**Cognitive Processes**

# Identification of the Human Factors Contributing to Maintenance Failures in a Petroleum Operation

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**Précis/Short Abstract:** Structured interviews used the Human Factors Investigation Tool to identify the most frequently occurring factors in 38 maintenance-related failures in a petroleum organisation. The three most frequent human factors contributing to the maintenance failures were found to be incorrect assumptions, communication, and the design of equipment and plant for maintainability.

**Objective:** This research aimed to identify the most-frequently occurring human factors contributing to maintenance-related failures within a petroleum industry organisation. Commonality between failures will assist in understanding reliability in maintenance processes thereby preventing accidents in high-hazard domains.

**Background:** Methods exist for understanding the human factors contributing to accidents. Their application in a maintenance context has been most advanced in aviation and nuclear power. Maintenance in the petroleum industry provides a different context for investigating the role that human factors play in influencing outcomes. It is therefore worth investigating the contributing human factors to improve our understanding of both human factors in reliability, and the factors specific to this domain.

**Method:** Detailed analyses were conducted of maintenance-related failures (N=38) in a petroleum company using structured interviews with maintenance technicians. The interview structure was based on the Human Factor Investigation Tool (HFIT) which in turn was based on Rasmussen's Model of Human Malfunction.

**Results:** A mean of 9.5 factors per incident were identified across the cases investigated. The three most frequent human factors contributing to the maintenance failures were found to be *Assumption* (79% of cases), *Design & Maintenance* (71%) and *Communication* (66%).

**Conclusion:** HFIT proved to be a useful instrument for identifying the pattern of human factors that recurred most frequently in maintenance-related failures. The high frequency of failures attributed to assumptions and communication demonstrated the importance of problem-solving abilities and organisational communication in a domain where maintenance personnel have a high degree of autonomy and a wide geographical distribution.

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**Running Head:** Human Factors in Maintenance Failures

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# INTRODUCTION

## Human Factors in Maintenance Failures

The consequences of poor reliability in maintenance operations can be as simple as delayed production, or as severe as the loss of many lives. Serious accidents, such as the Bhopal Chemical plant explosion (Pidgeon & O'Leary, 2000) are frequently attributed to failures in maintenance processes (Reason & Hobbs, 2003). Attempts to improve maintenance processes and ensure operational reliability are generally focussed on technical factors (International Standards Organization, 2006). However, the role of human factors in technical failures, particularly those involving hazardous technology, is increasingly recognised by both technical (Bea, 1998) and organisational (Heimann, 2005) specialists. For example, in the Piper Alpha disaster in which 167 lives and $3 billion were lost, Pate-Cornell (1993) attributed the failure to "inexperience, poor maintenance procedures and deficient learning mechanisms" (p.232).

In researching the human factors in maintenance-related failures, Hobbs & Williamson (2003) focussed on the role of human error, and Reason, Parker, & Lawton (1998) suggested violations of workplace procedures, as the root cause of failure. Both human error and rule violations are frequent themes in human factors research. However, Reinach & Viale (2006) described the changes taking place in conceptual frameworks with a recognition of the influence of a larger array of organisational processes in the workplace. Examples of these other processes have been included in studies of communication failures in rail maintenance (Holmgren, 2005), decision-making in nuclear power plants (Carvalho, dos Santos, & Vidal, 2005), problem-solving in hospital systems (Tucker, Edmondson, & Spear, 2002) and teamwork in petroleum industry drilling teams (Crichton, 2005). This broader approach aligns with Rasmussen's (1982; Rasmussen et al., 1981) development of a Model of Human Malfunction. In this model, Rasmussen recognised the impact of the internal cognitive elements of human malfunction, such as acquiring information, assessing situations, and deciding how to proceed, all of which were deemed critical in maintenance tasks by Oedewald & Reiman (2003). The model also recognised the role of elements of the external work environment, namely *Performance Shaping Factors* (PSFs) that influence, at different levels, the way that humans perform. Such a multi-level approach to workplace processes was extensively developed by Zohar & Luria (2005) in their considerations of industrial safety and reliability. Their theoretical approach was to posit that influences on safety behaviour could reside at any of the three hierarchical levels within the work environment, namely the individual, the workgroup, or the organisation. An analysis of the role of human factors on performance then proceeds from consideration of the contribution at each of these organisational levels.

One approach to identifying the contributors to failures from among the many PSFs has been through the development of domain-specific investigation methods. These have been developed to identify the human factors responsible for incidents that influence operational reliability, such as maintenance failures within a particular type of workplace. Dekker (2003) advocated understanding "how universal patterns of breakdown occur repeatedly across operational particulars" (p.104). In this way, the most frequent factors contributing to operational failures can be identified and corrected, particularly in high-hazard workplaces. O'Leary (2002) described these human factors investigation methods in the aviation domain, while Suksi (2004) described incident analysis in the nuclear power context. Both investigation methods are based on taxonomy that evolved out of a framework for observing and understanding human-task interactions in their particular domain (Ross, Wallace, & Davies, 2004). For the petroleum industry, Gordon et al (2000) developed the *Human Factors Investigation Tool* (HFIT) which adopts a frame of reference based on Rasmussen's Model of Human Malfunction.

**The context of this study – the petroleum industry**

Petroleum production facilities are complex, technologically-advanced, and highly-hazardous in terms of the potential for severe injuries, substantial financial losses, and environmental disasters. As such, they need to be what Vogus & Welbourne (2003) describe as reliability-seeking organisations. However, compared to other industries, i.e., commercial aviation and nuclear power plants operations, petroleum production has not been as thoroughly researched in terms of the role of human factors in ensuring reliability. This may be partly due to petroleum operations being less-proceduralised and more widely-distributed geographically than nuclear power plants or aviation maintenance operations. In his analysis of the Deepwater Horizon explosion, Urbina (2010) noted that activities in the petroleum industry are often loosely regulated, and that companies and individuals have tended to operate autonomously. He quoted Professor Tad Patzek of the Petroleum and Geosystems Engineering Department at the University of Texas, Austin, who commented in relation to Deepwater Horizon, "It's a very complex operation in which the human element has not been aligned with the complexity of the system."

In this less-regulated context, different performance shaping factors may be more significant than in highly-regulated domains. Petroleum processing was therefore identified as a suitable environment for studying the impact of human factors on maintenance reliability in a setting where activities are less-specified. The tight couplings and interdependencies of humans and complex technology have been similarly recognised by Øien (2001a; 2001b) as risk factors in research into petroleum operations. As a consequence of the concern with management of the safety of workers, research on leadership (Crichton, 2005) and decision-making (O'Dea & Flin, 2001) have tended to predominate over consideration of other human factors, such as communication, problem-solving behaviour, and organisational learning, which may be equally relevant. Research into a broader range of factors is warranted to provide guidance for future interventions aimed at improving reliability. For these interventions to be effective, it is important that they be targeted towards risk factors specific to the petroleum industry (Sklet, 2006), rather than towards generic factors which are presumed to influence all organisational outcomes, irrespective of the domain.

The aim of the current study was to investigate the recurring human factors contributing to unsuccessful maintenance processes in the petroleum industry. This was intended to expand our understanding of the influence of PSFs on operational reliability in the petroleum industry, and other similar maintenance environments in which workers have a higher degree of discretion in determining how work is to be done, and where there is a greater range of acceptable practice and more individual responsibility for interpretation of information and decision-making.

## METHOD

### Research Setting

The research setting for this study was the production facilities of a major producer of oil and gas. The organisation under study operates three distinct types of production facility, namely, 1) gas platforms, 2) floating production, storage, and off-take (FPSO) vessels, and 3) gas processing plants.

### Participants

A cohort (N=38) of experienced instrumentation/electrical and mechanical maintenance personnel were interviewed for this study.  All participants were over the age of 18 years old and all participated voluntarily.  The demographic distribution of participants involved is provided in Table 1, and compared to overall data for operational personnel employed by the company.

Participants included maintenance technicians, coordinator/ planners, and supervisors.  Maintenance personnel generally fall into two distinct categories, namely facility-based Core Crew and fly-in/fly-out Major Maintenance crew, responsible for assisting during shutdowns.  Core Crews are employed at a particular facility, either on a full-time basis in the case of the on-shore Process Plant or on a fly-in/fly-out roster on the off-shore facilities.  Major Maintenance crews are based at the company's headquarters and are sent to off-shore facilities when large maintenance projects or plant shutdowns are undertaken.

**Table 1. Distribution of participants in interviews.**

| Demographic | Type of Interviewee | Number of Interviews | % of Interviews | Organisational Data (%) [a] |
|---|---|---|---|---|
| Position | Maintenance Technician | 21 | 55.3 | 81.0 |
| | Maintenance Coordinator | 11 | 28.9 | 13.9 |
| | Maintenance Supervisor | 6 | 15.8 | 5.1 |
| Workgroup Type | Core Crew (Off-shore) | 12 | 31.6 | 60.2 |
| | Core Crew (Process Plant) | 11 | 28.9 | 33.7 |
| | Major Maintenance /Shutdown | 15 | 39.5 | 6.0 |
| Gender | Male | 38 | 100 | 97 |
| | Female | 0 | 0 | 3 |

[a] Based on overall operational staffing levels

**The Investigation Instrument**

In order to understand the mechanisms of failures, a suitable taxonomy was required to categorise the human factors contributing to each of the failures investigated. A taxonomy provides a basis for understanding the mechanisms expected in the particular domain being investigated. Since Rasmussen described his Human Malfunction model in 1982, many researchers (e.g., Reinach & Viale, 2006; Hobbs & Williamson, 2002; Gordon, Flin, & Mearns, 2005) have made use of this model to investigate the role of human factors in failures of safety and reliability. Rasmussen et al (1981) provided advice on how research might quantify the contributors to failure:

> To be able to quantify the frequency of inappropriate human acts in a meaningful way, it is necessary to separate cases of intrinsic human variability and spontaneous human errors from cases of psychologically normal human reactions to external events or changes in the work situation, This means that a simple classification of human errors with reference to the task sequence in terms of omission, commission, timing errors etc. is not adequate. Careful efforts

> should be spent to identify potential external causes with reference to categories which allow estimates of frequencies in another particular situation. (p. 5)

One approach to determining the predominant contributors to accidents has been through the development of investigation methodologies for characterising the human factors responsible for reliability-related incidents, such as maintenance failures. A number of taxonomies have been developed which are generally domain-specific or purpose specific, for example,

- British Airways' Human Factor Reporting Programme (O'Leary, 2002)
- U.S. Department of Energy's (1999) Accident Investigation Program for nuclear power plant investigations, and
- Human Error Reduction in Air Traffic Management (HERA) and JANUS techniques (Pounds & Isaac, 2003) developed for air traffic management.

The taxonomy for the current research needed to be consistent with the framework of a petroleum production environment, while capturing the various workplace behaviours related to desired maintenance outcomes (Ross, Wallace, & Davies, 2004). The Human Factors Investigation Tool (HFIT) was developed for the North Sea petroleum industry (Gordon, Mearns, & Flin, 2000), but with broad potential applicability across different industries. As such it was relevant to the potential contributors to failure in the context of this investigation.

HFIT is also a comprehensive human factors accident investigation instrument (Gordon, 2001), developed in an effort to utilise the elements of Rasmussen's Human Malfunction model. It integrates other applicable elements, found in existing investigation taxonomies, into an appropriate investigation tool for the offshore petroleum industry (Gordon, 1998). With HFIT, the developers succeeded in translating a number of theoretical constructs of human factors into a practical instrument for conducting detailed investigations into failures and accidents. It was intended for use by engineers and other investigators in the petroleum industry, who would have varying degrees of expertise in human factors. This is in contrast to the other investigation tools listed above which were designed for use by human factors specialists in their respective fields.

A further strength of HFIT lies in adopting a multi-level approach to analysing the factors associated with failures). Such a multi-level approach to workplace factors is supported by Zohar and Luria's (2005) research into industrial safety. Their hypothesis was that safety drivers can reside at any of the three organisational levels within the work environment, namely the individual, the workgroup, or the organisational level. An accident analysis then proceeds from consideration of the contribution of each of these levels. Similarly, HFIT is structured in such a way as to allow an analysis of the individual, workgroup, and organisational contributors to a failure under investigation.

The instrument uses a guided interview format to determine which of 27 major factors relating to action errors, situation awareness, and organisational threats have contributed to an adverse event. HFIT relies on a series of sub-factor questions to determine if a particular factor contributed to the failure under investigation. For example, the question, "Did you think that you were using the correct procedures?" is one of several used to determine if the factor Assumption was present.

HFIT has been trialled on failures and accidents in the petroleum industry, and reliability testing was conducted on the trial results (Gordon, Flin, & Mearns, 2005). A weakness of HFIT is that the reported inter-rater reliability (IRR) was low (i.e.. $rwg < 0.25$) for several of the items in the instrument. This may be related to the design of the instrument for, and the subsequent trial with, non-specialists in human factors, such as engineers and failure investigators. Wallace and Ross (2006) explained that a danger in the use of taxonomic systems to categorise human errors is that low inter-rater reliabilities can occur due to differing frames of reference, either between raters with differing backgrounds, or between a rater and the developer of the taxonomy. Additionally, Gordon et al (2005) considered that the inter-rater reliability of HFIT was "not unexpected, since the investigators had only minimal training and practice using the tool. In addition, the accident scenarios were very simple with regard to the amount of detail given and the inability of the investigators to ask further questions of the people involved in the incident" (p.162).

To assess and improve inter-rater reliability in the present study a sample of the initial interviews was coded independently by two coders with human factors expertise. The two coders then reviewed differences in coding to identify the potential for mis-coding. No differences were found at the main category level, but discrepancies were identified in a limited number of factors at the code level. On that basis, modifications were made to HFIT to lessen the potential for mis-coding. A second sample was then coded, and only minor differences were found, which were also clarified by discussion. A random sample of 10% of the remaining interviews were then coded by the 2nd coder to confirm the consistency of the coding process. A frequency analysis demonstrated the consistency of the overall process.

Based on the outcome of the review process involving two independent coders described above, modifications were made to HFIT to remove ambiguities and lessen potential for disagreement. This involved a detailed review of the naming of codes and differentiation between codes in HFIT. Several ambiguities in the taxonomy were identified that could have contributed to low inter-rater reliability observed by Gordon et al (2005). Modification of the tool was deemed necessary both to improve the consistency in assessing failures, as well as to increase the applicability of questions used to the context of this research. As a consequence, the following modifications were made to the format and use of HFIT:

- Naming of codes. Table 2 provides a list of the HFIT codes pertaining to each of the major categories. Several of the top-level codes were renamed to better reflect the sub-factor questions used in HFIT. For example, Communication appears twice, both as an Action Error and again as an Organisational Threat. Communication Errors in the Action Error category was therefore renamed Information, as most of the questions in this item concern the quality of information supplied. The code for Communication then refers only to the item questions on flawed communication processes listed in Organisational Threats. Plant, Parts, Tools, and Equipment was renamed Design & Maintenance, as plant design and maintenance condition are the two principal lines of questioning, and to better distinguish this code from Human-Machine Interfacing, which includes questions that are mainly concerned with alarms. The generic code Quality was clarified by considering it as Work Quality in order to focus on this important source of maintenance failures.

Table 2. Major categories, and individual, group, and organisational level codes in HFIT.

| Action Errors | Situation Awareness | Organisational Threats |
|---|---|---|
| **Omission** | Loss of **Attention** | Inadequate **Procedures** |
| **Timing** errors | **Detection** failures | Inadequate **Work Preparation** |
| **Sequence** errors | **Memory** faults | **Job Factors** |
| **Selection** mistakes | **Interpretation** errors | **Person Factors** |
| **Work Quality** | **Decision-making** errors | Lack of **Competency & Training** |
| Incorrect **Information** | Mistaken **Assumption** | Faulty **Communication** |
| **Procedure Violations** | Flawed **Execution** | **Teamwork** issues |
| | | Insufficient **Supervision** |
| | | **Organisational Culture** |
| | | Difficulties with the **Work Environment** |
| | | Human-machine interfacing **(HMI)** flaws |
| | | Inadequate attention to **Design & Maintenance** |
| | | Difficulties in accessing **Policies & Standards** |

N.B. Names of HFIT codes are highlighted in bold text.

- Interpretation of codes. The questions in HFIT relating to the code *Organisational/Safety Culture* concern a broad range of organisational dimensions, such as management commitment, reporting culture, and improper incentives, much of which would be difficult to identify unambiguously in a brief interview. Also included in this code were questions concerning organisational learning. In consideration of the prominence in the literature (Marsick & Watkins, 2003; Schein, 1996; Tucker, Edmondson, & Spear, 2002) of this construct with respect to organisational outcomes, *Organisational Culture* was taken to refer to flaws in organisational learning in the incident. The code *Procedures, Standards, and Policies* refers generically to management documents, but also includes procedures, which has a separate code. Therefore, in considering the importance of standards and technical drawings to a technology-intensive operation, this code was selected in cases involving insufficient technical documentation. All failures attributed to procedures are included in the *Procedures* code.

- Overlap between codes. Despite the conceptual distinctions between codes, there remained overlaps between the sub-factor questions in several of the codes. This could lead to variability in attributing the event to one factor over another. For example, there is conceptual overlap between the categories of *Omissions* and *Memory*, and *Selection* and *Decision-making*. As a result, some overlap in coding was anticipated.

No additional inter-rater reliability studies were conducted as part of this research project. However, as an additional means of addressing concerns about IRR of HFIT, the original coding of responses from the interviews was cross-checked, as described below in the Procedure.

**Procedure**

Approval for the research was granted (Approval Number HR 147/2007) by the Human Research Ethics Committee of Curtin University. Experienced electrical and mechanical maintenance personnel were invited to participate in the current study of maintenance failures (N=38). Rather than have the interviewer specify the incident to be investigated, as would normally occur in an accident investigation, the participants were asked to consider a failure with which they were familiar. The intention was to prompt a recall of an incident with which the participant was personally involved, as opposed to reporting hearsay. Recall of incidents that were clear in the mind of the interviewee should carry richer detail than forced recall of a selected case. This approach facilitated the process of understanding the context of the participant's awareness and actions pertaining to the failure, which Dekker (2003) considered critical to uncovering "how universal patterns of breakdown occur repeatedly across operational particulars" (p.104).

Structured interviews were conducted in which the interviewee was queried about the influence, on the failure under discussion, of each of the 27 specific human factors described by HFIT. Following the logic of Wallace et al's (2002) minor event coding, a failure was defined as any maintenance activity that did not produce the expected outcome, such as a maintenance activity that:

- failed to correct the existing problem;
- did not proceed as originally planned;
- after completion, created subsequent operational problems.

Investigation sub-factor questions from HFIT were used as prompts to elicit responses from the interviewee and provide guidance as to the human factors coding of each interview. A dichotomous response to each code was recorded on a spreadsheet. Interviews were also recorded, with the interviewee's permission, to enable a qualitative review of the responses and obtain verbatim quotes as supporting evidence. The responses were coded a short time after the interview to ensure recency in interpreting each interview.

## RESULTS

### Frequency distribution of reported PSFs

The data from coding 38 interviews is provided in the Appendix and summarised in Table 3. A Cochran's Q test (Siegel, 1956) ($Q=157$, $df=27$, $N=38$, $p<.001$) demonstrated that a significant difference existed in the frequency of the reported factors. McNemar Tests of Change (Siegel, 1956) were conducted on pairs of the most frequent factors to determine whether the differences in occurrence were significant. There were no significant differences in frequency of reporting between adjacent pairs of the top five most frequent PSF. However, a significant difference was found between the first-ranked factor, Assumptions and the eighth-ranked factor, Competence & Training ($p=.008$).

*Table 3: Rank of performance shaping factors based on HFIT codes reported in failure interviews*

| Rank | Performance Shaping Factor | No of times Reported | % of cases |
|---|---|---|---|
| 1 | Assumption | 30 | 79 |
| 2 | Design and maintenance | 27 | 71 |
| 3 | Communication | 25 | 66 |
| 4 | Omission | 22 | 58 |
| 5 | Decision-Making | 21 | 55 |
| 6 | Information | 17 | 45 |
| 7 | Procedures | 17 | 45 |
| 8 | Competency & Training | 16 | 42 |
| 9 | Work Preparation | 15 | 39 |
| 10 | Organisational Culture | 15 | 39 |
| 11 | Detection | 15 | 39 |
| 12 | Policies & Standards | 15 | 39 |
| 13 | Job Factors | 14 | 37 |
| 14 | Timing | 14 | 37 |
| 15 | Attention | 12 | 32 |
| 16 | Selection | 12 | 32 |
| 17 | Supervision | 11 | 29 |
| 18 | Work Environment | 11 | 29 |
| 19 | Work Quality | 10 | 26 |
| 20 | Teamwork | 9 | 24 |
| 21 | Person Factors | 8 | 21 |
| 22 | Procedure Violations | 7 | 18 |
| 23 | Memory | 6 | 16 |
| 24 | Human-Machine Interface | 5 | 13 |
| 25 | Interpretation | 4 | 11 |
| 26 | Execution | 2 | 5 |
| 27 | Sequence | 0 | 0 |

The Work Category and Type of Production were classified for the incidents (Table 4), and compared to organisational data obtained from the target company's incident database (Antonovsky, 2010). The incidents examined were broadly representative of incidents recorded in the target company's incident database. In addition, each incident was assigned a Severity of Consequences rating, based on the consequences of the failure or the potential for injury or damage that could have occurred. The criteria applied for assessing minor, moderate and severe levels of Severity were derived from the International Standard "Petroleum, petrochemical and natural gas industries-Collection and exchange of reliability and maintenance data for equipment" (International Standards Organization, 2006, Table C.1). For example, a minor incident was the supply of an incorrect part, thereby delaying maintenance work. A severe failure involved an incorrect coupling to a well riser, resulting in damage to equipment and production losses amounting to $63 million. Moderate and Severe incidents were found to be over-represented in the interviews.

*Table 4: Classification of incidents reported in the interviews*

| Demographic | Incident | Number of Interviews | % of Interviews | Organisational Data (%) |
|---|---|---|---|---|
| Work Category | Instrumentation/Electrical | 15 | 39.5 | 38.4[a] |
| | Mechanical | 23 | 60.5 | 61.6[a] |
| Type of Production | Gas (Platforms and Process Plant) | 17 | 44.7 | 62.1[a] |
| | Oil (FPSOs) | 21 | 55.3 | 37.9[a] |
| Severity of Consequences | Minor | 9 | 23.7 | 45.1[b] |
| | Moderate | 16 | 42.1 | 35.3[b] |
| | Severe | 13 | 34.2 | 19.6[b] |

[a] Based on entries for maintenance-related incidents in the company incident database (Year 2007)
[b] Based on the entries in the company incident database having a reported human factor (Year 2007)

An analysis of the company's incident database (Antonovsky, 2010) indicated that the cases self-selected by participants were broadly representative of the overall distribution of past incidents. The incidents selected by participants were generally representative in terms of consequences and failure type (e.g. electrical or mechanical). The number of interviews concerning one type of facility, namely FPSOs, was disproportionately high due to difficulties accessing offshore staff. It was noted that severe failures, based on the company's consequence criteria, were over-represented, while minor incidents were under-represented. This is likely to be due to the tendency for people to recall incidents with more serious consequences (Glendon, Clarke, & McKenna, 2006). Although a strictly representative sample of plant failures could not be assured, a bias among interviewees towards more severe incidents provided an emphasis on the factors that lead to failures with greater consequences.

Chi-squared tests for Contingency were used to determine if the frequency of factors was related to Severity. Only the frequency of Violation ($\chi 2=6.34$, df=2 p=.042) and Procedures ($\chi 2=6.03$, df=2 p=.049) showed a significant positive relationship to Severity. Overall, it was found that the frequency of other factors was not statistically related to the severity of failure, and instead depended on the circumstances of the incident.

**Human Factors Reported in Interviews**

The factor Assumption was the most frequently reported code. Reported assumptions were associated with attempting to solve a maintenance problem without obtaining sufficient, accurate information or by resolving a maintenance problem on the basis of past experience alone. This was reported in many forms including the assumptions made that:

- the cause of stoppage was a faulty component when lack of cooling of that component was the true cause;
- the component supplied was similar to units previously supplied, when in fact additional machining was required before it could be successfully used;
- work on a particular electrical sub-system would not cause all production units to shut down when in fact it did cause a shutdown.

For example, in a number of cases, the correctness of components or procedures to be used was assumed but not verified. In one example, the failure of a transducer required a circuit breaker to be shut off. It was assumed that the breaker could be shut off without affecting other units. However, due to poor labelling of the unit involved, inaccurate drawings, and the fact that "maintenance procedures haven't been addressed" compressors were also switched off causing the entire production stream to shut down. The maintenance technician commented, "The majority of our work is trying to find the information to hand on to the inexperienced guys to make their work task safe, because they don't have that local knowledge." In another example from an interview describing an oil spill from an open valve, the person involved isolated a critical valve and "made the assumption it was working. If you close a valve, you assume it's closed."

The second most frequent code, Design & Maintenance (originally Plant, Parts, Tools, & Equipment in HFIT) was reported in 71% of the interviews, of which 50% related to poor maintainability due to the design of equipment, and inadequacies in the components or materials used. An example was a pump failure due to 1) the difficulty of inspecting it at the bottom of a 30 m sump, 2) the difficulty of repairing it as specialised tools for fitting parts were needed, and 3) the difficulty of testing repairs to it as there was no means of pre-testing bearings prior to return to service.

The remainder of this category included failures due to:

- inadequate labelling of equipment units or controls;
- need to repair non-standardised equipment;
- inadequate maintenance or condition-monitoring, typically due to inadequate maintenance programs.

For example, in a serious failure described, a modification to correct a design fault almost caused an explosion on-board an FPSO. The water seal used in a Pressure-Vacuum (PV) breaker was used to isolate hydrocarbon storage tanks from exposure to air. The gauge measuring the level of water in the seal was checked daily. However, due to insufficient maintenance, the gauge was difficult to read. New designs were considered, but never implemented. As a consequence, a maintenance technician decided to modify the gauge in order to alleviate the difficulties with reading it. Part of his modification included an elbow joint which eventually corroded, allowing water to drain from the seal. This released poisonous inert gas from the tank and exposed explosive hydrocarbons in the tank to air.

In another example, a steampipe for oxygen removal in an aerator was poorly designed and manufactured, and eventually cracked, shutting down the steam plant. Rather than re-manufacturing the pipe to a higher specification, a welder was flown to the FPSO to repair the crack. The pipe cracked again, this time causing 3-4 days of lost production, and risking damage to a boiler. If accurate drawings had been available, the pipe could have been replaced in 48 hours with a new pipe manufactured on-shore.

The third most frequently recorded factor was Communication. In these interviews it was apparent that participants in the work process (e.g. maintenance technicians, engineers, equipment suppliers, and maintenance planners) had failed to communicate needed information to each other. Typically, personnel charged with effecting solutions had failed to inform others of critical aspects of the situation, such as observations that would have changed the assessment of the corrective maintenance work required. The most common breakdowns in communication were between on-shore and off-shore personnel, and between engineers and maintenance personnel. From descriptions of the communication processes involved, it did not appear that the availability of technology was a limiting factor, e.g. communication between on-shore and off-shore personnel is supported by advanced technology. Rather, the lack of sufficient effective communication was an issue. For example, problems frequently arose when communication occurred mainly via electronic media, such as e-mail or the Information Management System, which did not encourage two-way exchange of information between those involved in the maintenance process. A frequent result, as demonstrated above, was a reliance on assumptions, often leading to flawed Decision-making, the 5th most frequent contributor to failures.

As an example of a communication failure, changes made to a lip sealing arrangement by a vendor in conjunction with the Engineering Department were not communicated to the shutdown team installing the seal. The changes were also not communicated via the on-line Bill of Materials parts list. The interviewee commented that communicating the change could have been as simple as marking the change of seal on the machine concerned. As the shutdown was re-scheduled from mid-week to the weekend, obtaining the correct seal required helicopter transport, at a total excess cost of $3 million in transport and lost production.

In another example, scaffolding was required for a task, but a lack of communication between planners and maintenance technicians meant that the need for scaffolding was not discussed, and not included in the work plan. A mechanical fitter reported that a job that should have taken a “couple of days, ended up taking a week, [due to] miscommunication between [our company's] resource estimators and [the contracting company]."

Several factors were reported less-frequently than expected despite their prominence in the organisational psychology and management literature. This finding indicates that although the human factors considered in the HFIT comprise a comprehensive list of potential causes for maintenance problems, differences can exist between industries and/or sites and caution is needed regarding the generalizability of causes for maintenance errors from one industrial setting to another. For example, of the factors expected to play a greater role in failures, out of the 27 possible HFIT factors, Supervision (#17) was rarely a factor, reflecting the high degree of autonomy and wide geographic distribution of maintenance personnel that distinguishes the petroleum industry from the aviation and nuclear power industries. Similarly, Teamwork (#20) as a factor was rare, as the interviews revealed a high degree of cohesiveness between team members, and between teams and their supervisors. Despite the attention given to rule violations in the human factors literature, Violation (#22) rarely contributed to failures. Maintainers queried about possible procedure violations reported that relatively few maintenance tasks were specified in procedures, compared to, for example, control room operations. When these less-frequent factors were present in the cases examined, the semi-structured interview methodology did uncover them. These overall results demonstrated that a number of human factors that are prominent in the literature, particularly in research studies from the aviation and NPP domains, appear not to be as influential in a different context, i.e. petroleum maintenance operations.

## DISCUSSION

### Frequency of Human Factors Contributors to Failures

Based on the interviews with maintenance personnel regarding the human factors contributing to failures, the three predominant factors identified were Assumption, Design & Maintenance, and Communication. Examining the data obtained (cf. Appendix) more broadly, problem-solving behaviours, encompassing the HFIT factors of Assumptions (#1) or Decision-making (#5), were identified in almost

90% of the failures.  Problem-solving in maintenance relies on correctly determining the source of a fault, deciding on the most efficient means of correction, and applying the solution effectively.  All of these cognitive processes are required for successful corrective maintenance and a logical flaw in any of these leaves the fault unresolved.  Where assumptions are made in preference to obtaining correct information, or decision-making fails to consider relevant factors or identify a suitable solution, the action taken may contribute to what Dekker (2005) describes as an on-going drift into failure.  Design & Maintenance (#2), representing the results of poor maintainability in the original or modified design of equipment, was reported in 71% of the failures.

At least one form of organisational communication, i.e. Communication (#3), Procedures (#6), or Information (#7), was identified as a contributor in 87% of the failures.   Incorrect information or deficient communication of that information in a complex, socio-technical system increases the probability of applying an inappropriate solution to a maintenance problem.  Procedures are a specific form of organisational communication and knowledge transfer that underpins the success or failure of maintenance tasks.  The frequent association of failures, examined in this research, with effectiveness of communication, quality of procedures, and accessibility of job-related information, demonstrated the importance of increasing the attention that an organisation devotes to communication between maintenance personnel and other members of the organisation.

The less-frequent contributors to failure also provided worthwhile information about the performance of the maintenance groups in this study.  Supervision (#17) was rarely a factor in the failures, reflecting the high degree of autonomy and wide geographic distribution of maintenance personnel that distinguishes the petroleum industry from the aviation and nuclear power industries.  Similarly, [lack of] Teamwork (#20) as a factor was rare, as the interviews revealed a high degree of cohesiveness between team members, and between teams and their supervisors.  Despite the attention given to rule violations in the human factors literature (Reason, Parker, & Lawton, 1998), Violation (#22) was rarely reported in the failures.  Maintainers queried about possible procedure violations reported that relatively few maintenance tasks, compared to control room operations, were specified in procedures and so there were relatively few rules to violate. These results demonstrated that a number of human factors that are prominent in many research studies, particularly in the aviation and nuclear power plant domains, appeared not to be as relevant in the context of petroleum production. Therefore, there appeared to be a specificity to the data obtained based on characteristics of the target organisation or petroleum production domain.

**Implications of the findings**

The premise of the current research study is that failures of maintenance have their origins not only in technical faults, but also in specific human factors. Consequently the development of a methodology for identifying these factors has the potential to inform the organisation and thereby obviate their reoccurrence. Each of the principal factors identified has complex underlying causes, and therefore the requirements for remedial action to eliminate them will also be complex. Thus, we have attempted to demonstrate that in the context of the petroleum industry, once the principle human factors have been identified, sufficient understanding can be achieved to begin the process of correcting the underlying causes. The methodology and the insights described in this study are intended to provide a basis for researchers to conduct similar analyses in other companies and industrial domains.

The findings in this study are specific to the context of the petroleum industry, and while not necessarily generalizable to all industrial domains, are important to an understanding of maintenance reliability. Failures related to poor communication or a problem-solving behaviour was identified in 95% of all failures examined, and represented fundamental organisational processes that have been identified in the literature as potential sources of unreliability. For example, referring to a Systems Theory approach to organisations, Muchinsky (2003) commented that “the Achilles’ Heel of most large organisations is failure to communicate…communication is the means by which the system can be responsive to its environment” (p. 250).

Similarly, problem-solving abilities and an organisational climate of methodical problem-solving have been studied as sources of reliability. Reiman, Oedewald and Rollenhagen (2005) examined the culture of maintenance organisations extensively and concluded that a number of cultural factors contribute to reliability. One of these is a construct they refer to as Methodicalness, as it applies to actions and methods in the 'maintenance core task'. They define this as an "ability to explain the actions taken and the methods used" (p.334). The complexity of a modern socio-technical system requires attention to methodicalness. Instead, a tendency towards what Klein (1997) refers to as Recognition Primed Decision-Making (RPD) appeared to underlie most maintenance activities, as the high rate of Assumption demonstrated. Caravalho, dos Santos & Vidal (2005) described the extensive use of RPD in nuclear power plant operations, in comparison to more analytical forms of decision-making. They concluded that this was the most efficient form of decision-making among experienced operators. However, the current study demonstrated how frequently assumptions, which are a fundamental aspect of RPD, contribute to failures. These assumptions are driven in large part by what Hollnagel (2002) describes as the mental and procedural shortcuts that occur in the trade-off between efficiency and thoroughness, which are inherent in optimising performance. The implications of this study were that avoidance of failures will require a deliberate cognitive shift, e.g., through training programs, from RPD towards more methodical modes of problem-solving.

At the organisational level, problem-solving processes may be influenced or even specified by management policy and procedures. In his description of the differences in problem-solving behaviours between three American automobile manufacturers, MacDuffie (1997) describes the way in which problem-solving processes could be hindered or enhanced by organisational policies. He demonstrated that methodical problem-solving practice, as with safety behaviour, could be deliberately developed among workers. Company policy was needed to empower those closest to a problem to act on it. In this way, problem-solving is not only a skill acquired by workers, but also a normative dimension of the organisational climate that can influence maintenance outcomes. The results of the current study support the notion that maintenance-related failures, which can be costly or dangerous to personnel, can be addressed through an organisational concern with problem-solving behaviours.

**Examination of the method**

The objective of the current study was to identify those human factors with the greatest influence on maintenance reliability, based on historical failures. The intention is not to predict future performance from past failures, but rather to analyse past failures in order to provide insights into organisational weaknesses that need to be addressed. The organisational flaws that Reason (1997) describes in his 'Defences-in-Depth' model may change with time and conditions, but are unlikely to disappear without active identification, comprehension, and correction of the underlying causes.

Structured interviews with maintenance personnel using HFIT were found in the present study to be an effective method of actively identifying patterns in the workplace, in a process of debriefing personnel about past events described by Lipshitz (2007).. Several modifications were made to the taxonomic names and categories in HFIT to eliminate what the authors perceived to be potential sources of inter-rater disagreement, i.e. ambiguous names and overlaps between categories.

This final form of the instrument provided a means for identifying the most frequently occurring dysfunctions affecting maintenance work processes in petroleum operations. Maintenance personnel were found to be a rich source of empirical information concerning organisational processes, as they often:

- worked nearest to the effects of failure and were directly responsible for outcomes;
- had an historical perspective on archetypical system failures;
- showed an intuitive understanding of the on-going impact of workplace factors on the effectiveness of their work.

Conversely, the data obtained by this method had several limitations, partly due to the methodology and partly due to the target organisation for the study. In terms of the cases examined, one limitation was the difficulty of accessing a more representative cross-section of the workforce. For example, coordinators and supervisors were over-represented in the interviews. This was constrained by the work rosters and the tendency for technicians to be unavailable outside of the time that they spend on their offshore facility.  In addition, the lack of female participants, although representative of the operational workforce, was potentially a source of bias in the findings.

Furthermore, interviewees were self-selected, and allowing them to choose the incident to be investigated may have introduced a sampling bias.  However, selecting incidents in order to ensure the representativeness of the incident sample would have introduced an additional source of bias.  The analysis was reliant on recall of past events.  Investigating only recent incidents may ensure better recall of the details relating to the case, and consequently more reliable reporting of human factors.

In terms of the methodology, interpretation of the human factors involved was reliant on the coder's interpretation of events described by the interviewees.  By using a second coder, and reviewing  a random selection of cases together, the consistency of the coding of human factors to the cases examined was improved.  Recoding the incidents and conducting a formal IRR study with the modified version of HFIT would provide quantitative evidence of the reliability of the revised taxonomy. Finally, the study involved a single organisation, and would need to be replicated in other organisations to determine whether the PSFs identified here are generalisable across the industry.

These issues notwithstanding, discussions with the actors most-influenced by human factors in the workplace provided insights into the organisational weaknesses within maintenance processes that needed to be identified, analysed and addressed (Antonovsky, 2010).

## CONCLUSION

Using the taxonomy in the Human Factors Investigation Tool (HFIT), structured interviews could be used to examine the human factors issues which recur most frequently in maintenance failures in a petroleum production organisation.  Teamwork, supervision, and procedural violations were found to have a less-than-expected influence on maintenance-related failures, in relation to the extent that they are reported in the literature, which often relates to studies in the aviation and nuclear power industries. Instead, problem-solving behaviours (assumptions), plant design, and organisational communication were identified as the human factors contributing most frequently to these failures. Their contribution to failures was found to occur regardless of the severity of the failure.

This is a positive finding for companies involved in petroleum production and for organisations generally. Improving problem-solving skills among maintenance technicians, designing plant and equipment with a view to maintainability, and internal organisational communication are all within an organisation's control. The training and skills acquisition involved in improving problem-solving and communication are addressed via the various Crew Resource Management (CRM) programs (Flin, O'Connor, Mearns, & Gordon, 1999), originally developed in the aviation industry, and later adapted into training programs for offshore petroleum workers (O'Connor and Flin, 2003). In relation to the value of CRM, Flin et al (1999) quoted a study of 1268 incidents from off-shore production from 1994 to 1996. Almost half (46%) of the human factors-related incidents were found to relate to the items included in CRM training. The current research supports the validity of their findings and the potential value that such training and improved organisational communication, including better procedures, would have in reducing the incidence of maintenance failures in petroleum operations. Our finding that maintenance tasks require greater focus on methodical modes of problem solving rather than RPD is an important factor to consider in designing CRM programs for the petroleum industry.

The current research also supports the value of ensuring the maintainability of plant and equipment at the design stage. As Bea (1998) argued, engineering practitioners have not sufficiently concerned themselves with the support systems needed for engineered structures, such as the non-technical systems for maintenance, warnings, and information. More significantly, he contended that engineers have also not developed the human systems needed to cope with the evolution of critical failures in technical systems. If this is the case, then the occurrence of failures identified in the current study as 'design and maintainability' may also be a symptom of not recognising the role of non-technical factors, for example training and communication, in technical systems. In addition to support for humans working with those designs, an equally important consideration is that engineers, if they wish to reduce failure rates and improve reliability, design with more consideration of the humans that will be responsible for maintaining plant.

Finally, in contrast to a focus on human errors and violations as the source of failures, identifying and correcting recurring sources of failure that the organisation can control, as identified by personnel who experience these factors on a daily basis, is a more promising avenue for achieving higher operating reliability.

# APPENDIX

| Incident Date | Type | Position Level | ACTION ERRORS | | | | | | | SITUATION AWARENESS | | | | | | | | THREATS | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Omis | Time | Seq | Qual | Sel | Info | Viol | Att | Det | Mem | Int | Dec | Ass | Exec | HMI | Design | Environ | Comm | Team | Superv | OrgCult | Skill |
| Aug-2007 | Mech | Supervisor | x | x | | | | x | | x | | | | x | x | | | x | x | | | x | x | |
| Apr-2008 | Elect | Technician | x | x | | | | | | | x | | | | x | | | x | | | | | | x |
| Jan-2008 | Mech | Fitter | x | | | | | | | | | | | x | | | | x | | x | x | | x | |
| May-2006 | Mech | Supervisor | | | | x | | | | x | x | | x | x | x | x | | x | | x | | x | | x |
| Mar-2008 | Mech | Fitter | | | | | | x | | x | x | | x | x | x | | | x | | x | | x | x | x |
| Oct-2006 | Elect | Technician | | | | | | x | | | | | | x | x | | x | x | x | x | | | | x |
| Mar-2008 | Mech | Fitter | x | | | | | | | | x | x | | | x | | | x | x | x | | | | x |
| Jun-2004 | Elect | Technician | x | | | | x | x | | x | x | | | | x | | x | x | | | | x | x | |
| Jan-1998 | Mech | Estimator | x | | | x | | | | | x | | | | x | | | x | | x | | x | x | x |
| Feb-2008 | Mech | Technician | x | x | | | x | | | | | | | x | x | | | | | | x | x | x | x |
| Jun-2006 | Elect | Supervisor | x | | | x | | x | | x | | | | | | | | | x | x | x | x | x | x |
| Mar-2007 | Mech | Coordinator | x | | | | x | | | | | | | | x | | | x | x | x | x | | | x |
| Feb-2008 | Mech | Coordinator | x | | | | | x | | | | | | | x | | | | x | x | x | | | x |
| Nov-2007 | Elect | Coordinator | x | | | | | | | | x | | | | | | | x | | | x | | | |
| Oct-2004 | Mech | Coordinator | | x | | x | x | | | x | | | | | x | | | x | | x | | | | |
| Oct-2006 | Mech | Supervisor | x | | | | x | x | x | | x | | | | x | | | | | | | x | x | |
| Nov-2006 | Mech | Planner | x | x | | | | x | x | | | | | x | | | | x | | x | | | x | |
| Jul-2007 | Mech | Coordinator | x | | | | | x | | | | x | | x | x | | | | | x | | | | |
| Jan-2008 | Mech | Coordinator | | x | | x | | | | | x | | | x | | | | x | | x | | | | x |
| Sep-2007 | Mech | Technician | x | | | | | x | | x | | x | | | x | | | | | x | x | | | |
| Jul-2007 | Mech | Coordinator | | | | x | | | | | | | | | x | | | x | | x | | | | |
| Feb-2007 | Mech | Technician | | x | | | | | | | | | x | x | x | | | x | | x | | | | |
| Feb-2008 | Elect | Coordinator | | x | | | | x | x | | | | | x | | | | x | x | x | | | | |
| Jul-2007 | Mech | Technician | | | | | | x | | x | x | x | | | | | | x | | | | | | x |
| Jul-2007 | Elect | Technician | | x | | | x | | | | | | x | x | x | | | x | | | | | | |
| Sep-2007 | Elect | Technician | x | | | x | | | | x | | x | | | | | x | | x | | x | x | | |
| Jul-2008 | Elect | Technician | x | | | | | x | x | | | x | | | x | | | | | x | | | | |
| Feb-2008 | Mech | Technician | x | | | | x | | | | x | | | x | x | | | x | x | x | | x | | x |
| Jan-2005 | Mech | Technician | x | x | | | | | | | | | | x | x | | | | | | | | x | |
| Jul-2008 | Elect | Technician | x | | | | | | | x | x | | | | x | x | x | | | | | | x | |
| Mar-2008 | Mech | Technician | | x | | x | x | | | x | x | | | x | x | | | x | x | x | | | x | |
| Jun-2003 | Mech | Coordinator | | x | | | | | x | | | | | x | x | | | x | | | | | x | x |
| Apr-2007 | Elect | Technician | | x | | | x | | | | | | | x | x | | | x | x | x | | | | |
| Jan-1999 | Mech | Supervisor | | | | x | | x | x | | x | | | x | x | | | x | | x | | | | x |
| Aug-2007 | Elect | Technician | | | | | x | x | | | | | | x | x | | | x | | | | | | |
| Jul-2008 | Elect | Technician | x | | | | x | x | | x | x | | | | x | | | x | | x | | | x | |

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## KEY POINTS

- Industry-specific accident investigation tools can provide a useful means for examining the weaknesses within organisational systems relating to human factors.
- Assumptions were found to be the most frequent contributor to maintenance failures, reflecting the need for more methodical problem-solving among maintenance personnel in the petroleum industry.
- Communication was the third most frequent contributor to failures, reflecting the wide geographical distribution of maintenance personnel, and the reliance on electronic means of communication.
- Consideration needs to be given to plant and equipment maintenance during the design phase to reduce human errors in maintenance.

## REFERENCES

Antonovsky, A. (2010). *Human Factors in Maintenance Reliability in a Petroleum Production Operation.* Curtin University of Technology, Perth. PhD thesis (unpublished)

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

Carvalho, P. V. R., dos Santos, I. L., & Vidal, M. C. R. (2005). Nuclear power plant shift supervisor's decision making during micro-incidents. *International Journal of Industrial Ergonomics, 35*(7), 619-644.

Crichton, M. (2005). Attitudes to teamwork, leadership, and stress in oil industry drilling teams. *Safety Science, 43*(9), 679-696.

Dekker, S. (2003). Illusions of Explanation: A Critical Essay on Error Classification. *International Journal of Aviation Psychology, 13*(2), 95-106.

Dekker, S. (2005). *Ten Questions About Human Error: A New View of Human Factors and System Safety (Human Factors in Transportation)* Mahwah: Lawrence Erlbaum Associates, Inc.

Flin, R., O'Connor, P., Mearns, K., & Gordon, R. (1999). *Crew resource management for offshore production and maintenance.* Paper presented at the 1999 Offshore Europe Conference, Aberdeen, Scotland.

Glendon, A. I., Clarke, S. G., & McKenna, E. F. (2006). *Human Safety and Risk Management* (Second Edition ed.). Boca Raton, USA: Taylor & Francis Group.

Gordon, R. (1998). The contribution of human factors to accidents in the offshore oil industry. *Reliability Engineering & System Safety, 61*(1-2), 95-108.

Gordon, R. (2001). Human Factors Investigation System HFIT: University of Aberdeen, Industrial Psychology Group.

Gordon, R., Flin, R., & Mearns, K. (2005). Designing and evaluating a human factors investigation tool (HFIT) for accident analysis. *Safety Science, 43*(3), 147-171.

Gordon, R., Mearns, K., & Flin, R. (2000). *The development and evaluation of a human factors accident and near miss reporting tool (HFIT) for the off-shore oil industry*. (Vol. 2). London: HSE Books.

Heimann, L. (2005). Repeated Failures in the Management of High Risk Technologies. *European Management Journal, 23*(1), 105-117.

Hobbs, A., & Williamson, A. (2002). Skills, rules and knowledge in aircraft maintenance: errors in context. *Ergonomics, 45*(4), 290-308.

Hobbs, A., & Williamson, A. (2003). Associations between errors and contributing factors in aircraft maintenance. *Human Factors, 45*(2), 186.

Hollnagel, E. (2002). *Understanding accidents-from root causes to performance variability.* Paper presented at the IEEE 7th Human Factors Meeting, Scottsdale, Arizona.

Holmgren, M. (2005). Maintenance-related losses at the Swedish Rail. *Journal of Quality in Maintenance Engineering, 11*(1), 5.

International Standards Organization. (2006). Petroleum, petrochemical and natural gas industries-Collection and exchange of reliability and maintenance data for equipment (Second ed., Vol. ISO 14224:2006(E)): International Organization for Standardization.

Klein, G. (1997). The current status of the naturalistic decision-making framework. In R. Flin, E. Salas, M. Strub & L. Martin (Eds.), *Decision-making under stress: emerging themes and applications* (pp. 11-28). Aldershot: Ashgate.

Lipshitz, R. (2007). *Demystifying organizational learning*. Thousand Oaks, Calif: Sage Publications.

MacDuffie, J. P. (1997). The road to `root cause': Shop-floor problem-solving at three auto assembly plants. *Management Science, 43*(4), 479.

Marsick, V. J., & Watkins, K. E. (2003). Demonstrating the Value of an Organization's Learning Culture: The Dimensions of the Learning Organization Questionnaire. *Advances in Developing Human Resources, 5*(2), 132.

Muchinsky, P. M. (2003). *Psychology Applied to Work* (Seventh ed.). Belmont, California: Wadsworth Thomson Learning.

O'Connor, P., & Flin, R. (2003). Crew Resource Management training for offshore oil production teams. *Safety Science, 41*(7), 591-609.

O'Leary, M. (2002). The British Airways human factors reporting programme. *Reliability Engineering & System Safety*, *75*(2), 245-255.

Oedewald, P., & Reiman, T. (2003). Core task modelling in cultural assessment: a case study in nuclear power plant maintenance. *Cognition, Technology & Work, V5*(4), 283-293.

Øien, K. (2001a). A framework for the establishment of organizational risk indicators. *Reliability Engineering & System Safety, 74*(2), 147-167.

Øien, K. (2001b). Risk indicators as a tool for risk control. *Reliability Engineering & System Safety, 74*(2), 129-145.

Pate-Cornell, M. E. (1993). Learning from the Piper Alpha Accident: A Postmortem Analysis of Technical and Organizational Factors. *Risk Analysis*, *13*(2), 215-232.

Pidgeon, N., & O'Leary, M. (2000). Man-made disasters: why technology and organizations (sometimes) fail. *Safety Science, 34*(1-3), 15-30.

Rasmussen, J. (1982). Human errors. A taxonomy for describing human malfunction in industrial installations. *Journal of Occupational Accidents, 4*(2-4), 311-333.

Rasmussen, J., Pedersen, O. M., Mancini, G., Carnino, A., Griffon, M., & Gagnolet, P. (1981). *Classification System for Reporting Events Involving Human Malfunctions* (No. RISØ-M-2240). Roskilde, Denmark: Risø National Laboratory, DK 4000 .

Reason, J. (1997). *Managing the Risks of Organizational Accidents*. Aldershot: Ashgate Publishing Ltd.

Reason, J., & Hobbs, A. (2003). *Managing maintenance error : a practical guide*. Aldershot, England Burlington, Vt.: Ashgate.

Reason, J., Parker, D., & Lawton, R. (1998). Organizational controls and safety: The varieties of rule-related behaviour. *Journal of Occupational & Organizational Psychology, 71*(4), 289-304.

Reiman, T., Oedewald, P., & Rollenhagen, C. (2005). Characteristics of organizational culture at the maintenance units of two Nordic nuclear power plants. *Reliability Engineering & System Safety, 89*(3), 331-345.

Reinach, S., & Viale, A. (2006). Application of a human error framework to conduct train accident/incident investigations. *Accident Analysis & Prevention, 38*, 396-406.

Ross, A. J., Wallace, B., & Davies, J. B. (2004). Technical note: measurement issues in taxonomic reliability. *Safety Science, 42*(8), 771-778.

Schein, E. H. (1996). Three Cultures of Management: The Key to Organizational Learning. *Sloan Management Review, 38*(1), 9-20.

Siegel, S. (1956). *Non-parametric statistics for the behavioral sciences* (International Student Edition ed.). Tokyo: McGraw-Hill Kogakusha Ltd.

Sklet, S. (2006). Hydrocarbon releases on oil and gas production platforms: Release scenarios and safety barriers. *Journal of Loss Prevention in the Process Industries*, *19*(5), 481-493.

Suksi, S. (2004). Methods and practices used in incident analysis in the Finnish nuclear power industry. *Journal of Hazardous Materials, 111*(1-3), 73-79.

Tucker, A. L., Edmondson, A. C., & Spear, S. (2002). When problem solving prevents organizational learning. *Journal of Organizational Change Management, 15*(2), 122.

Urbina, I. (2010, 6 June). In Gulf, it was unclear who was in charge of rig. *The New York Times*, p. A1.

U.S. Department of Energy. (1999). *DOE Workbook: Conducting Accident Investigations*. (Rev.2), Washington, D.C.: Department of Energy.

Vogus, T. J., & Welbourne, T. M. (2003). Structuring for high reliability: HR practices and mindful processes in reliability-seeking organizations. *Journal of Organizational Behavior, 24*(7), 877-903.

Wallace, B., Ross, A., Davies, J. B., Wright, L., & White, M. (2002). The creation of a new minor event coding system. *Cognition, Technology & Work*, *4*, 1-8.

Wallace, B., & Ross, A. (2006). *Beyond Human Error: Taxonomies and Safety Science* Boca Raton, USA: CRC Press.

Zohar, D., & Luria, G. (2005). A Multilevel Model of Safety Climate: Cross-Level Relationships Between Organization and Group-Level Climates. *Journal of Applied Psychology July, 90*(4), 616-628.

## Biographies

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