-following. It is increasingly recognised that major accident events such as explosions, fires and toxic releases are avoided not just by engineering and procedure-following but also by adaptive processes of mindfulness, sensemaking and expert improvisation. However, few studies have examined empirically the contribution and interplay of rule-following and adaptive practice in process safety and how people experience these tensions in practice. This study addresses this gap by comparing how informed actors construe different kinds of events relating to process safety: potential incidents (things identified that could have gone wrong but didn't) near misses (hazard released but contained or mitigated) and actual incidents (hazard released with significant consequences). Repertory Grid interviews were conducted with 55 people at three separate oil and gas and petrochemical sites in a single multinational company. Systematic analysis of their views revealed that organizational learning and understanding of risk were considered as stronger influences on process safety than compliance with established procedures, and that the influence of leadership on process safety was felt through the perceived relative extent of both work pressure and deference to hierarchy, and through the importance given by the organization to incident investigation and analysis. These findings support the theories of HRO, System Safety and 'Safety II'.

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1. INTRODUCTION

Many writers suggest that safety of high hazard technology such as oil & gas and chemical plants, 'process safety', comes not only from the traditional reliance on engineering and rule-following but also from adaptive processes such as 'sensemaking' (Weick, Sutcliffe and Obstfeld, 2005) 'mindfulness' (Weick and Sutcliffe, 2006) and 'expert improvisation' (Hale and Borys, 2013; Hollnagel, 2014; Leveson, 2013; Rego and Garau, 2007). These ideas have been well documented in 'High Reliability Organizing' ('HRO') theory (La Porte, 1996; Roberts, 1990; Weick, Sutcliffe and Obstfeld, 1999).

Process safety has been further conceptualised as not simply the 'dynamic non-event' (Weick, 1987) of having no events such as explosions, fires or toxic releases, arising from equipment failures or errors, but more fully as the continuous process of vigilant, competent, human interaction with the equipment and its physical processes, an actively managed state in which those operating the plant are constantly anticipating and identifying threats and potential system weaknesses, interpreting and coping with them before they lead to problems. This 'Safety-II' view sees human input to the system, or 'Work-as-Done' (Clay-Williams, Hounsgaard and Hollnagel, 2015) as inevitably variable, formed of 'multiple adjustments for multiple reasons' in service of making 'things go right' rather than the simple 'Work-as-Imagined' of compliance with a formal procedure (Hollnagel, 2014). Variability of human input, in the form of improvisations that are necessary to 'overcome design flaws and functional glitches' and 'interpret and apply procedures to match the conditions' is thus seen in this view 'not in the negative sense where variability is seen as a deviation from some norm or standard, but in a positive sense that variability represents the adjustments that are the basis for safety and productivity'. This is contrasted with a simpler 'Safety-I' paradigm based on assumptions of linear cause-and-effect and of safety resulting simply from reliability of equipment and minimal human error (Hollnagel, 2014).

'System safety' theorists, while basing their approach on systems engineering, sophisticated modelling techniques and organizational clarity, also accept that 'prescriptive command-and-control approach deriving rules of conduct top-down… is inadequate' for managing the safety of modern dynamic systems (Rasmussen, 1997) and that therefore flexibility is also necessary: 'Humans do not always follow procedures, nor should they. We use humans to control systems because of their flexibility and adaptability to changing conditions and ability to improvise when incorrect assumptions are made by the designers' (Leveson, 2013). Successful improvisation relies on competence which 'is not only a question of formal knowledge, but also includes the heuristic know-how and practical skills acquired during work and underlying the ability of an expert to act quickly and effectively in the work context' (Rasmussen, 1997). This view also acknowledges that socio-technical systems controlling high hazard technology are often 'complex' (Dekker, Cilliers and Hofmeyr, 2011) within which cause and effect may be non-linear (Hollnagel, 2014) so cannot be described completely and so demand a different approach to decision-making than merely complicated or simple systems (Snowden and Boone, 2007). Safety in these contexts is subject to the 'law of requisite variety' (Ashby, 1958) and so for complex systems must rely on interpretation of unforeseen situations and competent improvisation.

This Safety II theory, stated above, that 'multiple adjustments for multiple reasons' are made in service of making 'things go right' may be seen in the identification and correction of 'potential incidents' that identify system weaknesses before they can develop into 'actual incidents' with significant consequences such as injuries, fatalities, impact on the environment and damage to assets or reputation. This adaptive practice of 'seeing and fixing' is an important aspect of the mindfulness of HRO theory (Weick and Sutcliffe, 2006) as well as Safety II (Hollnagel, 2014).

Understanding the practices associated with potential incidents, and how they may differ from those associated with actual incidents, may provide some insights into the relationship between rule-following and adaptive practices as they relate to process safety. Other insights may be obtained by further comparing with an intermediate type of event, 'near miss' incidents, where a hazard was released but significant consequences were avoided either by chance or due to effective mitigation measures, perhaps working as designed or perhaps expertly improvised.

There are obvious tensions implicit in the proposition that process safety relies on engineering and operational discipline on the one hand, and flexibility and expert improvisation on the other. The prevalent organizational form in the oil and gas and petrochemical industries is the traditional bureaucratic hierarchy with a norm of rule-following. Analysis of major accidents routinely shows up system weaknesses and errors that could have been identified and corrected but were not, and the theory described above suggests that this can be attributed at least partly to inflexible and controlling forms of organising that did not take adequate account of the operational context and failed to reconcile this important paradox of control versus adaptation.

The interplay between rule-following and adaptive practices in process safety and how people experience these tensions in practice is not well understood. This study addresses this gap by comparing how informed actors construe the circumstances of the three different kinds of process safety event: actual incidents, near-misses and potential incidents. The rationale is that differences in how these different kinds of event are perceived may reveal some insight into these tensions or interplay between these apparently conflicting kinds of practices.

Repertory Grid interviews (Kelly, 1955) were conducted with a total of 55 people working at three different operational oil & gas and petrochemical sites, in the Middle East, Asia-Pacific and Europe. The sites were selected on the basis of having some similarity of technology and organizational context (all were operated by a single large multinational company) but also to allow some comparison on the basis of having some differences in organizational maturity and in safety performance. Interviewees were selected to achieve a spread of different types of job, including operator/technicians, first line supervisors, engineers and managers.

Before describing the research project in detail, this paper starts with a brief review of theory relating to process safety.

2. THEORETICAL BACKGROUND

The appointment of sociologist Charles Perrow to the team investigating the 1979 Three Mile Island nuclear power station accident brought a new perspective to understanding the safety of high hazard technology. His ‘Normal Accident Theory’ (‘NAT’) claims that industrial disasters are an inevitable result of ‘interactive complexity’ and ‘tight coupling’ between system components, at either a technological or organizational level (Perrow, 1984).

In response, HRO theory claims that some organizations avoid such disasters by having effective strategies to minimise and overcome the effects of interactive complexity and tight coupling. These strategies include having multiple redundant systems for detecting system weaknesses and communicating critical information, developing high competence levels in non-technical skills such as situation awareness, decision-making and teamwork, creating a safety culture that avoids blame and encourages strong responses to weak signals, and decentralising the normal hierarchical authority structure in conditions of high-tempo operations, enabling decision-making at the operational levels where specific relevant expertise has been developed (La Porte, 1996; Roberts, 1990; Weick, Sutcliffe and Obstfeld, 2005). It is recognised that there are limits to the benefit of redundancy within HRO theory, since if overdone it can lead to common-mode errors, social shirking or overcompensation (Sagan, 2004).

The ‘system safety’ response to NAT is that the complex socio-technological systems required for aeronautics, space and other high hazard technologies can be engineered and structured to minimise interactive complexity and tight coupling, so that despite the obvious high hazards, risks are well managed and accidents are rare (Leveson et al., 2009). Safety of high hazard technology, in this view, results not primarily from front line operators having freedom to do what they think makes sense, even though there may be cases where that could be important, but from strategic decisions about the design of the whole system (Marais, Dulac and Leveson, 2004). This theory proposes that modelling techniques can analyse all the conditions and restraints determining the design and manufacture of the equipment and all the conditions in which it is operated and maintained, that is, all the spheres of activity from which both accidents and safety emerge, and that decision-makers can use these techniques to assess the potential effects of their decisions (Hollnagel, Woods and Leveson, 2006). Safety is seen as a property of the entire system in which an organization operates; risk management processes internal to an organization are strongly influenced by factors generated in the broader system, including all the parties with which the organization has relationships: partners, regulators and other government agencies, contractors, suppliers, customers and wider society (Leveson, 2004).

An important implication of this broad view of the system is that since the conditions of and restraints on safety are set within the context of all of the (often-competing) goals of the organization, safety can only be managed effectively when the whole system is analysed and fully understood, and if that is not the case and decision-makers do not have a complete understanding of how their decisions will affect safety, their decisions will inevitably sometimes be fallible. This was of course seen in both of the space shuttle disasters (Levy, Pliskin and Ravid, 2010; Vaughan, 1997) and numerous other major accidents. Recognising that responsibility for safety will always rest with the managers and engineers directly in charge of projects and operations, the system safety defence against this risk is to maintain a powerful, independent, ‘system safety’ organisational function to provide ‘adequate challenge in management decision-making’ (Leveson et al., 2009).

The re-framing of safety theory under the heading of Safety II emphasises the role of mindful interpreting and adjusting practices in the light of the actual and dynamic working situation. This view contrasts with the traditional ‘Safety-I’ approach that focuses on compliance with formal ‘Work-as-Imagined’ procedures and regards deviation from them as undesirable. Safety-II conversely regards the adaptive variability of human performance in controlling systems arising from experiential learning about the idiosyncrasies of real systems, with their inevitable unintended but built-in characteristics, as essential for safe operation (Hollnagel, 2014).

The emphasis of Safety-I is on reliability engineering, probabilistic risk assessment, incident investigation and root cause analysis, learning from 'what went wrong' and measurement of incident data, while Safety-II is concerned with understanding the subtle reality of 'Work-as-Done', learning from 'what goes right' in normal operations, and acknowledges that the implications of real-world complexity are that there will always be unexpected behaviours of systems and unexpected modes of failure and interactions between system components and between systems and their operating environments (the 'NAT' view) that will demand creative improvised interventions, which at least for now means human interventions. Safety-II thus views vigilant, competent, human interaction with the equipment and its physical processes, the constant anticipation of the unexpected and readiness to respond with expert improvisation as the essential form of organisational safety (Hollnagel, 2014).

Safety-II does not preclude Safety-I but expands and complements it. This view of safety as an actively-managed condition of a system aligns with the idea of 'navigating the safety space' with both reactive and proactive measures as 'navigation aids' and driven by 'commitment, competence and cognisance' (Reason, 1997) and also corresponds with the idea of avoiding 'drift to failure' by the engineering of resilient systems that enable active monitoring and adjustment of 'system properties such as buffering capacity, flexibility, margin and tolerance' (Dekker and Pruchnicki, 2013).

In its view of system complexity and its implications, Safety-II thus shares an overlapping ontology of safety with 'HRO' and to a lesser degree with 'system safety', though some differences are evident. Human involvement in socio-technical systems has inevitably led to efforts to improve the human-system interface, and to the development of the science of 'human factors'. From the standpoint of system safety this has been primarily a Safety-I concern with human reliability analysis (Spurgin, 2010) and reducing human error (Reason, 1990). The Safety-II view aligns with engineering resilient systems to cope with error (Hollnagel, Woods and Leveson, 2006; Woods, 2003) and also with the HRO view of human factors that embraces human performance to include making use of human sensemaking and problem-solving capacities (Hollnagel, 2014; Reason, 2008; Weick, Sutcliffe and Obstfeld, 1999)

The practical application of human factors has been widely and successfully adopted by commercial aviation, in the form 'Crew Resource Management' (CRM) (Kanki, Helmreich et al., 2010) a suite of human factors training techniques aimed at improving crew effectiveness, originally developed by the Aviation Human Factors group at Texas University and endorsed by the International Civil Aviation Organization (ICAO). CRM has also been adopted in many hospital surgical theatres (Helmreich, 2000) and is being encouraged in other high hazard activities including oil & gas (Flin, Wilkinson and Agnew, 2014). A key component of CRM, that has found wide practical and successful application in other high hazard operations, is the concept of 'situation awareness' (Endsley, 1999) very akin to 'mindfulness' as described by Weick and Sutcliffe (Weick and Sutcliffe, 2006) and similarly applies at individual, team and organizational levels. Hopkins notes in particular that leaders of organizations operating with high hazards need to maintain a 'big picture' of the current effectiveness of risk management systems, requiring rapid and comprehensive information flows between control rooms and boardrooms and suggests that this 'mindful leadership' is the defining HRO characteristic (Hopkins, 2009). Endsley's work includes the design of equipment and systems to facilitate such information flows (Endsley, 1999).

Interest in human factors in the aftermath of the Three Mile Island, Bhopal, Chernobyl and Piper Alpha disasters led to the development of a theory of safety deriving from organizational culture (Bea, 1998; Hudson, 1999; Meshkati, 1991; Reason, 1990; Shrivastava, 1985). A form of 'safety culture' has been described as 'just, reporting, informed, learning and flexible' (Reason, 1998) and a safety culture model based on these characteristics working together as a system has been proposed: managers continually generating organisational learning, driven by a constant state of healthy, wary, concern for safety or 'chronic unease' (Fruhen, Flin and McLeod, 2014) maintained by their staying well-informed about the organisation's potential weaknesses by the continual reporting, by workers at all levels, of safety issues including their own errors, which they are willing to do since they trust the managers to exercise justice and fairness in dealing with them (Parker, Lawrie and Hudson, 2006). Dekker also emphasises the importance of justice and avoiding a blame culture (Dekker, 2011). Safety culture, CRM and situation awareness all share ideas with both Safety-II in its forward-looking approach of learning how to make things go right and with HRO theory; for example all these overlap with the concept of chronic unease, and effective interpersonal communication and teamwork, a cornerstone of CRM (Flin, Wilkinson and Agnew, 2014) is also fundamental to HRO theory (Roberts, 1990).

The UCLA Berkeley research conducted in the 1980s provided the first description of how HROs work: that despite the hazards, the likelihood of bad consequences is kept very low by having active organisational and interpersonal processes that reduce and contain human errors and system failures (Roberts, 1990). Roberts points out the previous dearth of organizational safety theory other than accident analyses, and the difficulty of deducing any useful theory based on such a trial and error approach. She notes that at that time the only social-science-based accident analyses, by Perrow, Sagan and Shrivastava, were based entirely on reviews of historical documentary evidence (Roberts, 1990). This led the Berkeley group to adopt the quite different ethnographic method of the in-depth 'embedded researcher' case study: they wanted to watch and talk to the people inside HROs to find out what they did that was so effective in avoiding accidents. Their research method is interesting: for three years, team members of different social science disciplines joined US Naval ships for intermittent periods of five to ten days. To reduce individual bias they rotated round all the relevant activities on the ships so that all researchers were able to observe all the activities (Rochlin, 2011). They looked specifically for ways that the organization minimised the negative potential effects of Perrow's 'interactive complexity' and 'tight coupling'. An important organizational capacity they noted was the ability to cope with paradoxes: for example standardisation versus flexibility (Roberts, 1990).

The ships' exercises were developed with much standardisation and specialisation of individual roles, but also with deliberate flexibility to encourage creativity in problem-solving (Roberts, Rousseau and La Porte, 1994). This was also noted in the considerable redundancy of systems: for example having many different means of instant communication, radios, public address systems and hand signals, and of people: crew members were deliberately encouraged to develop skills in many different tasks and teams were given the flexibility to decide themselves on a rapid dynamic basis who would do what (Roberts, 1990).

Another paradox-coping strategy noted was the deliberate maintenance of high workload for key individuals such as pilots, landing officers and nuclear plant operators, to gain high vigilance, develop high competence and reduce error, while at the same time avoiding the obvious potential negative effects from overstress and fatigue by means of a strategy of redundancy: multiple cross-checking and effective teamwork from 'many pairs of eyes' watching for errors or anomalies (Roberts, 1990). These factors were seen as important contributors to a safety culture that was reinforced by leaders committed to avoiding blaming individuals, instead frequently praising the reporting of errors and system weaknesses (Weick, Sutcliffe and Obstfeld, 1999).

An insight into how these paradoxes of control versus adaptation were managed is offered by the observed flexibility of authority structure. Although authority was predominantly hierarchical, as one would expected the military, this changed in busy periods: 'collegial patterns of authority based on skill and functional relationships emerge as the tempo of operations increases…As these clearly recognised patterns shift, communication patterns and role-relationships are altered to integrate the skills and experience called for by the situation.' (La Porte and Rochlin, 1994). 'In a sense the pyramid is inverted. The organization focusses on training and on letting people use that training. Low level decision making is part of that focus' (Roberts, 1990).

These ideas have been further developed into what has become possibly the best-known HRO model, the 'five characteristics model' (Weick, Sutcliffe and Obstfeld, 1999) and further developed under the key ideas of 'sense making' (Weick et al., 2005) and mindfulness (Weick and Sutcliffe, 2006). They suggest that Roberts' HRO characteristics of redundancy, high competence and vigilance from continuous training and strategic prioritization of safety as necessary but not sufficient, seeing high reliability more as an active process of seeking and fixing problems, than as a condition (Vogus and Sutcliffe, 2012). They describe an active nature of HROs, more sensitive to and dynamically responsive to the environment compared with normal or 'low reliability' organizations whose operating models lean more towards exploitation than exploration making them less adept at recognising and responding appropriately to changes to the operating situation. This 'organizational cognitive ability' is what they call 'mindfulness', and propose that this is the core of what differentiates an HRO(Weick and Sutcliffe, 2006).

Weick's research group analyse the components that they claim allow HROs to develop and maintain this mindfulness, as five key practices (Weick, Sutcliffe and Obstfeld, 1999): 1) 'preoccupation with failure' which implies maintaining a culture and infrastructure that support the reporting, expert analysis and embedding of learning from near-miss incidents and other learning opportunities, and which suppresses the complacency that often accompanies a focus on success; 2) 'reluctance to simplify explanations' that firstly, recognising that it takes a complex system to perceive the complexity of the actual environment, cultivates a 'requisite variety' of sensing mechanisms including 'diverse checks and balances embedded in a proliferation of committees and meetings, frequent adversarial reviews, selection of new employees with non-typical prior experience, frequent job rotation and re-training' (Weick, 2000) as well as sceptical but mutually respectful questioning of actual reported conditions, assumed competence and the like, and secondly expresses a willingness to accept 'false alarms' as the cost of habitually making a 'strong response to a weak signal', all of which call for excellent interpersonal skills to deal with the implicit lack of trust (Weick and Sutcliffe, 2001) 3) 'sensitivity to operations' which means the organization's leaders being well-connected to the operational 'sharp end' of their organisation, so they firstly, understand and actively contribute to overcoming the current problems and needs of operations, and secondly, maintain high organizational 'situation awareness' by sensing themselves what is happening in operating environment, making sense of that information as it relates to the organization's goals, and then projecting the developing situation forward to anticipate appropriate survival responses (Endsley, 1995); 4) 'commitment to resilience', which, more than simply accepting human fallibility and coping well with anticipated abnormal situations arising from predictable human and system failures, means having early warning systems to detect unexpected, anomalous errors or failures that have not been observed before, and developing the capacity to respond quickly and effectively by improvisation and ad hoc problem-solving to contain the situation, avoid escalation towards a major incident and swiftly restore normal operations (Woods, 2006); and 5) 'deference to expertise' which has one meaning that decision-making about safety-critical matters is not kept as the prerogative of the formal hierarchy of line management but instead the expertise of operational and technical specialists is given due weight and will normally take precedence (Sutcliffe, 2011) and another meaning of the overt acceptance that formal procedures cannot prescribe all situations, so people are expected to continually challenge and sense-check to avoid mindless operation of fixed processes (Weick, Sutcliffe and Obstfeld, 1999; Weick and Sutcliffe, 2001).

This portrayal of HROs as differentiated from other organisations by having these five attributes, the authors claim, is based on induction from a wide body of research and is intended to provide a framework of social infrastructural concepts that can be used by any organization wishing to improve its reliability (Weick and Sutcliffe, 2001). How they have done this appears to be by a combination of synthesis of observations of practices in case studies of HROs by the many writers they reference, together with an inversion from organizational weaknesses implicated in accident causation.

System safety theorists argue that both the NAT and the HRO views of safety are incomplete and flawed, claiming that reliability and safety are different properties and that although redundancy can reduce accidents caused by component failure (lack of component reliability) most accidents in complex systems have roots in cultural and human factors where component redundancy does not help and even, by increasing system complexity, tends to reduce rather than increase overall system reliability (Leveson et al., 2009).

Perrow objects that system safety is optimistic since 'the complexity and tight-coupling of complex, high-tech systems not only makes them opaque to the operators, but they also make it almost impossible for any one individual to understand such a system in its entirety' (Perrow, 1984). Sagan agrees, also maintaining that HRO Theory is optimistic (Sagan, 1995) and that notwithstanding both system safety and HRO arguments, NAT still prevails, citing among other reasons the difficulty of eliminating common-cause failures.

Despite these objections, system safety is the basis for 'safety management systems' commonly employed in high hazard industries (IPIECA and OGP, 2014) and 'safety reports' or 'safety cases' demanded by regulators (European Commission, 2012; UKHSE, 2005). Such safety management systems in the oil & gas and chemical industries commonly employ a bow tie hazard management model (Center for Chemical Process Safety and Energy Institute, 2018) an example of which is shown in **Fig 1.**

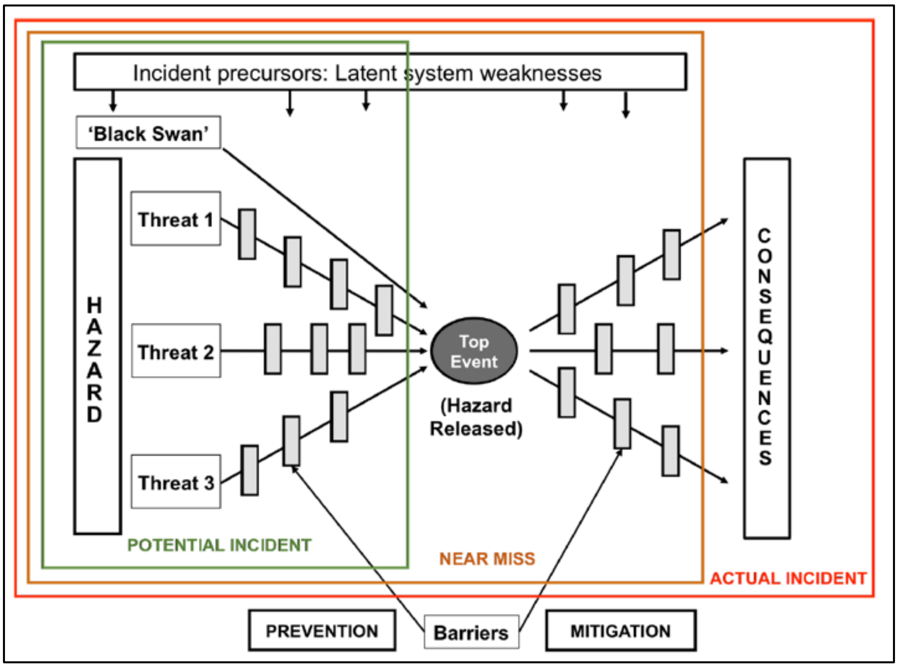

Fig 1 – Bow Tie hazard management model

Based on the 'Swiss Cheese' accident causation model (Reason, 1990) the left-hand side of the bow tie diagram portrays the known mechanisms by which a particular hazard could be released, shown as 'threat lines', together with the barriers designed to prevent the threats from releasing the hazard. Examples of such 'prevention' barriers are the steel containment envelope, a process control alarm with operator response, and an automatic shut-down system (Center for Chemical Process Safety and Energy Institute, 2018). If all the barriers designed to contain the hazard from being released by a specific threat were to fail, then a 'top event' would occur. In the process industries a typical 'top event' is a release of hazardous material such as flammable gas. This release of a hazard could also occur by a previously unknown mechanism or one considered so unlikely as not to warrant preventative controls, a so-called 'Black Swan' (Taleb, 2007). If a top event were to occur, then mitigation barriers are designed to minimise consequences such as injuries or damage resulting from explosions, fires or releases of toxic material. Examples of mitigation barriers are automatic water deluge firefighting systems, evacuation by lifeboat and wearing car seatbelts.

Three different types of process safety event are portrayed in **Fig 1**. An 'Actual Incident' is shown in the bow tie diagram as the occurrence of a 'top event' that then leads on to result in significant consequences due to the failure of the barriers on the right-hand side of the bow tie to mitigate them. Actual Incidents are shown within the (outer) red box, as events that have multiple contributory factors, failures both in prevention and in mitigation.

A 'Near Miss' is shown as occurring within the (middle) orange box, where a 'top event' occurs but without resulting in consequences because of effective mitigation barriers, which are shown on the right-hand side of the bow tie diagram. In reality, the mitigation could have been due to the effectiveness of designed mitigation barriers or due to a successful improvised mitigative intervention, such as a quick-witted operator who opened a valve to release an unexpected build-up of pressure, or just by chance, such as a gas cloud that dispersed before reaching a source of ignition.

By contrast, a Potential Incident is shown in **Fig 1** as an event that falls within the (inner) green box, as the detection and correction of a system weakness such as the failure or degradation of a barrier, an error or some other vulnerability, without the release of a hazard in a top event. The weakness could be detected by chance observation or by the operation of another barrier, perhaps the last prevention barrier remaining such as a pressure relief valve or an automatic shutdown system, indicating that all the other prevention barriers had failed; it could also be detected by either the successful operation of a designed system for detecting such weaknesses, such as an alarm or a routine program of inspection and testing, or by high vigilance, either of an individual or at the organizational level, perhaps including an improvised successful intervention. Potential Incidents identified by these latter mechanisms are of particular interest, since they may indicate high situation awareness, resilience and safety. Not shown in this simple diagram, but equally of interest, is another kind of Potential Incident: the detection of a weakness in a mitigation barrier on the right-hand side of the bow tie, before it was needed. As the diagram does show, weaknesses can exist anywhere in the whole prevention and mitigation system.

According to this theory, a system weakness could be the failure or degradation of one or more barriers in a particular causation trajectory (shown as threat pathways on the left hand side of the bow tie diagram and consequence pathways on the right hand side) or it could be a 'system pathogen' (Reason, 1997) such as unmanaged fatigue, an unclear procedure, loss of currency in a technical skill, incomplete communication or some other human performance influencing factor. These factors can lead, in the traditionally accepted analysis, to degradation of established barriers or omission of desirable barriers due to fallible decisions. In an alternative ('Safety II') view, they can also lead to degradation of mindfulness and expert improvisation that may normally be operating to maintain safety despite imperfect designs and understanding of risks (Hollnagel, 2014).

System weaknesses and pathogens can manifest themselves at any stage in the life of high hazard technology, from the design stage, through procurement of materials and equipment, construction and start-up, operation and maintenance and de-commissioning. Unplanned, improvised, human interventions to detect and prevent an incident may likewise be made by people at any stage: perhaps most often by people in the operational front line or maintenance, but also by engineers involved with design, construction or asset integrity, by management activities such as safety audit and risk assurance, or by managers, or anyone, asking the right questions. Such interventions can also raise doubts that are later seen to be unfounded, so they are false alarms. An organisation's tolerance of such false alarms may be an indicator of its level of safety.

While HRO theory is criticised for its principle of improvisation by the people working at the operational front line, who lacking full system knowledge may adopt local work-arounds with potential unintended negative consequences (Leveson et al., 2009) 'system safety' theory also recognises the importance of flexibility: 'Allowing latitude in how tasks are accomplished will not only reduce monotony and error proneness, but can introduce flexibility to assist operators in improvising when a problem cannot be solved by only a limited set of behaviors. Many accidents have been avoided when operators jury-rigged devices or improvised procedures to cope with unexpected events.' (Leveson, 2013). 'HRO' is somewhat aligned here, maintaining that although standard procedures and competent operational discipline in using those procedures are important, it is mindful use of them that stops things going awry: people at the operational sharp end need to be empowered and encouraged to make sense of situations and use their expert judgement, beyond merely following standard procedures: 'when problems occur, let decision making migrate to the people who have the most expertise to deal with the problem' (Weick and Sutcliffe, 2006).

A recent empirical case study of an offshore gas explosion (Denyer and Sibbick, 2015) found clear evidence that not all events can be anticipated; the explosion was initiated by a subtle technical failure of a gas cooler by a previously unknown failure mechanism – an example of the 'Black Swan' (Taleb, 2007) discussed earlier and shown in **Fig 1**. The study also showed that the potentially disastrous consequences were effectively mitigated by an operating organization that was demonstrably resilient and exhibited many aspects of the mindfulness described in HRO theory. Despite the extremity of the event ('simulation showed that the explosion and fire was caused by the release of 9.8 tons of hydrocarbon gas…released at half a ton per second'… 'the fireball expanded, engulfing the decks below and rising to 200 feet above…') there were no fatalities and no criticisms from the government safety regulator, an outcome that compares very favourably with the tragic consequences of the 1988 Piper Alpha explosion and fire in which 167 people died.

In response to this recent incident, a deep investigation was done in full collaboration with the regulator, and after some intensive engineering work and extensive repairs, nine months later the asset was back in operation. Several important aspects of mindfulness, that had been deliberately developed within the operating organization over the previous four years before the incident, were identified as having contributed to the effective response to and the positive outcome of the incident. These included an emphasis, with strong encouragement from the company directors, on the need to understand and manage the risks represented by the ageing asset, through technical inspection, condition assessment and monitoring processes, and to 'worry about failure'. These practices are evidently aligned with the HRO characteristics of 'sensitivity to operations' and 'preoccupation with failure' (Weick, Sutcliffe and Obstfeld, 1999).

Likely due to these practices, the bow tie 'mitigation barriers' of emergency shutdown and deluge systems worked perfectly and everyone on board was swiftly evacuated. There was no attribution of blame, instead a major focus on welfare of the people involved. An independent investigation team was set up, with forensic technical support from the regulator; 'There wasn't a hint of anybody trying to anything up…' (this aligns with 'reluctance to simplify explanations' and 'deference to expertise'). After the investigation, the organization actively shared the learning, drawing from the incident even more explicit focus on safety, risk and reliability through competence and adequacy of resources to deal with problems early (this aligns with 'commitment to resilience') and setting a change agenda that included both rule-based dimensions (multiple layers of protection of critical systems; systematic maintenance, inspection and monitoring) and mindfulness-based dimensions (competence, capability and authority; open reporting and situation awareness). This case 'illustrates how one organization recognised the importance of finding an appropriate balance between rule-based and mindfulness-based approaches in its attempts to become a high reliability organization' (Denyer and Sibbick, 2015).

In summary, process safety depends on overcoming NAT, and the major theories claim to do that, with paradoxically different emphases: 'system safety' prioritises engineering, reducing interactive complexity and tight coupling in the overall system design, together with maintaining accurate and complete models of the system to guide risk-based decision-making (Leveson, 2004) 'HRO' by acknowledging the inherent unpredictability and complexity of real systems and developing the capacity for mindful sense-making and competent adaptation within effective teamwork processes that are enabled by flexible forms of organizing and leadership (Weick and Sutcliffe, 2001). The Safety-II view embraces both theories and emphasises the importance of understanding the reality of expert adjustment and improvisation in normal operations (Hollnagel, 2014).

Reconciling the rule-following so essential to the 'traditional bureaucracy' view, with this expert improvisation, so essential to the Safety-II and 'HRO' approaches and accepted as necessary by system safety, represents a major paradox. This tension has interested researchers for some time. It has long been recognised that rules and procedures vary in their quality and usefulness. Two quotes exemplify this: firstly: 'It is probably true to say that procedures, together with the training and checking that goes with them, are the main reason commercial aviation is safe as it is' (Green et al, 1996) and secondly: 'In the nuclear industry nearly 70% of all human performance problems can be traced to unclear or otherwise bad procedures' (Reason, 1997).

Dekker points out the impossibility of writing a procedure to cover all situations, so that violating a procedure is sometimes the safest action (Dekker, 2003). And a study of anaesthetists' use of rules suggests rules could be seen alongside other principles to guide naturalistic decision-making and so could and should be violated when doing so met one of three principles: 'doing the right thing', 'doing what works in the circumstances' and 'using one's skills and expertise' (Phipps and Parker, 2014). Others agree that problems will arise from slavish adherence to rules that do not work in a changed context or if rules are not used to guide adaptation (Woods and Shattuck, 2000). That procedures should normally be followed but competently adapted when necessary is supported by a recent review of the literature on management of safety rules and procedures (Hale and Borys, 2013) and is well illustrated by the following quote: ''I don't enjoy making changes to procedures. It seems like the crew only does that when they feel there's some good need for it.'' Mike Collins, test pilot and astronaut, Apollo 11 crew debriefing following the first manned mission to land on the Moon, July 31, 1969 (English and Branaghan, 2012).

This aim of this empirical study was to explore how these two paradoxically different approaches, of reliance on rule-following on one hand, and support of adaptive practices such as vigilant detection and correction of system weaknesses with expert improvisation on the other hand, may operate in practice. The approach was to examine how informed actors construe and experience the circumstances of 'potential incidents' and how this may contrast with the construed circumstances of 'actual incidents' and 'near-misses'

How people construe the circumstances of potential incidents is interesting since their identification and the subsequent action to stop them from developing into actual incidents may provide evidence of the adaptive practices inherent in the theories of HRO and Safety II. This contrasts with actual incidents since evidently the (presumably latent) organizational safety system weaknesses that led to the incident were not identified. 'Near-miss' incidents may have characteristics of both actual and potential incidents.

3. RESEARCH DESIGN

3.1. Research Questions

Two questions are addresses by this study:

1. How do people at the operational sharp end of organizations operating high hazard technology construe the circumstances of three different kinds of event related to process safety: actual incidents, near misses and potential incidents?
2. How do the interplay and tensions between rule-following and adaptive practice figure in this?

3.2. Data collection

A total of 55 interviews were conducted at three different operational oil & gas and petrochemical sites, with people in a range of jobs from operator/technicians and shift supervisors to engineers and managers. Interviews followed the Repertory Grid Technique (Kelly, 1955) to elicit their views on the circumstances of a range of events relating to process safety.

Selecting fieldwork sites

The rationale was to allow for comparison between sites with similar technology and organizational context but different stages of organizational maturity and safety performance. This was achieved by selecting three geographically-separated sites operated by a single multinational company: a recently-constructed large petrochemical manufacturing operation in the Middle East with a mixed safety record (Site A) a multiple-location rapidly-developing upstream oil & gas production operation in Asia-Pacific with a safety record giving cause for concern (Site B) and a long-established offshore upstream oil & gas production operation in Europe with an above-average safety record (Site C). The different characters of each of these three sites are summarised below.

Site A was a very large petrochemicals complex in the Middle East that had been started up only a few years earlier. The site operated continuously with a typical 24h shift pattern, supervised from a state-of-the-art central control room in radio communication with field operators monitoring the physical plant. The organization was fairly hierarchical, emphasising the importance of compliance with procedures. The operations and maintenance organizations were populated largely with ex-patriot workers of numerous different nationalities, predominantly Asian, and also many from Europe, Australasia and North America. The organization was still in transition from project-based to operations-based, with a number of modification projects in process. The site received significant specialist support from the parent organization in engineering and other fields. An impressive construction safety performance had suffered in the translation into operation, the site having had a number of significant process safety incidents in the early years of operation, including fatalities.

Site B was an oil & gas onshore production operation with a large number of geographically-dispersed fields feeding a single large treatment and export plant. Many of the production units were in locations remote from support infrastructure and were only visited periodically by technical personnel. The number of production units had been growing rapidly over the previous decade, and the older units had been designed and built to lower standards than the more modern ones. The organization was very much in the stage of developing and maturing, having been rapidly expanding for some years, drawing operator/technicians from the local population and providing extensive training, while maintaining a fairly flat hierarchy. The operation was in the process of adopting and implementing a new set of parent organization engineering and operating standards, for which the parent organization was providing some specialist support. There was significant concern to improve the process safety record, the site having suffered a number of significant incidents, including some high potential consequence near-misses and potential incidents.

Site C was an offshore oil and gas production operation, with a single large offshore platform that had been in operation for over 25 years, supported by an onshore team of engineering and operations support personnel in a local office. The mature organization had evolved to be a fairly small stable team of people with considerable experience with a marked culture of mutual respect, open to much discussion up and down the fairly flat hierarchy; many people had worked together for some years and had rotated through a range of different roles. The local organization was largely self-sufficient in terms of operational and technical expertise with good support from the parent organization as needed. The safety performance was above-average; it had recently been given a major award for its process safety performance.

A summary of the profiles of the three sites is given in **Table 1.**

Table 1 – Summary profiles of the three sites

	Site A	**Site B**	**Site C**
Overview	Very large single site Petrochemicals complex	Onshore Oil & Gas production, Large number of remote production units dispersed geographically; single large treatment and export plant	Offshore Oil & Gas production, single platform; onshore technical and operations support
Location	Middle East	Asia Pacific	Europe
Organization form	Strong hierarchy	Hierarchy / open culture	Weak hierarchy / open culture
Personnel	Largely ex-patriot	Largely local	Largely local
No. of people	3000+	4000+	300+
Organizational maturity	In transition from very large Project to Operations	Mixed; rapidly growing number of physical assets	Stable; very mature
Years of operation	5+	10+	25+
Relation with Parent Org	Significant specialist support	In process of adopting new Parent Org technical standards	Fairly independent; supported as needed
Safety performance	Mixed	Cause for concern	Above-average

Selecting events

Events were selected of three different type as defined below, all involving process safety hazards such as flammable or toxic fluids (rather than 'personal safety': slips, trips and falls etc.) and that had, or could have had, significant consequences, defined as level 3 to 5 inclusive, on a scale of consequence severity commonly used in the industry (Summers, Vogtmann and Smolen, 2011) (see **Table 2**).

Table 2 – Consequence Severity Scale

	People	Environmental damage	Asset loss / Operation impact
5	Multiple fatalities	Catastrophic off-site damage	>$10M and substantial offsite damage
4	1 or more fatalities	Significant off-site damage	$1M - $10M and severe impact
3	Hospitalization injury	On-site or offsite release with damage	$100K - $1M and significant impact
2	Lost work day injury	On-site or offsite release without damage	$10 - $100K and some impact
1	Recordable injury	On-site release	< $10K and minor impact

Selecting interviewees

The rationale was to seek the views of people with a range of perspectives. The primary population sampled was the operations and maintenance staff employed by the operating company directly involved with day-to-day running of the plant, at three organizational levels, operator/technician, shift supervisor or engineer and manager. To gain a wider perspective, interviews were also sought with two other populations: firstly employees of companies contracted by the operating company, typically for work supporting maintenance such as scaffolding, welding, electrical work etc., and secondly people working in the design and construction of plant, generally in projects to modify or extend existing plant. Interviewees were sought who had a few years of experience working in the same organization or plant, and who had direct knowledge of process safety incidents and potential incidents.

The sample obtained is shown in **Table 3**. A total of 55 repertory grid interviews were conducted.

Table 3 – Populations sampled

Job Type	Organisational level	Interviews per site		
SITE		**A**	**B**	**C**
Ops/Maintenance	Contractors	7	0	0
	Operator/Technician	3	1	0
	Supervisor / Engineer	3	13	1
	Manager	3	13	8
Design/Construction	Contractors	0	0	0
	Operator/Technician	0	1	0
	Supervisor / Engineer	0	0	0
	Manager	1	1	0
	Totals	**17**	**29**	**9**

Repertory Grid Technique

Repertory Grid Technique was chosen for this research because it is considered a powerful and adaptable tool that can 'help interviewees articulate their views on complex topics without interviewer bias' (Goffin, 2002). The technique is based on Kelly's 'personal construct' theory, that people make our own personal sense of the world by observing and construing meaning from experiences; people develop, test and update 'constructs' as hypotheses in the light of their own experience, so constructs will therefore differ from person to person, although because we are influenced by other people, our personal constructs will often align and become socially constructed. We tend to think of our personal constructs in the context of their opposite; 'A construct is a way in which some things are construed as being alike and yet different from others.' (Kelly, 1955). The Repertory Grid Technique thus involves the identification of constructs and their opposites, or 'poles' in a structured manner. The interviewer follows a process that repeatedly asks the interviewee to think of ways that differentiate between changing sets of three 'elements', which are examples of or occurrences within a particular topic (Jankowicz, 2004). In this study, the elements were events of the three different types described above. This process of comparing sets of three elements ('triads') helps elicit from people their tacit views or constructs which can otherwise remain latent and unacknowledged using simpler interviewing techniques (Goffin et al., 2012). An interview normally elicits a number of constructs. The technique results in a matrix of quantitative data, the repertory grid, with the elements forming one axis and the constructs the other axis; the cells contain the interviewee's ratings of each element on a scale from full alignment with the construct to full alignment with its opposite, or pole. The repertory grids thus created can be analysed quantitatively, to extract meaning idiographically, that is relating to an individual's understanding, and nomothetically, which seeks patterns of understanding emerging from a number of people (Tan and Hunter, 2002). The interviews can also be analysed qualitatively, using usual qualitative text coding techniques, extracting phrases that exemplify the constructs.

Interview planning

A representative sample of people to interview was sought as described above. The identification of suitable interviewees was facilitated by a manager at each site nominated by the main contact in the host company for the research. Ahead of the interviews, the researcher contacted the interviewees to explain in outline the purpose and process; the interviewees were requested to choose a total of six events familiar to them, two events of each type described above, to be the subject of discussion in the interview. Pilot interviews held with a colleague before starting the fieldwork had shown that 60 mins was needed for the interview. This timing aligned with other researchers' experience (Jankowicz, 2004).

Interview Process

The interview, following a prepared script (started by asking the interviewee to describe briefly each of the six events they had chosen to discuss and to label a card for each one with a short name and its event type. The cards were pre-printed with a short definition of each of the three types of event, as a reminder to the interviewee how the types were differentiated. Any confusion about the event definitions was cleared up with a short discussion to gain a common understanding. Then, following a standard repertory grid process (Goffin, 2002; Jankowicz, 2004) the researcher selected three of these events (a 'triad') and asked the interviewee to compare them and to think of how any two of the events were similar and different from the third one. The researcher placed the cards relating to the three events in question in front of the interviewee to aid their reflection, and moved them about occasionally into different relative positions, to help the interviewee see the different possible comparisons. The process was later repeated with a series of different triads of events.

Since the research interest was in the area of how process safety incidents unfold, how their unfolding may be stopped by intervention and what may differentiate these two situations, with a view to shedding light on how the interplay and tensions between rule-following and adaptive practice may influence them, the interviewees were asked to think specifically about how the events in question did unfold, how they were identified as developing or actual incidents, and the human interventions that were involved. This was done by using the same wording with each new triad: “Considering these three incidents, please think about how two of these were similar, and thereby different from the third one, in regard to how people identified and responded to them”.

The interviewee’s response formed into a specific idea, a construct, that they felt was significant and relevant to a comparison of the events. Typically people found some difficulty with this at first, so the researcher prompted with open-ended questions to help the interviewee explain how they saw the contrast between the three incidents, and how the nascent construct was important to them in describing these events. Picking out one word or phrase used, the researcher then asked the interviewee to define the two extremes of that idea; e.g. if the interviewee had said ‘unusual situation’ they might then suggest as the two extremes ‘normal procedure’ and ‘never been done before’. The construct and its polar opposite or ‘pole’ were then summarised into short phrases describing these two extremes and after the interviewee had confirmed their agreement to the wording, these phrases were written down by the researcher at each end of the first line on a prepared repertory grid sheet. Next, the interviewee was asked to score the three events on a scale from 1 to 4, with 4 representing the extreme of the construct and 1 representing the extreme of the pole. Finally the interviewee was asked to score the remaining events on the same scale, thus creating the first line of the repertory grid. Further different combinations of three events, or triads, in a pre-determined standard sequence, were then used to elicit other constructs. With each triad, a new construct was sought; no repeat constructs were allowed, so the interviewee was encouraged to think more deeply about the events as the interview progressed. This process continued until the interviewee could think of no new constructs. Some interviewees quickly grasped the technique and were soon able to describe five or six constructs, while others found the process difficult and even with patient encouragement from the researcher were only able to express two or three ideas before they dried up. This was expected, since experience with this technique indicates that some people will have only a few genuinely different constructs concerning a particular topic (Jankowicz, 2004).

Data Analysis

The data collected was of two sorts, quantitative in the form of the repertory grids and qualitative in the form of the recorded interviews. The analysis was done nomothetically, i.e. seeking patterns of ideas emerging from multiple interviews. The outline process of data analysis was as follows:

1. Preparation and validation of the data
2. Analysis of overall key constructs
3. Analysis of constructs comparing between each event type
4. Analysis of constructs comparing between sites

Preparation of the data

Each of the 55 grids was made up of 6 elements i.e. the events chosen by the interviewee and between 1 and 6 constructs; the average number of constructs per interview was 2.6, resulting in over 800 quantitative data points, as well as the qualitative data of the recorded interviews. The quantitative data from the interviews were entered into a spreadsheet, with quality checks to avoid data entry errors. An extract from this spreadsheet is in **Table 4**.

Table 4 – Extract from Raw Repertory Grid Data spreadsheet

REF	CONSTRUCT	a	b	c	d	e	f	POLE
		Actual		Near-miss		Potential		
a.n.1	full understanding of hazard and required controls	1	2	4	4	3.5	3.5	unaware of hazard
a.n.2	unique incident	1	4	2	2	2	4	part of an incident cluster
a.n.3	occurrence due to response to previous circumstances	4	4	1	1	1	4	new occurrence
a.n.4	unexpectedly delayed identification of occurrence	4	4	2	2	2	1	occurrence identified as expected through routine inspection
a.p.1	required intervention	3	4	1	1	4	2	no intervention practical
a.p.2	early warning signs easy to see	2	1	4	4	3	1	early warning signs difficultto see
a.p.3	equipment integrity related	2	3	3	1	4	1	operator initiated
a.p.4	production prioritised over safety/environment	1	1	4	1	4	3	safety/environment prioritised over production
b.q.1	process safety barriers understood and good reporting of failures	4	3	1	2	3	1	poor understanding of PS barriers and poor reporting
b.q.2	reaction of isolate and make safe	4	1	1	1	1	1	reaction of immediate fix and return to service
b.q.3	proactive systematic identification of barrier weaknesses	4	4	2	1	3	3	reactive identification due to loss of primary containment
b.q.4	organisational reaction of independent deep investigation	4	1	4	1	3	2	local shallow investigation
b.q.5	engineered instrument detection	1	1	3	4	4	4	procedural human detection
b.q.6	correct risk perception and effectice emergency response	4	1	1	1	4	1	low risk perception and ineffective response

The interviews were transcribed, with quality checks for transcription errors. Explanatory quotes were extracted from the transcripts to obtain fuller descriptions of the meaning of each construct.

Data validation

Although the element scores data obtained from Repertory Grid Technique interviews is quantitative, the qualitative nature of the constructs allows interpretation of their meaning. To compensate for potential researcher bias in this interpretation, a one-day data workshop was run with two teams each with two researchers to categorise the constructs. To prepare for this, two identical sets of construct cards were made, each printed with the wording of the construct and its pole, the explanatory quote and the construct reference number, in the format [n1.n2.n3] n1 indicating the site, n2 the interview number at that site and n3 the construct number within the interview. To minimise personal biases and limitations, each team comprised one researcher who was an experienced faculty member and one doctoral researcher who was a 'knowledgeable practitioner with conceptual interests and more than one disciplinary perspective' (Miles and Huberman, 1994). Working independently in separate rooms, each team coded the constructs, sorting them into categories that the team defined.

After the workshop, following a process similar to that used by others (Goffin and Koners, 2011) the two sets of categories were compared in a 'reliability table'. This took the form of a matrix, one axis being the categories made by one team, each category also listing the constructs allocated to it, the other axis being the categories and allocated constructs made by the other team. Where both teams agreed on a common category, the respective cell contained a list of the 'common constructs' that both teams had allocated to that common category. The 'commonality ratio' of common constructs to the total number of constructs is an indicator of data reliability (Goffin et al., 2012).

The initial comparison of the two teams' categorisation yielded a commonality ratio of 40%. Check-coding discussion between the two teams, recommended in the case of low initial data reliability (Jankowicz, 2004) to 'aid definitional clarity' and as a 'good reliability check' (Miles and Huberman, 1994) resulted in the aligned set of categories shown **Table 5** and recategorisation of a number of constructs within these categories. This improved the commonality ratio to 85% which exceeds the suggested 80% acceptable criterion (Miles and Huberman, 1994). An extract of the final reliability table is shown in **Table 6**.

Table 5 – Aligned Categories of Construct

	Category Name	Definition
1	**Work pressure**	Tension or pressure on people created by competing priorities, time, productivity drivers and targets, leading to shortcuts instead of considered action
2	**Procedures**	Plans, procedures and instructions for how work is to be done
3	**Communication**	The processing and exchange of information relating to plant safety
4	**Compliance**	The action or fact of complying with prescribed rules or procedures
5	**Competence**	The requisite skill, knowledge and experience to do the job safely and effectively
6	**Hazard Detection**	The process of noticing and identifying hazards, risks or the signals of an impending incident
7	**Understanding of Risk**	The process of making sense and developing situation awareness of the potential consequences, events or incidents as they unfold
8	**Vigilance**	The action or state of keeping mindful watch for possible vulnerabilities and potential mitigations - vs an over-confidence and belief that nothing untoward is going to happen
9	**Deference to Hierarchy**	Submission to those in authority and hierarchy position in decision-making
10	**Supervision**	Guidance and instruction and management of direct reports
11	**Incident Investigation and Analysis**	Investigation and analysis of immediate and underlying causes, and follow-up and learning
12	**Emergency Response**	The immediate action of recovery from an unexpected event or dangerous situation, and the planning and preparation for that
13	**Organisational Learning**	The acquisition, dissemination, and implementation of knowledge or skills through experience, post-incident
14	**Checking, challenge and follow-up**	Intervention to challenge or review the safety of a decision, work method or situation, including follow-up checking
15	**Equipment Design**	System and technology that control and protect the organization against failure
16	**Unique Occurrence**	An unfamiliar or novel situation that has not been encountered before
17	**Mistake**	Actions with unintended consequences where people believed that they were doing the correct thing
18	**Mitigation**	Individual or collective actions to prevent or lessen the consequences of incidents and accidents
19	**Risk Assessment**	The process of determining the probability and consequences of a hazard or risk

Table 6 – Reliability Table (extract)

REF				1	2	3	4
	Team DN	Team EC		WORK PRESSURE	PROCEDURES	COMMUNICATION	COMPLIANCE
		COUNT		7	13	3	9
				1.1.1 1.10.4 1.14.2 1.20.1 2.4.4 2.5.2 2.24.2	**1.1.2*** 1.3.2 1.4.3 1.7.2 1.11.3 1.17.2 1.19.2 2.1.3 2.5.3 2.10.1 2.16.3 2.19.2 2.19.5	1.1.3 1.3.1 1.11.2	1.1.4 1.2.1 1.5.2 **2.1.1*** 2.1.2 2.4.3 2.9.5 2.24.3 2.26.1
1	WORK PRESSURE	6	1.1.1 1.10.4 1.14.2 1.20.1 2.4.4 2.24.2	1.1.1 1.10.4 1.14.2 1.20.1 2.4.4 2.24.2			
2	PROCEDURES	11	1.3.2 1.4.3 1.7.2 1.11.3 1.17.2 1.19.2 **2.1.1*** 2.5.3 2.6.2 2.10.1 2.16.3		**1.1.2 *** 1.3.2 1.4.3 1.7.2 1.11.3 1.17.2 1.19.2 **2.1.1*** 2.5.3 2.10.1 2.16.3		
3	COMMUNICATION	3	1.1.3 1.3.1 1.11.2			1.1.3 1.3.1 1.11.2	
4	COMPLIANCE	10	**1.1.2*** 1.1.4 1.2.1 1.5.2 2.1.2 2.4.3 2.9.5 2.24.3 2.26.1 2.26.2				**1.1.2*** 1.1.4 1.2.1 1.5.2 2.1.1* 2.1.2 2.4.3 2.9.5 2.24.3 2.26.1

When the interpretation and categorisation of the individual constructs was completed, the constructs for which no agreement was reached on a common category were discarded from further analysis; this process led to all of the constructs from two interviews being discarded. Also discarded were the data from two interviews for quality reasons: one since it proved too difficult to transcribe due to the strong accent, the other since it contained data from sites elsewhere than those being studied. This resulted in a final total of 135 'common constructs' in 19 categories and arising from 51 repertory grids. These data were now considered as valid for further analysis.

To confirm that enough data had been collected, a Pareto analysis (**Fig 2**) was conducted in a similar manner to that used by others (Goffin and Koners, 2011; Micheli et al., 2012). The x-axis is the repertory grid count and the y-axis is the increasing total of common construct categories identified as the interviews progressed. This analysis gives some confidence that theoretical saturation was achieved.

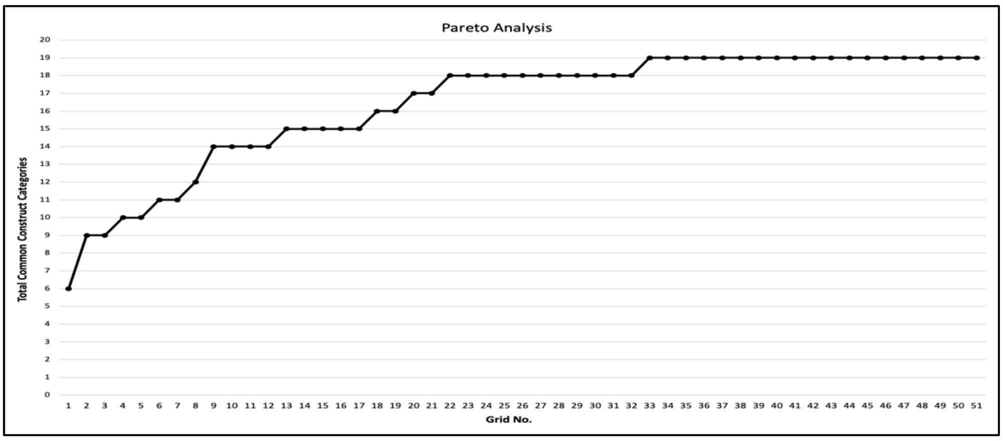

Fig 2 – Pareto Analysis of Common Construct Categories per Repertory Grid

Analysis of overall key constructs

Having validated the data, the analysis continued with the aim of answering the two research questions:

1. How do people at the operational sharp end of organizations operating high hazard technology construe the circumstances of three different kinds of event related to process safety: actual incidents, near misses and potential incidents?
2. How do the interplay and tensions between rule-following and adaptive practice figure in this?

Sorting the data into the 19 categories of construct provided a broad description of how people think about the events discussed in the interviews, but clearly some constructs appeared more important than others, simply because they occurred more frequently. Relying on frequency alone carries the risk of over-valuing some constructs that may occur frequently but are obvious and unimportant. However, if a construct has a wide variability of element scores compared with the element scoring of other constructs within a grid, this can be taken as a measure of its importance to the person (Kelly, 1955). Using a combination of both frequency and variability thus gives a more realistic assessment of the overall relative importance of constructs; setting criteria for these measures allows 'key constructs' to be determined.

Adopting the approach taken by others (Goffin, Lemke and Szwejczewski, 2006; Lemke, F., Clark,M. and Wilson, 2011) the measure of frequency used was '%Unique Frequency' (%UF) removing repetitive occurrences of constructs within individual grids, so that %UF represents the proportion of interviewees who mention a particular categorised construct. The measure of variability used was 'Average Normalised Variability' (ANV) which is the variability of a construct normalised for the different numbers of constructs per grid and then averaged over all the occurrences of that construct. The normalisation calculation for a particular construct within an individual grid is as follows, where %TSS is the percentage Total Sum of Squares:

Construct NV = %TTS*No. of constructs in the individual grid /Average No. of constructs per grid

The calculation of % TSS is typically done using specialist repertory grid software, and this study used the software ***Idiogrid*** (Grice, 2004). The construct NVs from each grid thus obtained were then averaged over all occurrences of that construct, to obtain the construct ANV. These calculations are based on the whole data set and thus the ANV values represent the overall view of the constructs without differentiating between event types, which is done later.

The criteria for determining 'key constructs' i.e. those of particular importance to the sampled population, were established following the same approach to that used by others (Goffin, Lemke and Szwejczewski, 2006; Raja et al., 2013). The %UF criterion was set as 'mentioned by at least 25% of interviewees' and the ANV criterion set as 'above average', the average being the mean of all the individual construct values of ANV.

The result of applying these criteria are shown in **Table 7**

Table 7 – Determination of Key Constructs (All Event Types)

				UF	%UF	>25		ANV	>37.8
1	WORK PRESSURE			6	12			43	
2	**PROCEDURES**			10	**20**			**37**	
3	COMMUNICATION			3	6			32	
4	**COMPLIANCE**			9	**18**			**38**	**Y**
5	COMPETENCE			4	8			26	
6	**HAZARD DETECTION**			19	**37**	**Y**		**39**	**Y**
7	UNDERSTANDING OF RISK			8	16			36	
8	**VIGILANCE**			11	**22**			**41**	**Y**
9	DEFERENCE TO HIERARCHY			5	10			32	
10	SUPERVISION			2	4			51	Y
11	**INCIDENT INVESTIG. & ANALYSIS**			13	**25**	**Y**		**38**	**Y**
12	EMERGENCY RESPONSE			5	10			39	Y
13	CHECKING, CHALLENGE & FOLLOW-UP			1	2			54	Y
14	ORGANIZATIONAL LEARNING			4	8			30	
15	EQUIPMENT DESIGN			4	8			32	
16	UNIQUE OCCURRENCE			3	6			50	Y
17	MISTAKE			2	4			44	Y
18	MITIGATION			4	8			42	Y
19	RISK ASSESSMENT			5	10			39	Y

Analysis of constructs comparing between each event type

To examine for differences in construct importance for each of the three different event types, addressing Research Question 1, a similar analysis was done as described above but with the data restricted to include only that for each event type in turn. ***Idiogrid*** was used to calculate the %TSS for each construct within each 'reduced' grid i.e. separately for each event type (Actual Incident, Near Miss and Potential Incident). From these NVs were calculated and then averaged over all occurrences of that construct to obtain individual construct ANVs specific to each event type. As before, the criteria for determining key constructs were a %UF of at least 25% with the ANV above average. The results of applying these criteria are shown in **Table 8**

Analysis of constructs comparing between sites

To examine for differences in construct importance between the three sites A, B and C, a similar analysis was done as described above but with the data restricted to include only that for each site in turn. As before, the criteria for determining key constructs were a %UF of at least 25% with the ANV above average. The results of applying these criteria are shown in **Table 11.**

4. RESULTS

In **Table 8** columns 1 and 2 show the construct %UF and ANV scores without differentiating between the three types of process safety event or between the three sites. The other columns in Table 9 present the figures for ANV calculated individually for the three different types of process safety event: Actual Incident, Near Miss and Potential Incident, in columns 3, 4 and 5 respectively.

Fig 3 shows the comparison graphically, the height of the bars representing combined score of %UF * ANV.

Table 8 – Construct Frequency and Variability for each Event Type

		1		2		3		4		5	
		UF		ANV							
		ALL		ALL		AI		NM		PI	
	Construct	%UF	>25	ANV	>39	ANV	>35	ANV	>27	ANV	>28
1	WORK PRESSURE	10		43	Y	40	Y	46	Y	28	Y
2	PROCEDURES	20		37		12		26		31	Y
3	COMMUNICATION	6		32		38	Y	13		0	
4	COMPLIANCE	18		38		35	Y	43	Y	52	Y
5	COMPETENCE	8		26		26		48	Y	4	
6	HAZARD DETECTION	37	Y	39	Y	19		22		44	Y
7	UNDERSTANDING OF RISK	16		36		20		21		38	Y
8	VIGILANCE	22		41	Y	33		33	Y	24	
9	DEFERENCE TO HIERARCHY	10		32		44	Y	39	Y	22	
10	SUPERVISION	4		51	Y	19		0		0	
11	INCIDENT INVESTIG. & ANALYSIS	25	Y	38	Y	49	Y	45	Y	32	Y
12	EMERGENCY RESPONSE	10		39	Y	5		35	Y	7	
13	CHECKING, CHALLENGE & FOLLOW-UP	2		54	Y	68	Y	0		0	
14	ORGANIZATIONAL LEARNING	8		30		25		29	Y	6	
15	EQUIPMENT DESIGN	8		32		8		19		33	Y
16	UNIQUE OCCURRENCE	6		50	Y	52	Y	18		84	Y
17	MISTAKE	4		44	Y	55	Y	38	Y	43	Y
18	MITIGATION	8		42	Y	80	Y	18		53	Y
19	RISK ASSESSMENT	10		39	Y	47	Y	16		33	Y

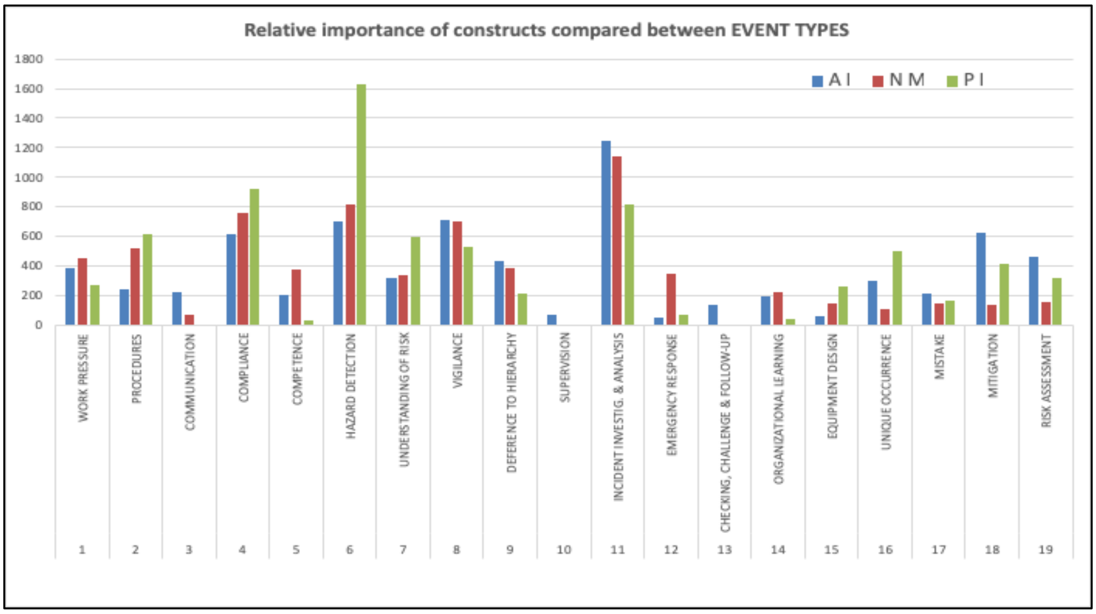

Fig 3 – Relative importance of constructs for each Event Type

As discussed earlier, for a construct to be determined to be a key construct, it should meet both of the two criteria: '%Unique Frequency (%UF) at least 25%' and 'Average Normalised Variability (ANV) greater than the mean'.

Constructs with above-average ANV scores indicate their importance to the people who mentioned them. The top 10 of these for each event type are listed in **Table 9**, ranked in order of their relative importance, inferred from their combined scores of %UF and ANV.

Table 9 – Relative importance of constructs for each Event Type

Ranking	Actual Incident	Near Miss	Potential Incident
1	Incident Investigation and Analysis (KEY)	Incident Investigation and Analysis (KEY)	Hazard Detection (KEY)
2	Vigilance	Hazard Detection	Compliance
3	Hazard Detection	Compliance	Incident Investigation and Analysis (KEY)
4	Mitigation	Vigilance	Procedures
5	Compliance	Procedures	Understanding of Risk
6	Risk Assessment	Work Pressure	Vigilance
7	Deference to Hierarchy	Deference to Hierarchy	Unique Occurrence
8	Work Pressure	Competence	Mitigation
9	Understanding of Risk	Emergency Response	Risk Assessment
10	Unique Occurrence	Understanding of Risk	Equipment Design

From **Table 9** the following observations can be made:

1. ‘Incident Investigation and Analysis’ is the only key construct associated with all event types
2. ‘Hazard Detection’ is a key construct only for Potential Incidents, but still important for the others
3. ‘Compliance’ and ‘Vigilance’ are important for all three event types
4. ‘Work Pressure’ and ‘Deference to Hierarchy’ are more strongly associated with Actual Incidents and Near Misses than with Potential Incidents
5. ‘Understanding of Risk’ is more strongly associated with Potential Incidents than with the other event types
6. ‘Procedures’ is more strongly associated with Near Misses and Potential Incidents than Actual Incidents

These observations are summarised in **Table 10**

Table 10 – Constructs seen as Key or Important (I) for each Event Type

Construct	Actual Incident	Near Miss	Potential Incident
Incident Investigation and Analysis	KEY	KEY	KEY
Hazard Detection	I	I	KEY
Compliance	I	I	I
Vigilance	I	I	I
Work Pressure	I	I	no
Deference to Hierarchy	I	I	no
Understanding of Risk	less	less	I
Procedures	no	I	I

Table 11 shows the construct %UF and ANV scores analysed for each Site, A, B and C.

Fig 4 shows the comparison graphically, the height of the bars representing combined score of %UF * ANV

Table 11 – Construct Frequency and Variability for each Site A, B and C

	Constructs	SITE A				SITE B				SITE C			
		%UF	>25	ANV	>35	%UF	>25	ANV	>39	%UF	>25	ANV	>46
1	WORK PRESSURE	**25**	Y	**37**	Y	8		**47**	Y	0		0	
2	PROCEDURES	**38**	Y	**35**	Y	15		32		0		0	
3	COMMUNICATION	19		28		0		0		0		0	
4	COMPLIANCE	19		**35**	Y	23		38		0		0	
5	COMPETENCE	13		22		8		30		0		0	
6	HAZARD DETECTION	13		33		**46**	Y	**39**	Y	**56**	Y	**48**	Y
7	UNDERSTANDING OF RISK	13		29		19		37		11		43	
8	VIGILANCE	**38**	Y	34		4		**50**	Y	**44**	Y	**55**	Y
9	DEFERENCE TO HIERARCHY	19		25		8		36		0		0	
10	SUPERVISION	13		**45**	Y	0		0		0		0	
11	INCIDENT INVESTIG. & ANALYSIS	0		0		**42**	Y	**39**	Y	22		0	
12	EMERGENCY RESPONSE	0		0		15		**40**	Y	11		40	
13	CHECKING, CHALLENGE & FOLLOW-UP	6		**48**	Y	0		0		0		0	
14	ORGANIZATIONAL LEARNING	0		0		4		36		**33**	Y	35	
15	EQUIPMENT DESIGN	19		25		4		**38**	Y	0		40	
16	UNIQUE OCCURRENCE	6		**58**	Y	8		**43**	Y	0		0	
17	MISTAKE	13		**39**	Y	0		0		0		0	
18	MITIGATION	0		0		12		**40**	Y	11		**60**	Y
19	RISK ASSESSMENT	19		34		8		**41**	Y	0		0	

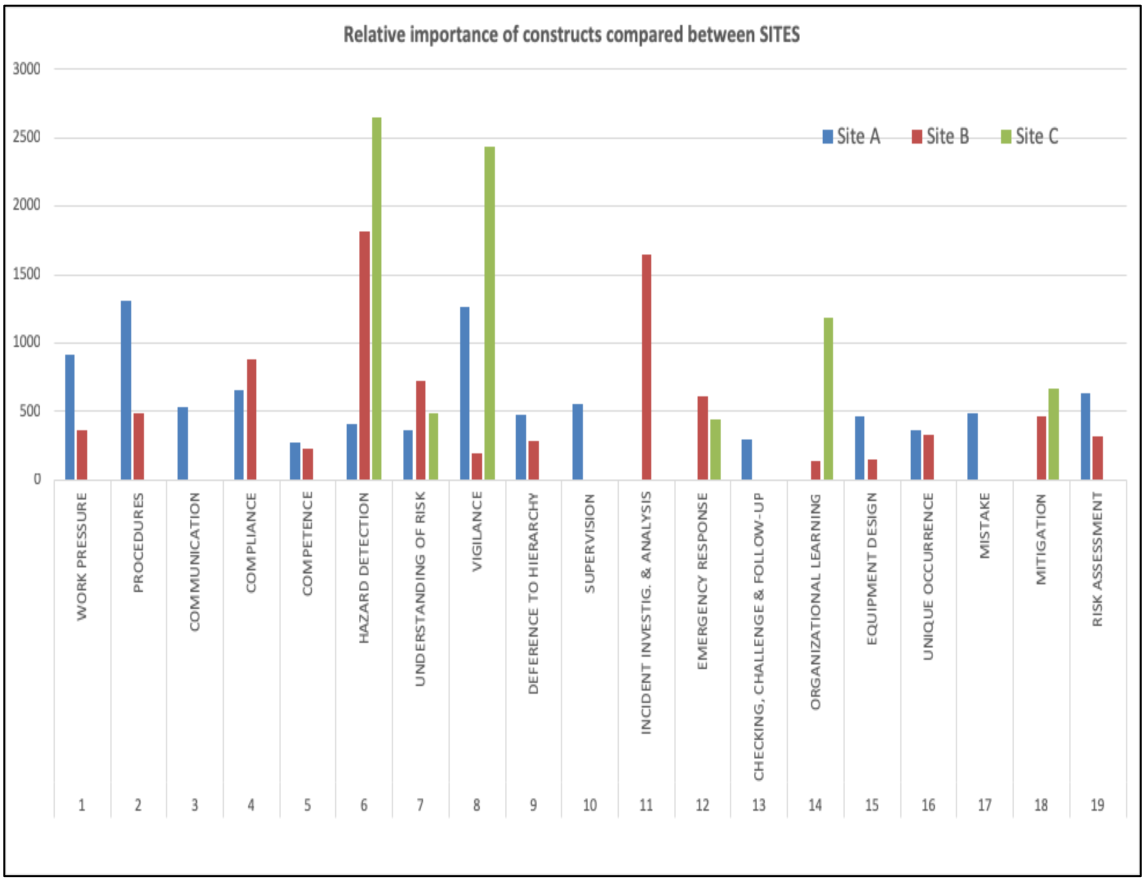

Fig 4 – Relative importance of constructs for each Site A, B and C

Table 12 lists the top 10 Constructs with above-average ANV scores for each Site, A, B and C, ranked in order of their relative importance, inferred from their combined scores of %UF and ANV.

Table 12 – Relative importance of constructs for each Site, A, B and C

Ranking	Site A	Site B	Site C
1	Procedures (KEY)	Hazard Detection (KEY)	Hazard Detection (KEY)
2	Vigilance (KEY)	Incident Investigation and Analysis (KEY)	Vigilance (KEY)
3	Work Pressure	Compliance	Organizational Learning
4	Compliance	Understanding of Risk	Mitigation
5	Risk Assessment	Emergency Response	Understanding of Risk
6	Supervision	Procedures	
7	Communication	Mitigation	
8	Mistake	Work Pressure	
9	Deference to Hierarchy	Unique Occurrence	
10	Equipment Design	Risk Assessment	

From **Table 12** the following observations can be made:

1. 'Hazard Detection' (key construct) 'Mitigation' and 'Understanding of Risk are all seen as important for Sites B and C but none of these are in the top 10 for Site A
2. 'Incident Investigation and Analysis' is a key construct for Site B but is not in the top 10 for Sites A and C
3. 'Vigilance' is a key construct for Sites A and C but is not mentioned in the top 10 for Site B
4. 'Procedures' is a key construct for Site A but is not mentioned in the top 10 for Sites B and C
5. 'Organizational Learning' is seen as important for Site C but not for Sites A and B
6. 'Compliance' and 'Work Pressure' are both seen as important for Sites A and B but not for Site C
7. 'Deference to Hierarchy' is seen as important for Site A but not for Sites B and C

These observations are summarised in **Table 13**

Table 13 – Constructs seen as Key or Important (I) for each Site

Construct	Site A	Site B	Site C
Hazard Detection	no	KEY	KEY
Incident Investigation and Analysis	no	KEY	no
Vigilance	KEY	no	KEY
Procedures	KEY	no	no
Organizational Learning	no	no	KEY
Mitigation	no	I	I
Understanding of Risk	no	I	I
Compliance	I	I	no
Work Pressure	I	I	no
Deference to Hierarchy	I	no	no

General observations on the results

'Work Pressure' and 'Deference to Hierarchy' associated with Actual Incidents and Near Misses but not with Potential Incidents; 'Work Pressure' is also seen as important for Site A and B but not for Site C. Thus neither Site C nor Potential Incidents have any association with 'Work Pressure'. Work Pressure also scores very highly at Site B on importance to individuals, as measured by ANV, even though the UF is low. This may indicate that Work Pressure is unevenly distributed at Site B, which is a multiple-location operation, but it is seen as very important where it occurs. By contrast, 'Organizational Learning' is seen as important only for Site C, and does not appear in the top 10 constructs for either Site A or Site B.

Finally, 'Hazard Detection' and 'Incident Investigation and Analysis' are the two key constructs for Site B. This aligns with the content of interviews, in which numerous different incidents were discussed that involved difficulties with detection due to their remote location and unmanned operation, with a range of approaches to investigation from a simple local 'technical fix' to a very thorough multi-disciplinary deep causal analysis.

5. DISCUSSION

The twin aims of this study were to gain insights about (Ref Research Question 1) how people working directly with high hazard technology construe the circumstances of the three types of process safety events, actual incidents, near misses and potential incidents, and (Ref Research Question 2) how the interplay and tensions between rule-following and adaptive practice figure in this.

Responding to the first question, 19 validated constructs were obtained from 51 repertory grid interviews (Kelly, 1955) at three operational oil and gas and petrochemical sites with different characters but using similar technology and operated by the same multinational organization.

The sites were at different stages of organizational maturity and had different levels of safety performance. Site A, a large recently-constructed petrochemical site in the Middle East, had a mixed safety performance, Site B, a rapidly-developing onshore oil and gas production operation in Asia Pacific with a large number of geographically-dispersed production units and a large central treatment and export plant, had a process safety performance giving caused for concern, and Site C, a mature offshore oil and gas production operation in Europe, had an above-average award-winning process safety performance.

The relative importance of these constructs for the interviewees was analysed, to compare between type of process safety event and between the three sites. Of the 19 constructs, those that emerged as yielding most insight were those with significant differences in these comparisons.

Two striking observations are that Work Pressure and were associated with Actual Incidents and Near Misses, but not with Potential Incidents, and also that Work Pressure was associated with Sites A and B, but not with Site C. Since as discussed earlier, the identification and correction of Potential Incidents can be seen as an HRO or 'Safety II' practice, and noting that Site C had an above-average safety performance, comparing well with the other two sites, this indicates a negative influence on process safety of Work Pressure and Deference to Hierarchy.

Two other observations that appear complementary are that Organizational Learning was associated with Site C, but not with Sites A and B, and that Understanding of Risk was more strongly associated with Potential Incidents than the other event types, so these two constructs can be seen as having a positive influence on process safety.

The constructs that emerged as important for Site C were Hazard Detection, Vigilance, Organizational Learning, Mitigation and Understanding of Risk. This set of constructs is interesting, as this site had an above-average process safety record and was seen as an exemplar in the company. The interviews at Site C also described a stable, mature organization with a marked open culture of mutual respect within the hierarchy and a strong emphasis on both process safety and personal safety; there was an active practice of reviewing process safety events of all three types with a focus on learning and follow-up.

An interesting similarity that emerged from the comparisons was that Compliance, Hazard Detection, Vigilance and Incident Investigation and Analysis were all strongly associated with all three process safety event types. Compliance and Incident Investigation and Analysis are representative of rule-following and administrative practices; Hazard Detection and Vigilance are more representative of mindfulness.

Responding to the second question, the consistent view of the importance of both these pairs of constructs to the interviewees appears to support the general proposition discussed in the Theoretical Background that both administrative (Safety I) and adaptive practices (Safety II) are important for process safety (Hollnagel, 2014; Leveson, 2013).

This study provides some insight into how rule-following and adaptive practices are perceived by people working directly with high hazard technology. Although both approaches can be seen as contributing to process safety, the adaptive practices of organizational learning and understanding of risk were seen to be associated significantly more closely with the better process safety outcomes of potential incident rather than actual incidents and near misses, while a negative influence on process safety outcomes was construed in the form of work pressure and deference to hierarchy.

5.1. Limitations of the research

Although the access to interview people working directly with high hazard technology was much valued and appreciated by the researchers, inevitable restrictions on time and availability of people limited the scope and opportunities for data collection. It is acknowledged that limitations on the research include some missing data points in some repertory grids, some doubtful distinction between the types of event by some interviewees, a small average number of constructs that were obtained per interview, and that the number of interviews at the three sites was not well-balanced. It is also acknowledged that although the characteristics of the three sites is described fairly, more complete data about process safety outcomes and culture at the three sites would have been useful.

6. CONCLUSIONS

The results of this empirical study provide some insight into how rule-following and adaptive practices are perceived by people working directly with high hazard technology. It has found evidence that people at the operational sharp-end of high-hazard technology in the oil & gas and petrochemical industry see both administrative practices such as compliance with procedures and investigation of incidents and also mindful, adaptive practices such as vigilance, hazard detection, understanding of risk and organizational learning are important for process safety.

Although both approaches can be seen as contributing to process safety, the adaptive practices of organizational learning and understanding of risk were seen to be associated significantly more closely with the better process safety outcomes of potential incident rather than actual incidents and near misses, while a negative influence on process safety outcomes was construed in the form of work pressure and deference to hierarchy.

These observations support the theory that the safe operation of high hazard technology relies on both engineering and rule-following and adaptive processes such as sensemaking, mindfulness and expert improvisation as described in the theories of HRO (Weick, Sutcliffe and Obstfeld, 1999) system safety (Leveson, 2004) and Safety II (Hollnagel, 2014).

The study has not investigated the mechanisms by which these two paradoxically different approaches are entangled successfully in practice. This is an area of much research interest, embracing the fields of organizational ambidexterity, culture and leadership, which will be explored in future research.

6.1. Implications for process safety practitioners

This study identifies four clear implications for practice within organizations operating high hazard technology:

1. Emphasise mindful compliance with written procedures, encouraging questioning and improvement, avoiding mindless compliance
2. Encourage hazard detection, vigilance, and understanding of risk and mitigation measures
3. Emphasise organizational learning from potential incidents, rather than actual incidents and near misses
4. Avoid negative influences on process safety from work pressure and deference to hierarchy

7. REFERENCES

Ashby, W.R. (1958) 'Requisite Variety and Its Implications for the Control of Complex Systems', *Facets of Systems Science*, , pp. 405–417.

Bea, R.G. (1998) 'Human and organization factors: Engineering operating safety into offshore structures', *Reliability Engineering and System Safety*, 61(1–2), pp. 109–126.

Center for Chemical Process Safety and Energy Institute (2018) *Bow Ties in Risk Management*. Wiley.

Clay-Williams, R., Hounsgaard, J. and Hollnagel, E. (2015) 'Where the rubber meets the road: Using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines', *Implementation Science*, 10(1) Implementation Science, pp. 1–8.

Dekker, S. (2011) 'The criminalization of human error in aviation and healthcare: A review', *Safety Science*, 49(2) Elsevier Ltd, pp. 121–127.

Dekker, S. (2003) 'Failure to adapt or adaptations that fail: Contrasting models on procedures and safety', *Applied Ergonomics*, 34(3), pp. 233–238.

Dekker, S., Cilliers, P. and Hofmeyr, J.H. (2011) 'The complexity of failure: Implications of complexity theory for safety investigations', *Safety Science*, 49(6) Elsevier Ltd, pp. 939–945.

Dekker, S. and Pruchnicki, S. (2013) 'Drifting into failure: theorising the dynamics of disaster incubation', *Theoretical Issues in Ergonomics Science*, (March 2015), pp. 1–11.

Denyer, D. and Sibbick, G. (2015) 'Towards a High Reliability Organization at CSL', in Denyer, D. and Pilbeam, C. (eds.) *Managing Change in Extreme Contexts*. Routledge.

Endsley, M.R. (1999) 'Situation Awareness and Human Error : Designing to Support Human Performance', *High Consequence Systems Surety Conference*.

Endsley, M.R. (1995) 'Toward a Theory of Situation Awareness in Dynamic Systems.pdf', *Human Factors*, , pp. 32–64.

English, D. and Branaghan, R.J. (2012) 'An empirically derived taxonomy of pilot violation behavior', *Safety Science*, 50(2) Elsevier Ltd, pp. 199–209.

European Commission (2012) Seveso-III *European Commission*.

Flin, R., Wilkinson, J. and Agnew, C. (2014) '*Crew Resource Management for Well Operations teams*', (501), pp. 1–34.

Fruhen, L.S., Flin, R.H. and McLeod, R. (2014) 'Chronic unease for safety in managers: A conceptualisation', *Journal of Risk Research*, 17(8), pp. 969–979.

Goffin, K. (2002) 'Repertory Grid Technique', in Partington, D. (ed.) *Essential Skills for Management Research*. Sage Publications.

Goffin, K. and Koners, U. (2011) 'Tacit knowledge, lessons learnt, and new product development', *Journal of Product Innovation Management*, 28(2), pp. 300–318.

Goffin, K., Lemke, F. and Szwejczewski, M. (2006) 'An exploratory study of "close" supplier-manufacturer relationships', *Journal of Operations Management*, 24(2), pp. 189–209.

Goffin, K., Raja, J.Z., Claes, B., Szwejczewski, M. and Martinez, V. (2012) 'Rigor in qualitative supply chain management research', *International Journal of Physical Distribution & Logistics Management*, 42(8/9), pp. 804–827.

Green et al (1996) *Human Factors for Pilots*. Ashgate Publishing Limited.

Grice, J.W. (2004) 'Bridging the Idiographic-Nomothetic Divide in Ratings of Self and Others on the Big Five', *Journal of Personality*, 72(2), pp. 203–241.

Hale, A. and Borys, D. (2013) ‘Working to rule, or working safely? Part 1: A state of the art review’, *Safety Science*, 55, pp. 207–221.

Helmreich, R.L. (2000) ‘On error management: lessons from aviation.’, *BMJ (Clinical research ed.)*, 320(7237), pp. 781–5.

Helmreich, R.L., Merritt, a C. and Wilhelm, J. a (1999) ‘The evolution of Crew Resource Management training in commercial aviation.’, *The International journal of aviation psychology*, 9(1), pp. 19–32.

Hollnagel, E. (2014) *Safety-I and Safety-II*. Ashgate Publishing Limited.

Hollnagel, E., Woods, D.D. and Leveson, N. (2006) *Resilience Engineering: Concepts and Precepts*. Ashgate Publishing Limited. Available at: http://www.amazon.co.uk/Resilience-Engineering-Concepts-Erik-Hollnagel/dp/0754649040 (Accessed: 17 December 2012).

Hopkins, A. (2009) *Learning from high reliability organisations*. CCH Australia. Available at: http://books.google.com/books?id=1bCjwxn8n20C&pgis=1 (Accessed: 17 December 2012).

Hudson, P. (1999) ‘Safety Culture-Theory and Practice’, *RTO HEM Workshop on "The Human Factor in System Reliability - Is Human Performance Predictable? "*

IPIECA and OGP (2014) ‘*Operating Management System Framework*’, (OGP Report No. 510), p. 44.

Jankowicz, D. (2004) *The Easy Guide to Repertory Grids*. Wiley.

Kelly, G. (1955) *The psychology of personal constructs. Vol. 1. A theory of personality. Vol. 2. Clinical diagnosis and psychotherapy*. Oxford: Norton.

Lemke, F., Clark,M. and Wilson, H. (2011) ‘Customer Experience Quality: An exploration in business and consumer contexts using repertory grid technique’, *Journal of the Academy ofMarketing Science*, 39, p. 55.

Leveson, N. (2004) ‘A new accident model for engineering safer systems’, *Safety Science*, 42(4), pp. 237–270.

Leveson, N. (2013) Engineering a Safer World *Engineering*.

Leveson, N., Dulac, N., Marais, K. and Carroll, J. (2009a) ‘Moving Beyond Normal Accidents and High Reliability Organizations: A Systems Approach to Safety in Complex Systems’, *Organization Studies*, 30(2–3), pp. 227–249. Available at: 10.1177/0170840608101478 (Accessed: 27 October 2012).

Leveson, N., Dulac, N., Marais, K. and Carroll, J. (2009b) ‘Moving Beyond Normal Accidents and High Reliability Organizations: A Systems Approach to Safety in Complex Systems’, *Organization Studies*, 30, pp. 227–249.

Levy, M., Pliskin, N. and Ravid, G. (2010) ‘Studying decision processes via a knowledge management lens: The Columbia space shuttle case’, *Decision Support Systems*, 48(4) Elsevier B.V., pp. 559–567.

Marais, K., Dulac, N. and Leveson, N. (2004) ‘*Beyond Normal Accidents and High Reliability Organizations : The Need for an Alternative Approach to Safety in Complex*’, , pp. 1–16.

Meshkati, N. (1991) ‘Human factors in large-scale technological systems’ accidents: Three Mile Island, Bhopal, Chernobyl’, *Organization & Environment*

Micheli, P., Jaina, J., Goffin, K., Lemke, F. and Verganti, R. (2012) ‘Perceptions of industrial design: The “means” and the “ends”’, *Journal of Product Innovation Management*, 29(5), pp. 687–704.

Miles and Huberman (1994) *Qualitative Data Analysis*.2nd Editio. Sage Publications.

Parker, D., Lawrie, M. and Hudson, P. (2006) ‘A framework for understanding the development of organisational safety culture’, *Safety Science*, 44(6), pp. 551–562. Available at: 10.1016/j.ssci.2005.10.004 (Accessed: 29 November 2012).

Perrow, C. (1984) *Normal accidents: living with high-risk technologies*. Basic Books. Available at: http://books.google.com/books?id=N3hRAAAAMAAJ&pgis=1 (Accessed: 17 December 2012).

Phipps, D.L. and Parker, D. (2014) ‘A naturalistic decision-making perspective on anaesthetists’ rule-related behaviour’, *Cognition, Technology & Work*, 16(4), pp. 519–529.

La Porte, T.R. (1996) High Reliability Organizations: Unlikely, Demanding and At Risk. *Journal of Contingencies & Crisis Management*.

La Porte, T.R. and Rochlin, G.I. (1994) A rejoinder to Perrow *Journal of Contingencies and Crisis Management*.

Raja, J.Z., Bourne, D., Goffin, K., Çakkol, M. and Martinez, V. (2013) ‘Achieving customer satisfaction through integrated products and services: An exploratory study’, *Journal of Product Innovation Management*, 30(6), pp. 1128–1144.

Rasmussen, J. (1997) ‘Risk management in a dynamic society - A modelling problem.pdf’, *Safety Science*, 27(2–3), pp. 183–213.

Reason, J. (1990) *Human error.*, *Cambridge University Press* Available at: https://extranet.cranfield.ac.uk/ehost/detail/,DanaInfo=web.b.ebscohost.com+detail?vid=22&sid=428f8c8f-da8f-4b3f-9a1e-0aa652511cd9%40sessionmgr113&hid=102&bdata=JnNpdGU9ZWhvc3QtbGl2ZQ%3D%3D#db=psyh&AN=1991-97559-000 (Accessed: 29 April 2015).

Reason, J. (2008) *The Human Contribution*. Ashgate Publishing Limited.

Reason, J. (1998) ‘Achieving a safe culture: Theory and practice’, *Work & Stress*, 12(3), pp. 293–306.

Reason, J.T. (1997) *Managing the risks of organizational accidents*. Ashgate. Available at: http://books.google.com/books?id=ZnhRAAAAMAAJ&pgis=1 (Accessed: 17 December 2012).

Rego, L. and Garau, R. (2007) ‘Stepping into the Void’, *Center for Creative Leadership*, (May), p. 69.

Roberts, K.H. (1990) ‘Some Characteristics of One Type of High Reliability Organization’, *Organization Science*, 1(2), pp. 160–176.

Roberts, K.H., Rousseau, D.M. and La Porte, T.R. (1994) ‘The culture of high reliability: quantitative and qualitative assessment aboard nuclear-powered aircraft carriers’, *The Journal of High Technology Management Research*, 5(1), pp. 141–161.

Rochlin, G.I. (2011) ‘How to Hunt a Very Reliable Organization’, *Journal of Contingencies and Crisis Management*, 19(1), pp. 14–20.

Sagan, S.D. (2004) ‘The problem of redundancy problem: why more nuclear security forces may produce less nuclear security.’, *Risk analysis : an official publication of the Society for Risk Analysis*, 24(4), pp. 935–46.

Sagan, S.D. (1995) *The Limits of Safety: Organizations, Accidents, and Nuclear Weapons*. Princeton University Press. Available at: http://books.google.com/books?id=4pV_wbOnphsC&pgis=1 (Accessed: 17 December 2012).

Shrivastava, P. (1985) The Lessons of Bhopal, *Business and Society Review*,

Snowden, D.J. and Boone, M.E. (2007) ‘A Leader ’ s Framework for Decision Making A Leader ’ s Framework for Decision Making’, *Harvard Business Review*, 85, pp. 68–76, 149.

Spurgin, A. (2010) *Human Reliability Assessment*. CRC Press.

Summers, A., Vogtmann, W. and Smolen, S. (2011) 'Improving PHA/LOPA by consistent consequence severity estimation', *Journal of Loss Prevention in the Process Industries*, 24(6) Elsevier Ltd, pp. 879–885.

Sutcliffe, K.M. (2011) 'High reliability organizations (HROs)', *Best Practice and Research: Clinical Anaesthesiology*, 25(2) Elsevier Ltd, pp. 133–144.

Taleb, N.N. (2007) 'Black Swans and the domains of statistics', *American Statistician*, 61(3), pp. 198–200.

Tan, F.B. and Hunter, M.G. (2002) 'The Repertory Grid Technique: A Method for the Study of Cognition in Information Systems', *MIS Quarterly*, 26(1), p. 39.

UKHSE (2005) '*Offshore Installations (Safety Case) Regulations 2005 (SCR05)*'

Vaughan, D. (1997) 'The Trickle-Down Effect: POLICY DECISIONS, RISKY WORK, AND THE CHALLENGER TRAGEDY', *California Management Review*, 39(2)

Vogus, T.J. and Sutcliffe, K.M. (2012) 'Organizational mindfulness and mindful organizing: A reconciliation and path forward', *Academy of Management Learning and Education*, 11(4), pp. 722–735.

Weick, K.E. (1987) 'Organizational Culture as a Source of High Reliability', *California Management Review*, 29(2), pp. 112–127.

Weick, K.E. and Sutcliffe, K.M. (2006) 'Mindfulness and the Quality of Organizational Attention', *Organization Science*, 17(4), pp. 514–524. Available at: 10.1287/orsc.1060.0196 (Accessed: 26 October 2012).

Weick, K.E. and Sutcliffe, K.M. (2001) *Managing the unexpected: assuring high performance in an age of complexity*. Jossey-Bass. Available at: http://books.google.com/books?id=Q94OAQAAMAAJ&pgis=1 (Accessed: 20 December 2012).

Weick, K.E., Sutcliffe, K.M. and Obstfeld, D. (2005) 'Organizing and the Process of Sensemaking', *Organization Science*, 16(4), pp. 409–421. Available at: 10.1287/orsc.1050.0133 (Accessed: 30 October 2012).

Weick, K.E., Sutcliffe, K.M. and Obstfeld, D. (1999) 'Organizing for High Reliability: Processes of Collective Mindfulness', in *Research in Organizational Behavior, Volume 1.* , pp. 81–123.

Weick, K.E.S.O. (2000) 'High Reliability : The Power of Mindfulness', *Leader to Leader*, , pp. 33–39.

Woods, D. (2003) *Creating Foresight : How Resilience Engineering Can Transform NASA ' s Approach to Risky Decision Making*,

Woods, D. (2006) 'Engineering Organizational Resilience to Enhance Safety: A Progress Report on the Emerging Field of Resilience Engineering', *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 50(19), pp. 2237–2241. Available at: 10.1177/154193120605001910 (Accessed: 16 December 2012).

Woods, D.D. and Shattuck, L.G. (2000) 'Distant Supervision–Local Action Given the Potential for Surprise', *Cognition, Technology & Work*, 2(4), pp. 242–245.