

**THE AETIOLOGY OF ERROR: COGNITIVE PROFILING
EVENTS WITHIN THE MINING INDUSTRY**

by

Douglas E Sweeney, P. Geol., P. Eng.

M.Sc. Mining Engineering, University of Alberta, 2004

B.Sc. Mining Engineering, University of Alberta, 1994

B.Sc. Geology, McMaster University, 1983

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ABSTRACT

Investigation of accidents, incidents and other unintended *events* in the workplace continues to evolve in the mining industry, as it has for other heavy industries. Traditional investigation approaches are grounded in causation – the determination of cause and effect relationships manifested by the evidentiary record. This approach, while intuitive and widely accepted, is not inclusive of the more distal elements of causality such as the influence of cognitive error and the perception of risk. This research examines the role of cognitive error in decisions that contribute to *events*; the nature of these errors and how they are indicative of organizational culture.

The main objective of this research is to develop and evaluate a cognitive error tool that can be used in the analysis of *events* within the mining industry. The current taxonomies are few, and are not available in a robust and structured model easily applied by accident investigators. This research seeks to address this by offering a theory of *event* causality based upon decision errors (Decision Error); taxonomy of decision errors (Lost Error); and, a model for profiling cognitive error (Cognitive Profiling). Further, through cognitive profiling, it will be shown that there is a collective, or distributed, cognition that exists precursory to an *event* that heretofore has not been addressed by conventional causation modelling of *events* in the mine workplace.

This research contributes to the field of human error analysis by proposing taxonomy based upon decision errors; and to the field of cognitive science by examining the role that risk perception has in cognition within the workplace. It provides a lexicon and a methodology that is exploratory in determining those *events* in the mine enterprise that are prone to escalation toward disaster; and by what errors in management such outcomes can be triggered. This research contributes to the field of accident theory and investigation by expanding on the notion of causation to include causality; and by defining accident, incidents and other *events* as systems. It is shown that when *events* and their investigation are considered as systems with inputs, outputs, and processes; then there is another system at play – the human error system that is antecedent to *events*. This research challenges the way that *events* are seen in the mine workplace.

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GLOSSARY

Truth is a good dog; but beware of barking too close to the heels of an error, lest you get your brains kicked out. Samuel Taylor Coleridge (Bartlett, 2000)

A

ACCIDENT: An unplanned event that results in harm to people, damage to property or loss to process (IAPA, 2007).

ACCIDENT CAUSATION: The many factors that act together to cause accidents. They include: personal factors, job factors, and lack of management control factors (IAPA, 2007)

ACCIDENT INVESTIGATION: The process of systematically gathering and analyzing information about an accident. This is done for the purposes of identifying causes and making recommendations to prevent the accident from happening again (IAPA, 2007).

ACTOR: Any person who is the originator of a behaviour, decision or action and is party to an accident scenario (this dissertation)

ADMINISTRATIVE CONTROLS: A category of hazard control that uses administrative/management involvement in order to minimize employee exposure to the hazard (IAPA, 2007)

AGENT: Any substance, force, organism or influence that affects the body, a part of the body, or any of its functions. The effects may be beneficial or harmful (IAPA, 2007).

ALARP: An acronym for 'As Low As Reasonably Practicable'. This term represents the level to which workplace risks are controlled to the degree considered practical and achievable (IET, 2007).

C

CODE OF PRACTICE: A set of prescriptive instructions documenting procedures and standards that are requisite to a specific hazard with such force of intent that failure to comply may result in legal proceedings (IET, 2007).

COMPETENT PERSON: A person who has sufficient skill, knowledge and experience to work safely without continuous direction. They also work within their scope of practice (IET, 2007).

CONSEQUENCE: outcome or impact of an event (AS/NZS 4360, 2004).

CONTROL: Measures designed to eliminate or reduce hazards or hazardous exposures. Examples include: engineering controls, administrative controls, personal protective

equipment. Hazards can be controlled at the source, along the path to the worker, or at the worker (IAPA, 2007).

COST: Of activities, both direct and indirect, involving any negative impact, including money, time, labour, disruption, goodwill, political and intangible losses (AS/NZS 4360, 2004).

D

DANGER: The circumstance in which negative outcomes to people, assets, production, reputation or the environment is plausible and reasonably foreseeable (IET, 2007).

DUTY OF CARE: An obligation imposed upon a person or persons requiring that their action fall within a standard of care towards others that reflects caution, care and prudence consistent with that of a reasonable person (Bruce, 1998).

DUE DILIGENCE: The taking of every precaution reasonable in the circumstances for the protection of the health and safety of workers (IAPA, 2007).

E

ENTERPRISE: A project or undertaking at the economic level involving all parties that govern its success, including but not limited to: federal and local governments, the community, corporate management, operations management, regulatory agencies, contractors, workers and the public at large (This dissertation).

ENVIRONMENT: The surrounding conditions, influences, and forces to which an employee is exposed in the workplace (IAPA, 2007).

ERROR: An act, assertion, omission or belief on the part of an individual or individuals that deviates from a known standard, norm, rule or expectation (This dissertation).

EVENT: occurrence of a particular set of circumstances (AS/NZS 4360,2004).

F

FIRST AID INJURY: An injury or illness requiring treatment by a designated first aid professional as per the requirements of the prevailing statutory authority (IET, 2007).

FREQUENCY: A measure of the number of occurrences per unit of time (AS/NZS 4360, 2004).

H

HARM: Any negative outcome including injury, illness, environmental excursion, financial loss or reputation (This dissertation).

HAZARD: A source of potential harm (AS/NZS 4360, 2004).

HEALTH AND SAFETY PROGRAM: A systematic combination of activities, procedures, and facilities designed to ensure and maintain a safe and healthy workplace (IAPA, 2007).

HUMAN ERROR: This term is used today to include not just workers' errors, but engineering deficiencies and lack of adequate organizational controls which together account for the majority of accidents (IAPA, 2007).

I

INCIDENT: An unwanted event which, in different circumstances, could have resulted in harm to people, damage to property or loss to a process. Also known as a *near miss* (IAPA, 2007).

L

LATENT PERIOD: The time that passes between exposure to a harmful substance or agent and the first sign(s) of damage or illness (IAPA, 2007).

LIKELIHOOD: Used as a general description of probability or frequency (AS/NZS 4360, 2004).

LOSS: Any negative consequence, financial or otherwise (AS/NZS 4360, 2004).

LOSS CONTROL: Measures taken to prevent and reduce loss. Loss may occur through injury and illness, property damage, poor work quality, etc. (IAPA, 2007).

M

MISTAKE: A lapse in judgement or error that results in an unintended consequence (Norman, 1983).

MONITOR: to check, supervise, observe critically or measure the progress of an activity, action or system on a regular basis in order to identify change from the performance level required or expected (AS/NZS 4360, 2004)

N

NATURE OF INJURY: The main physical characteristics of a workplace injury or illness (for example, burn, cut, sprain, dermatitis, hearing loss). (IAPA, 2007)

NEGLIGENCE: The omission to do something, which a reasonable person, guided upon those considerations which ordinarily regulate the conduct of human affairs would do, or something, that a prudent and reasonable man would not do (IET, 2007).

O

ORGANIZATION: Group of people and facilities with an arrangement of responsibilities, authorities and relationships (AS/NZS 4360, 2004)

P

PERSONAL PROTECTIVE EQUIPMENT: Any device worn by a worker to protect against hazards. Some examples are: respirators, gloves, ear plugs, hard hats, safety goggles and safety shoes (IAPA, 2007).

POLICY: A documented statement of intent by an organization that compels others to comply with a standard or expectation and for which consequences are implicitly or explicitly set out in the event of non-compliance (this dissertation).

PRACTICABLE: Technical feasibility without reference to costs (IET, 2007).

PRESCRIBED: As set out in the regulations under any Act (IAPA, 2007).

PROBABILITY: A measure of the chance of occurrence expressed as a number between 0 and 1 (AS/NZS 4360, 2004).

PROCEDURE: A step-by-step description of how to do a task, job, or activity properly (IAPA, 2007).

Q

QUALIFIED WORKER: One who is accepted as having the necessary physical attributes, who possesses the required intelligence, training and education, and has acquired the necessary skill and knowledge to carry out the work in hand to satisfactory standards of safety, quantity and quality (IET, 2007).

QUALIFIED PERSON: A person who is accepted as trained in accordance with a known standard, competent to carry out the duties without direction (this dissertation).

R

REASON TO BELIEVE: A conviction or belief that does not require empirical support or evidence (IAPA, 2007).

RESIDUAL RISK: Risk remaining after implementation of risk treatment (AS/NZS 4360, 2004).

RISK: The chance of something happening that will have an impact upon objectives. (AS/NZS 4360, 2004).

RISK ACCEPTANCE: An informed decision to accept the consequences and the likelihood of a particular risk (AS/NZS 4360, 2004).

RISK ANALYSIS: Systematic process to understand the nature of and to deduce the level of risk (AS/NZS 4360, 2004).

RISK AVOIDANCE: A decision not to become involved in, or to withdraw from, a risk situation (AS/NZS 4360, 2004).

RISK ASSESSMENT: The overall process of risk identification, risk analysis and risk evaluation (AS/NZS 4360, 2004).

RISK CONTROL: That part of risk management which involves the implementation of policies, standards, procedures, and physical changes to eliminate or minimize adverse risks (AS/NZS 4360, 2004).

RISK EVALUATION: The process used to determine risk management priorities by comparing the level of risk against predetermined standards, target risk levels or other criteria (AS/NZS 4360, 2004).

RISK IDENTIFICATION: The process of determining what can happen, why and how something could happen (AS/NZS 4360, 2004).

RISK MANAGEMENT: The culture, processes and structures that are directed towards realizing potential opportunities whilst managing adverse effects (AS/NZS 4360, 2004).

RISK REDUCTION: Action taken to lessen the likelihood, negative consequences, or both, associated with a risk (AS/NZS 4360, 2004).

RISK RETENTION: acceptance of the burden of loss, or benefit of gain, from a particular risk (AS/NZS 4360, 2004).

REASONABLY PRACTICABLE: A computation made in which the quantum of risk is placed on one scale, and the disadvantages involved in the measure necessary for averting the risk is placed upon the other. A balance between: risk and cost, inconvenience, effect on production (IET, 2007).

S

SAFETY: The absence of risk of injury or asset damage/loss (IET, 2007).

SAFETY AUDIT: Monitoring of the implementation of a safety policy by subjecting each area of an activity to a systematic critical examination with the purpose of minimising loss, and providing a quantified assessment of performance (IET, 2007).

SAFETY CASE: Formal explanation of methods to be adopted to reduce risk of accident often used in high potential risk situations - e.g. Petro-chemical, Nuclear Installations (IET, 2007).

SAFETY COMMITTEE: A committee representative of all staff with the objective of promoting co-operation in investigating, developing and carrying out measures to ensure the health, safety and welfare of the employees (IET, 2007).

SAFETY CULTURE: This term has no widely agreed definition. It may be described as a product of the individual and group values, attitudes, competencies and patterns of behaviour that determine the commitment to, and the style and proficiency of an organisations health and safety programmes (IET, 2007).

SAFETY INSPECTION: Systematic assessment of safety standards for plant, place of work, working. Carried out by a manager and not a safety adviser/engineer (IET, 2007).

SAFETY MANAGEMENT SYSTEM (SMS): Management of Safety in order to promote a strong Safety Culture and achieve high standards of safety performance (IET, 2007).

SAFETY MONITORING: Periodic checks on observance of corporate safety standards and procedures processes or areas (IET, 2007).

STANDARD: A guideline, rule, principle, or model that is used as a means to compare, measure or judge performance, quality, quantity, etc. (IAPA, 2007).

W

WORKPLACE: Any place where work is taking place or may be taking place (this dissertation).

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I also acknowledge the assistance and support of the management and staff of the Highland Valley Copper Mine. It is only through their leap of faith that I was able to secure disclosure of sensitive records and benefit from their high standards of operational excellence spanning decades of mining within the province of British Columbia. They know who they are; I could not have completed this project without their cooperation and counsel.

Finally, to my family who have sacrificed so much that I might complete this journey. With unwavering perseverance and humour, you have taught me how to balance family, work, and studies through these last few years. You have my gratitude, respect and love for all that you have endured.

DEDICATION

Dedicating this research is a challenge. The horror and sorrow associated with bearing witness to an injury in the workplace is a deeply moving experience. To an extent, this dissertation is a retrospective of a career investigating fatalities and other serious *events* in the industrial workplace. It is difficult to express how documenting the scene of a fatality haunts you; how much it reminds you that in an instant in time someone's future is extinguished forever. It is impossible to express on behalf of all the injured; the deceased; and their next-of-kin, how much they would all give to reverse a decision in time – to deny tragedy to the cruel hand of error.

I dedicate this work to all those who no longer have voices and to my parents who sacrificed so much that I might speak for them.

Who can discern his errors? Forgive my hidden faults (Psalm 19:12)

“Sometimes we may learn more from a man’s errors, than from his virtues” Henry Wadsworth Longfellow (Bartlett, 2000)

1 INTRODUCTION

Fallibility is part of the human condition. Man’s capacity for error is generally underestimated, but always is a sober reminder that the enterprises for which we toil are not without risk: risk of failure, risk of tragedy, and risk of disaster. This research considers human error from a cognitive perspective. It asks three interrelated questions: can we define the safety culture in terms of group cognition; how does group cognition manifest itself in the workplace; and, what are the benefits of profiling cognitive errors as an evaluative tool in mining related incidents and accidents? The product of this research is an analytical framework by which one can examine, classify and profile *events* in the mine workplace. The motivation and premise of this research is that an explicative tool is lacking with respect to *events* in the workplace that provides insight into the safety culture (ethos) of an organization or enterprise.

Mining in British Columbia traditionally has been a leader in workplace safety and environmentally sustainable practices. A new standard of social conscience is emerging within the mining community that expands sustainability to include the interests of the community, the aboriginal first peoples and the public at large. This trend is particularly true in the province of British Columbia, which has had to manage forestry, fisheries, tourism and mining in what is one of the more demanding, socially conservative jurisdictions in which to explore for and extract minerals. Mining builds on a tradition of social responsibility and leadership that has been its legacy. This research takes advantage of the long standing and well-developed standards, norms and statutes that have served mining so well by making it the safest heavy industry within British Columbia (MEMPR, 2005).

1.1 A Statement of the Problem

As long as there has been mining, there have been *events* (accidents, incidents, and environmental excursions) in the workplace that are unplanned, unpredictable and always deleterious to the enterprise of mining. By virtue of the shadow of uncertainty that these *events* cast upon shareholder confidence, public support, and regulatory oversight it is clear that these *events* are unacceptable and no longer considered part of 'doing business'. In recent decades, sincere and credible efforts has been made to investigate, analyze and extirpate these *events*; however, the holy grail that remains elusive is to understand and develop mechanisms for change of the organizational culture - or ethos - that govern these *events*. The problem therefore is to devise a model that examines the investigative record, and then predicts what human and/or organizational factors support and sustain an ethos of error within the mine enterprise.

1.2 The Question That This Research Will Address

Can we through the back-analysis of *events* within the workplace, develop a technology that is predictive, heuristic and practical in profiling the psychological precursors and cognitive errors that contribute to accidents and incidents? Secondly, is this a new lens through which we can look at mining enterprises and their organizational structure? If so, to what extent does this research contribute to organizational theory and a path yet to be followed to best management practices?

1.3 Scope of Application

The crucible for this research is the mining industry. The principles and precepts are equally applicable to any industry or sector, the common element being human error - the subject of this research. The word *event* occurs repeatedly in this dissertation, to represent any destabilizing scenario within the enterprise of mining that puts the integrity of the operation at risk. Typically, *events* include the usual suspects: accidents, incidents, production cessation and environmental excursions. A modern perspective would be remiss were *events* not to include the less definable occurrences of public outcry and challenge by First Nations. They are increasingly relevant in British Columbia and no less subject to human error.

1.4 Objectives of the Research

The principal objective described in this dissertation is to introduce a model of error analysis that will promote disclosure and examination of decision errors within the mining enterprise. To this end, a cognitive profiling model is presented as a tool to explore the contribution made by human errors and the organizational precursors that are antecedent to them. Furthermore, through the introduction of taxonomy of these errors based upon contemporary accident theory, this research will provide a framework by which cognitive error can be recognized, classified, and profiled. This objective can be broken down into four goals. This research will:

- i. Propose a new model for industrial *events*, one that is inclusive of the back-analysis of accidents and incidents to arrive at the psychological and organizational precursors that contribute to *events* in the workplace.
- ii. Provide a link between human error contributing to an *event* and the standard of care that would be appropriate to mitigate, if not prevent the occurrence.
- iii. Devise a means by which industry can evaluate the criticality of their mining enterprise and the potential for an *event* escalating to a disaster.
- iv. Introduce cognitive profiles commonly associated with organizations experiencing serious *events* and propose warning signs predictive in their occurrence.

1.5 Significance of this Research

The mining industry has entered the second century in which there have been increasing expectations upon operators to demonstrate self-awareness for social responsibility. A concept of sustainable management is emerging that includes numerous new dimensions of awareness: cultural consultation and accommodation, community engagement, regulatory compliance, resource management, public safety, worker health and safety and economic diversification being the notable examples. Each of these dimensions has their own challenges, but all are subject to the immutable laws of risk and uncertainty; notions that this research seeks to examine through the back-analysis of accidents and incidents (*events*). Currently there are few models that have

the capacity to evaluate the investigative record; and none of which the author is aware that explicitly considers the contribution made by decision error.

The significance of this research is the novel and innovative approach of closing the loop of the accident investigation cycle through the analysis of *events* in the workplace (Figure 1.1). To be proactive, mining enterprises must recognize the merits of considering decision errors of persons involved in day-to-day operations that have the potential to contribute to an *event* scenario; and engage these same human resources to become self-aware and adaptive to error control strategies. This research will make the case that human error is not limited to mine operations. Rather, we consider the entire enterprise as a source of human error. This enterprise approach will encourage the evaluation of all the workplace parties (operations, corporate management, unions and the regulators) in a mutual effort to candidly facilitate learning from human error.

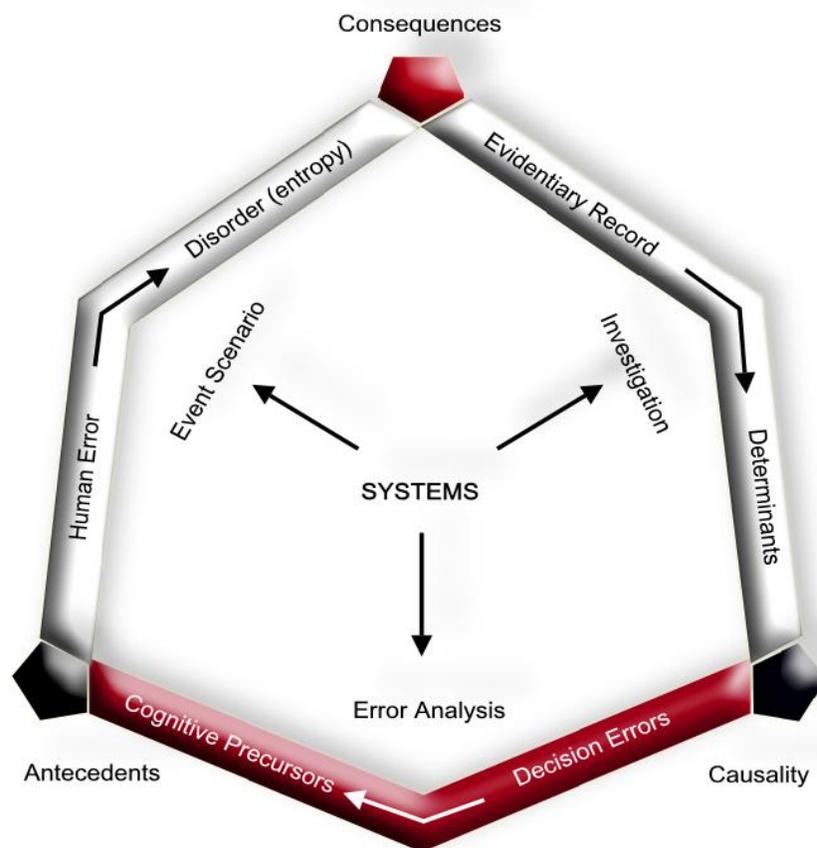


Figure 1.1: Schematic illustrating 'completing the loop' of accident investigation (Sweeney, 2004)

1.6 Motivation for this Research

Accident reports often resort to naming human error (pilot error, operator error) as the 'cause' of an *event* in the workplace. Frequently considered as a 'blame' setting (Busse, 2002; Storbakken, 2002), such characterizations fail to accurately model *events*; and often alienate those persons involved in the *event* scenario. The identification of human error should stimulate a deeper and more probative investigation, rather than arriving at statements of culpability or causation. Still, it is essential to consider human factors in the understanding of workplace *events*. Identifying human factors in causation should not connote "human error" as the cause of the *event*. Properly framed, human error can be examined in a less judgmental and incriminating manner that treats persons contributory to an *event* scenario as a participant in a larger *error-forcing system*. There is a lack of appreciation of this possibility in many contemporary investigations, and a paucity of tools or models available to consider this 'big picture'.

This research addresses this need and provides a methodology by which investigators can evaluate decision errors in the first instance; and provide analysts a tool for the back-analysis of investigations, in the second instance. By taking a candid and objective look at *decision errors* as symptoms of *events* in the workplace instead of causes, this research aims to provide a more appropriate and less judgmental lexicon of causality. In doing so, an organization will benefit by instilling within their enterprise social responsibility and personal accountability. Long-term, these organizational traits will translate into fewer errors, less risk and uncertainty and ultimately greater profitability through fewer *events*. Traditional mining companies typically organize their operations in conservative and predictable structures. An additional need that this research will address is how to examine *decision errors* within these structures, and seek to understand how the various groups perceive and act on risk. It is anticipated that, in so doing, mine management will gain insight and revelation as to the role risk perception plays in the cognitive processes antecedent to decisions, and adopt effective risk communication and mitigation strategies.

1.6.1 The Actuarial Toll - OECD

A report to the 27 member nations of the Organization of Economic and Co-operative Development (OECD, 1989:133-159) reveals that:

- i. In 1987, there were over 16,000 fatalities of workers, reported by the OECD Member nations (OEDC, 1989:152).
- ii. In 1987, there were over 10,000,000 loss time accidents to workers, reported by the OECD Member nations. This is out of the 300,000,000 workers who comprise the reporting population (OEDC, 1989:133).
- iii. In 1987, the direct accident insurance expenditures represent between 3 and 7 percent of the total social security expenditures, or by another measure 1 to 3 percent of the gross domestic product, depending upon nation (OEDC, 1989:134).
- iv. In 1987, 15 percent of the fatalities in mines reporting to the OECD Member nations occurred in Canada. However, in terms of injury rate, the injury rate of mineworkers was on average with those of Member nations (OEDC, 1989:144).

1.6.2 The Actuarial Toll - Canada

A report from Human Resources and Development Canada (HRDC, 2000:1-48) reveals that:

- i. In 1998, statistically on average, every day there were three fatalities of workers in Canada. This represents a ratio of 1 to 18,000 (HRDC, 2000:9)
- ii. In 1998, there was a loss time injury every 37 seconds, somewhere in Canada (HRDC, 2000:10).
- iii. In 1998, the cost of compensation payments to workers in Canada was \$77,500 per minute (HRDC, 2000:10).
- iv. In 1998, the percentage of workers in Canada participating in the mining industry was 1.25%. The percentage of workers in the mining industry reporting injuries was 1.07% (HRDC, 2000:12).

1.7 Contributions of this Research

This research flows from, and contributes to three scientific bodies of knowledge. They are accident investigation, cognitive science and human error theory (Figure 1.2). Although borrowing liberally from the latter two disciplines, it is the researcher's belief

that it is the contribution to the former field – that of accident investigation, that this research will make the greatest contribution. In recent decades, the field of accident investigation in the mining industry has evolved and become increasingly effective. The mining industry has both benefited from and contributed to founding principles of accident investigation such as sequence-of-event theory (Heinrich, 1931) and loss control (Bird, 1973). Comparatively however, the civil transportation, nuclear and medical sectors have made greater progress in the incorporation of the human factor, arguably because of criticality and complexity of their respective technologies.

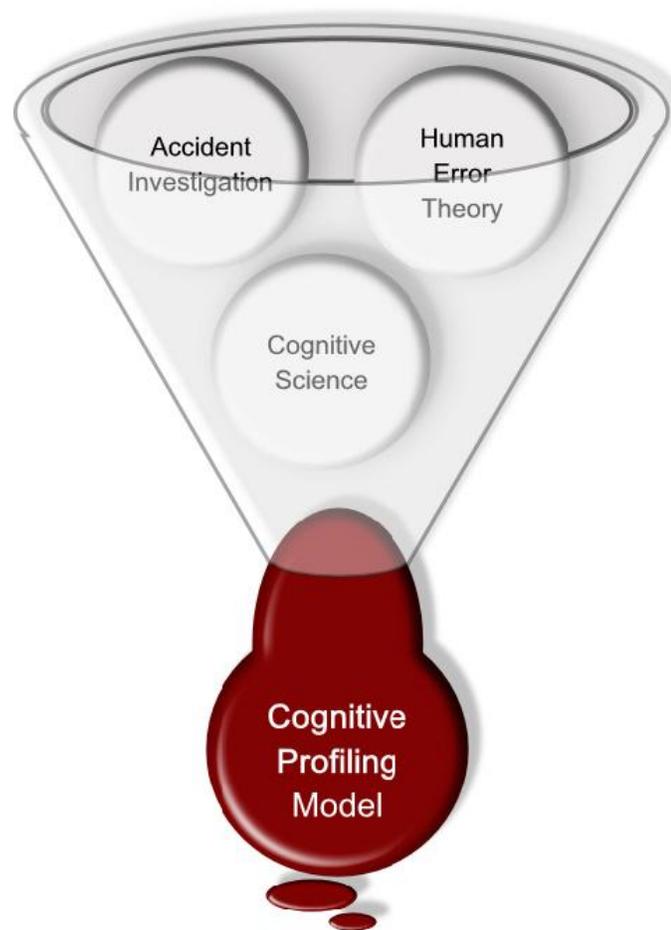


Figure 1.2: Diagram illustrating the various disciplines contributing to this research

The cognitive profiling model presented in this research is predicated upon the salient principle that behaviours in the past are potentially predictors of behaviours in the future. Whereas the researcher makes no claim of prediction of *events* with numerical

certainty, the utility of this research is the detail with which a future *event* can and will be described. Collectively: the time of day, seasonal considerations, mechanisms of injury, failure mechanisms, organizational structure, and worker vocation all provide a descriptive profile of what a future *event* might look like. Further, cognitive profiling will offer the analyst some insight into the cognitive errors that are likely to contribute to an *event*, and thereby suggest a preventative action or remedy.

1.8 Innovation

One definition of innovation is the creation and implementation of new processes, products and methods of delivery that result in significant improvements in efficiency, effectiveness and quality (Albury and Mulgan, 2003). The definition resonates with this research insofar as the model presented herein is unique, powerfully adaptive and offers to shift the utility of investigation of *events* from reactive and reflective to proactive and predictive. Additionally, decision error theory and cognitive profiling will increase effectiveness and therefore the quality of the investigative process by providing feedback to the workplace parties (at the enterprise level) by scrutinizing decision errors. It is anticipated that through such scrutiny, that mine operations will become more self-aware and less averse to introspection and organizational change. Lastly, key to innovation is that the new idea or invention is acted on or in some way put into effect. This research will demonstrate that cognitive profiling is an analytical tool that is practical and timely.

1.9 Quality

The quality of this research is not dependent upon statistical validity or revelation of phenomena. Indeed, the irony is that the inspiration and information upon which this work is founded already exists in the form of the investigative record: and is in plain sight. This research flows from years of empirical observation and firsthand experience. In this regard, the proof presages the research, and without biasing the outcome, provides a solid basis to situate decision error theory and attendant cognitive profiling model. To be clear, there is a considerable body of work in the disciplines of accident theory, human error theory and cognitive science from which to draw. The quality of concept is borne out through case studies and field research that is heuristic and adaptive in nature as opposed to presuming scientific rigour or precision. Lastly, the

quality of this research is evident in the manner by which the risk to mine operations can be measured and ranked as regards to their propensity to escalate to disaster.

1.10 Limitations of this Research

This dissertation draws upon existing human error research that is in its early stages of development in specific enterprises other than mining. Predominate among these is research within the civil transportation (Benner, 1995; Bove, 2002; Dekker, 2004), nuclear power (Perrow, 1984) and the medical sectors (Haddon, 1980; Reason, 1990, 2005). Research in these fields is strongly conclusive as to the contributions made to accidents and incidents by human error. It is speculative as to what applicability and commonality these findings have to the mining industry, or any heavy industry, as arguably there are distinct differences in culture and risk. Research in human error, regardless of the field of interest, benefits from the pioneering work of such theorists as Rasmussen, 1974; Hollnagel, 1988; Reason, 1990 and Dekker, 2004. It is this tradition that this research borrows from, in the belief that the principles and behaviours of people as regards to error are universal, whatever the enterprise.

The human error studies in the aviation, medical, and nuclear industries is necessarily rigorous; and the available data supports such a rigour. Whereas mining has a strong history of safety systems and safety culture, the data are not as transparent or sophisticated as those enterprises that are in the public domain. This research therefore is empirical in nature and by necessity draws upon a combination of both historical case studies and contemporary research to develop the cognitive profiling model. In this respect, models presented trade statistical rigour for utility and practicality, and by no means suggests mathematical certainty in respect to its conclusions.

1.11 Originality of Work

This dissertation presents a new and innovative model for considering the contribution made by cognitive error to the provenance of *events* in the mining industry. It does so with regard to existing human error taxonomies, but does not presume to add to them. Indeed, this research is the product of efforts to simplify and distil principles from the broad field of human error, with due respect to the field of industrial psychology.

1.12 Organization of Work

This dissertation is comprised of three parts (Figure 1.3). Part 1 is the traditional academic treatise that sets out the purpose, scope and body of knowledge related to this research. Part 2 consists of a series of five case studies applying cognitive profiling to historical disasters in a variety of industrial settings. Each case study is unique, and stands on its own merit; however, collectively they serve to show that regardless of industry type, technology or the nature of the enterprise - similar profiles emerge indicating commonalities as regard to organizational behaviour. In Part 3, the accidents and incidents from a contemporary operating mine are analyzed and profiled and presented as a field study. The study is a stand-alone report that was submitted to the operating mine in fulfilment of a written non-disclosure agreement.



Figure 1.3: Diagram illustrating the organization of this dissertation into its three constituent parts

1.13 Genesis of Concept

The researcher first considered the question of what contributes to *events* in the industrial workplace in the mid 1980s, as an inspector of mines. At that time, a credible, structured methodology to evaluate serious accidents was needed, the purpose of which was to apply appropriate strategies of intervention and mitigation. It was a simple enough concept. Nonetheless, it was a tall order given the early days of accident theory. Investigators made considerable progress in accident theory over the next decade, to the extent that analytical methods were incorporating epidemiological models and were increasingly widening the scope of cause and effect relationships. Still, there was no

methodology for the evaluation of investigations into *events* on a holistic scale. At the same time, the tolerance and acceptability of accidents and incidents in the mine work place (and all workplaces) was diminishing.

In the mid 1990s, the need for an explicative tool for the evaluation of accident investigations became critical for the expressed purpose of adducing whether an *event* was a result of misfeasance, malfeasance or otherwise. Depending upon the answer to this question, the *event* was subject to administrative penalties and sanctions – or not. Specifically, a model or tool had to incorporate the following principles:

- i. Establishing the duty of care of the parties involved in the event scenario.
- ii. Assessing the extent to which the party knew of, or ought to have known of an applicable standard of care.
- iii. Respectful of persons who were by circumstance making understandable errors, or errors for which there was exculpatory evidence.
- iv. Classify the errors in such a way that was defensible and had rigour.

It became immediately apparent to this researcher that simplicity was the key. What did all of the accidents within his experience have in common? What distinguished an honest error from an error that clearly demonstrated a lack of due diligence? What influence did human factors have, such as fatigue, noise exposure and heat exhaustion? At what point was human error subject to scrutiny? The answer to these questions, and many others, was that persons (parties) contributing to the *event* scenario made a conscious decision to do something, or not do something, or were somehow impaired or did not have the capacity to make a decision. A typology based upon decision error was born. It was not popular, as the ideology of the day was to distribute culpability for an accident systemically, organizationally, or not at all.

Decision error theory, and its derivation of cognitive profiling, was introduced in a M.Sc. thesis (Sweeney, 2004), in which the focus of study was an evaluative tool for accident and incident investigations. This research flows from, and applies this early research, to the contemporary field study and historical case studies in this dissertation. It will be shown that these case studies offer a well spring of *event* causal analysis; one that is surprising as a source of evidentiary and analytic record from which to draw upon.

These historical case studies will prove to be particularly revealing of those elements of causality, as insidious as they are common in the escalation of *events* toward disaster.

1.14 Literature Sources

The search for sources of literature was conducted over many years; more formally during the years of 2004 through 2009. There are six categories of literature sources. They are:

- i. Books on the subject matter
- ii. Internet web searches on the subject matter
- iii. Periodicals and journals on the subject matter
- iv. Digitized databases of public domain studies on the subject matter
- v. Academic theses on the subject matter
- vi. On-line discussion forums

1.14.1 Texts

The texts pertaining to this subject were purchased on line or borrowed from the library at the University of British Columbia or Thompson Rivers University. Too many to list here, those purchased are the most recently published in the categories of cognitive science and human error theory. Texts on loan from university libraries were most often associated with historical treatments of accident theory and case histories.

1.14.2 Internet Web Searches

The internet was used to narrow down and search articles and books from the general to the specific. Google™ was the search engine of choice for general searches; Google™ Scholar, for more specific searches. A number of free academic search engines were also experimented with, with mixed success. They were Wiley Interscience Search®, Infomine®, Web Lens® and Bubl Link®. A subscription online service of JSTOR accessed through Thompson Rivers University library services met with greater success, in the absence of which, access to the journals and articles would have been cost prohibitive.

1.14.3 Periodical Journals

The periodicals and journals accessed were specific to the domains of interest pertinent to this research. They were *Cognitive Science Society*, *Safety Science*, *Journal of Safety Research*, *International Journal of Risk Assessment and Management*, the *Journal of Accident Investigation*, the *Australian Journal of Mine Safety* and the *Journal of Organizational Behaviour*. All were searched exhaustively to the limit of their availability on-line.

1.14.4 Digitized Databases

Increasingly, one can order databases of accident records and public domain documents on line. The two that were particularly useful to this research were the records from the US Department of Labour, Occupational Safety and Health Administration available at <http://www.osha.gov/pls/publications/publication.html> and those of the province of Manitoba at www.gov.mb.ca/labour/safety. Available products were purchased on compact disk (CD).

1.14.5 Academic Theses

Academic theses and treatises pertaining to this research were searched online through a number of academic search engines. They were the Thesis Portal of Canada and the Networked Digital Library of Theses and Dissertations. More productive, were the dedicated web sites offered by respective universities in jurisdictions known for research in the subject matter. The University of British Columbia, University of Glasgow, Ryerson University and the University of Oregon are a few notable examples. They were accessed for the relevancy and volume of research in areas of mining engineering, cognitive research, safety theory, and risk perception respectively. Given the multifaceted nature of this research, there is no shortage of research on the subject matter. Key papers contributing to this research are those of Busse, 2002; Sklet, 2002; Trepas, 2003; Koning, 2006; and Visser, 2007. The work of Massaiu, 2005; Arvidsson, 2006; Garcia, 2006; Storbakken, 2007 and Bove, 2002 also influenced this research. The search terms were accident causation, workplace cognition, risk perception, human error, accident investigation, error taxonomy and variations thereof.

1.14.6 On-line Discussion Forums

Accident investigation is a techno-social science, and there is a surprisingly small group of theorists that span the domains of workplace, public safety and public transportation. A membership-by-invitation on-line discussion group is that of the website *Investigating Investigations* (©1997-2007) hosted by Ludwig Benner Jr., and accessed at <http://www.iprr.org/>. The purpose of this site is to 'advance the state-of-the-art of investigations, through investigation process and research.' The forum is a fertile ground for discussion of all things related to the science and art of investigation and posts numerous research papers, journal papers and resources.

1.15 How to Read This Dissertation

This dissertation relies heavily upon the medium of graphics. The deep maroon colour is evident in all figures and graphics and is used to identify contributions made by others to this research, and to emphasize important concepts introduced by the researcher. The chapters flow from the general to the specific in support of the conclusions. Words presented in italics are for the purpose of emphasis of concepts introduced by other authors contributory to this research, and concepts that are thematic in this dissertation.

“Error is certainty’s constant companion. Error is the corollary of evidence. And anything said about truth can equally be said about error: the delusion will be no greater.” Louis Aragon (Bartlett, 2000)

2 ACCIDENT THEORY

Accident theory is the cornerstone of accident investigation. Theory supports the investigative method, and the method supports the analysis of accidents. This distinction is an important one to this research, and other researchers (Benner, 1975; Sklet, 2004; Hollnagel, 2004) have shown that the theory influences the outcome of an investigation. Accident theory has naturally changed over time, and is implicit in emerging investigation technologies. Accident theory and its models reflect the culture and mores of the times. More often evolved than designed, accident models are the product of conditions and constraints of the day, inherently biased by the perceptions and philosophy of the theorist. It is this perception, on the part of both the theorist and the investigator, which is central to the understanding of accident theory.

The traditional view of workplace accidents is that of spontaneous occurrences (*events*) in time (Woodcock, 1989). To most, the causes of these *events* are by necessity, the *raison d’être* of investigation. As self-evident as these two assumptions appear to be, they are no longer truisms in emerging accident models. A more contemporary view is that *events* in the workplace should be referred to as *event* ‘scenarios’, as they are more akin to processes, as opposed to singular, spontaneous occurrences in time (Benner and Hendrick, 1987). This notion of ‘event’ is a long held belief, or perception, that most certainly contributed to the original thinking of accidents as a product of a single cause. Perception colours reality. Similarly, the notion of causes does not pass serious scrutiny in modern models, as there is no consensus or definition of what ‘cause’ means (Woodcock, 1989; Benner, 1980). The vernacular of cause is no longer both necessary and sufficient to explain *event* scenarios. A review of

contemporary accident models will illustrate that we still seek to understand their provenance, their organizational context - their aetiology.

2.1 Causation

Causation is the act or agency that produces an effect (Merriam Webster, 1993). It is without doubt the most misunderstood and misapplied concept in accident theory (Benner, 1985; Woodcock, 1989). Used in the enabling sense (sufficient condition) or in the mandatory sense (necessary condition), scientifically - 'cause' should be considered a stochastic concept. In many cases we cannot say with certainty what, or if, something is a factor of causation and the caveat of 'balance of probability' is applied. Balance of probability implies a variation of Occam's razor: 'that all things being equal the most likely solution is the best.' There are a number of principles that apply to accident models and by extension the determination of *causation* (Huang, 2007). These principles can work in both directions with respect to time. That is, these principles are equally applicable for the purposes of investigation (hindsight), or prevention (foresight). They are *attributed causes*, *system decomposition* and *causality*.

2.2 Attributed Causes

If an *event* occurs in any setting, it is within every person's self-interest to know about it and to understand why it happened. Depending upon the setting however, motivations may vary, if not be in conflict. In the workplace, employers often are predisposed to business continuity; organized labour to worker representation; and the regulatory agency to statutory compliance. Naturally, individual motivation will reflect subjective experiences and opinions, and these will colour their objectivity concerning investigation. These predispositions or predilections comprise what are *attributed causes* to an *event* (Huang, 2007). It is important that they do not become part of the investigative report of record, although they often do. Attribution of cause is instinctual as it is universal. People, regardless of their culture, status or affiliation will seek resolution of *events* for which they have little insight or control. They will often do so by making assertions of cause and effect which may, or may not be, correct. They draw upon their own experiences in an effort to reconcile, or attribute the cause of one thing as a result of another on the basis of correlation. The resulting model of causation is frequently

inaccurate and rarely complete. Causal attribution is the road of good intention that often diverts us away from the destination of understanding and prevention.

2.3 System Decomposition

System decomposition is the deconstruction of the system into smaller sub-systems or components (Huang, 2007). Essentially, it is how you eat an elephant – one bite at a time. By breaking down the overall system into smaller and logical pieces, the analysis is more manageable and resources can be allocated accordingly. A mine operation can be broken down into mining, milling and services, and mining further broken down to mine design, mine operations, and mine maintenance. And so on. Any, or all, of the sub-systems can contribute to factors of causation.

2.4 Causality

Causality is essentially the principle that one state can affect another state (Huang, 2007). When the effect of state 'A' is the occurrence of state 'B', we can deduce that there is cause and effect. However, state 'A' may be related to state 'B' in a number of ways. State 'A' could be management commitment to environmental sustainability, or lack thereof. State 'B' could be poor worker attitudes toward pollution prevention. Management commitment could be lacking, but this does not necessarily mean it 'caused' the workers to have poor attitudes toward pollution. Societal values, familial values and social-economic considerations may also be an influence.

Causality is complex. It has many dimensions that tend to be simplified and overlooked. People are intrinsically reductionists; we are products of our past, that we tend to overstate; and are poor prognosticators of future complexity, which we understate (Kida, 2006; Van Hecke, 2007). *Causality* is dependent upon *representativeness* and *availability heuristics* (Reason, 1990); principles that explain why we often prepare for too few contingencies of failure. Causality is the more fulsome, albeit less deterministic, manner in which things are related. This is not to say that one thing does not result in another; rather, that the 'causes' are subtle, time dependent and often influenced by unknown and unseen factors that act as catalysts or triggers. This uncertainty, or lack of connectedness associated with *causality*, is why traditional

accident and incident investigations hold so strongly to the notion of causation (cause and effect).

2.4.1 Representativeness Heuristics

Representativeness heuristics (RH) is the principle that we limit our perception of causality to causes and effects that we are familiar with (Huang, 2007). In many instances we will set aside a factor that influences an outcome in preference to one for which there is similitude - even if illusory. *Representativeness heuristics* motivate us to indulge in our biases and then validate them by self-justification. An example is that of a worker choosing not to wear eye protection. The worker 'has been doing the job for 25 years, and has not had an eye injury yet'. He concludes that if a risk really existed, he would have already experienced an injury. Further, he asserts that by wearing eye protection he is in danger of reduced visibility owing to restricted field of view and dirty lenses. In doing so, he discounts the effectiveness of eye protection as experienced by a larger population, in preference to his own; albeit lesser experience. He marginalizes the likelihood of the hazards that are known, by speculating on hazards that are much less likely in support of the *status quo* and a worldview that he is comfortable with.

2.4.2 Availability Heuristics

Availability heuristics (AH) is the principle that we are limited in identifying causal relationships to the extent that we have the capacity to identify, comprehend and explain them (Huang, 2007). We cannot act on causality that we fail to recognize. If we recognize a possible causal relationship, we may not understand it, and further if we cannot explain it in a concise way, we may discard it in favour of causality that we can. An example is the hazard of asbestos. The physical properties of asbestos fibres are not immediately recognizable, or apparent to the naked eye. As acicular fibres that are smaller than fifty microns in size, it is counterintuitive to most that they would be a problem for respiration. Further, their causal connection to mesothelioma (asbestosis) is a stochastic relationship expressed in the language of industrial hygiene and pathology. It required decades for management, and workers, to accept the correlation between asbestos and lung cancer. Eventually, the sheer numbers of cases of mesothelioma and the attendant dread of this disease compelled people to consider the possibility that respired asbestos causes cancer. Consequently, after considerable scientific

investigation into mesothelioma, the industrial community and the public alike accepted the high risk of cancer inherent to the exposure of respiratory asbestos (AMRC, 2008). The *availability heuristics* test was satisfied; the causal link between asbestos and mesothelioma was established, and the public became asbestos averse.

2.5 Social Context

We generally appreciate that only through investigation can we understand the causation of accidents, and set standards for their prevention. Lesser appreciated perhaps is that only through standards and the rule of law can society have sway over conduct in the workplace. This was known as long ago as 1760 BC. As Draconian as it may have been, the Babylonian *Code of Hammurabi* set the standard of the day and provided the first rule of law. Several of the 282 tenets conceivably relate to a contractual obligation between employer and employee. Johns (2007) interprets:

On the other hand carelessness and neglect were severely punished, as in the case of the unskilful physician, if it led to loss of life or limb his hands were cut off, a slave had to be replaced, the loss of his eye paid for to half his value; a veterinary surgeon who caused the death of an ox or ass paid quarter value; a builder, whose careless workmanship caused death, lost his life or paid for it by the death of his child, replaced slave or goods, and in any case had to rebuild the house or make good any damages due to defective building and repair the defect as well. The boat-builder had to make good any defect of construction or damage due to it for a year's warranty.

These tenets set the stage for what we might now refer to as a 'social justice' model, or a 'retribution model'; depending upon whether you were on the arbiter or the recipient. Clearly, the perception of the day must have been one of deterrent by reckoning, and this would naturally influence the way society scrutinized *events* resulting in injury. This relationship between accident theory (models) and the way in which we investigate them is no less true today - as it has been throughout time. This is the concept of *self-perception theory* (Bem, 1972), that proposes how we frame or model *events*, influences how we explain them or attribute their causes.

Any accident model contains the equivalent of a conceptualized blueprint for the accident investigation, and its ultimate explanation. It is a 'how to' structure in which the investigator sets and prioritizes his objectives, and collects and analyzes the evidence.

As the adage goes, 'if the only tool in your tool kit is a hammer, then everything looks like a nail' (author unknown). Similarly, if your accident model seeks to find the 'guilty parties,' then blame will be the outcome. In the vernacular of one researcher (Huang 2007:41), insofar as accident methodology is concerned, 'what you look for is what you find', and 'what you find is what you fix.'

2.6 History of Accident Theory

Many authors have documented the progression of accident theory with time (Benner, 1975; Harvey, 1985, Davies et al, 2003, and Stranks, 2007). There will always be debate as to why accidents occur; however, there is much concordance as regards to the emergence of accident theory. There are at least four schools of thought or models of accident theory, more if you consider their variants (Benner, 1985). There are the sequence-of-events, epidemiological, systemic (Dekker, 2005) and unequal initial liability theories. Two cautionary principles to consider when evaluating accident theory (models) are:

- i. Consider accident theory in the context of the times. We do not hold the same values, beliefs or perceptions of risk of those that theorized on accident theory during the 1930's.
- ii. It is easy to confuse what are models for investigation, and what are methods of analysis (Benner, 1975). Simply stated, any comparison of methods of investigation or their analysis should be limited to those subscribing to the same accident theory or model.

2.6.1 Unequal Initial Liability Theory

At the turn of the 20th century, the prevailing theory was that of *accident proneness* (Visser, 2007). This theory, also known as the *Unequal Initial Liability Theory* (Stranks, 2007), asserts that there are those within society that are predisposed to accidents and owing to their own carelessness cause calamity and misfortune. Central to this theory is the notion that persons prone to accidents have inherent character flaws or personality characteristics that put them at risk. Compensation funds were in their infancy, and accidents were largely subject to litigation. Dickinson and Flemming (1950:769) write:

For more than a quarter century there has been in the psychological literature a concept that some individuals are more likely to have accidents than are people at large. Their greater liability to accidents has been called 'accident proneness', which 'may be regarded as a combination of human abilities which make a person highly proficient in bringing about accidents'. The implications of this concept may best be brought out by casting its treatment into three sections: (A) Are there accident-prone individuals? (B) What causes accident proneness? (C) What can be done to decrease the number of accidents due to accident proneness?

As predicted by self-perception theory (Section 2.5), if accidents are modelled in a blame setting (vehicle insurance is an example of an at-fault system) then the method of investigation and the outcomes are necessarily influenced. The standard of investigation for vehicular accidents does not meet that of accidents occurring in the workplace. Domestic accidents are likely to be investigated to an even lesser standard than vehicle accidents. It is paradoxical that when we perceive accidents in a blame setting for the purpose of settling insurance claims and determining liability, the investigative rigour is less. One can only speculate what reductions in injuries could be realized if vehicle accidents and domestic accidents were to be investigated with the same rigour as in other domains (workplace, transportation and environmental *events*).

2.7 The Sequence-of-Event Model of Accidents

The *sequence-of-events* model considers multiple failures as a chain-of-events in which the antecedent failure directly causes a succeeding failure, eventually leading up to the defining *event* (Hollnagel, 2004). The *sequence-of-events* model is also known as the cause attribution model (Perneger, 2005) because, as its name suggests, the model seeks to attribute the cause(s) of an *event*. The theory holds that in order to prevent an *event*, one has only to stop a failure or establish a barrier between any two failures (Woodcock, 1989) (Figure 2.2). Still relevant for simple *events*, the model is limited to technical failures or failures in which the cause and effect relationship is obvious (Leveson, 2004).

2.7.1 Advantages

The model is appealing as it is intuitive. The *sequence-of-events* model keeps the narrative simple and explicitly (not explicatively) states the cause-effect relationships (Harvey, 1985). It has dominated the discipline of accident investigation from the early

1960s until the late 1970s; influencing such analytic methods as Fault Tree Analysis, Failure Mode and Effect, and Energy and Barrier Analysis. The model lends itself graphically, and communicates causes and their effects well (Dekker, 2004).

2.7.2 Disadvantages

The *sequence-of-events* model fails to establish any intrinsic connection between the failures (Dekker, 2004). The model promotes looking for causes and failures, and in doing so can lead an investigator from a more explicative approach (Hollnagel, 2004). There is a question of subjectivity as to what are the failures, and how far back one goes to establish the chain (Benner, 1975). The investigator has discretion, thus introducing opportunity for bias into the analysis (Harvey, 1985; Perneger, 2005). When attributed to unsafe acts or unsafe conditions, the failures interpretations of the data rather than a pure presentation of the physical evidence (Benner, 1985).

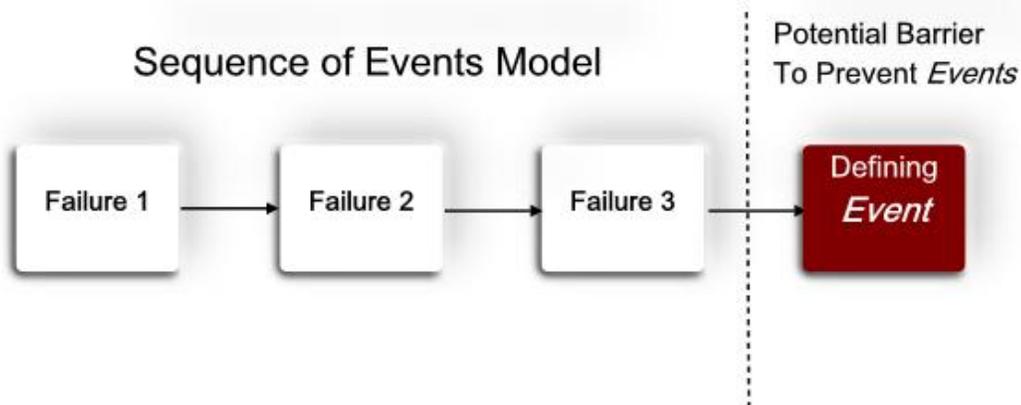


Figure 2.1: Schematic illustration of the Sequence-of-Events Model

2.8 The Work of Heinrich

Heinrich was a pioneer in accident theory at a time when there was little data or research of accident prevention. As an engineer for an insurance company, Heinrich studied the causes of 75,000 accident cases and noted the overwhelming rarity of actual accidents to minor accidents and near misses (Heinrich, 1931). He identified a ratio of 300:1 of accidents and incidents; describing what is now known as the “Heinrich ratio” (Busse, 2002) (Figure 2.2). This ratio implies that by intervening in near misses, a more

serious *event* is pre-empted (Hollnagel, 1988). Heinrich was well acquainted with actuarial science, which permeates his theories; theories that are still popular today.

Heinrich proposed that accidents were the product of five cascading dominos; thus coining the term 'domino theory' (Figure 2.3), and published the concept as early as 1931 (Heinrich, 1931). His work epitomises sequence-of-event accident modelling; however, it has its detractors owing to the inference that there can be a single cause to an *event* (Stranks, 2007). The inference is probably justified, for Heinrich was drawing from accident records written during a period when investigators of accidents were disposed to accident proneness theory. Heinrich asserted that the immediate causes of accidents consist of unsafe acts and unsafe conditions, with the former contributing as high as 88 percent of the time. The veracity of this number has drawn considerable criticism and doubt (Petersen, 1988), as revisionist theorists consider it blame oriented.



Figure 2.2: The original accident triangle depicting injury ratios (Heinrich, 1931)

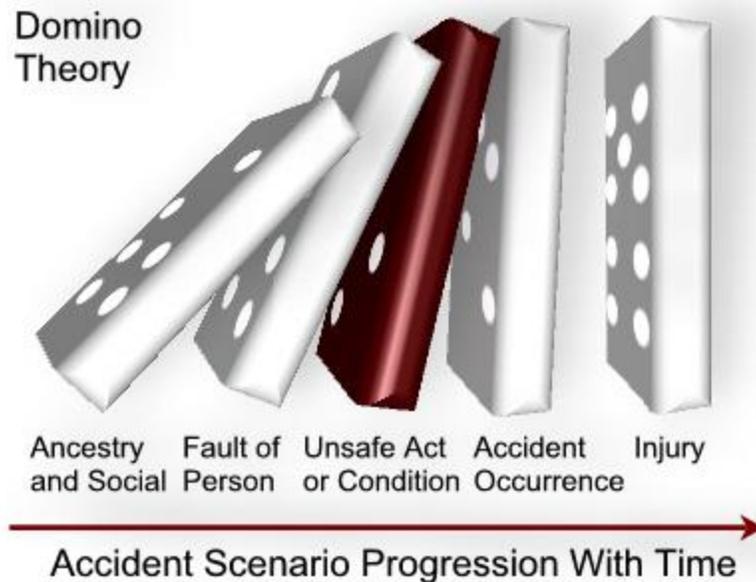


Figure 2.3: The original Domino Theory of accident causation (Heinrich, 1931)

By framing the causes of *events* as attributable to personality characteristics, Heinrich limited his modelling of accidents to more anthropocentric factors, or failures. Heinrich *et al* (1980) later introduced a new model of safety management featuring recursive hazard control (Figure 2.4). The feedback loop was based on the determination of an acceptable level of safety by considering hazards in a monitor-analyse-remedy fashion. In this regard, Heinrich *et al* were moving towards the notion of risk, and its management. However, as control process go, the model had a characteristically very long feedback response time (Huang, 2007). That is, in the Safety Management model there was an early indication that causality was something more complex than causation; that the cause and effect implicit of the Domino Theory was not sufficient or as inclusive as was previously thought to be the case. There was a deeper, more incipient meaning to causation that was emerging. Heinrich *et al* (1980) anticipated that there were artefacts within the workplace such as policies, plans, and procedures that reflect the principles and beliefs of their makers and to this extent defined a standard of care and conduct to which the workplace parties were expected to conform.

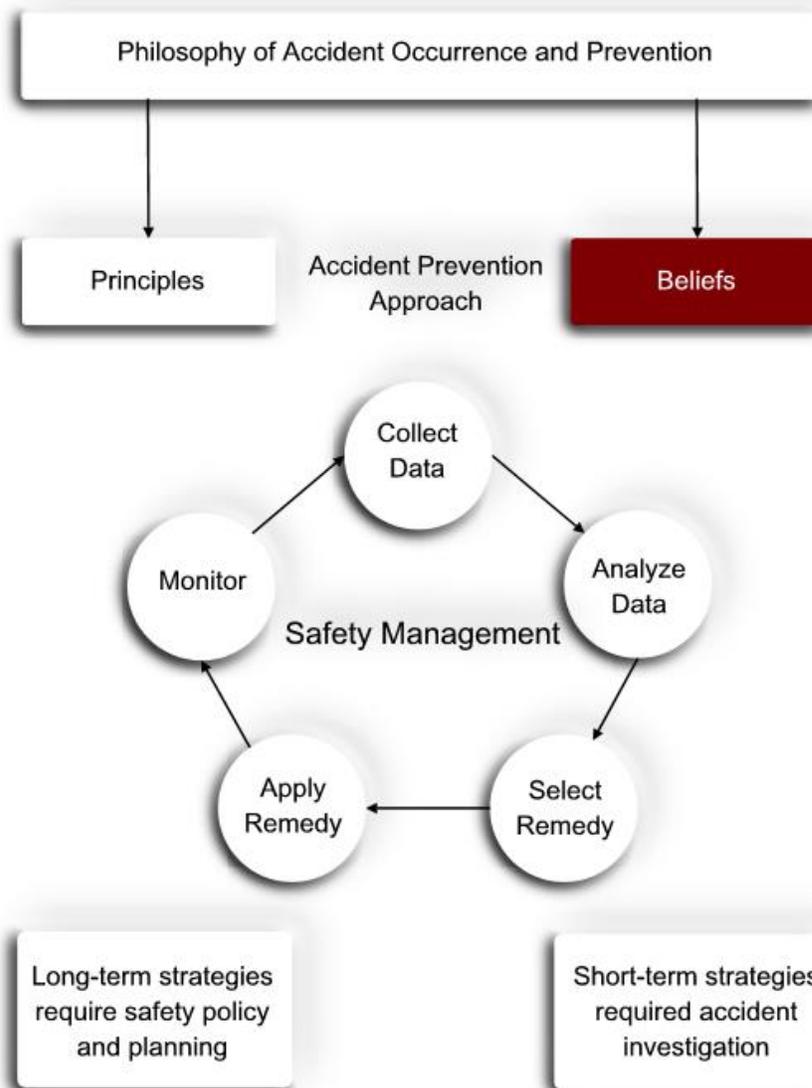


Figure 2.4: Graphic illustration of the Safety Management model (Heinrich et al, 1980)

2.9 The Work of Bird and Germain

The work of Heinrich strongly influenced that of Bird and Germain (1974), co-authors of the *Practical Loss Control Leadership* marketed by the International Loss Control Institute (ILCI). The International Safety Rating System (ISRS) was based on the Loss Causation model (Figure 2.5), which saw global application as an emerging technology in loss prevention during the 1980s and 1990s (Kjellen, 2000). Building on

Heinrich's earlier work, the Loss Causation model improved on sequence-of-events modeling, but still incorporated aspects of the Domino Theory (Vinicoli, 1994).

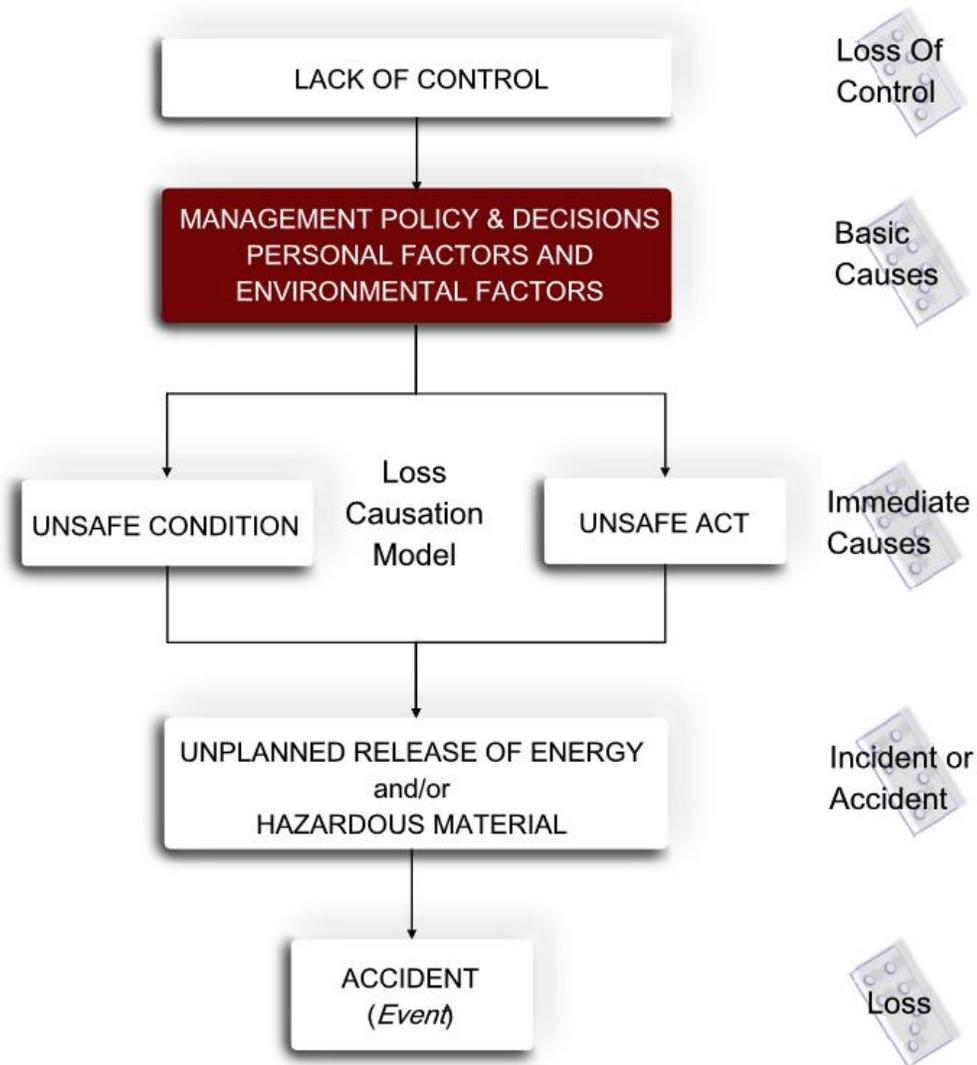


Figure 2.5: Graphical illustration of the Loss Causation model (Bird and Germaine, 1974)

This explicit and expanded application of the Domino Theory included the phases of loss of control, basic causes, and immediate causes, the incident, and the loss. The first domino was 'lack of control' and the nascent concepts of environmental and personal factors were introduced as basic causes; very much under management control. The subsequent unsafe acts and unsafe conditions were considered as immediate causes of an incident that had a potential for downgrading to an accident

(Storbakken, 2007). The twenty-module program, known as the ILSI program, proposed a very detailed schema for the codification of accidents (mechanism of injury, body part, and type of injury) that is still popular today with compensation boards and underwriters (Kjellen, 2000). Further, by integrating 'loss control' into the existing management systems in the workplace, the Loss Causation model made the case that loss prevention was a function of management no less important than production, organization and other priorities (Vinicoli, 1994).

Society's perception of *events* in the workplace was shifting. The management of losses was an expected and prudent way of conducting business. This change in perception from losses being a 'cost of doing business' altered the way in which *events* in the workplace were investigated and reported. Consequently, the Loss Causation model was, and still is, a very successful application of sequence-of-events theory.

2.10 The Epidemiological Model of Accidents

By the late 1970's, it was apparent that accident models should identify how cause and effect relate - organizationally, environmentally and socially (Dekker, 2004). The *epidemiological model* does not seek to determine cause, but to reveal statistical relationships of populations (age, experience, vocation and training) between risk factors and the outcome of the *event* (Haddon, 1980). The strategy is to identify the associated personal and situational characteristics to any variable that co-varies with the occurrence of an *event* (Harvey, 1985). *Epidemiological models* apply the same rigour and structure to accident theory (injuries) as is used in infectious disease control (Huang, 2007). In the control of infectious diseases, a host-agent-environment model exists that describes how an agent (virus) can infect a host (bird) within an environment conducive to infection. To apply the analogy to an *event* in a mine, we consider a scenario involving a fatality of a worker in an underground mine. The host (the worker) is exposed to loose rock (the agent) in the back of the mine, in which the rock is geo-mechanically weak and poorly supported by bolting and screening (the environment). Intrinsically, the model seeks to relate the experience and training of the worker, the mine design, the monitoring and support of the rock mass with the working conditions and organizational nature of the mine. The investigation is necessarily broader and more inclusive.

An *epidemiological model* considers both *active* and *latent failure*. *Active failures* are the failures that we typically think of triggering an *event*, and are proximal to the

event. *Latent failures* are those that are not as obvious and conceivably may exist for days to decades in dormancy until having triggered by circumstances (Dekker, 2004). An example in mining is the occurrence of high-wall failures. Decades ago, it was common practice to dump waste rock over a high-wall without a high-wall design contemplating the drainage of ground water. In this scenario, as time progresses, the movement of water results in the erosion of fine-grained material as it percolates through the waste dump causing sub-surface channelling. Eventually a storm *event* occurs. The interstitial pore spaces of the waste rock are saturated, and due to reduced cohesion and internal friction within the granular material, tension cracks occur – resulting in high-wall failure. The *active failure* may be the lack of inspection, monitoring and control; however, the *latent failure* is the waste dump design lacking water drainage and diversion.

2.10.1 Advantages

By design, this model is inclusive of multiple causes, and identifies factors as opposed to causes. This model provides a more meaningful analysis of factors distal to the *event*, and does not attribute causes to *events*, but seeks to establish more stochastic associations between risk factors and their outcomes. *Epidemiological models* are broader in scope and context than sequence-of-events models. *Events* are considered inclusive of environmental and social factors, as a techno-social system. The model also encourages the investigator to scrutinize the organizational contributions to an *event* (Dekker, 2004).

2.10.2 Disadvantages

Epidemiological models tend to be linearly sequential. Time flows only in one direction and time appears in most epidemiological models as the determining dimension. *Epidemiological models* tend not to explain the process by which holes in defences (both active and latent) come about (Dekker, 2004). Investigators fall into the old paradigm of being satisfied with identifying them as failures. They also may generalize the non-conformities as system, organizational or cultural failures. These characterizations do not take full advantage of the utility and comprehensiveness of *epidemiological models*. Although perception bias is reduced, the complexity and scope of the model introduces *selection bias* (how evidence is selected), *information bias* (what

is data and what is information) and *confounding bias* (lack of comprehension regarding error interaction) (Perneger, 2005).

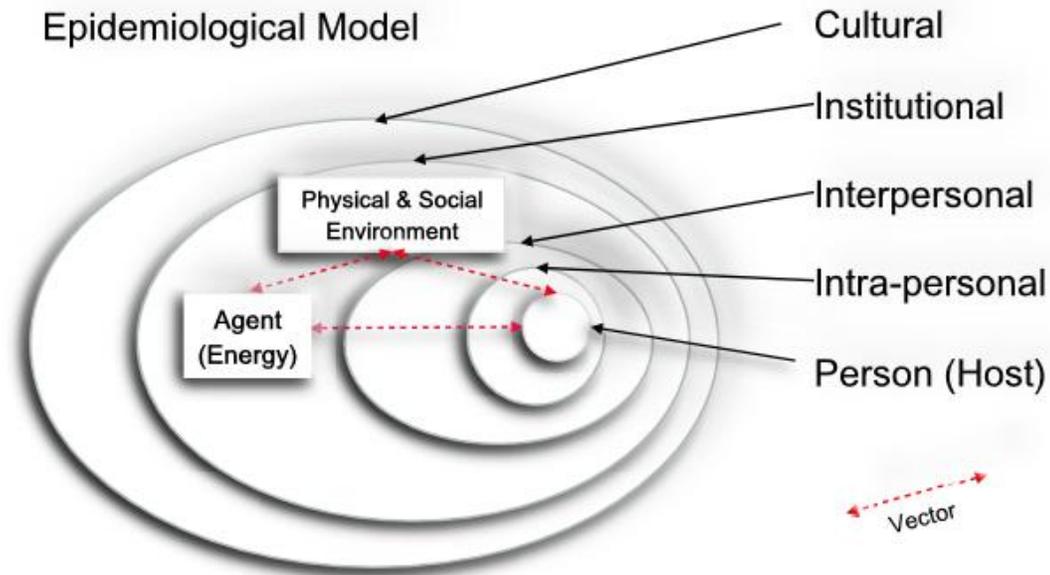


Figure 2.6: Bronfenbrenner's epidemiological model of illness and injuries (Runyan, 2003)

2.11 The Work of Haddon

William Haddon was a physician as well as an engineer. Schooled and skilled in curative and preventative aspects of medicine, Haddon worked with road designers on highway traffic safety. Building on conventional epidemiology theory, Haddon recognized that injuries and illness were two sides of the same theoretical coin. Haddon was influenced by Drs. John E. Gordon and James J. Gibson, early progenitors of epidemiological theory applied to injuries. Haddon proposed a structure that facilitated epidemiological modelling in a graphical, concise format known as the Haddon Matrix (Huang, 2007; Runyan, 2003). In the matrix (Table 2-1), the *host*, *agent* and *environmental* factors are enumerated across the matrix, whilst time flows down the matrix. The *host* refers to persons at risk. The *agent* of injury can be any form of energy. The *environment* can be either physical or social; the former speaking to the setting in which the *event* occurs, the latter referring to norms, mores and cultural considerations.

Given Haddon’s medical background, it was only natural that the matrix provided an aetiological perspective of accident theory. As such, the model has utility as a means of identification of risk factors and a method to devise strategies for their prevention (Runyan, 2003). By example, consider the Haddon Matrix as applied to an *event* involving a worker exposed to an unguarded piece of energized equipment (Table 2-1). The matrix allows a structured analysis of the hazard before, during and after an *event*.

Phase	Host (Workers)	Agent (Energized Equipment)	Physical Environment (Mine)	Social Environment (Workplace)
Pre- event	Instruct workers as to the regulatory standards in the workplace (the requirement for lock and tagging)	Design and construct equipment with attachments for locks and tags to assist in compliance with standards	Establish preventative maintenance programs to reduce unplanned work	Encourage right to refuse unsafe work, right to know, and right to participate legislation
Event	Train workers not to work on energized equipment (apply lock and tag procedures)	Ensure that equipment is in the zero energy state to reduce worker exposure to hazard	Provide personal protective equipment and hazard detection alarms/systems	Employ accident prevention strategies and workplace monitoring
Post- event	Ensure that all workers are trained and knowledgeable in emergency procedures	Maintain ease of access and safe passage for workers and rescue workers to the work areas	Investigate and review all near miss incidents to ensure efficacy of safety systems	Ensure funding for emergency personnel appropriately trained in elevated and confined spaces

Table 2-1: Table illustrating the Haddon Matrix as applied to an *event* in the mine workplace

2.11.1 Hosts

In an *epidemiological model*, *hosts* are the recipients of harm. For the purposes of accident theory, the same is true; only with wider scope. *Hosts* are the recipients of harm or potential harm and can be people, assets, production, or the environment. *Hosts* define that which is protected and for which controls and defences are put in place. For the purposes of traditional mine settings, *hosts* are the various workplace parties, the equipment, production values or the receiving environment of mine effluent.

2.11.2 Agents

In an *epidemiological model*, an *agent* is the mechanism or vehicle by which the *host* is subjected to a pathogen. For accident theory, in the most common sense, the *agent* is energy – potential, kinetic, thermal, nuclear, electrical or chemical. However, as both the environment and humans are subject to disease and toxins, the *agent* can also be a biologic pathogen. *Agents* can be passive or dynamic. An example of a passive agent is someone or something at rest falling from height. An example of a dynamic agent is the weather, with all of its fluctuations and unpredictability.

2.11.3 The Environment

In an *epidemiological model*, the *environment* is that which the pathogen originates or comes from. For accident theory the *environment* can be physical or social, and defines the nature of the *environment* in which a *host* and *agent* are present. The mine workplace environment is one that is particularly of issue as regards to risk, and should factor prominently in any analysis or *event*, epidemiologically speaking. Paradoxically, the mine environment is often omitted from investigations of *events*, as investigators are over familiar with the hazards, to the point of complacency.

2.12 Perspective

The principal disadvantage of epidemiological models is the perspective of the observer, or investigator. The model is one that ‘sees’ accident causation from the perspective of an outside observer looking in. In doing so, the model does not facilitate appreciation as regards to how actors within the *event* scenario could have recognized the hazards, or the risks, for what they were (Dekker, 2004). Further, it does not help us to understand why the actors saw those risks the way that they did – as acceptable, or not. It does not identify decisions made by actors within the *event* scenario and evaluate those decisions for veracity of assumptions from the point of view of the decision maker.

The *epidemiological model* considers *events* through the objective lens of probability, in terms of host/agent/environment interactions. The typical mine workplace offers analogous examples of *environments* and *hosts* suitable for epidemiological modelling, however, the identification of *agents* is not as intuitive or meaningful. This limitation underlines the lack of theoretic foundation of the *epidemiological model* and

suggests that disease prevention models and injury prevention models are comparable only to a point.

2.13 Systems Model for Accidents

All of the previous models apply the premise of analysis by deconstruction. By doing so, they do not consider how things are supposed to work; how the components come together to make the whole and interact with each other (Dekker, 2004). In many cases, causation can only be determined and made sense of by considering the system holistically. Increasing complexity of organizations and technology requires accident modelling based as much on synthesis as analysis.

Systems are dynamic, and consequently *event* models should consider an *event* scenario as a process of disequilibrium or instability within the *system*. Systemic theory holds that an *event* can occur when the performance of the system is unable to meet the demands of the environment (Huang, 2007). Complex techno-social systems may start out with an initial state of balance or equilibrium, but spontaneously reach a critical state of *self-organized criticality* spontaneously without any intentional alteration of operational parameters (Blanchard et al, 2000). The faculty to describe this state of 'criticality' of *systems*, much less predict it, is still in its infancy and is very much the promise and the challenge of developing *system* models.

2.14 The Work of Reason

A contemporary example of *system modelling* is the 'Swiss cheese' model (Reason, 1990) (Figure 2.7). In this model, failure trajectories line up, and the concept of *latent failures* and *active failures* is central. The slices of Swiss cheese represent various defences to prevent an occurrence, and the holes represent failures and flaws in those defences (active and latent). The *trajectory* through the slices represents the circumstance when all of the factors come together to create a destabilizing *system* culminating with an *event*. The model also incorporates the idea of defences existing and then being defeated by a variety of mechanisms, metaphorically referred to as *pathogens*. It is curious to note that once again, medical jargon has crept into the lexicon of accident theory. Poor management practices, inadequate procedures, failed

engineered controls and lack of training are cited as examples of human *systems* subject to error and failure (Reason, 1990).

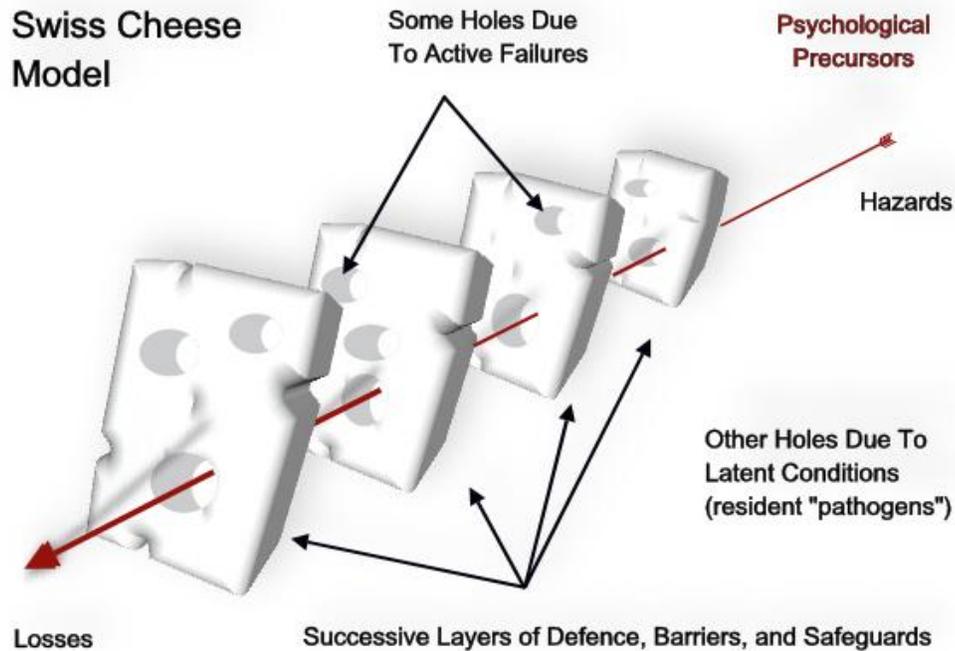


Figure 2.7: Illustration of the Reason's 'Swiss cheese' human systems model

The Swiss cheese model introduces the concept of psychological precursors at the organizational level, thus opening the door to evaluating safety culture and the organizational ethos. The model is graphical and encompasses the idea of a hierarchy of controls (elimination, substitution, engineered, administrative, and personal protection controls) and their vulnerability. The model does not however, explain or account for how these trajectories occur, nor suggest their remedy (Dekker, 2004). It incorporates stochastic constructs of risk, and in this regard is suggestive of epidemiologic influences. Reason's Swiss cheese model has become iconoclastic, and synonymous with human *systems*, and therefore is an early progenitor of *system* theory; particularly as applied to the medical profession. It is acknowledged, however, that the Swiss cheese model is no less relevant to other industry sectors; and, has substantially influenced this research.

Within complex techno-social *systems* are flaws in design and sub-systems that can interact in inexplicable and unpredictable ways (Perrow, 1984). *System* models do not require that a component or sub-system fail, or otherwise be the cause of anything. The *system* itself, under normal operating conditions, has such interaction and coupling that catastrophic failure occurs because of changing operating conditions, or degrading compliance and operability. The degree of coupling and interaction is thought to be a measure of complexity of *systems* (Perrow, 1984) and a good indicator of the insidious potential of complex *systems* in emerging high technology enterprise (Figure 2.8).

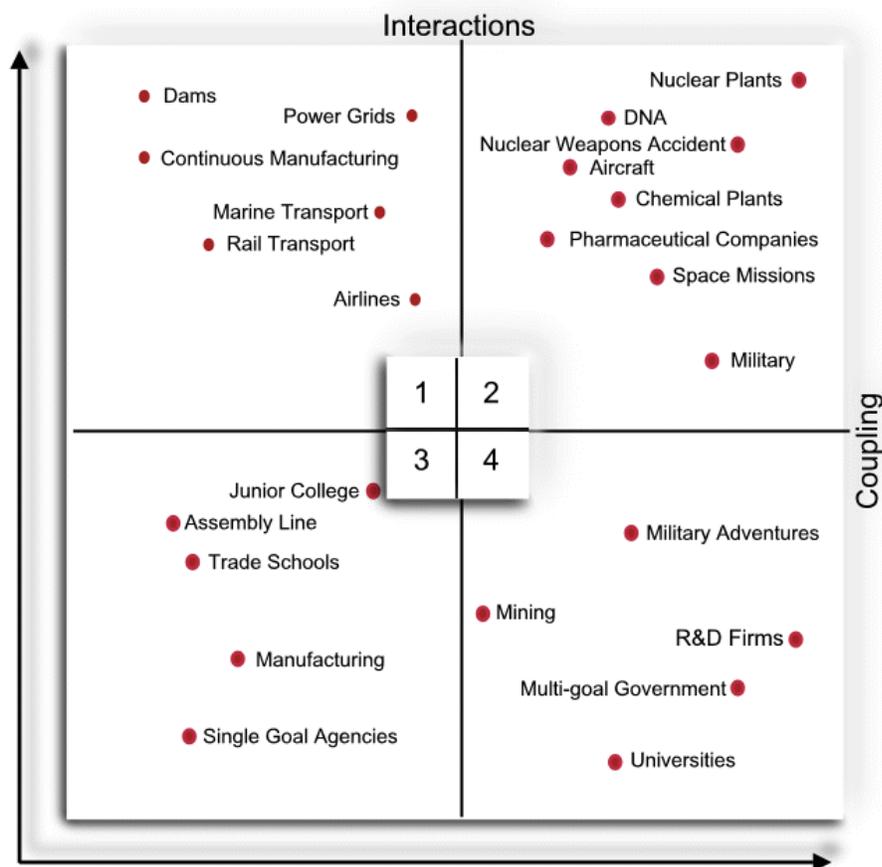


Figure 2.8: Schema of mapping enterprises by system interaction and coupling

2.14.1 Coupling

Coupling refers to the degree of 'connectedness' between sub-systems or their components. The systems can be social, organizational, physical, or process domains.

Regardless, *coupling* is the amount of buffer in time, space or behaviour between components that will allow for intervention if there was a problem or upset condition (Perrow, 1984). For some enterprise, tight *coupling* is a good thing; the pharmaceutical industry for example is highly coupled with tight controls so that the pharmaceutical product meets a high standard – every time. There is little margin for error. Other enterprises, like mining, benefit from low *coupling* and realize the benefit of being able to start and stop different parts of their mining cycle depending upon the geology and operating conditions. If an upset condition occurs in the tailings, the mining system can accommodate this by stockpiling ore and modifying the mill circuit. Government organizations, research and development, universities and most manufacturing benefit from, and are examples of, loosely *coupled systems* (Perrow, 1984:97) (Figure 2.8).

2.14.2 Interaction

Interaction refers to the degree of complexity or linearity within systems. Linear *interactions* are at one end of the spectrum, and complex *interactions* at the other (Figure 2.8). Linear *interactions* are typically sequential, transparent to the operator, and generally planned and anticipatory. Complex *interactions* are more subtle and problematic from the point of view of the potential for *system* upset conditions. They are unplanned and unexpected, and are not conducive to comprehension or detection (Perrow, 1984). Complex interactivity is common to petrochemical plants, avionics, and nuclear power generation systems. Typically within the enterprise of mining, systems are not very complex (Figure 2.8), however deep mining and complex mill circuits are pushing the envelope, and mines of tomorrow and beyond are likely to increase in complexity with technological advancement (Sweeney and Scoble, 2006).

2.14.3 Self-organized Criticality

Self-organized Criticality is a theory proposed by Bak *et al.* (1987) that holds that dynamic systems over time incrementally move toward criticality, or a point at which they appear to be operating under normal operating conditions, but are moments away from failure. Although the original research was applied to avalanche theory of granular material, the theory has seen applicability in geology, ecology, biology, economics, sociology and physics. Potentially, the Chernobyl, Space Shuttle Challenger and the Three Mile Island disasters were systems that exhibited the characteristics of *self-*

organized criticality. These enterprises, presumed to be in a state of equilibrium, responded to minor perturbations within their system design. Stable systems have the capacity to absorb or accommodate minor perturbations in proportion to their magnitude. *Self-organized critical* systems respond differently, as described by Bak and Paczusky (1995:6690):

The basic idea is that large dynamical systems naturally evolve, or self-organize, into a highly interactive, critical state where a minor perturbation may lead to events, called avalanches, of all sizes. The system exhibits punctuated equilibrium behaviour, where periods of stasis are interrupted by intermittent bursts of activity. Since these systems are noisy, the actual events cannot be predicted; however, the statistical distribution of these events is predictable. Thus, if the tape of history were to be rerun, with slightly different random noise, the resulting outcome would be completely different. Some large catastrophic events would be avoided, but others would inevitably occur.

Self-organized critical systems are remarkable, in that the distribution response to perturbations appears to follow a power-law mathematically, and their escalation from incidents to disaster is not unlike thermodynamic systems (Blanchard *et al.*, 2000). Necessarily then, any accident model must have the facility to determine what are normal operating conditions of a system; and within these, what are its limits. This can only be achieved by a holistic approach, and hence the benefit of systemic modelling. *Self-organized criticality*, while not well understood, has great potential as applied to *event* causality, and this research introduces the concept as a mechanism that is explicative of latency and the intrinsic stochastic nature of *events* in the workplace.

2.15 Injury Compensation Models

As mentioned previously, perceptions strongly influence accident theory models of both theorists and investigators - and their outcomes. This is true at the societal level as well; as society's perceptions of risk and causality is manifested in their elected representatives in a democratic society, to the extent that elected representatives set public policy. It is revealing to examine the evolution of injury compensation funds as a measure of how society's perception and values have changed and shaped through time. As it turns out, Canada's contribution to the development and implementation of injury compensation funds is one of distinction and leadership. Canada was one of the first nations (Canada, the United Kingdom and Germany) to introduce workers legislation

governing workers compensation; and within Canada, the province of British Columbia was one of four provinces to first do so (British Columbia, Saskatchewan, Quebec and Ontario).

2.15.1 Emerging Workers' Compensation in Canada

The province of British Columbia narrowly missed the opportunity to become the first jurisdiction in the world to have a public funded accident compensation fund. In 1878 a bill was introduced to the BC Legislature known as the '*Workman's Protection Act*', which did not make a second reading for reasons unknown (Chaklader, 1998). During this period in Canadian history, coalmines on Vancouver Island were renown throughout the world for hazardous conditions as much as the quality of their coal. The only remedy to injured workers was to sue the employer, which many did not have the financial resources to do. A lawsuit had less than a 30% chance of being successful, which reflected society's perception that the risk of injury and death to coal miners was an 'assumption of risk.' Societies' understanding of accident causation reflected their perception of risk: that mine accidents were not preventable.

Six years later in 1884, Germany enacted the first workmen's compensation law. During this period, Saskatchewan, Ontario and Quebec enacted *Factories Act*, the first safety regulations for the workplace. Employers in contravention were subject to fines; however, there was no compensation for injured workers. The province of BC enacted the first Canadian fund in 1891 called the '*Employer's Liability Act*.' The *Act* required that the employer be liable only if an injury was a direct result of their negligence (Chaklader, 1998). Until this time, employers could legally provide a defence of 'faulty machinery or equipment' in the event of an injury – again reflecting the society's perception of the inevitability of accidents.

In 1897, the province of Saskatchewan passed the *Workmen's Compensation Act* providing workers compensation for injuries. However, it was limited to 'dangerous work' and the worker could not have contributed to the cause of the accident. It was not until 1902 that British Columbia enacted the first *Workmen's Compensation Act*, a rather liberal adoption of that of England passed in 1897 (Chaklader, 1998). An injured worker received compensation for lost wages resulting from injuries received 'as a result of or in the course of employment', and this was a turning point for society. Societal values had changed and the assumption of liability to workers for accidents in the workplace was no

longer acceptable. The province of Ontario introduced a similar fund in 1910 and was instrumental in defining the guiding principles of Workers' Compensation, embodied in the Meredith Report that set the cornerstone for compensation boards throughout Canada (Table 2-2) (AWCBC, 2007).

#	Meredith's Cornerstone Principle
1	No-fault compensation: Workplace injuries are compensated regardless of fault. The worker and employer waive the right to sue. There is no argument over responsibility or liability for an injury. Fault becomes irrelevant, and providing compensation becomes the focus.
2	Collective liability: The total cost of the compensation system is shared by all employers. All employers contribute to a common fund. Financial liability becomes their collective responsibility.
3	Security of payment: A fund is established to guarantee that compensation monies will be available. Injured workers are assured of prompt compensation and future benefits.
4	Exclusive jurisdiction: All compensation claims are directed solely to the compensation board. The board is the decision-maker and final authority for all claims. The board is not bound by legal precedent; it has the power and authority to judge each case on its individual merits.
5	Independent board: The governing board is both autonomous and non-political. The board is financially independent of government or any special interest group. The administration of the system is focused on the needs of its employer and worker clients, providing service with efficiency and impartiality.

Table 2-2: Table summarizing the five Meredith principles for workers compensation funds

The significance of these principles cannot be overstated. Not only are they the guiding principles of one of the most enduring of Canadian values and institutions; they set the tone for how Canadians perceive accidents in the workplace. This is truly a 'no-fault' system, and this fact alone has enormous implications for how Canadian citizens internalize and cogitate on accidents in the workplace. Within the collective ethos that is Canadian society, the attribution of *events* must be value neutral and as blame averse as practical. Our method of investigation is shaped by how we as a society, frame the causation (the theory) of accidents. We look for system errors, organizational errors, errors of cultural - errors of any nature other than those attributable to persons.

In 1909, an explosion in a coalmine took the lives of 32 workers near Nanaimo. The forest industry was also reporting a record number of fatalities. Consequently, a Royal Commission on Labour was set up in 1912 to amend the *Act*. Mining companies

and unions alike were polarized respecting how to protect workers from gassy mines. The Commission reported back in 1914. It was not until 1917 that the *Act* was amended including a provision for workers to receive medical aid compensation – the first of its kind in North America. The *Act* was further amended in 1938 to include benefits to widows and dependents. In 1942, a new commission was set up to review the *Act* to ameliorate increasing alienation of both Labour and Management on the issue of workmen's compensation.

It was not until 1954 that the *Act* was amended, due to World War II and several Royal Commissions. Recovery of lost wages and benefits to dependents was increased. In 1955, 1968 and 1972 the *Act* was again amended, with cost of living adjustments and increased benefits once again setting a global standard for workmen's compensation. In 1993, the *Act* was amended once again to include farm workers and domestic workers. The *Act* was renamed the Workers' Compensation *Act* to be more in alignment with societies values of inclusion of women in the workplace. A fourth and final Royal Commission occurred in 1996. No doubt, the *Act* will be amended again, in accordance with the changing perception of risk on the part of the citizenry of British Columbia.

2.16 Why Model?

A model is actually a framework; 'a structure in which all of the ideas and thoughts one has about a subject can be organized' (Hendrick and Benner, 1987:8). Reflecting on the advancement in accident theories that have been made in recent decades, it is tempting to conclude that the systemic model will win the day. History will judge, however it will be some time before the 'new investigators' will be sufficiently trained and empowered to investigate *events* in the workplace within the scope and context of a systemic approach. The reason for this is that a systemic approach to the investigation of *events* in the workplace requires more of the investigator(s) than is currently afforded to them by mine management. This is not an indictment of mine management, but an observation that there are 'disconnects' between the typical organization structure of mine operations, and the goals and objectives of systemic modelling (Figure 2.9).

Systemic investigations are holistic; inclusive of human, organizational, techno-social factors and the way these interact as a system. This is a 'big picture' view of the organization, one that requires a perspective of the entire enterprise – from the influence

of the regulatory authorities down to that of the worker at the face (Figure 2.9). It is imperative that all departments and their personnel be considered as potential decision makers in an *event* scenario. This is problematic. Most mine organizations delegate the investigation of *events* in the workplace to persons with narrowly defined job descriptions limited in scope and authority. This is not to say that they are not professionals, or discharge their duties in a professional way. In the absence of seeing all of the parts of the whole, it is difficult for investigators to take a holistic approach. If they are restricted to the time and resources limited to determining cause and effect relationships (causation), then they will not be successful in understanding the *event* and the inherent complexities of techno-social interactions required of systemic modelling.

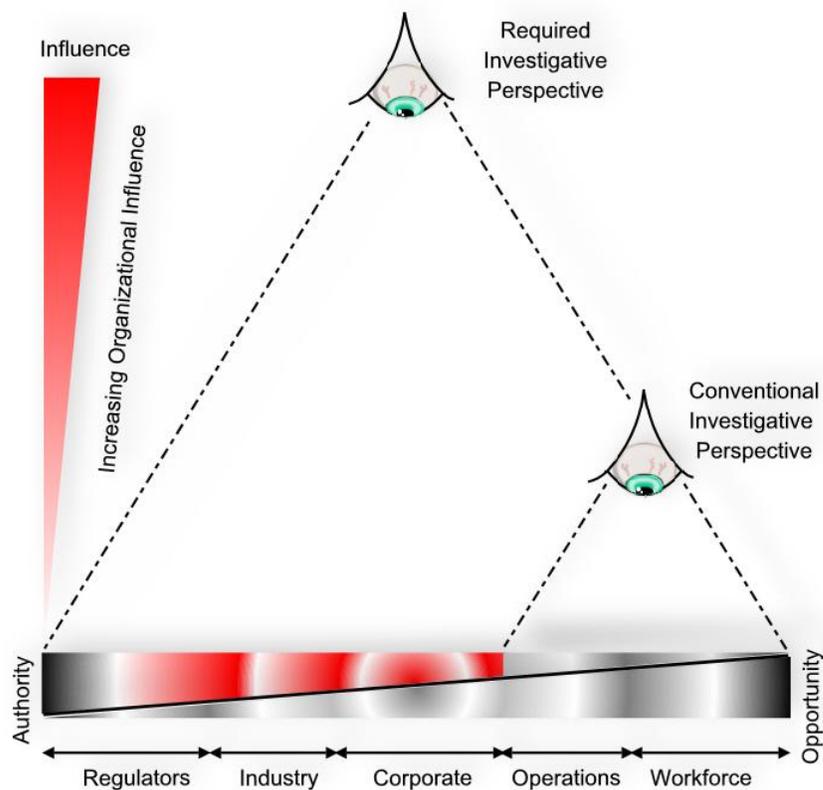


Figure 2.9: Diagram illustrating the value of shifting investigative perspective

Health and safety, environmental and human resource professionals seldom have access to information at the enterprise level. When they do, sadly it is because the *event* is so grievous or tragic that the investigation is necessarily thorough and inclusive.

Clearly, this is not proactive. The traditional hierarchical organizational structure of mine operations is not aligned with modern systemic accident investigation approaches. This is also true of parties outside operations, but still within the enterprise of mining. Chief among these are corporate management, the regulatory community and organized labour. These enterprise parties have an immense capacity for influence of a mine operation, yet, rarely are they considered contributory to an *event* in the workplace.

The possibility that a corporate officer or a regulatory official made a decision error that contributed to the very *event* scenario that they are arbiters of, is a particularly vexatious one. However, within the evolving landscape of regulatory reform, there are indications that corporate officers, general contractors, regulatory inspectors and public officials are all accountable. Bill C-45, in the wake of the Westray Inquiry (Richard, 1996), is a recent enactment that serves to improve accountability in the workplace. It is federal legislation passed in 2004 that brings health and safety offences into the criminal courts of Canada, should a person or persons be convicted. It is anticipated that successful prosecutions under this *Act* will, in the fullness of time, engage senior officers and public officials to act within enlightened self interest (self-perception theory) and actively participate in the prevention of *events* in the workplace.

2.16.1 Attribution Theory

Attribution theory holds that people attribute causality based upon their own behaviours, or self-perception of those behaviours and the circumstances in which they occur (Bem and McConnell, 1970). Further, peoples' self-perception of those behaviours will influence how they recall *events*. In this respect, they are evaluating the covariance between their behaviours or actions and causation (Gyekye and Salminen, 2004) with a sub-conscious bias toward externalizing attribution. Workplace parties involved in an undesirable outcome (*event*) tend to attribute causation to external factors such as actions of others, lack of training, poor communication; a whole host of reasons excepting their own involvement and attribution.

Conversely, when the occasion provides a positive outcome, *attribution theory* holds that workplace parties will lean towards internal attribution. That is, they will consider it a reflection of their skills and abilities and will model future behaviours on decisions on this self-perception. It is prudent therefore that in evaluating decisions of parties to an *event*, that it is done without blame or value judgement as the parties will

devolve into external attribution and the decision record will be incomplete if not confounded. This research will examine the collective role that culture plays in the attribution of causality through the analysis of decision error.

2.17 Causation and Perspective

Causation is a concept that has outlived its usefulness in modern-day accident modelling. One can get lost in the fuzzy logic and convoluted world of causation (Davies et al. 2003). There has been much debate over the lexicon as well as the rules of causation, but at the end of the day, causation limits understanding and prejudices the outcome in an increasing litigious society. Invariably, causes of *events* in the workplace are a matter of perspective, as the cause of an *event* from someone inside an *event* scenario will be different from that of someone outside the *event* scenario (Dekker, 2004). The reasons are elementary. Parties inside and outside an *event* scenario are subject to varying biases (Reason, 1990). Parties inside the *event* scenario have the benefit of the knowledge of 'what were they thinking' and the reasons why a decision or action took place. The outside perspective is one of objectivity, one that tends to be limited to the 'what' and the 'how' (Wright *et al*, 2007). Understanding is not complete without the benefit of both perspectives. Hence, a systemic investigation is optimal in rolling back the layers of perceptions and biases in an effort to adduce what the parties within the enterprise were doing, and thinking. The cognitive element is a factor that has eluded many investigators and constitutes the threshold at which many investigations have ended. Only by asking what the thought processes were, and what decisions were made, is it possible to track the human factors and techno-social interaction of the workplace parties. Causation, as an attribution of cause, is not far removed from blame.

2.17.1 The Role of Determinants

Replacing causation is a more general notion of causality that can be best described in the language of determinants. Determinants are influencing, or determining factors, that consider a constellation of elements contributory to an *event* (Figure 2.10). They are neither necessary nor sufficient to 'cause' an *event*, but in their aggregate they come together as a system of hazards, errors, decisions and actions that have internal order and structure. This internally chaotic model of accidents (Perrow, 1984) does not require upset conditions, or the exceeding of design parameters, for *events* to occur.

This *normalization of deviance* (Vaughan, 1996) suggests that deviant behaviour and aberrant conditions are somehow internalized by organizations motivated to do so. As examples, we look to Space Shuttle Challenger disaster of 1986, the Westray Mine disaster of 1992, and the Exxon Valdez disaster of 1989. Common to all three disasters was that these enterprises were operating within acceptable limits and behaviours of the day, from the point of view of someone internal to the *event* scenario.

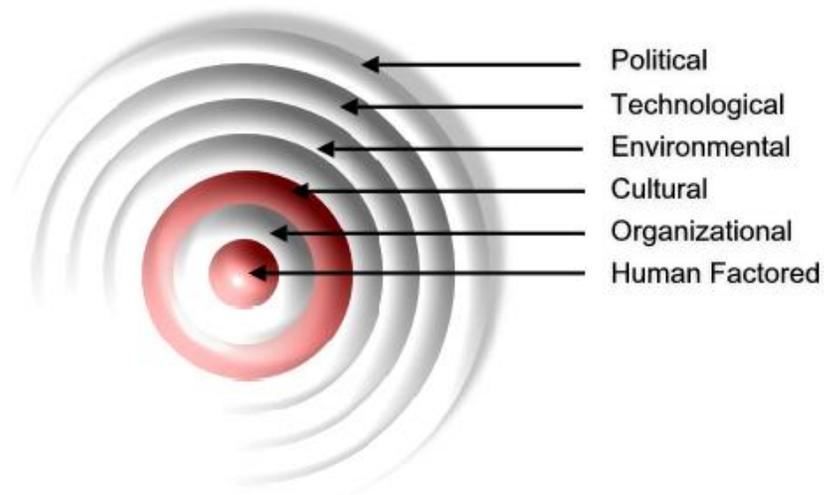


Figure 2.10: Diagram illustrating the broad spectrum of determinants comprising causality

This is more the case when you examine these disasters at the enterprise level. In each disaster, the regulatory agencies and local governments were implicated in their occurrence. Broadly speaking, determinants are categorized as political, technological, environmental, cultural, organizational, and human factored (Figure 2.10).

2.17.2 Events as Systems

Investigations are *systems* (Figure 2.11). This dissertation contends that *events* are also *systems* (2.13). A *system* is a 'network of many variables, in causal relationships with one another' (Dörner, 1996:73). The analysis of cognitive error is no less a system, completing the investigation loop (Figure 2.12). The inputs are decision errors discerned by investigation, and the outputs are cognitive precursors as determined by cognitive profiling. The cognitive profiling methodology proposed in this dissertation will show that decision errors are influenced by the perceptions of risk of the

decision makers, and that these perceptions are covariant with the psychological and cognitive precursors articulated by Reason (1990, 2005).

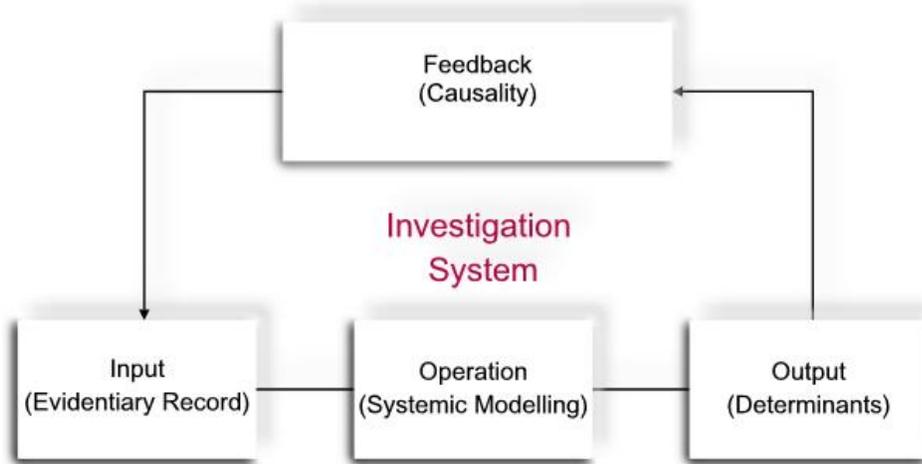


Figure 2.11: A schematic illustration of the recursive nature of systems applied to investigation

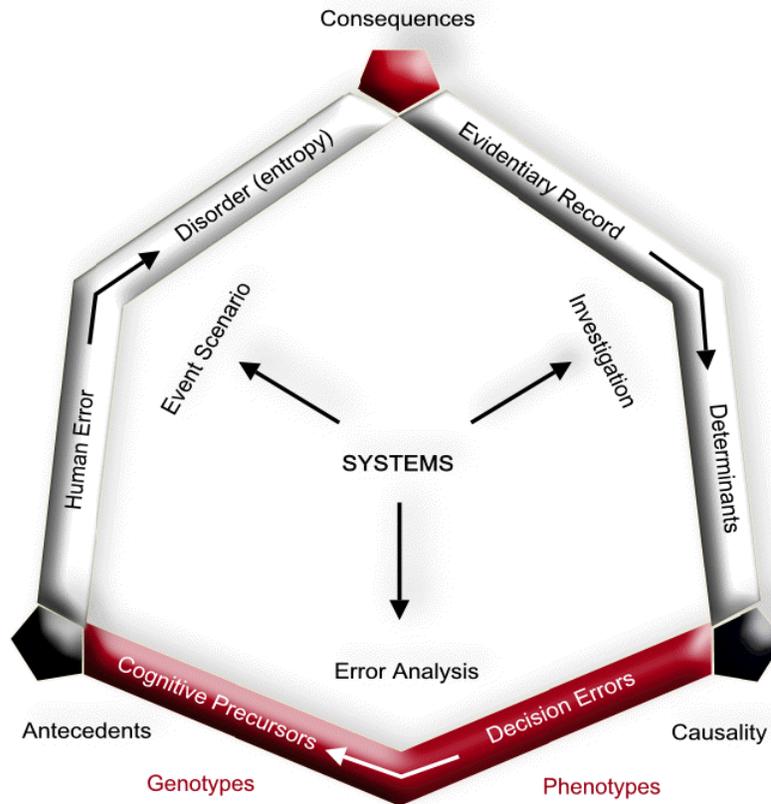


Figure 2.12: Schematic 'completing the loop' of accident investigation (Sweeney, 2004)

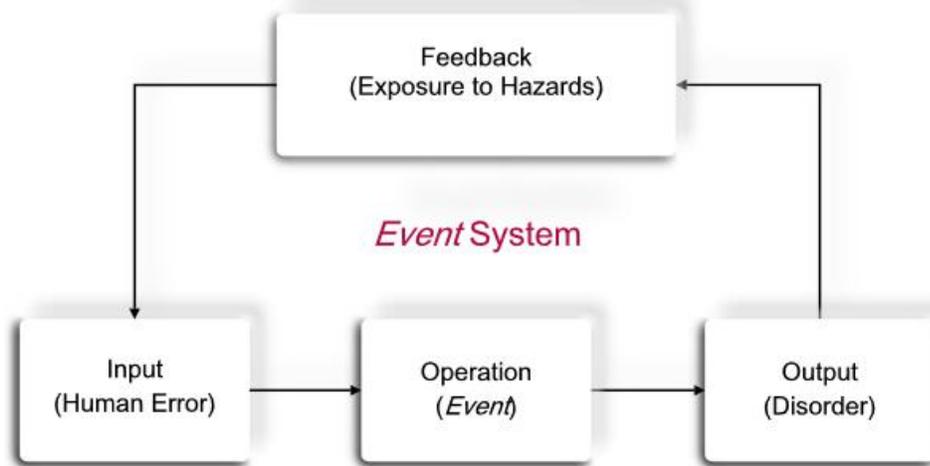


Figure 2.13: A schematic illustration of the recursive nature of systems applied to *events*

2.17.3 Error Analysis as a System

Contemporary methodologies in the investigation of *events* in the workplace are incomplete. Accident theorists are moving towards accident modelling that increasingly takes a *system* view of accidents (Benner and Hendrick, 1987; Perrow, 1984), which by their example are leading us toward a more holistic approach. The current paradigm of investigations is very much one wedded to responding to a consequence and working backwards to devise a model of cause and effect (causation).

A more holistic approach would be to define the error system inclusive of the *event*, and establish the determinants (inclusive of Reason's psychological precursors) of causality endogenous to the *system* (Figure 2.13). In so doing, one addresses the determinants of the *event*, as well as those *events* not yet realized. This is true prevention; one that is not limited to the immediate cause and effects; but includes all constituent errors in the error-forcing *system*.

The term 'error-forcing system' remains purposely vague in this dissertation. The mechanism of 'forcing' remains elusive and the concept of error as a system is more the point insofar as analysis is concerned. The revelation that errors can, and do, have self-organized criticality is paradoxical in light of the energy and resources that we as a society expend to prevent them. Nonetheless, it is by modelling *events* as symptomatic

of error *systems* that we achieve a more enduring and probative appreciation for the psychological precursors and perception of risk that are antecedent to them.

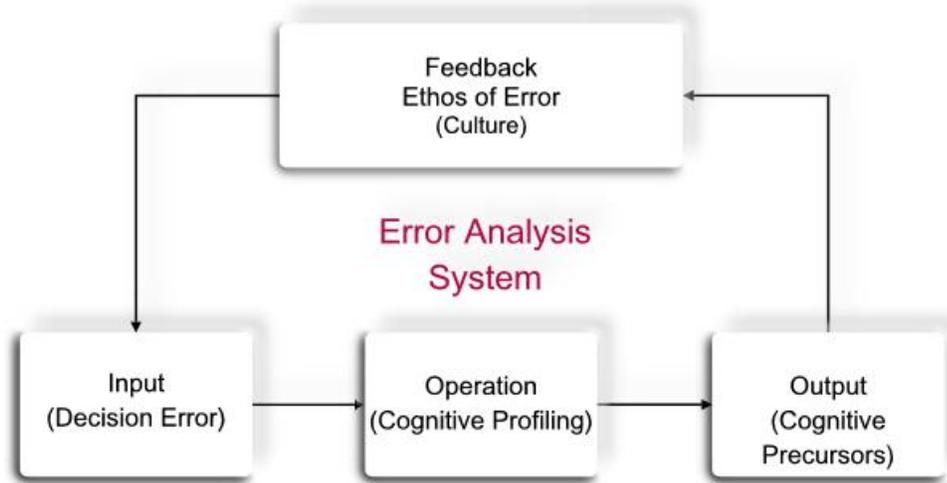


Figure 2.14: A schematic of the recursive nature of systems applied to cognitive profiling

2.18 Conclusions

This dissertation defines an *event* as a dynamic *system* of techno-social interactions between workplace parties, their technology and their working environment manifesting increasing disorder, or entropy. It is important to note that loss of operational integrity is the deleterious effect, but not necessarily a culminating effect. Loss of operational integrity may, or may not, result in an incident, accident or environmental excursion. The implication is that an *event* can be in progress that is not physically manifested. A mining operation that accepts increased risk and uncertainty may be operating outside of design parameters or the expectation of the parties within the enterprise – or it may not. Yet, without taking a *systemic* approach to investigation of upset conditions and close encounters, the *event* may go unnoticed until the active and latent factors exceed defences (Reason, 1990), and criticality occurs.

Davies *et al.* (2003) note that from the point of view of the observer *events*, causes, and their consequences are not simply properties of the physical world. Further, they argue that an observer cannot apply corrective action to *events* they don't perceive until such time as consequences or causes of those *events* are realized. The

perspective of the observer is paramount and upon it hinges the very notion of 'cause.' If for some reason the observer is not present as the *event* transpires, or lacks awareness, or ignores indicators that the *event* scenario (system) is in progress; then, they have a limited perception of the *event*, its risk and presiding uncertainty.

Systems are subject to external influences, but by virtue of their structure and integration, have a capacity for achieving internal equilibrium in response to these influences. Accordingly, it is proposed that within an *event* scenario (*system*) there is a similar, but opposing mechanism that causes disequilibrium – and that mechanism is entropy (Figure 2.12). By acknowledging that *events* are *systems*, we are recognizing their complexity; their dynamic nature; and, that they are not singular moments in time. They are not serendipitous or products of misadventure. Rather, *events* are unintentional products of humanity's effort toward enterprise; yet within them are seeds of disorder akin to *self-organized criticality* (Section 2.14.2). The question then becomes: where or to what do we attribute this disorder, and can disorder be predicted, if not prevented? The answer as determined by this research in the examination of historical records is – an unequivocal yes.

This dissertation proposes that *events* are *systems*, rather than singularities. Akin to Reason's (1990) pathogenic trajectories, *event systems* have destabilizing influences that require countering as entropy (disorder) increases with time. Inherent in this model of *events*, is the first hypothesis of this research, that:

Events are not random: they are physical manifestations of interactive systems between humans and their environment in which the likelihood of their occurrence is presaged by, and proportionate to, the dissonance between actual risk and its perception.

“Irrationally held truths may be more harmful than reasoned ones.”
Thomas Huxley (Bartlett, 2000)

3 COGNITIVE SCIENCE

Cognitive science is the discipline within the field of psychology concerned with human information processing, and includes attention, perception, learning, and memory; their structures and representation (Dawson and Medler, 2004). As the workplace becomes increasingly complex and automated, we can expect there to be a commensurate increase of the cognitive load carried by all of the workplace parties. We are steadily transforming from a world in which physical demands have dominated the workplace to one in which cognitive demands will be the determinants of *events* in the workplace. Sträter (2005:6) makes the case:

Humans at the working level are forced to make decisions based on constraints from targets set at the management level, the procedures and interfaces given, the required communication with working partners and the operational tasks to be performed. This leads to the phenomena of induced mental workload. The term ‘induced’ comprises the additional effort due to the type of interaction with the system. A frequently selling argument of automation is that it reduces workload. However, induced workload may cause an even higher net workload for the user than the workload an automated system is designed to reduce.

If we accept that the cognitive demand on workplace parties is increasing, then it follows that this demand will necessarily influence the provenance of errors contributing to *events* (Sträter, 2005). Human error will shift from proximate to the *event*, to more distal, as those parties making decisions respond to demands and constraints at the system and organizational level. The impact of these decisions and any associated error becomes more latent and distributed within the organization with the degree of separation from decisions and their unintended result. This ‘cognitive fog’ confounds accident investigation and requires us to understand the cognitive context for error, both

individually and collectively. It is therefore essential that we appreciate the linkages between management design decisions and the functional operating decisions at the working level. Both require cognitive processing and collectively determine behaviour and ultimately the amount of risk accepted in the workplace (Figure 3.1). In other words, 'we behave in a certain way based on the thought patterns which preceded the behaviour' (Gibson, 2001).

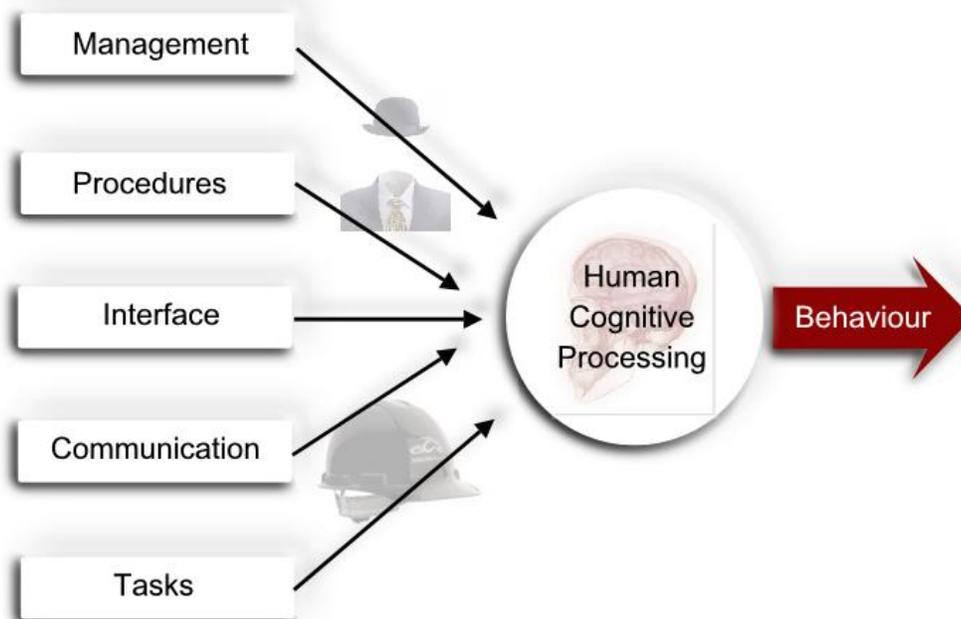


Figure 3.1: Influence of management and worker cognition on behaviour (Sträter, 2005).

3.1 The Cognitive Mill

The human brain is an information processor and is constantly comparing external stimuli of the 'external world' with that of its own representations, or 'internal world', (Sträter, 2005). As a process referred to as the *cognitive mill*, cognition is iterative, subconscious and stability seeking. That is, the *cognitive mill* is like an inertial guidance system in which our world view is being sampled through experience, perception and reasoning and then aligned with reality (Figure 3.2). Nominally, the internal and external worlds are in balance or otherwise in agreement; however, should there be discordance then a state of *cognitive dissonance* exists and some accommodation or intervention is sought. The implication is that in the absence of *cognitive dissonance*, there is no

perception or mismatch between the learned behaviour and the *event* scenario and it is therefore unlikely that a decision maker will alter their established behaviour. *Cognitive dissonance* is thereby a prerequisite for corrective action or behaviour change on the part of the observer.

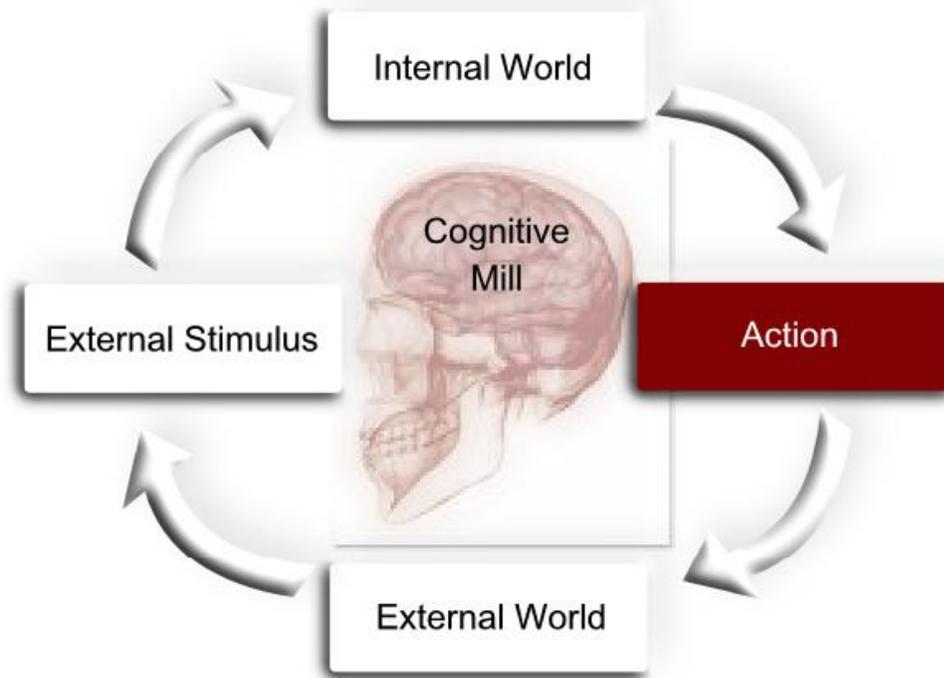


Figure 3.2: The cognitive mill model of human cognitive processing (Sträter, 2005)

3.1.1 Cognitive Dissonance

Cognitive dissonance is a cognitive science term that refers to a state of dissonance or discord between one's perceptions and their behaviours. In effect, two cognitions are competing for accommodation and a tension exists between a decision maker's perception of how things should be, and how things appear to be. In the absence of mitigating information, the decision maker is compelled to accept the duality or seek resolution by acquiring new beliefs, attitudes or information. *Cognitive dissonance* can cause decision makers to suspend disbelief, or resist accepting mental cues that they are uncomfortable with – effectively deferring responding appropriately to the new reality, as it would require them to depart from established behaviours and norms (Aronson and Travis, 2007). *Cognitive dissonance* impairs the decision maker's

ability to accurately assess and respond to a new perception of risk. *Cognitive dissonance* explains why people behave counter intuitively when provided with information that conflicts with their worldview. Ironically, when confronted with evidence contrary to their beliefs, an individual who holds a position (as regards to risk for example) often exhibits an increased commitment to their belief. They are prone to biases and heuristics such as confirmation bias and self-justification, through which they are able to shore up and defend their beliefs.

As an example, consider an underground mineworker who is a smoker and disposed to smoking underground in areas where smoking is prohibited. When presented with information that stipulates that such a practice puts others at risk of fire, or the health effects of second hand smoke, their compulsion to smoke is dissonant with their perception that they are putting others in harm's way. People do not do well with dissonant perceptions, and seek resolution by one of two mechanisms. They will accept the information and change their behaviours, or reject the information in support of their behaviours. Research in dissonance (Aronson and Travis, 2007; Plous, 1993) predicts that we are often pre-disposed to the latter, particular in matters of risk and its perception.

Thus, subconsciously our underground miner seeks to resolve his dilemma and must formulate a response that will achieve consonance. He can adjust his worldview to incorporate this new, but, dissonant information and modify his behaviours by complying with the expectation – or he can dissent. Dissent is lower energy physiologically, as it accommodates his compulsion. Mentally, however, dissent introduces the need for counter measures, as perceptions of guilt and remorse are associated with non-compliance. This is the paradox of *cognitive dissonance*. In order for the underground miner to achieve consonance, he must provide evidence or information that not only supports his behaviours, but also defeats the argument that his behaviours are harmful. If he is mildly dissonant, he may argue that there are no flammable materials underground and that the rest of the crew are smokers as well. If he is strongly dissonant, he may argue that smoking reduces risk by providing an indicator of ventilation speed and direction; or that smoking provides a means of detecting oxygen deficiency. The stronger the dissonance on the part of the miner, the stronger is his bias.

Either way, our underground miner must resolve the apparent discord between his preferred worldview (his behaviours) and his perception of risk in the workplace. In

order to effect compliance, mine management can apply a number of traditional strategies. Mine management can institute severe disciplinary policies that change the risk equation by making the risk of smoking subject to dismissal; or, they may chose to reward the correct behaviour by providing a benefit. Both of these traditional strategies are likely to result in some measure of efficacy; however fleeting. A better approach would be to reduce, if not remove, the mechanism of dissonance by providing the miner a safe place to smoke, or with the assistance of a smoking cessation program.

3.1.2 Self-Justification

In the absence of reforming ideas, beliefs and attitudes the decision maker is left with one alternative (the lower energy one) – to reconcile *cognitive dissonance* by shoring his beliefs and attitudes with *self-justification*. Dissonance is the engine that drives *self-justification* (Aronson and Tavris, 2007). *Self-justification* restores self-image and at the root of every decision is the belief that the decision, and by extension, the decision maker are validated. The more pain, discomfort, or effort required to arrive at the decision or action in question, the more committed the decision maker is likely to be toward that decision (Aronson and Mills, 1959). Aronson and Tavris (2007: 19) write:

Neuroscientists have recently shown that these biases in thinking are built into the way the brain processes information – all brains, regardless of their owners' political affiliation. For example, in a study of people who were being monitored by magnetic resonance imaging (MRI) while they were trying to process dissonant or consonant information about George Bush or John Kerry, Drew Weston and his colleagues found that the reasoning areas of the brain virtually shut down when participants were confronted with dissonant information, and the emotion circuits of the brain lit up happily when consonance was restored. These mechanisms provide a neurological basis that once our minds are made up, it is hard to change them.

Clearly, humans, as sentient beings, are not comfortable with *dissonance*. We claim, and more often hear, that we should learn from our mistakes. How many of us have the courage of that conviction? History records examples of men of exceptional character who did: Abraham Lincoln, Thomas Edison and Robert E Lee to name but a few (Aronson and Tavris, 2007:223). They conclude:

Perhaps the greatest lesson in dissonance theory is that we can't wait around for people to have moral conversions, personality transplants, sudden changes of heart, or new insights that will cause them to sit up straight, admit error, and do the right thing. Most human beings and

institutions are going to do everything in their power to reduce dissonance in ways that are favourable to them, that allow them to justify their mistakes and maintain business as usual. They are not going to be grateful that their methods of interrogation have put people in prison for life. They are not going to thank us for pointing out to them that why their study of some new drug, into which they poured millions, is fatally flawed. And no matter how deftly or gently we do it, even the people who love us dearly are not going to be amused when we correct their fondest self-serving memory ... with the facts.

3.1.3 Cognitive Consonance

The antithesis of cognitive dissonance is *cognitive consonance*. *Cognitive consonance* is the state of harmony and equanimity that exists between a person's attitudes, beliefs and behaviours with their worldview. Perhaps counter intuitive to the process of decision making is that *cognitive consonance* is not necessarily a good thing. As much as groups for purposes of reaching consensus seek concordance, *cognitive consonance* can devolve to *groupthink* in the absence of examination of goal setting and the objective evaluation of risk. Thus, we appreciate that from the point of view of the individual, *cognitive consonance* represents a lower energy demand state than is the case for *cognitive dissonance*. However, in the collective of group decision making some degree of *cognitive dissonance* is appropriate and indicative of healthy truth testing. The Bay of Pigs fiasco of 1961 and the battle of the Somme of 1916 are both examples of decision making that arguably were the product of excessive *cognitive consonance* among those that influenced decision-making (Reason, 1990).

3.1.3.1 Groupthink

In the classic example of the Space Shuttle Challenger (Vaughan, 1996), engineers employed by a NASA contractor suspended all rational thought and established standards to accept an imperative presented by NASA mission management to proceed with the pending launch. In doing so, they (the engineers) replaced a single cognition (exceeding a launch design parameter) with another - the acceptability of the risk. NASA expressed increasing expectations and pressure to the contractor to concur with the decision to launch. The decision was without merit however, but the degree of dissonance was not sufficient to cause an intervention and the engineers working for the contractor collectively acquiesced to a 'go for launch', that history has recorded as a classic case of *groupthink*.

The phenomenon of *groupthink* (Janis, 1982) is explicative to accident theorists respecting the final moments preceding *events* that are synonymous with tragedy (Sunshine Mine Disaster in 1972) and infamy (Westray Mine Disaster in 1992). *Groupthink* speaks to a mechanism whereby cognition transcends the individual/collective boundary and describes an interaction between members of the workplace social unit whereby decision makers forsake rationality and good judgement in deference to authority, peer pressure and status. Janis (1982:9) writes that *groupthink* 'is a mode of thinking that people engage in where they are deeply involved in a cohesive in-group, when the members' strivings for unanimity override their motivation to realistically appraise alternative courses of action,' and attributes *groupthink* to eight specific symptoms of group interaction (Table 3-1).

#	Symptom or Attribute	Description
1	Illusion of invulnerability	Members share excessive optimism and a collective acceptance for risk.
2	Collective Rationalization	Members discount new information that contradicts their worldview or warnings that might require them to commit to another action.
3	Illusion of Morality:	Members share an unquestioned belief in the group's inherent morality inclined to ignore moral and ethical consequences.
4	Excessive Stereotyping	Members stereotype those holding opposing thoughts as incompetent, weak or inferior.
5	Pressure for Conformity	Members apply direct and defensive pressure to any dissenter in the group who would offer a contrary or unsupportive argument.
6	Self-Censorship	Members strive to align themselves with consensus, suppressing doubts and countervailing opinion.
7	Illusion of Unanimity	Members share a belief that majority rules and that in the absence of any opposing view, consensus is established and supported by all.
8	Mind guards	Certain members become self-appointed guardians of the values and beliefs, and protect the group from information or argument that weakens group complacency.

Table 3-1: Table summarizing symptoms of Groupthink as enumerated by Janis (1982).

In the context of the *events* in the mine workplace, *groupthink* is an interesting phenomenon, that attributes to a small number of decision makers their contribution in the destabilization of a critical *event* and ultimately in its escalation towards disaster. Ostensibly, the phenomenon of *groupthink* is an example of collective cognition impairing an individual decision maker's ability to act on sufficient cognitive dissonance to bring to bear objectivity, critical thinking and rationality in the acquisition of a more realistic perception of risk associated with a worldview. In reference to the Space Shuttle Challenger disaster of 1986, Vaughan (1996:405) writes:

For at its essence, the case is a picture of individual rationality irretrievably intertwined with position in a structure. Position in the engineering profession, the aerospace industry, and the various organizations made up the labyrinth NASA-contractor network was a key determinant of individual and collective determinations of risk. Position determined social mission. Position determined access to information. Position determined responsibility for acting on information and the actions legitimately could be taken. Position contributed to ability to interpret information and the worldview brought to the organization. Perhaps most important, position determined power to shape opinions and outcomes in one's own and other organizations.

3.1.4 Risk Polarization

Risk Polarization, describes the dynamic whereby cognitive consonance results in a shift in risk perception. This can occur when individuals holding a more moderate view alter their views to accommodate the extreme views of others. This polarization of the group is subject to the organizational structure and labour relations constraints within the workplace. We anticipate that the more stratified organizations are, the greater the opportunity there is for *risk polarization*, owing to the influence of position and status. Similarly, for organizations in which labour relations are difficult and politically charged, we can expect there to be a high degree of cognitive consonance on both sides of the bargaining table.

Unfortunately, cognitive consonance is likely to permeate other domains and endeavours and one can expect to see consonance in matters such as risk perception and its quantification. Thus, cognitive consonance, once established within an organization or social unit, is likely to become entrenched with the possibility of devolving into groupthink. *Risk polarization* is therefore symptomatic of a social unit that exhibits cognitive consonance, to the extent that individual perceptions of risk shift

sympathetically towards perceptions that reflect social integration. In this manner, the individual decision maker achieves consonance in terms of their perception of risk vicariously through others, and may not benefit from direct ideation of risk and an accurate representation of hazards within the workplace.

3.2 Group Cognition

Most young adults graduating today from high school have a basic awareness if not understanding of *events* like the sinking of the Titanic, the Halifax explosion, Chernobyl and the space shuttles Challenger and Columbia disasters. How many would have any awareness of the Piper Alpha Disaster of 1988, the Sunshine Mine disaster of 1972 or the Springhill Mine disaster of 1958, which claimed 167, 91 and 75 lives respectively? How many would know that at Three Mile Island in 1979, the core of the reactor experienced a true meltdown – or the reasons why? As much as the questions are rhetorical, they serve to illustrate our capacity as human beings to limit our awareness inter-generationally.

Similarly, in a much smaller social unit: that of the workplace, there is a tendency to give a passing interest to failures both at the organizational and at the individual level. Individually, we all can relate in the humility of coming to terms with our errors; that much is understandable, particularly in a blame culture. Organizationally is it the same thing? Are we predisposed collectively to accommodate error? Do we share an organizational hubris? These questions speak to the existence of psychological precursors to accidents and incidents (*events*) in the workplace. They suggest that *events* are not as isolated and unrelated as we would (like to?) believe. They suggest that there may be a group dynamic; an ethos towards error – a culture that however inadvertent sustains if not cultivates human error, and therefore the inevitability of *events* in the workplace.

There is increasing support for the notion that beyond individual cognition, collective cognition exists within social groups (Busse, 2002; Reason and Sasou, 1997; Busby and Hughes, 2003). Most taxonomies of human error are attributed to individuals, and there is a paucity of modelling of human error as applied to group dynamics within the workplace. This research aims to address this by considering interaction of workplace parties based upon the analysis of decision errors made, and the effects of their perception of risk on those decisions. Accident theory is evolving toward the inclusion of complex techno-social systems and organizational influence (culture).

Consequently, determinants are becoming more distal to causality, but no less contributory. By implication, organizational and system theory and artefacts of their design must be considered communal or collective in nature. Any attribution of error at the organizational level is more appropriate to the many, than the few.

Cognition as it applies to human error can be considered occurring in three modes of mental processing. They are: attention allocation, pattern recognition and decision making (Alexanderson, 2003). It is the latter mode, decision making, that is within the scope of this research. By no means is it intended to marginalize the contribution of the other two modes of cognition. It is decision making however that has plurality in terms of parties to the decision. It is the making of a decision that involves the mental processing of risk outcomes. And finally, it is the perception of risk that is affected by the organizational culture and 'distributed' throughout the societal fabric of the workplace.

3.2.1 Distributed Cognition

The workplace as a collective is a social aggregation, which is brought together not by chance, but by common purpose and mission. Recent research has suggested that groups or organizations (workplace or otherwise) have the capacity to function as information processing systems (Gibson, 2001). If we expand our understanding of the meaning of cognition, we can appreciate how this might be the case. If cognition is more than a process of the brain, but is inclusive to the concept of ideation; no matter the source, then conceivably groups forming ideas is cognition – in the aggregate.

Accepting that cognition can be attributed to social units and that decisions are influenced, if not explicitly made by these groups (committees, teams and collective bargaining units), we are obligated to shift our paradigm for the attribution of causality concerning *events*. Moreover, such a paradigm benefits our understanding of causality owing to the insight *distributed cognition* provides us as regards to how information (risk, hazards and events) is disseminated and integrated within the social fabric of the workplace. Busby and Hibberd (2006:26) explain:

In terms of defining distributed cognition, Hutchins' central concern is how information is represented and how representations are transformed and propagated in the performance of tasks. Propagation can occur across a social group, across the boundary between what is internal and external to the individual actor, and across time (Hollan, Hutchins, & Kirsh, 2000).

This means that cognition is associated with processes that extend beyond the individual human mind, and the appropriate unit of analysis becomes a sociotechnical system, or functional system (Roger & Ellis, 1994), rather than the individual person. Thinking and learning, it is then claimed, depend on the characteristics of relevant knowledge, such as its retrievability, and not on whether it is located in person or surroundings – the so-called “equivalent access” hypothesis (Perkins, 1993).

We understand how norms and standards are explicated within contemporary mining workplaces. As an industry, mining is both consistent and progressive in articulating expectations, behaviour and performance related, within the workforce. This is accomplished by regulation and codes at the statutory level, policies and systems at the organizational level, and procedures and practices within operations. These *artefacts* are the structures with which the enterprise expresses its acceptance or aversion to risk. They by design, transcend individuality and are rarely attributed to a single actor or limited in terms of those who are responsible for compliance. The advent of electronic communication makes this more the case, as such *artefacts* are both instantaneous and anonymous. Coupled with an increased reliance of teams and committees in the development of policies, practices and procedures, the transmission and distribution of these *artefacts* via electronic media further removes us from the idea of their attribution in the singular.

An early model of group cognition (distributed cognition), as it applies to human error, is that of Reason and Sasou (1998). Reason and Sasou provide an appealing model in which to consider *distributed cognition* within the context of *individual* and *shared* errors (Figure 3.3). Further, they introduce a subset of these errors as being *dependent* or *independent*. *Independent* errors are errors for which the actor(s) had correct and complete information upon which to base their action or decision. In contrast, *dependent* errors have the distinction of the information being incorrect or incomplete. The model offers four error types as taxonomy to be used against a backdrop of three phenotypes. They are: failure to detect, failure to indicate and failure to correct (Figure 3.3).

Within this schema, error is propagated in a ‘Swiss cheese model’ fashion as trajectories). Any combination of shared and individual error has opportunity for detection, indication or correction (barriers to error) – and failing any or all can result in team errors. The model is as simple as it is robust. It opens the door for the attribution of

error to teams and other social units, and distributes the cognition and the attribution of error in a pluralistic fashion. In many ways this model makes antiquated existing theories of causation, as the distinction between cause and effect is further blurred.

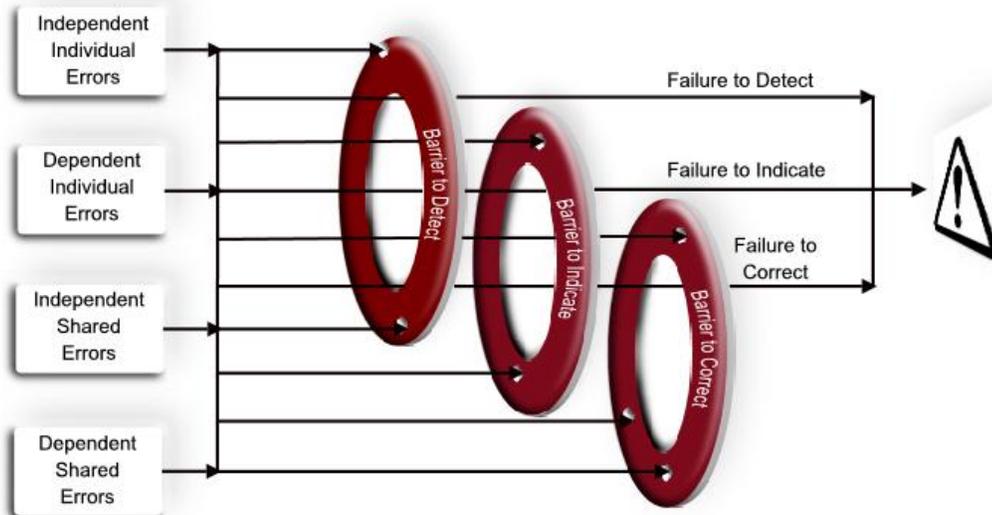


Figure 3.3: Group cognition model based upon fallibility of barriers (Reason and Sasou, 1998)

Within contemporary system accident theory, for which distributed cognition naturally lends itself, there is a paucity of methodology in its treatment. Busby and Hughes (2003) write:

Our intention is to look for failures of distribution as contributors to accidents and incidents in hazardous, complex systems. The notion of distributed cognition was a useful one in several respects. Firstly, developing and applying knowledge is socially distributed in the systems we are studying, and this distribution is usually problematic. It is very common for people involved in the system to refer to 'communications problems'. Secondly, the process of designing and operating such systems draw upon knowledge and that has been developed by people at earlier times. For example, design is strongly influenced by standards and codes of practice. They have important functions, such as accumulating empirical knowledge in the engineering discipline, economizing on resources by reusing knowledge, and protecting against whimsical practices. But when a designer applies a standard, he or she rarely knows the same things as the people who compiled the standard, and rarely analyzes the applicability of the standard in as much detail as a design done from scratch. It is certainly as if the design process is distributed over different people and different times – with the designer

incorporating partial solutions embodied in standards developed by other people at other times.

In a new paradigm of distributed cognition, decision making becomes less of a cognitive function and more cognitive processing – particularly as regards to the perception of risk. Busby and Hughes (2003) illustrate this in their model (Figure 3.4):

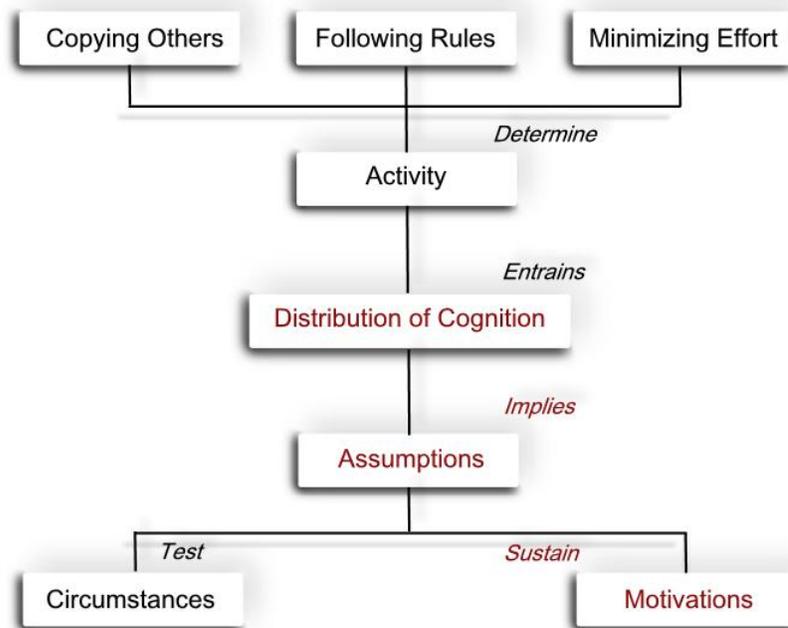


Figure 3.4: The role of distributed cognition in accident causation (Busby and Hughes, 2003)

One can appreciate that there are expedients that govern our behaviours, be they cognitive or otherwise. There are economies with copying others, simply following the rules or minimizing effort by any other means (Figure 3.4). To this extent, Busby and Hughes (2003) suggest that the cognitive effort of others occurring over time is a mechanism for distributed cognition. They go further and illustrate that within these economies are also assumptions – the biases and risk perceptions that then sustain motivations on the part of the recipient actors through time. Indeed, the originators of the artefacts being copied, followed, or otherwise employed - may no longer be physically present. The legacy of their mental processing is still present, however, by way of replication or adaption of their endeavours. Their cognition is distributed over time and throughout the social unit; and, entrained within are their assumptions, values and perceptions.

3.3 Discussion

This dissertation argues that human error plays a major role in the occurrence of accidents within the mining enterprise – and that of all enterprises. Further, human error is a factor unlike other causal factors; as we are the unwitting architects of the system in which all factors reside. Hence there is an inherent lack of objectivity in the analysis of *events*, as the examination of error has within it the very biases and heuristics that in the first instance are present when the systems were designed. These biases and heuristics are influenced by the perception of risk and its detection. Investigators have by their vocation and circumstance a lower tolerance of risk than the subjects of their investigation, and this bias is a disadvantage to their endeavours to the extent that it is not appreciated or taken into consideration.

Identifying human error in an *event* scenario is, however, not necessarily sufficient to identifying causality. With respect to the actual occurrence of any *event*, the design of organizational artefacts might not be appropriate or conducive to cognitive processing and the prevention of the *event*. The salient issue is that the person or persons present at the time of the *event* must be aware of, and have contextual understanding of these artefacts to be compliant with them. Complicating the issue is that as decisions relevant to the *event* are more distributed, the more removed the decision makers are from the consequence of the *event*. There is a lack of appreciation for the role of distributed cognition in general and the lack of mechanisms for its detection in particular. This is a shortcoming that this research is intended to address.

Distributed cognition by its nature entrains all the economy as well as all of the limitations of its contributors. However, as a social dynamic there is a ‘distillation’ of values and perceptions of risk that is anything but averaging in its outcome. Were these values and perceptions to be skewed to the more risk averse, this research would not be necessary. In the experience of this researcher however, the reverse is normally the case whereby a recipient of distributed cognition is likely to be less aware of, or cautious, in the application of artefacts in the workplace than was the intention of the originators. The mechanism by which the perceived risk is diminished from the actual risk, through the distribution of cognition by these workplace artefacts is essential to the understanding of decision error and therefore of interest to this research. Busby (2001:251) writes:

Hutchins writes about a 'culture' as passing partial solutions from one generation to the next. In this study, it was a specific aspect of culture – the norms which designers shared – which provided much of this solution passing, and played a part in many errors. Norms were often seen in fact as things that had been implemented in the aftermath of past errors, in order to avoid their recurrence. They ranged from informal understandings (how, for example, structural and piping design was demarcated), through explicit procedures (for example, how to represent un-modelled piping branches), to codes that specified necessary properties of an artefact (which could be as simple as the height of a handrail). These norms were especially important when different people's work had to be consistent, but when in isolation they would have found it hard to predict what their colleagues' would have been.

3.4 Conclusions

The goal of this dissertation is to demonstrate the use of cognitive profiling as a method of analysis of decision error and its taxonomy. The lexicon of cognitive error, like the syntax of a language, serves to define and focus this modelling process. Modelling decision error within a cognitive framework will enable the analyst to measure risk perception beyond that of the individual; but, inclusive of the social unit through distributed cognition theory. Although the decisions of the collective are generally distal and not as directly linked in causality, they are no less potent in the ideation of risk and its perception. Perception of risk becomes a barometer of an organization's acceptability of risk and a strong indicator of the direction it, as a social unit, is evolving as measured by its artefacts; its treatment of *events* in the workplace; its ethos of error.

Cognitive demand is increasing in the workplace (Busse, 2002; Sträter, 2005). Inherent in human cognition is bias, heuristics and error (Slovic *et al.*, 2002). In the absence of any countervailing strategy or mitigation, it is reasonable to suggest then that cognitive error is also increasing within the mine workplace. Further, increased organization of the mine workplace, its social units and its artefacts, would lead those that subscribe to distributed cognition to appreciate the second hypothesis of cognitive profiling *events* in the mine workplace:

Decision error, as it contributes to causality, is not limited as an attribute of individuals, but is distributed within the cognition of the social unit and its system(s) of governance.

“It is easier to perceive error than to find truth, for the former lies on the surface and is easily seen, while the latter lies in the depth, where few are willing to search for it.” Johann Wolfgang Von Goethe (Bartlett, 2000)

4 HUMAN ERROR THEORY

4.1 Introduction

Human error became a mainstream study of interest because of increasingly horrific disasters occurring in the 1970s and early 1980s (Trepess, 2003). The Flixborough disaster of 1972, followed by Three Mile Island in 1979 and Chernobyl in 1986 served to galvanize the attention of both government and public alike (Reason, 1990). Clearly, human error is timeless as it is ubiquitous; and as a civilization, we have only recently realized the true enormity of our vulnerability in the face of increasing technology and its complexities (Perrow, 1984). One might ask whether human fallibility has insidiously crept into our modern existence; or, rather has it always been an unwelcome companion and we have chosen to ignore it? We have only to look at the historical record to realize that as a society we have developed a singularly convenient ability to move beyond disasters, ostensibly to heal and rebuild. Such is our nature. But, in so doing is it not also true that we often fail to take the time to truly understand the reasons of our failures; at the very least the lessons to be learned from them?

Human error is a broad and highly studied subject. Yet, as a subject matter, it is not a comfortable one. Investigators of human error draw upon their humility; their fallibility and ultimately their humanity. As theory is built upon theory, human error theorists have increased the scope and relevance of this field to all enterprises and intellectual disciplines. As example, a pioneer in human error, Norman (1981) set the stage in his categorization and analysis of slips (execution failures). Building on this work is that of Rasmussen (1987), who broadened the field with his work in skill, rule and knowledge errors. Similarly, Reason (1990) built on the foundation of Rasmussen and

Norman in his composite model of human error: the *Generic Error Modelling System* (GEMS). Norman's understanding of errors of execution has led to understanding of errors in design, which is currently generating understanding of errors at the organizational and the systems levels (Dörner, 1996; Whittingham, 2004; Sträter, 2005). Accident theorists are currently experiencing a renaissance in the study of human error that layer by layer is unveiling the intricacies of human behaviour within the workplace.

4.2 The Nature of Human Error

The study of human error transcends many disciplines. Contributions are being made by the disciplines of psychology, reliability engineering, cognitive science and system software (Busse, 2002). Fundamental to understanding human error is its scope and definition. A common element in many definitions is the notion that the error or action is intended to achieve a desired outcome (Whittingham, 2004). With this in mind, the definition of Whittingham (2004:6) is adopted which defines human error as:

A human error is the unintended failure of a purposeful action, either singly or as a planned sequence of actions, to achieve an intended outcome within set limits of tolerability pertaining to either the action or the outcome.

There are three tenets within this definition of human error worthy of note within the context of *events* in the workplace. First, there must be an *a priori* purposeful action, or intent. Second, the error is outside the limits of established tolerability. Lastly, implicit in the definition, is that a failure flows from the error or action resulting in a consequence. Unfortunately a measure of human error is commonly perceived as concomitant with the severity of consequence (Woods and Cook, 2008).

4.2.1 The Tenet of Intent

Strictly speaking, an error cannot have occurred unless there is a standard to which the action or perceived error can be compared. In this regard, we do not define human error by a negative outcome. It is neither a necessary, nor a sufficient condition. An error is established only when the consequence is clearly outside the tolerability of the purposeful action. Intent of the action is inextricably related to tolerability, and by this reasoning, precludes chance or random *events* from the analysis. The tenet of Intent forces us to examine the rationality of our standards in terms of a desired outcome.

4.2.2 The Tenet of Tolerability

Tolerability is a natural requisite of human fallibility. Whereas intent speaks to the expectation on the part of the operator, *tolerability* goes to the quintessence of what really matters – the acceptability of risk. *Tolerability* encompasses those deviations that accommodate the action, and prescribes those that cannot, and by this measure establishes limits of failure (Whittingham, 2004). *Tolerability*, in a *systems* framework, is the amount of variability implicit in the actions of operators that is permissible to achieve the desired results. *Tolerability* predicates the amount of acceptable risk.

4.2.3 The Tenet of Consequence

Most familiar as a tenet, is *consequence* – and largely misunderstood. The reason is one of availability heuristics. If we consider two scenarios with identical error, but with markedly different consequences or outcomes, we discover a paradox. As an example: consider failing to lockout an energised device within the workplace. Most workers in heavy industry can describe a time in which they either forgot to lockout, or did not know that lockout was required, while working on energised equipment. For the vast majority, the *consequence* would be a stern conversation with someone in authority setting them straight regarding the risk. Tragically, for some, the consequence is extreme – in the form of a disabling or fatal injury. The error remains the same; however, the outcomes are tragically different. In the former instance, the error is characterized as small; in the latter instance, the error would be considered grievous. How can this be? Availability heuristics teaches us that as information processors, human beings lack the capacity for sanctioning our actions in the absence of empirical consequences. Errors without *consequences*, are too often overlooked or ignored; and rarely reported. We are limited by, and prisoners to, our own worldview shaped by our perceptions.

A dilemma associated with consequence is cause and effect (Woods and Cook, 2008). In our zeal to ‘discover’ the cause of an *event* (often confused with consequence), we as sentient beings, suffer from the cognitive equivalent of myopia. The consequence of an error, as stated previously, is not required to establish that we have exceeded tolerability parameters. Too often however, it is the signal that something is amiss. Typically the greater the consequence, the more likely we are to find the one ‘fix’ or factor that by its elimination would have prevented the consequence – but not

necessarily the *event*. Clearly, *consequence* as a tenet is a necessary, but not sufficient condition in establishing human error. Busby (2001:234) writes:

Error has a basic importance in most human tasks. It is a necessary element in learning a task and adopting it to changing needs, but is also one of the main influences that limits performance in a task. This importance increases at the organizational level, where error can be very widespread. Error is also revealing: it often helps us understand the nature of a task that has become habitual, automated or just taken for granted. When an organism is well adapted to its environment satisfactory performance says more about the environment than its internal nature. It is when performance fails that this internal nature becomes evident.

We require a new paradigm with which to frame human error, one that considers *consequences* as perturbations of a system in disequilibrium, one that is organizationally holistic - and heuristic. We are best served by considering human error not as discrete failures of individuals (although these do occur), but rather as *forced errors* that are a product of interaction of people within their workplace environment and as prescribed by organizational and its techno-social artefacts (norms, rules and standards).

4.2.4 The Notion of Failure

In the context of human error the word 'failure' has a connotation all its own. It is not a positive one; nor is it particularly helpful as a declarative statement. That said; literature on human error is replete with reference to *failure* - as are the vast majority of accident reports. By way of example, within their discourse on learning from error, Cannon and Edmondston (2001:162) write:

We conceptualize failure as a deviation from expected and desired results. This includes both avoidable errors and unavoidable negative outcomes of experiments and risk taking. It also includes interpersonal failures such as misunderstanding and conflict. Our conceptualization is deliberately broad, encompassing failures of diverse types and magnitude, because we propose that opportunities for learning exist in both minor understandings and major mishaps. We note also that the amount or significance of learning is not necessarily proportional to the size or scope of a failure. Clearly, learning can emerge from major failures such as launching a highly visible product only to have it rejected by the market, or implementing a new technology that cannot be made to work in the intended context. Additionally, however, significant learning can come from uncovering a small failure to communicate in a work relationship, and such seemingly small failures can lead, ultimately, to highly preventable major failures.

Although there is no argument against the substance of what the authors offer in his discourse, the word ‘error’ can be substituted for the word ‘failure’ and their meaning would not be altered. There is subtle shift in tone and context in a way that is not trivial; one that is less judgemental. We should bear in mind that *failure* is more appropriate as a verb than as a noun, acknowledging the fact that we fear, if not disdain, the latter. *Failure* (or error), once determined, whatever the context, should be a starting point for examination, not an end-point (Busse, 2002). Therefore, this researcher stipulates in this dissertation that ‘failure,’ as a noun, is reserved for the description of degraded mechanical components, and the verb is more appropriate for its human condition analogue. Although the definition of human error subsumes the notion of *failure*, in the absence of consideration of the environment and circumstances in which the human error occurred, any explicit reference to human *failure* is misleading, if not prejudicial.

4.3 Human Reliability Assessment

One approach to the understanding and the prediction of human errors is the methodology known as *human reliability assessment* (HRA). HRA encompasses a class of models for the purpose of analyzing and predicting human error. As a methodology, HRA has been subject to much debate that as a process it is more psychosocial than technical in its derivation (Hollnagel, 2005). Nevertheless, HRA addresses three fundamental questions, each of which has its counterpart within the process of causation attribution (Table 4-1).

	Human Reliability Assessment (HRA)	Causation Attribution (Investigation)
1	What are the errors that can occur?	What were the circumstances of the event?
2	How likely are the errors to occur?	What were the reasons for the <i>event</i> ?
3	What means are there to reduce the likelihood of error?	How do we prevent a recurrence of the <i>event</i> ?

Table 4-1: Table illustrating the complementary nature of HRA and causation (Hollnagel, 2005)

HRA is a methodology that is forward-looking as opposed to investigations, which are by nature post-*event*. HRA provides us with some insight as how to better

frame human error – more by its limitations than by its example. There have been many HRA techniques developed: Technique for Human Error Rate Prediction (THERP), Accident Sequence Evaluation Program (ASEP), Cognitive Reliability and Error Analysis Method (CREAM) and A Technique for Human Event Analysis (ATHEANA), are a few of the more common examples (Hollnagel, 2005). The details of these models are beyond the scope of this dissertation; however, the precepts of HRA bear closer examination within the context of causality.

Heavily weighted in epidemiologic and human factors theory, HRA complements the investigation of *events*, in particular from the perspective of sequence-of-events modelling. Further, HRA provides a cognitive analogue to system destabilization known as *cognitive decomposition*. The analysis essentially accomplishes this by a reduction of cognitive function into its constituent parts and then expresses errors therein: as failure probabilities. In consideration of any given *event* scenario, a primary goal of HRA is the quantification of probabilistic risk (Hollnagel, 2005). Herein lies the promise, as the quantification of human error is the holy grail of risk assessment and fundamental to forward-looking (predictive) models. Hollnagel (2005) illustrates the graphical utility of HRA, through the analysis of *cognitive decomposition* (Figure 4.1).

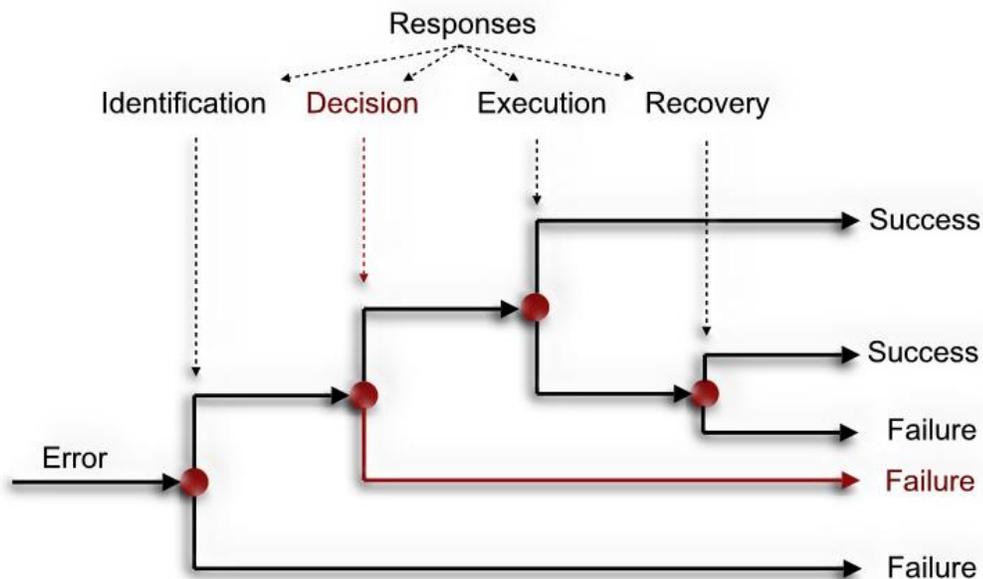


Figure 4.1: Schematic illustrating an HRA model of cognitive decomposition (Hollnagel, 2005)

Cognitive decomposition, as depicted above, illustrates the essentials of HRA analysis. The nodes represent opportunities for intervention and the arrows the error trajectories or probabilistic outcomes. In its full evolution, the *cognitive decomposition* model characterizes degrading cognitive processing in which the outcome results in failure. Notwithstanding the unfortunate reference on the word 'failure,' the model is indicative of a binary event tree approach that is common in technical systems (e.g. fault tree analysis, failure mode and effect analysis). Hollnagel (2005:163) argues that such an approach is impractical - and invalid. He opines:

HRA has in common with many accident analysis methods the assumption that it is reasonable to consider the inherent variability of human performance by itself, hence that a performance failure is an attribute of the human component rather than the circumstances during which the actions take place. In this sense of 'human error' is – metaphorically, at least – the sought for signal rather than the noise. This assumption is strangely inconsistent with one of the main tenets of information processing approach, which states that:

A man, viewed as a behaving system, is quite simple. The apparent complexity of his behaviour over time is largely a reflection of the complexity of the environment in which he finds himself.

To be fair, Hollnagel's (2005) treatment of *human reliability assessment* was directed at the earlier models of HRA, and models that are more recent have made considerable inroads in integrating the cognitive dimension of human failure with the cultural, organizational and environmental dimensions of the workplace. It is ultimately a challenging and complex analysis that has crossed the line for which a single practitioner can master, owing to the depth of knowledge required in reliability engineering, systems design, and cognitive science. Clearly, to pursue this emerging discipline, the next generation of accident theorists and investigators will require additional, if not a new set of skills than those that currently exist in the industrial workplace. This is the challenge.

We can learn from HRA, to the extent that models predicated on human error need to be circumspect respecting approaches taken. The lesson learned is that humans do not make errors in the absence of a culture or organization that enables if not contributes to error, by the very artefacts and systems that prescribe the workplace. Further, these artefacts (norms, rules and standards) are not limited to the organizational level. Particularly in the mining industry, the rules, norms and standards governing the workplace are an interdependent mix of corporate policy, generally accepted industry

practices and regulatory statute. In a democratized society, statutes are in a constant state of review and reform, strongly influenced by organized labour, industry associations and the public at large.

We emphasize that the perception of risk that these parties bring to the analysis will ultimately dictate the terms and height to which the bar is set as regards to the acceptability of risk. Any attribution of human error to *events* within the workplace must be inclusive of the influence of the collective worldview, as well as that of other discrete social units comprising the enterprise.

4.4 Taxonomies

Any treatment of human error and its taxonomy is necessarily reliant upon a lexicon of terminology that is at first glance strange to the uninitiated. Taxonomy itself is a term borrowed from the field of biology to mean nomenclature or classification. So too are numerous other terms that describe the cognitive and human error schemas; consequently this research will respect this convention. Human error is, as previously stated, ubiquitous as it is broad and therefore it is essential that as we compare models and schema, we appreciate what exactly is in or out of the box in terms of analysis. We start with the general, and move to the particular, as established by Whittingham (2004). An important taxonomic distinction respecting human error is the degree to which error can be organized as a *genotype* or a *phenotype*. In biology, the distinction between these terms is self evident; not so for the taxonomy of error - but no less fundamental.

4.4.1 Error Genotypes

The origin of an error determines its *genotype*. A variation of *endogenous error*, errors classified by *genotype* originate within the cognition of an individual(s), such that the even if the task was executed correctly the task could be intrinsically flawed. Within the context of human error therefore, the *genotype* refers to errors that are defined by their mental processing, and not the manifestation of the error in terms of cause and effect. Whittingham (2004) illustrates this with an example involving a task in which a faulty item passes an inspection process (Figure 4.2). The immediate determinate is that there was a deficiency in the lighting conditions. In terms of *genotype*, the error is attributable to the inability of the person(s) to mentally process a 'fault' owing to the lack

of acuity. How that deficiency is manifested in terms of effect is not relevant to the *genotype*.

4.4.2 Error Phenotype

How an error manifests beyond the faculty of cognition determines the *phenotype*. It is a variation of *exogenous error*. The error, having a physical effect on the workplace, is observable. In the inspection process example above, the error in terms of *phenotype* is the failure of detection of the faulty item through the physical process of inspection (Figure 4.2). The cognitive aspects of the error are not relevant to the *phenotype*.

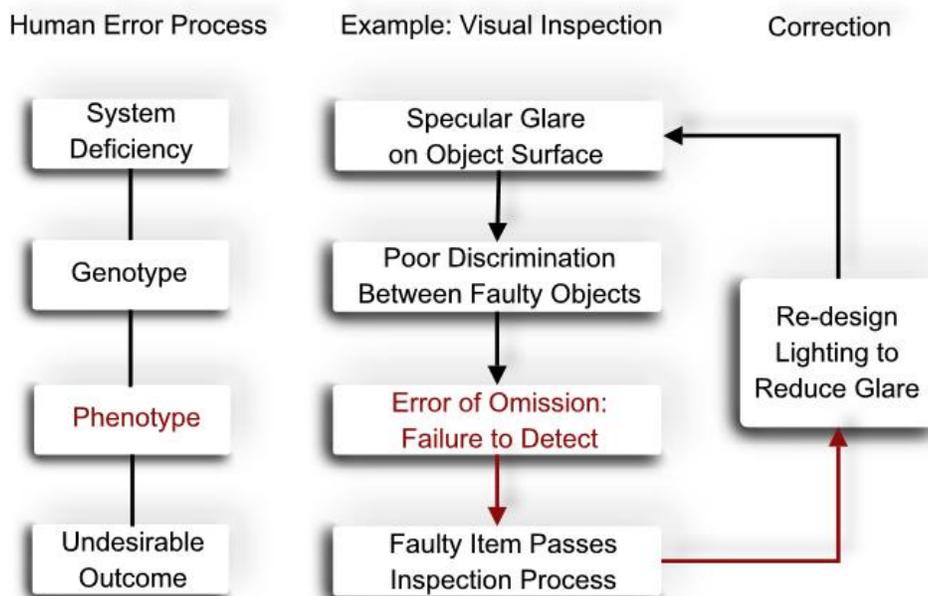


Figure 4.2: A schema differentiating error genotypes from phenotypes (Whittingham, 2004)

4.4.3 Exogenous and Endogenous Errors

In reference to their biological origins, *endogenous* and *exogenous* refer to originating with and without the body, respectively. Used by many disciplines, 'body' can represent any number of allegorical entities. In economics, *endogenous* can refer to internal to a nation's economy, and *exogenous* those influences outside of a nation. The terms are useful in attributing causation, as they implicitly define the scope of the *event* under investigation. Conventional investigations into mining *events* consider

determinants and factors of causation within the care and control of the mine proper to be *endogenous*. The influences from the corporate management may or may not be *endogenous* to the investigation, depending upon the corporate culture. It is rare that investigations consider influences from collective bargaining units, industry associations or the regulatory community. These would be *exogenous* factors in the traditional sense. It is central to this research however, from the perspective of considering the role of risk perception on the collective cognition, that we consider all parties to the enterprise as *endogenous* to the investigation until determined otherwise.

Rasmussen and Svedung's (2002) schema illustrates this enterprise perspective, identifying the various parties to the enterprise; both individuals and organizations—in a complex techno-social system (Figure 4.3).

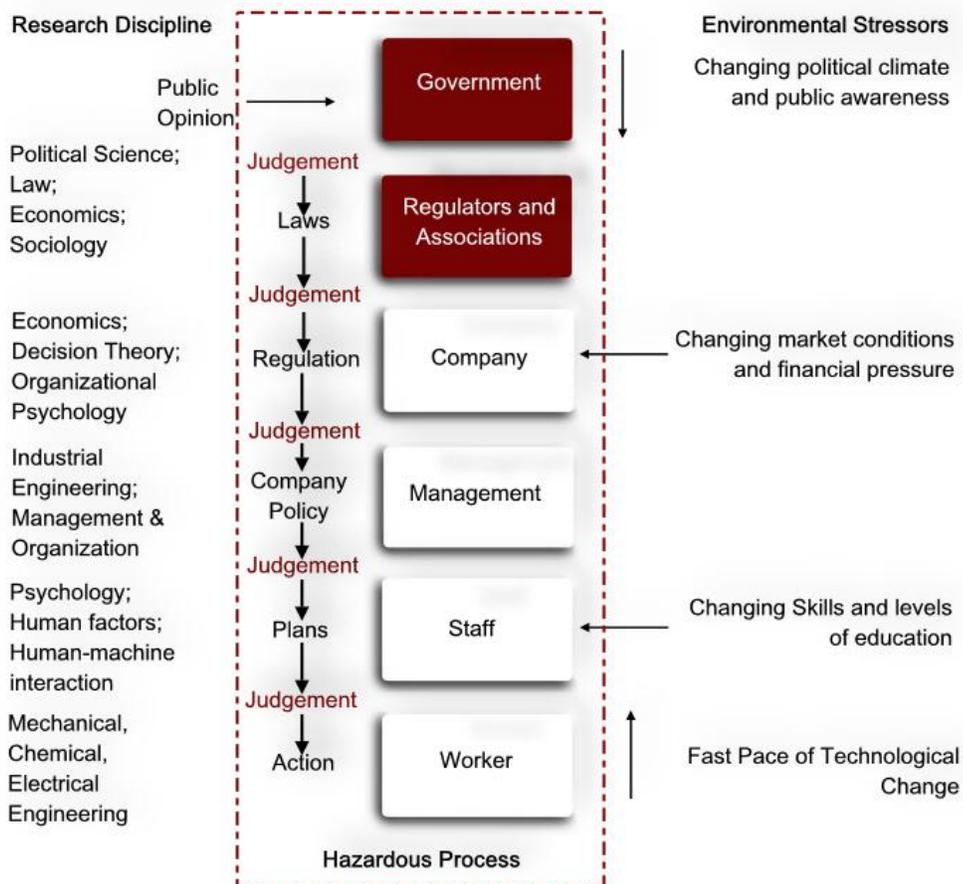


Figure 4.3: Graphical illustration of a techno-social system (Rasmussen and Svedung, 2002)

In this schema, the authors implicate the changing techno-social forces as being retarding forces to effective vertical integration of risk within the enterprise. Ironically, it is only through such vertical integration that an effective and cohesive perception of risk can be realized.

This dissertation examines the role and contributions of decision errors to *event* scenarios in the mine workplace. As a specific subset of human errors, we characterize decision errors in terms of both their *genotype* and *phenotype*. The model presented in this research will use the decision error *phenotype* (physical manifestation) to adduce something about the *genotype* (psychological precursors) of the decision error. We will illustrate that the cognitive profiles presented through decision error analysis can apply to individuals, small social units or to the mining enterprise as a collective. The analysis is only limited to the extent that the investigation of the *event* considers the various parties to the enterprise as *endogenous* to the investigation. It is axiomatic that the contribution that human error or behaviour makes cannot be considered if we exclude parties from the process of investigation and the evidentiary record.

4.5 An Age of Error

Models of human error have been in existence for many years. However, only in recent decades has their study garnered the attention of accident theorists (Norman, 1981; Rasmussen, 1987; Reason, 1990). The focus of these early models was in high technology, such as civil aviation, petrochemical and nuclear plants. This is attributable to the litany of disasters that took place during the 1970's and 1980's – many of which reaped unprecedented deaths and losses (Table 4-2). Public outcry was matched only by their increased awareness. Public safety, worker safety and environmental concerns gained a voice as once again the public's perception of risk and its uncertainty urged lawmakers and industry to reform standards and regulations (Reason, 1990; Perrow, 1984). It was becoming increasingly clear that high technology and large-scale enterprise did not guarantee reliability; thus, a new era of reliability and performance engineering was being ushered in (Hollnagel, 1998; Reason, 1990).

Error prediction and modelling has become increasingly accessible with the advent of the personal computer as a platform for an emerging software market specializing in risk analysis. The stage has been set for a renaissance in human error modelling and its classification. This research will show through the analysis of historical

case studies (including many of those in Table 4-2) that human error transcends time in the historical record, and that an effective taxonomy of error can be elucidated retrospectively with an appropriate methodology. We introduced this methodology in Chapter 5, as cognitive profiling.

Year	Disaster	Location	Description
1972	Sunshine Silver Mine	Kellogg, Idaho	91 miners killed in the worst metal mine event in US history
1972	Three Mile Island Disaster	Middletown, Pennsylvania	The worst civil nuclear accident in the history of the United States
1974	Flixborough Disaster	Flixborough, UK	28 persons killed and the hamlet heavily damaged
1977	Tenerife Airport Disaster	Tenerife, Canary Islands	583 persons killed in the worst aviation accident in global history (collision of two 747's on runway)
1984	Bhopal Chemical Disaster	Bhopal, India	1,408 citizens of the community died in the worst chemical plant disaster in world history
1986	Space Shuttle Challenger	Offshore Florida	The worst accident in US space program history (of the day) killing 7
1986	Chernobyl Nuclear Disaster	Chernobyl, Ukraine	Untold fatalities and the worst industrial disaster in world history
1988	Piper Alpha Disaster	North Sea, Scotland	167 workers died in production platform fire – worst in history
1989	Exxon Valdez Disaster	Valdez, Alaska	11 million gallons of spilt oil resulting in the most expensive clean-up in US history

Table 4-2: Table of unprecedented disasters defining the 1970's and 1980's high technology era

4.6 Existing Taxonomies

The classification of human error has empirical underpinnings, largely based upon advanced technology and military operations (Rasmussen, 1987; Reason, 1990). However, there is ample evidence to suggest that other industries are equally susceptible to human error. Existing taxonomies are to a varying extent based upon the information technology and civil aviation industries, as indicated by the work of Busse

(2001), Bove (2002) and Leveson (2004). The cockpit of an aircraft in particular lends itself well to the study of human error, with its contained working environment, man-equipment interface and well-established procedures and regulations. Yet, the modern airframe is still subject to the same vagaries of exogenous factors (weather state and maintenance standards), and the endogenous factors (human perception and cognition) as the mining, or any other enterprise. In this respect, the aviation industry provides us with a crucible in which to examine the techno-social interaction of the crewmembers and their collective cognition. For the purposes of this research, we acknowledge that regardless of the domain (industry type, scope of research) in which human error taxonomies are devised we can draw upon them for principles and lessons. Human error taxonomies provide the syntax for the mechanisms of causality underlying human error, and their analysis (Busse, 2001).

4.6.1 Cognitive Reliability and Error Analysis Method

Hollnagel (1998) has devised a *human reliability assessment* (HRA) model that referred to as Cognitive Reliability and Error Analysis Method (CREAM). This model provides a unique approach to human error analysis insofar as it can be used both as a performance prediction tool (prospectively) and as an *event* investigation tool (retrospectively), and hence its inclusion in this research. The CREAM model addresses the early shortcomings of HRA by being inclusive of both the genotype and phenotype taxonomies. Ultimately aimed toward using the phenotype (behaviour) taxonomy of error in the analysis of the error mode, CREAM also provides insight into the genotype (cause) of the error in question. The three genotypes are individual, organizational and technologic causes of error. The eight phenotypes are timing, duration, sequence, object, force, direction, distance and speed. Hollnagel provides subgroups of the latter in the form of actions; actions at the wrong time, place, type and object. The method offers a structured analysis of tasks at risk through the classification by phenotype in the first instance, followed by genotype to determine or predict causation (Figure 4.4).

Hollnagel (1998) makes the distinction between observable phenomena (manifestation) and the cognitive mechanism (cause), providing an empirical schema for their classification. The strength and utility of CREAM is in this differentiation, which separates behaviour from its cause and effect antecedents. In doing so, this model also avails the analyst with a structured methodology (that is in short supply) to the

separation of subjective and objective error. This feature harkens back to the reasoning of Dekker (2004), that in the evaluation of an *event*, one must consider two worldviews: that of the observer and that of the participant in the *event* scenario. The former provides a measure of the state of entropy and the latter a measure of the perception of risk.

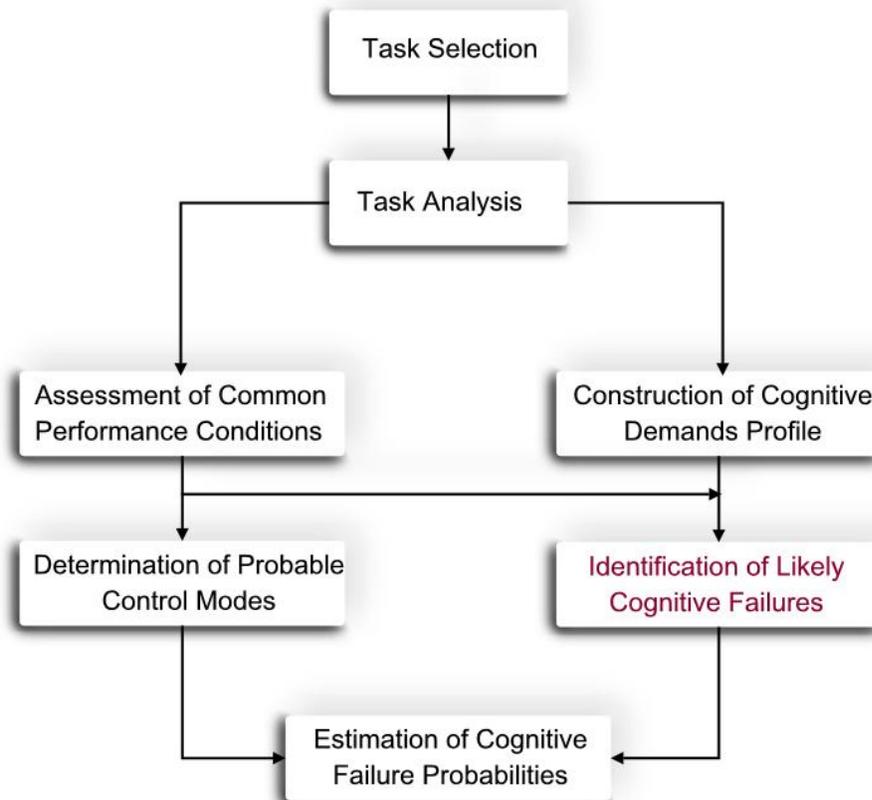


Figure 4.4: The structures methodology of CREAM in evaluating human error (Hollnagel, 1998)

4.6.2 Skill – Rule – Knowledge Model

A model, which dominates the discipline of human error analysis as it applies to human performance, is that of Rasmussen (1983) and known as the Skill-Rule-Knowledge (SRK) model. In this taxonomy of behaviour, Rasmussen envisions three levels of conscious control existing depending upon the degree of interaction between the operator and their environment (Bove, 2002). These levels of control, in order of complexity are *skill-based behaviour*, *rule-based behaviour* and *knowledge-based behaviour* (Figure 4.4). *Skill based behaviours (SBB's)* are thought to exhibit the lower cognitive demand as it is prone to automation and repetition. Examples of *skill-based*

behaviour are activities involved in trades or the arts in which operators respond to 'signals' without conscious effort for control. Next in this hierarchal taxonomy are *rule-based behaviours*. *Rule-based behaviours (RBB's)* are characterized as sequential subroutines in a familiar working environment, in which the subroutines are reliant upon stored rules and well-defined standards (Bove, 2002). The operation of complex machinery such as aircraft and heavy equipment fall in this category in which the operators respond to 'signs' to establish the operational state of their work environment (Figure 4.5).

Finally, at the highest level of cognitive demand are *knowledge-based behaviours* that respond to 'symbols'. Symbols are abstract constructs and representations such as language and mathematics (Figure 4.5). Rasmussen cautions that *knowledge-based behaviours*, while attractive in their sophistication, require considerable investment in time and effort to master, and consequently are employed when the lower cognitive demand will not suffice (Rasmussen, 1983). Examples of *knowledge-based behaviours* are activities involving problem solving and diagnostics in which the goal is explicitly formulated (Busse, 2001).

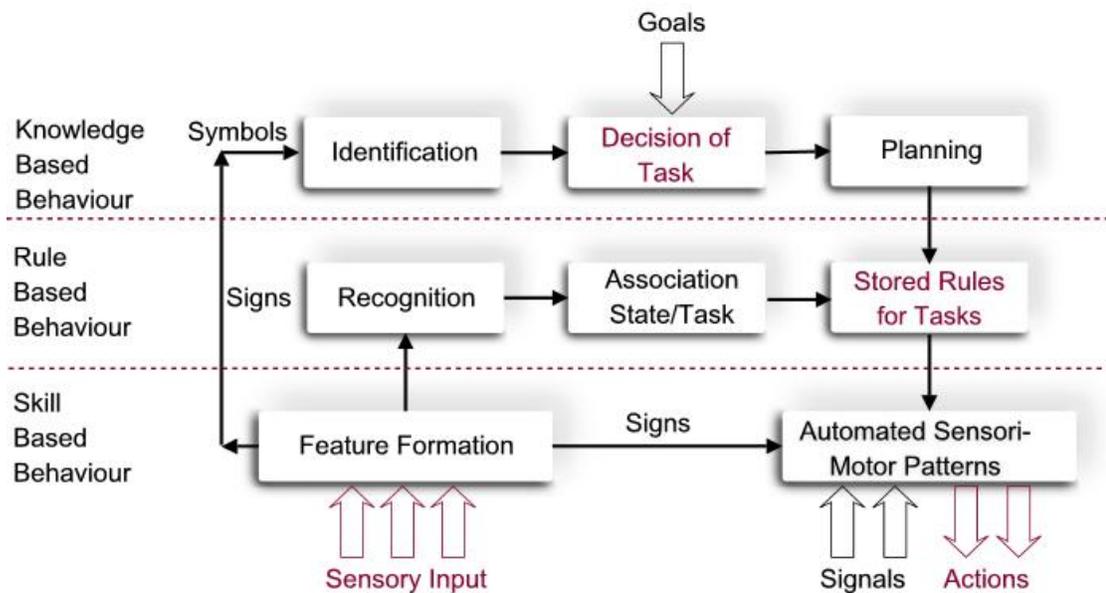


Figure 4.5: The SRK taxonomy depicting three hierarchical control strategies (Rasmussen, 1983)

Rasmussen's (1983) SRK taxonomy is still a touchstone of human error modelling in providing insight into the apparent opportunity for mismatch between the

human element and their tasks. Variability within human performance or the workplace environment (or both) are attributed to be human error or component failures, respectively (Busse, 2001). Implicit in this model is that there be adequate and correct sensory input, *a priori* standards (stored rules) in place and the appropriate cognition for both *rule-based behaviour* and *knowledge-based behaviour* to take place. Busse (2001:42) summarizes:

In general, skill-based performance flows without conscious attention and the actor will be unable to describe the information used to act. The higher level rule-based co-ordination in general is based on explicit know-how, and the rules used can be reported by the person, although the cues releasing a rule may not be explicitly known.

During unfamiliar situations, for which no rules for control are available from previous encounters, the control must move to a higher conceptual level, in which performance is goal controlled and knowledge based. The goal is explicitly formulated. Then a useful plan is developed. Different plans are considered and their effect tested against the goal, physically by trial and error, or conceptually by means of 'thought experiments'.

Rasmussen's SRK taxonomy is the foundation for which he offers a 'decision ladder' representing the intricate cognition that is dynamic to the process of decision-making (Rasmussen, 1987). Rasmussen's decision ladder is composed of eight 'states of knowledge' and eight 'information processing' activities in a sequential and logical framework (Figure 4.6). In this model, Rasmussen explicitly reveals the dynamic complexity between the various nodes of prototypical 'states of knowledge' and the cognitive activities that link them.

Upon first inspection, the decision ladder appears very complex, however depending upon the connectedness between the decision-maker and their environment, the framework in reality presents ten cognitive pathways, one of which: the decision-maker subscribes. The ten pathways are inclusive of the nine short cuts (pathways with inherent error susceptibility) and the default path way in which all of the states of knowledge and cognitive activities take place (the nominal path). Rasmussen's model is significant, lest we as analysts are under the misapprehension that decision-making is a discrete and binary process. The decision ladder illustrates that for individual cognition, decision-making is dynamic; however, for distributive cognition the implication is that there would be permutations of decision pathways that would provide for intrinsic incoherence. This incoherence is intriguing to this research, as it is consistent with the

cognitive fog that appears to surround many of the decisions identified in case studies into the disasters such as the Piper Alpha production platform, the Sunshine Silver mine fire, and the Chernobyl nuclear power plant (Table 4-2). This incoherence presents challenges to the characterization of distributed cognition; however, it also offers opportunity for understanding and study.

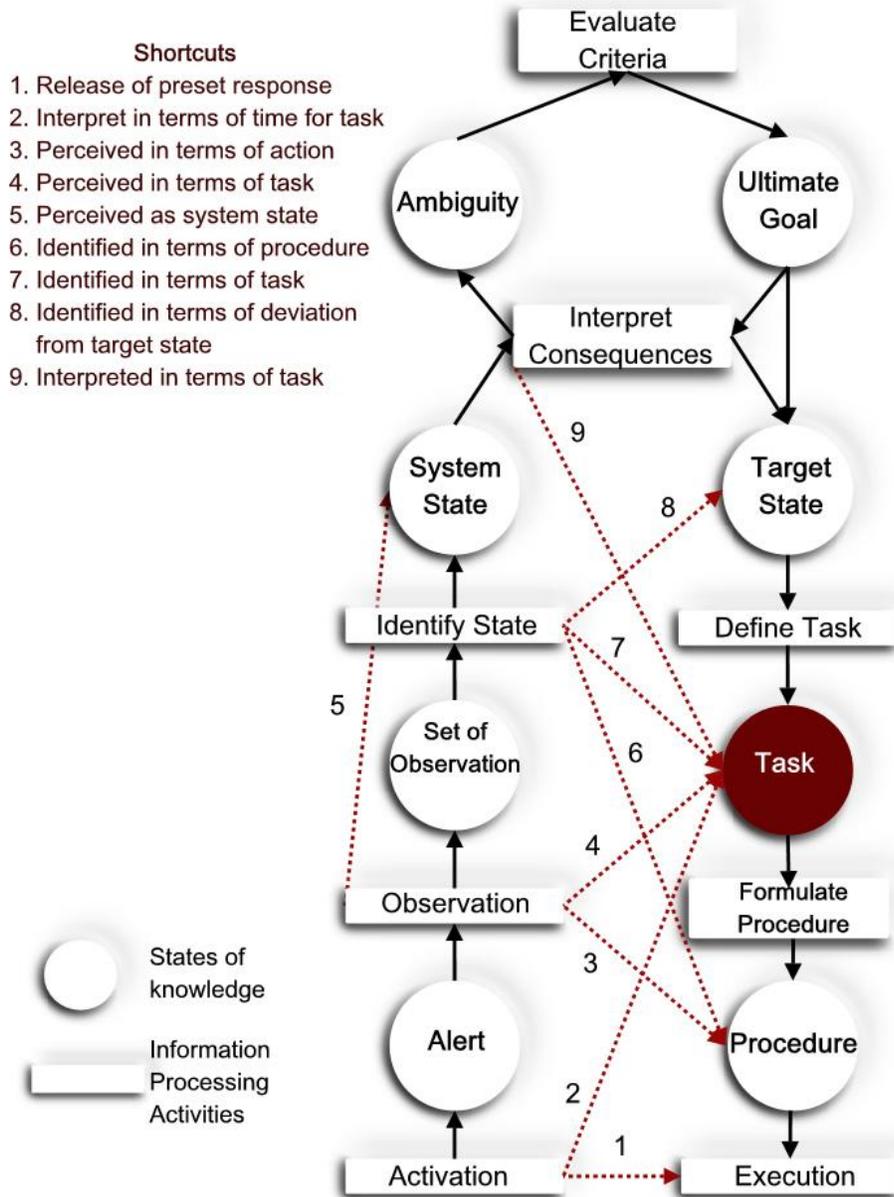


Figure 4.6: The decision ladder model for Cognitive Task Analysis (Rasmussen, 1987)

4.6.3 Seven Stages of Action Model

One model, that of Norman (1981) is significant in its simplicity and symmetry as applied to the formation of intention and its execution. That model is the Seven Stages of Action, and this model has strongly influenced subsequent human error taxonomies. Norman's taxonomy (Figure 4.7) enumerates the cognitive actions that are intermediary to a decision-maker's worldview (the world) and carrying out an action in alignment with a prescribed decision (the goal). Central to this model are the two sides of the cognitive processing (actions): the *evaluation actions* and the *execution actions*. Perception, interpretation and evaluation fall into the former group and intention, sequencing and execution fall into the latter.

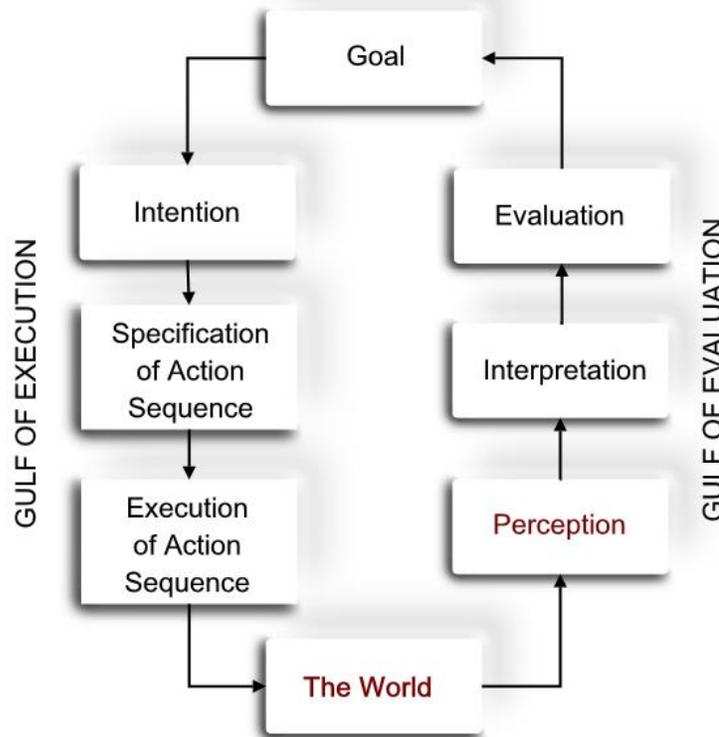


Figure 4.7: Schematic illustrating the Seven Stages of Action taxonomy (Norman, 1981)

The source of human error is explicitly within the domains of evaluation and execution; however, implicit is a correct worldview. In Norman's model, to the extent that the actor does not have a correct ideation of the world the formation of the goal and its

execution is degraded. Any degradation in the perception of the world, its interpretation and evaluation constitutes the 'gulf of evaluation' between the actor's worldview and the goal. Similarly, any degradation in the formation of intention, specification of sequencing and execution constitutes a 'gulf of execution' between the actor's goal and their worldview (Figure 4.7). This process is one of circular logic in which the errors are potentially self-correcting through the changing ideation of goals becoming concordant with a correct perception of the real world.

Norman goes further. Within the action of specification of sequence, he identifies errors that he calls *mistakes* and *slips*. *Mistakes* are associated with specification of sequencing that are concordant with the intention (or plan) but are inappropriate to the goal. In contrast, *slips* are associated with execution of sequencing that is discordant with the intention, but appropriate to the goal. *Mistakes* tend toward cognitive deficiency - errors in understanding or the adequacy of information. *Slips* are more akin to inadequacy caused by memory and inattention.

4.6.4 The Generic Error Modelling System

Reason (1990) improves on both the work of Norman (1981) and Rasmussen (1983) with his taxonomy called the Generic Error Modelling System (GEMS). Reason's GEMS model is an effort to improve on his predecessors' model by providing an integrated model of error mechanisms not prescribed by the Seven Stages of Action model. He does this by starting with the presumption of an unsafe act, and then making the distinction between *intended* or *unintended actions* (Figure 4.8). In doing so, Reason is consistent with the tradition of Heinrich *et al* (1980), and Bird and Germaine (1985) in the identification with unsafe acts and their primacy with cause. Reason subdivides further and explicates *slips* and *lapses* as deriving from *unintended action*; and *mistakes* and *violations* as a derivation of *intended action*.

In doing so, Reason bases his taxonomy on skill-based slips and lapses on the *unintended action* side and rule-based and knowledge based errors on the *intended action* side (Busse, 2001). Consistent with Norman (1981), Reason designates *mistakes* as higher cognition demand and being appropriate with intention, but inadequate for the reaching of the goal. By contrast, *slips* and *lapses* are inconsistent with intent, and inconsistent with the goal. Thusly, GEMS taxonomy is based upon three types of error: *slips*, *lapses* and *mistakes*. Intended violations fall outside of the taxonomy, as they are

neither deviations from the intention nor the goal in the conventional sense of the schema.

Reason's GEMS model represents a phenotype taxonomy in which the distinction of error types is based upon their outward physical manifestation, and therefore can be considered a behaviour model that has a capacity to determine cognitive control processes. The utility of Reason's GEMS taxonomy is the specification of mechanisms of failure that he explicates in association with each error type. In particular, Reason provides mechanisms for rule-based and knowledge-based error beyond that of Rasmussen (1983) and Norman (1981). Within rule-based error, he discriminates between 'misapplication of good rules' and the 'application of bad rules' (Reason, 1990). We interpret the former as the lack of perspicacity in applying rules that are correct, and the latter as the selection of rules that are wrong, respectively.

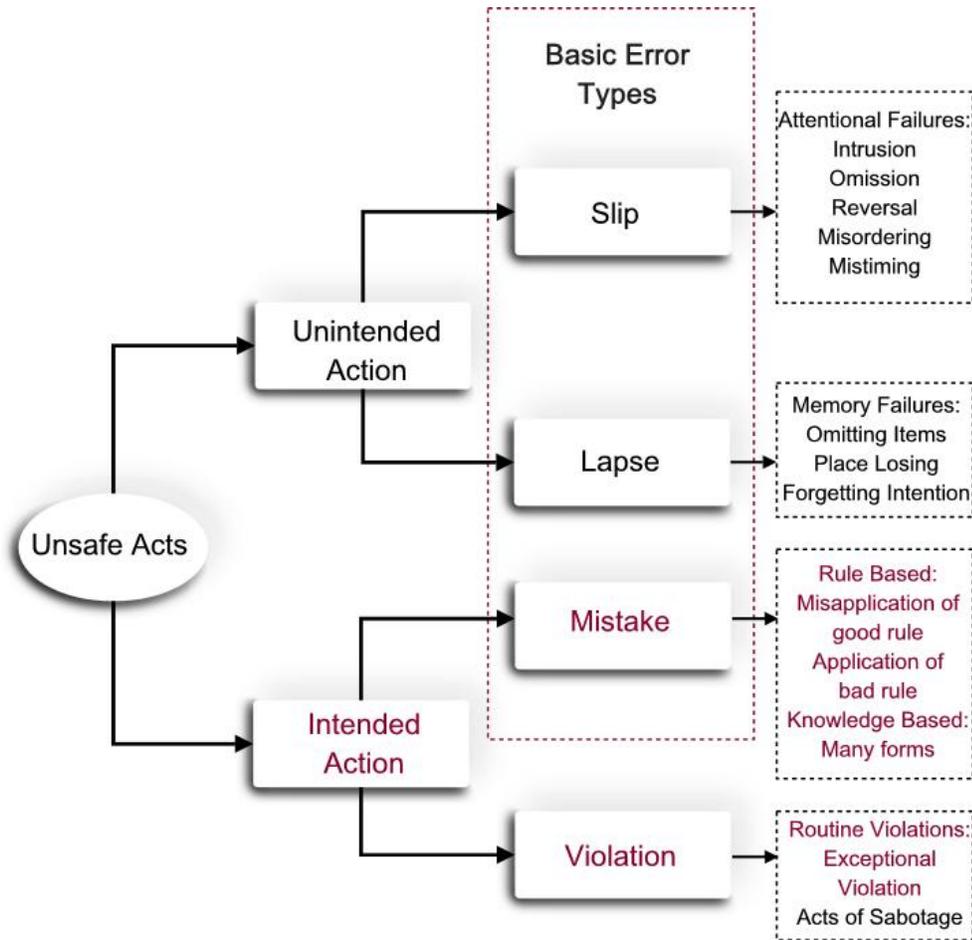


Figure 4.8: Schematic illustrating the Generic Error Modelling System taxonomy (Reason, 1990)

4.7 Knowledge-based Error Mechanisms of Failure

Within the error type of knowledge-based rules, Reason (1990) provides eleven failure mechanisms as a foundation. These failure mechanisms represent a genotypic characterization of cognitive error based largely on biases and heuristics. We have seen in Chapter 2 how availability and representativeness heuristics influence our perception of risk as applied to causality. Reason expands on this theme both in terms of the variety and the scope with which biases and heuristics contribute to cognitive error. Each of Reason's eleven mechanisms for knowledge-based error is of particular relevance to cognitive profiling.

4.7.1 Selectivity Bias

Selectivity bias is the tendency for variability in evidence or information to as determined by the manner in which the data selected. Reason (1990) is more specific and brings into question whether the decision-maker's selection is based upon information that is relevant in terms of logic, as opposed to its psychological salience. An example of *selectivity bias* is persons who subscribe to psychic phenomena. Often, people who are believers in psychic phenomena will call upon anecdotal evidence of its support and not consider countervailing evidence of its repudiation. They do so because they are predisposed to a favourable determination as to the validity of psychic phenomena, and select evidence that supports their belief, consciously or not.

4.7.2 Workspace Limitations

The *workspace* that Reason (1990) refers to is the cognitive *workspace*. Reason argues that the human mind has limitations in terms of the order that it considers inferential data. Thus, it is more economical to consider information in the order perceived by working memory, than in any other order. We can extrapolate from this principle that evidence that is out of sequence with that of the order in which received will not be considered with the same weight as evidence entered in sequence.

4.7.3 Out-of-sight, Out-of-mind

A variation on availability heuristics, *Out-of-sight*, *Out-of-mind* refers to the tendency of people to affiliate with the immediacy of knowledge, but also to ignore

information that is unfamiliar to them. Thus, a decision-maker is likely to fall back on experiences with similitude to the solving of a problem in preference to models requiring adaptation or careful consideration. It would appear that cognitively, we as human information processors instinctually strive for economy over quality.

4.7.4 Confirmation Bias

Complementing availability heuristics, is the tendency of problem solvers having once formed a conclusion – no matter the paucity of evidence supporting it, are predisposed to supporting the conclusion even in the face of mounting evidence to the contrary. Once again, there appears to be an intrinsic lack of economy in the disposal of established ideas in deference to new ones for which, there is better evidence.

4.7.5 Over-confidence

Reason (1990:89) offers that: “A plan is not only a set of directions for later action, it is also a theory concerning the future state of the world. It confers order and reduces anxiety.” Confounded by confirmation bias, a decision or plan once established will take on an inertia that, in spite of new or stronger evidence--will resist change. Further, such resistance is more likely to the extent that the plan is elaborate, is the product of considerable resources or people, or has hidden objectives.

4.7.6 Biased Reviewing

Reiterating the notion of the cognitive workspace having limited capacity, Reason (1990) makes the case that a problem solver may not review in entirety their evidence and rationale respecting a solution or decision. Indeed, given the limited capacity of workspace their review may only be inclusive of that information and evidence that directly supports their determination.

4.7.7 Illusory Correlation

Illusory correlation speaks to the lack of capacity problem solvers have in detecting and establishing co-variation and its logic (Reason, 1990). Racial stereotyping is a common example of illusory correlation. Racial stereotyping occurs when an

identified minority is assigned a statistically significant characteristic, when in reality, no such correlation exists.

4.7.8 Halo Effects

The *halo effect* refers a cognitive bias exhibited when there is attribution concerning one trait, and that attribution is applied to a second trait because the human mind is averse to two different attributions. By example, a Nobel prize-winner for science will be afforded more credibility for their political views by virtue of their scientific acclaim, which has no bearing on their political views or affiliation.

4.7.9 Problems with Causality

Problems with causality essentially flow from representativeness and availability heuristics as covered in Chapter 2. Reason (1990) explains that insofar as a problem solver is prone to oversimplification of causality, they also are similarly predisposed to under-represent the state of future impacts. Reason also brings into play the role of *hindsight bias*, which also contributes to a distorted perception of causality. *Hindsight bias* effectively prejudices a problem solvers ability to model and solve one problem because they remember by similitude a previous problem for which they have already determined a solution.

4.7.10 Problems with Complexity

Problems with complexity are a heuristic that refers to the lack of congruity of the human cognitive processes with the highly interactive and tightly coupled problems and processes occurring in reality. We, as problem solvers, are limited in terms of our capacity to deal with many parallel problems, or problems that change faster than our ability to mitigate them. Coupled with *problems with causality*, complex and dynamic scenarios simply exhaust our capacity to reason and mediate.

4.7.11 Problems in Diagnosis

Reason (1990) argues that diagnosis of problems involves two separate logical reasoning tasks. The first is the evaluation of information related to the determination of symptoms. The second is the synthesis of theory that explains the symptoms and

observations. The problem according to Reason is the lack of consistent application of reasoning to the detection of symptoms and to the determination of their explanation. That is, both cognitive tasks must have applied the same rigour of reasoning.

4.8 Discussion

There is much concurrence concerning the role of human error in *events* within the workplace (Dekker, 2002; Leveson, 2004; Whittingham, 2004; Hollnagel, 2005; Reason, 2005). Human error however, has numerous dimensions and domains that are currently under examination by theorists based upon the early taxonomic work of Norman (1981), Rasmussen (1983) and Reason, 1990). From these taxonomies, technologies such as Tripod© (Doran and Van der Graaf, 1996) have emerged that are more inclusive of human error and its antecedents. Incorporating both the theoretical framework of the Swiss Cheese Model (SCM) of Reason (1990) and his GEMS taxonomy, the Tripod© model utilizes bow-tie accident modelling in the analysis of accidents and incidents (Figure 4.9). Explicit in the model are error types, SRK performance levels (Rasmussen, 1983), as well as decisions made by policy makers (UK P&I Club, 2008).

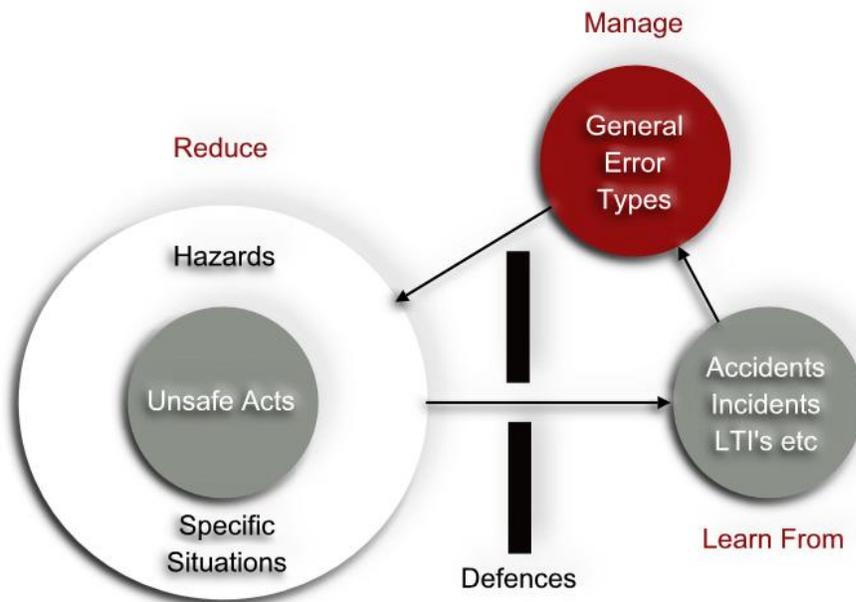


Figure 4.9: Schematic illustrating inclusion of error types in the Tripod model (UK P&I Club, 2008)

In the examination of the integration of human error analysis into techniques and technologies of investigation, it is important to understand not in the abstract, but tangibly – from where does an error of decision-making originate. Decision errors are, for the purposes of this research, subsumed by cognitive error. Cognitive errors are in turn a general subset of the broader class of human error, for which there is an emerging taxonomy. Within this taxonomy are the specific phenotypes of slips, lapses, mistakes and violations (Table 4-3). The phenotypes of mistakes and violations correspond with decision error, and are the focus of the remainder of this dissertation. More particularly to the phenotype of violations, are violations that are routine or exceptional in nature.

Error Type	Description	Possible Causes	Precondition
Slip	Unintended deviation from a correct plan of action	Attention failure Mis-timing	Distraction from task Preoccupation with other things
Lapse	Omission/repetition of a planned action	Memory failure	Change in nature of task, change in task environment
Mistake (Rule-based)	Unintended action inappropriate to the circumstances	Sound rule applied in inappropriate circumstance Application of unsound rule	Failure to recognize correct area of application Failure to appreciate rule
Mistake (Knowledge-based)	Erroneous judgement in situation not covered by rule	Insufficient knowledge or experience – immaturity Time/emotional pressures	Organizational deficiency Inadequate Training
Routine Violation	Habitual deviation from required practice	Natural human tendency to take path of least resistance	Indifferent operating environment; no rewards for compliance
Exceptional Violation	Ad hoc infringement of regulated practice	Wide variety – dictated by local conditions not planned for	Particular tasks or circumstances
Acts of Sabotage	Deliberate violation for malicious reasons	-----	-----

Table 4-3: Taxonomy of human error and their performance levels (UK P&I Club, 2008)

4.8.1 Decision Error

The psychological precursors (antecedents) to any *event* are triggering mechanisms and a product of a culture of safety of any organization (Reason, 2005; Hollnagel, 2005). Whereas it is understood that they contribute widely to the provenance of error, it is specifically the error in mental processing – the cognitive errors that are particularly susceptible. Cognitive errors are by their nature, difficult to ascertain, post *event* or otherwise. However, it is their physical manifestation, or phenotype, that is observable - post *event*. The process of investigation sheds some light on their characterization. Profiling cognitive error presents the opportunity to observe these decision errors, and then provide insight about the perceptions of risk held by the decision-makers, individually or collectively. Rasmussen and Svedung (2000:17) state the case plainly:

Study of decision making for protection against major accidents involves an identification of the interaction found between the effects of decisions made by different actors distributed in different organizations, at different levels of society and during activities during different points in time. We have to consider that all these decision-makers are deeply emerged in their normal, individual work context. Their daily activities may not be coupled in any functional way, only the accident as observed after the fact connects their performance into a particularly coupled pattern. By their various independent decisions and acts, they have shaped a causal path through the landscape along which an accidental course of events sooner or later may be released. A release that is very likely caused by yet another quite normal variation in somebody's work performance – which will be very likely then to be judged the 'root cause' after the accident.

Thus, we are not looking for the decision errors that are traditionally being considered causes of the accident, we seek to identify all the organizational bodies that contributed to the creation of the accident scenario, whether or not they have violated rules or committed errors. For this analysis we have to develop further the traditional formats for accident analysis.

An important point requires emphasis. As earnest as one can be in the pursuit of human error, it is not the end game, but rather the start. Hollnagel (2005:164) states: "The consequence of this line of argument is that the variability of human performance constitutes the noise rather than the signal." Human error insofar as it presents as a failure mechanism is a symptom (i.e. noise), and not the disease (signal). The human factor is just one factor within the system of human/machine/environment that through interaction, complexity and coupling potentially results in failure. Understanding the way

in which this interaction becomes destabilized and deleterious to the enterprise speaks more about its design and governance, than it does about the emergence of operator error. Humans are inherently fallible and any system design needs to be sufficiently robust and resilient as to afford the detection of such errors and their correction without becoming critical to the enterprise.

4.9 Conclusion

The classification of human error and its taxonomy (phenotypes) examines the distinction between types of human error and their underlying mechanisms (genotypes). There has been a renaissance of modelling in human error taxonomy as it applies to causality that has served us well – starting with the Seven Stages of Action (Norman (1981) and evolving with GEMS (Reason, 1990) and culminating with CREAM (Hollnagel, 2001). These models provide a blueprint for progressing forward. By their example, a number of elements must preside in any model or theory, the purpose of which is to determine the psychological precursors (antecedents) of an *event* through the back-analysis of decision errors. First, the model must offer a clear taxonomy based upon empirical data and supportive of current system accident theory. Second, the taxonomy must observe the physical manifestation (phylogeny) of the error and have the capacity to transcend the observable to the inferential; by attributing the cause (ontogeny) of the error. Third, the model must apply equally to the collective as it does the individual, as decisions in the modern workplace are pluralistic constructs, and not limited to the singular. Leveson (2004:6) summarizes the latter, and writes:

Effectively preventing accidents in complex systems requires using accident models that include that social system as well as the technology and its underlying science. Without understanding the purpose, goals, and decision criteria used to construct and operate systems, it is not possible to completely understand and most effectively prevent accidents.

Lastly, it is essential that whatever the methodology, modelling of human error must explain not only the cause, but also the human dynamics underlying causality. The third hypothesis of cognitive profiling and this research is:

The profiling of cognitive errors (particularly decision errors) is not only local and must consider, if not explicate, the biases and heuristics of all of the parties to the enterprise.

My failures have been errors in judgment, not of intent."
Ulysses S Grant (Bartlett, 2000)

5 DECISION ERROR THEORY

Decision error theory (Sweeney, 2004) holds that any decision error contributing to an *event* scenario can be classified as one of four mutually exclusive decision error phenotypes. They are *errors of commission*, *errors of omission*, *errors of mistaken belief* and *system errors* (Figure 5.1). The color coding of each decision error is an integral part of the graphical analysis of decision errors and will be maintained throughout this dissertation.

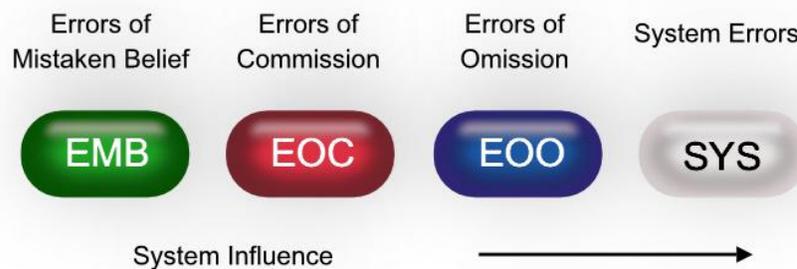


Figure 5.1: Depiction of the four genotypes of decision error theory (Sweeney, 2004)

5.1 Decision Errors Defined

Decision errors are decisions made by a decision maker, or makers that are determined to be contributory to an *event* scenario, or in the absence of an *event* -

deleterious to the enterprise. The decision is the object of the analysis and the subjects of the analysis are the party or parties who make the decisions. A decision is established when a standard that exists *a priori* to the decision is transgressed, defeated or otherwise rendered ineffective by its derivative actions. A decision error is established when the standard is not met owing to human intervention, or the lack thereof. That is, the operator(s) must have known that a rule, norm or statute was applicable, and that some action was required, but failed to take correct action, or failed to take adequate action.

In this model, decision errors are unique to human error analysis, insofar as an objective non-participant in the *event* scenario – typically the accident investigator determines the degree of correctness. Understandably, from the perspective of the decision maker, their decision may, or may not, be deemed contributory to the *event* scenario. This determination is that of the analyst who must consider the decision under the lens of intention and in the context of evidentiary record concerning the *event* scenario in question.

5.1.1 Nomenclature

It is essential that there be no ambiguity respecting the existence of a standard, rule or duty of care, or the party or parties that were cognizant of its transgression. For this reason, the terms used in this model are necessarily both precise and explicit. The standards that are the object of examination are any norm, rule, statute or duty of care that demonstrably exists *a priori* to the *event* in question. The measure that these standards exist is not necessarily by their documentation, but the degree to which the decision maker(s) were aware of and understanding the standards. In this regard, their existence must flow from the evidentiary record; however, of particular relevance is the techno-social dimension – was the standard a real artefact of the workplace for the decision maker(s)? The question is not whether they were in agreement with the standard, rather that there was an expectation or obligation imposed on the decision maker(s). Documentation is a necessary, but not a sufficient, condition of substantiation. The aim of this research is to evaluate the cognition (collective or individual) of the parties, and is not limited to primary evidence. The analyst must go beyond the evidentiary record and consider the state of mind of the decision maker(s), and determine their worldview to truly appreciate and understand causality (Dekker, 2004).

The decision makers of decision errors are inclusive of all parties within the enterprise, in keeping with the second hypothesis of this research (Chapter 4). They may be individual, or a collective (distributed cognition) as stated by the first hypothesis of this research (Chapter 3). Within this dissertation, the makers of decisions are those that are most proximal to the deleterious action, in the first instance, and successively distal thereon. As the subjects of this research, parties to the enterprise are referred to as decision maker(s), actors or operators - depending upon the context and meaning. The noun 'actor' applies in the vernacular of accident theory, and the noun 'operator' appears in case studies and examples.

5.1.2 Errors of Commission

Errors of commission are decision errors in which an actor knows that a standard, norm or rule exists; but elects to transgress the standard for reasons only known to themselves, and in so doing contributes to the realization of the *event* scenario. An example of error of commission is the sinking of the Titanic. Captain Smith was making nearly 22 knots when the vessel under his control struck an iceberg. The standard of the day was to slow down – indeed, in many instances come to a stop when in the vicinity of 'iceberg alley'; particularly as far north as he was. There is much speculation as to why he was steaming so fast; however, the reason died with him, and is an example of experience trumping prudence – and an *error of commission*.

5.1.3 Errors of Omission

Errors of omission are decision errors in which an actor knows that a standard, norm or rule exists; but, elects to defer applying the standard for reasons of conflicting priorities – usually human factors such as panic, fatigue, confusion, exhaustion, boredom; or environmental factors such as distractions or ambient noise. Often times, an actor will defer a decision to another in an attempt to gain time to resolve stimuli both internal and external to their worldview. They may do so because they genuinely believe that other parties are more competent to make the decision or because they feel that that a decision would be prejudicial to their immediate interests. In the absence of deference to a second party, an actor may also defer the decision for an undetermined period of time, in the hopes that circumstances will resolve or that additional information or resources will come forth that will bring alacrity. An example of an *error of omission*

was the Hinton rail disaster, which took 23 lives in February, 1986. Two trains collided when one train failed to yield to a track signal. The engineer was operating the freight train with only two hours sleep. It is surmised that he was literally asleep at the switch at the time of collision. Fatigue and sleep deprivation are common human factors attributed to *errors of omission* (Edwards, 2006).

5.1.4 Error of Mistaken Belief

Errors of mistaken belief are decision errors in which an operator either does not know that a standard, norm or rule exists; or, was aware of the standard but as a result of insufficient or incorrect information makes a decision error ultimately contributing to the *event* scenario. Implicit in this definition, is that had the information been true, the decisions would have been rendered harmless. An example is that of the 'Gimli Glider'; an *event* involving a 767 running out of fuel over Manitoba. The pilot had mistaken the amount of fuel on board owing to a metric conversion error. He simply believed that he had more fuel on board than he actually had. He was able to glide the aircraft safely to an old WWII airstrip near Gimli, Manitoba and narrowly averted a disaster (Williams, 2003).

5.1.5 System Error

In addition to the three mutually exclusive decision error types, there is a default error, or *system error*. *System errors* are inherent in complex technical systems known to occur when subsystems or their components interact in inexplicable and unpredictable ways (Perrow, 1984). However, for the purposes of this research, we consider a broader definition of *system error* inclusive of organizational and cultural determinants. These *system errors* result in a defence or control to become inoperable, not by direct human intervention, but by changes, or perturbations in the organization with time. Notable among these may be *unintended consequences* when an organization restructures or changes through time.

A well-intended organizational improvement can result in substandard conditions through lack of change management on a very gradual scale. Latent factors can go unnoticed until they become symptomatic with time; and yet, no apparent decision error is attributable. *System errors* in this taxonomy are colour coded white (Figure 5.1) and indicate that the system complexity obscures the evidentiary record to the extent that the

error cannot be connected to any one action or inaction. Nonetheless, a standard is transgressed, and by this definition, a decision opportunity presents itself, but is not attributable to any particular party to the enterprise.

5.1.6 Unintended Consequences

A phenomenon not well understood is that of *unintended consequences*, and serves as the exception that proves the rule in decision error theory. More a theory akin to Murphy's Law than a scientific fact, the phenomenon describes the observation that through the implementation of actions toward some goal or purpose, there are unpredicted effects that can have serious consequence. An example is the codification of bicycle helmets throughout many communities in North America. Known to reduce the severity of injuries, contemporary theories suggest (Sloan, 2006) that from the perspective of motor vehicle operators, bicyclists wearing helmets can be afforded less room on the road; thus causing an increase in collisions.

Apparently, a decision to legislate the use of a sensible device to mitigate head injuries has resulted in the *unintended consequence* of increasing the frequency of collisions between motor vehicles and bicyclists. One can see however that from the perspective of policy that this claim merits closer examination. The policy achieves its desired result – it modifies the behaviours of cyclists to protect their heads. The fact that some motor vehicle operators change their behaviours to be less risk averse is another example of *risk homeostasis*. The decision makers in this example are the operators of motor vehicles – not the policy makers. There is no causal connection (other than sequential) between the policy of wearing helmets and the perception of risk on the part of motor vehicle operators. Thus, in this example, there is no causal connection between collision frequencies to the policy of wearing bicycle helmets. From a societal/system point of view, there may be an apparent covariance between the implementation of the policy and the increase in bicycle/vehicle collisions, however there is no causality between the intention of the policy (reduce risk) and the behaviours of the motor vehicle operators alleged to increase the frequency of collisions.

To be clear, there are occasions when unintended consequences do flow from decisions in the workplace. However, unless there is a causal connection in the first instance, and a violation of a known standard in the second instance – they are not decision errors in the purest application of decision error theory (Figure 5.2). The

objective of decision errors analysis is not to bring under scrutiny all decisions in the workplace – only decision errors for which there is a causal connection to an *event* scenario or actions deleterious to the enterprise.

5.1.7 Decision Error Logic

As is the case for other models of human error (Rasmussen, 1983; Reason, 1990), the foundation of decision error analysis is their correct determination and taxonomy. The logic of decision error analysis is deceptively simple (Figure 5.2). Either through the process of investigation or by evaluation of the investigative record, conditions resulting from the defeat of controls or defences is examined. This is the starting point, and one that is common with most investigation methods. More subtle and difficult is the determination of those parties who knew that these conditions existed, and through action or inaction missed the opportunity to remedy the condition. This is often the analysis 'lost' in conventional investigations, as emphasis is on cause and effect. It is during this moment of action or inaction that goes to the very heart of decision error theory and cognitive science. What were they thinking? What was their motivation? What was their perception of risk and what did the *event* scenario look like from the point of view of these actors (Dekker, 2004)? These lost opportunities (decisions) are the lament of many experiencing *event* scenarios, and central to decision error analysis.

Having determined that a condition/decision existed contributing to an *event* scenario the next step is to determine what standard, norm or duty of care existed prior to the decision (Figure 5.2). The pre-existence of a standard, and that the standard was violated is pivotal to the argument that a decision was reached resulting in action or inaction by some party. The standard may be any number of artefacts ranging from implicit to explicit (Figure 5.3). The absence of violation of any standard, defence or control is indicative of the lack of management systems and preventative strategies respecting the *event*, and is a determination of some importance. In terms of the logic of decision error theory however, the absence of standards precludes any further analysis.

The next consideration in the logic of decision error is to determine if the decision maker did in fact have knowledge of the standard employed as a defence or control (Figure 5.2). In the case of a deficiency of knowledge of the standard or lack of experience to apply it, the error would be one of mistaken belief. Both decision errors of commission and decision errors of omission require that the person making the decision

have full and complete knowledge of the standard, otherwise they are not advertently participatory in its transgression. Discounting the case of error of mistaken belief, the next test is the extent to which the actor intended to meet the standard, norm or duty of care – or not (Figure 5.2). In those instances where the decision maker elected to not meet the standard then the error is one of commission; one where through affirmative action or inaction, the standard was not met.

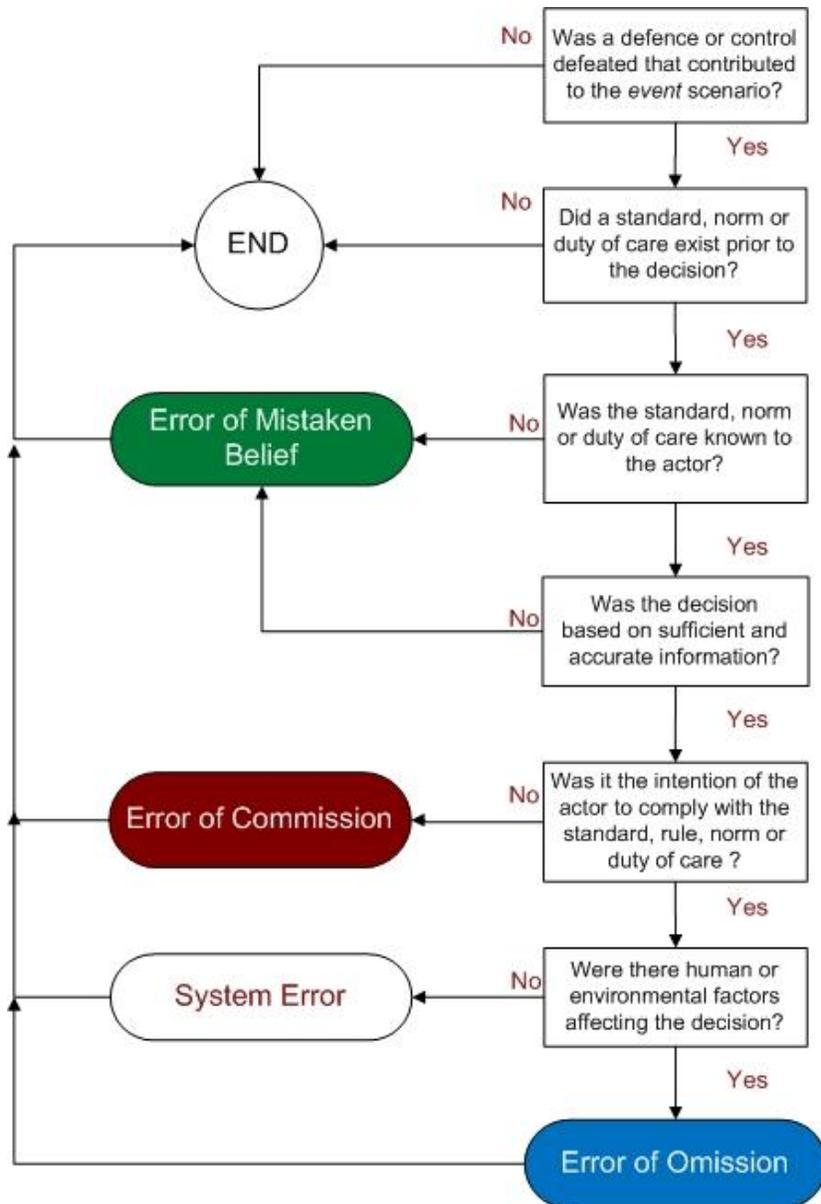


Figure 5.2: Flow-chart illustrating the logic of decision error classification and their determination

In the absence of errors of omission, commission or mistaken belief, the default classification is that of system error (Section 5.4). If no decision can be found that can account for a defeated defence or compromised control, then other error mechanisms must be considered; suggestive of a system of defences and controls that is dysfunctional or inactive. It is noted that such a degree of complexity and coupling rarely occurs within the mining industry, however it is anticipated that as the enterprise of mining embraces larger and deeper mines requiring technologic innovation, mines may well encounter system errors and their effects (Sweeney and Scoble, 2006).

The last remaining decision error class is error of omission. The test of error of omission is that the decision maker was cognizant of the standard but deferred or otherwise failed to meet the standard for reasons beyond their ability to cope (Figure 5.2). The reasons could be environmental or human factored; or a combination of both that compromise cognitive performance. An example illustrating this is workers who function beyond the 'red line' in terms of hyper-vigilance; a state in which our bodies revert to fight or flight instinct and shed more advanced skills and training cues (Chiles, 2002). Control room operators during the Three Mile Island crisis in 1979 and the Chernobyl disaster in 1986, as well as numerous air traffic incidents, are examples of *cognitive lock*; a state of diminished capacity when too much information overwhelms human cognition. The decision maker wants to make correct decisions and meet the requisite standards, but is unable to do so within their impaired frame of reference. They take a 'time-out' to reset their perceptions and either omit key decision opportunities or defer decisions until it is too late. Ultimately they may make poor decisions that would otherwise be well within their capacity to make under normal circumstances. Heat-exhaustion, fatigue and overstimulation to alarms, lights and enunciators can have a similar effect, as can boredom, coercion and anxiety.

5.1.8 Standards of Care

Requisite in the application of decision error theory is that some standard of care pre-exist the *event* occurrence. It is presumed that most people in the workplace are conscientious and caring individuals who want to make a contribution and fulfill their employment contract. Implied in this contract however, is that there are standards and norms that guide if not set the expectations of performance, behaviour and conduct. These standards can take on many forms and artefacts within the workplace, or

enterprise. Standards may be implied or explicitly stated and documented (Figure 5.3). The rule of law (civil statute) is an example of a minimum standard of care imposed on workplace parties that is explicit. Roles and responsibilities for workplace parties are set out by legislation (an *Act*), and the means by which this standard is measured is prescribed by regulation.

In British Columbia, the governing statute for mining and exploration is the *Mines Act for British Columbia*, and the Health, Safety and Reclamation Code for Mines in British Columbia (Mines Act, 2008). Within most statutes there is an explicit requirement that a responsible party demonstrate due diligence in their conduct and actions in the workplace (usually the employer). Thus, due diligence is the definitive standard of care under civil code (Keith, 2006); explicitly imposed on the workplace parties (Figure 5.3).



Figure 5.3: A schema illustrating the primacy of standards of care used in this research

At the lower end of the spectrum of standards of care are those that are assumed by the workplace parties and are largely implied by virtue of affiliation with the mine workplace, or the organization. Within the scope of the workplace, it cannot be over emphasized that all parties to the enterprise are compelled by numerous standards of care, and that in general the more authority and special knowledge of the enterprise – the more numerous and imposing are these standards of care. It is often not appreciated that every party to a mine workplace has, as a minimum, a *duty of care* to every other party respecting their health and safety. It is a shared duty that cannot be abrogated.

5.1.9 Duty of Care

Afforded special treatment is to the notion of *duty of care*, as it requires some knowledge of tort law. *Duty of care* is the implied obligation one person has to another to use all prudence, caution and attention of a reasonable person in their actions. If a *duty of care* can be established (as one workplace party has to another), and it can be shown that a person's actions breached that duty resulting in harm; then a claim of negligence can be alleged (Bruce, 1998). Of issue is whether a person's act or omission is one of *misfeasance* or *nonfeasance*. Bruce (1998:1) explains:

Even if the defendant *has* foreseen the harmful event, he/she will often not be found to owe a duty of care if his/her failure to act is one of nonfeasance rather than misfeasance. If it is the actions of the defendant which *create* the circumstances in which a third party may be harmed, failure to take precautions to avert that harm is called *misfeasance*. In that circumstance, the defendant will be held to owe a duty of care. If, however, the defendant has merely *observed* that a third party may be harmed if a certain precaution is not taken, and has not taken that precaution, that failure to act is termed *nonfeasance*. In that circumstance, the defendant may be found to owe no duty of care (assuming that he/she did not create the circumstances – i.e. that he/she was not also a misfeasor). For example, if A knocks down a stop sign and lack of that sign subsequently contributes to the injury of B at that intersection, A may be found to have owed a duty of care to B – and may be found negligent for having failed to report the initial accident. On the other hand, if, after A has knocked over the stop sign, C notes the absence of the sign and fails to report that fact, C will not be found to have owed a duty of care to B.

Acts of malfeasance are deemed in this investigation to be equivalent to Reason's acts of sabotage, and fall outside of the scope of this research. Acts of nonfeasance and misfeasance are very much of interest, although the legal distinction

becomes moot. Of interest is the fact that in either case the party knew of a standard, defence or control that was being compromised and their responsibility to act speaks to the degree of their *duty of care*.

5.2 Lost Error Taxonomy

Explicit in the decision error theory proposed by this research is the observation that there is a gap in *event* modelling (Figure 1.1). Typically missing from analysis is the identification of cognitive precursors, antecedent to an *event*. Human error analysis in general and cognitive profiling in particular addresses the taxonomy of these cognitive precursors. A more declarative description is that there are human errors that are lost to the 'fog of causality' (*errata ignotus*); and to know something about them requires a more indirect methodology than is available with current error analysis. This methodology involves cognitive profiling and builds upon the insight of Norman (1981), Rasmussen, (1983) and Reason (1990). We cannot observe cognitive processing in the workplace, much less cognitive errors. We can however, observe the behaviours and actions that are derivative of cognitive errors. As manifestations of error, they are known and measurable – as the phenotypes of errors of commission, omission and mistaken belief.

Decision errors fall within the *intended acts* of Reason's (1990) GEMS model. Errors of commission and omission are clearly rule-based violations. Similarly, errors of mistaken belief are knowledge-based mistakes, in terms of the GEMS model. The 'lost errors' of the taxonomy proposed in this dissertation are analogous to Norman's gulf of evaluation (Norman, 1981). In contrast, the decision errors of commission, omission and mistaken belief are analogous to Norman's gulf of execution because they are consonant with intention, but inappropriate to the goal. Only by observing the error phenotypes can we adduce something about the error genotypes.

The Lost Error Taxonomy presented in this dissertation (Figure 5.4) is an adaptation of the Seven Stages of Action (Norman, 1981), and is a reduction of other human error taxonomies insofar as it is restricted to decision errors. Specifically, this taxonomy corresponds with the SRK (Rasmussen, 1983) basic error types of mistakes and violations. It is not a general theory as epitomized by Reason's GEMS model, but rather a theory specific to cognition. Nonetheless, the objective of cognitive profiling is a holistic characterization of decision errors determinant to an *event*, with the attendant

benefit of providing insight into the collective ethos of error within the organization under whose governance *events* occur.

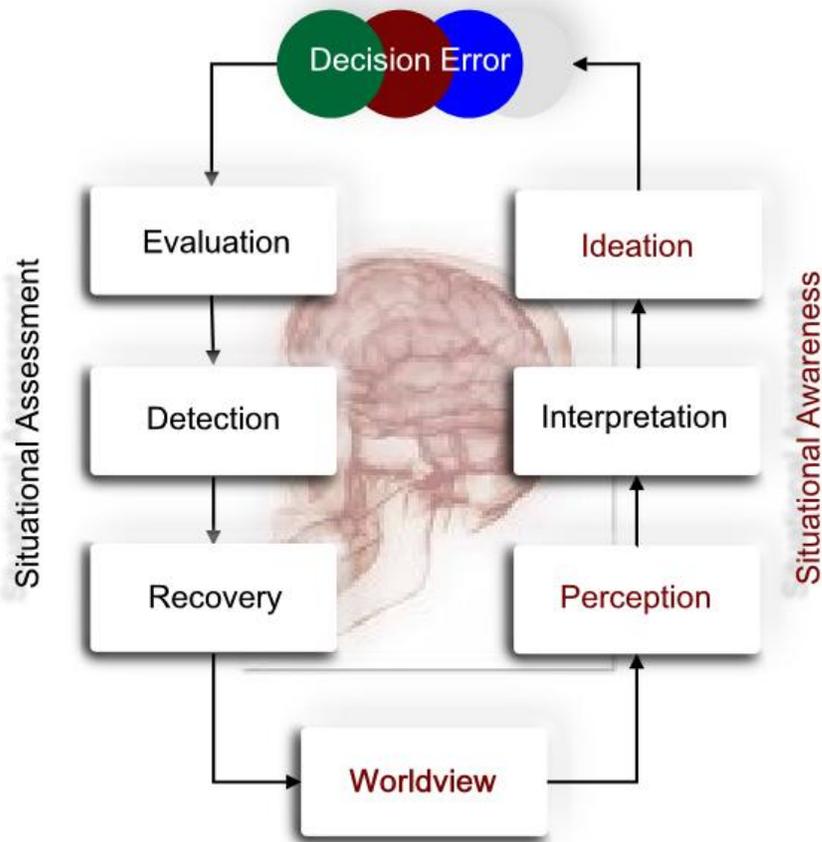


Figure 5.4: Lost Error Taxonomy schema, an adaptation of that of Norman (1981)

Worldview is the starting point for this model. In a perfect world, the actor's perception of risk is accurate and their interpretation of that risk results in ideation that is appropriate to their goals. This represents a state of consonance between the actor's perception of risk and their decisions (cognitive consonance). Alternatively, an actor's perception of risk may not be equal to the worldview (either risk averse or risk tolerant), and their ideation would not be appropriate to their goals. This represents a state of dissonance between the actor's perception of risk and their decisions (cognitive dissonance). Such decision errors are elusive; and, are lost to conventional *event* analysis, because of the lack of evidentiary record and the limitations imposed by cause and effect modelling. Regardless, a decision, once formed, must result in action - in

order that the decision, or decision error, exist. The characterization and classification of these decision errors is essential to the understanding of perception and cognitive error.

This taxonomy (Lost Error Taxonomy) is predicated on decision errors, and by their presence, there are opportunities for error detection and correction (Figure 5.4). Errors such as 'failure to detect' and 'failure to correct' are errors commonly missed in the investigation of *events* owing to increasingly complex and coupled systems (Perrow, 1984). The capacity to evaluate, detect and correct errors is tantamount to their prevention, and is one of the goals of human reliability assessment (Hollnagel, 2005). Furthermore, there is reason to believe that this tactical faculty is resonant with the concept of *situational assessment* (Stanton *et al*, 2001). To complete this symmetry, a good sense of *situational awareness* lends itself to good decisions, and alternatively, its absence contributes to decision error (Figure 5.4). Clearly, *situational awareness* is antecedent to decisions (Endsley, 2000) and their validation (*situational assessment*).

5.2.1 Situational Awareness

Endsley (2000:5) defines *situational awareness* as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and a projection of their status in the near future.” In this definition, perception is explicitly the determining factor. Endsley (2000) emphasizes the dynamic nature of *situational awareness*, and by extension *situational assessment*. Theoretically, the absence of *situational awareness*, and a failure of operators to adapt to changes in status could conceivably lead to a decoupling of an operator’s perception of risk and a rational worldview (Woods, 1988). The taxonomy proposed within this dissertation by its recursive nature, provides a mechanism that accommodates the notion that if decision errors are left unchecked – a decision error could result in a failure.

This dissertation asserts that *situational awareness* is antecedent to *situational assessment*. By this reasoning, if the perception of risk determines *situational awareness*, then an operators’ capacity for *situational assessment* is determined by how well they reconcile the dissonance between their worldview of risk and the actual risk in the workplace. Next, in this dissertation, we will expand on decision error theory and the Lost Error taxonomy to introduce decision error analysis and cognitive profiling as an innovative error modelling technology.

5.3 Decision Error Analysis

The technique employed in this research to map decision errors is that of decision error analysis (Sweeney, 2004). The decision error analysis diagram (DEAD) is a graphical method of recording and tracking decision errors contributory to an *event* scenario with respect to chronology and the actors within the scenario. The purpose of the analysis is to distil from the evidentiary record, or investigative records, standards that are defeated, violated or otherwise compromised in accordance with chronology. This is achieved by use of a 'radar diagram' structure, with which the decision errors are plotted (Figure 5.5). The technique can be applied post-*event*, as part of the investigative process, or as an audit tool to evaluate the contribution of human errors to an enterprise, and their characterization.

5.3.1 Radar Diagram Structure

The decision error radar diagram is populated by decision error in accordance with decision error theory (Figure 5.5). The centre of the diagram represents an *event*, and the rays diverging from this point represent potential decision errors of actors participating in the scenario. Concentric circles emanating from the epicentre (the *event*) of the diagram, represent conditions contributing (determinants) to the *event*, and are covariant with time. Chronology flows in retrograde from proximal to the *event* to distal. Thus decisions plotted closer to the *event* are closer in time than those further away.

The conditions can be any determinants found to contribute to the *event*, physical, organizational or behavioural. In the abstract, the conditions are akin to unsafe acts or unsafe conditions (Heinrich *et al*, 1980), however they also represent standards (artefacts, controls and defences) that have been compromised. With this analysis, a condition cannot be plotted unless a standard of care pre-exists the *event*, consistent with decision error theory. The conditions are identified by number or letter and are tabulated prior to being plotted accordingly (Table 5-1).

5.3.2 Characterization of Actors

The actors are identified by vocation, workplace parties or individually, depending upon the scope of the analysis. At the enterprise level, parties may be appropriate; at the operational level, their occupations may suffice. It depends upon the specificity desirable

by the analyst. If the analysis is broad and there is reason to believe that distributed cognition is of interest, then the workplace parties or parties to the enterprise are plotted. In contrast, in an *event* where the behaviours specific persons are of interest, their occupations or titles may be plotted. As a precaution, there is little to be gained by identifying actors by name, as participants to a scenario are likely to be sensitive to being identified by name in the analysis.

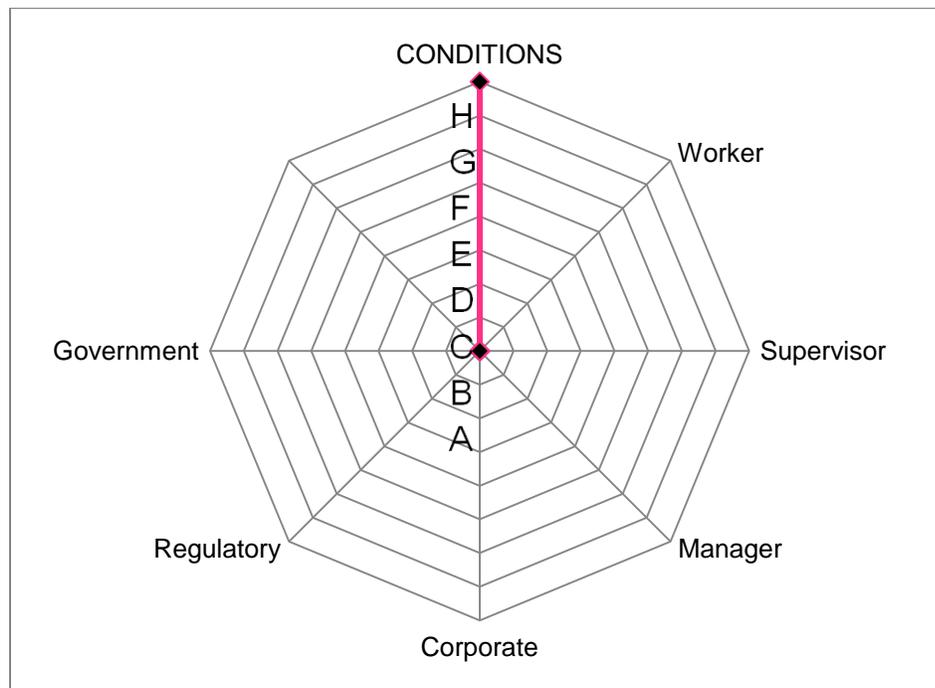


Figure 5.5: An unpopulated example of a decision error analysis radar diagram (Sweeney, 2004)

5.3.3 Radar Diagram Principles

Designed and intended for clarity, decision error analysis is simple in its presentation. The determination of the conditions contributory to the *event* and participants to their existence is another matter. A number of salient principles will assist in its application. They are:

- i. For every analysis, there must be one, and only one, well defined *event*.
- ii. Conditions are plotted in reverse order of their chronology.
- iii. Each condition is uniquely identified and appears only once.

- iv. Each condition specifies a standard, defence or control that was in place prior to the *event*.
- v. Each decision error plotted is a graphical representation of either an error of commission, omission, mistaken belief or system error.
- vi. Actors are plotted in reverse order of standard of care; or, as a rule - in order of their organizational reporting hierarchy.
- vii. Additional diagrams can be concatenated to accommodate many actors or many conditions, appropriate to the scale of the diagrams.

5.4 Decision Error Analysis Tutorial

An example of a mine *event* resulting in a fatality will serve to illustrate the functionality and richness of cognitive profiling. Starting with a description of the *event* scenario, we will proceed sequentially through the analysis that will culminate in a cognitive profile of this hypothetical mine organization. It is important to bear in mind that there are a limited quantity of data points (decision errors) that are presented by any one *event*, and hence the benefit of combining the data from numerous *events* to determine an accurate profile of the risk culture.

5.4.1 A Hypothetical Event Scenario

The setting is an underground metal mine. A two-man bolter/screener crew composed of a seasoned miner and a junior helper was working at the 4200 feet level on the day-shift installing screen. They were working off the back of a MacLean scissor-lift truck with a 'stopper' and materials. The mine was seismically active with a history of bad ground on the 4200 level, to the extent that a recent consultant's report suggested that production be reconsidered, if not abandoned. The morning of the *event*, the cross-shift had noted many falls of ground; something that had occurred in recent weeks but not entered in the log books as per company policy and procedure.

The senior bolter set up his scissor-lift and proceeded to drill holes without scaling or sounding the back. The drift was crossing the transition ground between country rock and ore, and was visibly 'slabbing'. Previously, the cross-shift drillers and blasters had elected not to drill the requisite blast pattern. They took the same ground with more powder and less holes, in an effort to increase production. They were on a

bonus system per tonne of ground taken. This was not an accepted practice, but not unknown.

Minutes prior to the *event*, the senior bolter drilled a hole for which he could not insert a bolt (evidence of 'slabbing'). The standard operating procedure for this contingency is that drilling be stopped and for the crew to withdraw from the face. It is a 'one hole—one bolt' rule that should not to be violated. The senior bolter/screener elected to continue however, and asked the helper to prepare the scissor lift truck to advance a few feet. The helper dismounted the scissor-lift truck and the senior bolter/screener collared a second hole when approximately 4.5 tonnes of slab ground from the back fell on him, crushing him instantly. All attempts to resuscitate the miner failed, and he expired before he could be transported to surface.

An investigation revealed that all of the seismic monitors had exceeded trigger levels, but the mine ground control department did not cause cessation of operations or warn the crews. The heading was known to be actively working. All entries of major ground fall that were made in the ground control log were estimated at 4.9 tonnes so that reports did not have to be made to the regulatory agencies of major ground fall (5 tonne trigger-level). All parties working on the 4200 level had heard, if not witnessed significant falls of ground during the preceding hours to days to the *event*.

5.4.2 Compromised Standards of Care

Sixteen decision errors compromised existing standards and contributed to this *event* scenario (Table 5-1). References to cross shifts are synonymous with crews working the night shift. For clarity, the conditions contributing to this *event* scenario are (from proximate to distal to the *event*):

- A:** The senior bolter violated the one hole – one bolt standard for bolting and screening.
- A:** The miner's helper deferred to his more senior partner, and did not challenge the decision of his partner, believing that he was not empowered to do so.
- B:** The senior bolter did not scale the back nor sound for rock mass competency.
- B:** The helper also did not scale of sound as he believed that if it needed doing, his partner would direct him to.

- C:** The senior bolter did not refuse to work in the drift that was clearly slabbing with major ground falls observed when he entered the drift.
- C:** The helper did not refuse work, as he was in a junior position and did not want to jeopardize his job.
- D:** The cross-shift blasters had not drilled and blasted the face of the drift in question with the correct pattern and had compromised the back.
- E:** The ground control technician had not alerted the crews of incipient failure of the ground within the 4200 heading, as indicated by the seismometers.
- F:** The cross-shift shift-boss did not adequately evaluate and control workplace for hazards and risks.
- F:** The day-shift shift-boss did not adequately evaluate and control workplace hazards and risks.
- G:** The cross-shift mine captain did not inform the day-shift mine captain of the falls of ground during the back shift (night crew) owing to lack of time.
- H:** The cross-shift mine captain had not been entering the observed falls of ground into the ground control logbooks for reasons of competing priorities.
- H:** The day-shift mine captain had not been entering the observed falls of ground into the ground control logbooks for reasons of competing priorities.
- I:** The mine superintendent had elected to not report ground falls that exceeded 5 tonnes to the regulatory authorities.
- J:** The mine superintendent deferred to the mine manager the decision to mine the 4200 level, in spite of having knowledge of ground control problems.
- J:** The mine manager did not take seriously the consultant's report advising him of bad ground conditions and incipient ground failure at the 4200 level.

5.4.3 Observations: Decision Error Analysis

The table summarizing decision error analysis depicts ten actors contributing to sixteen decision errors in which ten standards were violated (Table 5-1). Of the sixteen decision errors, ten were errors of commission, three were errors of omission, and three were errors of mistaken belief. The hourly workers contributed to 50% of the decision

errors, the supervisory staff contributed 19%, and management to 31% of the decision errors (Table 5-2). The overall character of this decision error analysis diagram (DEAD) is a 'spiralling down' pattern in which the decedent and his fellow worker made decision errors heavily weighted in errors of commission (Figure 5.7). It is evident from the diagram that the helper took his lead from the more senior miner, and was working under his direction. Also evident is that there was a cluster of errors of commission proximal to the *event* that the shift-bosses or more senior mine management did not participate in. Both the day shift-boss and the cross shift-boss made the same decision error (error of commission), respecting condition F, which was that the headings were not evaluated for hazard and risk. This decision error was a violation of procedure, statute and the duty of care to the workers (Table 5-1).

The decision error analysis diagram (DEAD) illustrates that there are increasing instances of errors of commission with proximity to the *event* (Figure 5.7). This is indicative of mine operators who lack commitment to the standards of care and conduct in their workplace, and in the absence of direction, will serve to perpetuate a 'signal' (Hollnagel, 2005) that such standards are discretionary. In contrast, the mine management/supervision exhibit errors disposed to errors of omission and mistaken belief that suggest a management ethos that is out of touch with the standards of care under their management. The outlier is the Mine Superintendent, who presents two errors of commission. Given the status and authority of mine superintendents within underground mine operations (Figure 5.6) it would be prudent for management to examine closely the influence that this party (Mine Superintendent) has on the errors of commission of subordinate parties in this scenario.

The spiral pattern exhibited in this analysis may be misleading. One would not expect to see a string of unsafe acts or conditions in a mine workplace where there are so many workers present, and for which there is attribution to only a single party. It is likely, that a more in depth investigation at a system level would have revealed that were other parties cognizant of the lack of compliance to workplace standards within this mine. However, insofar as this investigation was based upon sequence-of-events modelling, the determination of cause and effect limits the scope of investigation. This is the disadvantage of sequence-of-events modelling: there is an implicit assumption that a party to an unsafe act or condition is the cause, and not the symptom of the cause.



Figure 5.6: Hierarchical ‘command and control’ structure of traditional Canadian hard-rock mines

5.4.4 Discussion

This *event* scenario is consistent of the *events* occurring within operating hard-rock mines in Canada. The organizational structure of hard-rock mines dates back to the early 20th century, and reflects a command and control style of management. The hierarchy is highly structured and stratified (Figure 5.6). As societal values and regulations have changed, the organizational structure of operating mines has not adapted to suit. Consequently, there is a lack of empowerment of subordinate parties, as regards to challenging decisions and asserting their right to safe work. The regulatory statutes (*Mines Act*, 2008) have undergone reform explicitly providing all mine workers with these rights and mine operations have changed management systems to accommodate, but the organizational culture is handicapped by hierarchical rigidity.

Paradoxically, a command and control ethos can be ineffective in the implementation of mine workplace standards when those in position of authority do not have an accurate worldview of the risk. The opportunity for correction rests with those parties who are closest to the work – and the risk (Figure 5.6). It is these parties (miners and technicians) who have the most opportunity to detect and mitigate risk; their perception of risk critical for motivation. Mine supervisors by comparison, have a balance

of authority and opportunity. When coupled with knowledge of the mine workplace, the shift-bosses and mine captains clearly are in the best position for both the oversight and enforcement of standards in the mine workplace. In this hypothetical *event* scenario, the mine shift-bosses and mine captains contributed 19% of the decision errors (Table 5-2). The mine shift-bosses exhibited errors of commission, and the mine captains exhibited errors of omission. The mine shift-bosses abdicated their responsibility for assessing the workplace for hazards, a duty of care that is assumed by those in supervision and imposed by statute (*Mines Act*, 2008). The mine shift-bosses would benefit from education and training of their roles and responsibilities as supervisors. The mine captains made errors of omission that were communication related (Table 5-1). These occurred during shift change and are likely attributed to too many expectations over too little of time. Mine management would benefit from streamlining and prioritizing communication and documentation during shift change.

5.4.5 Decision Error Analysis Critique

The objective of decision error analysis is to examine the nature of contributions by actors in an *event* scenario, as evidenced by the state of standards (controls, defences and artefacts) put in place to prevent such an *event*. It does so in a straightforward, graphical manner that adds value to *event* analysis by considering the human error element in the context of the conditions prevailing prior to *event*, as opposed to after. The technique implements a simple and robust phenotype taxonomy that is as objective as the evidentiary record. Herein lays its weakness, insofar as it requires a concise narrative of the determinants contributory to an *event*. This is a dichotomy of proximity to the *event*. If the analyst is too affiliated with the actors involved in the scenario, they will be prone to subjectivity. If they are too removed from the worldview of the actors involved in a scenario, they will lack insight as to the cognitive state of the actors. Clearly, an emerging skill set for this analysis is cognitive science.

Letter	Workplace Party	Condition Contributing to the Event Scenario	Standard Transgressed	Error
A	Miner (Decedent)	Continued drilling after bolt failed to install	Standard Industry Practice	EOC
A	Miner's Helper	Continued drilling after bolt failed to install	Standard Industry Practice	EOC
B	Miner (Decedent)	Back not scaled or sounded for 'slabbing'	Regulatory Statute	EOC
B	Miner's Helper	Back not scaled or sounded for 'slabbing'	Regulatory Statute	EOC
C	Miner (Decedent)	Continued to work in conditions of imminent danger	Duty of care to helper	EOC
C	Miner's Helper	Continued to work in conditions of imminent danger	Duty of care to miner	EMB
D	X-shift Blaster	Drilled a deficient pattern weakening the back	Standard Operating Procedure	EOC
E	Ground Control Technician	Seismicity not communicated to crews	Duty of care to miners	EOO
F	X-shift Shift Boss	Heading not evaluated for hazard and risk	Duty of care to miners	EOC
F	Day-shift Shift Boss	Heading not evaluated for hazard and risk	Duty of care to miners	EOC
G	X-shift Mine Captain	Ground fall conditions during the night not communicated to day shift workers	Duty of care to miners	EMB
To be continued on next page			Table 5-1a	

Letter	Workplace Party	Condition Contributing to the Event Scenario	Standard Transgressed	Error
H	X-shift Mine Captain	Ground conditions not entered into logbooks	Standard Operating Procedure	EOO
H	Day-shift Mine Captain	Ground conditions not entered into logbooks	Standard Operating Procedure	EOO
I	Mine Superintendent	5 tonne ground falls not reported	Regulatory Statute	EOC
J	Mine Superintendent	Consultants report disregarded	Due Diligence	EOC
J	Mine Manager	Consultants report not taken seriously	Due Diligence	EMB
		-End-	Table 5-1b	

Table 5.1: Table specifying the various workplace parties making decision errors contributing to the *event* scenario

Workplace Party	EOC	% EOC	EMB	% EMB	EOO	% EOO	Totals	Total %
Hourly Mine Workers	6	75%	1	13%	1	13%	8	50%
Mine Shift Bosses	2	100%	0	0%	0	0%	2	13%
Mine Captains	0	0%	1	33%	2	67%	3	18%
Mine Superintendent	2	100%	0	0%	0	0%	2	13%
Mine Manager	0	0%	1	100%	0	0%	1	6%
All Workplace Parties	10	62.5%	3	18.8%	3	18.8%	16	100%

Table 5.2: Table summarizing the distribution of the decision errors by the workplace parties

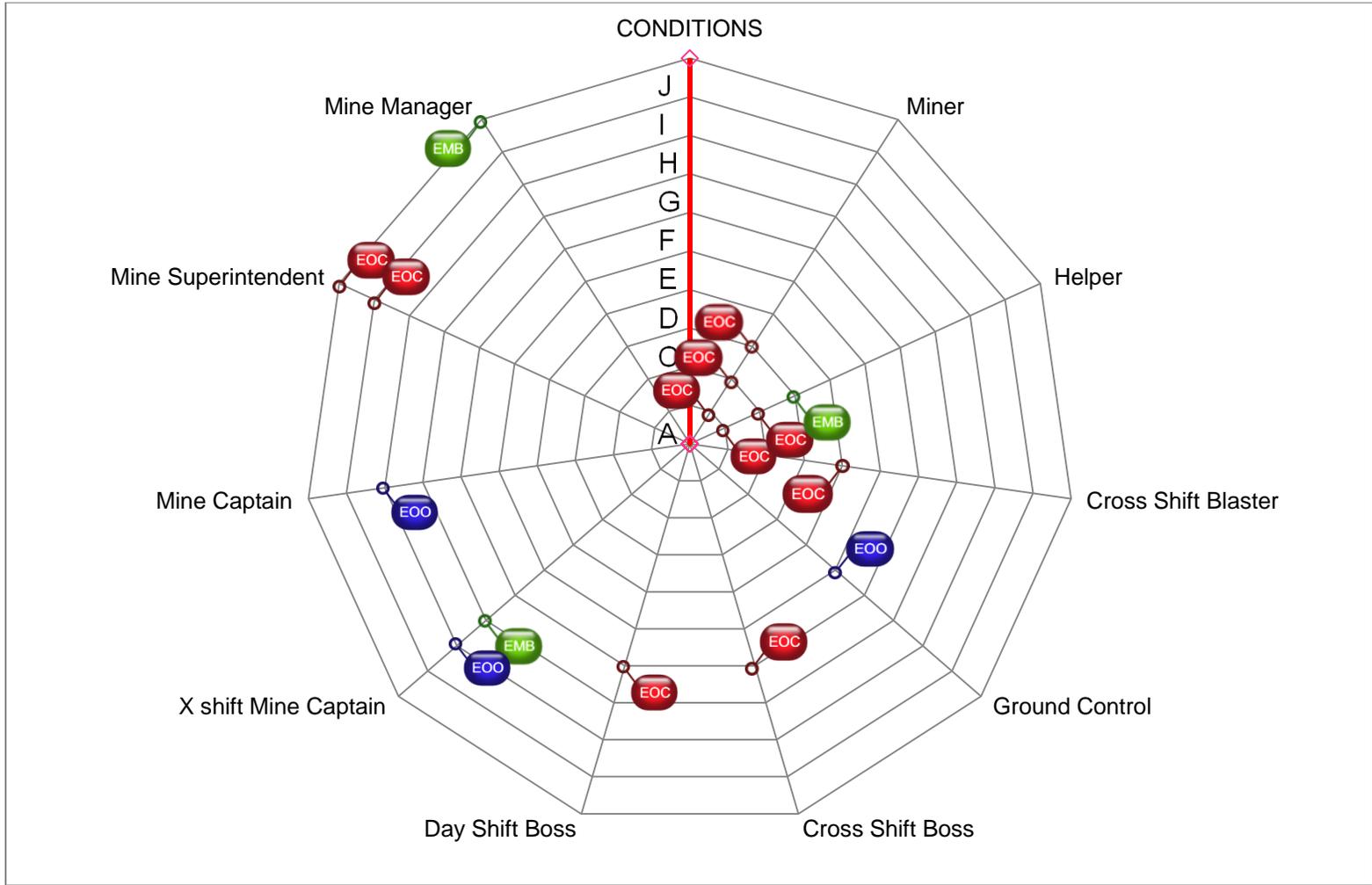


Figure 5.7: Decision error analysis diagram illustrating the decision errors contributing to an underground mine event resulting in a fatality

5.5 The Cognitive Profiling Methodology

The cognitive profiling technology presented in this dissertation is a complete and incremental methodology for profiling decision errors within a mining enterprise (Figure 5.8). Starting with decision error theory, the analyst examines the determinants to an *event* in accordance with the lost error taxonomy. Having characterized the determinants for which there were known standards present that were compromised resulting in unsafe acts or conditions, it is left to the analyst to plot them on a decision error analysis diagram (DEAD). This graphical analysis will enumerate and tabulate each decision error, unsafe act or condition, presiding standard of care, actors involved, and the phenotype of the decision error. These phenotypes are inputs to cognitive profiling.

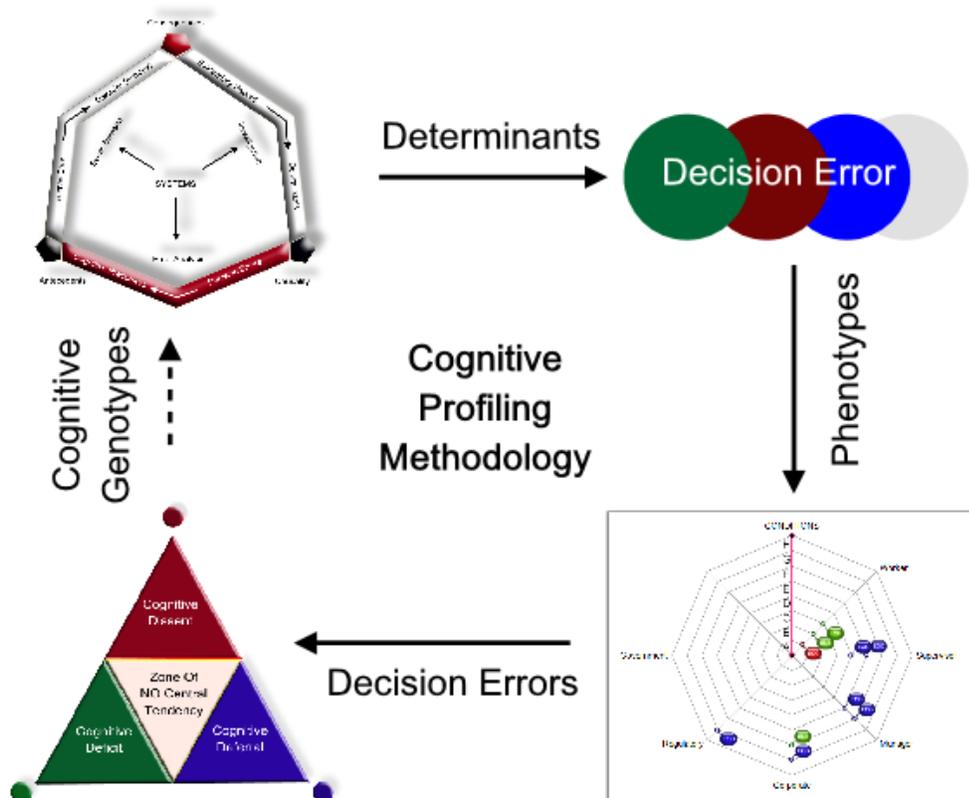


Figure 5.8: Diagram illustrating the sequence of analysis in the cognitive profiling methodology

The overarching objective of the cognitive profiling methodology is to apply a model supportable by theory and practice that transforms decision error phenotypes

(Lost Error Taxonomy) into cognitive error genotypes. These genotypes are characterizations of the ethos of error - the collective perception of risk of parties to the *event* under scrutiny. The method by which this is achieved is by plotting the weighted percent of the decision error phenotypes (excluding *system error*) onto a ternary diagram (Figure 5.9). There are four regions within this ternary diagram, three of which correspond to the end-member genotypes of *cognitive deficit*, *cognitive dissent* and *cognitive deferral*. Each of these regions corresponds to a distinct genotype of error and denotes a different perception towards standards of care in the workplace. Accordingly, these cognitive errors are not manifested directly, but must be connoted by decision errors observed in the evidentiary record.

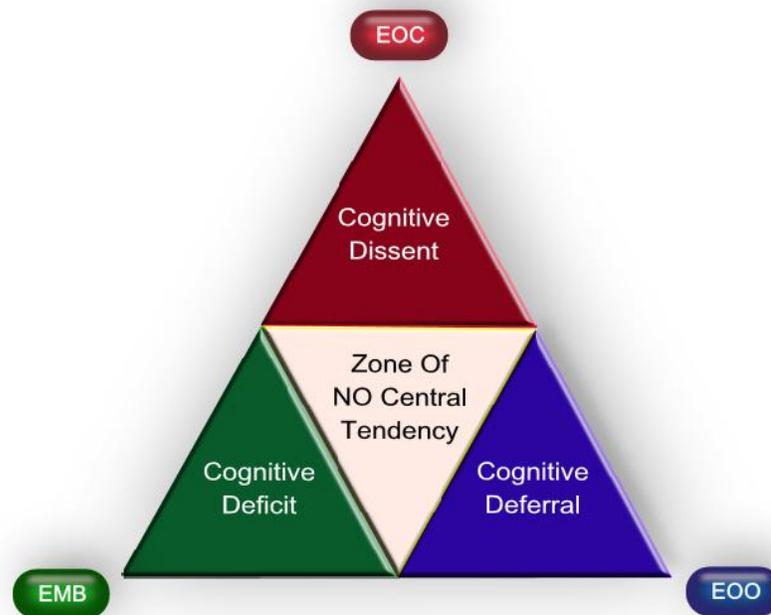


Figure 5.9: A ternary diagram depicting the three cognitive genotypes (Sweeney, 2004)

5.5.1 Cognitive Deficit

Cognitive deficit is the region of the ternary diagram that corresponds to the preponderance of decision errors reporting as errors of mistaken belief. Arbitrarily, this region is bounded by 50% percent of errors of mistaken belief, as a proportion of the total decision error population under scrutiny. The region of *cognitive deficit* is

representative of a cognitive error genotype that is largely knowledge dependent and therefore corresponds with knowledge-based errors of the SRK taxonomy (Rasmussen, 1983). By definition, errors that report to this region are made by parties who do not know that a standard applies to a situation, or do not have adequate knowledge or experience to apply the standard.

Typically, organizations that report to this region have workplace parties that are junior or inexperienced, have inadequate on-the-job training, or are lacking in knowledge of the risks. For front line workers, this presents as poor situational awareness and unfamiliarity with workplace standards and their artefacts. Supervisory personnel present as deficient in risk assessment and knowledge of their roles and responsibilities. Managers present as deficient in leadership, knowledge of their standards of care, or specialized technical knowledge. Common biases associated with *cognitive deficit* are confirmation bias, selectivity and availability heuristics whereby the actor has an incomplete worldview or set of facts on which to formulate a worldview.

5.5.2 Cognitive Dissent

Cognitive dissent is the region of the ternary diagram that corresponds to the preponderance of decision errors reporting as errors of commission. Arbitrarily, the region is bounded by 50% percent of errors of commission, as a proportion of the total decision error population under scrutiny. The region of cognitive dissent is representative of a cognitive error genotype that is largely rule dependent and therefore corresponds with rule-based errors of the SRK taxonomy (Rasmussen, 1983). By definition, errors that report to this region are made by parties who know that a standard applies to the circumstance, but choose not to comply with the standard for reasons known only to them. To be clear, this is not a case of an actor avoiding 'the application of a bad rule' phenomena (Reason, 1990). It is presumed that the standard is both appropriate and necessary to the circumstance.

Typically, organizations that report to this region have workplace parties that are senior, experienced and often times a member of another social unit that may, or may not, be directly affiliated with the workplace (collective bargaining units). Front line workers present in stages of denial; first by refuting objective reality, followed by anger, and finally by self-justification. Supervisors present behaviours ranging from impugning the motivations of subordinates to profound shame or guilt. Managers present by

challenging authority, misdirection or capitulation. Common biases are the halo effect, overconfidence and availability heuristics whereby the actor forms a worldview that they alone have situational awareness and special knowledge.

5.5.3 Cognitive Deferral

Cognitive deferral is the region of the ternary diagram that corresponds to the preponderance of decision errors reporting as errors of omission. Arbitrarily, this region is bounded by 50% percent of errors of omission, as a proportion of the total decision error population under scrutiny. The region of *cognitive deferral* is representative of a cognitive error genotype that is largely skill dependent and therefore corresponds with skill-based errors of the SRK taxonomy (Rasmussen, 1983). By definition, errors that report to this region are made by parties who know that a standard applies, but defer making a decision appropriate to the circumstances to others, or for some undetermined time in the future - owing to competing or misplaced priorities.

Typically, organizations that report to this region have workplace parties that are exposed to environmental and human factor challenges. They are working in work environments that exhibit noise, temperature or other extremes that are physiologically deleterious, or high cognitive demands beyond which they can cope – or both. Workers commonly appear overwhelmed, fatigued, frightened or confused. Supervisors present as frustrated, indifferent or agitated. Managers do not frequently make decisions in such an operating environment, but during periods of duress or emergency will present the same physiological symptoms as workers or supervisors, depending on the extent that their decisions direct others. Biases common to cognitive deferral are illusionary correlation and problems with complexity and causality.

The methodology is entirely dependent on the correct taxonomic classification of the decision errors, which is in turn dependent on a systemic evaluation of the scenario, or enterprise, in terms of determinants to the *event*. The cognitive genotypes represent the psychological precursors, or cultural determinants that are indicative of the distributed perception of risk (ethos) of the organization, qualitatively. It will be demonstrated by research conducted at an operating mine, that in combination with a semi-quantitative assessment of risk of the enterprise, one can derive a rich and detailed profile of the organizational ethos covariant with a variety of domains. These domains include, but are not limited to, worker age, worker experience, occupation, mine

department, calendar month, hazard type, and mechanism of injury. Armed with these profiles, mine management can incorporate stronger controls and standards, mitigating the risks and appropriately allocating scarce resources.

5.5.4 Cognitive Profiling Tutorial

Again, the best understanding of cognitive profiling is achieved by means of example. To continue the analysis of the hypothetical mine fatality, the decision error analysis diagram (Figure 5.7) and supporting summary table (Table 5-2) are useful. In this instance, we are interested in the profiling of cognitive error as correlated with the domains of workplace party. Thusly, we plot the calculated percentile proportions of decision errors on the ternary diagram and observe the distributions, as well as the overall character (centroid) for the *event* (Figure 5.10). The ternary logic of this analysis reflects the mutually exclusive phenotypes of errors of commission, omission and mistaken belief. System errors, by definition and default, have no cognitive attribution and do not appear on this diagram (had there been any in this example).

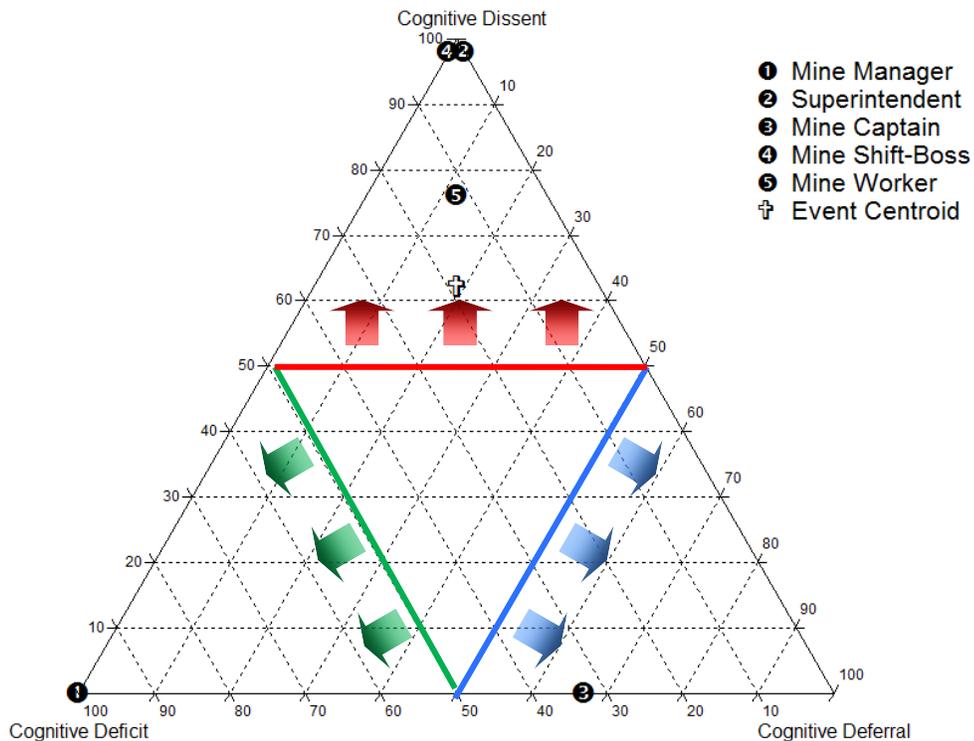


Figure 5.10: Ternary diagram illustrating the respective cognitive profiles of the workplace parties

There are no weighting factors. An error or commission has no less or more weight than an error of omission or mistaken belief. Objectivity is preserved in their equivalence, and to do otherwise would require context in terms of causation. There is no presumption or intimation of causation. The analysis remains judgement neutral - consistent with the imperative that the analysis is part of a system that examines another system: the error producing system comprising the *event* scenario. As much as decision analysis is retrospective, cognitive profiling is prospective and attempts to describe what is, not what was. It is in this spirit of heuristics that cognitive profiling is a predictive model.

5.5.5 Observations: Cognitive Profiling

Upon observation, it is self evident that the workplace parties do not share the same cognitive distribution, and we adduce that their perceptions of risk may also vary, respecting the *event* in question (Figure 5.10). For this example scenario, other parties in the enterprise were not considered (organized labour, regulatory agency or industry association), thus the analysis is not of the enterprise level, but is restricted to the mine operations as is typically the case. The aggregate value of decision errors for this fatality was 62% errors of commission, 19% errors of omission and 19% errors of mistaken belief (Table 5-2). Thus, decision errors of commission for all the workplace parties exceeded 50%, and therefore the preponderance of decision errors report to the region of cognitive dissent.

Mine shift-bosses and mine superintendents were both highly disposed (100%) to errors of commission and report to the extreme vertices of the cognitive dissent region. By comparison, the mine manager was in cognitive deficit and the mine captains reported to the cognitive deficit/cognitive deferral axis. The mineworkers contributed the most decision errors (50%, Table 5-2) and are profiled near the centroid of the diagram. There is a marked difference in distribution between the workplace parties; occupying the three cognitive regions of the diagram.

5.5.6 Interpretation

Overall, the workplace parties contributing decision errors to this *event* are in cognitive dissent (Figure 5.10). However, the lack of close grouping around the centroid is indicative of the absence of distributed cognition, such as groupthink. By definition, the

parties making errors of commission did so knowing that a standard existed, but chose to violate standards for reasons that bear further investigation. The Mine Superintendent and the mine shift-bosses were particularly disposed to dissent. In contrast, the Mine Manager and the mine captains reported to the cognitive deficit and cognitive deferral regions, respectively. It would be interesting to examine what dynamic exists between the mine captains who present with cognitive deferral and the Mine Superintendent, to whom they report, who presents cognitive dissent.

5.5.6.1 Discussion: Confirmation Bias

The Mine Manager either did not understand the risk presented by the mine conditions, or was deficient in his capacity to discharge his duty of care; in this case - due diligence on behalf of the mine corporation. Given that, the Mine Manager had received an expert opinion advising him of the incipient risk (Section 5.4.2) we surmise that he was not duly diligent for reasons connected to his perception of the risk of ground failure. What biases or heuristics influenced his perceptions? We know that he had adequate information on which to act (the consultant's report). There was no argument with the science, as it was based upon the seismometer readings within the mine. What would compel someone not to act on information for which he paid handsomely?

The answer may be in his selection of the information influencing his decision. The mine had been seismically active for some time. They had not experienced a catastrophic failure in spite of the routine observation of falls of loose ground. The consultant's report was predictive in nature, but was clearly not consonant with the worldview held by the Mine Manager. The Mine Manager is presenting with what we know to be a familiar pattern or heuristic when a decision maker is confronted with data that is contradictory to their worldview. They are loath to accept it (Reason, 1990). This is the very definition of confirmation bias.

The Mine Manager discarded a worldview that was supported by objective reality and scientific rigour in favour of a worldview (the mine was not at risk of catastrophic failure) that was increasingly difficult to support. To the extent that the Mine Manager disregarded the consultant's report, he was exhibiting *cognitive strain* (Reason, 1990) whereby his worldview did not contain a scenario that was inclusive of lost production, catastrophic failure and tragedy. Subsequent to the *event*, the Mine Manager would be extremely sensitive and responsive to deteriorating ground conditions. His experience

would shift his worldview by altering his perception of risk. This is availability heuristics in action. Until a more compelling experience becomes available to him, the Mine Manager reconstructs his worldview to a new and more sobering perception of risk.

5.5.6.2 Discussion: Problems with Causality

The mine captains had expectations upon which they could not deliver given their limited resources, and they deferred to other parties (Mine Superintendent, Mine Manager), and other priorities that they believed to be more pressing. That is, the mine captains deferred acting on their duty of care to other mine personnel, and standard operating procedures (Section 5.4.2) because they perceived there were other risks more salient than that of falls of ground. Again, exactly what these other risks were bears closer examination. On first inspection, this may appear to be an example of mistaken belief insofar as the mine captains, in hindsight, were incorrect that other priorities during shift change took priority over reporting falls of ground and incident reports. However, they could not have known that they were inadvertently contributing to a system of errors that would culminate in tragedy. This is for the same reason as was true for the Mine Manager and all of the workplace parties at the mine. It was not within their worldview. Here we observe a collision of perspectives. First, there is the perception of the mine captains without knowledge of the *event*. Second, there is that of the analyst with full knowledge of the *event*. Neither perception is incorrect. Both perspectives are based upon their perceptions of risk. To the mine captains, the catastrophic failure was remote and not causally connected to the recording of falls of ground and incident reports. To the analyst looking through the rear view mirror, the causality is sequential and the danger apparent.

What were the biases and heuristics of the mine captains? We can only surmise their thought processes respecting the missing log and reports. They knew that the reporting of ground falls and incident reports would aid somebody, somewhere, in their knowledge of the workplace conditions within the mine. The mine captains already knew what those conditions were; they had firsthand knowledge. The safety department and the mine regulators did not work in the mine, in the here and now. The logs and reports could wait. What purpose could the reports make if there was a danger; it would be too late? These musings are understandable and reflect the concept of bounded rationality

wherein decision makers restrict their worldview to accommodate what they consider to be in their own best interests (Simon, 1997).

Within the context of their rationality, the decision of the mine captains was to optimize their efforts in response to this rather restricted – bounded worldview. Their worldview ‘is bounded’ by what they considered necessary to achieve their goals. It was not inclusive of the complexity of the system, nor was it impaired by any *problems of causality* – ground fall related, or other. In the words of Reason (1990:91): “Because they are guided primarily by stored recurrences of the past, they will be inclined to disregard any irregularities of the future”. Until the reporting of ground falls and their occurrence shape the outcome of their goals, the decisions of the mine captains are likely not to be inclusive of them. Parties in cognitive deferral reduce their cognitive demand to accommodate their perception of rationality, particularly during times of diminished capacity (environmental, human factor stressors) or limited resources.

5.5.6.3 Discussion: Availability Heuristics

The hourly workers, the mine superintendent and the mine shift-bosses were disposed to cognitive dissent (Figure 5.10). Particularly in an underground mine environment, standards relating to ventilation, geo-mechanics and blasting are critical. Yet within this scenario is empirical evidence to support that the parties closest to the hazards were dissident in their amelioration and control. The blasters did not blast to standard. The geo-mechanical technician did not alert the workforce of imminent danger. The shift-bosses did not evaluate the headings for incipient failure. The decedent and his helper did not scale the back or bolt to standard. How could this be, and how could the Superintendent of the Mine accept this ethos in consideration of the underground risks?

The answer lays in their biases, and in their motivations. The bias that they bring to the workplace is not only their own, but a collective one. The theory of availability heuristics tells us that we are limited to the application of causality by what we experience and can explain (Section 2.4.2). The hourly workers and their supervisors in this scenario example had long since come to terms with ground fall hazards. They worked in mine conditions on a daily basis. Their experience with surviving these risks apparently outweighed their aversion to them. Self-awareness of the probability of personal injury that would change this risk equation was outside of their worldview.

Miners exhibiting availability heuristics are influenced by experiences and cognition that are immediately available to them, not by some future state. Additionally, selectivity comes into play. They are motivated to mine (bonuses, halo effect, hubris), and will select the perception of risk that is consonant with their preferred worldview. Self-justification will address the internal conflict concerning the contravention of workplace standards (Fine, 2006). In this manner, dissenters of workplace standards minimize cognitive dissonance between their worldview and objective risk - by selecting their perceptions of risk, instead of the other way around. It is therefore the role of management through education, deterrence or by any means necessary to assert the existence of objective risk, thus altering the worldview of dissenters and motivating a change in behaviours.

5.5.7 Significance

Cognitive profiling, similar to any analysis of human error, is the start, not the end to examination (Busse, 2001). This is the value of cognitive profiling: it goes to what the workplace looked like from the perspective of the parties, what perceptions they held and what motivated or de-motivated them to alter their situational awareness and worldview (Dekker, 2004). The significance of cognitive profiling is in its richness and utility. With successive analysis of *events* in the workplace over time, the analyst can track changes in the cognitive culture or the effect of remedial action. This is an important dimension in profiling, as cognitive errors are not directly associated with cause and effect; yet, are part of the system of *event* causality that changes with time.

To the extent that social units exert an influence over the distributed cognition of its members, cognitive profiling is applicable to differentiate these social units covariant with their perception of risk. Predictably, mine operators junior in experience will not have the same perception as those more senior. In addition, tradesmen may have different risk perceptions than haul truck drivers or office workers. In a similar fashion cognitive profiling by mechanism of injury, mine department, and age may also show variations that can be addressed through tactical changes of the management systems. This research will explore these potentialities by profiling a variety of domains covariant with time by means of a study of a contemporary operating mine (Chapter 7).

5.5.8 Characteristic Cognitive Profiles

In the absence of extensive and rigorous field trials, it is difficult to ascertain what the precise shape or limits of the cognitive regions are within a ternary diagram. However, based upon this research we can assume some symmetry exists and that there is a basic geometry (Figure 5.10) from which we can extrapolate profiles and relationships between workplace parties (Figure 5.11).

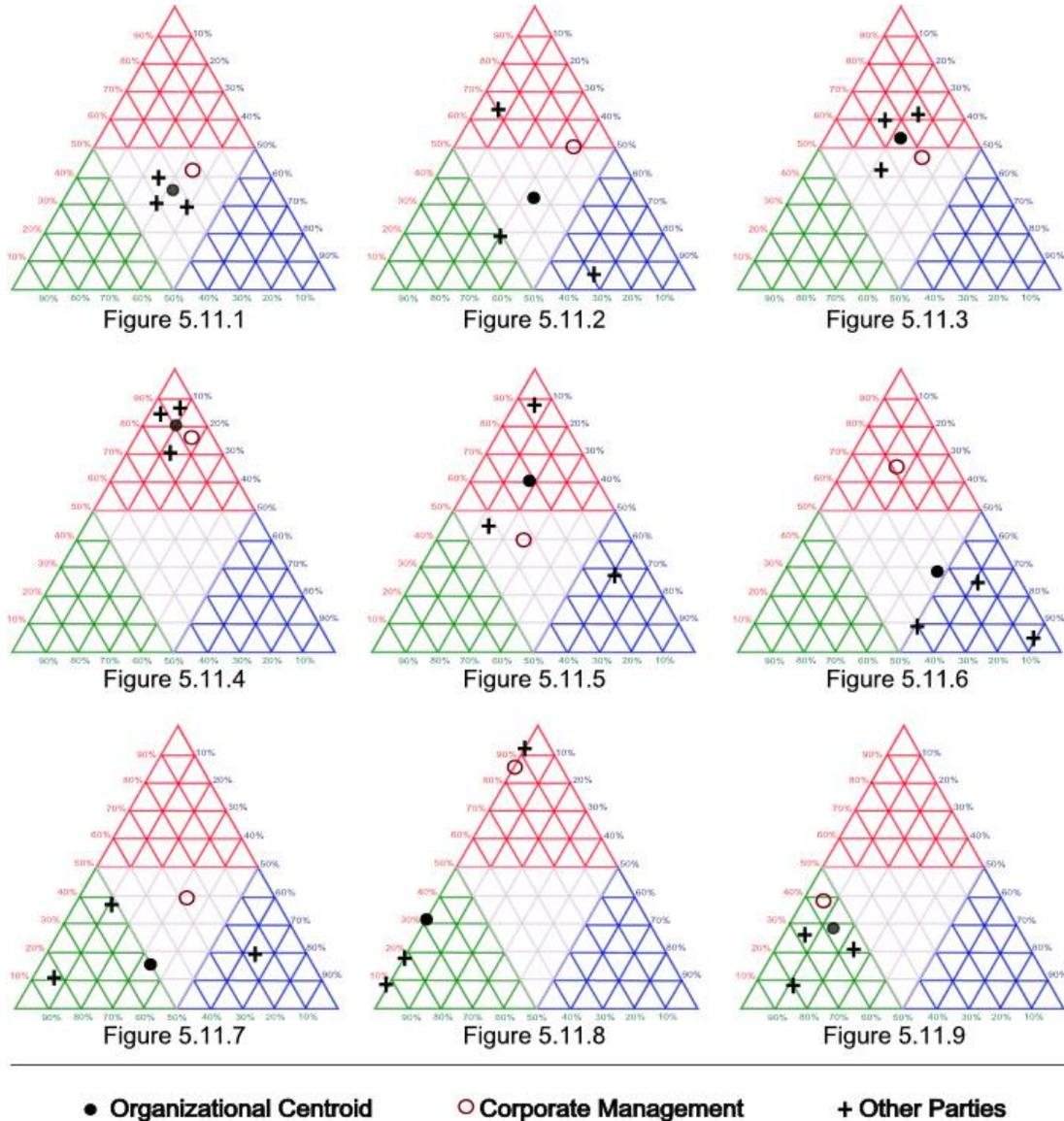


Figure 5.11: A series of nine characteristic profiles illustrating cognitive profile prototypes

For simplicity and clarity of these prototypes, we consider that there are four workplace parties, consisting of corporate management, mine management, supervisory staff and workers (Figures 5.11.1 through 5.11.9). In each example, a black dot represents the decision error centroid; a red circle represents corporate management; and black crosses represent one of the remaining parties. These nine profiles illustrate the significance and utility of cognitive profiling (Figure 5.11). These nine cognitive prototypes are abstractions of empirical *events* observed in the workplace, some of which are contained Chapter 6, in this dissertation.

5.5.8.1 Organizational Consonance with No Central Tendency

An organization that does not exhibit any collective predisposition toward cognitive error as discerned by this model reports to the centre region of the ternary diagram (Figure 5.11.1). In this region, there is a balance between the three error phenotypes, and therefore no preponderance of error ascribed to any particular cognitive genotype. In the instance of workplace parties reporting in a close cluster around the organizational centroid in the diagram, presumably whatever management style or ethos exists within the organization is well communicated and the organization is effective in its messaging regarding risks and their mitigation.

This is an optimal state of distributed cognition, and a prototype to be aspired to within the context of cognitive profiling. The profile of management is concordant with the other workplace parties and representative of the desired organizational ethos toward risk and error. The workplace parties are respectful of the standards of care and conduct, and are likely have a perception of risk that is consonant with the effective risk and with that of each other.

Fortunately, most contemporary mines within Canada fall within this cognitive profile, as standards of care are high and the industry is highly regulated.

5.5.8.2 Organizational Dissonance with No Central tendency

Collectively, an organization may fall within the region of no central tendency, but upon examination of the discrete parties within the enterprise, these parties report out to the other regions of the cognitive diagram (Figure 5.11.2). These parties present markedly different cognitive error genotypes, and by inference, perceptions of risk. In the illustrated example, the cognitive profile of corporate management is marginally

disposed towards cognitive dissent, influencing at least one other party to be disposed towards cognitive dissent. The remaining two parties by comparison are disposed to cognitive deferral and deficit. This dissonance in cognitive error is indicative of the absence of distributed cognitive error at the organizational level. Management is ineffective in their messaging as regards to standards, and it is likely that they are not communicating an accurate depiction of risk. At least one party is dissenting against the standards of care and conduct that would otherwise mitigate risk.

Any strategy to mediate this dissonance must address human factors, environmental factors, as well as deficiencies in knowledge and experience, as indicated by the cognitive error genotypes. This cognitive profile suggests that management would benefit by achieving alignment concerning risks and their mitigation by a combination of strong messaging, education and training and progressive discipline in support of normative compliance.

Large mining enterprises in which numerous contractors are present with separate and distinct operational cultures typify this cognitive profile. It is incumbent upon management to be cognizant of disparate cultures toward risk and instil the parties with a common and accurate perception of risk. Within the mining industry in Canada, underground metal mines under development often exhibit this profile, owing to the incremental project management practices and the fractionation of the workforce through contracting and sub-contracting.

5.5.8.3 Organizational Consonance with Nascent Cognitive Dissent

An organization that is effective in messaging, but not diligent in communicating the true nature of the risk empowers workplace parties to adopt a discounted perception of risk, or worse – influences these parties towards cognitive error. This may occur in any of the three cognitive genotypes, but is most egregious in the instance of cognitive dissent (Figure 5.11.3). Management may only be marginally disposed to dissent of standards, but subordinate parties amplify this influence, as they are closer to the risks and more likely to participate in the evolution of an *event*. By this logic, the reverse is also true; that management can move towards risk aversion and through effective messaging influence the other workplace parties by their example.

In this cognitive profile, management is best served by paying attention to standards of care and developing policies in support of standards to consolidate expectations and intent. Subordinate parties are emboldened by any prevarication toward standards on the part of management and are prone to compromise standards through the mechanism of *risk homeostasis*(Section 7.1.2.2). Management of consonant organizations in which the perception of risk does not fairly represent the effective risk are prudent to consider changing their messaging and putting in place near miss reporting systems. Additionally, these systems should be inclusive of all parties within the enterprise to benefit from the increased operational intelligence respecting risk. Most importantly, management benefits from shifting the perception of risk by responding to emerging risks in a manner that is both timely and appropriate to the circumstances. Near miss reports left unresolved serves to further entrench the ethos of discounting risk.

Within the Canadian mining industry, small quarries and aggregate pits are prone to fall within this cognitive profile. The operations are cyclical, often undercapitalized and do not have a large pool of human resources upon which to draw. Larger, more traditional mining operations have the benefit of offering higher wages and greater job security. Aggregate operations rely therefore on entry level and a less skilled workforce. These workers are influenced by the perceptions of risk presented to them by their employers and other parties to the enterprise. The enterprise is naturally organizationally consonant. Quarry and aggregate operations are also very competitive, with smaller operators often equating an entrepreneurial ethos with risk taking.

5.5.8.4 Organizational Consonance with Incipient Cognitive Dissent

Enterprises that are organizationally consonant exhibit cognitive profiles that are tightly grouped indicating similar cognitive error and perceptions of risk (Figure 5.11.5). Reporting to the cognitive dissent region of the cognitive diagram, the individual cognition of all parties reflects the collective cognition error of the enterprise and the cognitive error of management in particular. More likely to evolve in low to mid risk enterprises, the various parties may be influenced by personal gain, collective bargaining or fear of economic and competitive disadvantage.

The dissent is incipient, however the party's perception of risk is consonant with that of management and they will only alter their worldview to the extent that

management demonstrates and has the capacity for intervention. With decisive management change, persistent leadership and messaging concerning risk, the collective cognition of these parties will modify in step with their worldview. Clarity of roles and responsibilities is essential for affecting change in this cognitive profile, as dissident parties strive to maintain an ethos that compliance with standards is discretionary.

In Canada, a mining organization consonant with incipient cognitive dissent is not likely to evolve because of three factors. First, there is an ethos within the industry for normative compliance with the support of its membership. Second, there is a strong regulatory framework within each province within Canada. Lastly, the typical mining enterprise within Canada is by nature a risk-based venture – both with respect to uncertainty of operations and economics. Consequently, the vast majority of operators mediate these risks by applying established standards of care such as risk controls, management systems and artefacts (practices and procedures) within the workplace.

However, by this same logic, in the absence of any or all three of these factors, a mining operation could be susceptible to devolving to this cognitive profile. Hypothetically, such an operation would work within the exploration phase of the mining industry. In exploration, the workforce is junior in age and seniority and disposed to working in remote locations. These remote locations are subject to a rapidity of change of locale, thus they are prone to poor governance by both the regulatory authorities and corporate oversight. The parties at an exploration prospect are inherently risk takers – albeit by nature. Finally, the operational risks at exploration sites are situational, depending upon the mode of transport, the threat from local wildlife and climatic conditions. Thus, mineral exploration enterprises may be prone to this cognitive profile because of their mobility, paucity of regulatory oversight and the illusion of low risk.

5.5.8.5 Organizational Dissonance with Incipient Cognitive Dissent

Enterprises profiled as organizational dissonant with incipient cognitive dissent exhibit loosely clustered parties in terms of cognitive error (Figure 5.11.4). The organization collectively reports to the cognitive dissent region of the cognitive diagram. This cognitive profile is indicative of a disregard for risk and the consequences thereof. Organizations in incipient cognitive dissent are opposed to statutory oversight and therefore are not given to self-impose standards of care as artefacts in the workplace. In

the absence of *events* that would correct this worldview, there is an expediency by the parties to replace risk aversion with an aversion towards the expenditure of resources on anything that does not realize immediate return - operationally, commercially or socially. Existing standards of care are subject to interpretation and to competing operational demands that inevitably devolve into *operational creep* (Section 7.1.2.3).

A command and control decision structure will support, if not promote, this ethos to the extent that the parties are subject to intimidation and coercion. Additionally, bonuses, risk pay or other benefits intended to reward production, inappropriately augment motivation. Designed to motivate efficiency, reward programs have the potential for creating a new bounded rationality (Simon, 1997) for the target workers by offsetting the perception of risk with an implied benefit further biasing and contributing to cognitive error. A more palatable worldview of personal gain, reward and success replaces a future state of injury, calamity or disaster through availability heuristics. This cognitive prototype is an example of directing minds within the operation (or enterprise) forming the intention of achieving competitive advantage at the expense of risk to other workplace parties. Such conduct and behaviour falls within the purview of statutory decision makers, indeed within the criminal justice system to expurgate and prosecute.

Fortuitously, examples of this cognitive profile within the Canadian mining industry are rare. There are however, two infamous exceptions. In 1980, a mud rush claimed the lives of nine miners working within the Balmoral Mine, for which corporate management was prosecuted (Beaudry, 1981). A second, and more recent, mine disaster occurred in 1992 at the Westray Mine, in which 29 lives were lost, and is the archetypical disaster for which directing minds were clearly at play (Richard, 1996). This dissertation examines both of these disasters in detail in Chapter 6.

5.5.8.6 Organizational Dissonance with Nascent Cognitive Deferral

Enterprises that operate within high to extreme risk regimes are more likely to experience cognitive deferral owing to formalized command and control hierarchies and the workplace stressors on the workplace parties. Should management not practice effective risk communication they risk a dissonant organization as well as workplace parties that lack the training and confidence to respond to operational adversity (Figure 5.11.6). In an evolving *event* these parties will defer making difficult decisions to others according to rank, and in so doing abdicate responsibility and control for the mitigation of

risks. Such a linear decision process is not optimal in an emergency scenario unless there are clear lines of duty and responsibility.

Over time, the cognitive deferral is likely to become more pervasive resulting in worker apathy and the normalization of the behaviours and declining performance. It is essential that management consider the workload and functional limitations of these parties: to re-establish standards of care that will not only mediate risk but also reduce the effects of the human and environmental factors. The best countermeasure for cognitive deferral is an empowered workforce that has the training and resources to respond to adversity without an elaborate and time-consuming approval process. Further, drills and simulations with careful consideration of the environmental and human factors that can reduce cognitive performance best assure their efficacy of response.

There is a paucity of highly coupled and complex control enterprises within the mining industry that fall within this cognitive profile. In the petrochemical and chemical industries, however, refining and offshore drilling and production platforms are prone to this cognitive profile. The Piper Alpha platform disaster of 1988 in which 167 lives were lost is an example of an enterprise that was inexorably moving towards *self-organized criticality* by becoming increasingly risk tolerant in the face of economic and logistical challenges of the day (Chapter 6).

5.5.8.7 Organizational Dissonance with Nascent Cognitive Deficit

Organizations that do not communicate risk or the standards of care and conduct that mitigates risk are vulnerable to *events* that are prone to escalate in severity. These enterprises exhibit a deficit of knowledge and experience and therefore are doubly at risk (Figure 5.11.7). Absent is a capacity for the realistic ideation of risk and the attendant forethought concerning emergency preparedness. Without oversight by a standard setting body, an organization presenting nascent cognitive deficit is subject to declining seniority and situational awareness, further compromising operational integrity.

Organizations exhibiting cognitive deficit occur in all risk regimes and benefit by evaluating the efficacy of their management systems, adopting best practices and subscribing to continuous improvement strategies in training and mentoring. Within the mining industry, underground coal mines are prone to this cognitive profile, as coal mining experience and knowledge is lost with the retirement of the 'baby boomers'. In

Canada, the regulatory authorities are equally challenged, if not more so, to recruit and retain coal mining experience owing to the declining number of underground coalmines. Therefore, within the context of *events* as systems, the regulatory authorities as a party to the enterprise of coal mining, present a potential for latent error should the industry not move toward 'beyond regulation' normative compliance.

5.5.8.8 Organizational Dissonance with Incipient Cognitive Deficit

An enterprise that exhibits incipient cognitive deficit is one in which the organizational centroid is demonstrably in the cognitive deficit region (Figure 5.11.8). In combination with a dissonant ideation with respect to the perception of risk, this cognitive profile is pernicious insofar as latent errors are likely to mount and there is a deficit of normative oversight. The profile is aggravated by parties in authority exhibiting cognitive dissent, as arguably they are directing minds in an enterprise that compromise, if not violate, the right-to-know of other parties. This cognitive profile exhibits a characteristic bipolar distribution along the cognitive deficit/cognitive dissent axis.

Organizations exhibiting this profile benefit from an extensive compliance audit, management interventions, and training in roles and responsibilities. Knowledge and experience is the obvious countermeasure, particularly respecting workers' right-to-know, right-to-participate and right-to-refuse unsafe work. An enterprise that exhibits incipient cognitive deficit relies on skill and rule based cognition, and are challenged by operational states in transition such as maintenance shutdowns and upset conditions, as they do not have the cognitive capacity for problem solving. Consequently, these enterprises often outsource or subcontract those aspects of their operations that require higher cognitive demand and experience, and this further contributes to organizational dissonance.

An example of this cognitive profile is the Ocean Ranger drilling platform disaster of 1992, in which all 87 of the platform's crewmembers were lost at sea. The Ocean Ranger enterprise had every technologic and material advantage to operate as an ocean-going drilling platform, but through a combination of poor risk communication and experience in operating in the Atlantic, was lost at sea during a storm while other lesser equipped platforms survived (Chapter 6).

5.5.8.9 Organizational Consonance with Incipient Cognitive Deficit

An organization that is consonantly in cognitive deficit epitomizes the lack of situational awareness – at an enterprise level. That is, all parties are in deficit of operational knowledge and experience, and are thereby equally disposed to a worldview based upon an incorrect ideation of risk. Largely occurring in enterprises with low to mid levels of risk, these organizations do not experience a great many *events*, and are prone to overconfidence. Equally, in the absence of *events*, these enterprises do not attract statutory or normative oversight and many latent errors remain undetected. Further, there is an absence of emergency preparedness resulting from the lack of substantiation of risk, which would otherwise require an alternate worldview.

Organisations exhibiting this cognitive prototype benefit from peer audits and statutory oversight. In addition, there may be an absence of standards of care and therefore industry associations have a significant role to play. Parties to the enterprise often do not know what they do not know and cannot effectively marshal resources for contingencies. Governments can play a major role in these prototypical enterprises by looking to other jurisdictions and industries in the evaluation of risk and its mitigation.

Within the mining industry, high production mine technologies such as block caving and solution mining are examples of this cognitive profile. The Sunshine Mine disaster of 1972, is an example of organizational consonance with cognitive deficit insofar as all parties within the enterprise held the mistaken belief that polyurethane foam insulation was not flammable (Chapter 6).

5.6 Conclusions

Decision error theory examines a subset of cognitive error as presented by the decisions of actors within a known techno-social system. Decision error theory enables the investigator to integrate the conventional evidentiary record as presented by the determinants to an *event* (the investigative perspective) with the worldview of the decision maker (the actor's perspective) in terms of decision error attribution. This is achievable through the application of Lost Error taxonomy, a method of classification of decision errors that elucidates the contribution of risk perception and its ideation to decision error (situational awareness); and the contribution of decision errors to error detection and recovery (situational assessment).

Decision error analysis provides a structured, graphical framework for the purposes of examining the chronological occurrences of decision errors, in a manner that is intuitive and practicable. The analysis has a great potential for examining the dynamics in which different actors or social units interact (or not) as well as the artefacts that are representative of standards, rules and norms within the mine workplace. Decision error analysis is predicated upon the existence of these standards within the workplace and is particularly applicable to those enterprises, such as mining, that have a strong and documented history of establishing these standards of care and conduct. In this regard, decision error analysis is a tool that is sensitive to the regulatory and social mores that exist within an enterprise or system, to the extent that standards of care and conduct vary by organizational culture and regulatory regime.

Cognitive profiling of *events* offers a powerful and candid approach for assessing the psychological precursors and the perceptions of risk that shape the worldview of decisions makers (Dekker, 2004), within the mine workplace. As a framework for the examination of these errors and their taxonomy, cognitive profiling transcends the physical phenotypes (the behaviours) of these errors and explores their genotypical origins (the cognitive processes). Cognitive profiling complements the quantitative and semi-qualitative assessment of risk by offering a qualitative and explicative model for risk perception. By examining the magnitude and the perception of risk from the perspective of the decision maker, this dissertation will show that a more fulsome and holistic appreciation of the gap that exists between the actual risk and its perception can be realized. The application of decision error theory through the methodology of cognitive profiling reacquaints us with the concept of *bounded rationality*. Simon (1997:88) writes:

Finally, to assert that behaviour in organizations is boundedly rational does not imply that the behaviour is always directed toward realizing the organization's goals. Individuals also strive rationally to advance their own personal goals, which may not be wholly concordant with organizational goals, and often even run counter to them. Moreover, individuals and groups in organizations often strive for power to realize their own goals and their own views of what the organization should be. To understand organizations, we must include all these forms and objectives of rationality in our picture. We must include human selfishness and struggles for power.

When we speak of people behaving irrationally what we generally mean is that their goals are not our goals, or that they are acting on the basis of invalid or incomplete information, or that they are ignoring future consequences of their actions, or that their emotions are clouding

their judgements or focussing their attention on monetary objectives. We do not often mean that their action is so apparently random as to be inexplicable.

Bounded rationality accounts for the apparent variation in rationality or perception of risk between one party and another; or, as the circumstance may dictate, the variation in the perception of risk of one party when given different or competing priorities. *Bounded rationality* in part explains the phenomenon of unintended consequence, whereby an unanticipated outcome is attributed to a decision or action. The unintended consequence may, or may not, be directly causally linked to the action; however, the bounded rationality of the observer and the decision maker will undoubtedly vary.

Finally, *bounded rationality* predicts and accounts for the dissonance, or consonance, that exists between the various workplace parties respecting their ideation and perception of risk. We are reminded that without cognitive dissonance, a decision maker would be less likely to challenge or expand the bounds of their rationality, and alter their worldview and behaviours in such a way as to mediate, if not eliminate the dissonance. Similarly, social units can also exhibit a collective dissonance or consonance organizationally: and to this extent, distributed cognition is a potent indicator of the organization's capacity for communicating risk and conveying the standards, rules and norms (artefacts) in place to manage it.

"If all else fails, immortality can always be assured by spectacular error."
John Kenneth Galbraith (Bartlett, 2000)

6 HISTORICAL CASE STUDIES

6.1 Introduction

The selection of case studies presented in this research is based on the availability of data and their influence on regulatory reform, industry practices and accident theory of the day. Whereas mining, oil and gas related case studies have been sought out as the principle domain of interest, case studies from other heavy industry sectors provides insight and comparative analysis. Five detailed case studies are profiled and presented within this dissertation: three mine tragedies and two oil and gas related disasters (Figure 6.1). In addition, an environmental, chemical manufacturing and nuclear energy disaster have been profiled to discern the applicability of decision error theory and the cognitive profiling methodology.

6.2 Methodology

For each case, the investigative report of record was selected as the definitive document from which to extract determinants to the defining *event*. In four instances, the official record is a report of a commission or official public inquiry. In one instance, the official record was not available, in which case other credible historical records were considered for causal analysis. No attempt has been made to validate the veracity of these reports. These case studies provide the subject matter for the cognitive profiling technology espoused in this dissertation, and illustrate its utility, ease of application and potential for cognitive analysis. Other supporting media such as documentaries and docudramas were also sourced to gain understanding of the more qualitative aspects of these disasters, such as risk perception, risk communication, and public outrage.



Figure 6.1: Geographic distribution of the case studies profiled within this dissertation

There is a great deal of variation in style and substance of official reports of inquiry and investigation; a shortcoming that falls far short of their gravity and import. Some reports of inquiry such as that of Westray Mine disaster (Richard, 1996) enumerate the determinants of the *event* with clarity and logic. For others, such as that of the Piper Alpha (Cullen, 1988), one has to search for context and meaning of determinants hidden within great detail and technical analysis. To be true to the theory and models of this research, the articulation of determinants is a necessary, but not sufficient, condition for the examination for cognitive error. In addition to the identification of the standard of care, the actor or actors, and their chronology, cognitive profiling requires that the investigator know something of the context and worldview of the decision maker.

This contextual requirement does not translate well in reports of inquiry; hence these reports of inquiry were scrutinized for explicative evidence of the environment within which actors make decisions in terms of cognitive influences. These influences ranged from the benign to criminal; depending upon what standards were applicable to the circumstance. In keeping with the phenotypes of errors of commission, omission and

mistaken belief, the cognitive context for decision errors was characterized in terms of cognitive dissonance, cognitive capacity and cognitive performance.

6.2.1.1 Cognitive Dissonance

For the purposes of this research, *cognitive dissonance* (Section 3.1.1) speaks to the state of tension or discord that exists internally to an actor respecting their worldview and an accurate (situational) perception of risk. For each historical case study, decision errors of actors (or parties) were examined in this light to determine if the actor's worldview was dissonant with the situational risk associated with the *event*, at the time of decision. Two states exist. The first state is that of no dissonance: that the actor's decisions are representative of a situational awareness whereby the worsening circumstances and the actor's perceptions of risk are consonant.

Alternatively, the circumstances and their perception of risk could be discordant. Two possibilities are derivative of this state. The first possibility is that the actor's perception of risk is less than the risk presented by the situation known to them at the time of their decision, and antecedent to the *event*. The actor's perspective of risk is optimistic from the perspective of the observer, and their worldview is dissonant with the *event* scenario. A second possibility is that the actor's perception of risk is greater than the risk presented by the situation known to them at the time of their decision. The actor's perspective of risk is pessimistic from the perspective of the observer, and their worldview is dissonant with the reality presented within the *event* scenario.

In the former case, the actor is a risk taker. In the latter case, the actor is risk averse. In both cases, from the perspective of the actor (the decision maker), their behaviours and the derivative decisions are perceived as appropriate. Their biases and heuristics influence their perception of risk and the formation of their worldview. Similarly, in both cases, from the perspective of the observer (the analyst), the actor lacks situational awareness. This is the challenge and the paradox of perspective altering our notion of human error and its investigation (Dekker, 2004).

6.2.1.2 Cognitive Capacity

We know that capacity for information processing (cognition) is limited by human physiology (Sweeney and Scoble, 2007). Factors, both internal (human factors) and external to the human element (environmental), affect our capacity for cognition.

Particularly relevant are those factors that are deleterious to cognition and antecedent to an *event*. Typical among these are exhaustion (mental and physical), inappropriate motivation (coercion, intimidation), and cognitive impairment associated with incipient/imminent danger. Through the analysis of historical case studies, it is possible to appreciate how diminished cognitive capacity impairs decision making. Environmental and human factors were identified directly, as stated by the reports of inquiry, or indirectly by considering the state of mind of the parties to the *event* and their interaction with each other. Essential to this analysis is the state of diminished capacity exhibited by persons or parties whose cognition is compromised when they confront a situation or *event* scenario for which they are not equipped or trained for.

It is appreciated that there are *event* scenarios for which any participant would exhibit reduced cognition owing to confusion, anxiety and panic. Arguably, the less trained and prepared a person or party is, the more we expect that their behaviours and decisions would exhibit reduced cognition. Interestingly, perhaps more indicative of the absence of preparation and training are those that are faced with imminent danger and tragic circumstances, yet fail to respond to it in any rational or predictable manner. Ostensibly, they suspend disbelief. They appear in a state of denial or shock. They defer to others decisions that are intrinsically within their own self-interest to make. Within this backdrop of lack of control and spiralling chaos is the certain knowledge that the evolving situation has exceeded all operating parameters - and yet they fail to act. Their perception of risk is escalating. They become hyper-vigilant when their perception of risk exceeds their capacity to form a worldview acceptable to them, in terms of their ability to control or affect the outcome.

These case studies examine the diminished cognitive capacity of parties faced with extreme circumstances; scenarios that exhibit systems of error and an escalation of outcomes. Through these case studies, this research explores the extent to which diminished cognitive capacity is indicative of parties for whom physiological needs have not been met and/or have no strategies to cope with a worldview that far exceeds their concept of acceptable risk. It is suggested that a similar, albeit more subtle and less dramatic cognitive capacity is demonstrated by parties contributing to lesser *events* that do not culminate in *events per se*, but are no less insidious in reducing operational integrity within the mine workplace.

6.2.1.3 Cognitive Performance

Contemporary human error taxonomies (Rasmussen, 1983; Reason, 1990) explicitly define human error phenotypes based upon cognitive performance. The SRK model (Rasmussen, 1983) starts with skill-based errors and progresses cognitively through rule-based errors and knowledge-based errors, in terms of cognitive performance. For each case study, there is a great variety of cognitive performance demands put upon the actors, or parties, contributing to the *event* in question. Some, such as the Westray Mine disaster in 1992, are enterprises that exhibit a preponderance of skill and rule-based cognitive demands. Still others, such as Piper Alpha disaster in 1988, and the Ocean Ranger disaster in 1982 exhibit higher order knowledge-based cognitive demands. Clearly, the cognitive demands vary by enterprise, and within an enterprise, by vocation and level of responsibility.

In the evaluation of case studies for causality, particular attention is afforded to causal determinants and the standards of care that ground them. These standards could be low cognitive demand, subscribing to an actor's skill in their application, or high cognitive demand requiring an actor to interpret or problem solve a situation in accordance with their professional standards or duty of care. In general, the higher the standard of care, the higher the cognitive demand on the part of the actor. The decision errors were analyzed and tabulated accordingly. The standards of care do not alter in any way the characterization of decision error phenotypes; however, they do suggest mitigating or aggravating circumstances surrounding the roles and responsibilities of the workplace parties exhibiting them.

6.2.2 Scope of Analysis

Analysis of historical case studies offers a unique opportunity to examine the human error of parties at the enterprise level. That is, owing to their gravity and tragic nature, these *events* garnered much public consternation and attention; and inquiry into their causation appropriately increased the rigour and scope of investigation. Reports of inquiry and public commission are compelling in their detail, and more inclusive of the parties brought under scrutiny – not just those parties at the scene of the *event*, but also those parties who influenced the enterprise. Thus, inquiries into disasters examine the actions and decisions of the workplace parties, the corporate entities, contractors, and the regulatory authorities. In so doing, a much richer fabric representing the ethos of

error is produced and a more systematic approach to error analysis is embodied. This research takes advantage of the increased scope that these historical case studies bring to causality, to make the case for, and validate, decision error analysis and cognitive profiling as technologies for understanding distributed cognition.

6.2.3 Nomenclature

Within each case study, the subjects of analysis are referred to as ‘parties’ as opposed to ‘actors,’ and by this nomenclature, it is implied that cognitive error is being attributed to a social unit or class of participant to the *event* scenario. A distinction is drawn between workplace parties and parties to the enterprise. Parties to the enterprise are inclusive of all parties referenced by the investigative record and typically include the workplace parties, corporate governance, contractors, regulatory authorities, and in some case the public at large. Workplace parties include those parties that were physically attendant to the *event* scenario or had control or direction in its outcome. Typically, these parties include the workers, their supervisors, site management and persons internal or external to the enterprise that may have been involved in first response.

Traditional investigations consider workplace parties endogenous to the *event* scenario and other, ostensibly more remote, parties exogenous for the purposes of investigation. In this dissertation, we defer the determination of those enterprise parties considered as probative to the investigation to the authors of the official record, and their notion of causation. Understood, if not anticipated, is that there will not be a great deal of concordance between case studies on this point owing to the absence of standards in investigations.

6.2.3.1 Profiling Causality versus Causation

The verb ‘profiling’ occurs throughout this dissertation and is particularly prevalent in the analysis of historical case studies within the context of cognitive profiling. The concept of cognitive profiling explicated throughout this dissertation is a technology and methodology for human error analysis; however, there is a broader and perhaps more profound implication that bears specific treatment. The closest analogue to cognitive profiling currently in existence as a technology is that of behaviour profiling within the domain of criminal investigation. Just as the analysis of forensic evidence

reveals something of the psychosocial factors that can be helpful in stochastically 'profiling' perpetrators of serious crimes and their future actions, the determinants found within the accident record are predictive of future predispositions toward error – either individually or collectively. It is important not to take this comparison too far, however, and it is emphasized that cognitive profiling does not necessarily say anything about the specific causation of an *event*, only the systems of causality that are antecedent to and enabling of the *event*.

The distinction between causality and causation is an important one, as presumably all factors of causality are inherently not knowable, whereas the vernacular of causation typically connotes inclusivity of cause and effect. Therefore, to the extent that persons or parties are characterized as exhibiting a certain cognitive profile within these cases studies, it is essential to appreciate that the profile, although supported by the evidentiary record, describes causality with the brush of cognitive error – one of many errors in a constellation of errors within an *event* system.

6.2.4 Limitations and Bias

The analysis of historical case studies provides both challenges and opportunities for decision error analysis and cognitive profiling. Fundamentally, the challenge is the bias and subjectivity inherent to the investigation process, with the uncertainty of not knowing by what method or to what standard the *event* was originally investigated. In this respect, the products of analysis may reflect the ethos of error of the investigators as well as that of the enterprise under scrutiny. This paradox is most evident by the Sunshine Mine disaster in 1972, in which the regulatory authorities (US Bureau of Mines) were both complicit in, and the investigators of record of the *event* (Lundhardt, 1997). Clearly, the US Bureau of Mines would be vulnerable to hindsight bias, as are any investigators. However, they may well have been looking at the *event* through a lens biased by the same cognitive error that was contributory to the *event* in the first instance – that they had failed to act on knowledge of clear and present danger.

The historical record of tragedies and disasters within heavy industry is by nature one that chronicles adversity and crisis. Those parties to the critical *event* would be naturally more disposed to errors of omission; and, we expect that there would be a 'cognitive red shift' towards cognitive deferral in response to the potential of diminished capacity or any other imposed physiological limitation. Thus, cognitive profiling of case

studies documenting disaster and tragedy may over represent decision errors that are factored by, and biased towards, parties exposed to critical incident stress. This reality further substantiates the argument that cognitive profiling, not unlike causality in general, benefits from data sets inclusive of *events* that do not result in crisis or loss, such as near misses and unusual occurrences. By way of comparison and balance, this dissertation applies cognitive profiling to a contemporary operating mine (Chapter 7), for which the effects of this bias may be reduced, if not absent.

6.3 Westray Mine Disaster

On May 09, 1992, an underground methane/coal dust explosion claimed the lives of 26 miners at the Westray coal mine located near Plymouth, Nova Scotia. Considered an economic lifesaver in an otherwise depressed economy, Westray offered jobs to 160 miners in a region considered too dangerous to mine because of gassy coal conditions. The enterprise had the financial backing and support of local, provincial and federal governments (Richard, 1996).



Figure 6.2: Location of the Westray coalmine in Pictou county, Nova Scotia

6.3.1 Nature of the Enterprise

Curragh Resources incorporated the Westray Mine in November of 1987. The coal mine was the last of eight mines to mine the Foord seam, part of the Pictou coalfield in Pictou county, Nova Scotia (Figure 6.2). The financial matters of the mine were subject to considerable contention for some time; but in 1990, a deal was signed between Curragh Resources and Government of Nova Scotia based upon a take-or-pay agreement which would see 275,000 tonnes per year of low sulphur coal provided to the coal fired generating station in Trenton, Nova Scotia (Richard, 1996). The term of the contract was fifteen years.

From the outset, the Westray Mine was plagued with problems, both bureaucratic and geo-mechanical in nature. The Department of Labour had issues with emergency response procedures, training and certification, and the timely formation of a Joint Health and Safety Committee. The Department of Natural Resources took issue with the

alignment of the mine workings with respect to a major geologic fault – with the potential for the development of bad ground; a concern that would become a reality (Richard 1996). In 1991, roof conditions continued to deteriorate and Westray took over the development of the mine from Canadian Mine Development. In an effort to achieve production sooner, the mine management elected to digress from the original mine development plans, and advance the mine into two separate directions – and operating units. This required two separate crews, which were formed by the promotion and appointment of mine supervisory staff; many of whom were not qualified or competent in their new positions, particularly as regards to safety.

6.3.2 Summary of Events

Westray Mine was commissioned in September of 1991, in spite of frequent falls of ground, which mine management marginalized as ‘under control.’ With a workforce of 160 workers, most of whom reported underground, Westray earned a reputation of being unsafe in matters of ground control and stone dusting. In 1991, the mine workforce failed in its attempt to unionize in a certification vote. A second attempt was successful in early 1992; however, the certification was pending at the time of the disaster. In March of 1992, ground conditions presented such imminent danger that the miners were forced to abandon the southwest workings because of unstable conditions in the back (roof). The mine was not meeting its production quotas, and the Department of Natural Resources was threatening to pull Westray’s mine permit unless they produced new plans. Westray produced new plans that met the letter of the legislation, but were far from adequate.

Production pressures, ground control problems and a lack of priority for safety resulted in a mine management style so accepting of risk that flammable materials were stored underground; non-flameproof equipment condoned; and basic gas monitoring equipment was not fit for service. It was becoming increasingly evident to mine operators and the inspectorate alike that the mine ventilation systems within the Westray Mine were under-designed, under-maintained and under-performing (Richard, 1996).

Frequent falls of ground in this gassy coal seam increased the rate of flammable gas emissions, making inadequate ventilation a critical issue. These factors combined to increase the risk of a gas explosion. As this risk increased, both the Department of Labour and the Department of Natural Resources failed to meet their responsibilities to

intervene and protect the interests of the provincial stakeholders, to say nothing of the health and safety of the workforce.

In late April of 1992, Westray was ordered to implement a rock-dusting program that would prevent the spread of a coal dust explosions. The orders were not complied with and there was no follow-up or review. Early Saturday morning on May 09, 1992 an explosion occurred within Westray coal that destroyed the underground mine workings, shocked the mining community and took the lives of 26 miners. It was ‘a predictable path to disaster’ (Richard, 1996).

6.3.3 Parties to the Enterprise

Westray Enterprise Parties	Roles and Responsibilities
Curragh Resources	Registered owners and operators of Westray mine
Mine Management	GM, surface and underground managers
Mine Supervision	Foremen and senior technicians at the mine
Mine Workforce	Miners and other hourly personnel
Canadian Mine Development	Mine development contractor
Department of Labour	Administered Mines Act and health and safety
Department of Natural Resources	Administered mine licenses and operating permits

Table 6-1: Table summarizing the parties to the Westray enterprise and their roles

6.3.4 Consolidated Findings of the Commission

The following is a complete analysis of all of the errors contributing to the Westray Mine disaster as documented by Commissioner Richard. The investigative source is that of the *Report of the Westray Mine Public Inquiry* (Richard, 1996). It is rare that a report produces the detail and candour of that of Richard (1996) and the report is paraphrased herein as the source of data for decision error analysis.

6.3.4.1 The Westray Mine Enterprise

- 1) Curragh Resources were more interested in government support of the project than the project itself (Richard, 1996:609).

- 2) Curragh Resources were reliant upon government support for the project (Richard: 1996:609).
- 3) The Premier may have exceeded his limits of ministerial prudence in his desire to have a coalmine in his constituency (Richard: 1996:609).
- 4) The Premier acted improperly in committing the province to the take-or-pay agreement, which had not passed cabinet approval (Richard: 1996:609).
- 5) The Premier did not give thoughtful and prudent consideration of the take-or-pay agreement as provided by his department staff (Richard, 1996:610).
- 6) Premier formed a mistaken belief that take-or-pay agreement would never be exercised (Richard, 1996:610).

6.3.4.2 Westray Organization

- 7) Westray Mine supervision were coerced in not discharging their duties as supervisors; they were expected to carry out the orders of management.
- 8) Westray Mine management disdainfully rejected input from others (Richard, 1996:611).
- 9) Two mine managers misrepresented their qualifications and experience (Richard, 1996:611).

6.3.4.3 Training

- 10) Westray management did not follow-up on training plans and proposals (Richard, 1996:611)
- 11) Westray mine workers and supervision were not provided adequate training or orientation (Richard, 1996:611)
- 12) Workers lacked awareness for the right to refuse unsafe work, as they did not have an appreciation for the hazards underground (Richard, 1996:612).

6.3.4.4 Underground Conditions

- 13) Mine management knowingly permitted workers underground during conditions of dangerous levels of coal dust, a violation of Coal Mines Regulation Act (Richard, 1996:612).
- 14) Mine management permitted workers to remain underground during gassy conditions in violation of the Coal Mines Regulation Act (Richard, 1996:612).

- 15) Mine management only addressed those safety issues that affected production, such as ground control and conditions in the back (Richard, 1996:612) .
- 16) Mine management permitted 12-hour shifts, in violation of the Coal Mines Regulation Act (Richard, 1996:612).
- 17) Mine management and supervision failed to set-up and enforce a tagging system to track workers underground (Richard, 1996:613).
- 18) Mine management instructed supervisors and workers to store fuel underground in contravention of the Coal Mines Regulation Act (Richard, 1996:613).
- 19) Mine Management condoned the operation of acetylene welding equipment underground at the Westray Mine (Richard, 1996:613).
- 20) Methane detection equipment was defeated or altered in the interests of production (Richard, 1996:613).
- 21) Mine management sent into the mine foremen and workers who were untrained and inadequately supervised (Richard, 1996:613)
- 22) Mine management knowingly condoned the use of non-flameproof equipment underground (Richard, 1996:613).
- 23) Mine management knowingly condoned temporary cable repairs in violation of the Coal Mines Regulation Act (Richard, 1996:614).
- 24) Mine management directed workers to shutdown main fans for maintenance, without consideration of safety for themselves or others (Richard, 1996:615).
- 25) The environmental monitoring system installed at Westray was not installed and maintained properly (Richard, 1996:614).
- 26) Mine management permitted roof bolting in gassy conditions (Richard, 1996:614).
- 27) Mine management failed to provide properly maintained underground equipment (Richard, 1996:614).
- 28) Mine management discouraged any meaningful dialogue on safety from mineworkers and took an aggressive and authoritarian attitude towards workers (Richard, 1996:615).
- 29) Mine management actively discouraged a safety mentality within the JHSC and failed to respond to safety concerns (Richard, 1996:615).
- 30) The production bonus scheme was based solely on productivity, and was not conducive to safety (Richard, 1996:615).

31) Curragh Resources and Westray Mine management were derelict in their duty in not instilling an attitude of respect for safety beyond any other consideration (Richard, 1996:615).

6.3.4.5 The Explosion

32) Quantities of methane exceeding the explosive limit were probably ignited by the picks of the continuous miner as they struck pyrite or quartz (Richard, 1996:616).

33) The fire and explosion propagated as coal dust was liberated to produce an explosive atmosphere (Richard, 1996:616).

34) Methane was permitted to 'layer' within the mine; the inadequate ventilation permitting it to propagate (Richard, 1996:616)

35) Mine management did not monitor barometric pressure (Richard, 1996:617)

36) Mine management failed to provide a water gauge to monitor ventilation (Richard, 1996:617).

37) The ventilation systems at Westray were very inadequate to clear methane from the mine face (Richard, 1996:617).

38) Mine management knowingly permitted production to continue in areas of the mine in which there was excessive coal dust presenting imminent danger to the workers (Richard, 1996:617).

39) The methanometer in the southwest section of Westray mine had been tampered with (Richard, 1996:617).

6.3.4.6 Ventilation

40) The regulating, control and monitoring of ventilation air was inadequate and poorly planned (Richard 1996:618).

41) Mine management tolerated or ignored the poor quality of ventilated air in the north and southeast sections of the mine (Richard, 1996:619).

42) Mine management were apathetic or unaware (through incompetence) of the low ventilation pressures and airflows in the southwest section of the mine (Richard, 1996:618).

43) The auxiliary ventilation at Westray was defective and in violation of the Coal Mines Regulation Act.

- 44) Mine management implemented a ventilation plan that was inadequate and did not address dilution of methane with fresh air (Richard 1996:619).
- 45) The permit authority accepted the ventilation plan without a comprehensive study (Richard, 1996:619).

6.3.4.7 Methane Gas

- 46) Mine supervision knowingly permitted tampering of the methane detection equipment for the purpose of reducing alarm levels.
- 47) The coal dust and methane conditions at Westray had become commonplace at Westray (Richard, 1996:620).
- 48) Curragh Resources and mine management failed to recognize the permeability within the Foord seam and the history of coal mine fires (Richard, 1996:620).

6.3.4.8 Coal Dust

- 49) Mine management knew of the standards respecting coal dust, but failed to discharge their responsibilities in following their own procedures and those under the Coal Mines Regulation Act (Richard, 1996:622).
- 50) The inspectorate knew that the Westray Mine was out of compliance respecting the treatment of coal dust, and was derelict in their responsibility to safeguard the miners by ensuring compliance (Richard, 1996:622).

6.3.4.9 Ground Control

- 51) The complexities and challenging mining conditions made mining at Westray a dubious venture from the outset (Richard: 1996:623).
- 52) There was a lack of continuity of planning respecting mine development (Richard, 1996:623).
- 53) In spite of warnings, mine management proceeded with mine development without proper study (Richard, 1996:623).
- 54) Mine management were ill prepared to deal with the adverse geologic conditions at Westray, and did not know how to deal with them (Richard, 1996:623).
- 55) Mine management did not consider and implement advice from mine professionals (Richard, 1996:623).

56) Curragh Resources and its senior management lacked planning, competence and responsibility in dealing with the challenging ground conditions (Richard, 1996:624).

6.3.4.10 The Permitting Authority (Department of Natural Resources)

57) There was a lack of communication and cooperation between the Department of Natural Resources and the Department of Labour subsequent to the reorganization (Richard, 1996:624).

58) Officials within the permitting authority either misunderstood or overlooked their duty to ensure that the Westray Mine plans were safe (Richard, 1996:624).

59) The Department of Natural Resources (permitting authority) and the Department of Labour (inspectorate) did not address serious gaps in regulatory systems when they reorganized into two regulatory units (Richard, 1996: 625).

60) The permitting authority did not discharge their duty to ensure that the Westray Mine plan would result in safe and efficient mining (Richard, 1996:625).

61) The permitting authority failed in their duty to take reasonable measures to ensure that Westray's mine proposal resulted in safe mining (Richard, 1996:615).

62) The permitting authority provided a permit to mine based upon mine plans that were inadequate and for which they had concern (Richard, 1996:625).

63) The permitting authority did not discharge their statutory mandate in ensuring that the mine plans provided for safe and efficient mining (Richard, 1996:625)

64) The permitting authority did not have sufficient knowledge and experience with the mining technology proposed for the Westray Mine (Richard, 1996:625).

65) The permitting authority did not ensure that Westray Mine management were operating the mine consistent with the mine plans (Richard, 1996: 626).

66) The permitting authority failed in its statutory mandate to ensure that Westray Mine practiced safe and efficient mining (Richard, 1996:626).

67) The permitting authority failed to take action when made known that Westray Mine management made unapproved changes to their mine plan (Richard, 1996:626).

68) The permitting authority failed to monitor Westray in conformity with approved mining plans from time to time (Richard, 1996:626).

6.3.4.11 The Inspectorate (Department of Labour)

- 69) The experience and training of inspectors of mines was inadequate and not properly monitored by the Director (Richard, 1996:626)
- 70) The inspectorate did not review the Westray Mine plans (Richard, 1996:626).
- 71) A mine inspector was not competent to perform his duties as an inspector of mines (Richard, 1996:627).
- 72) The Executive Director of the inspectorate did not have an adequate understanding of the Internal Responsibility System (Richard, 1996:627).
- 73) The Executive Director of the inspectorate abdicated any leadership role and did not understand his role or the Internal Responsibility System. He had an incorrect perception of his legislative mandate (Richard, 1996:627).
- 74) The inspectorates used the Internal Responsibility System to draw attention from their own responsibilities (Richard, 1996:627).
- 75) The inspectorate did not understand their role nor discharge their role in support of the Joint Health and Safety Committee at Westray Mine (Richard, 1996:628).
- 76) The mine inspectorate gave Westray Mine management prior notice of their schedule of inspections (Richard, 1996:628).
- 77) The mine inspectorate did not include worker representation during their inspections of the Westray Mine (Richard, 1996:628).
- 78) The inspectorate limited its inspection to routes selected by Westray Mine management (Richard, 1997:628)
- 79) The inspectorate altered official records in favour of Westray Mine management on matters of health and safety (Richard: 1996:628).
- 80) An inspector failed to investigate safety related complaints and relied upon Westray statements without verification (Richard, 1996:628).
- 81) An inspector failed to uphold his statutory mandate of enforcing the Coal Mine Regulation Act and the Occupational Health and Safety Act (Richard, 1996:629).
- 82) Westray management intimidated the mine inspectorate. Mine inspectors left the enforcement of conditions for equipment use to Westray management (Richard, 1996:629).
- 83) The inspectorate knowingly tolerated hazardous conditions and illegal practices underground and were not sufficiently trained, competent or motivated (Richard, 1996:629).

6.3.4.12 Role of Government

84) The Premier was in error in his assumption that the government would not have to honour the take-or-pay agreement (Richard, 1996:629).

85) The Premier did not have a clear understanding of his role as a Premier or a cabinet minister in his support of the Westray coalmine project (Richard, 1996:630).

6.3.4.13 Emergency Response

86) Curragh Resources and mine management lacked a cohesive disaster plan and was ill prepared for May 09, 1992 (Richard, 1996:630).

87) The mine inspectorate role in the response was ill defined and peripheral (Richard, 1996:630).

88) There was a lack of breathing apparatus, supplies and testing equipment, which resulted in some delay of response (Richard, 1996:630).

89) The community and volunteer groups would have benefited from some definition of roles and coordination on-site (Richard, 1996:630).

6.3.5 Decision Error Analysis of the Westray Disaster

Analysis of the official report of inquiry (Richard, 1996) reveals 65 decision errors contributing to the Westray Mine disaster (Table 6-3). The standard of care not met by the workplace parties was in many instances duty of care and due diligence (Table 6-2).

Westray Mine Enterprise Parties	Standard or Duty of Care Not Met
Regulatory Authorities	Legislated mandate
Curragh Resources	Due diligence
Mine Management	Due diligence and duty of care
Mine Supervision	Duty of care and statutory compliance
Mine Workforce	Statutory compliance and competency

Table 6-2: Table summarizing the standard or duty of care not met by the enterprise parties

Mine management reported the largest number of decision errors (31%), followed closely by the regulatory authorities (29%), (Table 6-4). It is not clear as to the

extent the regulatory authorities influenced the behaviour of Curragh Resources – or *vice versa*. It is clear however that the behaviour of Curragh Resources influenced that of mine management; and mine management's behaviour that of mine supervision and the workforce.

6.3.5.1 Curragh Resources

Curragh Resources made eleven (17%) decision errors, ten of which were errors of commission and one an error of mistaken belief. All of the decision errors violated the standard of due diligence (Table 6-3). Primary elements of due diligence for corporate directors is that they ensure that there is competent management and supervision; ensure that management has sufficient resources to operate safely; and to have in place appropriate management systems to protect the workers, the environment and the enterprise from harm. The one error of mistaken belief was regarding the qualification of their management personnel. It is reasonable to assume that because the regulatory authorities provided provisional certification, Curragh Resources held the belief that such certification was legitimate. The radar diagrams (Figures 6.3 to 6.5) illustrate that the nine errors of commission made by Curragh Resources were throughout the enterprise at both the project (mine planning) and operating stages (unsafe equipment underground), indicating that they were fully aware of mine conditions.

6.3.5.2 Westray Mine Management

Westray Mine management contributed to twenty (31%) decision errors; nineteen of which were errors of commission and one of mistaken belief (Table 6-4). Mine management collaborated in each of the decision errors of commission made by Curragh Resources (Figures 6.3 to 6.5). The radar diagrams illustrate a succession of errors of commission pervasive throughout the *event* scenario, leaving no doubt as to their knowledge of conditions as they unfolded. They knew of perilous and deteriorating conditions; they knew that these conditions were in contravention of the *Coal Mines Regulation Act*; and they knew that they had a responsibility to protect the workforce.

6.3.5.3 Westray Mine Supervision

Mine supervision by comparison contributed ten (15%) decision errors, of which one was an error of commission, three were errors of omission and six were errors of

mistaken belief. This is consistent with the determination in the report of inquiry (Richard, 1996) that Westray supervisors were selected from the workforce, and in general lacked supervisory knowledge and expertise. The three errors of omission were occasions when mine supervision complied with a directive from mine management under coercion. Again, this observation is consistent with the report of inquiry that held that all mineworkers were intimidated and fearful of showing any dissent toward mine management regarding safety.

6.3.5.4 Mine Workforce

Only five decision errors (8%) were attributable to the mine workforce, four of which were errors of mistaken belief (Table 6-4). Clearly, the workers did not have sufficient information regarding hazards or their control, and were largely not aware of their right of refusal of unsafe work. Given the number of workers at Westray and the many hazards and circumstances of imminent danger that they endured, there were likely many more errors of mistaken belief by workers than are represented in the report of inquiry (Richard, 1996). That the mine workforce contributed only 8% of the decision errors could also be indicative of their lack of engagement in workplace health and safety.

6.3.5.5 Regulatory Authorities

The regulatory authorities were the Nova Scotia Department of Natural Resources and the Nova Scotia Department of Labour. Together, they contributed nineteen (29%) decision errors to the *event* scenario, thirteen of which were errors of mistaken belief, five errors of omission and one error of commission (Table 6-4). The error of commission was the alteration of official records in favour of Curragh Resources. This impropriety and the five errors of omission are strongly suggestive of regulatory authorities who were intimidated, if not coerced by Curragh Resources. Additionally, that nearly 70% of errors were errors of mistaken belief is evidence that the Department of Natural Resources and Department of Labour did not understand their legislated mandate, or their fiduciary responsibilities as safe keepers of the public's trust.

6.3.5.6 Decision Error Analysis Interpretation

There were a number of standards of conduct and duties of care transgressed by nearly all of the workplace parties that speak to an inherent lack of competence and prudence, which is otherwise demanded by a high-risk operating environment such as underground coal mining (Figure 6.3). These transgressions provide a hint of the ethos and the common perceptions shared by the parties in the enterprise. Furthermore, they provide some insight into what systemic issues made Westray a 'predictable path to disaster' (Richard, 1996). They are conditions B, F and G:

- i. Condition of workers not competent to work underground
- ii. Condition of workers underground in gassy conditions
- iii. Condition of workers in imminent peril conditions (coal dust)

6.3.6 Cognitive Profiling of the Westray Disaster

6.3.6.1 Profile Distribution

The cognitive profile (ternary diagram) of the Westray disaster reveals that the enterprise as a whole was marginally in the region of no central tendency (Figure 6.6). However, when we look at the workplace parties, there is some polarization of cognitive predispositions. Curragh Resources and the Westray Mine management report to the cognitive dissent extreme of the ternary diagram, and the remaining workplace parties report to the cognitive deficit region of the ternary diagram (Figure 6.6). This conspicuous disparity typifies the phenomenon of *organizational dissonance* between senior mine management and mine supervision as well as the regulatory authorities.

6.3.6.2 Cognitive Dispositions

Curragh Resources and the Westray Mine management were highly affiliated, and both disposed to cognitive dissent. The Westray supervisors as well as the regulatory authorities were disposed to cognitive deficit, with significant dispositions toward cognitive deferral (Figure 6.6). The errors of omission of both mine supervision and the regulatory authorities are attributed to intimidation and coercion on the part of Curragh Resources. The Westray hourly workers were clearly disposed to cognitive deficit, with some disposition towards dissent. The dissent reflects a risk accepting

behaviour that was modelled by management. Nonetheless, causing a cessation of ventilation in any underground mine would be a violation of standard for which no special knowledge is required, and hence an error of commission on the part of the workers.

6.3.6.3 Interpretation

Both the regulatory authorities and mine supervision desired a safe and efficient enterprise, but were coerced into acquiescence with senior mine management's priority toward production. Had the regulatory authorities or mine supervision been more competent in their respective roles, they might have been less intimidated and more assertive in their desire for standards and their respective duties of care. In this respect Westray is an example of an enterprise in which management (both corporate and operational) abused their authority, their influence and their relationships with other workplace parties for personal gain and ultimately to the detriment of the enterprise. On the part of the mineworkers: they were denied their right of refusal of unsafe work, their right to participate in matters of health and safety and their right to know of hazards in the workplace. The primacy of these rights in the creation of a safe and just culture cannot be overstated. The mine supervision at Westray may not have understood this, however it is a fundamental principle of regulatory enforcement that the regulatory authorities most certainly were aware of, or ought to have been aware.

6.3.7 Mission Criticality

The mission criticality index of the Westray coalmine enterprise is 10^8 out of a possible 10^{10} (Table 6-5). We would expect an index of 10^3 from any underground coal mine enterprise because of the limited access and egress, the large amounts of combustible material (coal, methane), and the manner in which coal and methane interact in a *positive feedback loop*. Elements present at Westray that exacerbated these conditions were:

- i. the absence of risk communication respecting coal dust and methane,
- ii. the fact that mine management were predisposed to cognitive dissent,
- iii. the fact that the mine was in transition from development to production,
- iv. the lack of emergency response plans and preparedness; and,

- v. the absence of effective regulatory oversight.

Heuristically, the mission criticality analysis suggests that preventative strategies at Westray be based upon an enterprise in which mine management were compliant with standards, the workforce was knowledgeable of the risks, the regulatory authorities were competent, the mining plan was followed, and emergency response preparedness was a day-to-day reality and priority.

6.3.8 Significance and Outcomes

As a direct result of the Westray Mine disaster, Bill C-45, federal legislation that makes workplace safety violations criminal offences, became law on March 31, 2004. The legislation brings those who are of “determining minds” under the scrutiny of the law and criminal liability, addressing the complexity of modern corporate governance. Section 2.17.1 of Bill C-45 states ‘everyone who undertakes, or has the authority, to direct how another person does work or performs a task is under a legal duty to take reasonable steps to prevent bodily harm to that person, or any other person, arising from that work or task.’ (CCOH&S, 2007):

Specifically, it seeks to impose legal remedy for health and safety violations by:

- i. senior officers of corporations that oversee operations, but may not be Directors.
- ii. any corporate officer with operational authority that directs employees to commit offences (health and safety related) for the benefit of the organization.
- iii. any corporate officer with operational authority that knows of or can be expected to reasonably ought to have known of offenses (OH&S) of employees.
- iv. any corporate officer with operational authority that through the demonstration of lack of care, permit an unsafe workplace constituting criminal negligence.

The only defence is that of due diligence: to take all reasonable measures to protect the health and safety of the employees and the public. At the time of writing of this dissertation, there have been three charges under C-45, one of which has resulted in a successful conviction. The maximum fine for minor convictions is \$100,000 with no maximum limit set for more serious offences. An individual convicted of criminal negligence resulting in a fatality may face life imprisonment.

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
A	Miner Workers	Workers not aware of underground hazards	Regulatory Compliance	EMB
A	Mine Supervision	Workers not aware of underground hazards	Duty of Care to mine workers	EMB
A	Mine Management	Workers not aware of underground hazards	Due Diligence	EOC
A	Regulatory Authorities	Inspectorate did not follow-up training plans	Legislated Mandate	EOO
B	Miner Workers	Workers not competent to work underground	Regulatory Compliance	EMB
B	Mine Supervision	Workers not competent to work underground	Duty of Care to mine workers	EMB
B	Mine Management	Workers not competent to work underground	Due Diligence	EOC
B	Regulatory Authorities	Inspectors not sufficiently trained or experienced	Legislated Mandate	EMB
C	Mine Supervision	Unsafe use of mine equipment underground	Competency	EMB
C	Mine Management	Unsafe use of mine equipment underground	Due Diligence	EOC
C	Curragh Resources	Unsafe use of mine equipment underground	Due Diligence	EOC
	(Page 1 of 7)	Continued on next page	Table 6-3 (a)	

Letter	Enterprise Party	Condition Contributing to the <i>Event</i> Scenario	Standard of Care	Error
C	Regulatory Authorities	Providing notice of inspection of the mine	Generally Accepted Practice	EMB
D	Mine Supervision	Unsafe mine equipment underground	Competency	EMB
D	Mine Management	Unsafe mine equipment underground	Due Diligence	EOC
D	Curragh Resources	Unsafe mine equipment underground	Due Diligence	EOC
D	Regulatory Authorities	Inspectorate not knowledgeable of technology	Competence	EMB
E	Mine Management	Roof-bolts installed in gassy conditions	Due Diligence	EOC
E	Curragh Resources	Roof-bolts installed in gassy conditions	Due Diligence	EOC
F	Mine Workers	Working in imminent peril conditions (coal dust)	Competency	EMB
F	Mine Supervision	Workers in imminent peril conditions (coal dust)	Duty of care to mine workers	EOO
F	Mine Management	Workers in imminent peril conditions (coal dust)	Due Diligence	EOC
	(Page 2 of 7)	Continued on next page	Table 6-3 (b)	

Letter	Enterprise Party	Condition Contributing to the <i>Event</i> Scenario	Standard of Care	Error
F	Curragh Resources	Workers in imminent peril conditions (coal dust)	Due Diligence	EOC
F	Regulatory Authorities	Worker complaints not investigated (coal dust)	Legislated Mandate	EOO
G	Mine Workers	Working underground in gassy conditions	Competency	EMB
G	Mine Supervision	Workers underground in gassy conditions	Competency	EOO
G	Mine Management	Inadequate and poorly maintained ventilation	Due Diligence	EOC
G	Regulatory Authorities	Mine ventilation not inspected or tested	Competency	EMB
H	Mine Management	Continued development in bad ground conditions	Due Diligence	EOC
H	Curragh Resources	Continued development in bad ground conditions	Due Diligence	EOC
H	Regulatory Authorities	Mine development outside of permit conditions	Legislated Mandate	EOO
I	Mine Supervision	Permitting the tampering of methane detectors	Regulatory Compliance	EOO
	(Page 3 of 7)	Continued on next page	Table 6-3 (c)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care t	Error
I	Mine Management	Permitting the tampering of methane detectors	Due Diligence	EOC
J	Mine Workers	Workers causing cessation of mine ventilation	Duty of care to other mine workers	EOC
J	Mine Supervision	Permitting the cessation of mine ventilation	Duty of care to mine workers	EOC
J	Mine Management	Permitting the cessation of mine ventilation	Due Diligence	EOC
K	Mine Management	Permitting unlawful work practices	Due Diligence	EOC
K	Curragh Resources	Permitting unlawful work practices	Due Diligence	EOC
K	Regulatory Authority	Inspectorate tolerating unlawful work practices	Legislated Mandate	EOO
L	Mine Supervision	Permitting dysfunctional environmental monitor	Regulatory Compliance	EMB
L	Mine Management	Permitting dysfunctional environmental monitor	Due Diligence	EOC
M	Mine Management	Permitting heavy coal dust underground	Due Diligence	EOC
	(Page 4 of 7)	Continued on next page	Table 6-3 (d)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
M	Curragh Resources	Orders for stone dusting not complied with	Due Diligence	EOC
M	Regulatory Authorities	Coal Mines Regulation Act not upheld	Legislated Mandate	EMB
N	Mine Supervision	Permitting storage of fuel underground	Regulatory Compliance	EMB
N	Mine Management	Permitting storage of fuel underground	Due Diligence	EOC
N	Regulatory Authorities	Inspection routes selected by mine management	Legislated Mandate	EOO
O	Mine Management	Workers sent underground without training	Due Diligence	EOC
P	Regulatory Authorities	Worker training not monitored or reviewed	Legislated Mandate	EMB
Q	Regulatory Authorities	Mine not inspected sufficiently for hazards	Legislated Mandate	EMB
R	Regulatory Authorities	Mine inspected without worker representation	Legislated Mandate	EMB
S	Regulatory Authorities	Mine inspector not knowledgeable of Mine Act	Fiduciary Responsibility	EMB
	(Page 5 of 7)	Continued on next page	Table 6-3 (e)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
T	Regulatory Authorities	Senior regulatory officials unfamiliar with IRS	Competency	EMB
U	Mine Management	Permitted 12-hour shifts underground	Regulatory Compliance	EOC
V	Mine Management	Joint Health and Safety Committee fettered	Regulatory Compliance	EOC
V	Curragh Resources	Joint Health and Safety Committee fettered	Regulatory Compliance	EOC
V	Regulatory Authorities	Role of inspectorate not understood	Legislated Mandate	EMB
W	Mine Management	Mine managers certificate not valid	Professional Ethics	EMB
W	Curragh Resources	Mine managers certificate not valid	Professional Ethics	EMB
W	Regulatory Authorities	Director issued a provisional certificate	Fiduciary Responsibility	EMB
X	Mine Management	Developing mine outside of mine plans	Regulatory Compliance	EOC
X	Curragh Resources	Developing mine against expert advice	Due Diligence	EOC
	(Page 6 of 7)	Continued on next page	Table 6-3 (f)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
X	Regulatory Authorities	Permit amendments without prudent review	Legislated Mandate	EMB
Y	Mine Management	Intimidated workers/supervisors to remain silent	Regulatory Compliance	EOC
Y	Curragh Resources	CEO failed to promote safe mining practices	Due Diligence	EOC
Y	Regulatory Authorities	Alteration of records and presence to Curragh	Fiduciary Responsibility	EOC
	(Page 7 of 7)	-End-	Table 6-3 (g)	

Table 6-3: Table summarizing the 64 decision errors contributing to the Westray Mine disaster according to enterprise party

Enterprise Party	EOC	% EOC	EMB	% EMB	EOO	% EOO	Totals	Total %
Curragh Resources	10	91%	1	9%	0	0%	11	17%
Mine Management	19	95%	1	5%	0	0%	20	31%
Mine Supervision	1	10%	6	60%	3	30%	10	15%
Mine Workforce	1	20%	4	80%	0	0%	5	8%
Regulatory Authorities	1	5%	13	68%	5	26%	19	29%
All Enterprise Parties	32	49%	25	39%	8	12%	65	100%

Table 6-4: Table summarizing the distribution of the Westray decision errors by the workplace parties

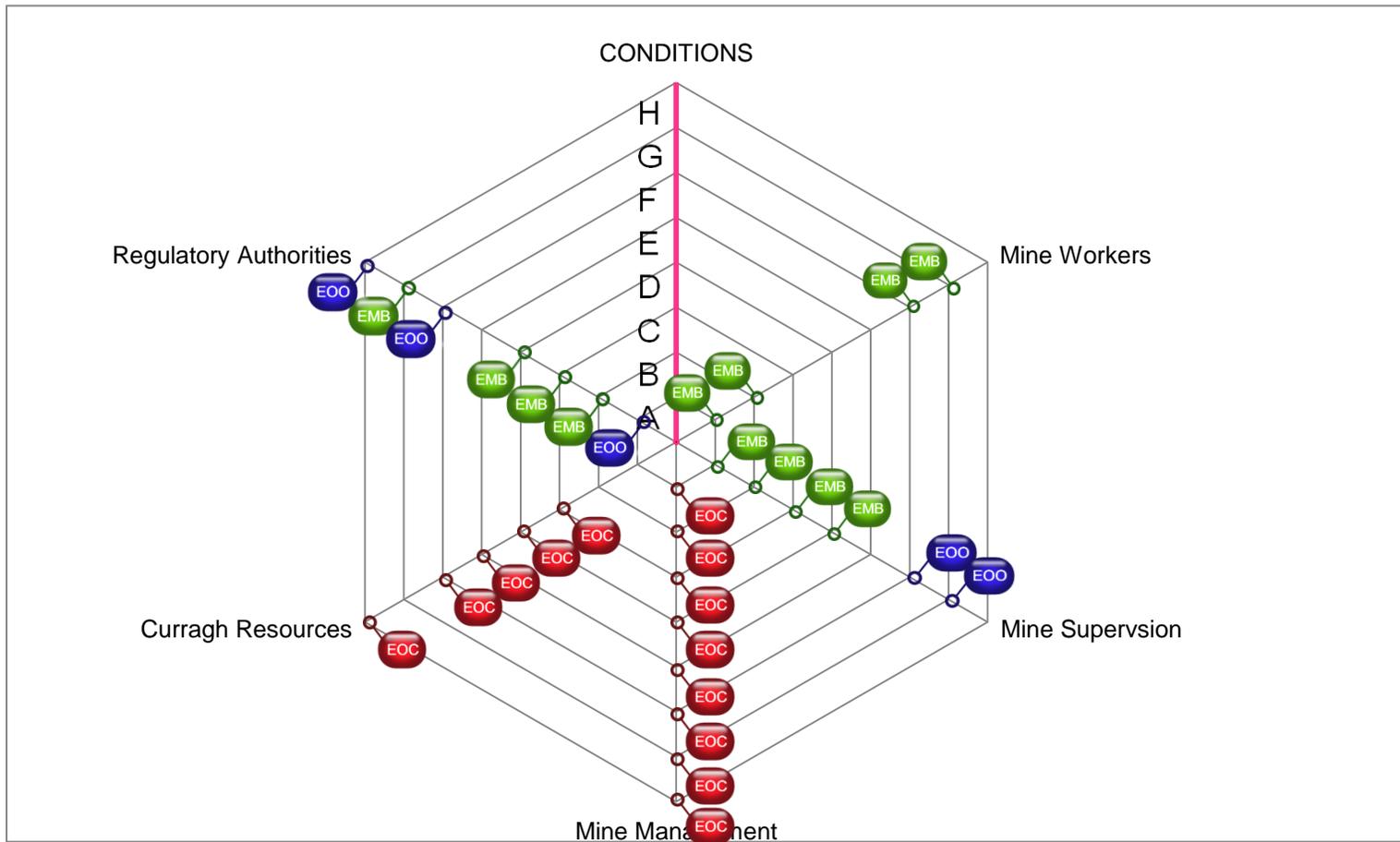


Figure 6.3: Decision error analysis diagram for conditions A through H of the Westray Mine disaster

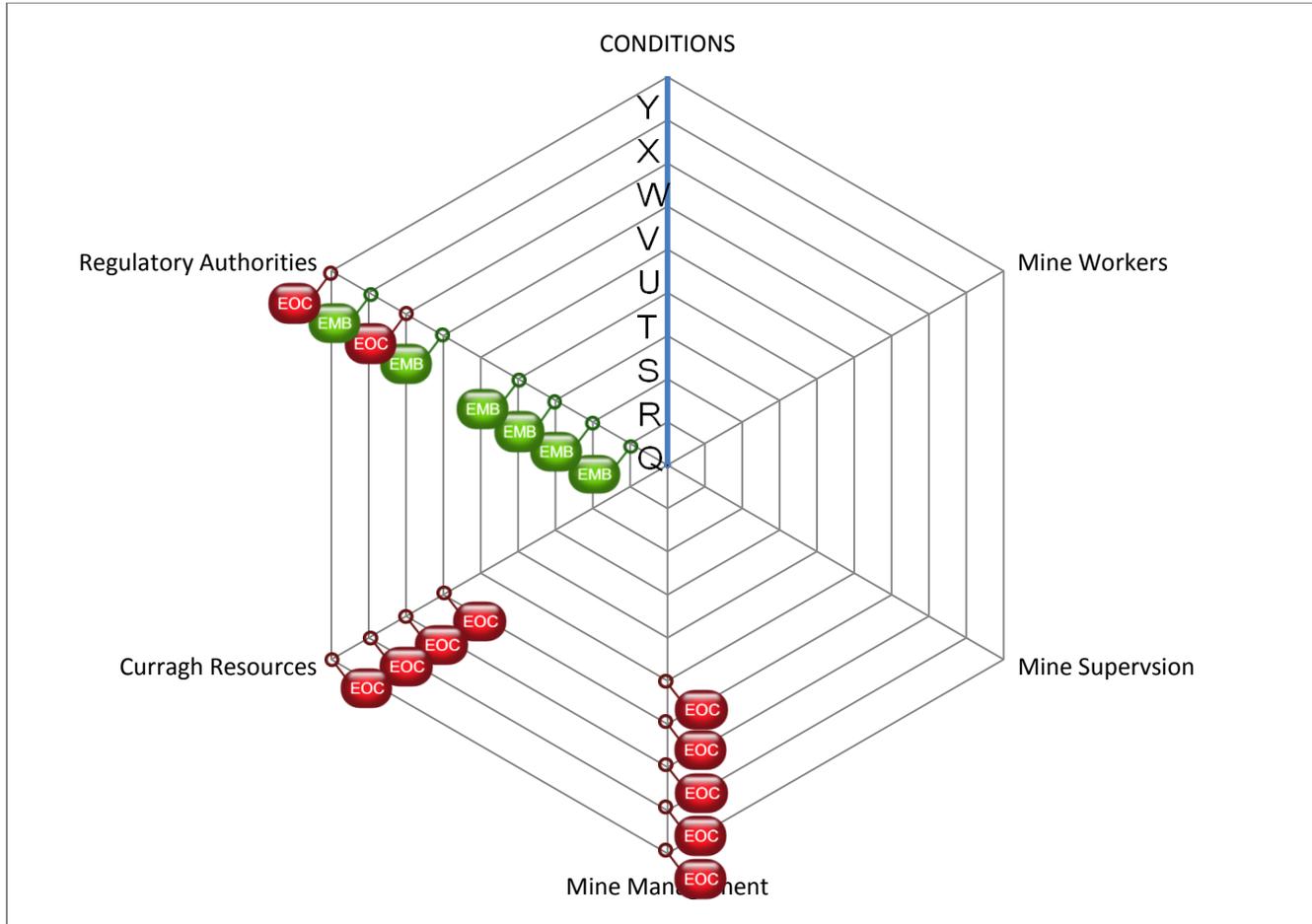


Figure 6.5: Decision error analysis diagram for conditions Q through Y of the Westray Mine disaster

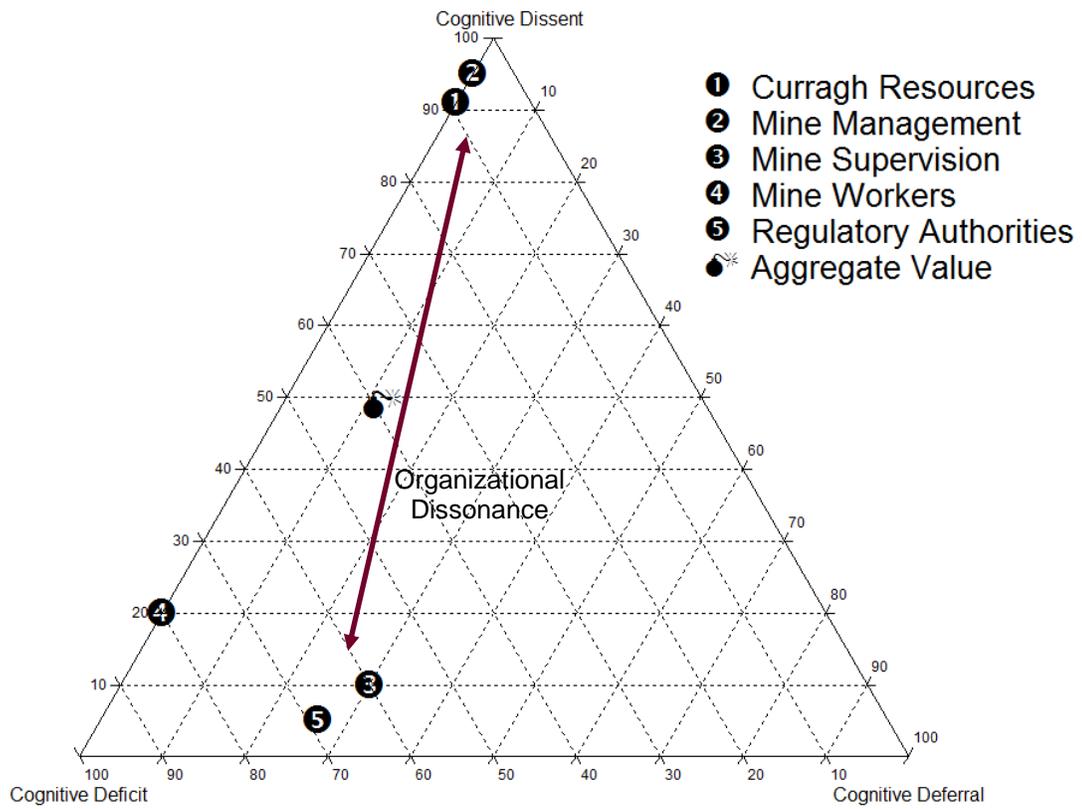


Figure 6.6: Ternary diagram illustrating the cognitive profiles of the Westray parties

Criticality Element	Supportive Description	Demerit	Westray
Presence of Positive Feedback Loop	Methane bump causing coal dust dispersion	10	10
Limited Access and Egress	Underground coal mine	10	10
Highly Coupled or Complex Systems		10	
Absence of Risk Communication	Imminent danger of methane and coal dust being ignited not understood by workers	10	10
Enterprise in Cognitive Deficit		10	
Lack of Effective Emergency Response	Curragh Resources did not have a disaster response plan	10	10
Excessive Amounts of Stored Energy	Incipient migration of methane combined with pervasive coal dust	10	10
Enterprise/Operation in Transition	Mine in production to produce cash flow ahead while in mine development	10	10
Absence of Regulatory Oversight	Departments of Labour and Natural Resources did not fulfil their mandate to enforce the regulations	10	10
Management in Cognitive Dissent	Curragh Resources and Mine management and in cognitive dissent	10	10
Mission Criticality	Total Demerit	10¹⁰	10⁸

Table 6-5: Table summarizing mission criticality elements associated with the Westray disaster

6.4 Piper Alpha Production Platform Disaster

The Piper Alpha was a production platform working approximately 120 miles northeast of Aberdeen, Scotland in the North Sea. Designed originally as an oil-drilling platform in 1976, she was converted to an oil and gas production platform in 1980. The Piper Alpha and three other platforms comprised a network of oil and gas platforms that pumped oil and gas products to an oil terminal in the Orkney Islands, in which the Piper Alpha platform was the central gathering point and distribution hub (Cullen, 1990).

A consortium owned the Piper Alpha platform, with Occidental Petroleum having controlling interest at 36.5%. The platform was supported by a steel structure called a jacket, anchored on the seabed 474 feet (144m) beneath the sea. The platform was located 68 feet (21 m) above sea level. There were four decks on the platform, the top most being the heli-deck located above the crew quarters. The lowest deck contained the oil and gas processing modules: modules A through D. The second deck contained equipment modules, pumping modules and material storage modules. The third deck consisted of four levels in which all of the crew accommodation, ancillary support services, recreational facilities and offices were located. The drilling derrick was situated above the A module of the lower deck and could travel the width of the platform (Cullen, 1990).

The platform was serviced by the supply vessel *Sandhaven*, and regular transshipments of personnel flown in by helicopter. The Piper Alpha platform was equipped with two radio rooms, six self-contained lifeboats, thirteen life rafts and 519 life jackets. Her maximum capacity was 241 persons, of which 226 were present the night of the disaster.

The Piper Alpha had an unusual capacity to drill for oil and gas; produce oil and gas; receive oil and gas from other platforms, and separate and process the oil gas while continuously distributing it to shore. At the time of the disaster, she was receiving and distributing oil and gas products, but had just come off a production shut down requiring a cessation of gas processing and compression in a module that had been changed out. Consequently, on July 06, 1988 the Piper Alpha platform was not processing gas products but was drilling. Concurrently it was separating 138,294 barrels per day of oil, 119,000 barrels of which was sent to shore; separating condensate ends, 7,500 barrels per day sent to shore; and receiving and distributing from the Tartan platform 33 million

standard cubic feet per day of gas – all sent to shore. At the day of this disaster the Piper Alpha oil and gas production platform was bringing her gas compressor modules on-line (Cullen, 1990).

6.4.1 Chronology of Events

On the July 06, 1988, the Piper Alpha production platform was bringing her gas compression modules back on line after a maintenance shutdown so that she could return to processing and compressing gas product from her risers. The dayshift operators had been working on one of two gas compression module pumps (module A) that was believed to have been plugged by hydrated gas product. A pressure safety valve was removed from the pump so that it could be assessed for damage prior to recertification. The dayshift crews were operating personnel and not maintenance personnel related to the maintenance shutdown. Those personnel had previously completed their work and departed the platform. At the end of their shift, the operators reassembled the compression pumps with (blind flanges), but left the spools loosely assembled with the intention of reinserting the pressure relief valve and tightening the nuts at a later point. The operators then departed the area and did not return as it was near end of their shift. The operators had failed to ‘tag-out’ or ‘lock-out’ the pump as unserviceable, as is customary and a requirement of procedure.

During the late evening of July 06, while the gas compressing module B was functional and processing gas, the gas compression module (pump B) tripped (probably for the same reason – formation of hydrated gas product) and the operators had to take it off line, consequently causing a cessation in production. Instead of bringing the gas compressor module down and verify the integrity of compressor module A, the operators elected to switch the production flow over to the “A” side of the process, which was redundantly designed for this purpose. The operators had no knowledge of the compressor module A being out of service, and made the switch without any concern for its operational integrity. The gas compression pump was not sealed sufficiently and gas condensate leaked from the spools at approximately 22:00 hours (Cullen, 1990).

The amount of condensate was not very large, and the pressure drop across the pump caused an immediate trip of the gas compression module, but the harm was done. Gas condensate found a source of ignition, flashed and ignited a fireball that would damage other areas of the gas compression module, causing them to fail and discharge

oil and gas products. The fire spread down the Piper Alpha platform as oil product found its way to the lower levels by force of gravity. Eventually, the burning oil found the gas riser from the Tartan production platform and broke it, releasing huge amounts of processed gas into the atmosphere, causing the explosion that was observed by many at 22:20 hours. Thirty minutes later, the riser from the MCP-01 production platform failed and again gas was observed to explode into a fireball at approximately 22:50 hours. Incredibly, neighbouring platforms refused to shut down their production of gas on the basis that they did not have the authority to do so – while in plain sight of the now fully involved Piper Alpha production platform. The Claymore gas riser was next to ignite causing further explosions as observed by many responding and fighting the fire. The hydrocarbons continued burning into the night causing the complete destruction of the Piper Alpha platform (Cullen, 1990).

Workers working on the lower deck jumped into the sea and many survived the experience. Workers on shift that night on the 2nd and 3rd decks were not so fortunate and many died when the oil and gas processing stations exploded. The drilling crew was able to shut in the well and move to assembly areas (the galley), to await evacuation orders – orders that would never come. The off-shift crew also assembled as per their understanding within the galley area and awaited evacuation orders. Standard operating procedure was to wait at the muster point for direction from emergency response authorities. At least 109 persons mustered in the galley; 80 waited for direction and died; at least 29 did not wait – instead made their way off the platform in any manner they could, eventually by jumping into the sea. These 29 crewmembers from the galley assembly area survived. Incredibly, five persons jumping from the heli-deck (53m) also survived the ordeal. One crewmember on the supply vessel *Sandhaven* received fatal injuries during the ensuing effort to render assistance to the Piper Alpha platform.

6.4.2 Parties within the Enterprise

Piper Alpha Enterprise Parties	Roles and Responsibilities
Occidental Petroleum	Owner and operators of the platform
Platform Management	Supervision of Piper Alpha operations
Platform Master/Captain	Safety of ship's (Piper Alpha) company
Platform Workforce	Roughnecks, divers, operators
The <i>Sandhaven</i>	Contract supply vessel to the Piper Alpha
The UK Department of Energy	UK federal regulatory authority

Table 6-6: Table summarizing the parties to the Piper Alpha enterprise and their roles

6.4.3 Consolidated Findings

The following are the consolidated findings contributing to the Piper Alpha production platform disaster. The investigative sources are the *Public Inquiry into the Piper Alpha Disaster* (Cullen, 1990), and the documentary *The Human Price of Oil* (Furneux, 1988). The emergency response to this disaster was ineffectual, poorly documented and involved many parties who only through serendipity were able to lend assistance. Consequently, these findings are of the events preceding the fire and explosion, up until and including the egress of casualties from the platform. In approximate chronological order, the findings are:

- 1) There was no effective means of egress from the burning platform other than jumping into the sea.
- 2) Personnel gathered at the muster station within the accommodation galley and waited for direction to evacuate from persons in authority – as per procedure.
- 3) The Tartar and Claymore platforms continued to pump gas into the system (to Piper Alpha) because they believed they had no authority to do otherwise.
- 4) The operators of the gas compressor module failed to respond to four alarms within the gas compression module 'A' by initiating emergency procedures.
- 5) Supervising operators observed, but did not investigate an unusual amount of volume issuing from the flare stack.
- 6) Compressor module 'B' was fouled (with hydrate) and the gas compressor module switched over to the gas compressor module 'A' without verification.

- 7) The maintenance engineer neglected to inform the gas compressor module operator that gas compressor module 'A' was out of service.
- 8) Operators removing the pressure relief valve from compressor module 'A' did so without following lock and tag-out protocols and procedures.
- 9) Automated fire pumps were placed on manual override so that divers could conduct underwater work without fear of being trapped by intake suction.
- 10) *Piper Alpha* production platform was coming off a maintenance shut-down of the gas compression modules and operating personnel (not maintenance) were completing maintenance to expedite start-up.
- 11) A recent fatality (December 1987) involving a fall from height while maintaining equipment outside of standard operating procedures did not initiate review of maintenance procedures or protocols.
- 12) The gas compression module was not designed with blast walls or firewalls.
- 13) The central control room was designed and located adjacent to the gas compression module (a known source of hazard of explosive atmosphere).
- 14) Crew's accommodation was located immediately above the gas compression module (and in line of fire).
- 15) Occidental engineers could not conceive of an *event* that would require the evacuation of the gas compressor control room.
- 16) Occidental did not conduct a risk assessment on their production platform subsequent to retrofitting in 1980.
- 17) Occidental converted a drilling rig from the Gulf of Mexico into a multiphase oil and gas production platform requiring several times the operating space.
- 18) Occidental had experienced diminished profits and had cut maintenance and capital budgets at a time of aging capital assets.
- 19) The Department of Energy could only inspect platforms 2 days per year.
- 20) The Department of Energy inspectors relied upon the oil company transport and consequently provided notice of when inspecting a production platform.
- 21) The Department of Energy did not evaluate the risk of the production platform when they provided the operating permit.
- 22) The Department of Energy inspector for *Piper Alpha* was not sufficiently trained and experienced as regards to maintenance in general and lockout procedures in particular.

6.4.4 Decision Error Analysis of the Piper Alpha Disaster

Analysis of the official report of inquiry (Cullen, 1990) reveals 33 decision errors contributing to the Piper Alpha production platform disaster (Table 6-8). Occidental Petroleum reported the largest number of decision errors (30%), followed by the platform management (24%), and the Department of Energy (21%), (Table 6-9). The contribution of error from the platform workforce was surprisingly low (18%) indicative of the systemic nature of this type of *event*, and the latency and complexity of errors antecedent to the *event*. The standards of care breached by the parties were essentially ‘duty of care’ standards that are fundamental to parties of any enterprise (Table 6-7). That such basic breach of duty of care on the part of the workplace parties could result in a disaster is indicative of the mission criticality (Table 6-10) of the Piper Alpha enterprise.

Piper Alpha Enterprise Parties	Standard or Duty of Care Not Met
Department of Energy	Fiduciary Responsibility
Occidental Petroleum	Engineering Standards and Due Diligence
Platform’s Master	Duty of Care to Ship’s Company
Platform Supervision	Duty of Care and Standard Operating Procedures
Platform Workforce	Competency and Standard Operating Procedures

Table 6-7: Table summarizing the standards of care not met by Piper Alpha enterprise parties

6.4.4.1 The Department of Energy

The Department of Energy (DOE) contributed to seven of the 33 decision errors; three of which were errors of mistaken belief and four errors of omission (Table 6-9). The DOE were the sole regulatory agency governing offshore platform safety and were experiencing a ‘perfect storm’ of economic factors, not uncommon with regulatory authorities. The oil and gas industry had come off a cyclic downturn in the demand in 1988; consequently, the DOE was staffed accordingly. However, there was an increase in demand for oil and gas in 1988 that triggered an increase in offshore production activity. The DOE could not compete for experienced offshore personnel at a time when they required additional inspectors. Fewer inspectors were required to ‘risk manage’ more offshore platforms at a time when technological advances were being made in the industry. Consequently, decision errors were made on two fronts: inspectors did not have the requisite skills for the complexity of offshore oil and gas production, and the

inspectorate were under significant time and logistic stress to inspect a large inventory of platforms. The DOE was challenged with meeting its fiduciary responsibilities. The radar diagram illustrates that the decision errors of the DOE were distal to the actual *event*, and that they influenced Occidental Petroleum to the extent that expectations regarding safety were not taken seriously (Figure 6.9).

6.4.4.2 Occidental Petroleum

Occidental Petroleum contributed ten decision errors, five of which were errors of mistaken belief, three errors of commission and two of omission (Table 6-9). Principal among the errors was design errors of the Piper Alpha platform itself. The Piper Alpha was refitted as a production platform without meeting many engineering standards of the day, given her complexity (Cullen, 1990). As the platform was not under the scrutiny of the Department of Energy, many design faults (blast doors and firewalls) were not implemented, that would otherwise have been required (errors of commission). At the time of the disaster, the Piper Alpha was in transition from maintenance shutdown to production, and the Occidental Petroleum representatives were under some pressure to ramp up in production, as the Piper Alpha was the hub of four platforms. This sense of urgency and expectation contributed to errors of omission. The errors of mistaken belief were related to the belief that Piper Alpha could never experience a conflagration of the magnitude that would require the evacuation of her control centres and the platform itself. Consequently, the Piper Alpha crew and company were without emergency response training, drills and equipment. The radar diagram reveals that the decision errors of Occidental Petroleum had little influence on those made by other parties, suggestive of a lack of information sharing and consultation (Figure 6.8).

6.4.4.3 Platform Management

The management personnel (supervision) on the Piper Alpha contributed eight decision errors, four which were errors of omission, two errors of commission and two of mistaken belief (Figure 6.8). They were under pressure to get the condensate pumps on line so that production could continue. Their errors were in asking the operating personnel to conduct maintenance repairs in the place of maintenance crews who had departed the platform. They mistakenly believed that the repairs were not demanding and that the operators could accomplish them. They also cut corners as regards to

putting the fire-water pumps on manual without proper documentation and communication. This was followed by further errors of omission as matters worsened with both condensate pumps. The radar diagram reveals that the decision errors of platform management influenced those of the platform workforce, and *vice versa* (Figure 6.9). Many of the decision errors were common to both platform management and the platform workforce, and it is likely that the two parties were highly affiliated with each other and shared a common ethos for safety.

6.4.4.4 The Platform Master

The Piper Alpha platform was a registered maritime vessel, and as such would be under the care and custody of a master or captain. It is not clear as to what authorities the master had on board the Piper Alpha whilst in production, regardless he/she had a duty of care to the platform's company to ensure their safety while aboard. A primacy of this duty was preparations for the safe and efficient evacuation of Piper Alpha's company. That this was lacking indicates a mistaken belief that it would not be required, or that it was some other parties responsibility. Consequently, during the ensuing crisis, the Master was as much at a loss as the other parties to respond with the rapidity of the *event*. It is likely that the other workplace parties looked to the Master of the Piper Alpha regarding maritime safety, and that his perceptions of risk strongly influenced their perceptions of risk (Figure 6.9).

6.4.4.5 Interpretation

The common standard of care absent by most of the workplace parties was the capacity to give instructions for the safe and efficient evacuation of the Piper Alpha. In this respect, there was a tragedy within a tragedy as the standing orders were for the platform's company to muster inside the galley. Those that did did not survive and sadly, their last moments were waiting for directions or instructions. Decision error analysis indicates that Piper Alpha's company were not disposed to dissent; rather, they were highly skilled technicians and operators who were deficient in knowledge and skills associated with maritime emergencies. The standards and duties of care not met were not grievous, yet they came together insidiously culminating in disaster. This speaks to a lack of standards and sophistication of regulations and procedures; a deficiency that was addressed extensively in the official report of inquiry (Cullen, 1990).

6.4.5 Cognitive Profiling of the Piper Alpha Disaster

6.4.5.1 Profile Distribution

The cognitive profile (ternary diagram) of the Piper Alpha disaster reveals that the enterprise as a whole was marginally in the region of no central tendency; but trending towards the region of cognitive deferral (Figure 6.10). The distribution is moderately clustered indicating consonance of the parties as regards to safety culture in general and risk perception in particular. Occidental Petroleum was not participatory in the day-to-day operations of the Piper Alpha, and this is indicated by their position on the ternary diagram in which they are removed from other parties in terms of cognition.

6.4.5.2 Cognitive Dispositions

The aggregate value shows an enterprise that was equally disposed to cognitive deficit and deferral; one that was not given to dissent (Figure 6.10). That four out of five parties report to the region of cognitive deferral is an indication that operationally they were under stress. It is likely that as a collective, the parties involved in the Piper Alpha enterprise were moving towards cognitive deferral for some time, and that an *event* was inevitable. This is supported by the fact that in December of 1987, Piper Alpha experienced a fatality (Cullen, 1990); possibly a harbinger of things to come.

6.4.6 Mission Criticality

The mission criticality index of the Piper Alpha production enterprise is 10^7 out of a possible 10^{10} (Table 6-10). We would expect an index of 10^3 from such an enterprise because of the limited access and egress, the large amounts of combustible material (oil and gas), and high complexity and coupling of its systems. Elements present at Piper Alpha that exacerbated these conditions were:

- i. the absence of risk communication respecting explosive atmospheres,
- ii. the fact that the platform was in transition from maintenance to production,
- iii. the lack of emergency response plans and preparedness; and,
- iv. the absence of effective regulatory oversight.

Heuristically, the analysis of mission criticality suggests that standards of care respecting Piper Alpha were inadequate throughout the enterprise. Particularly deficient were standards ensuring that the platform's company were knowledgeable in maintenance procedures with flammable products; the regulatory authorities were knowledgeable and effective; and, that all personnel were trained in (and equipped for), maritime emergencies and their response.

6.4.7 Significance and Outcomes

As a direct consequence of the Piper Alpha production platform disaster, the regulatory framework of the UK Department of Energy was greatly reformed and improved. Responsibility for ensuring the health and safety of offshore workers was shifted to the operator. The safety case concept for the North Sea was brought into alignment with existing standards of industries operating onshore. In the report of public inquiry, 57 of the 106 recommendations concerned the then Department of Energy (Cullen, 1990). To the credit of the Government of the UK, changes were made and improvements realized (Beynon, 2007). Currently the offshore oil and gas industry in the United Kingdom has a regulatory framework that meets, if not exceeds that of the onshore industrial community; setting a global standard in offshore safety.

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard or Duty Not Met	Error
A	Ships Master	No means of egress from the Piper Alpha platform	Duty of care to ship's company	EMB
A	Occidental Petroleum	No means of egress from the Piper Alpha platform	Due Diligence	EMB
A	Department of Energy	No means of egress from the Piper Alpha platform	Legislated Mandate	EOO
B	Platform Workforce	No knowledge of emergency response procedures	Competency	EMB
B	Ships Master	No instructions or directions during emergency	Duty of care to ship's complement	EOO
B	Platform Management	No instructions or directions during emergency	Duty of care to workers	EOO
B	Occidental Petroleum	No instructions or directions during emergency	Due Diligence	EOO
C	Platform Management	Continued transfer of gas from Tartan & Claymore	Duty of Care	EOC
D	Platform Management	Failure to shut down compressor module after alarm	Standard Operating Procedure	EOO
E	Platform Workforce	Uncharacteristic volume of flare not investigated	Standard Operating Procedure	EOO
E	Platform Management	Uncharacteristic volume of flare not investigated	Duty of care to workers	EOO
	(Page 1 of 4)	Continued on next page	Table 6-8 (a)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard or Duty Not Met	Error
F	Platform Workforce	Gas compressor B switched to A without verification	Standard Operating Procedure	EOO
F	Platform Management	Gas compressor B switched to A without verification	Standard Operating Procedure	EMB
G	Platform Workforce	Control room not informed of operational status	Standard Operating Procedure	EOO
G	Platform Management	Control room not informed of operational status	Standard Operating Procedure	EOO
H	Platform Workforce	Failure to lock-out and tag gas compression module	Standard Operating Procedure	EMB
I	Platform Management	Control room not informed fire-pumps on manual	Duty of care to platform personnel	EOC
J	Platform Workforce	Operating personnel performing maintenance work	Competency	EOO
J	Platform Management	Operating personnel performing maintenance work	Breach of Collective Agreement	EOO
J	Occidental Petroleum	Operating personnel performing maintenance work	Generally Accepted Practice	EOC
K	Occidental Petroleum	Platform was not designed with blast/fire walls	Engineering Standards	EOC
	(Page 2 of 4)	Continued on next page	Table 6-8 (b)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard or Duty Not Met	Error
L	Occidental Petroleum	Control room was built adjacent to the compressor module	Engineering Standards	EMB
M	Occidental Petroleum	Crew's accommodation was located above the gas compression module	Engineering Standards	EMB
N	Occidental Petroleum	Control room not designed for evacuation scenario	Engineering Standards	EMB
O	Occidental Petroleum	No risk analysis during re-fit of Piper Alpha in 1980	Due Diligence	EOC
P	Occidental Petroleum	Maintenance not reviewed after previous fatality	Due Diligence	EMB
P	Department of Energy	Maintenance not reviewed after previous fatality	Legislated Mandate	EOO
Q	Occidental Petroleum	Maintenance and operating cuts to aging platforms	Engineering Standards	EOC
R	Department of Energy	Production platforms inspected only infrequently	Fiduciary responsibility	EOO
S	Department of Energy	Inspectors reliant on oil companies for transport	Fiduciary Responsibility	EMB
	(Page 3 of 4)	Continued on next page	Table 6-8 (c)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
T	Department of Energy	DOE issued Piper Alpha permit without benefit of risk assessment	Legislated Mandate	EMB
U	Department of Energy	DOE had two statutory mandates potentially in conflict, with insufficient human resources	Fiduciary Responsibility	EOO
V	Department of Energy	DOE inspector of Piper Alpha lacked knowledge and experience of maintenance procedures	Fiduciary Responsibility	EMB
	(Page 4 of 4)	-End-	Table 6-8 (d)	

Table 6-8: Table summarizing the 33 decision errors contributing to the Piper Alpha disaster according to enterprise party

Enterprise Party	EOC	% EOC	EMB	% EMB	EOO	% EOO	Totals	Total %
Platform Workforce	0	0%	2	33%	4	67%	6	18%
Platform Management	3	25%	1	25%	4	50%	8	24%
Occidental Petroleum	3	30%	5	50%	2	20%	10	31%
Platform's Master	0	0%	1	50%	1	50%	2	6%
Department of Energy	0	0%	3	43%	4	57%	7	21%
All Enterprise Parties	6	18%	12	36%	15	46%	33	100%

Table 6-9: Table summarizing the distribution of the Piper Alpha decision errors of the enterprise parties

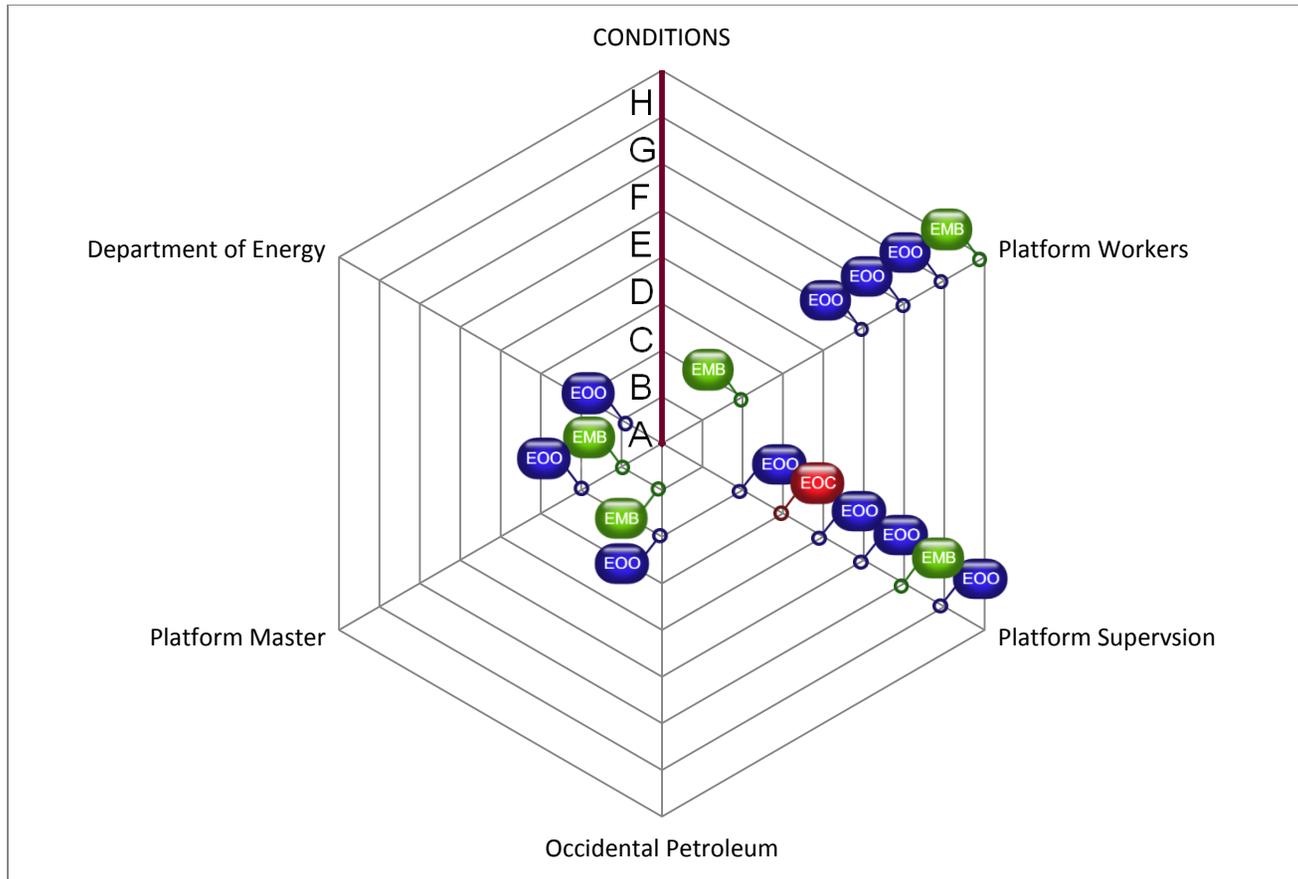


Figure 6.7: Decision error analysis diagram for conditions A through H of the Piper Alpha disaster

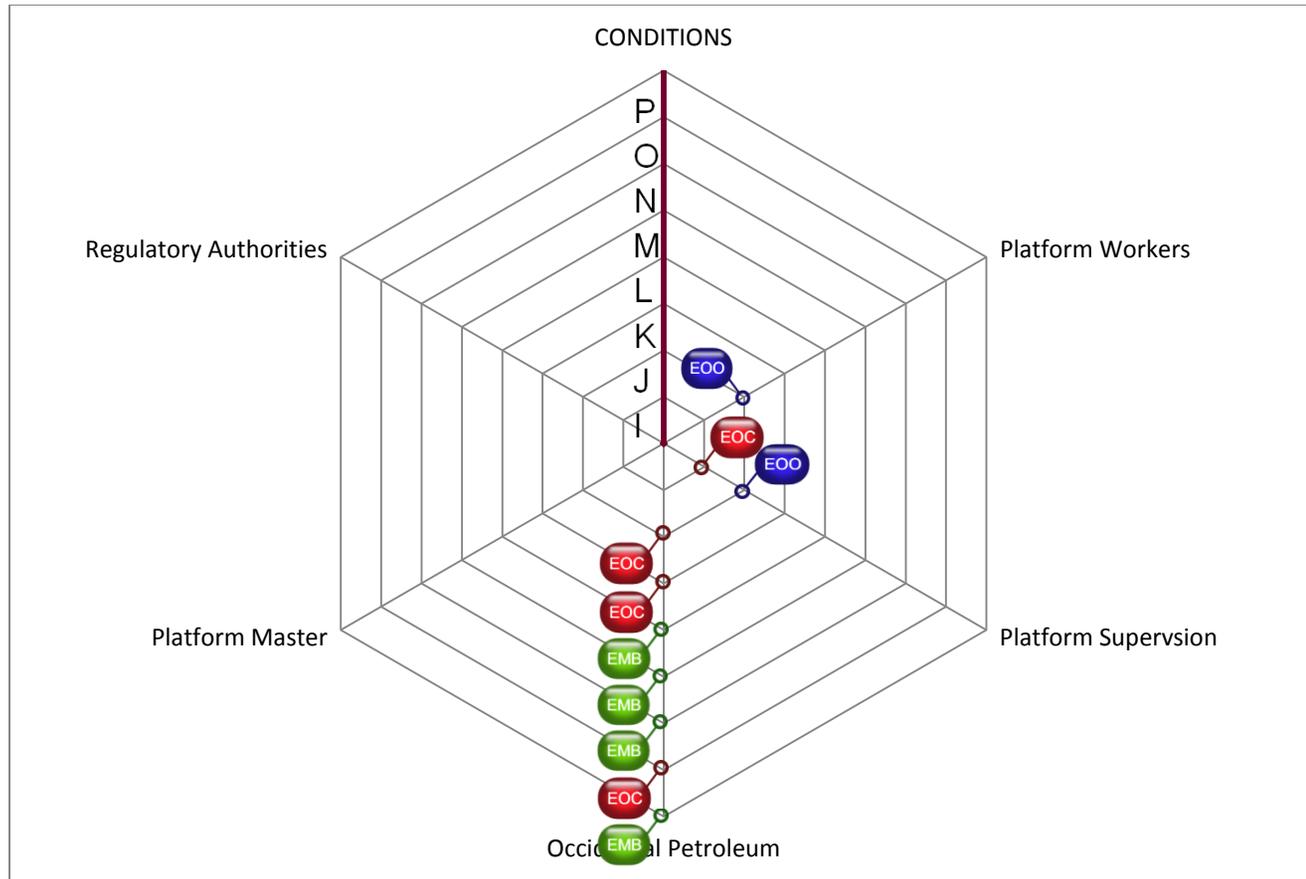


Figure 6.8: Decision error analysis diagram for conditions I through P of the Piper Alpha disaster

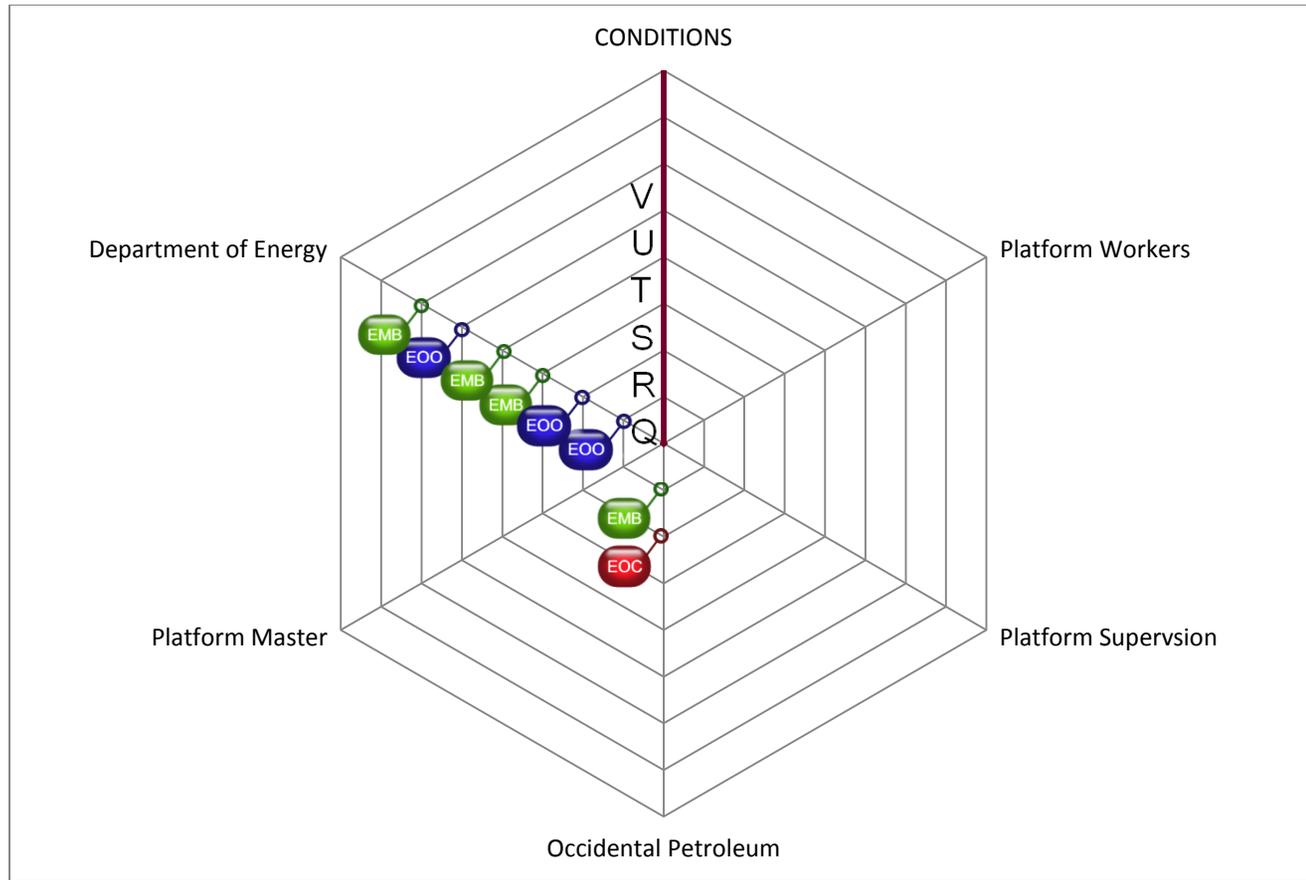


Figure 6.9: Decision error analysis diagram for conditions Q through V of the Piper Alpha disaster

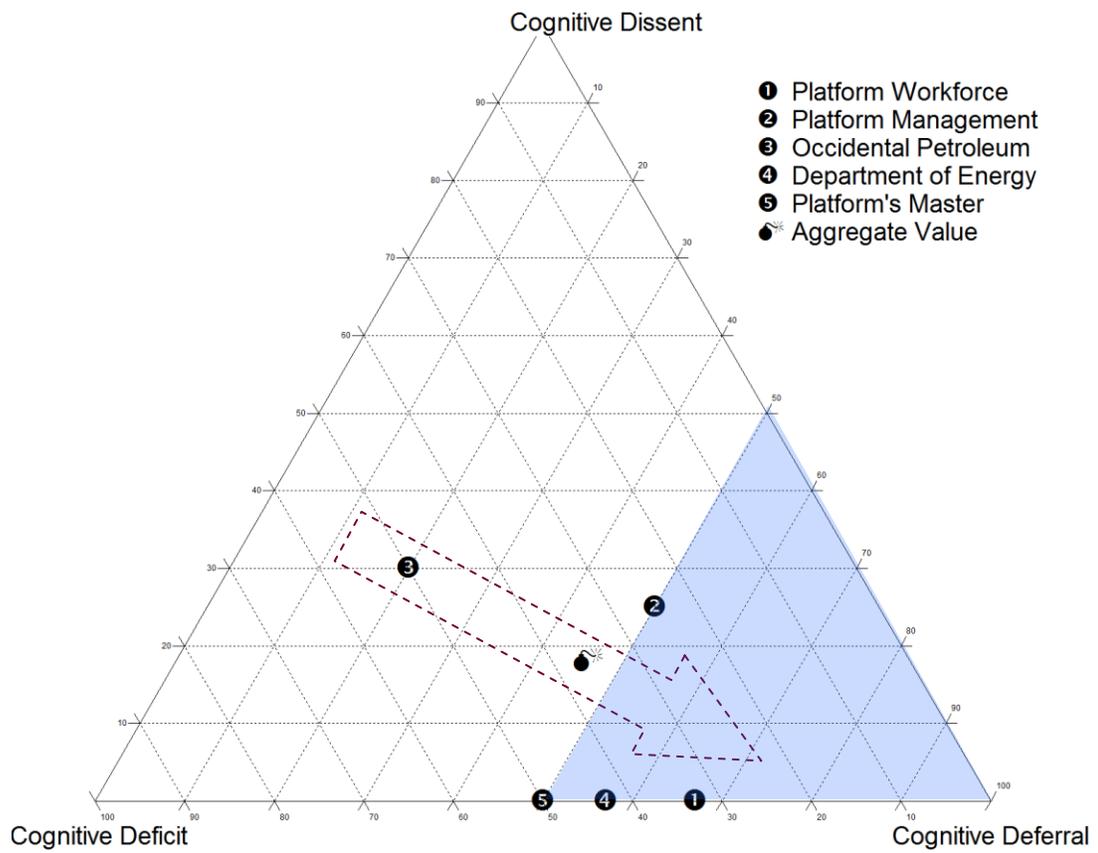


Figure 6.10: Ternary diagram illustrating the cognitive dispositions of the Piper Alpha parties

Criticality Element	Supportive Description	Demerit	Piper Alpha
Existence of Positive Feedback Loop		10	
Limited Access and Egress	Ocean going production platform	10	10
Highly Coupled or Complex Systems	Oil and gas production, separation and processing on a platform too small of a footprint	10	10
Absence of Risk Communication	General apathy towards working in explosive atmospheres	10	10
Enterprise in Cognitive Deficit		10	
Lack of Effective Emergency Response	Muster stations above source of fire – no means of egress from platform.	10	10
Inordinate Amounts of Stored Energy	Immense amounts of oil and gas from four different platforms.	10	10
Enterprise/Operation in Transition	Platform coming off of a period of maintenance	10	10
Absence of Regulatory Oversight	Department of Energy was experiencing a staff shortage and inspected platforms infrequently	10	10
Operations in Cognitive Dissent		10	
Mission Criticality	Total Demerit	10¹⁰	10⁷

Table 6-10: Table summarizing criticality elements associated with the Piper Alpha disaster

6.5 The Ocean Ranger Platform Disaster

ODECO Engineers Ltd designed the Ocean Ranger drilling platform and Mitsubishi Heavy Industries built the platform in Japan, in 1976 (Hickman, 1984). She was designed as a Marine Offshore Drilling Unit (MODU), and was 120 m in length by 46.2 meters in height – the biggest drilling platform of her day. The Ocean Ranger had operated in the Bering Sea, United States coastal waters and the Irish Sea before mobilization to the Grand Banks in November of 1980. ODECO Engineering Ltd operated the Ocean Ranger platform at the time of her sinking. The Ocean Ranger was under contract to the Mobil Corporation for drilling operations in the Hibernia oil and gas field 184 miles east of St. John's Newfoundland.

The Ocean Ranger was a semi-submersible drilling platform supported by two enormous pontoons and eight watertight vertical columns. The columns provided structural support to the two upper decks of the platform, and contained equipment space, electrical and piping conduit, as well as additional buoyancy (Hickman, 1984). Each of the two pontoons contained sixteen tanks that held fuel oil and drilling fluids. Each pontoon also contained a pump room and a propulsion room in the aft ends, with a system of motors, bilge pumps, hydraulic motors and valves controlling propulsion and the trim of the platform. The columns were fitted with stairs, elevators and watertight hatches providing access vertically between the platform proper and the pontoons on which she floated. To keep the platform stable while drilling the pontoons were flooded to lower them 24 meters beneath the sea. The controls for the flooding and trim of these two pontoons were located in one of the inner columns, with the mooring control room situated above it. The ballast control room was situated 33 meters above the keel (bottom of the pontoons), and had one porthole looking out.

Each of the four corner columns of the Ocean Ranger was fitted with chain lockers that contained the mooring lines (wire rope) and chains that moored it in place over the seabed. Thus, when she was in drilling operations, the chain lockers were empty. The lockers were not sealed; in fact, there were two openings necessitated by the mooring lines and chains when in use. The chain lockers were not fitted with drainage points, pumping systems, or any indicators - should flooding take place. They were in fact the first place in which flooding would take place should the platform encounter high seas or poor trim (Hickman, 1984). The derrick was located in the centre of the platform surrounded by two decks providing services and accommodation to the

platform. On the lower deck were electrical generators, air compressors, machine shops and material storage as well as the crew's quarters, offices, a hospital, and radio room. The top deck of the platform was where the majority of materials handling and work took place, with three cranes to assist in moving supplies to and from supply boats. The top deck was 46 metres above the keel of the Ocean Ranger platform.

The Ocean Ranger platform had four lifeboats on davits, ten inflatable life rafts, 170 life preservers and no cold-water immersion suits. The Master of the platform had been aboard for 19 days and was not competent in some aspects of his duties (Burke, 1998). The ballast control operator had two years experience on drilling platforms but had received no qualifications or training in ballast operations. The support ship, the *Seaforth Highlander* was too far away to assist and was not equipped to provide rescue. The helicopters were two hours away in fair weather conditions, but grounded because of weather. The crews lacked emergency drills in evacuation procedures during heavy seas or when the Ocean Ranger was in poor trim.

6.5.1 Parties within the Enterprise

Ocean Ranger Enterprise Parties	Roles and Responsibilities
Mobil Corporation	Hibernia exploration drilling lease holder
Platform Management (ODECO)	Owners and operators of the Ocean Ranger
Platform Workforce	Operation of the drilling rig and platform
Master/Captain	All maritime aspects of the Ocean Ranger
The <i>Seaforth Highlander</i>	Contract supply ship to the Ocean Ranger
Regulatory Authorities	US and Canadian Regulatory Authorities

Table 6-11: Table summarizing the roles and responsibilities of the Ocean Ranger parties

6.5.2 Chronology of Events

On the day before the disaster (February 14, 1982), a low-pressure system moved into the Hibernia area from the eastern seaboard of the United States. The forecast included gale force winds of 90 knots and wave heights of eleven metres (Patterson, 2002). Two other drilling platforms located in the area reported a set of

'rogue waves' that were unusually large heading for the Ocean Ranger. At approximately 20:00 hours, one such wave struck the Ocean Ranger on the starboard side, breaking the porthole to the ballast control room and shorting out the ballast control panel. The control panel was electrical over pneumatic and provided the means to open and close valves and to operate pumps that controlled the trim of the platform's two semi-submersible pontoons. The weather observer aboard the Ocean Ranger gave his weather report at 23:30 hours, with only routine weather observations (Hickman, 1984).

At approximately 00:30 hours on February the 15th, power was restored to the control panel. This resulted in the unexpected opening of several of the ballast control valves. The forward tanks of the port pontoon took on seawater ballast that caused a forward list to port. A series of attempts were made to correct the trim, with no success. At 01:00, the drilling foreman of the Ocean Ranger contacted his superior by ship to shore radio with no mention of a MAYDAY. At 01:05, the Ocean Ranger contacted the *Seaforth Highlander* and requested that she respond to the Ocean Ranger and standby. The *Seaforth Highlander* was 13 km away from the Ocean Ranger at the time. At 01:09 hours on February 15th, the Ocean Ranger issued a distress call by telex via the maritime satellite system (MARISAT). The telex did not mention MAYDAY but was considered one and treated as such. A MAYDAY did go out shortly after on the maritime emergency frequency. It did not reach shore for reasons of inadequate power. A neighbouring drill platform did hear the distress call and attempted to relay it to the Canadian Coast Guard, but was unable to do so until 01:45 hours.

Evacuations commenced on the *Ocean Ranger* at approximately 01:30 hours, with at least one of the lifeboats making it into water with persons on board. Conceivably, only two of the four of the lifeboats were capable of being lowered from the davits because of the extreme list to the port side. The one lifeboat capsized and sank in heavy seas as the *Seaforth Highlander* approached and tried to effect rescue. The last sighting of the Ocean Ranger was at 02:55 hours by the vessel *Boltentor*, with no signs of life on board. At 09:35 hours on February 15th, 1982 the first search and rescue, (SAR) aircraft arrived on scene (Hickman, 1984). There were no survivors. All 84 persons onboard the Ocean Ranger were lost at sea.

6.5.3 Consolidated Findings

The following is a consolidated list of findings believed to have contributed to the Ocean Ranger maritime disaster. The source of information is the report of the Royal Commission Report (Hickman, 1984) and the Maritime Casualty Report (US Coast Guard, 1983). They are largely in concurrence as to the causes and contributing factors. In approximate order of chronology, the findings are:

- 1) The crew abandoned the platform without the benefit of immersion survival suits. A published report of inquiry into a maritime disaster before the *Ocean Ranger* disaster recommended these suits.
- 2) The crew could not safely launch the lifeboats when the platform was out of trim, or in heavy seas
- 3) There were not a sufficient number of trained qualified marine personnel to man the life boats.
- 4) The number of lifeboats was less than required by the US Coast Guard directive to the ODECO.
- 5) The supervisors on the platform did not issue a MAYDAY distress call as per procedure or appropriate to their circumstance.
- 6) The Master of the platform did not evacuate the platform when it was timely to do so – when conditions were favourable for launching the lifeboats.
- 7) The supply ship *Seaforth Highlander* did not have equipment on board appropriate for a rescue on the high seas.
- 8) The *Seaforth Highlander* stood off too far from the Ocean Ranger in the absence of instructions of what to do in an emergency.
- 9) Platform management (ODECO), or Mobil Oil had not considered or arranged for rescue capability for the Ocean Ranger.
- 10) The Master of the platform did not request assistance from the *Seaforth Highlander* until it was too late for them to provide assistance.
- 11) The crew of the *Seaforth Highlander* was not trained in emergency operations.
- 12) ODECO did not inform the Master of the supply ship *Seaforth Highlander* of his duties to the Ocean Ranger.
- 13) The drilling supervisor, the tool push and the vessel's Master were all without situational awareness of the *event* they were in until just moments before declaring a crisis and did not take appropriate action until too late.

- 14) None of the vessel's company, including the Master, knew how to override the ballast control console in an emergency.
- 15) None of the vessel's company, including the Master, knew how to operate the ballast control console.
- 16) The Ballast Control Operator was not trained, qualified or competent for the job.
- 17) The Ocean Ranger did not have a valid certificate of inspection at the time of sinking as per the US Coast Guard requirements.
- 18) Mobil failed to ensure that all persons aboard the Ocean Ranger were trained in all aspects of their operational and safety duties (COGLA Regulation).

6.5.4 Decision Error Analysis of the Ocean Ranger Disaster

Analysis of the official reports of inquiry reveals 38 decision errors contributing to the Ocean Ranger drilling platform disaster (Table 6-14). The platform management reported the largest number of decision errors (34%), followed by Mobil Oil (21%), and then the platform's Master (18%). The standards and duties of care not met concerning the Ocean Ranger were not procedural; rather, project design and engineering related. There were many findings (66) that found issue with the engineering design of the Ocean Ranger and these have been excluded from this analysis by reason of not being decision or standard of care in nature. They were simply inadequacies in the design of the Ocean Ranger that occurred long before being deployed to the north Atlantic.

More immediate and relevant were the project management and operational governance errors that occurred subsequent to the Ocean Ranger being mobilized to the Grand Banks. These standards were frequently duties of care (Table 6-12) and emphasized the lack of understanding that parties to the Ocean Ranger offshore drilling enterprise had regarding their roles and responsibilities. It is noted that Mobil Oil (the Operator) had a lesser standard of care (duty of care) than did ODECO (the rig owner and platform management), as the Ocean Ranger was contracted to Mobil Oil under the care and custody of ODECO. Thus, the higher standard of care of due diligence was imposed upon ODECO, as the employer of the majority of the platform personnel.

Ocean Ranger Enterprise Parties	Standard or Duty of Care Not Met
Regulatory Authorities	Legislated mandate
Mobil Oil	Duty of care
Platform Management	Due diligence and duty of care
Platform Master	Duty of care to vessel and company
Platform Workforce	Standard of training, and competency
Seaforth Highlander	General Maritime Standards

Table 6-12: Table summarizing the standards of care not met by Ocean Ranger enterprise parties

6.5.4.1 Mobil Oil

Mobil Oil contributed to eight of the 38 decision errors, seven of which were errors of mistaken belief and one an error of omission (Table 6-14). Mobil Oil was the exploration company and held the tenure for the mineral reserves explored for by the Ocean Ranger, and the principal contractor of the project. As such, Mobil Oil enjoyed an ‘arms length’ relationship with the day-to-day operations of the Ocean Ranger, owned and operated by ODECO (the platform manager). Many of Mobil Oil’s decision errors were based on the incorrect premise that they were obviated from any responsibilities or liabilities to the Ocean Ranger or her company. As the principal contractor and architect of the drilling program and project management however, Mobil Oil had a duty of care to the parties to ensure compliance with legislation and standards, to the extent that they had knowledge of them. In addition, Mobil Oil was obligated by license to operate within the limits imposed by the permit conditions – which included the safe and efficient operation of the offshore platform. The radar diagrams (Figures 6.11 and 6.12) illustrate that Mobil Oil shared six decision errors with ODECO, and may have shared a common perception of risk with ODECO.

6.5.4.2 Platform Management (ODECO)

The platform management contributed to thirteen (34%) of the 38 decision errors, six of which were errors of commission, five errors of mistaken belief and two errors of omission (Table 6-14). The platform management were responsible for the day-to-day operation of the drilling platform and obligations imposed on them as an employer to most of the platform’s complement. The errors of commission occurred early on in the

project when they did not take reasonable measures to prepare the platform workers for maritime emergencies in general, and cold-water evacuation in particular. Additionally, they were operating the Ocean Ranger without a current Certificate of Inspection. The errors of mistaken belief were concerning the operation of the ballast control panel and capacity of the *Seaforth Highlander* to affect a maritime rescue. The errors of omission understandably were made during the moments of the crisis and it is surprising there were so few, suggestive of the rapidity of the capsizing event. Decision errors shared with the platform workforce are the standards of training and competency concerning the operation of the ballast controls (Figures 6.11 and 6.12). The ballast control operator was not competent to operate; had no formal training and insufficient experience at the ballast controls. The platform management and the ballast control operator both knew this to be the case.

6.5.4.3 Platform Master

The Master of the Ocean Ranger platform contributed seven decision errors, one of which were errors of commission, three errors of mistaken belief and three errors of omission (Table 6-14). As the platform's Master, the captain had an overarching responsibility for the safety of the vessels crew, in particular their safe and efficient evacuation in the event of an emergency. That the Master of the platform went to sea without a current Certificate of Inspection or assurance that the vessel's company were competent to evacuate the platform was gross misfeasance and errors of commission. The errors of omission occurred when he deferred abandoning the platform or summoning a MAYDAY. The Master of the Ocean Ranger had in common one very significant decision error with Mobil Oil and the platform management: namely, neither he nor any other person aboard the Ocean Ranger knew how to operate the ballast control panels. As the panel controlled the platform's stability, a characteristic that fell under the Master's responsibility – this was a major oversight and lack of knowledge.

6.5.4.4 Platform Workforce

The workforce of the platform contributed five decision errors, four (80%) being errors of mistaken belief and one (20%) an error of commission (Table 6-14). The workforce were removed from matters of engineering design or project management and hence their low contribution to decision errors. The errors of mistaken belief were related

to the absence of enlightened self-interest. The workforce would never have gone to sea had they known the requisite standards of training for a drilling platform in the north Atlantic, and in that they had in common a deficit of knowledge. The ballast control-room operator and the radio operator were both under qualified and inexperienced in their safety-sensitive positions. No worker should assume a safety-sensitive job without basic knowledge, and owe a duty of care to other workers to ensure they are competent.

6.5.4.5 Regulatory Authorities

The two governing regulatory agencies, the US Coast Guard and the Canadian Oil and Gas Lands Administration (COGLA), contributed two decision errors, both of which were errors of mistaken belief. There was a lack of clarity of roles and responsibilities respecting the American and Canadian maritime authorities, and each made assumptions about the other that were in error. In so doing, they failed to meet the mandate of their respective legislation and demonstrated inadequate oversight over the Ocean Ranger.

6.5.5 Interpretation

There were two unsafe conditions (M and O) that, had the appropriate standard of care been demonstrated by the various workplace parties, could have prevented the Ocean Ranger from capsizing (Figure 6.12). Had there been someone on board who knew how to operate the ballast control panel, or alternatively how to manually by-pass it, the Ocean Ranger would conceivably not have become unstable. Failing this, had the Ocean Ranger's company been trained and equipped with maritime cold water evacuation procedures, many, if not all, may have survived the crisis.

6.5.6 Cognitive Profiling of the Ocean Ranger Disaster

6.5.6.1 Profile Distribution

The cognitive profile (ternary diagram) of the Ocean Ranger disaster reveals that the enterprise as a whole was in the region of cognitive deficit (Figure 6.13). The distribution is poorly clustered indicating the parties exhibited organizational dissonance as regards to risk and its perception and were in incipient cognitive deficit.

6.5.6.2 Cognitive Dispositions

The platform master and the platform management acquitted themselves poorly during the crisis, insofar as they deferred making the decision to abandon ship or call for assistance until it was too late – for reasons unknown, but no doubt attributed to deteriorating human and environmental factors. They were disposed to cognitive deficit and cognitive deferral - with the imminent capsizing of the Ocean Ranger bringing out the latter. The other workplace parties were disposed to cognitive deficit, Mobil Oil being particularly prone. Whereas the magnitude of the storm that fateful day could not have been foreseen, the complexity of the Ocean Ranger drilling platform and the unforgiving nature of the north Atlantic was known; and to this extent demanded a far greater degree of prudence and competence of the parties to the enterprise.

6.5.6.3 Mission Criticality

The mission criticality index of the Ocean Ranger drilling platform enterprise is 10^7 out of a possible 10^{10} (Table 6-15). We would expect an index of 10^3 from such an enterprise because of the limited access and egress, high complexity and coupling and the nature of platform stability characteristics comprising a positive feedback loop. Elements present at Ocean Ranger that exacerbated these conditions were:

- i. the absence of risk communication respecting cold water emersion,
- ii. the fact that the enterprise was largely in cognitive deficit,
- iii. the lack of emergency response plans and preparedness; and,
- iv. the absence of effective regulatory oversight.

Heuristically, the mission criticality analysis suggests that preventative strategies at Ocean Ranger be based upon an enterprise in which the platform's company be knowledgeable regarding ballast control and maintaining vessel stability; that all personnel are trained and equipped for cold water maritime evacuation; and, that greater standards of professional conduct and competence be required by those in safety sensitive positions.

6.5.7 Significance and Outcomes

As a direct consequence of the Ocean Ranger maritime disaster, operations aboard offshore platforms in Canadian waters would change dramatically. During the

late '80s, the Canadian provincial and federal authorities assembled boards to oversee and regulate off shore platforms. All offshore workers were required to achieve a level of training and qualification as documented by a card to be on their person. Engineering of safety and survival systems have improved greatly during the decades since the disaster. Weather system networks have improved with the installation of weather buoys strategically located throughout Atlantic Canada waters for early warning to mariners. Funding has been provided for extensive research in cold-water simulators (The Centre for Simulation) to test persons, equipment and materials in the harsh Atlantic maritime conditions. The Canada Shipping Act New has enacted new regulations and training standards (Patterson, 2002).

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
A	Platform Management	Platform workers not provided with emersion suits	Due Diligence	EOC
A	Mobil Oil	Platform workers not provided with emersion suits	Duty of Care	EMB
B	Platform Workforce	The crew could not launch lifeboats in high seas	Standard of Training	EMB
B	Platform Management	The crew could not launch lifeboats in high seas	Duty of Care	EMB
C	Platform Management	Insufficient number of trained personnel to man lifeboats	Due Diligence	EOC
C	Mobil Oil	Insufficient number of trained personnel to man lifeboats	Duty of Care	EMB
D	Platform Management	Insufficient number of lifeboats as per Directive	Due Diligence	EOC
D	Mobil Oil	Insufficient number of lifeboats as per Directive	Duty of Care	EOC
E	Platform Workforce	Radio operator used telex to send out distress without explicitly declaring a MAYDAY	Emergency Radio Protocol	EMB
F	Platform's Master	Platform not evacuated in a timely and efficient manner	Duty to Vessel and Company	EOO
	Page 1 of 4	To be continued on next page	Table 6-13 (a)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
G	Seaforth Highlander	Supply ship did not have rescue equipment	General Maritime Standards	EMB
G	Platform Management	Supply ship did not have rescue equipment	Due Diligence	EMB
G	Mobil Oil	Supply ship did not have rescue equipment	Duty of Care	EMB
H	Platform's Master	Supply ship not summoned until too late to do so	Duty to Vessel and Company	EOO
H	Platform Management	Inadequate preparation for maritime emergency rescue	Due Diligence	EMB
H	Mobil Oil	Inadequate preparation for maritime emergency rescue	Duty of Care	EMB
I	Seaforth Highlander	Supply ship crew not trained in emergency response	General Maritime Standards	EMB
I	Platform Management	Supply ship crew not trained in emergency response	Due Diligence	EMB
I	Mobil Oil	Supply ship crew not trained in emergency response	Duty of Care	EMB
J	Seaforth Highlander	Master of Seaforth Highlander was indecisive in his response to the <i>Ocean Ranger</i> event	Duty to Vessel and Company	EOO
	Page 2 of 4	To be continued on next page	Table 6-13 (b)	

Letter	Enterprise Party	Condition Contributing to the <i>Event Scenario</i>	Standard of Care	Error
J	Platform Management	Master of Seaforth Highlander was not informed of duties in the event of maritime emergency	Due Diligence	EMB
K	Platform Workforce	Lack of situational awareness to affect evacuation	Standard of Training	EMB
K	Platform Management	Lacked situational awareness to affect evacuation	Duty of Care	EOO
K	Platform's Master	Lacked situational awareness to affect evacuation	Duty to Vessel and Company	EOO
L	Platform Workforce	Operator not competent to operate ballast control panel	Duty of care to other workers	EOC
L	Platform Management	Operator not competent to operate ballast control panel	Due Diligence	EOC
L	Platform's Master	Operator not competent to operate ballast control panel	Duty to Vessel and Company	EMB
M	Platform Management	No one on board the Ocean Ranger knew how to operate or override the automated ballast controls	Due Diligence	EMB
M	Platform's Master	No one on board the Ocean Ranger knew how to operate or override the automated ballast controls	Duty to Vessel and Company	EMB
	Page 3 of 4	To be continued on next page	Table 6-13 (c)	

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard or Duty Not Met	Error
M	Mobile Oil	No one on board the Ocean Ranger knew how to operate or override the automated ballast controls	Duty of Care	EMB
N	Platform Management	<i>Ocean Ranger</i> did not have Certificate of Inspection	Regulatory Compliance	EOC
N	Platform's Master	<i>Ocean Ranger</i> did not have Certificate of Inspection	Duty to Vessel and Company	EOC
N	US Coast Guard	<i>Ocean Ranger</i> did not have Certificate of Inspection	Flag-state Mandate	EMB
O	Platform Workforce	Platform's company not trained in maritime emergency	Standard of Training	EMB
O	Platform Management	Platform's company not trained in maritime emergency	Due Diligence	EOC
O	Platform's Master	Platform's company not trained in maritime emergency	Duty to Vessel and Company	EOC
O	Mobil Oil	Platform's company not trained in maritime emergency	Duty of Care	EOC
O	COGLA	Platform's company not trained in maritime emergency	Legislated Mandate	EMB
	Page 4 of 4	-End-	Table 6-13 (d)	

Table 6-13: Table summarizing the 38 decision errors contributing to the Ocean Ranger disaster according to enterprise party

Enterprise Party	EOC	% EOC	EMB	% EMB	EOO	% EOO	Totals	Total %
Platform Workforce	1	20%	4	80%	0	0%	5	13%
Platform Management	6	46%	5	38%	2	16%	13	34%
Mobil Oil	1	12%	7	88%	0	0%	8	21%
Platform's Master	2	29%	2	29%	3	42%	7	18%
<i>Seaforth Highlander</i>	0	0%	2	67%	1	33%	3	8%
Regulatory Authorities	0	0%	2	100%	0	0%	2	6%
All Enterprise Parties	10	26%	22	58%	6	16%	38	100%

Table 6-14: Table summarizing the distribution of the Ocean Ranger decision errors by the enterprise parties

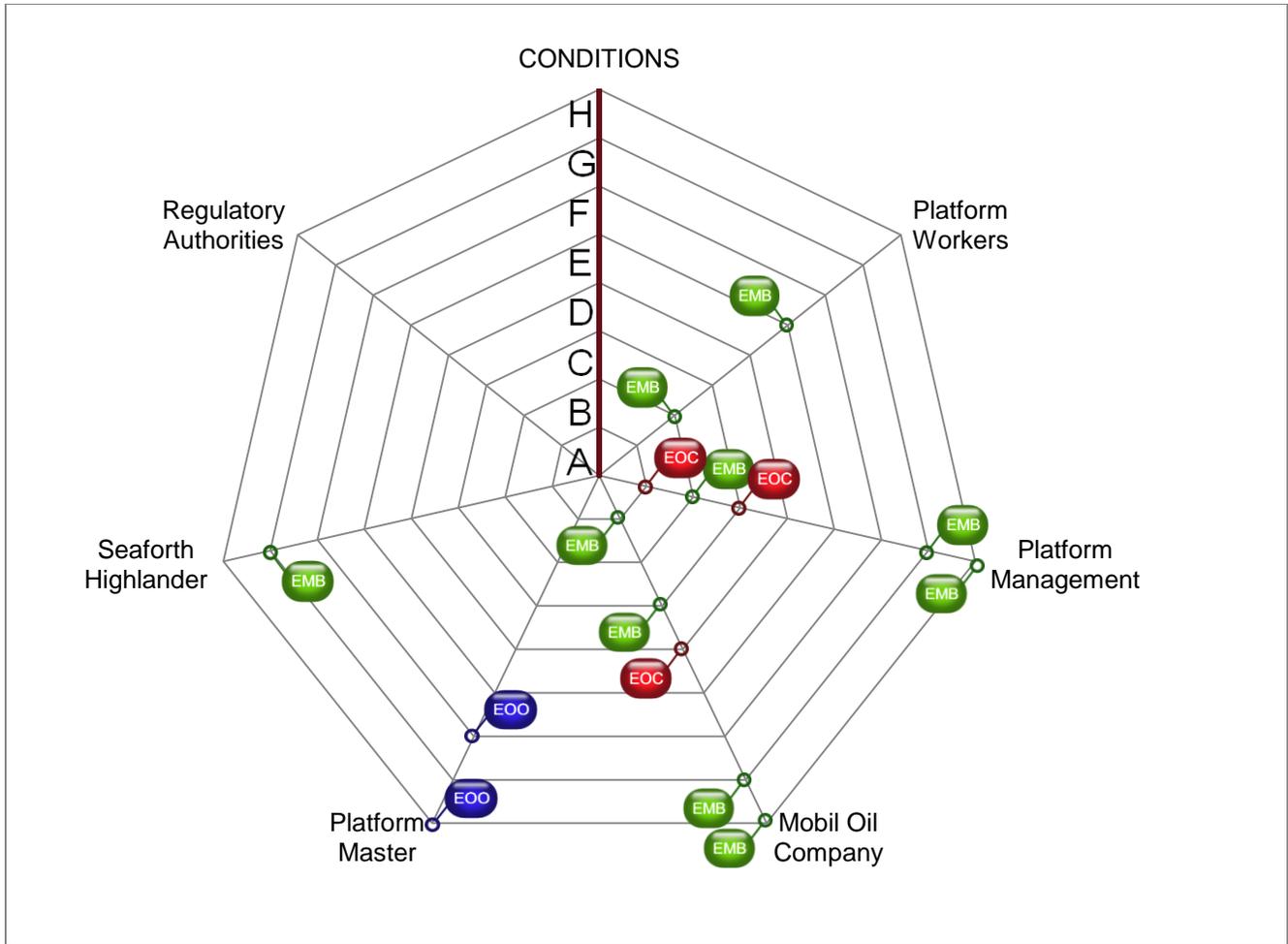


Figure 6.11: Decision error analysis diagram for conditions A through H of the Ocean Ranger disaster

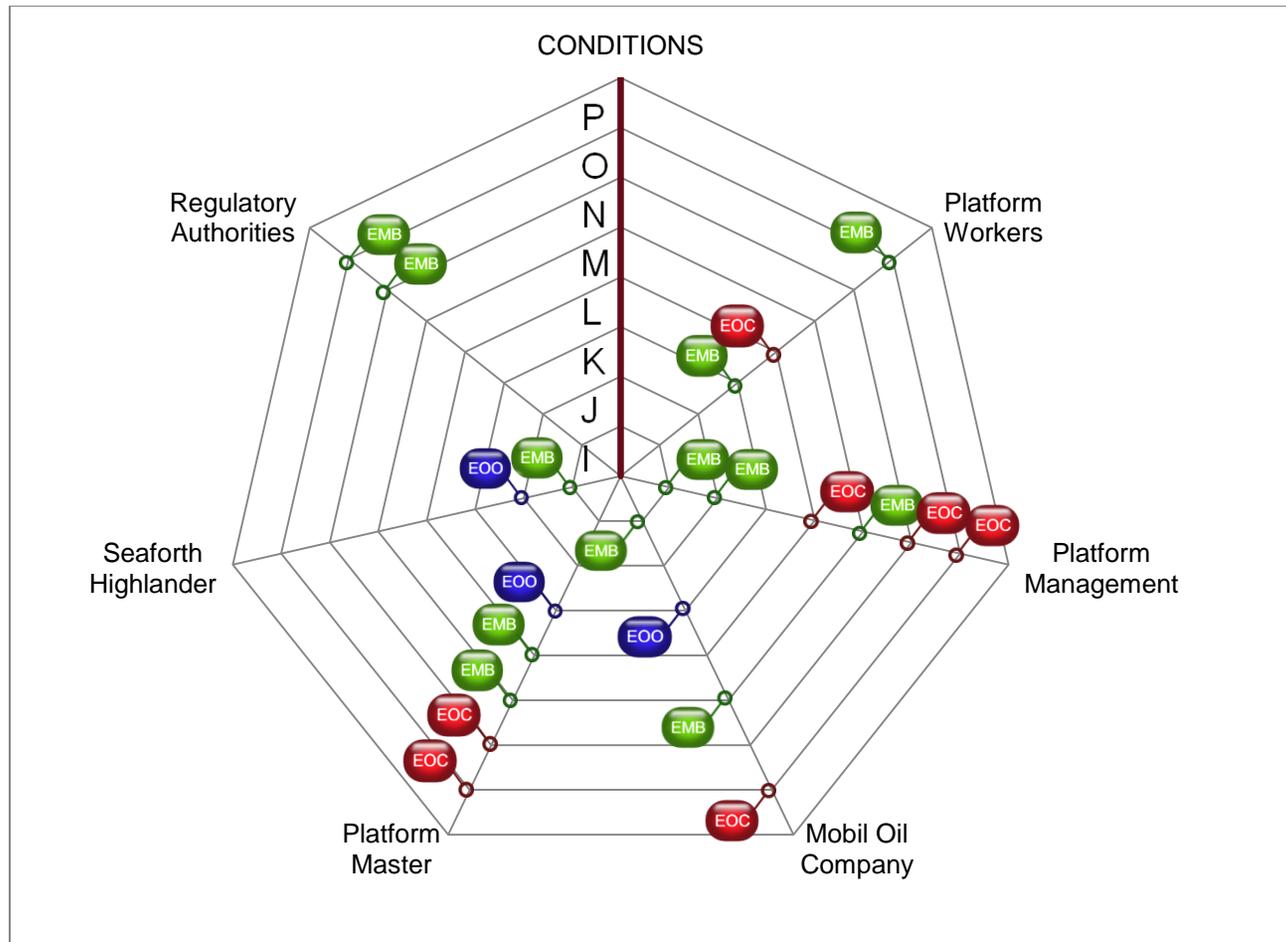


Figure 6.12: Decision error analysis diagram for conditions I through P of the Ocean Ranger disaster

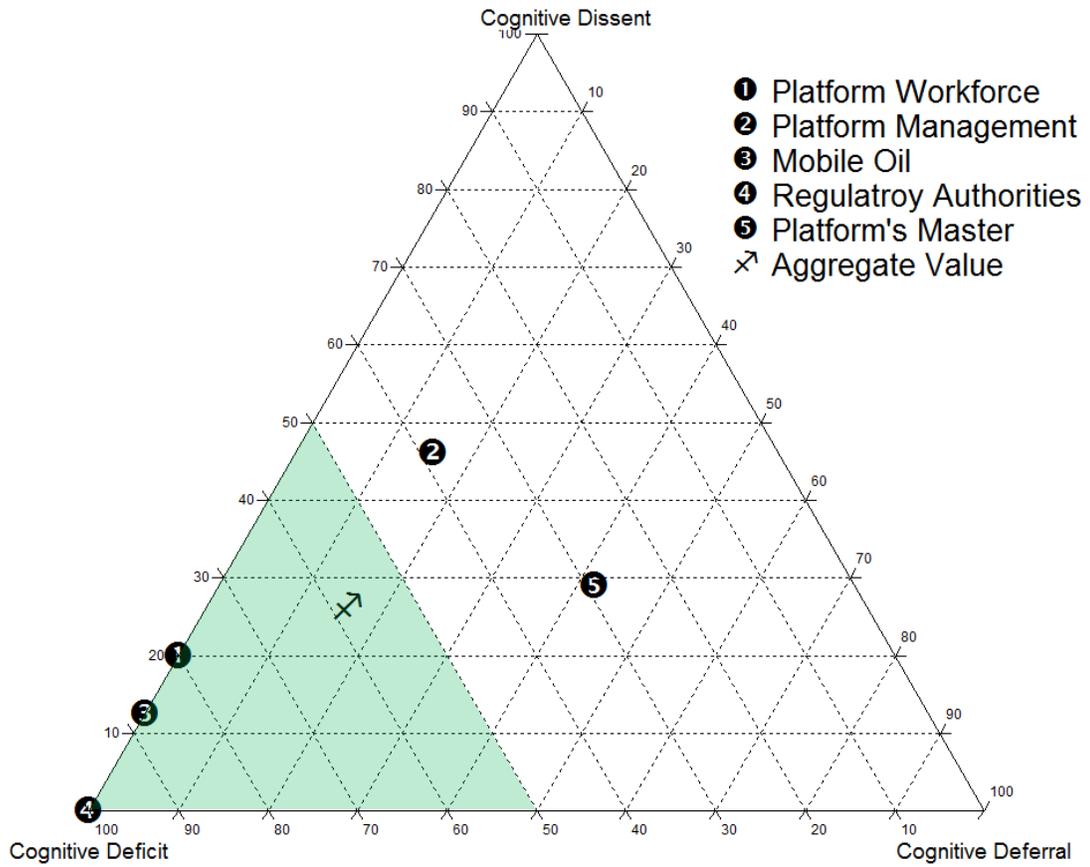


Figure 6.13: Ternary diagram illustrating the cognitive dispositions of the Ocean Ranger parties

Criticality Element	Supportive Description	Demerit	Ocean Ranger
Existence of a Positive Feedback Loop	The more water the platform took on the more it listed, the more it took on water into the chain lockers	10	10
Limited Access and Egress	Ocean going drilling platform	10	10
Highly Coupled or Complex Systems	Over complex ballast compensation systems with high coupling of controls	10	10
Absence of Risk Communication	All concerned did not have knowledge of difficulty of cold water emergency evacuation	10	10
Enterprise in Cognitive Deficit	Strongly led by Mobil Oil	10	10
Lack of Effective Emergency Response	No emergency preparedness. All safety measures failed including the supply vessel.	10	10
Inordinate Amounts of Stored Energy	Possibly in the form of buoyancy or storm energy.	10	
Enterprise/Operation in Transition		10	
Absence of Regulatory Oversight	Two jurisdictions without clear lines of role and authority	10	10
Operations in Cognitive Dissent		10	
Mission Criticality	Total Demerit	10¹⁰	10⁷

Table 6-15: Table summarizing criticality elements associated with the Ocean Ranger disaster

6.6 Sunshine Mine Disaster

6.6.1 Nature of the Enterprise

The Sunshine Mine was, and remains, the most prolific producer of silver within the United States. Producing 12,963,460 tons of ore at an average grade of 28.47 ounces per ton, the mine yielded 350 million ounces of silver since first coming into production in 1884 (Olsen, 2005). The mine was (is) located near (12 km) the town of Kellogg, Idaho, and was the chief employer within Shoshone County for many decades. The mine employed 522 persons, 429 who worked underground. The mine consisted of a vast network of raises and drifts, as deep as 6000 ft (1818 m). The mine was producing ore from the 4000 through 5800 levels (Figure 6.14). The workers gained access by walking in the Jewel Portal (also source of clean air intake) and then descending the Jewel Shaft where they were lowered to the 3100 and 3700 levels. Then, transported by underground rail conveyance to the number 10 shaft, they again descended by shaft conveyance (cage) to the production levels. The underground miners worked three 8-hour shifts, five days a week. Ore was 'skipped' up the same shafts in skips and moved laterally throughout the mine by locomotive. Clean air was downcast through the Jewel shaft, number 5 shaft, number 10 shaft, and the number 12 borehole. Exhaust air was up-cast through the mine workings via the escape-ways to the 3400 level where it was 'boosted' by two 150 HP fans; then up-cast through the number 3 shaft and the inclined borehole on 1900 level where it was again 'boosted' via fan before being exhausted to surface via the Sunshine Tunnel (Figure 6.14).

6.6.2 Chronology of Events

On the day of the disaster (May 02, 1972), 173 men started working underground at 07:00 hours (Olsen, 2005). Three miners were enlarging the 3400 ventilation drift to decrease the resistance to return air (exhaust) flow. The work required drilling and blasting of rock along the back and ribs, and the cutting of existing ground support rock bolts with the use of an acetylene torch. The work took place downstream of the two 150 horsepower booster fans on 3400 level (Figure 6.14). The welder completed his work and returned to the 3700 shaft station where he tidied up for lunch. The two miners left their work to have lunch at an unknown time and location.

At approximately 11:35 hours, two tradesmen stepped out of their shop at the Jewel shaft station and smelled smoke (Olsen, 2005). They immediately communicated their concerns to two supervisors, who together with the tradesman proceeded east on 3700 in the direction that they perceived the smoke was coming from. When they arrived at the number 10 shaft, they discovered the smoke was coming down the raise (shaft). The four men met the locomotive operator at the raise and when they could not see the source of the fire, the locomotive operator was directed to close the fire door (a stopping) and to return to Jewel Shaft station, on 3100 level (Figure 6.14). Two other foreman telephoned a machine shop on 3100 located west of the number 10 shaft, and requested that the tradesmen working their report if they were experiencing a fire. When the answer was negative, he was asked to proceed east towards the number 10 shaft station and report any smoke. He reported that smoke was too dense to enter, and was instructed to return to the Jewel Shaft station, which he did. Mine management decided to evacuate the mine and release stench for this purpose. On the way back to the Jewel shaft station however, all the above-mentioned miners and supervisors experienced extreme fatigue and weakness and summoned assistance. Stench was released into the mine at 12:05 hours, and breathing apparatus was sent to the number 10 shaft station at 3100 where underground workers were expected to be evacuated to - from the 3700 level.

Shortly after the release of stench, the number 10 shaft 'chippy' hoist operator on 3700 level had to abandon the hoist room. At 12:13 hours, the first load of men were hoisted from 3700 level to the 3100 level shaft station, consisting of 12 miners. Five more loads of men would follow until 13:02 hours. Underground workers were directed to make their way to the Jewel Shaft station (1.6 km) by foot. There were self-rescuers stored at the shaft stations at the Sunshine Mine, which although were not required by regulation, had been in the mine for as many as nine years. Many of the outbound underground workers attempted to use them, but in many cases, they were found either inoperable, or thought not to be working when the heat from the catalyst burned their mouths. Many discarded them. Many died of carbon monoxide poisoning long before reaching the Jewel shaft station; some made it within metres before succumbing to smoke and carbon monoxide.

At about this time the first four underground mine-rescuers (apparatus men) entered the mine to make their way to the number 10 shaft station to provide what

assistance they could. In their attempts to provide assistance, one of the mine rescuers removed his breathing apparatus to provide air to a miner in distress – and the mine rescuer collapsed (ostensibly from carbon monoxide poisoning). The remaining mine rescuers assisted their fallen colleague and two stricken miners to the Jewel Shaft station via locomotive, where they escaped. Simultaneously, three barefaced miners at the 3700 level shaft station proceeded towards the number 10 shaft via locomotive – slowly as there were fallen victims on the track, until they too fell victim of the carbon monoxide and had to make their egress by way of the number 5 shaft. There were two more rescue attempts, in which one or more of the would-be rescuers succumbed to carbon monoxide poisoning (Olsen, 2005).

At 15:06, the decision was to cease the booster fans on 3400 level in an effort to stop re-circulating the smoke. The tactic appeared to work and the workings were clear as far as the number 10 shaft station at 3100 level. At about 16:00 hours the number 10 shaft was assessed, but it was apparent that due to heat and smoke within the shaft and lower levels, that any further rescue attempts would have to be abandoned until the mine emptied of carbon monoxide and heat. All concerned were of the mistaken belief that there was nothing in the mine to burn, and yet it would be hours to days before they could re-enter. It was not until 03:40 am on May 08th that rescue operations resumed – and then only with special two-man rescue cylinders designed for this purpose. On May 9th, two men were rescued at the 4800 of number 12 borehole, where they had retreated with the hopes that good air would be down-casting from the Jewel Shaft. They were the last two to found alive. All persons were accounted for by May 11th. Of the 173 workers that tragic day, 82 escaped the mine, and 91 were found deceased. The count was not certain, however, owing to the ineffective means of tracking of underground workers by counting headlamps reported missing from the mine dry (Olsen, 2005).

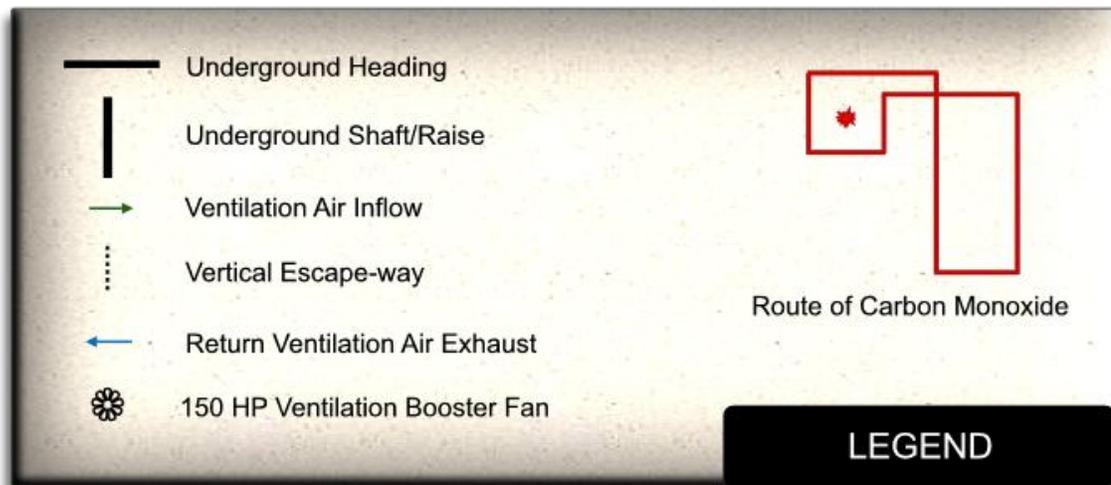
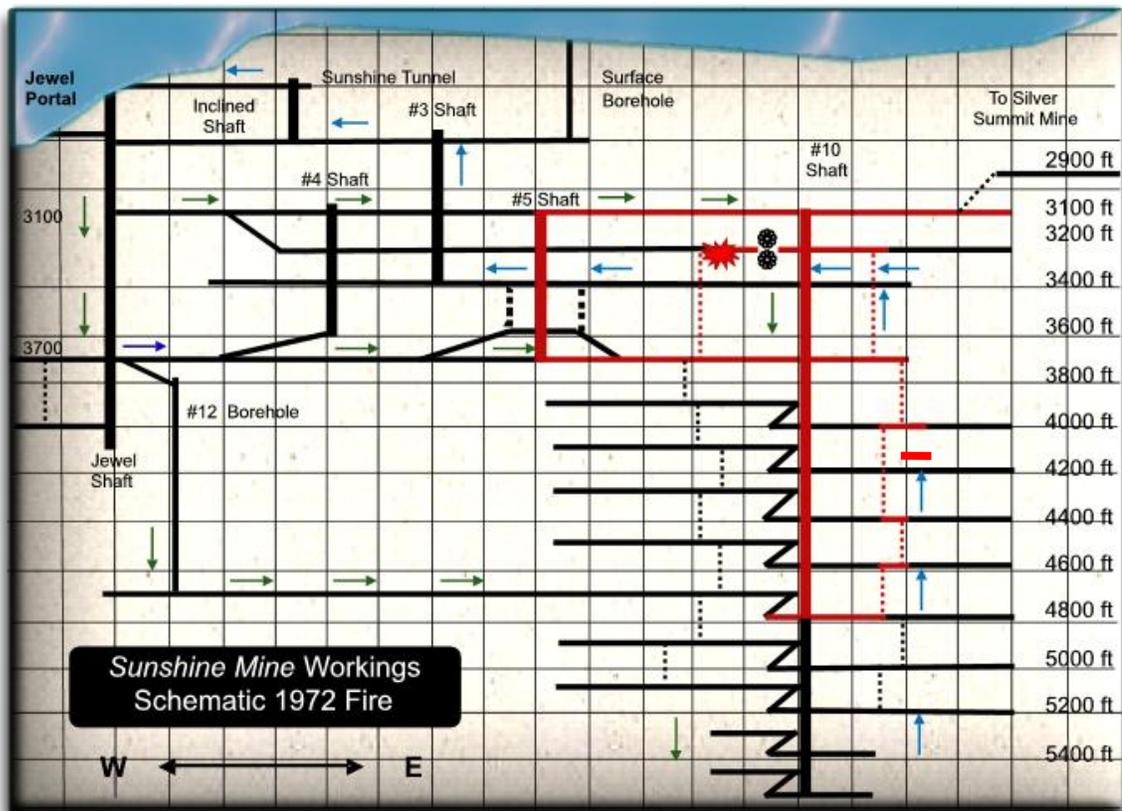


Figure 6.14: Sectional view of the Sunshine Mine workings and ventilation circuit.

6.6.3 Parties within the Enterprise

Sunshine Mine Enterprise Party	Roles and Responsibilities
Sunshine Mine Company	Corporate owners and mine operators
Mine Management	Onsite management of Sunshine Mine
Mine Supervision	Supervising hourly workers at the mine
Mine Workforce	Miners, technicians and hourly personnel
United States Bureau of Mines	Federal Regulatory Authority

Table 6-16: Table summarizing the roles and responsibilities of the Sunshine Mine parties

6.6.4 Consolidated Findings

The following are the consolidated findings of conditions contributing to the Sunshine mine disaster. The investigative source is the memoir of the *event* by Launhardt (1997), the safety supervisor at the time of the disaster, and the definitive book on the subject *The Deep Dark* (Olsen, 2005). In approximate chronological order, the findings are:

- 1) No worker (including supervision and management) could conceive of anything combustible being in the mine – and largely were in denial that there was a mine fire until the carbon monoxide levels took its toll in lives.
- 2) The emergency escape-way system from the mine was not adequate for rapid evacuation (emergency man-ways vertically, walking out a mile laterally).
- 3) Most of the underground employees lacked training in the use of self-rescuers.
- 4) Some of the self-rescuers supplied by the mine were not in serviceable condition.
- 5) Underground workers lacked training in evacuation procedures, barricading, and hazards of gases – such as carbon monoxide.
- 6) There were insufficient mine ventilation controls to isolate the #10 shaft from the workings.
- 7) The series design of ventilation was not sufficiently robust enough to allow for a recovery from a short circuit within the system containing smoke and toxic carbon monoxide.

- 8) Mine supervision delayed ordering the evacuation of the mine for 20 minutes.
- 9) Top mine officials were not present at the mine on the day of the fire and no person was in charge of operations.
- 10) Sunshine Mining Company had not conducted emergency evacuation drills and the emergency fire plan was ineffective.
- 11) The ventilation stopping and bulkheads were sealed with polyurethane foam, suspected at the time of the disaster to be a fire accelerant with toxic properties.

6.6.5 Decision Error Analysis of the Sunshine Mine Disaster

Analysis of three accounts of the Sunshine Mine disaster reveals that 26 decision errors contributing to the *event* (Figures 6.15 & 6.16). Mine management and mine supervision reported 42% and 23% of these errors respectively (Table 6-18). The Sunshine Mine Company and the US Bureau of Mines each contributed four (15%) decision errors, with only one error being attributed to the workforce. That error was the mistaken belief that metal mines are not at risk of fire. However, given that this one error was repeated many times by most, if not all, of the workforce, this decision error defines the Sunshine Mine disaster (Figure 6.16).

6.6.5.1 Sunshine Mine Company

The Sunshine Mine Company made four decision errors ultimately contributing to the disaster; three of which (75%) were errors of commission; one of which (25%) was an error of mistaken belief. The errors of commission were violations of the existing regulatory statute, and the error of mistaken belief was that polyurethane foam was acceptable in the underground mining environment – because the USBM had not sanctioned otherwise. It is important to note that the official report was conducted by the US Bureau of Mines, who were particularly prejudicial toward the Sunshine Mine Company, in spite of the fact that they were also implicated in the decision errors.

6.6.5.2 Sunshine Mine Management

The mine management at the Sunshine Mine were disposed to decision errors of mistaken belief (55%), and to a lesser extent decision errors of commission (36%). Mine management held the belief that there was no risk of fire within the Sunshine mine, as

there was nothing to burn. The decision errors of commission were regulatory contraventions concerning the ventilation design and emergency response preparedness (Table 6-17).

6.6.5.3 Sunshine Mine Supervision

This belief that underground metal mines were not at risk of fire was also shared by mine supervision, with 50% errors of mistaken belief, and by the mine workforce (Figures 6.15 & 6.16). The remaining decision errors were that of errors of commission (33%) and errors of omission (17%), the latter being notable considering the disastrous scale of the conflagration (Table 6-18). It is reasonable to expect that mine supervision would have presented more errors of omission as this disaster unfolded, given the enormity. That they did not is a testament to their professionalism and courage, in spite of their lack of situational awareness. The errors of commission violated regulatory statute and their duty of care in not conducting emergency drills and training the workers in the use of the self rescuers (Table 6-17).

6.6.5.4 Sunshine Mine Workforce

Ninety-one lives were lost during the Sunshine Mine disaster. Each of these fatalities is attributable to some degree to the mistaken belief that underground metal mines are not at risk of fire. To this extent, the decision error analysis is exceedingly weighted towards errors of mistaken belief. In addition, many of the miners probably exhibited other errors of mistaken belief concerning the use of wet rags to aid breathing and the operation of the self-rescuers. However, there was no standard of care that required self-rescuers; and, the official investigation found only that the self-rescuers were not in serviceable condition. Therefore, consistent with the principle that a standard of care must exist prior to the *event*, this mistaken belief is not included in the analysis.

6.6.5.5 US Bureau of Mines

The US Bureau of Mines was equally disposed to errors of commission and mistaken belief (Table 6-18). As the regulatory authority of the day, the US Bureau of Mines had a legislated mandate to ensure that emergency drills were conducted within the mine, and that the ventilations systems met appropriate design standards. There was an implied assumption on the part of the US Bureau of Mines that this was the case.

As regards to the use of polyurethane foam in underground mines, the US Bureau of Mines had reason to believe that there was an incipient risk of flammability (Launhardt 1997), and they therefore had a fiduciary responsibility to decertify the use of polyurethane in mines and to communicate the risk of combustion to the mining community.

6.6.6 Cognitive Profiling of the Sunshine Mine Disaster

6.6.6.1 Profile Distribution

The cognitive profile (ternary diagram) of the Sunshine Mine disaster reveals that the enterprise as a whole was in the region of cognitive deficit (Figure 6.17). The distribution is closely clustered indicating that the parties were organizationally consonant as regards risk and its perception. All parties were in deficit respecting the risk of polyurethane foam in underground mine applications; the exception being the US Bureau of Mines, who had knowledge of several underground mine disasters occurring in the UK and South Africa in which polyurethane foam was found to be a factor (Launhardt 1997).

One would expect, and frequently observes, errors of omission during *events* involving crisis in general, and fires in particular. That this was not the case reinforces the underlying ethos within this enterprise that underground metal mines were not susceptible to the risk of fire. This perception was pervasive as an antecedent to the disaster, and subsequently tragic in terms of outcomes.

6.6.6.2 Cognitive Dispositions

With the exception of the US Bureau of Mines, all parties were strongly disposed to cognitive deficit, and given the degree to which this was the case (Figure 6.17), the enterprise exhibits incipient cognitive deficit. The deficit of knowledge is both entrenched and long standing, as it was grounded on a belief that underground metal mines did not contain combustible material. In part this belief was supported by the historical record, and in part it was perpetuated by the modern mine design that no longer used timber sets as a means of ground control. The mineworkers were in particular deficit of knowledge respecting the risk of fire from polyurethane, as was the Sunshine Mine Company, the mine supervision and mine management, respectively. That there was

cognitive deficit at the enterprise level factored prominently in the escalation of the fire and the resulting loss of life.

6.6.7 Mission Criticality

The mission criticality index of the Sunshine silver mining enterprise is 10^5 out of a possible 10^{10} (Table 6-19). It is important to note that any deep mine would incur a mission criticality penalty of 10^2 , because of being limited in access and egress and a location of large amounts of stored energy. In the case of the Sunshine mine, the source of stored energy was the geothermal energy of the rock itself that at depth can cause 'run of sulphides' which is ore that is so high in concentration of metallic sulphides, that it starts to smelt – in-situ. This is not what is thought to occurred during the day of the disaster, however, it is considered likely that the introduction of oxygen within the abandoned stope that was being reopened near 3400 level may have developed 'back-draft' conditions to be present and permitted spontaneous combustion of the timber cribbing soaked in oils (aerosolized hydraulic) and diesel particulate.

It is theorized (Launhardt, 1997) that the elevated geo-thermal temperatures may have created a volatile inflammable mixture of organic compounds within the abandoned stope, which spontaneously combusted upon exposure to oxygen. The abundance of polyurethane foam used as sealant in the bulkheads and the stoppings was the fuel that fed the Sunshine Mine fire. The higher the ambient temperature, the more flammable polyurethane becomes, and a positive feedback loop is created when ignited in confined spaces. Hence, the criticality elements at the Sunshine Mine that exacerbated the underground conditions were:

- i. the absence of risk communication respecting underground fires,
- ii. the presence of large amounts of polyurethane foam,
- iii. the positive feedback created by polyurethane vapour; and,
- iv. the enterprise in cognitive deficit respecting the risk associated with the use of polyurethane foam in underground mine applications.

6.6.8 Significance and Outcomes

The Sunshine Mine disaster was instrumental in changing the perception of risk associated with underground mines throughout the United States on behalf of the mining

industry, the trade unions, the regulatory agencies and the public at large. This new awareness resulted in significant changes in regulatory governance, and a new health and safety framework was put into effect for both metal and non-metal mines (US Department of Labour, 2007). Immediately there were improvements and enhancements of the miner training programs and fire protection procedures throughout the United States. By 1973, the United States federal government created the Mine Enforcement and Safety Administration (MESA) with the mandate of assuring the healthy and safe working environment of miners. Evacuation drills, self rescuer training and the requirement for two mine rescue teams for any underground mine were only a few of the new standards put into place.

In 1977, the Mine Safety and Health Administration (MSHA) was formed under the Department of Labour, repealing the Federal Metal and Non-metal Mine Safety *Act* and amending the Federal Coal Mine Health and Safety *Act* into a combined Federal Mine Safety and Health *Act*. This *Act* set a new standard for fire prevention and miner training for the industry and increased enforcement powers of mine inspectors.

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard or Care	Error
A	Mine Management	Emergency escape-ways not adequate for purpose	Regulatory Compliance	EMB
B	Mine Supervision	Underground workers not trained in use of self rescuers	Duty of Care	EMB
B	Mine Management	Underground workers not trained in use of self rescuers	Due Diligence	EMB
C	Mine Supervision	Self rescuers not maintained in serviceable condition	Duty of Care	EMB
C	Mine Management	Self rescuers not maintained in serviceable condition	Due Diligence	EMB
D	Mine Supervision	Underground workers not trained in evacuation strategies	Regulatory Compliance	EOC
D	Mine Management	Underground workers not trained in evacuation strategies	Due Diligence	EMB
E	Mine Management	Insufficient ventilation controls in place to isolate shaft	Due Diligence	EMB
E	US Bureau of Mines	Insufficient ventilation controls in place to isolate shaft	Legislated Mandate	EMB
F	Mine Management	Inadequate design of ventilation system in series	Regulatory Compliance	EMB
G	Mine Supervision	Mine officials delayed evacuation of mine by 20 minutes	Standard Practice	EOO
	Page 1 of 3	To be continued on next page	Table 6-17(a)	

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard or Care	Error
G	Mine Management	Mine officials delayed evacuation of mine by 20 minutes	Duty of Care	EOO
H	Mine Management	Top mine officials were not present at the mine site	Regulatory Compliance	EOC
H	Sunshine Mining Co.	Top mine officials were not present at the mine site	Due Diligence	EOC
I	Mine Supervision	Workforce had not been trained in emergency drills	Regulatory Statute	EOC
I	Mine Management	Supervisors had not conducted emergency drills	Duty of Care	EOC
I	Sunshine Mining Co.	Management had not conducted emergency drills	Due Diligence	EOC
I	US Bureau of Mines	Management had not conducted emergency drills	Legislated Mandate	EMB
J	Mine Workforce	Did not know that there was flammable materials in mine	Right to Know	EMB
J	Mine Supervision	Did not know that there was flammable materials in mine	Right to Know	EMB
J	Mine Management	Workers not informed of the flammability of polyurethane	Duty of Care	EOC
	Page 2 of 3	To be continued on next page	Table 6-17(b)	

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard or Care	Error
J	Sunshine Mining Co.	Workers not informed of the flammability of polyurethane	Due Diligence	EOC
J	US Bureau of Mines	Workers not informed of the flammability of polyurethane	Fiduciary Responsibility	EOC
K	Mine Management.	Management continued using urethane – a known hazard	Due Diligence	EMB
K	Sunshine Mining Co.	Management continued using urethane – a known hazard	Due Diligence	EMB
K	US Bureau of Mines	Sunshine Mine continued using urethane – a known hazard	Fiduciary Responsibility	EOC
	Page 3 of 3	-End-	Table 6-17(c)	

Table 6-17: Table summarizing the 26 decision errors contributing to the Sunshine Mine disaster according to enterprise party

Enterprise Party	EOC	% EOC	EMB	% EMB	EOO	% EOO	Totals	Total %
Sunshine Mine Company	3	75%	1	25%	0	0%	4	15%
Mine Management	4	36%	6	55%	1	9%	11	42%
Mine Supervision	2	33%	3	50%	1	17%	6	23%
Mine Workforce	0	0%	1	100%	0	0%	1	5%
US Bureau of Mines	2	50%	2	50%	0	0%	4	15%
All Enterprise Parties	11	42%	13	50%	2	8%	26	100%

Table 6-18: Table summarizing the distribution of the decision errors by Sunshine Mine enterprise parties

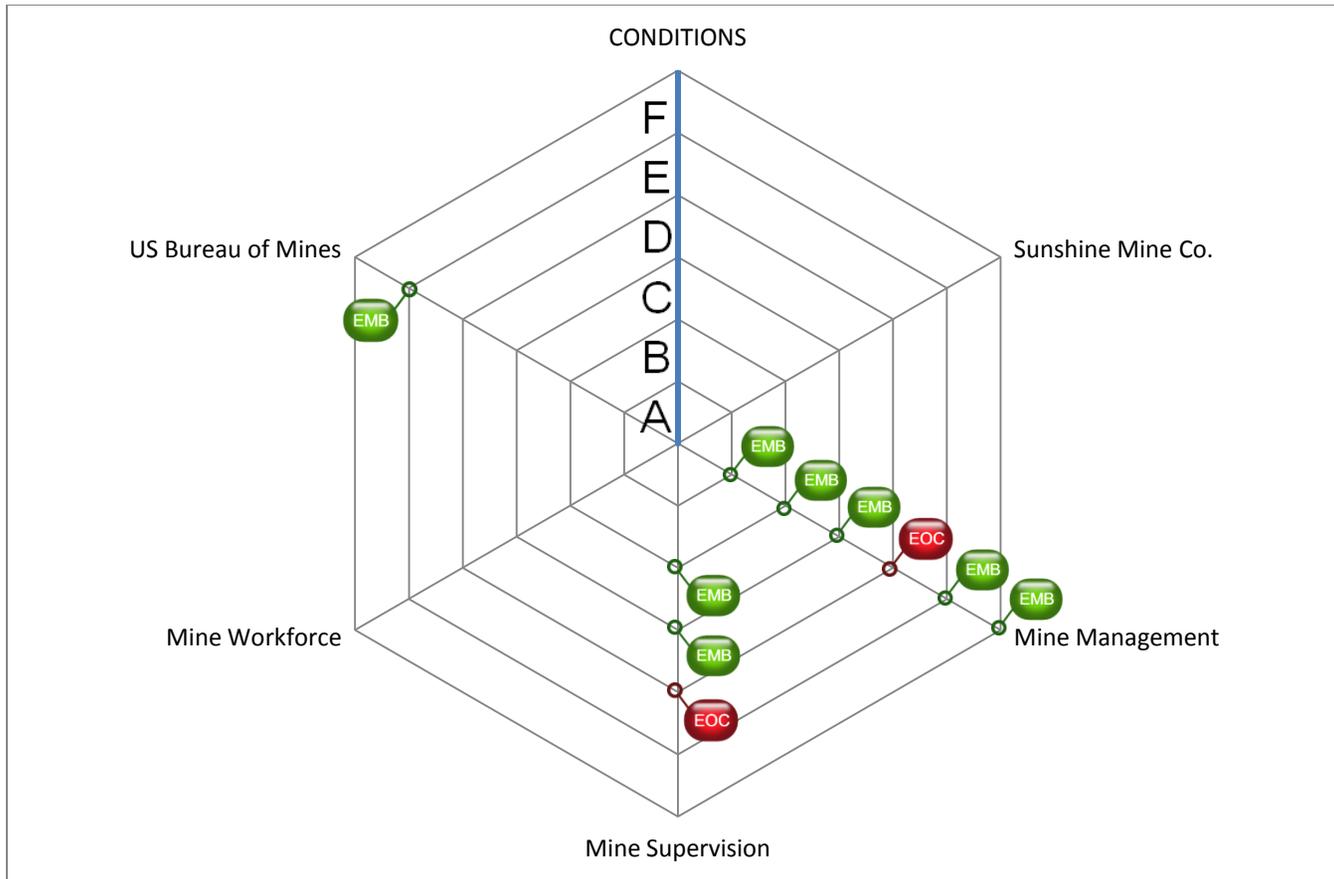


Figure 6.15: Decision error analysis diagram for conditions A through F of the Sunshine Mine disaster

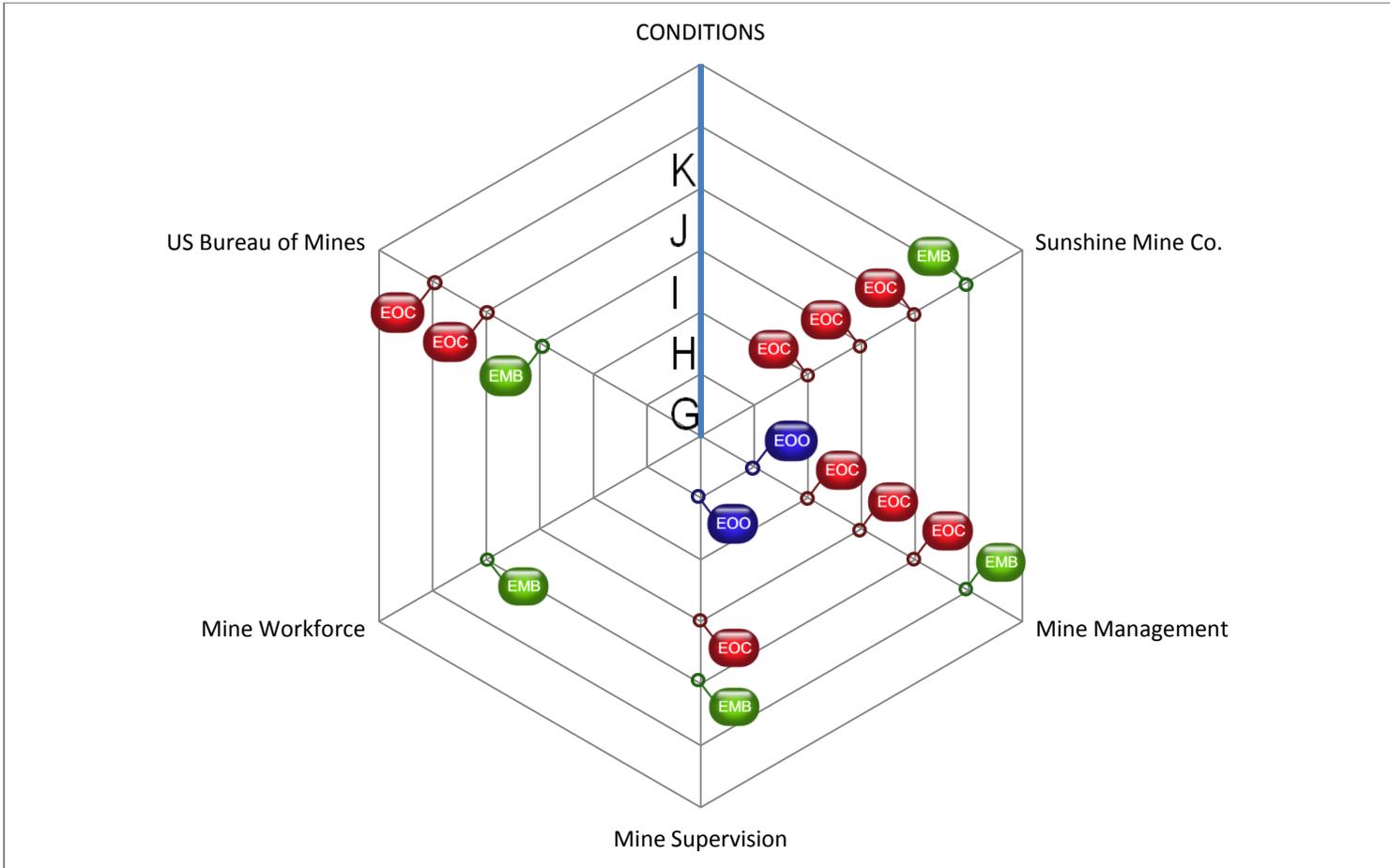


Figure 6.16: Decision error analysis diagram for conditions G through K of the Sunshine Mine disaster

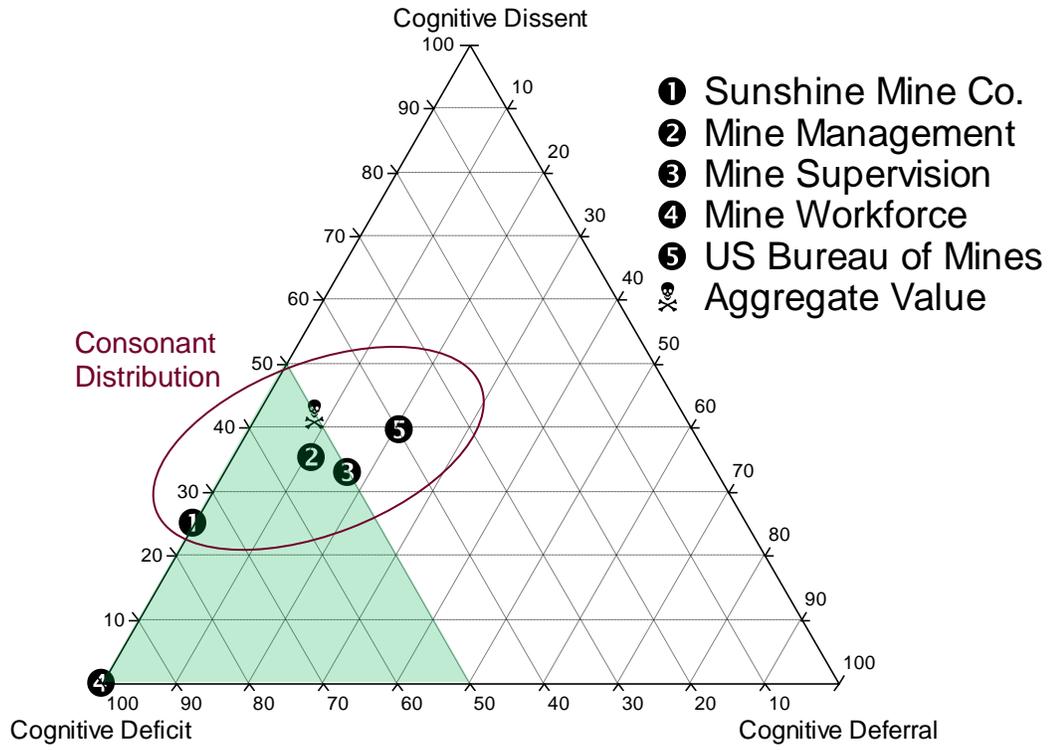


Figure 6.17: Ternary diagram illustrating the cognitive dispositions of the Sunshine Mine parties

Criticality Element	Supportive Description	Demerit	Sunshine Mine
Existence of Positive Feedback Loop	As the temperature within the mine increased from burning gases, the polyurethane foam became more flammable	10	10
Limited Access and Egress	Underground metal mine	10	10
Highly Coupled or Complex Systems		10	
Absence of Risk Communication	Belief system that there was nothing to burn within an UG metal mine	10	10
Enterprise in Cognitive Deficit	All parties were of the mistaken belief that underground metal mines have no risk of fire	10	10
Lack of Effective Emergency Response		10	
Inordinate Amounts of Stored Energy	Underground polyurethane	10	10
Enterprise/Operation in Transition		10	
Absence of Regulatory Oversight		10	
Operations in Cognitive Dissent		10	
Mission Criticality	Total Demerit	10¹⁰	10⁵

Table 6-19: Table summarizing criticality elements associated with the Sunshine Mine disaster

6.7 The Balmoral Mine Disaster

6.7.1 Nature of the Enterprise

The Balmoral mine disaster occurred at or about 22:00 hours on May 20, 1980 in the Ferderber Mine, located 10 km northeast of the town of Val d'Or, Quebec. The mine started development in October of 1978, and had been in production since August 1979. The principal mining method was shrinkage stoping, with the possibility of sub-level stoping for wider ore zones. The development of the mine consisted of a trackless access ramp from surface at a grade of 17%, connecting four levels at 100, 200, 250 and 500 feet depth (Figure 6.22). There were eight stopes at the time of the disaster: four in production on the 200 level, two in production on the 350 level and two in development on the 350 level (Beaudry, 1981). Twenty-four miners were working underground during the evening of the disaster, eight of whom lost their lives, sixteen narrowly escaping serious injury or death.

6.7.2 The Event

The *event* that tragic day was a failure of the crown pillar directly above the 1-7 stope consisting of 55 feet of bedrock, followed by nearly 50 feet of water saturated varved clays, silts and gravels. The failure produced 100,000 tons of water-borne sediment that infiltrated the mine through a conical-shaped penetration of the crown pillar (Beaudry, 1981). The failure in geo-mechanical terms is best described as a 'chimney failure' (Betournay, 1994), and can be considered behaving analogous to mixed granular material within a large hopper (Kvapil, 1965) passing through a narrow opening. There was ample warning to mine management of an impending disaster, as the ingress of fluidized sediments were observed in previous days, months – and years; as the decision analysis will show. However, on the part of the underground miners, the only warning of the crown pillar failure was an air blast, followed by a wall of fluidized sediments and debris two metres high that swept away materials, rolling stock and miners alike. The time taken for the mud and sediments to reach the 350-foot level was estimated to be in the order of fifteen minutes. The funnel shaped crater remaining was later measuring 200 feet in depth parallel to the axis of the ore-body. In plan-view, the crater was oval in shape and 185 feet wide at the long axis (Beaudry, 1981).

6.8 Mine Workings

The mine underground development was designed in 1978. Predicated upon the application of shrinkage stoping as the mining method, the mine design was in two phases of production (Beaudry, 1981). The first phase involved four levels of development and production down to a depth of 510 feet (155 metres). The proposed levels were at 100 feet, 200 feet, 350 feet and 500 feet (Figure 6.22). They were accessed by a ramp driven at a grade of 17% with two 180 degree 'switch-backs'. The choice of a ramp access over a production shaft was made so that production could start earlier, and consequently, so would the cash flow. Each level was designed with one ventilation shaft and an escape-way at 70 degrees to vertical; following the general dip of the ore-body. The second phase was to go to 650 feet (198 metres), incorporating a second escape-way and ventilation raise. There was consideration for the possibility of changing the mining method to sub-level stoping, should the ore-body thicken. Ironically, no decision was made regarding the size of the horizontal pillar separating the 200 and 350 levels at the design stage of the underground workings (Figure 6.22).

At the time of the disaster, phase one was well under way, having been in development since October of 1978, and production since August of 1979. The 100 level had a single abandoned stope and exploration drift, connected with crosscuts to a haulage drift and the access ramp. The 200 level, where most of the production was taking place, was complete with four stopes in production (2.5, 2.7, 2.9 and 2.11); and the development of crosscuts, ventilation raise, stope raises, pillar raises and haulage ways were complete (Figure 6.22). The 350 level was in the process of completion concerning stope development, with two stopes in production and two more under way. The ramp, haulage way, crosscuts, ventilation raise escape-way were all completed. The sumps were complete on all levels and two lunchrooms were in place off the ramp on the 200 and 350 levels.

The 500 level was in the early stages of development. There were no stopes in production at the 500 level. At the time of the disaster, there were two crews working on the 500 level, one diamond drill crew, and a second crew - an Alimak raise crew completing the ventilation raise. The Alimak raise crew was nearing completion of the ventilation raise with 40 feet to complete before joining the existing raise at the 350-foot level. There was no secondary escape-way at the 500 level. The ramp was the only means of secondary egress from the 500 level (Figure 6.22).

6.9 Chronology of Events

The events leading up to the Balmoral mine disaster were numerous, well documented (Beaudry, 1981) and in some cases, predictable. The first warnings of geologic and geo-mechanical problems occurred in May and June of 1979, when the mine flooded as the driving of the ventilation raise was underway. This was the first hint of a broader context for the disaster; a lack of understanding and respect for the large amounts of stored water within the overlying surface soil materials in the region. Not long after, in July of 1979, an exploration drift under development on the 100 level was abandoned after just fifty feet of advance, due to ground instability problems. In November, a second attempt to advance the exploration drift also met with incipient ground failure. Concurrently, the 2-7 stope was put into production, some of which was below the 1-7 drift (Figure 6.22). As a precaution, a 25 foot (8 m) high horizontal pillar was left between the 2-7 stope and the 1-7 drift. It is not clear how this dimension was calculated, or by whom. December saw the tragic death of a miner within the 2-9 stope; a fatality that apparently did not galvanize mine management into action concerning the deteriorating condition of the 2-7 stope. It is not clear as to what the circumstances were concerning this fatality; only that it was a tragic harbinger of future *events*.

By February of 1980, the falls of ground within the 2-7 stope were sufficient to erode the 25 foot pillar to just 8 feet (2.5 m). By March of 1980, ore was being pulled from the 2-7 sporadically, as dictated by production targets (Figure 6.23). The sporadic production contributed to the instability in the back of the stope by permitting void space to develop. Succeeding days to weeks would see a continuous dilution of the muck from the 2-7 stope, with respect to ore grade. This was another clear indicator of the failure of the pillar between the 2-7 stope and the 1-7 exploration drift above. On May 13 of 1980, it was common knowledge among the mine workforce that the pillar was failing, to the extent that mine supervision explicitly cautioned the miners as regards to ground conditions (Figure 6.24). On May 15 of 1980, it was decided to isolate the 2-7 stope from the remainder of the mine, and bulkheads were installed for this purpose.

Owing to a lack of monitoring instrumentation and geo-mechanical expertise, the 2-7 stope and the 1-7 exploration drift were now without means of inspection. Regardless, the production of sediment laden ground water and the poor condition of the backs and walls of mine workings near the 2-7 stope suggested that a catastrophic failure of the crown had in fact occurred. What was not expected was that during the

long weekend of May 17 through 19, the crown pillar between 1-7 stope and the overburden would also be in the process of incipient failure (Figure 6.24). The following day of May 20 witnessed a heavy mobile crane travel over the very spot where, in a matter of hours, a 185-foot crater would exist. The operator reported no unusual ground effects during his transit; nor did anyone else. At approximately 22:00 hours, the crown pillar above the 1-7 exploration drift failed admitting 100,000 tons of sediment laden water into the mine, taking the lives of eight underground miners, and causing the closure of the mine for months.

6.9.1 Consolidated Findings

The following is a list of the consolidated findings of conditions that contributed to the Balmoral Mine disaster. The investigative source is the report of public inquiry into the disaster (Beaudry, 1981). In approximate reverse chronologic order, the findings are:

- 1) None of the workforce was trained in, or prepared for an underground mine emergency.
- 2) The back and the walls of 2-7 stope were producing muddy water at an increasing rate without investigation into the matter.
- 3) The ore in the 2-7 stope was increasing in dilution while the draw rate also increased for purposes of production.
- 4) Supervisors spoke to workers often of bad ground conditions within the 2-7 stope, but no action was taken.
- 5) Production was increasing in spite of the deteriorating geo-mechanical conditions.
- 6) The mine openings were not designed according to generally accepted engineering standards.
- 7) The crown pillar was sloughing between the 1-7 and 2-7 stopes with no means of detection or evaluation.
- 8) There was a lack of emergency egress on the 350 foot level when the regulatory authority provided a wrong interpretation of the relevant statute.

- 9) A fatality occurred within the 2-9 stope, that did not receive appropriate investigation or review in terms of contributing factors.
- 10) Ore was continued to be drawn from the 2-7 stope, even as geo-mechanical conditions worsened.
- 11) The 1-7 exploration drift was re-entered with the assumption that it had become geo-mechanically stable.
- 12) The 1-7 exploration drift was abandoned with no investigation as to why the ground conditions were so poor.
- 13) An unusual flow of water flooding the mine while driving a ventilation raise was not investigated or mitigated.
- 14) The dimensions of the underground openings were not designed to generally accepted engineering standards.
- 15) The Ferderber mine operated without any safety management systems or any person responsible for health, safety and training.
- 16) The choice of mine method was not appropriate for geologic conditions, and the regulatory authority lacked consultation and status reports.

6.9.2 Decision Error Analysis of the Balmoral Mine Disaster

Analysis of the official report of inquiry (Beaudry, 1981) reveals 53 decision errors contributing to the Balmoral mine disaster (Table 6-20). Ferderber mine management reported 30% of the decision errors, followed by Balmoral Mine Ltd and the mine supervision with 23% decision errors each (Table 6-21). The standards of care not met within the Balmoral mine disaster were largely duties of care and due diligence; indicative of a lack of understanding of roles and responsibilities. The decision error analysis diagrams (Figures 6.18 through 6.20) illustrate an enterprise in which mine management was strongly influenced by corporate management, with similar distributions of errors of commission and mistaken belief. Deteriorating conditions in the mine were clearly not communicated with mine workers and the regulatory authorities, as evidenced by the corresponding preponderance of errors of mistaken belief presented by these parties. The mine supervisors, by comparison, were under

considerable stress to accommodate the interests of management, and account for the majority of errors of omission (75%) contributing to the Balmoral mine disaster.

There were three standards violated for which most, if not all, of the parties to the enterprise were complicit. They are conditions 'A', 'J' and 'M' on the decision error analysis diagram and deserve particular attention (Figures 6.18 & 6.19). Condition 'M' corresponds to the observation that water was flooding the Ferderber Mine whilst driving a ventilation raise early during mine development. That this was not investigated by any of the parties is tragic in its outcome as an opportunity was presented to evaluate the hydraulic conductivity of the rock mass and the source of the water. Following this was condition 'J', corresponding to the observations by all parties that the 2-7 stope was subject to suspect, if not failing, ground conditions. Indications are that had parties with only basic understanding of geo-mechanics been present, the nature and origins of the failing crown pillar would have been manifest. Tragically, the mine management continued to pull the stope in deteriorating and counterproductive ground conditions.

Finally, condition 'A' refers to the lack of emergency preparedness and response that was, and is, basic to all underground mine operations. Were it not for the valiant heroism on the part of two miners during the ensuing minutes of the crown failure, the loss of life would have been greater. The absence of emergency preparedness and response to the Balmoral mine disaster reinforces that the collective ethos was one of production at any cost, a lack of perception and control of risk.

6.9.3 Cognitive Profiling the Balmoral Mine Disaster

6.9.3.1 Profile Distribution

The Ferderber Mine enterprise cognitive profile is that of organizational dissonance with incipient cognitive dissent (Figure 6.21). That is, the cognitive errors exhibited by cognitive profiling were latent and entrenched within the collective ethos of the parties to the enterprise and imminence of an *event* presaged by the numerous ground failures as well as the fatality of December 1979. That the workplace parties did not share a common understanding or perception of risk is perhaps an understatement. Moreover, the open dissent of Balmoral Mines Ltd. and the Ferderber Mine management is suggestive of *directing minds* (CCOH&S, 2008) that took advantage of their authority

and the lack of geo-mechanical acumen of the mineworkers to advance their productivity agenda.

6.9.3.2 Balmoral Mines Ltd.

On the part of Balmoral Mines Ltd, corporate management were disposed to 83% errors of commission, and 17% errors of mistaken belief and report to the cognitive dissent region of the cognitive ternary diagram (Figure 6.21). The standard most often violated was the standard imposed upon all directors of corporations – the diligence to ensure competent supervision within the workplace, a standard for which there is no argument for circumstance or ignorance of fact. Corporate directors assume accountability for the workplace, and the health and safety of all who work therein.

In general, Balmoral Mines Ltd. failed to assure that there was adequate engineering and geo-mechanical resources at the Ferderber mine to operate the mine in accordance with established mine engineering practices and the regulatory requirements. More specifically, Balmoral Mines Ltd. did not have the management systems to ensure that emergency response procedures were in place, and that qualified persons evaluated, reported and investigated deteriorating mine conditions.

6.9.3.3 Ferderber Mine Management

The Ferderber Mine management report to the cognitive dissent region of the cognitive diagram, in close proximity to the profile of Balmoral Mines Ltd (Figure 6.21). Evidently, the mine management at the Ferderber mine was strongly influenced, if not directed, by Balmoral Mines Ltd. Mine management at the Ferderber Mine were ultimately responsible for the day-to-day operational decisions at the mine, and failed to demonstrate a duty of care to the mine workers by this measure. Specifically, they lacked knowledge and the capacity for decision making concerning geo-mechanical matters; the very matters that would become so critical to the operation of the mine during the days to weeks antecedent to the May 20, crown pillar failure.

6.9.3.4 Ferderber Mine Supervision

Mine supervision include all mine personnel directing the activities of others, as well as those professionals and technologists with whom the responsibility resides concerning technical matters such as mine ventilation and ground control. Mine

supervision has an onerous and presiding obligation to ensure the health and safety of workers in the workplace. They have the authority, opportunity, and - by definition - the competence to direct the work. The Ferderber Mine supervisors report to the region of no central tendency within the cognitive diagram, although marginally so (Figure 6.21). They are the only party to the Balmoral mine disaster to do so. This is indicative of a workplace party that was exhibiting cognitive dissonance between their perceptions of the risks at the Ferderber Mine and their ability to mitigate these risks. This is supported by the observation that supervisors spoke openly as to the hazard associated with the failing crown pillar, but did not take action appropriate to the threat (Beaudry, 1981).

The standard of care not met by mine supervision was their duties of care to the workers, and compliance with the regulatory requirements of the day. Their capacity for demonstrating this duty of care was compromised by their lack of technical acumen concerning geo-mechanical matters and a lack of appreciation for their roles and responsibilities. The mine supervision at the Ferderber Mine presents a profile similar to that of the regulatory authorities, with the exception that they were disposed to cognitive deferral. This cognitive deferral is attributed to inappropriate motivation to sacrifice prudence and caution in deference to management's preoccupation with production.

6.9.3.5 Mine Regulatory Authorities

The regulatory authorities to the Balmoral mine disaster report to nearly mid-way along the cognitive deferral/cognitive dissent axis of the cognitive ternary diagram (Figure 6.21). The mines inspectorate mistakenly believed that that Balmoral Mines Ltd. were actively and competently managing the geo-mechanical problems, a belief that was not based upon firsthand knowledge. This belief was compounded by their lack of regulatory oversight concerning the mine method of the Ferderber Mine at the design stage, as well as the investigation of the occurrence of *events* within their mandate. The regulatory authorities have a fiduciary responsibility to the public and to the mining community through the issuance of licenses, to ensure that mine plans meet the standard of sound engineering principles and generally accepted industry practice. It is not clear as to the degree that Balmoral Mines Ltd. disclosed their mine plans and method, however in the absence of active processes of inspection and investigation, the regulatory authorities were clearly at a disadvantage in carrying out their mandate.

6.9.3.6 Mine Workers

The mineworkers at the Ferderber Mine report to the cognitive deficit region of the cognitive diagram; marginally disposed to cognitive deferral (Figure 6.21). The Ferderber mineworkers were strongly disposed to cognitive deficit and demonstrated a lack of understanding and/or willingness to exercise their fundamental rights to know of the hazards in the workplace, to participate in their investigation and to refuse unsafe work. A miner killed in December of 1979, was sufficient reason for the mineworkers to have concerns that they were working in risky and deteriorating mine conditions. Add to this the lack of safety training and standards, and the conditions were such that any number of mine emergency scenarios presented unacceptable risk to the Ferderber workforce.

6.9.4 Mission Criticality

The mission criticality index of the Ferderber Mine enterprise is 10^7 out of a possible 10^{10} (Table 6-22). We would expect an index of 10^1 from such an enterprise because of the limited access and egress associated with underground mining. Elements present at Balmoral mine disaster that exacerbated these conditions were:

- i. the existence of a positive feedback loop whereby the more water entering the mine, the wider the opening and greater the forces,
- ii. the absence of risk communication concerning shallow stopes making water,
- iii. the lack of emergency response plans and preparedness,
- iv. the excessive potential energy contained within the water and marshes overlaying the Ferderber underground mine workings,
- v. the concurrent activities of exploration, development and production; in some instances within the same mine openings; and,
- vi. the absence of regulatory inspection, investigation and consultation.

Heuristically, the mission criticality analysis suggests that preventative strategies at the Ferderber Mine should have been based upon the establishment of geo-mechanical and mine safety expertise; a relationship with regulatory authorities based upon transparency and disclosure; a more prudent, capitalized mine design; and empowered workplace parties secure in their roles and responsibilities.

6.9.5 Significance and Outcomes

The Office of the Attorney General of Quebec, Canada charged officers of Balmoral Mines Ltd. with manslaughter. The verdict of that trial was acquittal. The Quebec Court of Appeal, ordering a new trial based on judicial error, overturned the verdict in 1987. The decision of the Quebec Court of Appeal was appealed to the Supreme Court of Canada in 1989, and the decision of the Quebec Court of Appeal was upheld. The defendants would face a new trial. The outcome of that trial is unknown.

6.9.6 Interpretation

The presiding ethos of the Ferderber Mine enterprise was one of risk taking. All parties contributing to the day-to-day operation of the mine were disposed to errors of mistaken belief. They were, to various degrees, not competent to work in such a high risk setting as presented by the Ferderber mine in May of 1980. The workers did not have the requisite knowledge of hazard assessment, safety or emergency response. The mine supervision lacked an understanding of their roles, responsibilities and geo-mechanical acumen. Mine management was motivated and influenced by production targets at the expense of prudent and considered ground control strategies.

The enterprise at the Ferderber mine would have benefited from greater expertise and leadership by Balmoral Mines Ltd, and much greater engagement and oversight by the mines inspectorate. That this was not the case is tragic in its consequences, and serves as a lesson to all mining enterprises as to the value of consultation, collaboration and caution when mining of challenging geologic conditions.

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard of Care	Error
A	Balmoral Mines Ltd	Workforce not trained in underground emergency response	Due Diligence	EOC
A	Mine Management	Workforce not trained in underground emergency response	Due Diligence	EOC
A	Mine Supervision	Workforce not trained in underground emergency response	Regulatory Compliance	EOC
A	Mine Workforce	Workforce not trained in underground emergency response	Duty of Care	EMB
A	Regulatory Authority	Workforce not trained in underground emergency response	Fiduciary Responsibility	EOC
B	Mine Management	No investigation into muddy water in backs and walls of 2-7	Due Diligence	EOC
B	Mine Supervision	No investigation into muddy water in backs and walls of 2-7	Duty of Care	EMB
C	Mine Management	Ore in 2-7 stope was increasing in dilution and draw rate	Mine Engineering Standard	EOC
C	Mine Supervision	Ore in 2-7 stope was increasing in dilution and draw rate	General Industry Practice	EMB
D	Mine Supervision	Supervisors warned workers of 2-7 stope, without action	Duty of Care	EOC
D	Mine Workforce	Supervisors spoke often of bad ground conditions in 2-7 but workers did not exercise their right to refuse work.	Duty of Care	EOO
	Page 1 of 4	To be continued on next page	Table 6-20 (a)	

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard of Care	Error
E	Balmoral Mines Ltd	Production increasing in deteriorating ground conditions	Due Diligence	EOC
E	Mine Management	Production increasing in deteriorating ground conditions	Due Diligence	EOC
E	Mine Supervision	Production increasing in deteriorating ground conditions	Duty of Care	EOO
F	Balmoral Mines Ltd	Mine openings not designed to standard	Due Diligence	EOC
F	Mine Management	Mine openings not designed to standard	Engineering Standards	EOC
G	Mine Management	Failing crown pillar above 2-7 stope not evaluated	Due Diligence	EOC
G	Mine Supervision	Failing crown pillar above 2-7 stope not evaluated	Duty of Care	EOC
H	Balmoral Mines Ltd	Lack of emergency egress at the 350 foot level	Due Diligence	EOC
H	Mine Management	Lack of emergency egress at the 350 foot level	Due Diligence	EOC
H	Mine Supervision	Lack of emergency egress at the 350 foot level	Duty of Care	EOC
H	Regulatory Authority	Lack of emergency egress at the 350 foot level	Legislated Mandate	EMB
	Page 2 of 4	To be continued on next page	Table 6-20 (b)	

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard of Care	Error
I	Balmoral Mines Ltd	A fatality in 2-9 stope was not fully investigated for factors	Due Diligence	EOC
I	Mine Management	A fatality in 2-9 stope was not fully investigated for factors	Due Diligence	EOC
I	Regulatory Authority	A fatality in 2-9 stope was not fully investigated for factors	Legislated Mandate	EOC
J	Balmoral Mines Ltd	Ore was continued to be drawn from 2-7 while failing	Due Diligence	EOC
J	Mine Management	Ore was continued to be drawn from 2-7 while failing	Due Diligence	EOC
J	Mine Supervision	Ore was continued to be drawn from 2-7 while failing	Duty of Care	EOO
J	Mine Workforce	Ore was continued to be drawn from 2-7 while failing	Duty of Care	EMB
K	Mine Management	Exploration drift 1-7 entered when it was unsafe to do so	Due Diligence	EOC
K	Mine Supervision	Exploration drift 1-7 entered when it was unsafe to do so	Duty of Care	EOO
K	Mine Workforce	Exploration drift 1-7 entered when it was unsafe to do so	Duty of Care	EMB
L	Balmoral Mines Ltd	Exploration drift 1-7 abandoned without investigation	Due Diligence	EMB
	Page 3 of 4	To be continued on next page	Table 6-20 (c)	

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard of Care	Error
L	Mine Management	Exploration drift 1-7 abandoned without investigation	Due Diligence	EMB
L	Mine Supervision	Exploration drift 1-7 abandoned without investigation	Duty of Care	EMB
L	Regulatory Authority	Exploration drift 1-7 abandoned without investigation	Fiduciary Responsibility	EMB
M	Balmoral Mines Ltd	Unusual flow of water while driving raise not investigated	Due Diligence	EOC
M	Mine Management	Unusual flow of water while driving raise not investigated	Due Diligence	EOC
M	Mine Supervision	Unusual flow of water while driving raise not investigated	Duty of Care	EMB
M	Mine Workforce	Unusual flow of water while driving raise not investigated	Standard Operating Procedure	EMB
M	Regulatory Authority	Unusual flow of water while driving raise not investigated	Fiduciary Responsibility	EMB
N	Balmoral Mines Ltd	Underground openings not designed to standard	Due Diligence	EMB
N	Mine Management	Underground openings not designed to standard	Duty of Care	EMB
N	Regulatory Authority	Underground openings not designed to standard	Fiduciary Responsibility	EMB
	Page 4 of 5	To be continued on next page	Table 6-20(d)	

Letter	Enterprise Party	Condition Contributing to the Event Scenario	Standard of Care	Error
O	Balmoral Mines Ltd	Water flooding ventilation raise not investigated	Due Diligence	EOC
O	Mine Management	Water flooding ventilation raise not investigated	Due Diligence	EOC
O	Mine Supervision	Water flooding ventilation raise not investigated	Duty of Care	EMB
O	Regulatory Authority	Water flooding ventilation raise not investigated	Fiduciary Responsibility	EMB
P	Balmoral Mines Ltd	Absence of any health and safety management systems	Due Diligence	EOC
P	Mine Management	Absence of any health and safety management systems	Due Diligence	EOC
P	Regulatory Authority	Absence of any health and safety management systems	Legislated Mandate	EMB
Q	Balmoral Mines Ltd	Inappropriate mine method given geologic conditions	Due Diligence	EMB
Q	Mine Management	Inappropriate mine method given geologic conditions	Due Diligence	EMB
	Page 5 of 5	-End-	Table 6-20 (e)	

Table 6-20: Table summarizing the 35 decision errors contributing to the Balmoral mine disaster according to enterprise party

Enterprise Party	EOC	% EOC	EMB	% EMB	EOO	% EOO	Totals	Total %
Balmoral Mine Ltd	10	83%	2	17%	0	0%	12	23%
Mine Management	13	81%	3	19%	0	0%	16	30%
Mine Supervision	4	33%	5	42%	3	25%	12	23%
Mine Workforce	0	0%	4	80%	1	20%	5	9%
Regulatory Authority	3	38%	5	62%	0	0%	8	15%
All Enterprise Parties	30	57%	19	35%	4	8%	53	100%

Table 6-21: Table summarizing the distribution of the decision errors by Balmoral mine enterprise parties

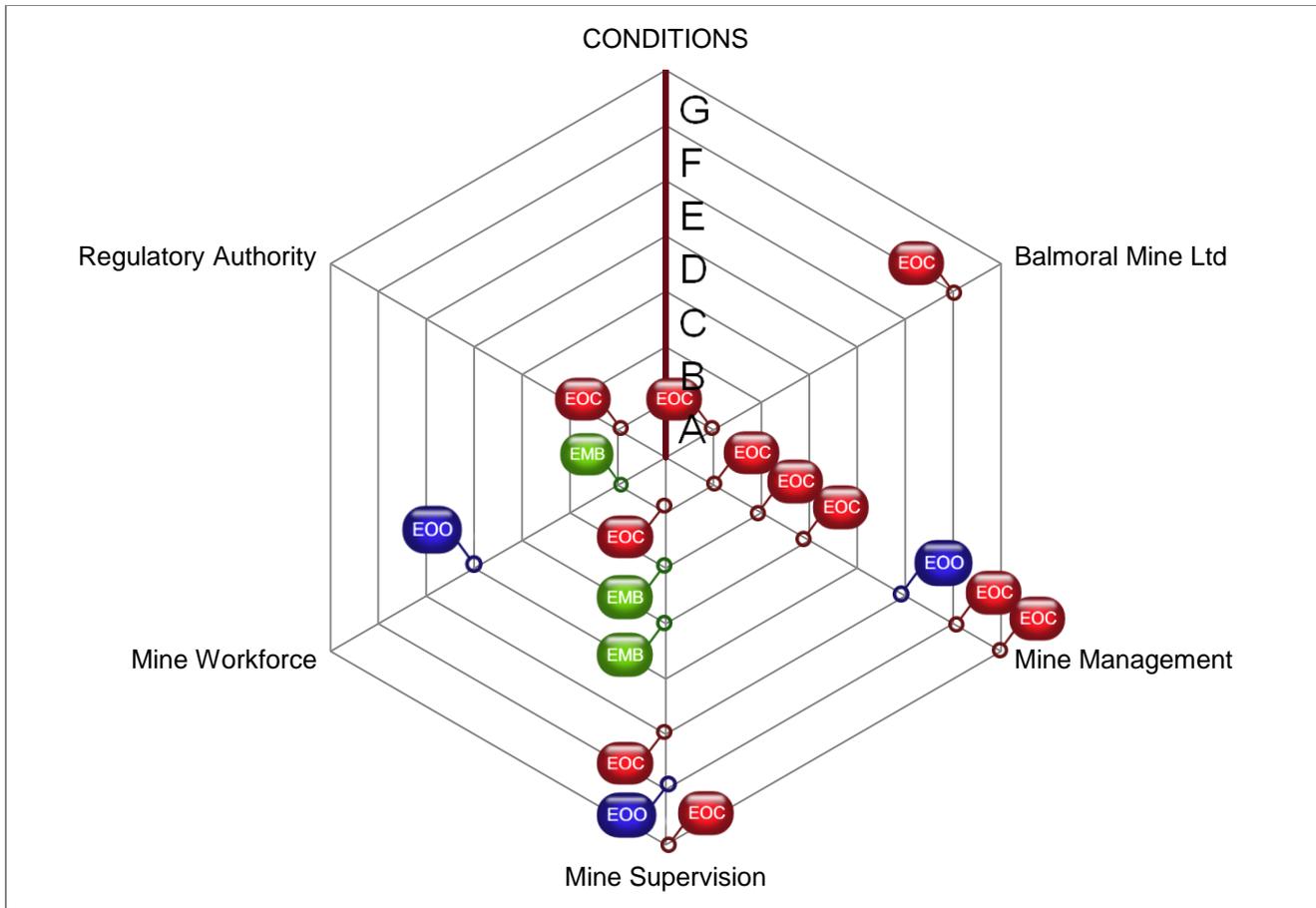


Figure 6.18: Decision error analysis diagram for conditions A through G of the Balmoral mine disaster (1 of 3)

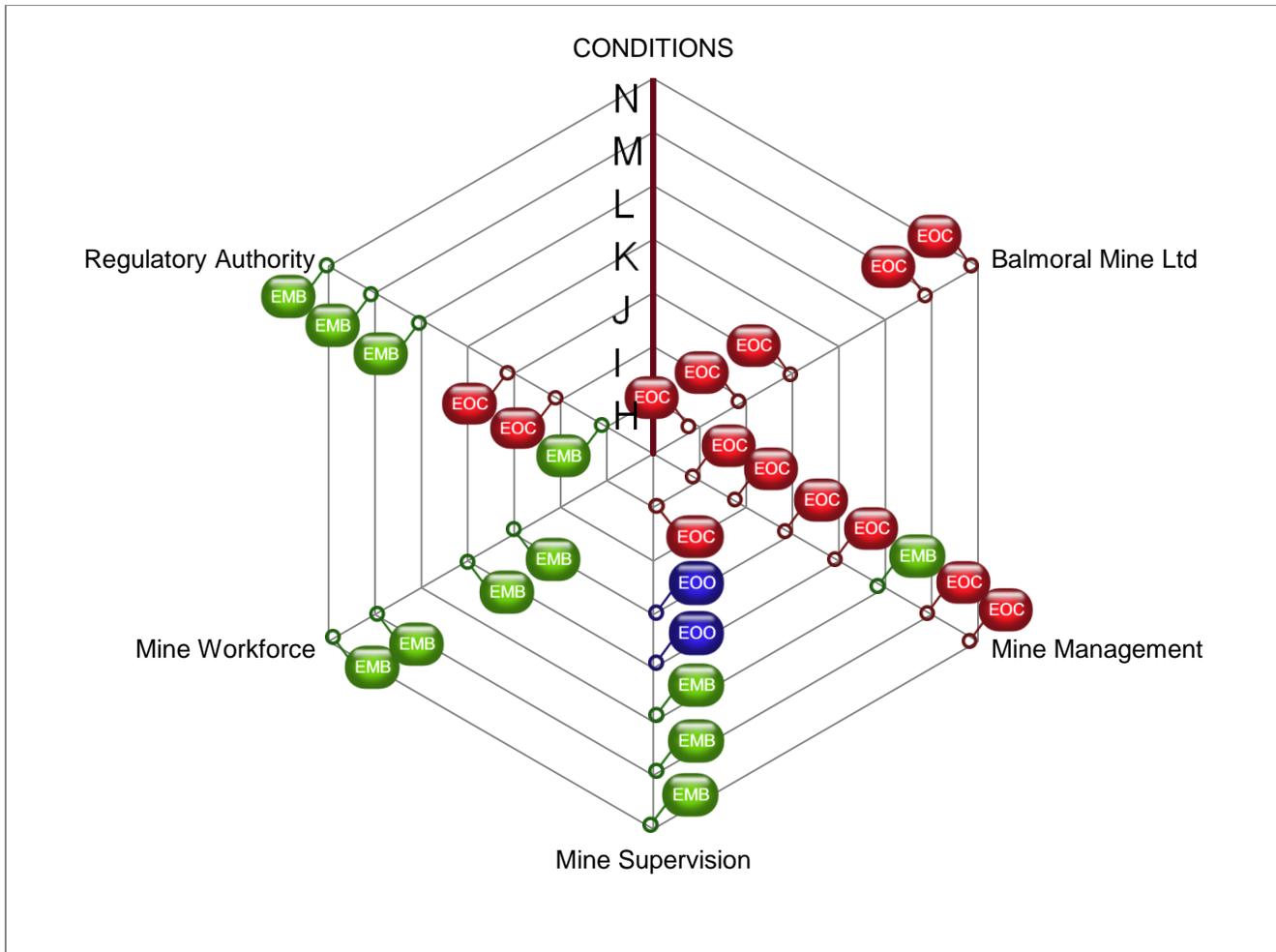


Figure 6.19: Decision error analysis diagram for conditions H through N of the Balmoral mine disaster (2 of 3)

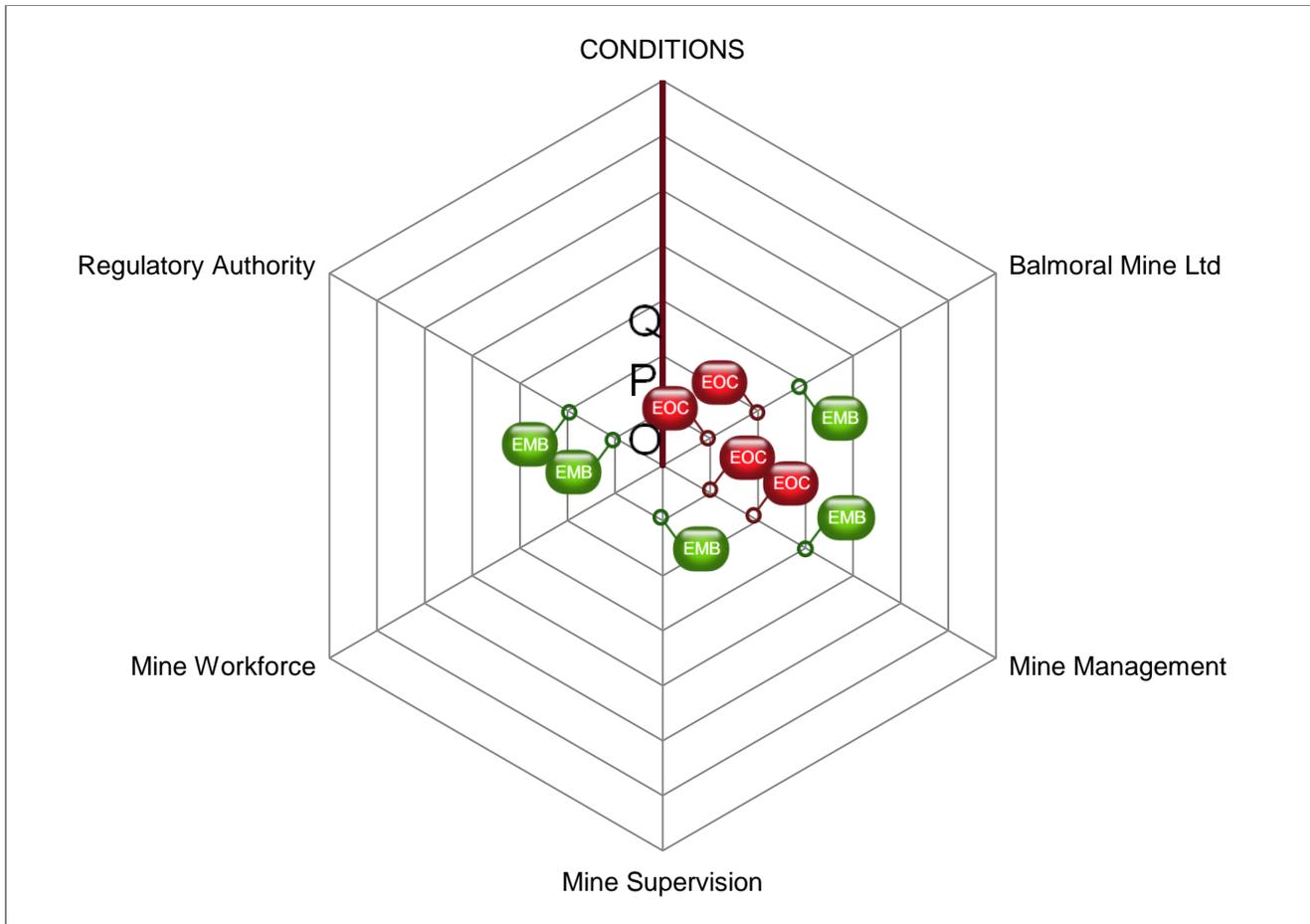


Figure 6.20: Decision error analysis diagram for conditions O through Q of the Balmoral mine disaster (3 of 3)

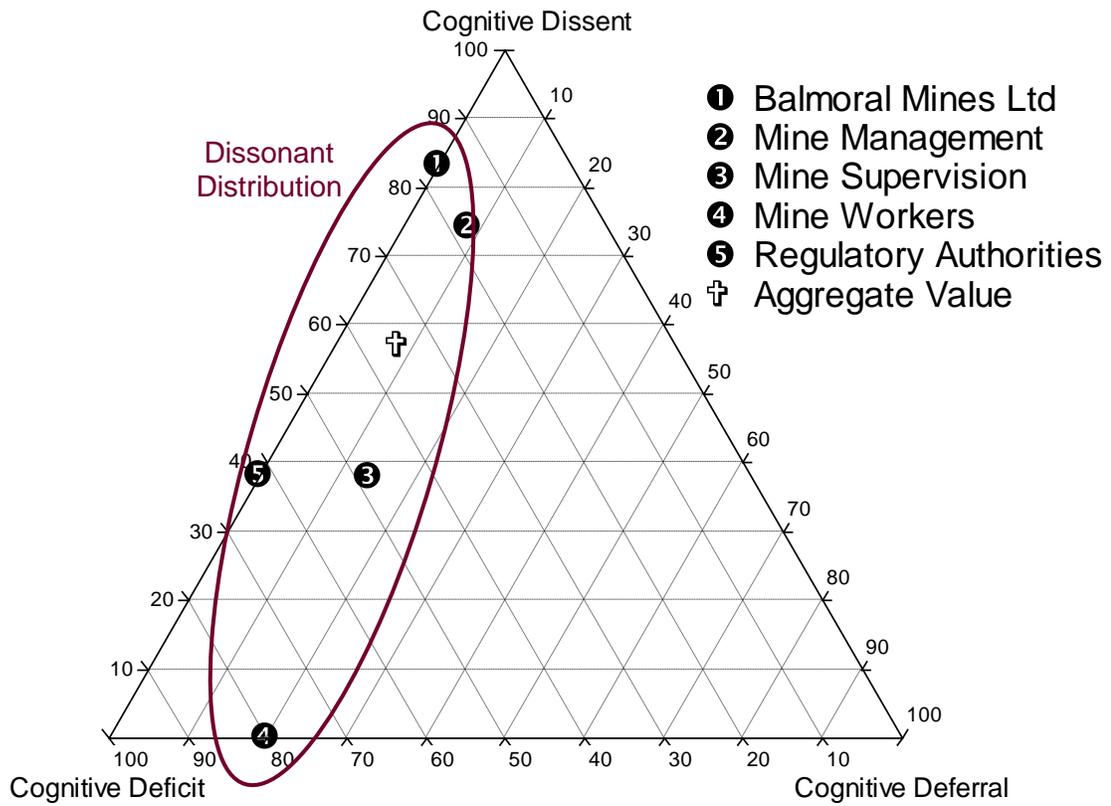


Figure 6.21: Ternary diagram illustrating the cognitive dispositions of the Balmoral mine parties

Criticality Element	Supportive Description	Demerit	Balmoral Mine
Existence of Positive Feedback Loop	As more water entered the mine the crown pillar was further weakened and causing a 'chimney effect.'	10	10
Limited Access and Egress	Underground gold mine	10	10
Highly Coupled or Complex Systems		10	
Absence of Risk Communication	Knowledge as to the extent and gravity of the weakened 2-7 stope not shared/communicated	10	10
Enterprise in Cognitive Deficit		10	
Lack of Effective Emergency Response	No emergency response capacity or preparation	10	10
Inordinate Amounts of Stored Energy	Millions of cubic metres of water and gravel at surface	10	10
Enterprise/Operation in Transition	Mine under development and production concurrently	10	10
Absence of Regulatory Oversight	Quebec regulatory authorities did not visit mine or follow up on ground falls and accidents	10	10
Operations in Cognitive Dissent		10	
Mission Criticality	Total Demerit	10¹⁰	10⁷

Table 6-22: Table summarizing criticality elements associated with the Balmoral mine disaster

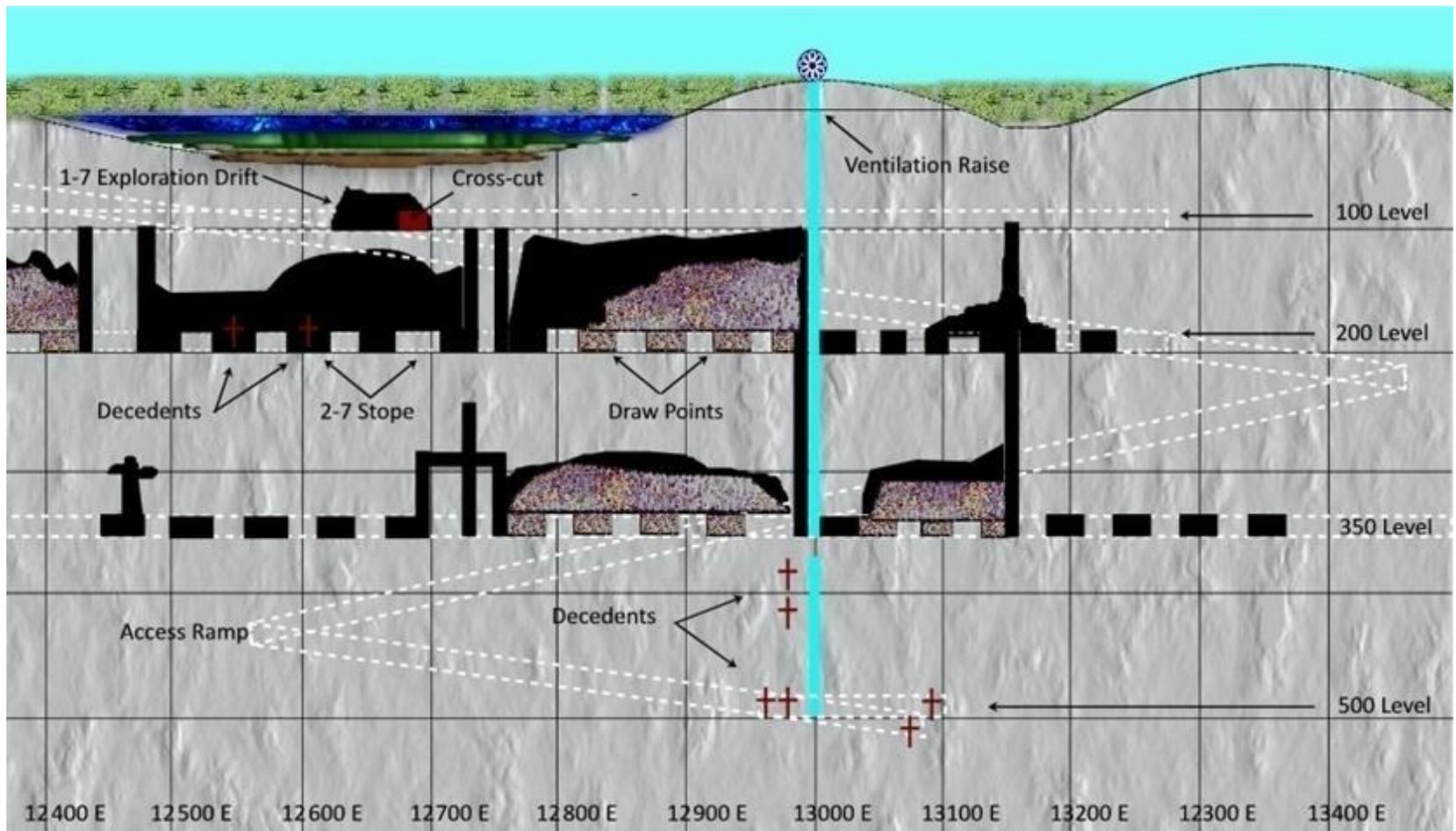


Figure 6.22: Illustration of the Ferderber mine workings and the location of the decedents after the failed crown pillar (Beaudry, 1981)

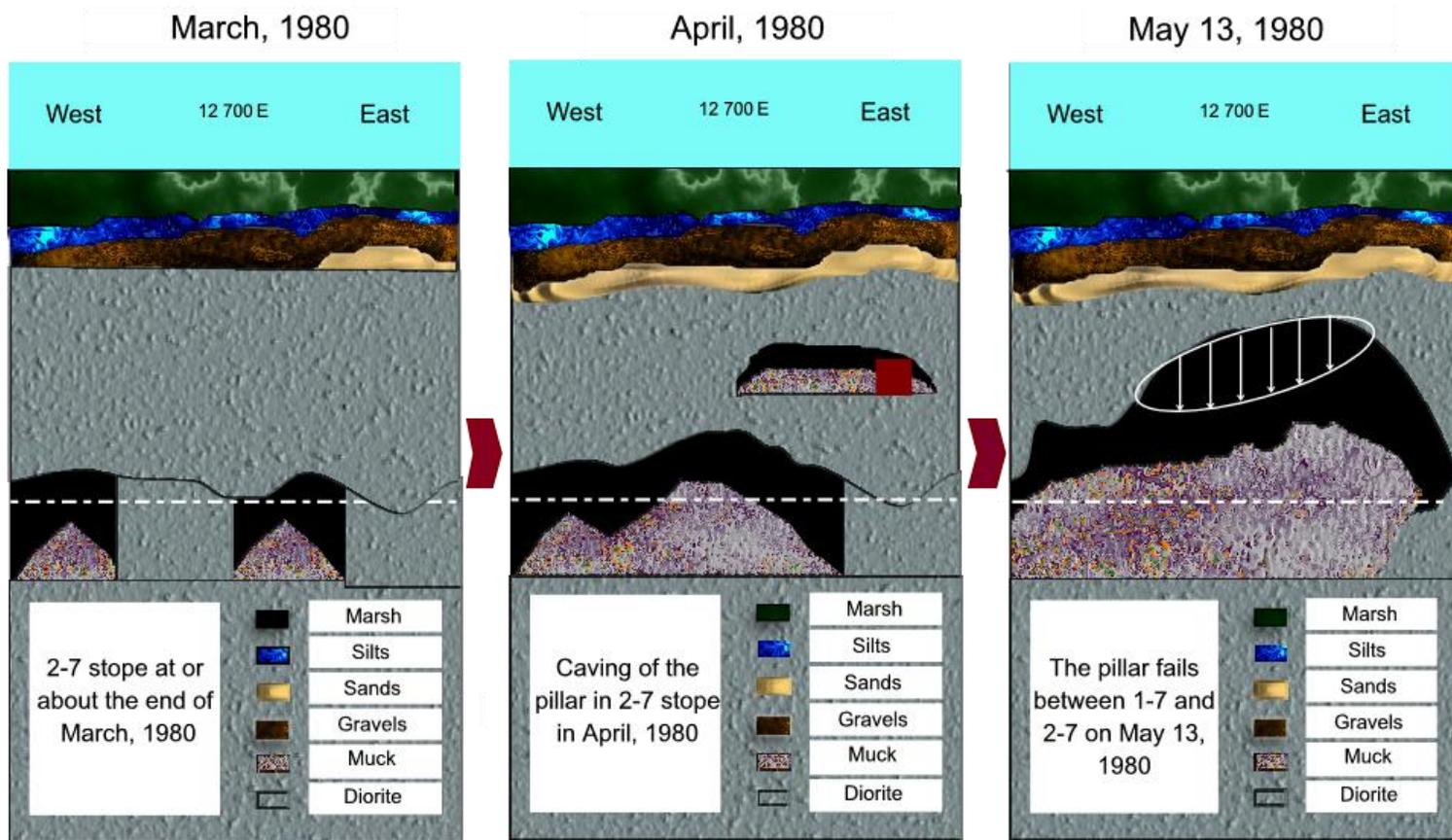


Figure 6.23: Illustration of the sequence of geo-mechanical failure events occurring in the 2-7 stope of the Ferderber mine (page 1 of 2) (Betournay, 1984)

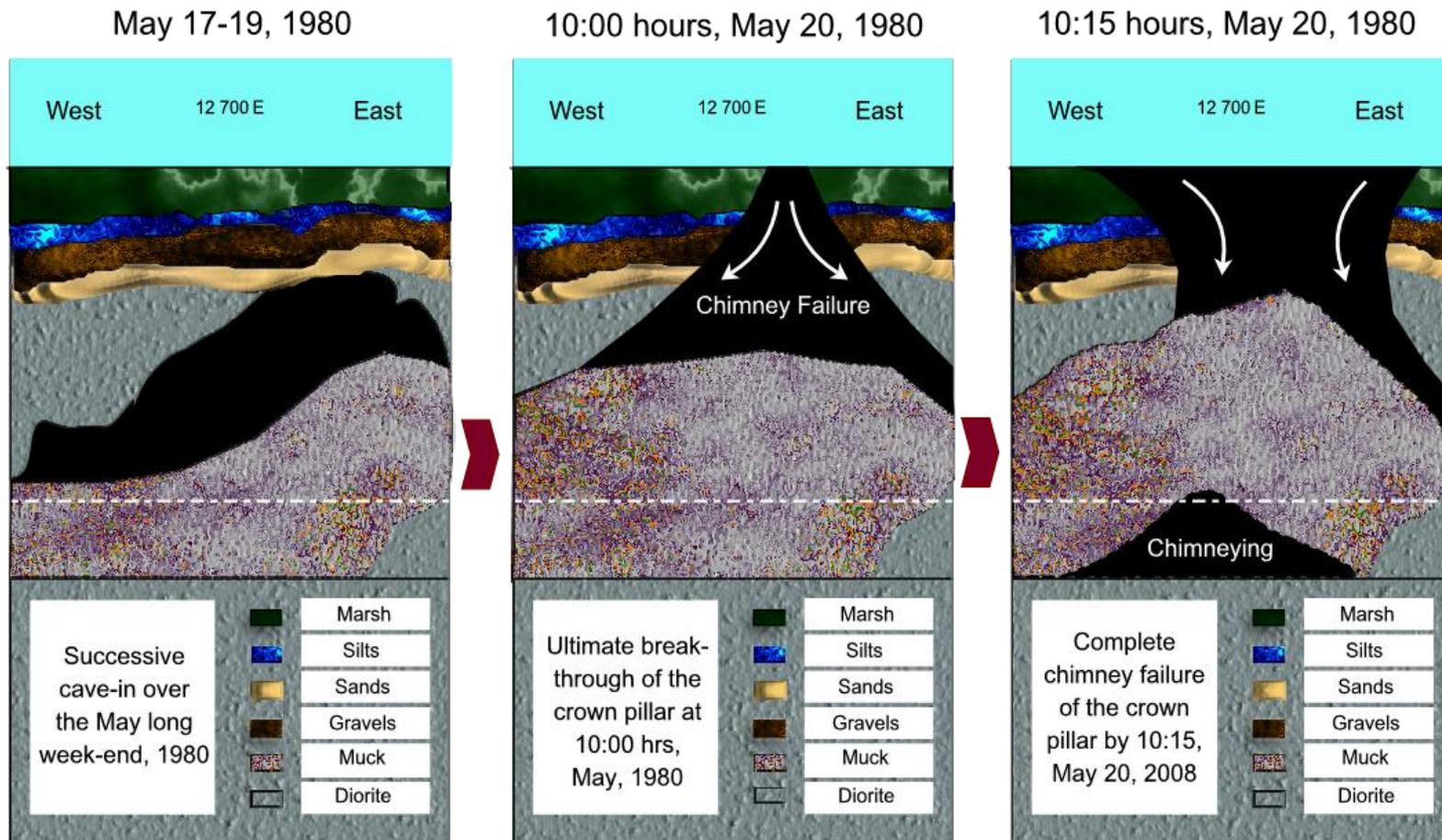


Figure 6.24: Illustration of the sequence of geo-mechanical failure events occurring in the 2-7 stope of the Ferderber mine (page 2 of 2) (Betournay, 1984)

6.10 Mission Criticality

The inclusion of case studies of historical disasters presents an opportunity to examine what factors or elements that are systemic in the escalation of an *event* that would be unacceptable in terms of operational integrity -- to an *event* that is truly calamitous; a disaster that by any definition defies prediction and explanation. What are these elements and how can they be detected and characterized so that error-forcing systems do not go unmitigated and result in much larger defining *events*? The answer to this fundamental question is immensely important and underlies the importance and predictive capacity of this research. Surprisingly, a cursory evaluation of only a handful of disasters spanning thirty years of industrial enterprise reveals that common to them are ten *criticality elements* that when present predispose these enterprises to not only mission failure, but the potential for calamity. Each of these ten *criticality elements* will be considered in turn.

6.10.1.1 Enterprise in Cognitive Deficit

Self-evident perhaps, is that enterprises disposed to cognitive deficit are vulnerable to error: human error or otherwise. Taken to an extreme, this vulnerability degrades operational integrity to the point of *self-organized criticality*. Lacking internal mechanisms of error detection, appropriate standards of care, and effective regulatory oversight, these enterprises exhibit operational imperatives that discount, if not disregard, risk and its perception. The Chernobyl nuclear disaster in 1986 epitomizes this *criticality element* as an enterprise driven to marginalize technical competence, operational standards and any semblance of regulatory governance (Medvedev, 1996).

By definition, an enterprise exhibiting cognitive deficit is comprised of parties that are disposed to errors of mistaken belief and does not have within it a capacity for situational awareness or cognitive dissonance. Absent this stimulus-pain response between the human element and potentially dangerous work environment, there is no natural error detecting mechanism that generates tension between intention and goals (Norman, 1981) that challenge risk-taking behaviours. To be clear, enterprises exhibiting cognitive deficit are inclusive of the operational parties, as well as organized labour, contractors, corporate management and regulatory authorities.

6.10.1.2 Operations in Cognitive Dissent

Second only to not knowing what the standards are, is the liability and risk of an operating mine compromising standards of care at the operational level. That is, parties closest to the hazards and controls (workforce or operations management) form an intention that is inappropriate with the goals. The Westray Mine disaster in 1992 exhibited this *criticality element* when mine management formed the intention of achieving short-term expediency (cash flow) at the expense of the operational goals (safe production).

Operations in cognitive dissent are particularly perilous when parties in authority exhibiting cognitive dissent do so at the expense of other parties in cognitive deficit. This was the case at the Westray Mine when mine management routinely denied the workers their right-to-know of hazards in the mine through intimidation and coercion (Richard, 1996). Ultimately, the best efforts of all parties to the enterprise are ineffectual, if those that have operational control of an enterprise exhibit cognitive dissent regarding standards of care and conduct within the mine workplace.

6.10.1.3 Inordinate Amounts of Stored Energy

A physical limitation of any enterprise is its capacity to mitigate uncontrolled energy release. If losses occur whereby people and equipment are exposed to energy beyond their operating limits, then there is a potential for the enterprise to experience a release of energy that it cannot control and from which it cannot recover. For this to occur, the amount of energy must be sufficient to destroy the plant, environment or workforce (or any combination therein) with little opportunity for intervention or mitigation. The energy type can be kinetic (rail transport), potential (dam structures), nuclear (power plants), electrical (lightning), chemical (reactions), thermal (fires) or biologic (biohazard).

The release of a biohazard is the exception insofar as the lethality is not defined by energy release; rather by its capacity for propagation and dormancy. In this regard, biohazards represent a special case of inordinate stored energy. Inordinate amounts of stored energy may be introduced as part of the enterprise, or may be the product or by-product of the enterprise. The Sunshine Mine disaster in 1972 is an example of the

former, by the introduction of polyurethane foam as a source of chemical energy, beyond their capacity to control. Coal mining (Westray Mine disaster in 1992) and petrochemical processing (Piper Alpha platform disaster of 1988) are examples of the latter, wherein the mineral commodity is a form of energy in and of itself.

6.10.1.4 Complexity and Coupling

Coupling and complexity (Perrow, 1984) speak to the connectedness of a system or its sub-systems, and more importantly from the perspective of *mission criticality*, the opportunities for failure detection and correction. In many ways, technologic advancement is synonymous with increased complexity (the interaction of components), as there is less transparency and understanding of how modern technologies works as systems become more specialized and sophisticated. Equally, higher production, closer tolerances and faster processing tends to increase coupling between processes and sub-systems resulting in reduced opportunities for intervention and correction. High complexity and coupling played a role in both the Piper Alpha platform disaster in 1988, and the Ocean Ranger platform disaster in 1982, when the operators were unable to anticipate and intervene in the rapidity of the degrading control systems. Complexity and coupling reduce the effectiveness of emergency response and crisis intervention.

6.10.1.5 Positive Feedback Loops

Negative feedback loops are dynamic systems that are intrinsically stable: when one or more of the initial operating conditions is altered, the system will naturally seek equilibrium. An example of a naturally occurring negative feedback loop is that of predator/prey relationships (Dörner, 1996). In this system, should there be an increase in prey (e.g. mice), their predators (e.g. coyotes) will increase in number because of the availability of food; thus increasing predatory pressure on the prey population. Eventually the numbers of prey decrease until the numbers of predators is not sustainable; and thus, the predator/prey populations maintain equilibrium.

Positive feedback loops are intrinsically unstable. Upon alteration of initial operating conditions, one or more variables can go to zero or infinity in a 'run-away' response that causes the system ultimately to fail. An example of a positive feedback

loop in nature is plant populations; the larger the plant population the more likely the plant population will establish itself within the ecosystem at the expense of other species. In technology, an example of a positive feedback loop is the Bhopal chemical plant disaster in 1984. The Bhopal chemical plant disaster occurred when water found its way into a containment vessel containing large quantities of the chemical methyl isocyanate (MIC), a precursor chemical in the formulation of pesticides. When in the presence of water, MIC reacts with an exothermic reaction. The higher the temperature, the greater the reaction rate, and the more heat that is produced. When contained, such a reaction 'runs away', and the limited confining volume causes pressure to increase until the vessel eventually ruptures, which is what occurred on the night of December 03, 1984. Consequently, a cloud of aerosolized MIC descended on the community of Bhopal killing as many as 2700, and injuring many more thousands (Morehouse and Subramaniam, 1986).

In the context of causality, positive feedback loops are analogous to catalysts in their capacity for escalating an otherwise limited tragic *event* into a disaster. Within the phenomenon of positive feedback systems is a dynamism and *criticality* making disaster scenarios appear irreversible, if not spontaneous in their occurrence. This research has determined that positive feedback loops contributed to the Westray Mine disaster in 1992; the Sunshine mine disaster in 1972; the Balmoral mine disaster in 1980; the Ocean Ranger platform disaster in 1982; the Bhopal chemical plant disaster in 1984; the Exxon Valdez ecologic disaster in 1989; and the Chernobyl nuclear reactor disaster in 1986. Positive feedback loops are so predominate in industrial disasters that they may be the single *criticality* element common to industrial disasters.

6.10.1.6 Operation/Enterprise in Transition

It is common knowledge that within steady state manufacturing and processing environments, there is an optimal range of operational parameters within which stability is achievable. Similarly, we observe that such systems exhibit intrinsic instability to the extent that these systems operate outside these parameters. Yet, for reasons of maintenance and other considerations, systems such as smelters and chemical reactors must transit sub-optimal ranges of operating parameters occasionally, thus presenting the concomitant risk of instability and failure. Operations in transition from development

to commission; production to maintenance; or generally from one state to another are thereby at substantial risk of system instability and the attendant 'forcing' of latent errors that manifest as upset conditions and ultimately as system failures.

This instability associated with a system in transition is not scale dependent, and hence applies to sub-systems as well as at the enterprise level. Thus, an enterprise subjected to fluctuating economic market conditions has within it the seeds of instability, if not failure. The Piper Alpha platform disaster in 1988 was one such enterprise in which the commodity price for oil and gas was exerting a cyclical response on the development and deployment of production assets that ultimately resulted in instability within the enterprise (Cullen, 1990). This culminated in one of the worst industrial disasters of twentieth century, fatally injuring 167 workers on July 06, 1988 when the Piper Alpha production platform erupted into fire while operating in the North Sea.

Systems in transition are commonplace and their influence can appear innocuous, as in the case of curtailing production in a manufacturing facility (Bhopal in 1984); or, as pernicious as the tests conducted within a nuclear reactor while under load (Chernobyl in 1986). In retrospect, the Chernobyl disaster appears predictable; however, the parties to the Bhopal disaster were more prescient as to a disaster in the making. Common to both disaster scenarios were sub-optimal operating conditions that induced system instabilities that were clearly self-evident, but remained unmitigated.

6.10.1.7 Lack of Effective Emergency Response

The importance of emergency response as a means of harm reduction and mitigation cannot be overstated. Less appreciated is the role that emergency preparedness and response have in communicating risk and creating consonance within the parties concerning risk perception. In both the Piper Alpha and the Ocean Ranger platform disasters, emergency preparedness and response would have benefited from a greater understanding of risk by all of the parties to the enterprise. The reverse is also true. Drills and training in emergency response actively promote and engage the parties in the communication (ideation and perception) of risk.

In both of the Piper Alpha and Ocean Ranger platform disasters, the workplace parties were lacking in the most fundamental knowledge concerning the platforms upon

which they worked: how to evacuate. That this is true suggests their worldview of their workplace was not inclusive of an *event* scenario that would require such knowledge and capability. This worldview was not present, because they lacked a perception of risk that would have suggested it. This research proposes that effective emergency response and preparedness capabilities incorporate risk communication, and to this extent offer a worldview, that engages the workplace parties through their own enlightened self-interest.

6.10.1.8 Lack of Risk Communication

Risk communication can take on many forms with a variety of messages and processes (Lundgren and McMakin, 2004). Communicating risk can occur before, during or after the encountering of risk, but is most effective as a continuum over time. Organizations that fail to communicate risk prior to exposure to a hazard typically are not diligent in risk identification; not effective in risk mitigation, and challenged in the communication of risk when crisis occurs. In the absence of risk communications, parties to the enterprise will formulate risk as determined by biases and heuristics, formulating a worldview that supports the distributed cognition of the social unit to which they are most affiliated (collective bargaining units, work-groups, trade organizations) and influenced by. Thus, poor risk communication enables the workplace parties to interpret the standards or artefacts of the workplace in a manner that supports their notion of their best interests. Consequently, a disparity of risk perception exists that reflects the variety of biases and heuristics exhibited by each of the various workplace parties. This disparity serves to widen the gap between the actual risk and its ideation. Poor risk communication is common within the case studies presented within this dissertation, and is second only to positive feedback loops in its revelatory and predictive capacity.

6.10.1.9 Lack of Regulatory Oversight

The lack of regulatory oversight includes, but is not limited to, the oversight of regulatory compliance by legislated authorities. We acknowledge that within any enterprise, all parties have to some degree a duty of care respecting the statutory requirements. Be it the legislated mandate and fiduciary responsibility of the regulatory authorities, or the duty to comply with the artefacts in the workplace imposed on the

workforce; the standards of care must be articulated, explained and enforced. This duty does not fall to any one party, but when all parties fail to exercise their role in ensuring statutory compliance, then for all practical purposes the standards and duties of care cease to exist. The Piper Alpha Platform disaster in 1988 and the Westray Mine disaster in 1992 are examples where the absence of regulatory oversight was a factor in their causality, and subsequently heralded new regulatory frameworks and legislation. Out of the furnace of adversity and tragedy is forged the anvil upon which the acceptability of risk for future enterprises is determined - and judged. In no small measure, failures of enterprises such as the Westray Mine and the Piper Alpha Production Platform have left a legacy from which we must all learn.

The term 'regulatory oversight' is inclusive of regulatory enforcement as well as the oversight of the mandate, statutory authorities and conduct of regulatory authorities. That is, without some form of judicial review or examination of the processes of statutory decision-making, regulatory authorities are subject to the same operational creep and normalization of deviance (Vaughn, 1996) as are other social units. Surprisingly, error(s) in statutory oversight was a factor in every case study presented within this dissertation, establishing its commonality, if not the degree of its contribution to causation.

6.10.1.10 Limited Access and Egress

Limited access and egress speaks to the ability of the workplace parties to remove themselves from the incipient or imminent danger localized by the workplace, or the ability to isolate that hazard. Mines, by their nature, are limited in access and egress, and are therefore a special class of workplace in which there is one degree of *criticality* inherent to the enterprise. Offshore drilling and production platforms also share in this element, and this observation may account for the establishment of standards and safety artefacts within these industries, and the associated ethos of error.

The perception of limited access and egress creates a worldview incorporating interdependence and self-dependence as imperatives because of the certain knowledge that one cannot walk away from *events* specific to the enterprise. Insofar as this vulnerability is anticipated and mitigated, limited access and egress can be managed within the context of acceptable risk. However, by this same measure limited access and

egress requires a higher level of risk communication and emergency preparedness, that if absent may render the risk unacceptable and the enterprise unfeasible. As example the Westray, Sunshine, and the Balmoral mine disasters all failed to mitigate the limited access and egress inherent with underground mining by not putting in place effective risk communication and emergency preparedness strategies.

6.10.2 Quantification of Mission Criticality

Mission criticality elements, as presented in this dissertation, are cumulative insofar as they are measures of potential for an *event* to escalate to a disaster. It is likely that mission criticality elements are not equally weighted; however, it would require a much larger sample of case studies to determine what that weighting should be, and how any criticality element combines to increase the *criticality* of another. Consequently, this research applies an exponential scheme of the quantification of mission criticality, whereby each criticality element is assigned a factor of 10, and the resulting Richter-like calculus is exponential.

The case studies examined by this research provide empirical evidence to suggest that within this scheme of quantification of mission criticality is some notion of the inherent risk associated with an enterprise. Nominally, for mines and offshore platforms, intrinsic to these enterprises are limited access and egress and inordinate amounts of stored energy. This represents an intrinsic mission criticality of 10^2 , and we acknowledge that these enterprises, by today's standards, do not present unacceptable risk. However, were the same operations to operate with as little as one additional mission criticality element present, a tipping point is reached: such is the nature of high-risk enterprises.

By this reckoning, and for the purposes of these case studies, any enterprise achieving a mission criticality of 10^3 indicates incipient danger of escalating to disaster. Similarly, a mission criticality of 10^4 represents imminent danger of escalation to disaster, where "disaster" is an *event* that results in the permanent cessation of the enterprise and loss of life. A working definition of disaster in terms of loss of life is any *event* resulting in five or more fatalities (Source and date unknown).

6.10.3 Mission Criticality as a Predictive Tool

Inordinate amounts of stored energy in combination with a positive feedback loop are a particularly insidious combination to avoid within any enterprise. Underground coalmines, by this classification, are inherently at risk for the potential for escalation to disaster, as they are limited in access and egress, subjected to positive feedback loops (coal dust explosion) and contain huge amounts of stored energy (methane and coal).

Similarly, a mine operation exhibiting cognitive dissent within an enterprise disposed to cognitive deficit is a 'red flag' insofar as the aetiology of error is concerned. These are examples wherein the application of the concept of mission criticality is applicable in a predictive manner through the profiling of cognitive error. Within an error-forcing system, cognitive error genotypes may manifest as decision error phenotypes and ultimately result in an *event* and tragedy – in proportion to the degree of mission criticality.

6.11 Case Synopses

This research profiled eight historical case studies of industrial disasters, five of which are presented in detail within this dissertation (Figure 6.25). The three case studies not examined in detail are the Bhopal chemical plant disaster in 1984, the Chernobyl nuclear reactor disaster in 1986, and the Exxon Valdez maritime disaster in 1989. The Bhopal chemical plant disaster is an example of an *event* within the chemical processing industry, and serves as a comparison to *events* within the mining and oil and gas industries. Similarly, the Chernobyl nuclear plant disaster is an example of an *event* from the nuclear industry, and the Exxon Valdez maritime disaster is an example of an *event* from the maritime shipping industry.

There are variations in the nature of investigations within those industries involving high technology and manufacturing processes: not in terms of human error or cognition, but in the chronological detail and documentation of culminating events. Maritime shipping, chemical manufacturing and power generation rely upon enunciated systems and programmable logic control processes, all of which leave an auditable record that are both precise and detailed as regards to sequence of events and their chronology. The Chernobyl nuclear plant disaster is a case in point in which the records

of degrading systems was measured not in hours or minutes, but in seconds. *Events* occurring in enterprises that have documented and detailed process-monitoring systems benefit not only the operators in error detection, but also provide a richer and more supportable evidentiary record in their investigation. The aviation industry in particular strives to achieve such acuity of material failure and engine performance by incorporating flight data recorders (black boxes) and cockpit voice recording technology.

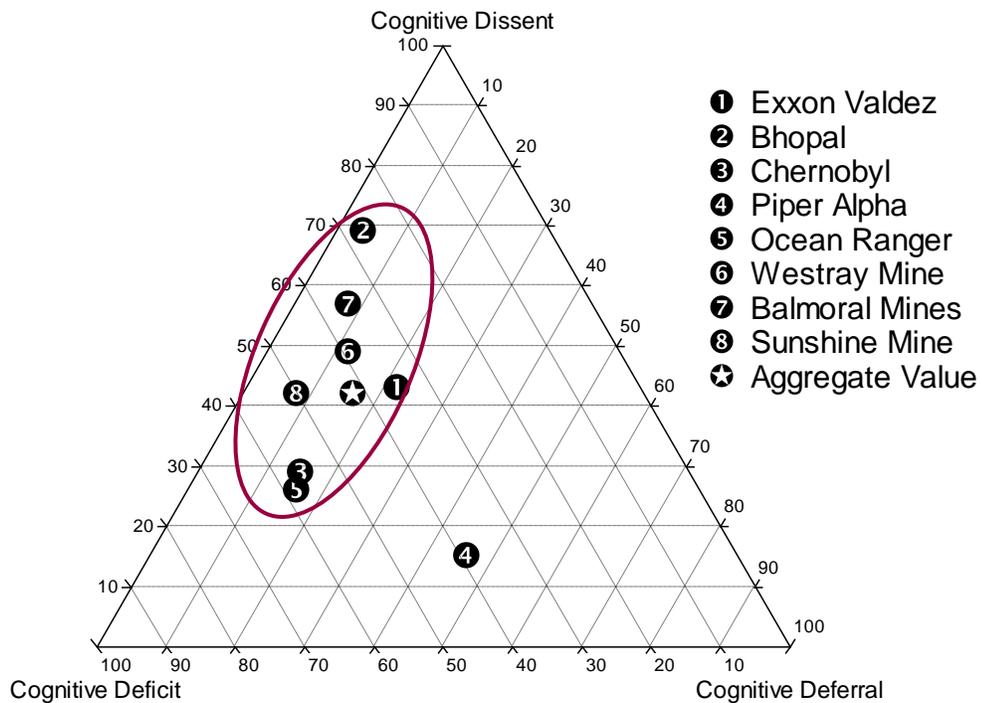


Figure 6.25: Ternary diagram illustrating the cognitive profiles of eight historical case studies

Comparatively, the eight case studies indicate that there is an axial distribution between the cognitive deficit and cognitive dissent regions of the cognitive ternary diagram (Figure 6.25). That is, errors of commission and mistaken belief dominate the historical decision error landscape. The exception was the Piper Alpha platform disaster, which by all accounts (Cullen, 1990) was an enterprise under mounting economic stress

and tight timelines. The Piper Alpha cognitive profile reflects this by being strongly disposed to cognitive deferral, more so than the other case studies. Predictably, one would not expect errors of omission throughout the enterprise. Errors of omission are defined by their interactivity; the manner in which the decision maker interacts with other parties or the work environment. To this extent, it is predictable that analysis of *events* at the operational level would be more disposed to cognitive deferral than *events* inclusive of other enterprise parties. These case studies illustrate the point that holistically, the character of the cognitive profile is sensitive to the scope of the *event* under scrutiny.

6.11.1.1 Decision Error Analysis

Decision error analysis has great potential in establishing the chronology of decision errors, the patterns of decision errors, and the manner in which one decision maker influences others. Within the context of these case studies however, the latter virtue is reduced – if not absent. The reports of inquiry and historical records simply do not contain the detail and perspective to determine the subtle manner in which the various parties to an *event* interact and influence the decision-making processes of each other. This potentiality is best realized by investigators with more intimate knowledge of the *event* and its determinants, and reinforces the imperative of investigations incorporating the dual perspectives of the investigator and the decision maker.

The character of all of the decision error diagrams is suggestive of a sequence-of-events approach to accident modelling. The investigations reflect the expedient of the investigator's desire to determine cause and effect; however, once determined the investigators tend not to consider how pervasive the cause(s) are, or the mechanism by which it was achieved. By this reasoning, decision error analysis may not fulfil its full potential as an analytical methodology until investigations of *events* within the workplace move beyond sequence-of-event modelling, and incorporate system theory.

6.11.1.2 Cognitive Profiling

Cognitive profiling of historical case studies is surprisingly effective. The scope and scale of the reports of inquiry and historical records is conducive to the characterization of the social structures and sub-units to the enterprise. The profiles of

these *events* are richer and more descriptive of the perceptions of risk shared by the various parties to the enterprise. The observation that historical case studies of disasters are inclusive of all industries suggests that one cannot discriminate between them based on cognitive error and that industry type is not a determinant of cognitive error; indeed, cognitive error is universal to all human enterprise.

6.12 Significance

The evaluation of mission criticality within the context of case studies is revealing. The commonality of mission critical elements is striking in consideration of the breadth of time and type of enterprise. Further, the concept of mission criticality adds a dimension to *event* causality that is both heuristic and holistic. The revelation is that the *events* documented by these case studies were not without precedent, if not portent. It is often overlooked that industrial tragedies and disasters are presaged by lesser *events* that are, in and of themselves, defining *events* and provide early warnings of incipient failures and systems that are creeping towards self-organized criticality. The Piper Alpha platform disaster of 1988, Bhopal chemical plant disaster of 1984 and the Balmoral mine disaster of 1980 all recorded fatalities that were early warnings of incipient system error; that had they been heeded, may have prevented subsequent and more calamitous *events*. In every case study excepting the Sunshine Mine disaster in 1972, there was a previous, albeit less dramatic, fatality or loss that presaged the tragedy or disaster that was to follow.

The analysis of case studies of industrial disasters reveals that just as cognitive error is antecedent to decision error; decision error is antecedent to the transgression of standards and hazard control (Figure 6.26). Similarly, *events* portend more serious and disastrous potentialities, or defining *events*, if left unmitigated. This suggests a fractal-like geometry for which *events* are systems within systems, depending upon the scale under scrutiny and the perspicacity of the observer. This non-linear geometry is consistent with the complexity and opaqueness of system theory and is in stark contrast to the early pyramid model of Heinrich (1931). Heinrich's model was linear and restrictive to *events* of similar causation, if not scale. The variation was in the magnitude of loss and suggested that there was in fact a numerical correlation between defining *events* and lesser *events*. In comparison, this fractal model is scale independent, and by

inference, there are systems nested within systems limited only by the discernment of the observer. By extension, within this fractal model there are error-forcing systems precursor to decision errors grounded in psychology (Reason, 1990). Similarly, there are *event* systems with greater potential for calamity than the tragedies and disasters that precede them – and many variations in between (Figure 6.26).

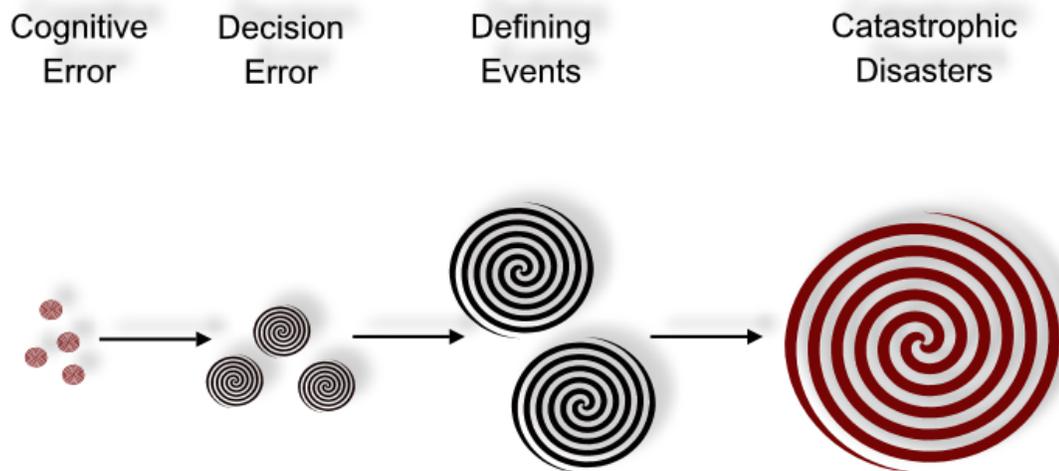


Figure 6.26: Fractal like geometry of error systems dependent upon scale and complexity

The significance of these case studies is in their commonality. Outwardly unique as evidenced by the variation in their enterprise, their locale and their organization, these case studies reveal inner clockwork, which through the reductionism of cognitive profiling is observable. The cognitive profiles of historical case studies describe cognitive underpinnings and perceptions of risk that are contributory to management system failure. Further, through a basic characterization of mission criticality elements, these case studies provide a capacity for prediction of latent errors and incipient failure modes that may reside within other, more contemporary mining enterprises.

Lastly, these case studies expand on the notion of causality on many levels. They suggest that to examine the aetiology of error, we must be attentive to scale. They suggest that the calculus of error is not linear, but something more complex – fractal-like. They suggest a notion of causality that is more complex than cause and effect; that

causality is defined not by the *event*, but rather by a system of errors of which the *event* is but one (but not necessarily the first of last) physical manifestation.

6.13 Conclusion

Cognitive profiling as applied to case studies is effective, robust and revealing. Cognitive profiling complements the investigative process, and is applicable as a third party analytical methodology. That is, an analyst applying cognitive profiling does not have to have firsthand knowledge of the investigation under consideration. To have firsthand knowledge would be of great value, but is not an imperative. This essential and practical virtue enables cognitive profiling to be applicable after the fact, by persons with expert knowledge in its application. The one challenge to the application of cognitive profiling to historical case studies is the lack of specificity of cultural and organizational norms that would otherwise prescribe duties of care. We all have a sense for how cultural mores and organizational structures shape our roles and responsibilities; however, that can be attributable to our cultural context. Examination of duties of care is very much culturally, and in some cases organizationally sensitive.

Decision error analysis is not as effective in the analysis of historical case studies, as it would be post-*event* as part of the investigative process. Decision error analysis greatly benefits from second party knowledge of the determinants to an *event* scenario, as well as awareness of the techno-social relationships between the respective workplace parties. Still, decision error analysis complements cognitive profiling, and enables cognitive profiling by providing an instrument (decision error analysis diagram) by which decision errors are organized and documented; however, the relationships between the various parties is not discernible through accounts within the historical record. In the absence of establishing relationships between the respective parties, it is difficult to appreciate the roles and responsibilities of the parties and the extent to which they shared decisions contributory to the *event*. Thus, decision error analysis does not have as great a utility for the back-analysis of investigations after the fact (historical case studies), but has more merit as a tool used in the investigation phase of *events* and their determination.

"A man of genius makes no mistakes. His errors are volitional and are the portals of discovery." James Joyce (Bartlett, 2000)

7 CONTEMPORARY FIELD RESEARCH

The contemporary operating mine study was selected by virtue of the reputation of the mine operation for its best practices respecting health and safety management systems. The researcher did not have any knowledge of the mine operations, nor did he visit the mine or contact representatives of the mine operations, to avoid biasing the study. To be clear, it was only the written investigation reports that were the subject of scrutiny and analysis. The types of *events* provided also limited the scope of study. Safety incidents predominated, followed by health and environmental incidents. The reports were not inclusive or representative of any events that had impact on communities, labour relations or First Nations.

7.1 Methodology

The subject of this field study was the Highland Valley Copper Mine, owned and operated by Teck Cominco. The mine is an open pit copper/gold property located near Logan Lake, British Columbia. The methodology of this study was grounded by previous work in Alberta (Sweeney, 2004), and seeks to determine the decision error characteristics of the mine without detailed knowledge of their operations or culture of safety. Teck Cominco, as a mine operator, was selected because it had a reputation for proactive investigation of accidents and a proven system of investigation. More importantly perhaps, Teck Cominco was prepared to disclose its accident history and share 'raw' reports of investigation. These reports were not edited in any way and were replete with identities, risk assessments and disciplinary actions as warranted. It was understood that these reports were to be used solely for the purposes of this research.

In an early stage of the study (first cohort), only 27 investigative reports spanning three years were evaluated, for the purpose of developing the methodology and designing the database for numerical analysis. The reports were determined to be unsatisfactory in terms of applying decision error analysis as they lacked chronology, specificity and scope of investigation. That is, they were based upon cause and effect relationships restrictive to the physical evidence and primary workplace parties directly witnessing or participating in the *event* scenario. In other words, the reports did not consider or scrutinize supervisory, management or corporate error contributions. They were also incomplete over the duration of the three years and therefore not statistically representative. A larger sample (second cohort) of 94 investigative reports spanning the year 2005 was analyzed and was found to be complete and inclusive. These reports proved satisfactory for the purposes of this research and comprise the bulk of the data for the field study, and have been sealed as external documents.

Templates were developed that could efficiently compile and record numerous *event* variables pertaining to each *event* record (investigation), and these summaries were then entered into a database. Reports were cross-referenced and cross-analyzed a variety of ways to determine what, if any, correlations existed. Analysis of the 94 *event* investigative reports generated in excess of 18,000 data permutations providing a wealth of information and *event* scene relationships. The analysis was conducted twice to empirically establish a margin of error in terms of reproducibility. That margin is 9% and is incorporated in all of the graphical analysis as the baseline margin of error.

7.1.1 Data Collection

Upon scrutiny for completeness, each of 97 reports was placed in chronological order and authenticated. Three reports were rejected for lack of completion, leaving 94 reports for study. Authenticated records were assigned a unique identifier. Reports were then randomly selected for analysis to reduce selection bias. The unique identifier was the means by which the data were collated and recorded to reduce attribution bias. Reports were evaluated twice; once by decision errors analysis and a second time by semi-quantitative risk assessment. Reports selected for decision error analysis were selected randomly and remained separate from those selected for risk assessment to

avoid attribution error. The objective was to evaluate every investigative report for risk as perceived by the researcher using an objective and standardized research methodology.

Decision error analysis and semi-quantitative risk analysis are considered complementary to each other; decision error analysis being a qualitative analysis (Figure 7.1) with respect to risk, and conventional risk matrices being semi-quantitative analysis with respect to risk (Figure 7.2 and 7.3). For each report of investigation, a distinction was made respecting those decision errors that were explicitly articulated by the investigator(s) as causally related, and those decision errors that were implied elsewhere within the report. A tally of the number of implicit and explicit decision errors was maintained for each record to determine the ratio of implicit to explicit decision errors. This ratio is referred to as the cause and effect ratio, and serves to illustrate the discipline demonstrated by the investigators in grounding their conclusions on established determinants and causation.

7.1.1.1 Explicit Decision Errors

Explicit decision errors are those errors, on the part of parties, that were recorded as occurrences of some form of human error by the investigator(s) of record. If a standard or duty of care existed, then the error was evaluated for its decision error potential. Decision errors that were explicitly identified typically were characterized as operator errors, human failure or lack of caution by the investigator(s) of record. It then remained for the researcher to determine the typology of these errors through witness statements, declarative and conclusive statements on the part of the investigator(s).

7.1.1.2 Implicit Decision Errors

Implicit decision errors were those errors, for which no direct attribution of human error could be made, but human error was implied within the recommendations or corrective action taken, as identified within the reports. As an example, in one report a failed component was stated to be the direct cause of an *event*, but a recommendation was made that a worker be reacquainted with a procedure or practice, in the absence of any statement that a procedure or practice was violated. Again, an *a priori* standard of care, rule, or norm has to exist prior to a determination qualifying as a decision error.

7.1.2 Qualitative Risk Assessment

Risk is a concept with which most mine operators are familiar, and have some appreciation for, at least in terms of risk/reward. We all have different levels of risk tolerance, or risk aversion, depending upon our perception of risk. Risk perception is the compass we use to navigate through the myriad decisions that require a balance to be struck between risk and benefit. Perception is subject to many factors including cognition, experience, social mores and knowledge. In this research, the perception of risk is modelled by three risk/uncertainty regimes in the workplace in terms of observable behaviour. The three regimes are *due diligence*, *normative compliance* and *regulatory compliance* with respect to risk (Figure 7.1). These same three regimes correspond to *operational integrity*, *operational homeostasis* and *operational creep* with respect to uncertainty. The color of each of these three regimes (Figure 7.1) is significant and maintained in the matrix used for semi-quantitative analysis (Figures 7.2 and 7.3).

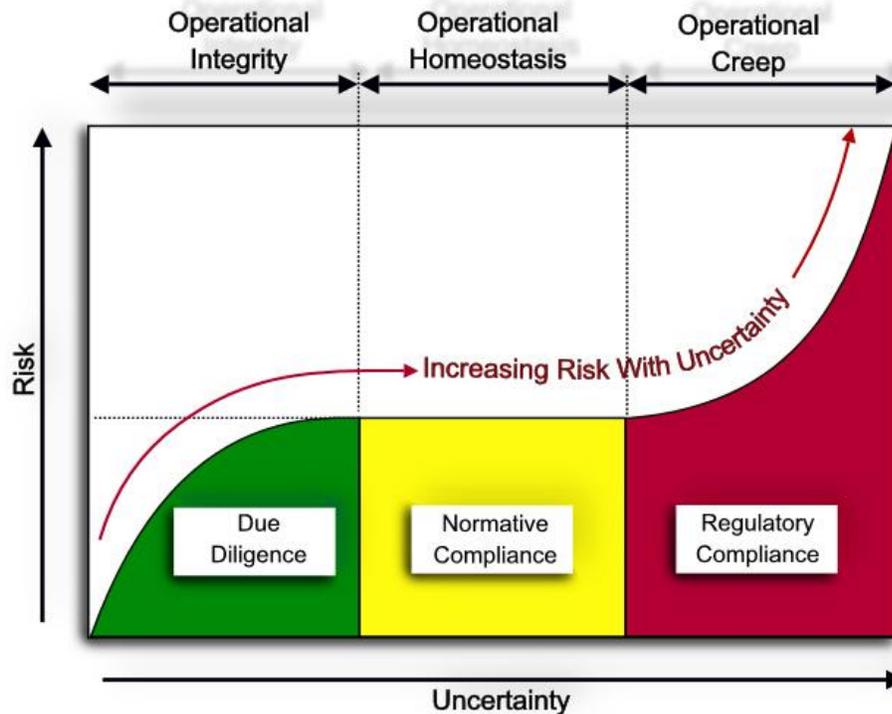


Figure 7.1: Graphical illustration of a risk behaviour model comprised of three risk-taking regimes

At the one extreme of this schema, there is a duly diligent behaviour or culture; one that is somewhat risk averse and prone to uncertainty avoidance (Strauch, 2005). In this regime, uncertainty is nominal, and mine management achieves *operational integrity*. At the other extreme is a risk tolerant behaviour, or culture, that strives to 'just meet' regulatory compliance as the standard of care. In this regime, risk and uncertainty are high because management is substituting management systems with statute that are subject to individual interpretation and prone to *operational creep*. Lastly, there is the middle ground of an organization that is risk averse enough to employ 'beyond compliance' standards but demonstrates a homeostatic relationship with risk, and therefore with uncertainty. Like most human enterprises, a mine organization will naturally evolve towards risk reduction, in response to the changing socio-economic expectations, competitiveness and self awareness of their social license to operate.

7.1.2.1 Operational Integrity

Operational integrity is the virtue of achieving sufficient reliability and acceptable risk within a known operating environment. Uncertainty is manageable and management has assurance that mine supervision is being duly diligent in their conduct; they are doing all that is reasonable and practical to protect the workers, the operation, and the environment from harm. The standard of care exceeds that of statute and normative compliance, striving for best practices or 'best in industry' practices in an effort to keep risk low and within acceptable limits (Figure 7.1). A duly diligent culture is not one in which errors are absent; but one in which errors are defensible and can pass the test of acceptability. Mine management achieving operational integrity are performance driven and frame risk and uncertainty as undermining their diligence to the operation. The absence of *operational integrity* is a state of uncertainty; of not knowing if the operating conditions are within design parameters or expectations.

7.1.2.2 Operational Homeostasis

A lesser standard of care in terms of risk and uncertainty is *operational homeostasis*. Here normative compliance is the expectation of mine management, a standard of care beyond regulatory compliance through the implementation of 'rule based' systems in the form of policies, procedures and practices. Mine operations in this

regime are more prescriptive in their operational requirements, but still sensitive to meeting statutory obligations (Figure 7.1). However, should management introduce technological improvements or operational changes that reduce uncertainty and risk (i.e. better traction on mine roads), there is a natural tendency for operators to change their behaviour to maintain the same risk (such as traveling at higher speeds). Consequently mine management is prudent to introduce increased expectations and standards of care when risk reduction is achieved. This phenomenon is known as *risk homeostasis* (Wilde, 1994), when presented individually, or as *operational homeostasis* in the collective.

7.1.2.3 Operational Creep

Operational creep is the risk/uncertainty regime that relies on statutory compliance as the prevailing standard of care. This 'just meeting' approach is an ethos that permeates the entire mine enterprise and serves to reinforce the argument that industry cannot regulate itself. Those that do not practice 'beyond compliance' standards are inclined towards risk taking as an economic advantage and a means by which they believe they exert control over their enterprise. Just meeting regulatory compliance is not a winning strategy for the prevention of *events* in the workplace, be it mining or any other industry. Canadian regulations are written to represent the public interest, honour the Crown and set expectations by way of a minimum standard of care and conduct in the workplace. Regulatory statutes are not meant as a substitute for injury prevention strategies or proactive risk management. Appropriately, the regulatory landscape is changing to reflect this reality by replacing prescriptive regulation with more performance- or outcomes-based regulation that obliges mine operators to identify and mitigate the risks (Treasury Board of Canada Secretariat, 2007).

Organizations without accident prevention strategies do so at their peril by devolving discretion and interpretation of the regulations to the mine workforce. In so doing they abdicate responsibility in managing hazards and risks in the workplace by permitting the mine workforce to 'creep' or drift toward non-compliance (Figure 7.1). This creeping occurs gradually over time as workers misplace priorities and gradually reinterpret regulation to support what they believe to be their best interests. The dynamic is one of scarce resources and competition resulting in compromise, influencing decisions and trade-offs (Dekker, 2005). An example of this is the removal of guards on

equipment to increase productivity, or taking procedural shortcuts for the same purpose. Occasionally, this *creep* towards non-compliance is accelerated through coercion, or insidiously through bonuses and production schemes that indirectly reward workers for non-compliance. Either way, organizations satisfied with a 'just meeting' compliance standard of care set themselves up for labour relations issues as workers will inevitably interpret legislation at odds with how their supervisors and management interpret legislation. Fortunately, within the mining industry of British Columbia, there is sensitivity towards achieving social license, and few mine operations are satisfied with regulatory compliance as a nominal standard of care.

7.1.3 Semi-quantitative Risk Assessment

Semi-quantitative risk assessment quantifies risk as the arithmetic product of the likelihood of an *event* (E_L) and the consequence of the realization of that *event* (E_C). This methodology of risk assessment is common within industry (Wilson et al, 2003), and produces risk matrices and tables that quantify probabilistic values of likelihood and consequence as related to the types of *events* under scrutiny. This research employs a similar matrix that specifies four types (domains) of *events* in terms of risk to people, assets, the environment and production (Figure 7.2 and 7.3).

Each investigative record was quantified with respect to effective risk, in consideration of possible risk associated with each domain; the highest risk determining the risk of record. Thus, were workers to be subjected to vapours from a diesel fuel spill, and the risk of that spill was greater to the environment; the risk to the environment was recorded as the risk of record. The resulting numerical value of risk is a relative (ordinal) quantification and not absolute, as it is relative to the types of *events* and their characterization, as well as the subjectivity and perception of the researcher. The ranges of values of risk are 0.001 (shaded green) to 100,000 (shaded black), and are without units (Figure 7.2).

The quantification of risk complements the qualification of risk, as illustrated by a second risk matrix (Figure 7.3) that translates the semi-quantified values of risk (Figure 7.2) into the qualification of risk (illustrated by the three risk regimes depicted in Figure 7.1). Within this model, risk values between 0.001 and 1.0 (shaded green) are

associated with a *due diligence* culture in which risks are as *low as reasonably practicable* (ALARP) and is the regime that achieves *operational integrity* in terms of uncertainty. Risk values between 1.0 and 100 (shaded yellow) are associated with a *normative compliance* culture in which the uncertainty is acceptable, but subject to *operational homeostasis*. Similarly, risk values between 100 and 1000 (shaded red) are associated with a regulatory compliance culture in which the risks are questionable, and uncertainty is subject to *operational creep*. Risks (shaded black) that are 10,000 (10^4), or greater, are non-compliant with both standards of care and regulatory compliance, and the uncertainty is so extreme as to be unacceptable (Figure 7.3). Thusly, every *event* identified within each investigative report was assessed a value of risk based upon these risk matrices, and this semi-quantification of risk is referred to as *effective risk* within this dissertation.

		Consequences				Increasing Likelihood				
		Generalized Risk Matrix				0.001	0.01	0.1	1.0	10
		People	Assets	Environment	Production	No Precedent Within Industry	Occurred Only Rarely Within Industry	Occurred Only Rarely Within Company	Occurred Only Rarely Within Mine	Occurred Regularly Within Mine
Increasing Severity of Events	10000	Multiple Fatalities	Mine Closure	External Mine Property Damage	Stop Work	10.0	100	1000	10000	100000
	1000	Fatality	Mine Threat	Internal Mine Property Damage	Stop Work Threat	1.0	10.0	100	1000	10000
	100	Critical Injury	Insurance Claim	Exceed Statute	Slow Down	0.1	1.0	10.0	100	1000
	10	Medical Aid	Requires Budget Approval	Exceed Mine Standard	Impact	0.01	0.1	1.0	10.0	100
	1	First Aid	Within Budget Limits	Within Accept Limits	No Impact	0.001	0.01	0.1	1.0	10.0

Figure 7.2: Matrix graphically illustrating risk as a product of *event* likelihood and consequence

		Consequences				Increasing Likelihood				
		Generalized Risk Matrix				0.001	0.01	0.1	1.0	10
		People	Assets	Environment	Production	No Precedent Within Industry	Occurred Only Rarely Within Industry	Occurred Only Rarely Within Company	Occurred Only Rarely Within Mine	Occurred Regularly Within Mine
Increasing Severity of Events	10000	Multiple Fatalities	Mine Closure	External Mine Property Damage	Stop Work					
	1000	Fatality	Mine Threat	Internal Mine Property Damage	Stop Work Threat					
	100	Critical Injury	Insurance Claim	Exceed Statute	Slow Down					
	10	Medical Aid	Requires Budget Approval	Exceed Mine Standard	Impact					
	1	First Aid	Within Budget Limits	Within Accept Limits	No Impact					

Figure 7.3: Matrix of a graphical illustration of three increasing zones of risk and uncertainty

7.1.3.1 Mission Criticality and Risk

Mission criticality for each investigative report was determined by considering each *event* in terms of the presence of any one of the ten mission criticality elements presented previously (Section 6.11). Accordingly, mission criticality elements were ascribed a value of 10, should they be present and contributory to the *event* in question. Consistent with semi-quantitative risk modelling, a mission criticality of 10^4 defines the threshold beyond which the risk is unacceptable. In this respect, mission criticality represents a measure of the potential for the *event* of record to escalate to an *event* of much greater magnitude - possibly to a disaster. The difference between the effective risk attributed to an *event* record and the mission criticality speaks to the degree to which the risk associated with the *event* was effectively mitigated. As an example, if the effective risk associated with the *event* of record was 8.0, but the mission criticality for that *event* was determined to be 100, there is evidence to support that in spite of the

occurrence of the *event*, there was some benefit from risk mitigation and control. This concept may appear to be contrary to our notion of prevention, but is inclusive of the possibility that *events* are systems in which the outcomes are pluralistic and stochastic in nature.

7.1.4 Data Validation

Although the worksheets were all validated for error, the best truth testing was accomplished by the researcher meeting with a representative of the Highland Valley Copper Mine to ensure that for each investigation report, the researcher had an accurate understanding of the risks and decision errors presented. This was done post-analysis only, to maintain objectivity, and served to more accurately understand the cost valuation of *events*, and the organizational structure of the mine. Also, it is considered a prudent step from the point of view of data integrity and credibility.

7.1.5 Cost Valuation

Valuation of cost associated with an *event* was modeled in a very structured way. Any incident that merited a written report was assessed at \$100; a medical aid was assessed \$1000; a lost time claim \$10,000; and, a permanent disabling injury \$100,000. Also considered were losses to assets on the basis of the description of the damages, and losses to the environment and production. *Event* cost valuation was determined and recorded by the higher of the costs associated with the *event*, if more than one category of loss applied. A work sheet was devised to record the pertinent data associated with each investigation record. The cost figures are not intended to be accurate; but rather a reasonable approximation for the purposes of modeling.

7.1.6 Statistical Analysis

The database for this research consists of numerous spreadsheets in which the investigative records were sorted and cross-referenced by category. These categories include mine department, mechanism of injury, occupation, job experience, calendar day of the *event*, time of day of the *event*, cost valuation of the *event*, mission criticality, effective risk, type of *event*, cause and effect ratio and decision errors. The analysis is

relatively straightforward. The values for each category or domain under examination have been totalled and averaged, and then plotted via scatter plot, bar, ternary, or radar diagrams. Best-fit curve analysis was conducted on the scatter plots, with the coefficient of correlation indicating the degree of fit for each curve. An error margin of 9% was applied for all analyses, as determined by an error evaluation.

7.2 Analysis

The analysis of the investigative records was completed over two time periods, as presented by two cohorts of records. The first cohort (2002-2004) was a small sample size (27 records) to determine feasibility and methodology for this research. The second cohort (2005) was more comprehensive (94 records) and comprises the majority of this research. The second cohort of data (2005) spanned all twelve calendar months.

7.2.1 The First Cohort

Year	No.	Average Exp. (Years)	Average Mission Criticality	Average Effective Risk	Average Cost Factor	EMB	EOO	EOC	C/E Ratio
2002	9	19	15	19	\$910	48%	19%	33%	65%
2003	10	13	4	19	\$2000	53%	18%	29%	58%
2004	8	09	23	26	\$2743	52%	18%	30%	62%
1	2	3	4	5	6	7	8	9	10

Table 7-1: First cohort of data according to year of investigative report

Of the 27 investigation reports comprising the first cohort, nine were from the year 2002, ten from the year 2003, and eight from the year 2004. Early on in this research it became apparent that, for the most part, these accidents did not generate enough data for decision error analysis diagrams. Additionally, there were data only from the last six months of each year, and this precluded analyzing the investigations in depth for the purposes of trend analysis. Still, analysis of these investigative reports provided the foundation for the development of the techniques and data structures that would prove to be successful in the second cohort. Data from the first and the second cohort have been analyzed separately. The analysis of the first cohort was conducted twice, to

get some appreciation for the repeatability or margin of error in the results. It was determined that there was an intrinsic margin of error of 9%. Bearing in mind the paucity of reports for each year, there is little to conclude about the first cohort data in terms of trend analysis. However, in general it was observed that:

- i. There is a significant decline in the job experience (column 3) of persons involved in *events* at the mine; from nineteen years in 2002 to nine years in 2004. This may be a result of general attrition of the more senior members of the workforce; or an increase in the accident rate of workers with less experience. Given that the errors of mistaken belief (column 7) are consistent over the three years, it is suggested that a significant number of experienced workers have left and been replaced with less experienced workers.
- ii. The values for mission criticality (column 4) are consistently low with a value of 14. This is indicative of an operation with only one mission critical risk element; in this case, the large amounts of kinetic energy associated with mobile mine equipment.
- iii. The values for average effective risk (column 4) are also relatively low. Within the context of the risk matrix, values of nineteen and twenty-six correspond to the low risk regime of demonstrating due diligence, and the low uncertainty regime of operational integrity. This classification is considered best-of-industry-class.
- iv. The values for average cost factor range from \$910.00 to \$2743.00 per *event*. These values are considered second order (> \$1000) according to the model, and are indicative of an *event* environment in which the harm is largely to people, and the likely outcome is a medical-aid loss.
- v. An analysis of decision errors reveals values consistent over the three years; certainly within the 9% margin of error. This suggests that both the accident investigation methodology and the safety culture in which *events* occur are consistent over the three year period. Moreover, the decision errors are significantly predisposed towards errors of mistaken belief, with the remaining errors being shared by errors of omission and errors of commission. The preponderance of errors of mistaken belief, in general speaks to a work climate in which workers are either not familiar with standards that apply, or make assumptions, that had they been true would have rendered the decision

innocent. The former case is indicative of a workforce with insufficient training; the latter a workforce that lacks maturity and experience on the job. It is not clear which of these applies from the limited amount of data.

- vi. The cause/effect ratio (column 10), as defined previously, is the ratio of decision errors that are identified explicitly as causes of the *event*, to all decision errors; explicit and implicit (through recommendations and action); presented as a percentage. The lower the percentage, the more the investigators intuitively assess the evidence, or lack thereof, for factors of causation. The values range from 58 to 66; again, fairly consistent throughout the three years and indicative of a systematized methodology of investigating accidents and incidents. Arithmetically, about one-third of the decision errors were implied through the process of recommendations and action. On the one hand, the investigators are demonstrating considerable insight and intuition in terms of the dynamics of the mine workplace. On the other hand, there appears to be a worker friendly bias at play that gives the mine operators the benefit of the doubt, at the expense of a more rigorous investigative approach. This speaks to an affiliated and accommodating relationship between management and mine operators that is probably highly valued by the workplace parties. It may also imply a lack of rigour of investigative process that could have implications concerning future *events*.

There is considerable difference between the first cohort of investigative reports (2002-2004) and that of the second cohort spanning the 2005 calendar year. The investigation reports submitted for 2005 appear more comprehensive in terms of both format and methodology. The second cohort reports are more inclusive of information; in particular risk assessments. They also have more detail in general, and narration in particular. These reports lend themselves readily to cognitive profiling, but attempts to depict the decision errors on decision error analysis diagrams were not as successful, owing to the lack of chronology and reporting relationships. These reports rarely address training issues or competencies. Also, any reference to management systems is conspicuous in its absence. To this extent Highland Valley Copper's health and safety management systems remain obscure, in terms of root causality, to this research.

7.2.2 The Second Cohort

There are a total of 94 records of investigations of accidents and incidents (*events*) in the second cohort (Table 7.2). The reports include all types of *events* including those involving near misses, environmental harm, equipment failure, vehicular collisions, first aid, medical aid and lost time. The second cohort of investigative reports are consistent and systematic in their detail; so much so, that they strongly influenced the structure and organization of the research database used in their analysis. Each of the worksheets is summarized, tabulated, and presented in turn.

Month	No.	Average Exp. (Years)	Average Mission Criticality	Average Effective Risk	Average Cost Factor	EMB	EOO	EOC
Jan	6	22	33	25	\$4,000	33%	17%	50%
Feb	8	11	143	33	\$4,375	47%	21%	32%
Mar	12	13	156	18	\$2,508	53%	14%	33%
Apr	11	18	155	16	\$2,473	54%	14%	32%
May	6	12	51	7	\$4,000	57%	10%	33%
Jun	8	10	134	8	\$2,888	53%	14%	33%
Jul	6	6	24	4	\$4,167	50%	8%	42%
Aug	6	8	42	10	\$5,350	56%	13%	31%
Sep	5	8	50	5	\$1,000	38%	8%	54%
Oct	15	17	177	12	\$3,467	36%	11%	53%
Nov	7	16	133	22	\$3,443	38%	8%	54%
Dec	5	9	14	6	\$1,000	40%	12%	48%
1	2	3	4	5	6	7	8	9

Table 7-2: Table summarizing data from the second cohort with respect to calendar month

7.2.3 Number of Events per Calendar Month

Each report of an investigation defines an *event* (incident/accident) that has been sorted by calendar month, as illustrated by the scatter plot in (Figure 7.4). When trend analysis is applied by mathematical regression, a third order equation reveals a correlation coefficient of 0.45. The curve appears to have two local maxima: one in March, and a second in mid-November. By comparison, there is a minimum of *events*

occurring during the summer months. This curve suggests that the hazards, and therefore the attendant *events* at the mine are affected, if not controlled by, seasonal weather. This behavior may also be explained, in part, as an effect of reduced production during the summer periods for any number of reasons, such as a maintenance turn-around. It is left to mine management to review the temporal pattern of operations during the year 2005.

7.2.3.1 Cognitive Profiles by Calendar Month

The values for decision errors according to calendar month are presented by way of a cognitive profile ternary diagram (Figure 7.5). The aggregate value reports to the 'neutral' region of the diagram, illustrating that overall, the mine workers are not disposed to any one particular decision error type. To this extent, Highland Valley Copper mine management manages the workplace objectively and with little cognitive predisposition. The decision errors by month are dispersed into three groups. From September through January the errors fall in the region of cognitive dissent; from February through June the errors are report to the region of cognitive deficit; and, for July and December the errors exhibit no central tendency. This distribution appears to be seasonally controlled; quite likely by the amount of moisture on the ground.

A more conventional way of presenting the decision errors is by scatter plots. There are three decision error phenotypes: errors of commission, errors of mistaken belief, and errors of omission; and we consider each in turn (Figures 7.6 to 7.8).

7.2.3.2 Errors of Commission by Calendar Month

The best fit curve is a third order equation with a correlation coefficient of 0.74, indicating a sinusoidal distribution of data (Figure 7.6). The minimum point on the curve occurs for those *events* occurring in, and around, the month of March. The maximum point on the curve occurs for those *events* occurring in, and around, the month of November. Examination of this graph and the specific *events* that occur during these months lead the researcher to the supposition that these *events* are strongly controlled by season – specifically fall freeze-up and spring break-up. The onset of winter appears to challenge compliant behavior, whereupon compliance improves toward spring.

7.2.3.3 Errors of Mistaken Belief by Calendar Month

When decision errors of mistaken belief are plotted, we see a similar phenomenon occurring (Figure 7.7). The distribution is again clearly sinusoidal when trend analysis is applied, with a correlation coefficient of nearly 0.81. There is a maximum occurring in and around the month of March, and a minimum in and around the months of October and November. Evidently, there are two seasons which are influencing cognitive error. Moreover the two curves are in transition from June through September; the months in which ground surface conditions are most stable. This again supports the supposition that *events* occurring at the Highland Valley Copper mine are seasonally affected. Further, the spring time conditions present the best opportunity for development and training, as evidenced by the peak in errors of mistaken belief.

7.2.3.4 Errors of Omission by Calendar Month

When we consider the third and final class of decision errors – errors of omission, we see a different distribution (Figure 7.8). Over the course of the year, there is a steady decline in the number of decision errors of omission occurring. Given that errors of omission are strongly affected by human factors and environmental factors, one can only speculate as to what is controlling this behavior. Yet, the correlation coefficient is high – nearly 0.80. Reflecting on the types of accidents that flow from errors of omission, it is less clear what human factor, if any, is contributing to this trend. How, and to what extent, these human factors are controlled by the time of year is not known and requires further examination. It is left to the Highland Valley Copper mine management to consider what might account for the decline in decision errors of omission over time.

7.2.3.5 Average Effective Risk by Calendar Month

It is noted the semi-quantitative assessment of risk was determined independent of the qualitative analysis of decision errors. That is, the two analyses were conducted separately. The risk that is modeled - post *event*, is known as the *effective risk* and is the arithmetic difference between the intrinsic risk and risk reduction, after risk controls and mitigation strategies have had effect. The average *effective risk* with respect to calendar months is plotted in Figure 7.9. The curve appears to have a maximum during January and February, and minimum during summer and early fall. The coefficient of correlation

is a modest 0.62; however, the 'best fit' trend line is supportive of the hypothesis of a seasonally affected risk profile at the Highland Valley Copper Mine site.

7.2.3.6 Mission Criticality by Calendar Month

Next, we consider average mission criticality (Figure 7.10) for each month. The 'best fit' curve in Figure 7.10 is a fourth order equation with a correlation coefficient of 0.656. It is once again evident that there are two local maxima during March and November. Further, there is the now familiar local minimum during the summer and fall months. Clearly, the distribution of mission criticality with respect to time resembles that of the analysis for decision errors and *event* frequency.

7.2.3.7 Average Cost of Accidents/Incidents per Calendar Month

The direct cost associated with each *event* was determined as described in the methodology section of this report; but is only a first approximation. It is possible, however, to arrive at a cost factor within an order of magnitude. No trend is apparent with respect to time. The average *event* cost factor of is approximately \$3,248.

7.2.4 Data Correlated With Respect to Mine Department

Mine Department	Count	Average Experience (Years)	Average Mission Criticality	Average Effective Risk	Average Cost Factor	EMB	EOO	EOC
Other	3	12	40	7	\$4,000	63%	0%	38%
Mine Ops	18	12	24	18	\$4,400	44%	21%	35%
Mine Main.	22	19	5	12	\$2,232	40%	13%	46%
Mill Ops	11	3	7	16	\$4,282	59%	14%	27%
Mill Main.	41	13	10	14	\$2,956	42%	10%	49%
1	2	3	4	5	6	7	8	9

Table 7-3: Table summarizing data from the second cohort with respect to mine department

7.2.4.1 Cognitive Profiling by Mine Department

When plotted on the cognitive profiling ternary diagram (Figure 7.11), the five mine departments are grouped around the aggregate value in a moderately tight group

of points, indicative of a cohesive and coherent organizational structure – a testament to organizational consonance. The departments do show some marginal predilection for decision errors of mistaken belief, as is evident by their proximity to that region of the ternary diagram. Mill Operations is a notable outlier insofar as it is clearly in the region of cognitive deficit. This observation must be considered with some context. The types of *events* demonstrating cognitive deficit are those in which the operators are in situations that demand considerable experience, or knowledge of operating procedures. To the extent that these scenarios are complex or coupled, they present increased intrinsic risk. Mill Operations is such a working environment. Mill operations are both moderately complex and tightly coupled in terms of work flow systems. Working in this environment requires greater critical task thinking. This being the case, Mill Operations operators may be required to meet a greater number of procedures and practices; and this is borne out by the decision error data, as presented in the cognitive profiling ternary diagram.

7.2.4.2 Mine Department Ranked by Number of Events

The bar graph (Figure 7.12) of mine department ranked according to number of *events* reveals that Mill Maintenance experiences a significantly greater number of *events* than does Mine Maintenance, Mine Operations, or Mill Operations in 2005; in that order. This can be misleading however, because the analysis does not take into consideration the numbers of full time equivalent positions reporting to each mine department. When normalized with respect to the number of full time equivalent positions, the bar graph is as illustrated in Figure 7.13. The character remains the same; only the ratios are different. Clearly, nearly 70% of the 2005 *events* can be attributed to maintenance activities; the other 30% are attributed to mine operations activities. Thus, Highland Valley Copper would benefit from allocating training and other prevention resources accordingly.

7.2.4.3 Mine Department Ranked by Average Effective Risk

There is additional insight by considering how the average effective risk varies according to mine department (Figure 7.14). In order of ranking, Mine Operations presents more risk than does Mill Operations, Mill Maintenance, and Mine Maintenance. Mill Operations and Mine Operations present the highest effective risk, yet they account

for only 30% of the number of *events*.

7.2.4.4 Mine Department Ranked by Job Experience

The other dimension to consider is job experience. Overall, the average number of years of experience for all workers involved in workplace *events* was 13. Figure 7.15 illustrates that Mine Maintenance reported the highest average work experience at 19 years, and Mill Operations reported the lowest average work experience at 3 years. One would expect that the departments of Mine Maintenance and Mill Maintenance would accept the least amount of risk, given their higher number of years of job experience. Experienced operators tend to accept less risk, which is what we observe. By the same token, experienced operators experience fewer incidents and accidents. That this is not the case suggests that something else is happening; and by looking at the distribution of the number of *events* occurring at the mine correlated by cost factor, a possible explanation is revealed.

7.2.4.5 Mine Event Frequency According to Cost Factor

Figure 7.16 predicts the number of *events* that the mine site should have experienced according to a geometric progression, based upon the Pyramid Theory (Heinrich, 1931). According to the model, the mine site should have experienced approximately 250 more *event* reports than was reported. It is suggested by the researcher that an opportunity exists to report, investigate and learn from the many *events* that are minor in nature (< \$100). Further, to the extent that the preponderance of these missing *events* report to Mine Operations and Mill Operations, the apparent discrepancy between job experience and the frequency of *events* may be explained.

7.2.4.6 Mine Department Ranked by Average Event Cost

When considering each department by the average cost associated with *events* at the mine site, the results are predictable (Figure 7.17). Mine Operations has the highest average cost valuation of *events*, followed by Mill Operations, Mill Maintenance, and Mine Maintenance. Activities in Mine Operations are associated with large and expensive mobile equipment; that when involved in an accident, is likely to have high valuation. Mill Operations personnel also operate specialized rolling stock, and in a

complex and highly coupled system environment. Review of the types of *events* occurring in each department supports an hypothesis that both the risk and cost valuation of *events* are related to the operation of mobile equipment. Thus, Highland Valley Copper would benefit from allocating more resources to the safe operation and control of their mobile equipment.

7.2.5 Data Correlated With Respect to Mechanism of Injury

Mechanism of Injury	Count	Average Experience (Years)	Average Mission Criticality	Average Effective Risk	Average Cost Factor	EMB	EOO	EOC
Contact Between/With	24	13	18	19	\$2,800	44%	20%	36%
Exposure To	5	14	5	3	\$1,000	40%	13%	47%
Fall From/On	7	21	1	23	\$5,000	53%	12%	35%
Fingers Injured	12	16	2	6	\$1,000	55%	18%	27%
Fire or Threat of	3	4	37	10	\$7,000	25%	25%	50%
Foreign in Eye	6	16	1	9	\$1,000	36%	9%	55%
Lost Control	16	9	21	13	\$4,769	50%	2%	48%
Roll-over	6	10	24	25	\$4,000	52%	10%	38%
Soft Tissue Strain	10	11	2	8	\$1,000	36%	18%	45%
Struck-by	6	14	6	22	\$8,683	35%	6%	59%
1	2	3	4	5	6	7	8	9

Table 7-4: Table summarizing data from the second cohort with respect to mechanism of injury

7.2.5.1 Mechanism of Injury Profiled by Decision Errors

We next consider the mechanism of injury associated with each *event*. The term is perhaps a misnomer, because not all *events* result in injury. In fact, this research has determined that of all the *events* reported in the year 2005, 51% resulted in an injury to a worker. Losses, or harm to assets occurred in 29% of the *events*, with 18% of the *events* impairing production, and 2% resulting in environmental harm. Of the 51% of harm to workers, approximately 80% of this number resulted in medical aids.

The cognitive profile ternary diagram (Figure 7.18) shows a moderately tight distribution of decision errors with respect to mechanism of injury. There are some

marginal outliers in both the cognitive dissent and cognitive deficit regions of the diagram. In cognitive deficit are injuries due to fall from height or on-same-level, injuries to fingers, lost control, and vehicle roll over. In cognitive dissent are incidents related to fires, struck by object, and foreign body in eye. Upon review of the injuries in each of these categories, there are some general observations to note. Falls tend to creep into cognitive deficit due to an assumption or mistaken belief that a worksite was safe. Injuries to fingers similarly tend to be based upon a lack of knowledge of procedures, or lack of situation awareness. Vehicle roll over is commonly attributed to operator inexperience and lack of knowledge of road conditions. In the case of fires, there were only three incidents; the results may not be particularly revealing. Eye injuries most often were the result of the operator not taking sufficient care and caution; most often they did not clean or prepare a surface that had accumulated dust.

7.2.5.2 Mechanism of Injury by Frequency of Events

When the various mechanisms of injury are examined as they vary by number of *events*, it is evident that there are four frequent offenders (Figure 7.19). Topping the list are *events* involving contact with or between; followed by lost control; then injuries to fingers; followed by soft tissue injuries. Most often 'contact between/with' involved a vehicle or mobile equipment; in many cases two vehicles were involved. There were 24 incidents involving mobile equipment – over 25% of all *events* in 2005. Lost control *events* rank second at 16% of all *events* in 2005. They invariably involve equipment and uncontrolled releases of energy; energy that does damage to plant and equipment and in most cases poses a threat of injury. Injured fingers rank third at 13% of the *events* and has already been spoken to. Soft tissue injury (10%) refers to muscle and tendon strain, and typically was the result of improper body mechanics when lifting or dismounting from equipment. These four mechanisms of injury account for 65% of the recorded *events*.

7.2.5.3 Mechanism of Injury by Average Effective Risk

Ranking mechanism of injury by effective risk reveals some interesting results (Figure 7.20). The most risky mechanisms of injury are: struck-by, roll-over, fall from height or on same level, and contact between/with. Fall from height or on same level is a mechanism of injury that would not necessarily be associated with mobile equipment

and heavy machinery; as are the other three. Fall from height is a particularly pernicious mechanism of injury that deserves more attention at the mine. Falling on-same-level is also underestimated, if not under-reported. More senior operators tend to have more frequent falls on same level than do their junior counterparts. These *events* produce a real possibility of blown knees, pulled groin muscles and back injuries – all of which are lost time injuries. Together these four mechanisms of injury comprise 68% of the injuries realized at the Highland Valley Copper Mine, for the year 2005.

7.2.5.4 Mechanism of Injury by Job Experience

When considering mechanism of injury by job experience, the results are also revealing (Figure 7.21). Fall from height or on same level corresponds to the greatest number of years on the job, followed by injury to fingers and then foreign body in eyes. These three mechanisms of injury are associated with over half of all *events* of 2005. That the top mechanism of injury is fall from height or on-same-level reflects the seniority of the operators both in terms of experience, and age. Injury to fingers and foreign body in eyes is indicative of the trades and hands-on nature of the workforce; in particular on the part of maintenance personnel.

7.2.5.5 Mechanism of Injury Ranked by Average Direct Cost

Mechanism of injury as correlated with average direct cost of an *event* is illustrated in Figure 7.22. Highest in terms of average cost are those *events* resulting in struck-by and fires. Both involve equipment; equipment that is significantly damaged. The cost factor is likely to be \$10,000, or more. In comparison, the three lowest cost mechanisms of injury are those *events* that cause harm to people; injured fingers, foreign body in eye and soft tissue injury. Fortunately, the majority of these resulted in medical aid or less. The cost factor for these *events* is therefore \$1000 or less.

7.2.5.6 Mechanism of Injury Ranked by Mission Criticality

The top ranked mechanisms of injury when modeled for mission criticality were: fire, roll-over, lost control and contact with/between; in that order (Figure 7.23). These four mechanisms of injury vary between numerical values of 17 and 37, which are dimensionless. The implication is that, on average, the top four mechanisms of injury

have between one or two criteria, or elements (out of 10), that could escalate an otherwise minor *event* into a tragedy or disaster. At the other end of the scale, we observe the mechanisms of fall from/on, foreign body in eye, injured fingers and soft tissue injury. Naturally, these types of *events* are very limited in nature and present no risk to the mine as a whole in terms of mission criticality.

7.2.6 Data Correlated With Respect to Occupation

Mine Occupation	No.	Average Exp. (Years)	Average Mission Criticality	Average Effective Risk	Average Cost Factor	EMB	EOO	EOC
Welder/Fitter	10	22	3	18	\$2,900	44%	0%	56%
Mill Op/MSU	11	6	7	16	\$4,282	50%	15%	35%
Millwright	25	10	10	15	\$2,728	46%	11%	43%
HD Mechanic	18	20	6	12	\$1,950	42%	13%	46%
Haul Truck Op.	7	12	26	7	\$7,429	50%	17%	33%
Carp/Electrician	10	11	14	6	\$2,800	46%	4%	50%
Cableman	9	10	9	30	\$5,111	45%	25%	30%
Driller/Blaster	5	12	64	8	\$640	36%	21%	43%
1	2	3	4	5	6	7	8	9

Table 7-5: Table summarizing data from the second cohort with respect to worker occupation

7.2.6.1 Occupation Ranked by Number of *Events*

When ranked by number of *events*, the top three occupations by frequency are millwright, HD mechanic and mill operator/MSU; reporting 25, 18 and 11 respectively out of a total of 94 *events* (Figure 7.24). These three occupations represent 59% of all of the *events* reported in 2005, and is consistent with the earlier observation that the frequency of *events* is greatest in the departments of Mine Maintenance and Mill Maintenance; where tradesmen typically report to. Highland Valley Copper would benefit from allocating training resources to these three occupations accordingly.

7.2.6.2 Occupation Profiled by Decision Errors

When the decision errors are plotted according to occupation, the distribution is once again a moderately tight locus of points (Figure 7.25). There are several outliers

marginally reporting to cognitive dissent, and they are: welder/pipe fitters, and carpenters/electricians. Also, there are several outliers reporting marginally to the region of cognitive deficit, and they are: haul truck operators and mill operators. Those reporting to cognitive dissent typically do so for reasons of not following known procedures or practices; while those marginally in cognitive deficit typically make assumptions that are not true, or act on incorrect information. Also of note is that cableman operators are showing signs of cognitive deferral. When *events* involving cableman are reviewed for what human factors may be present – issues of congestion and lack of attention are common.

7.2.6.3 Occupation Ranked by Average Effective Risk

The occupations exposed to the highest average effective risk are: cableman operators at 30, welder/pipe fitter at 18, mill/MSU operators at 16, followed by millwrights at 14 and HD mechanics at 12 (Figure 7.26). Cableman operators are at significantly higher risk than the others because the types of *events* that they experience are related to contact between/with heavy equipment. The welder/pipe fitters are prone to fall from height and on-same-level, as well as foreign body in eye. The mill/MSU operators are prone to soft tissue injuries, injuries to fingers and injuries involving contact between/with; as are the millwrights and HD mechanics. In aggregate, the top three occupations in terms of average effective risk reported 58% of the *events* in 2005.

7.2.6.4 Occupation Ranked by Average Job Experience

As mentioned previously, the average job experience of parties involved in *events* at Highland Valley Copper during 2005 was 13 years of service. When analyzing occupation by average job experience, two occupations predominate (Figure 7.27). They are: welders/pipe fitter with 22 years of service, and HD mechanics with 20 years of service. This is consistent with, and accounts for, the high average job experience of the departments of Mine Maintenance and Mill Maintenance. Lowest in terms of job experience, are millwrights and cableman operators at 10 years, and mill/MSU operators at 7 years; in that order. It is noted that the cableman operators have a low average job experience and present with the highest effective risk at the Highland Valley Copper Mine.

7.2.7 Data Correlated With Respect to Job Experience

Job Exp.	No.	Average Exp. (Years)	Average Mission Criticality	Average Effective Risk	Average Cost Factor	EMB	EOO	EOC	C/E Ratio
> 5 years	60	20	13	14	\$3,223	43%	14%	43%	71%
< 6 Years	35	2	9	15	\$3,291	51%	12%	37%	60%
1	2	3	4	5	6	7	8	9	10

Table 7-6: Table summarizing data from the second cohort with respect to job experience

7.2.7.1 Occupation Ranked by Average Event Cost

When compared to average cost per *event*, again two occupations predominate (Figure 7.28). They are: haul truck operators at \$7,429 average cost per *event*, and cableman operators at \$5,111 average cost per *event*. This can be compared to the mine average cost for 2005 of \$3,248 per *event*. The fact that haul truck operators and cableman operators top the list with regards to cost is consistent with the fact that the department of Mine Operations had the highest average *event* cost during 2005. Haul truck operators and cableman operators accounted for nearly 45% of the average costs associated with *events* in 2005.

7.2.7.2 Occupation Ranked by Average Mission Criticality

Comparing occupations by mission criticality reveals that there are two occupations that dominate all others. Drillers/blasters and haul truck operators accounted for the majority of the mission criticality during 2005 (Figure 7.29). The reason for this is the large amounts of kinetic energy associated with heavy haulers, and the huge amount of chemical energy stored in explosives. The blasting operators on the bench also presented communication problems in some of their *events*, which further elevated the criticality on their part. Lowest on the scale were welder/pipe fitters, HD mechanics, and mill/MSU operators.

7.2.7.3 Job Experience Profiled by Decision Errors

Column 1 of the table reveals that 60 (64%) of the 94 *events* occurring at the

Highland Valley Copper Mine in 2005 were operators with five or more years of job experience (Table 7-6). It follows then that 34 (36 %) of the recorded *events* have five years of job experience, or less. The mean number of years of job experience for the more senior operators is twenty years. The mean value for the more junior operators is only two years. The mean value for the entire cohort of *events* is thirteen years. There appears to be a polarized distribution with respect to job experience. It is left to mine management to compare the actual mine distribution of job seniority with these figures to observe to what extent the more junior operators are represented by the *event* record.

Columns 7 through 9 of the table are presented on the cognitive profile ternary diagram (Figure 7.30). It is noted that there is a fairly tight distribution of decision errors, so much so that one questions the influence of job experience. The more junior operators, however, are showing a slight predisposition towards errors of mistaken belief; and therefore report to the region of cognitive deficit. The more senior operators are equally disposed to errors of mistaken belief and errors of commission. The primary difference between the senior operators and the more junior operators appears to be that the more junior operators are 8% more disposed to errors of mistaken belief, and the senior operators are 6% more disposed to errors of commission (columns 7 and 9).

7.2.8 Data Correlated With Respect to Event Cost

<i>Event Cost Factor</i>	No.	Average Experience (Years)	Average Mission Criticality	Average Effective Risk	EMB	EOO	EOC	C/E Ratio
\$100	6	17	55	25	58%	11%	32%	67%
\$1,000	68	13	6	11	45%	13%	42%	69%
\$10,000	17	12	19	19	44%	13%	43%	61%
\$100,000	3	12	4	19	14%	14%	71%	67%
\$1,000,000	1	13	10	1	100%	0%	0%	100%
1	2	3	4	5	7	8	9	10

Table 7-7 Table summarizing data from the second cohort with respect to event cost

7.2.8.1 Event Cost Factor

The *event* cost factor is not a particularly useful factor as a predictive parameter. Cost is random with respect to years of experience. Cost is random with respect to

effective risk and mission criticality. The reason for the apparent high values of mission criticality associated with the cost factor of \$100 is that two of the associated *events* happen to be incidents involving detonator cords and ANFO trucks. It is considered fortunate that the cost factor is so low. The high value of errors of mistaken belief (58%) associated with *events* modeled at \$100 speaks to the lack of awareness of procedures.

The decision errors are random with respect to cost. The cause and effect ratio is consistent with the overall ratio of 67%; indicating that two thirds of the decision errors are explicitly identified in the causation section of the reports; the remaining third implicitly derived through the recommendations and action items. The total modeled cost of all of the 94 *events* is \$1,538,600; inclusive of the June 2nd mill feed rupture. A more realistic valuation of the lost time injuries (omitting the pipe rupture outlier) gives a total cost for 2005 of \$538,600.

7.2.9 Data Correlated With Respect to Hour of Day

Analysis of the time of *event* is particularly insightful. Overall, the median time of occurrence for the 94 *events* is 12:26 pm. When correlated by hour of the day (Figure 7.31 and 7.32), a pattern emerges. During the first 12 hours of the day, 52 (55%) of the 94 *events* occurred, with a median time of occurrence of 09:06 am. More significant perhaps is the observation that 90% of these *events* occur between 07:00 am, and 11:00 am. Conversely, 45% of the *events* occur during the second 12 hours of the day – with a median occurrence at 04:33 pm. Again, more significant is the observation that there are two periods of *event* frequency: one period between 12:00 p.m. and 03:00 pm; another between 06:00 pm and 09:00 pm. It is left to mine management to consider why these particular hours of operations are more prone to *events* at the Highland Valley Copper Mine.

7.3 Conclusions

The second cohort of investigative reports provided sufficient detail and narration to track trends by way of cognitive profiling and the back-analysis of risk. It was determined through this research that Highland Valley Copper has a bulk effective risk of 14. This is indicative of an organization that practices normative compliance as regards

to operational risk, and is in the low-middle category of uncertainty referred to as operational homeostasis. The significance of this classification scheme is that organizations in normative compliance have standards and norms that go beyond regulatory compliance. They have established policies, procedures and practices that mitigate risk specific to their operations. They have such controls in place to reduce the relatively high intrinsic risk to a more acceptable effective risk. The corresponding characterization with respect to uncertainty is operational homeostasis. This suggests that within the organizational ethos, an expectation has emerged concerning the amount of risk acceptable to the organization. As technology and systems develop that reduce the intrinsic risk, the workforce tends to modify their behaviors (behave riskier) such that the same level of effective risk is maintained.

It is essential that if Highland Valley Copper is to achieve a truly diligent ethos, that this paradigm be challenged – and changed. Based upon the bulk effective risk of 14, Highland Valley Copper does not have a great deal of safety performance improvement to make. The intrinsic risk in mining is such that if Highland Valley Copper were to realize a bulk effective risk in the single digits, it would translate into a significant change in safety culture.

This research has determined that Highland Valley Copper has a cognitive profile that reports to the region of *no cognitive tendency* (Figure 7.33). That is, Highland Valley Copper, through its mine management, is not disposed to any one specific type of cognitive error. Highland Valley Copper mine management demonstrates a cohesive, coherent and effective management style, as regards to environment, health and safety. This is not to say that there are not localized challenges – and opportunities, and these have been enumerated herein by way of profiling. This research has determined that:

- i. The frequency of accidents and incidents according to calendar month is strongly influenced by the seasons; more specifically ground conditions during spring break-up and winter freeze-up.
- ii. The departments with the highest effective risk are Mine Operations and Mill Operations; in that order.
- iii. The departments with the highest frequency of incidents and accidents are Mill Maintenance and Mine Maintenance; in that order.
- iv. The departments with the highest job experience are Mine Maintenance and Mill

Maintenance; in that order.

- v. The departments with the highest average cost per event are Mine Operations and Mill Operations; in that order.
- vi. The mechanisms of injury that are associated with cognitive deficit are: fall from height or on-same-level, and injuries to fingers.
- vii. The mechanisms of injury that are associated with cognitive dissent are: fires, and foreign body in eyes.
- viii. The mechanisms of injury that are most frequent are: contact between or with, lost control, injuries to fingers, and soft tissue injuries; in that order.
- ix. The mechanisms of injury that present the highest risk are: struck-by and roll-over, fall from height or on-same-level, and contact between/with; in that order.
- x. The mechanisms of injury with the highest mission criticality are: fire, roll-over, lost control and contact between/with; in that order.
- xi. The mechanisms of injury with the highest average cost are: struck-by, fire, and fall from height or on-same-level.
- xii. The occupations incurring the highest number of *events* are: millwrights, HD mechanics, and mill/MSU operators.
- xiii. The occupations exhibiting the highest average effective risk are: cableman operators, welder/pipe fitter, and mill/MSU operators.
- xiv. The occupations with the highest job experience are: welders/pipe fitter with 22 years of service, and HD mechanics at 20 years of service.
- xv. The occupations that show marginal predispositions to cognitive dissent are: welder/pipe fitters, and carpenters/electricians.
- xvi. The occupation that shows a marginal predisposition to cognitive deficit is cableman operators.
- xvii. The occupations that present the highest mission criticality are: drillers/blasters and haul truck operators; in that order.
- xviii. The occupations with the highest average cost of *events* are: haul truck driver and cableman; in that order.
- xix. The average number of years of job experience for all of the operators involved in *events* is 13.
- xx. The average number of years of experience for operators less than 6 years is 2.

- These operators report marginally to the region of cognitive deficit (51%)
- xxi. The average number of years of experience over 5 years is 20. These operators show no disposition toward any particular cognitive error phenotype.
 - xxii. The total cost of *events* as modeled in this research at Highland Valley Copper during 2005 was \$538,600.00. This figure does not consider the mill feed pipe rupture of June 02nd, 2005.
 - xxiii. The average cost of *events* during 2005 was \$3,248.
 - xxiv. The peak periods of time during the a.m. in which *events* occur is between the hours of 7:00 am and 11:00 am.
 - xxv. The peak periods of time during the p.m. in which *events* occur is between 1:00 pm and 3:00 pm; and between 7:00 pm and 8:00 pm.
 - xxvi. Of the 94 *events* reported at the Highland Valley Copper Mine during 2005, 51% reported as injuries to persons; 29% reported as damage to physical plant; 18% reported as losses or potential losses to production; and less than 2% reported as harm to the environment.
 - xxvii. The 2005 cognitive profile of Highland Valley Copper is 46% errors of mistaken belief, 13 % errors of omission; and, 41% errors of commission (Figure 7.33).
 - xxviii. There has been a general progression of decision errors away from errors of omission (cognitive deferral) in the years 2002 through to 2005 (Figure 7.33).

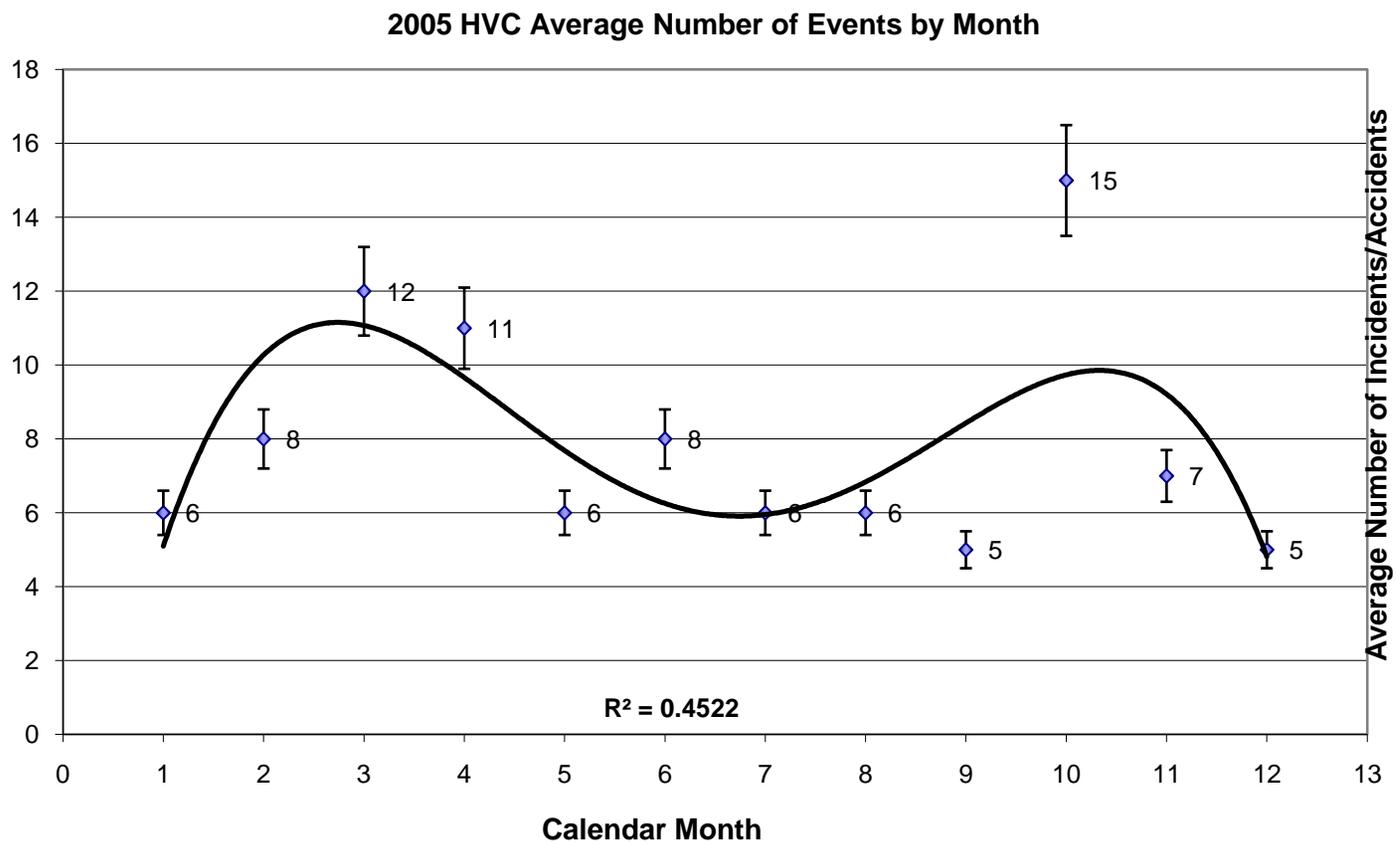


Figure 7.4: Scatter plot of the number of accidents/incidents with respect to time.

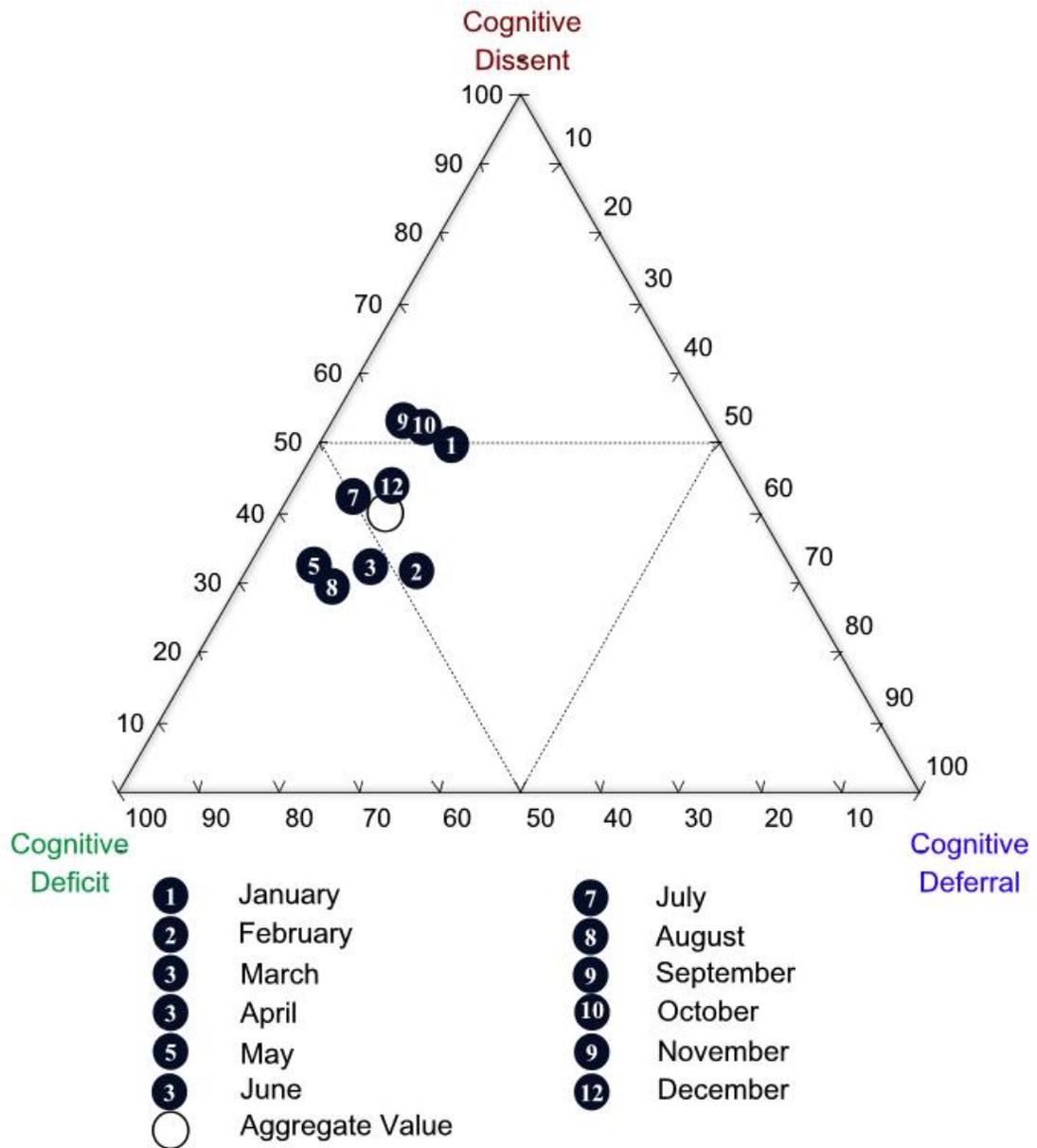


Figure 7.5: Cognitive ternary diagram illustrating decision errors according to calendar month

2005 HVC Percentage of Errors of Commission by Calendar Month

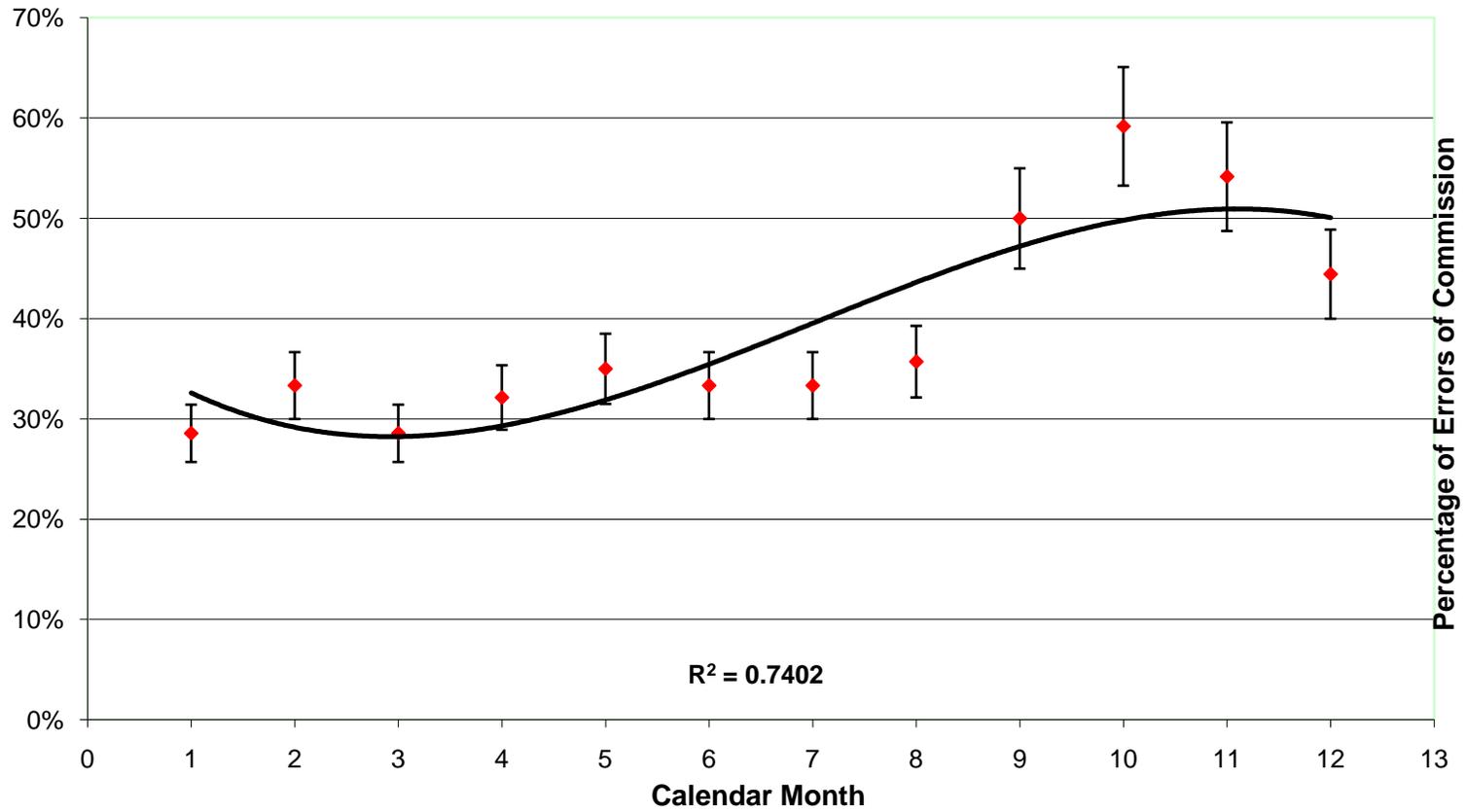


Figure 7.6: Scatter-plot illustrating percentage of errors of commission by calendar month

2005 HVC Percentage of Errors of Mistaken Belief by Calendar Month

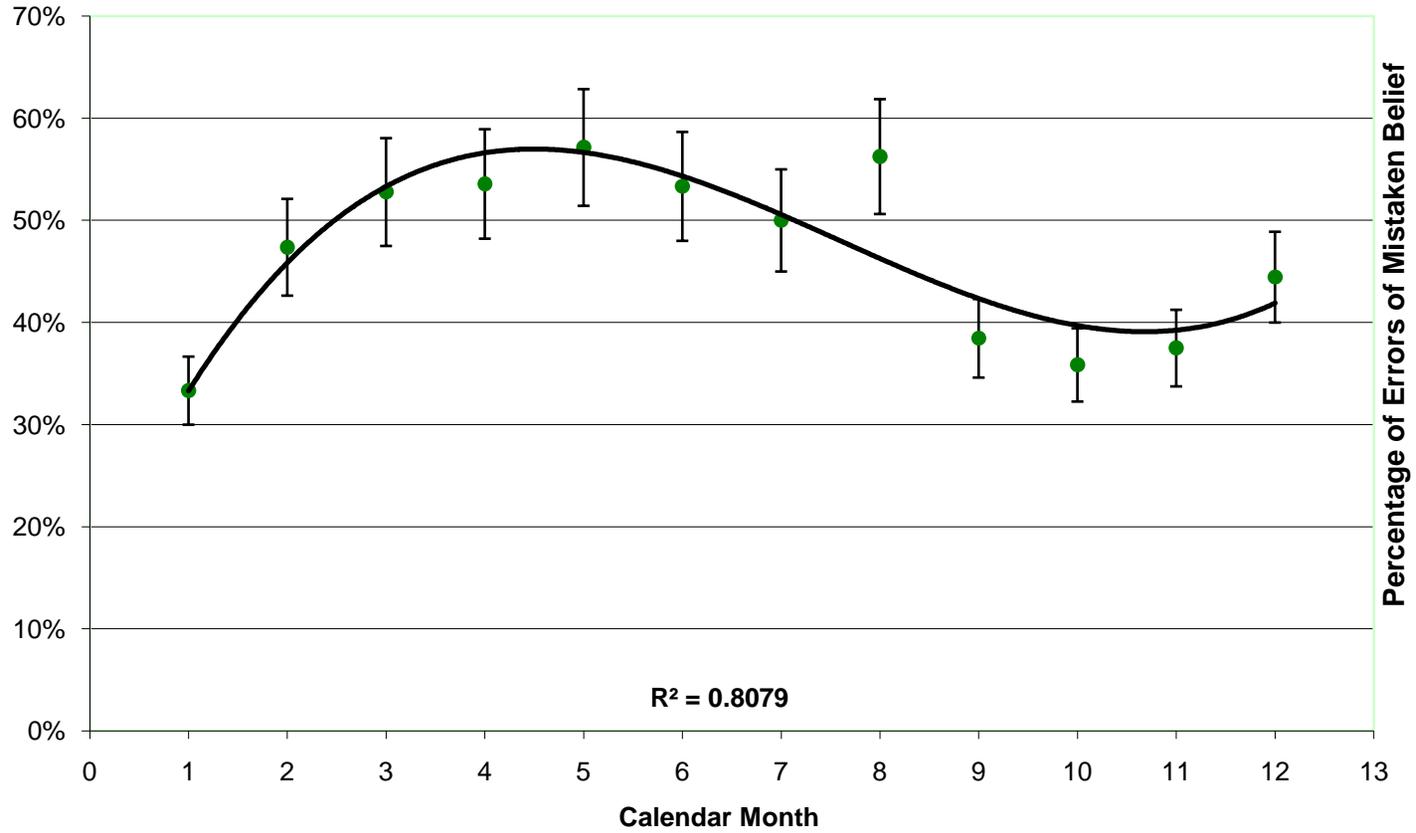


Figure 7.7: Scatter-plot illustrating percentage of errors of mistaken belief by to calendar month

2005 HVC Percentage of Errors of Omission by Calendar Month

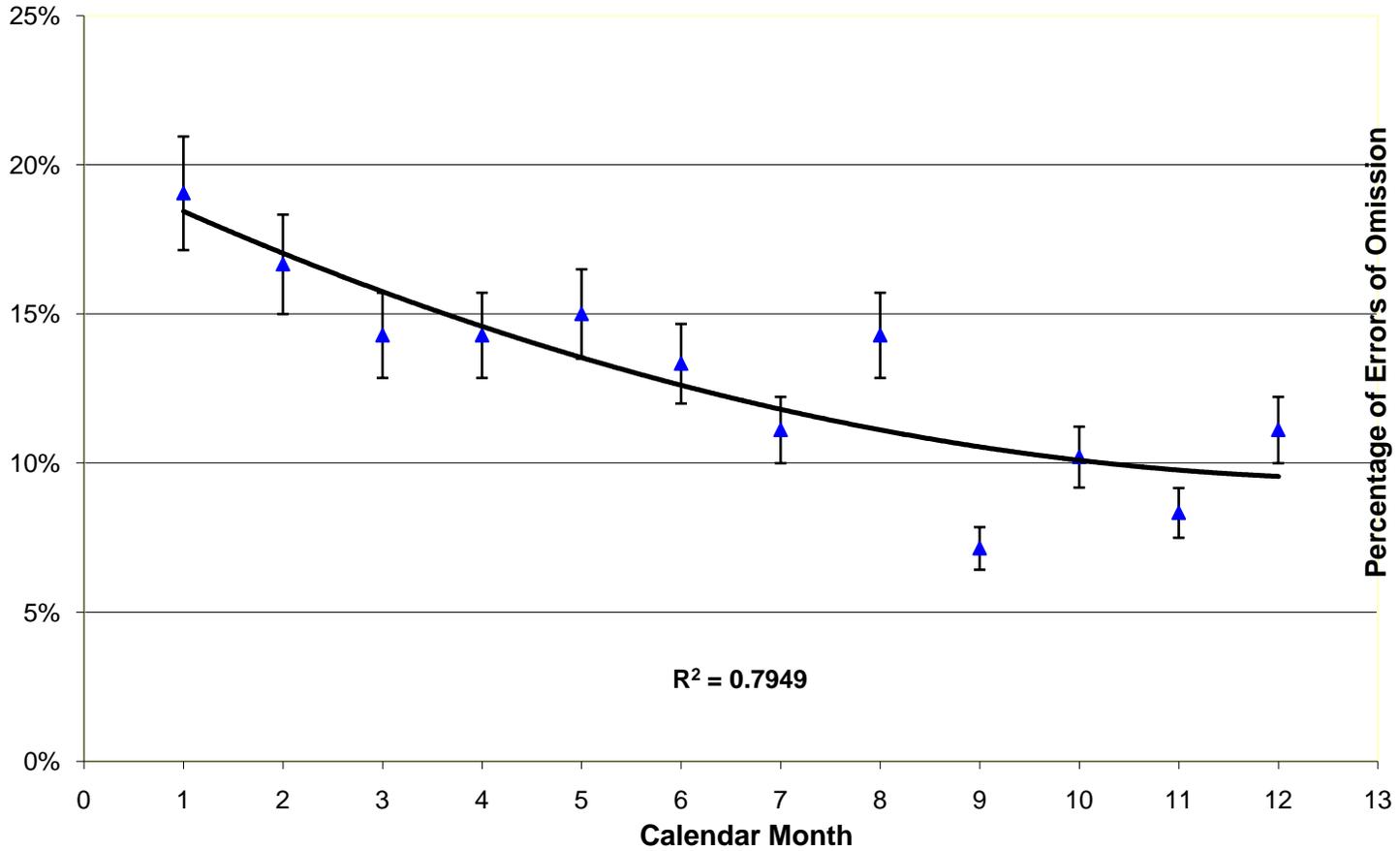


Figure 7.8: Scatter-plot illustrating percentage of errors of omission according to calendar month

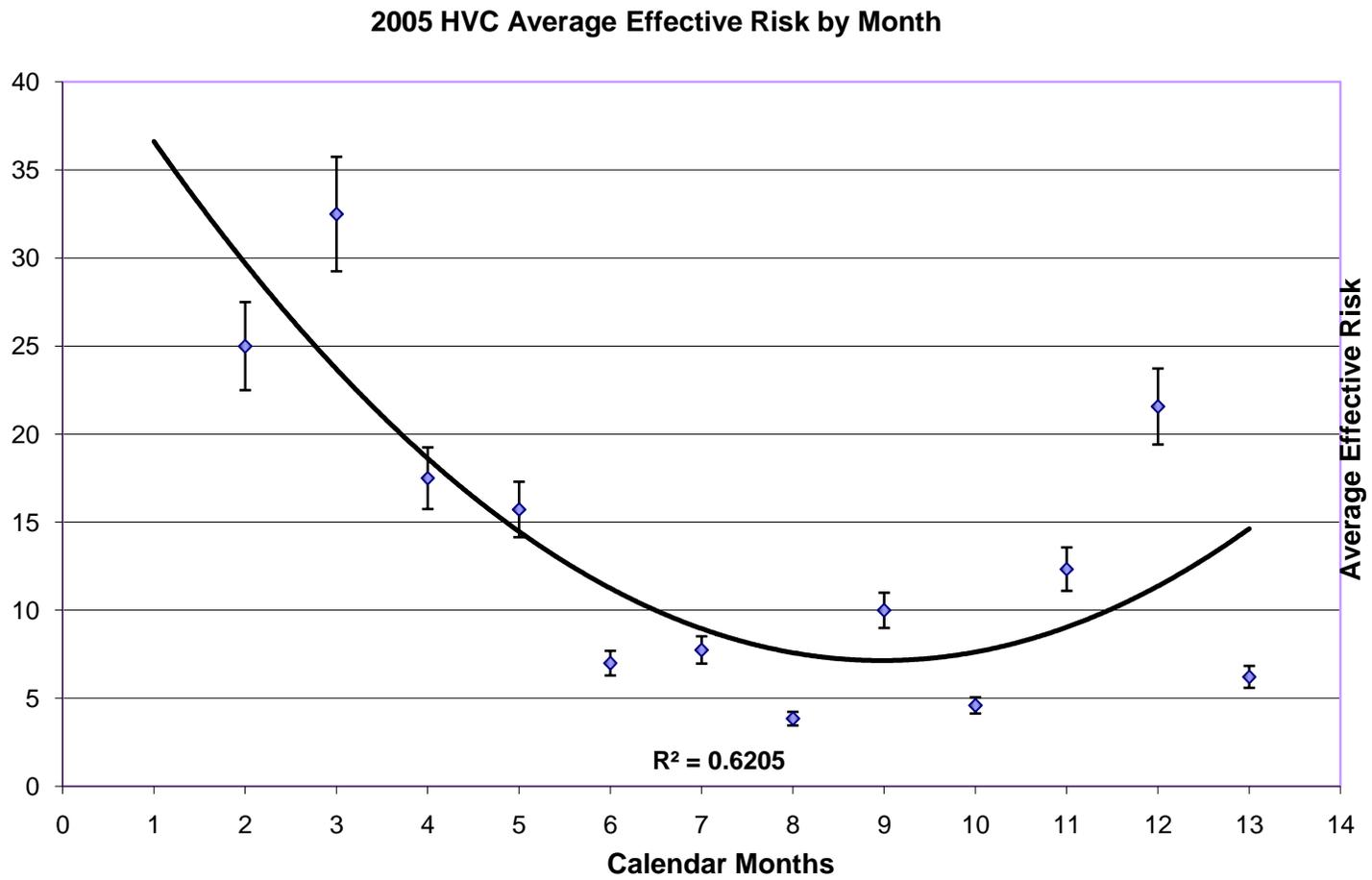


Figure 7.9: Scatter plot of the average effective risk by month with best-fit curve and error bars

2005 HVC Average Mission Criticality by Month

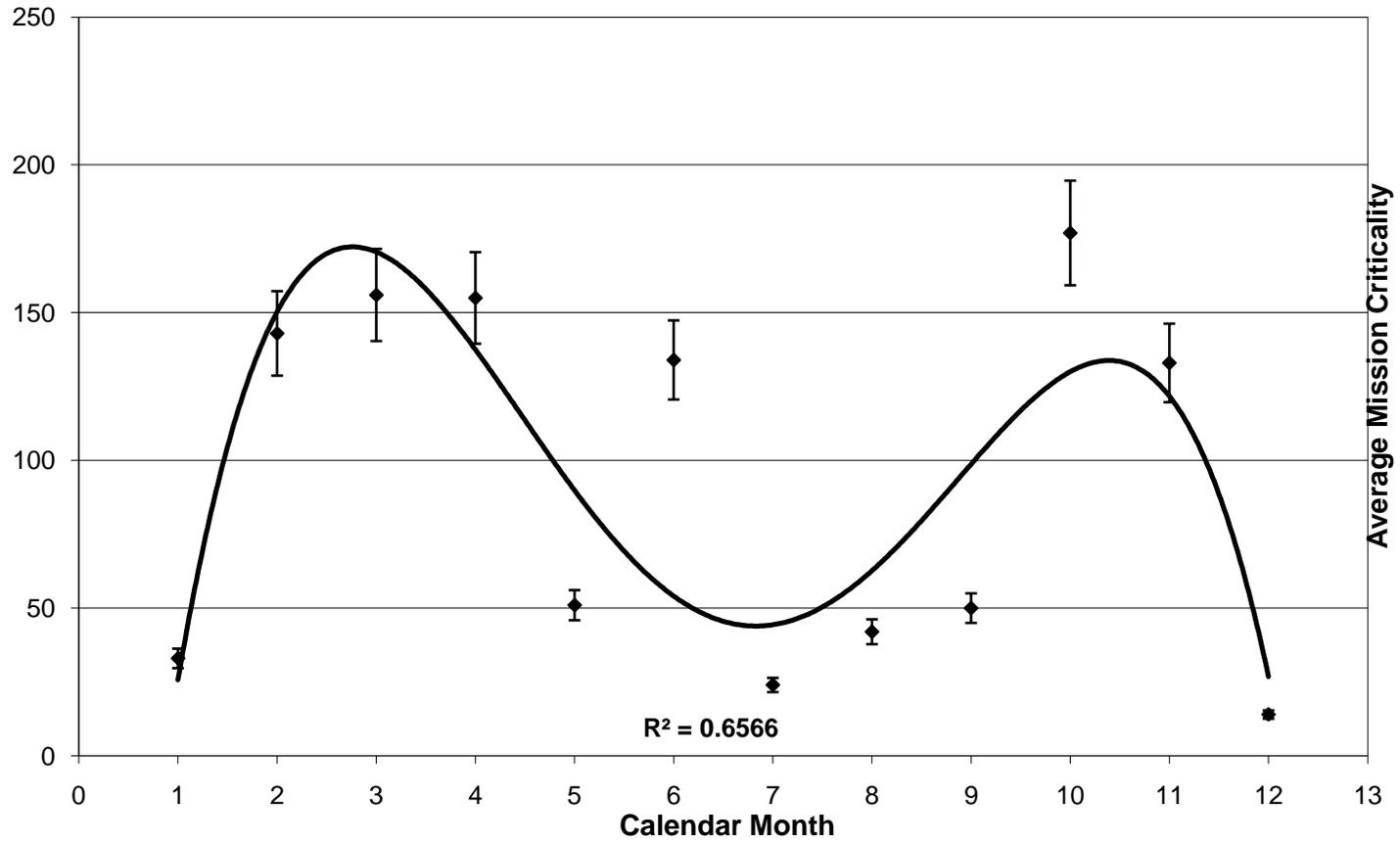


Figure 7.10: A scatter plot illustrating mission criticality with respect to calendar month.

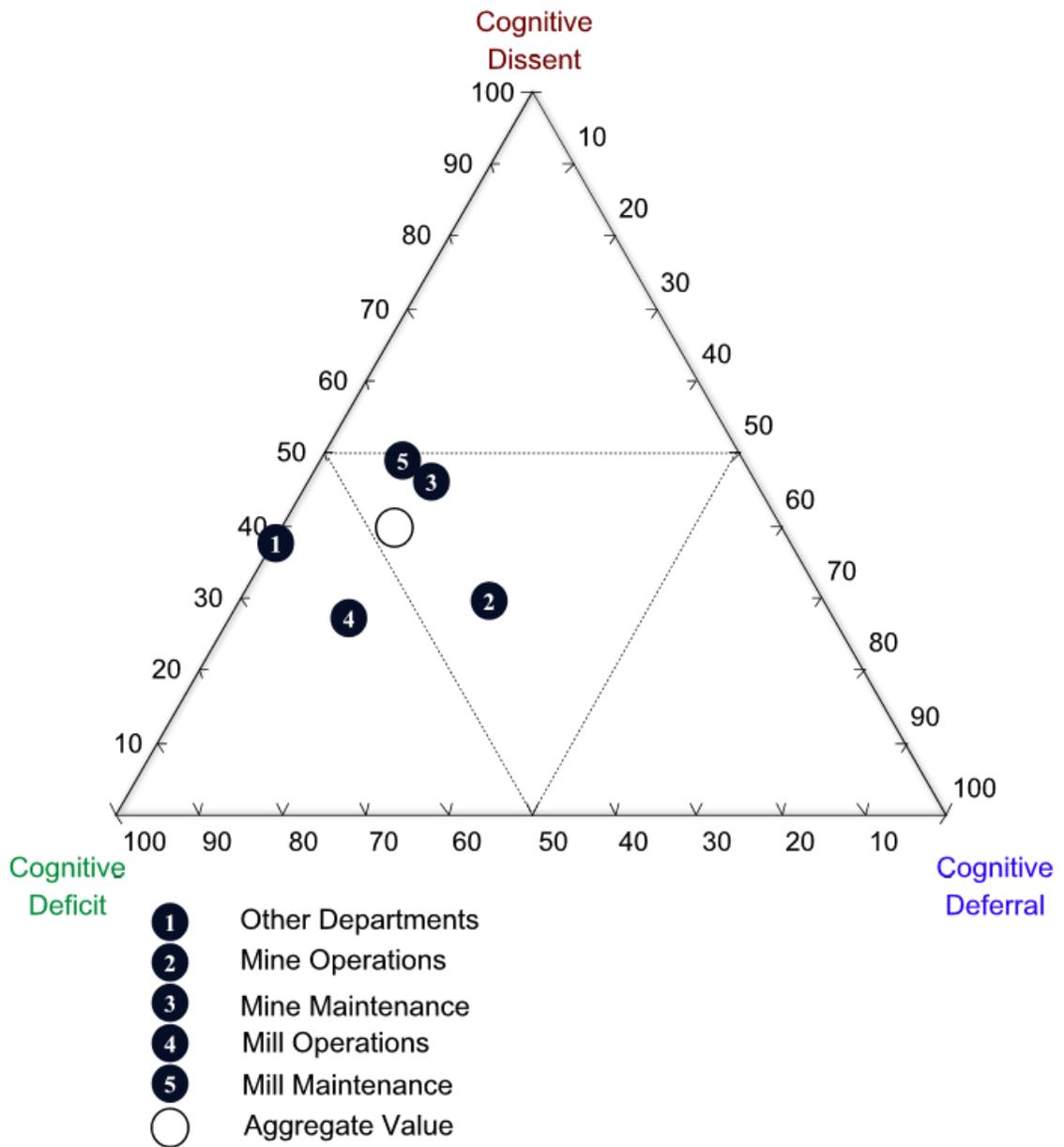


Figure 7.11: Cognitive ternary diagram illustrating decision errors according to mine department

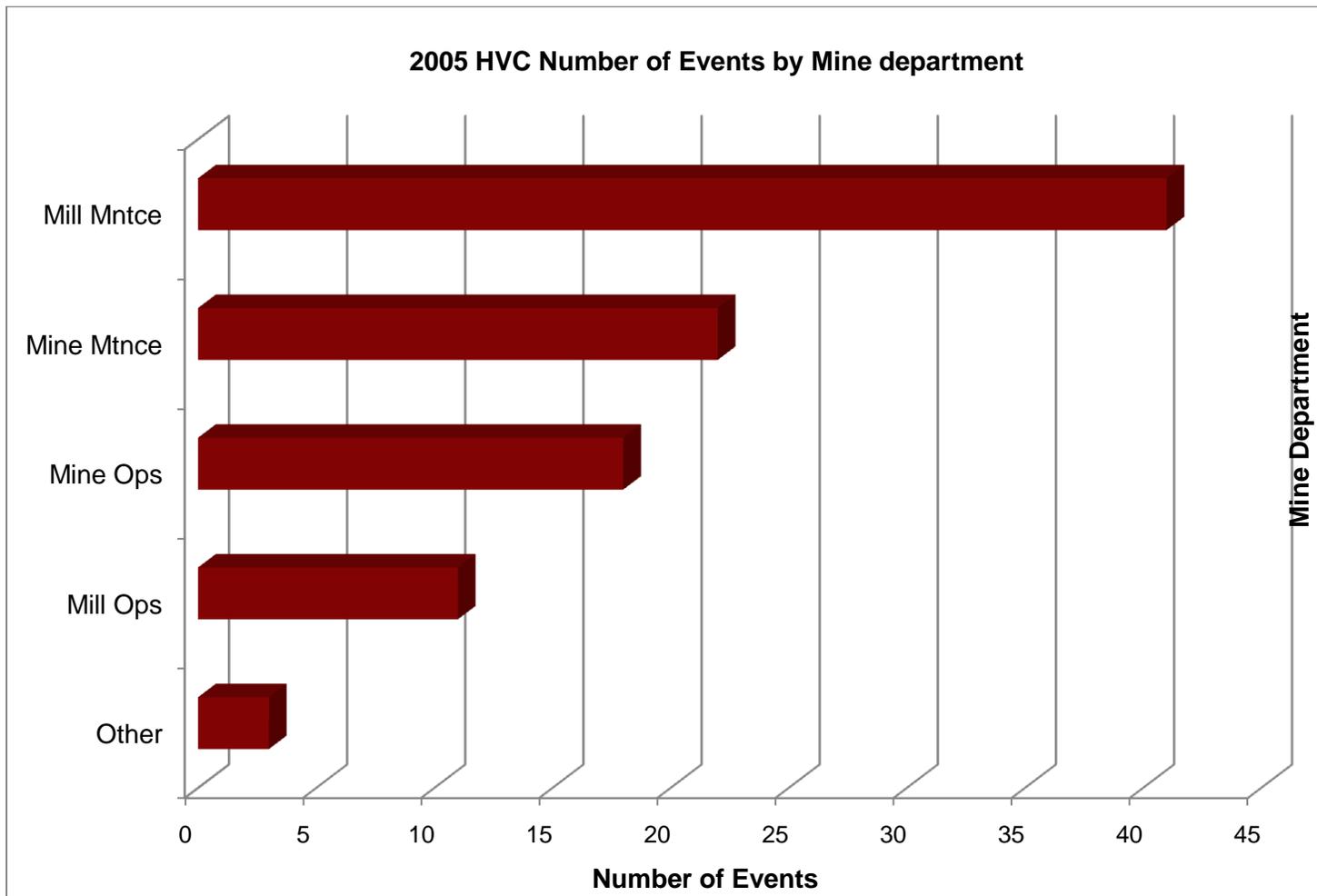


Figure 7.12: Graphical illustration of mine department ranked by number of *events* in 2005.

2005 HVC Normalized Number of Events by Mine Department

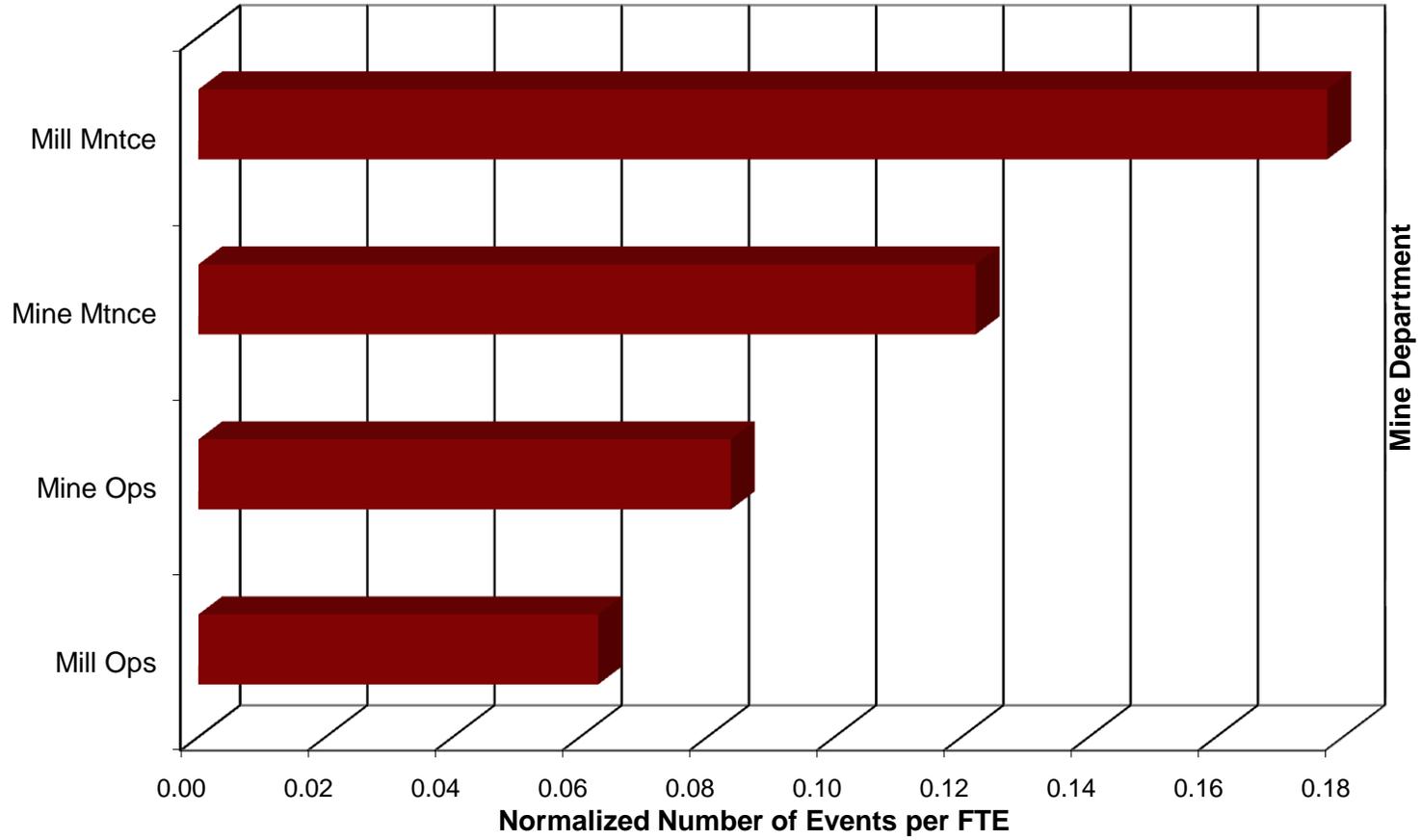


Figure 7.13: Graphical illustration of mine department ranked by number of events per FTE.

2005 HVC Average Effective Risk by Mine Department

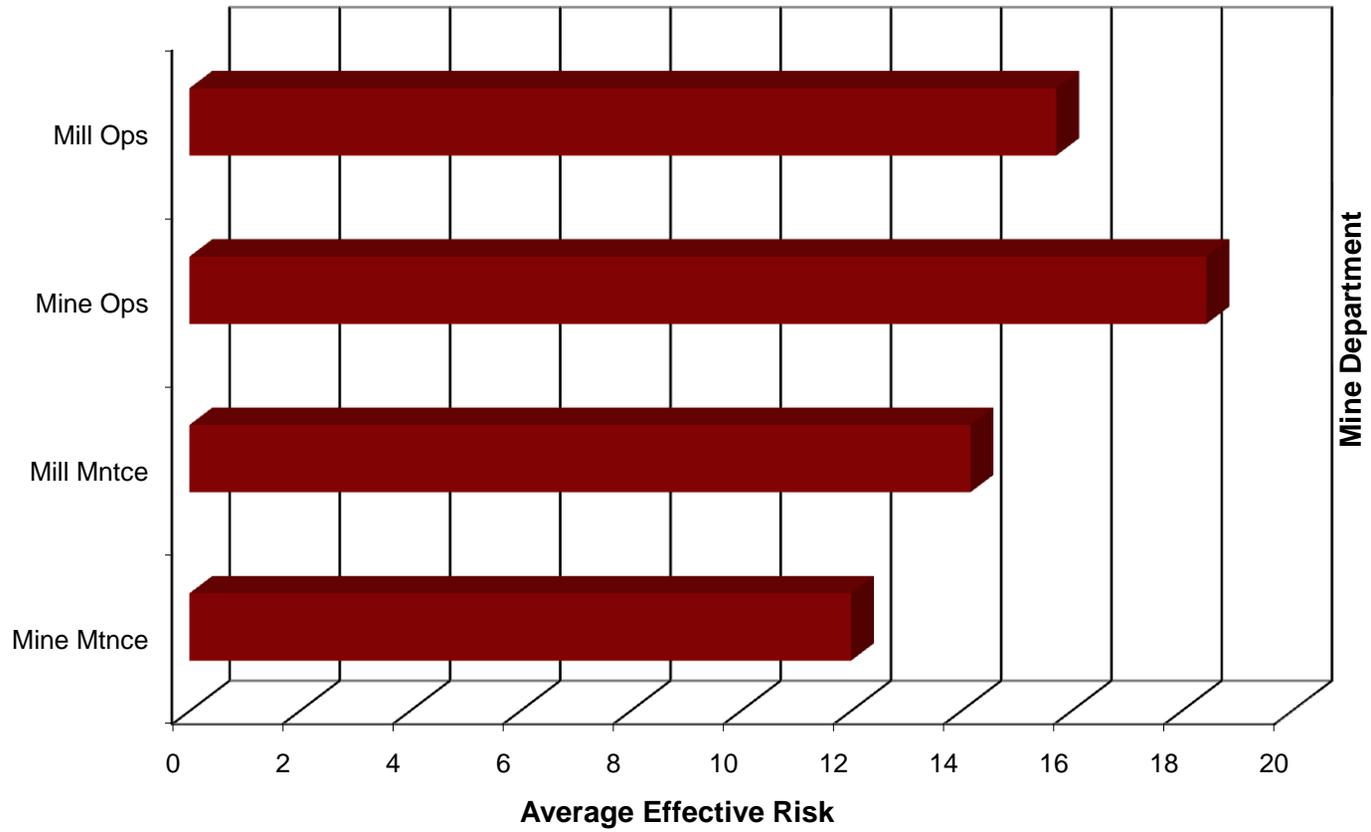


Figure 7.14: Graphical illustration of mine department ranked by average effective risk.

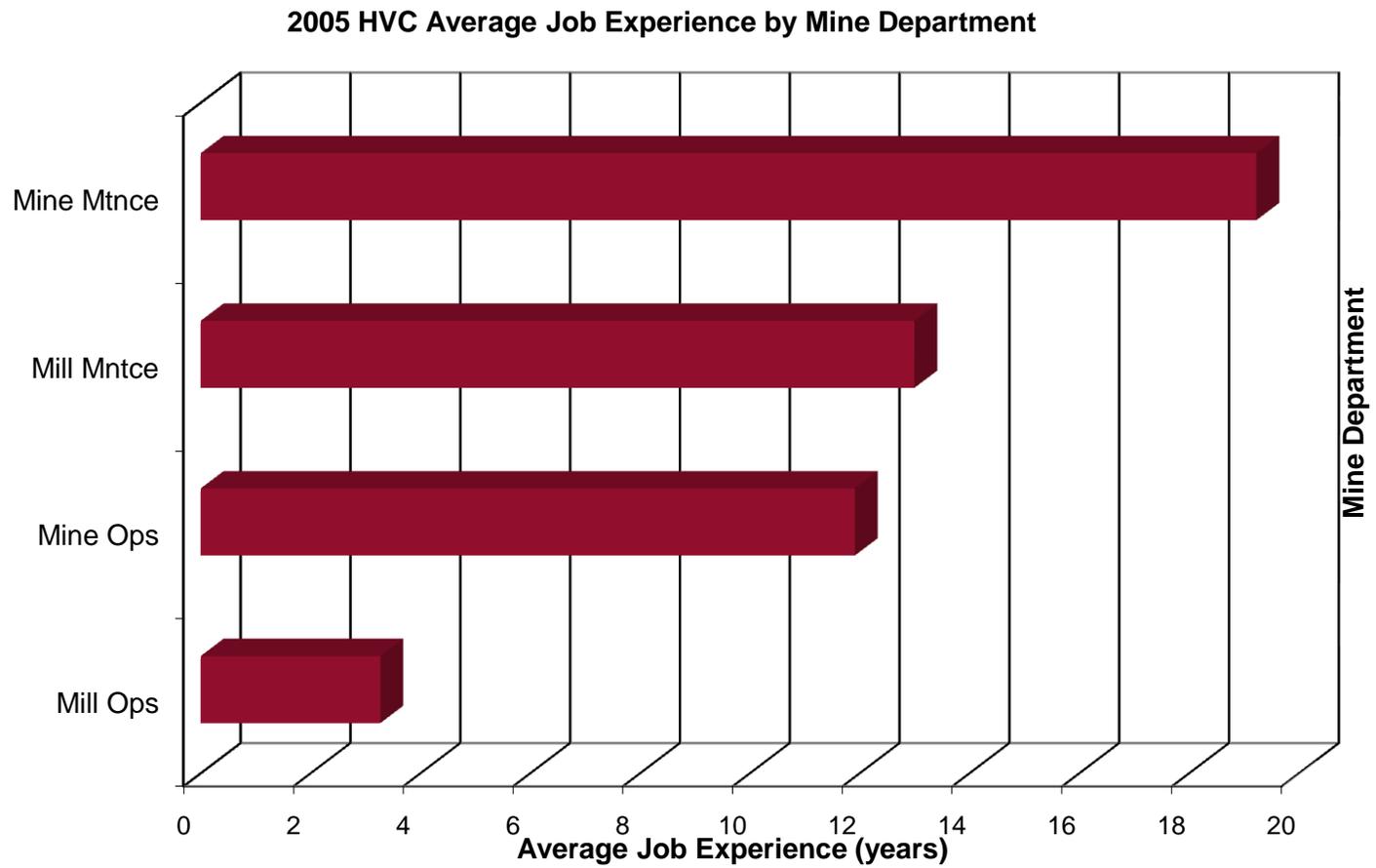


Figure 7.15: Graphical illustration of mine department ranked by average job experience.

2005 HVC Event Distribution by Cost Factor

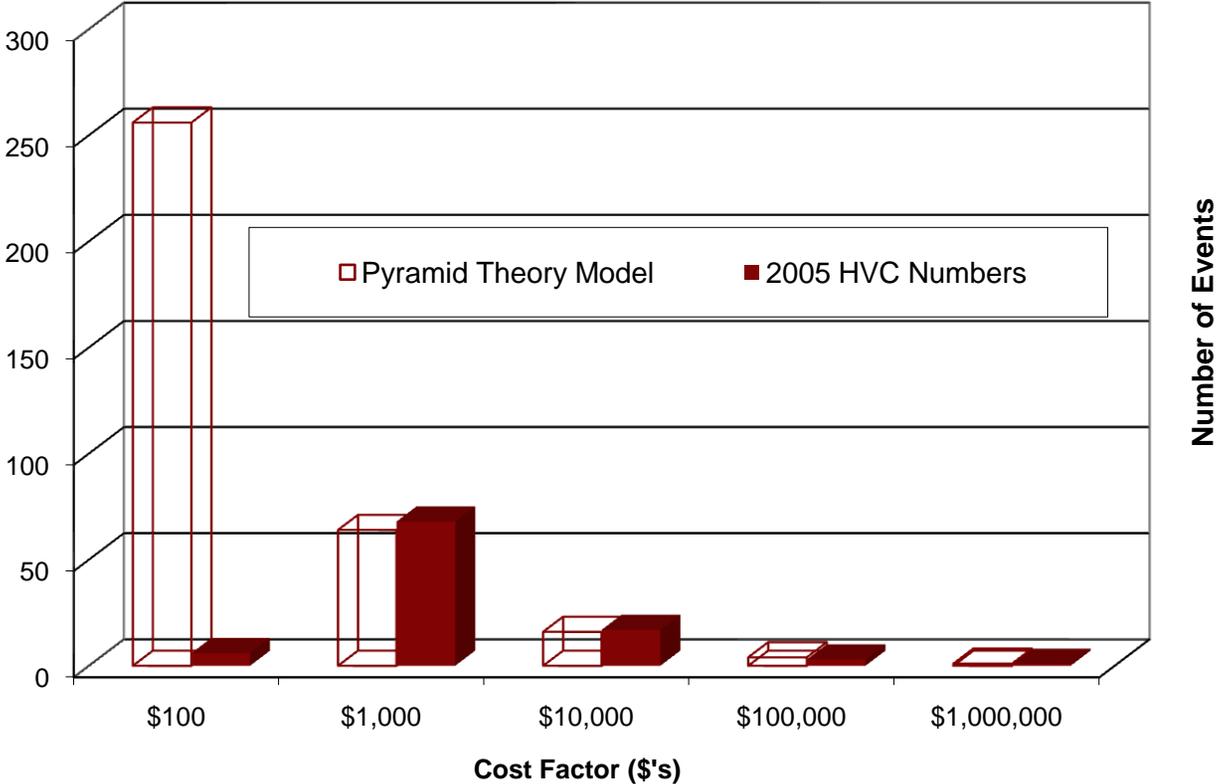


Figure 7.16: Distribution of *event* cost factor by model and by actual reported.

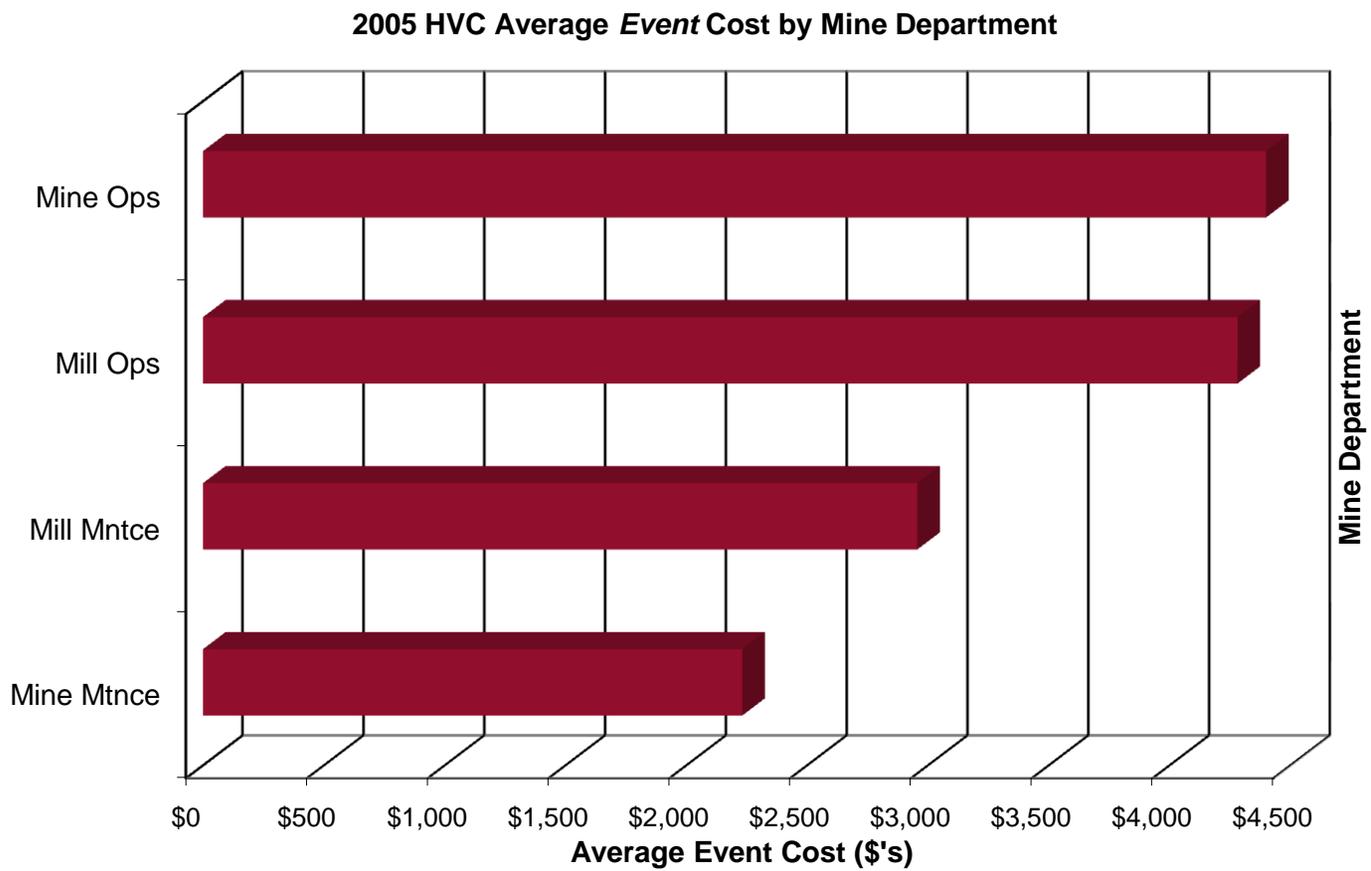


Figure 7.17: Graphical illustration of mine department ranked by average *event* cost.

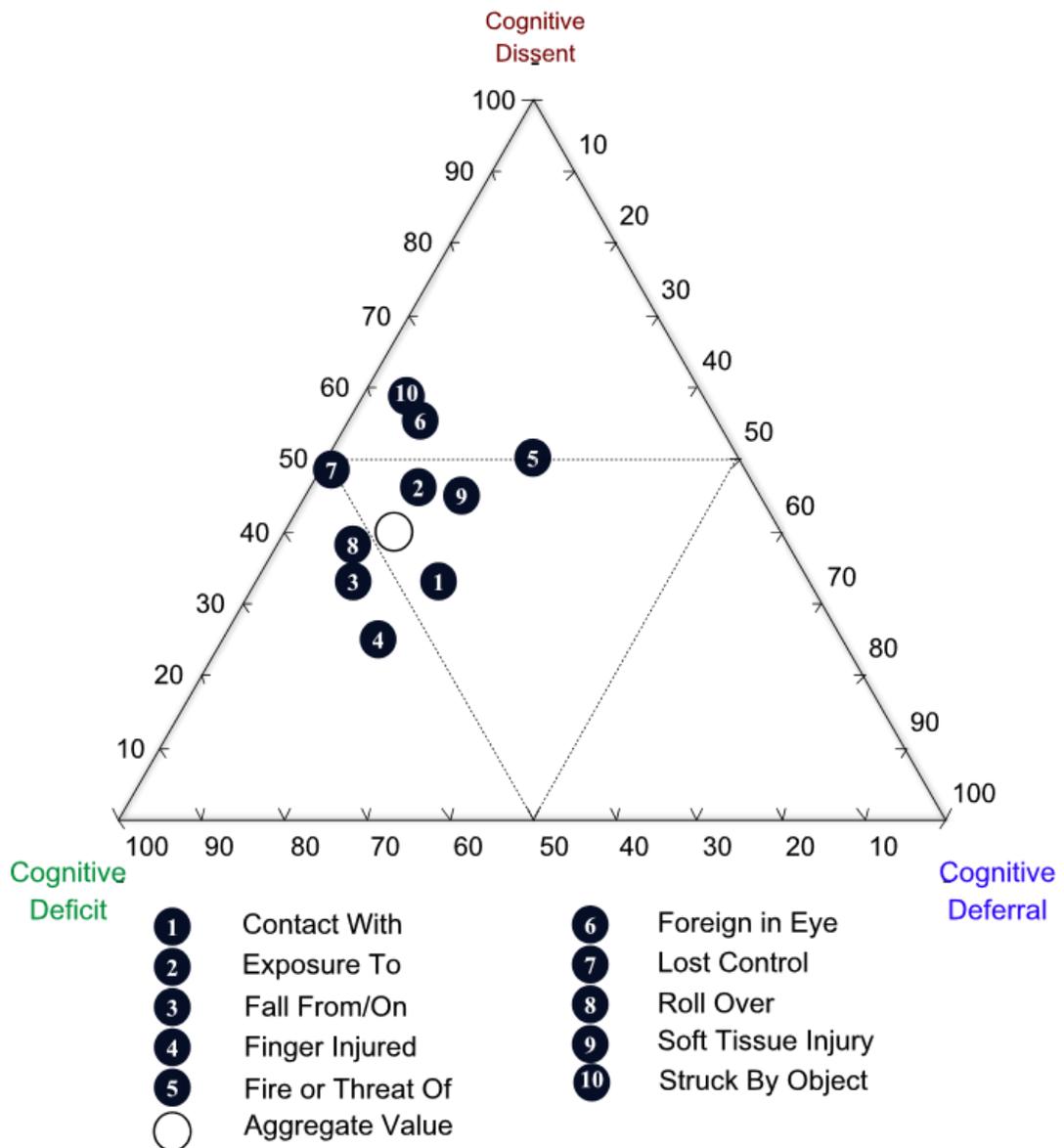


Figure 7.18: Cognitive profile ternary diagram illustrating decision errors by mechanism of injury

2005 HVC Number of Incidents/Accidents by Mechanism of Injury

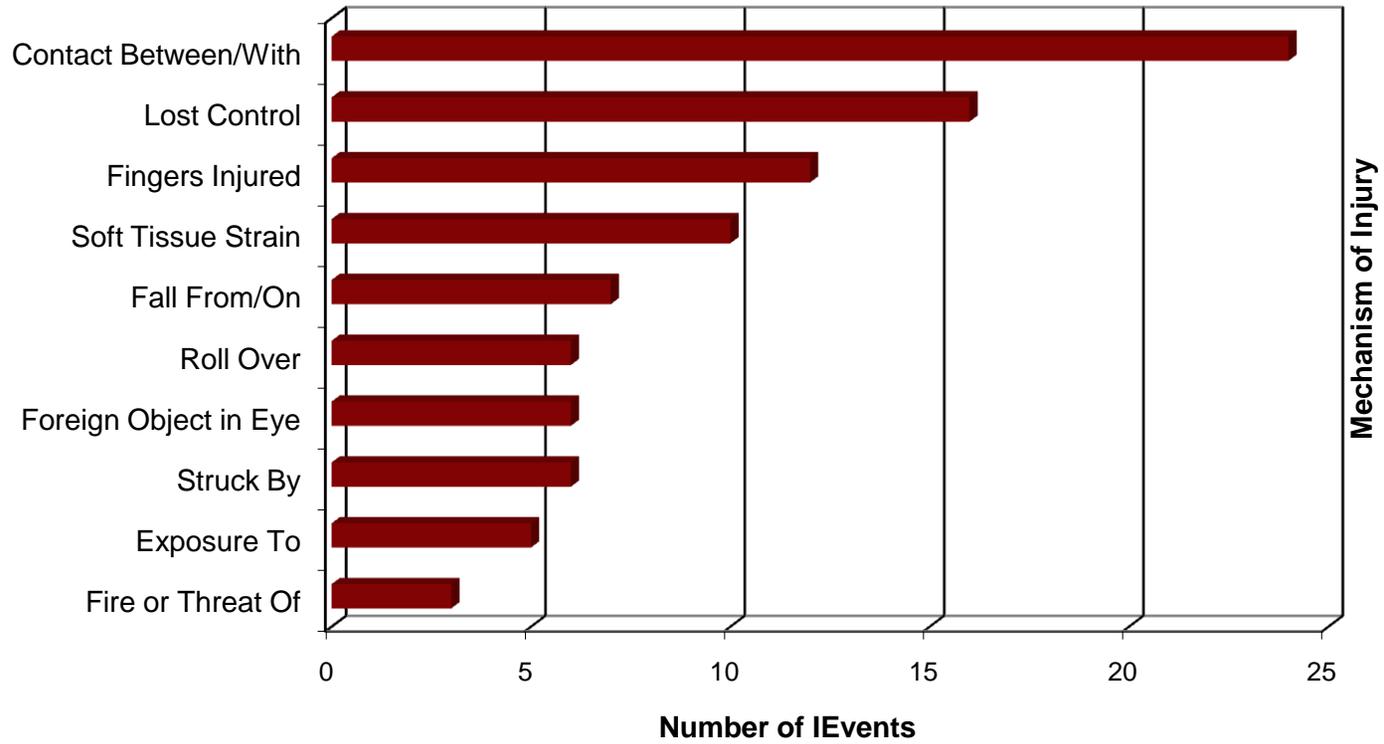


Figure 7.19: Graphical illustration of mechanism of injury ranked by number events.

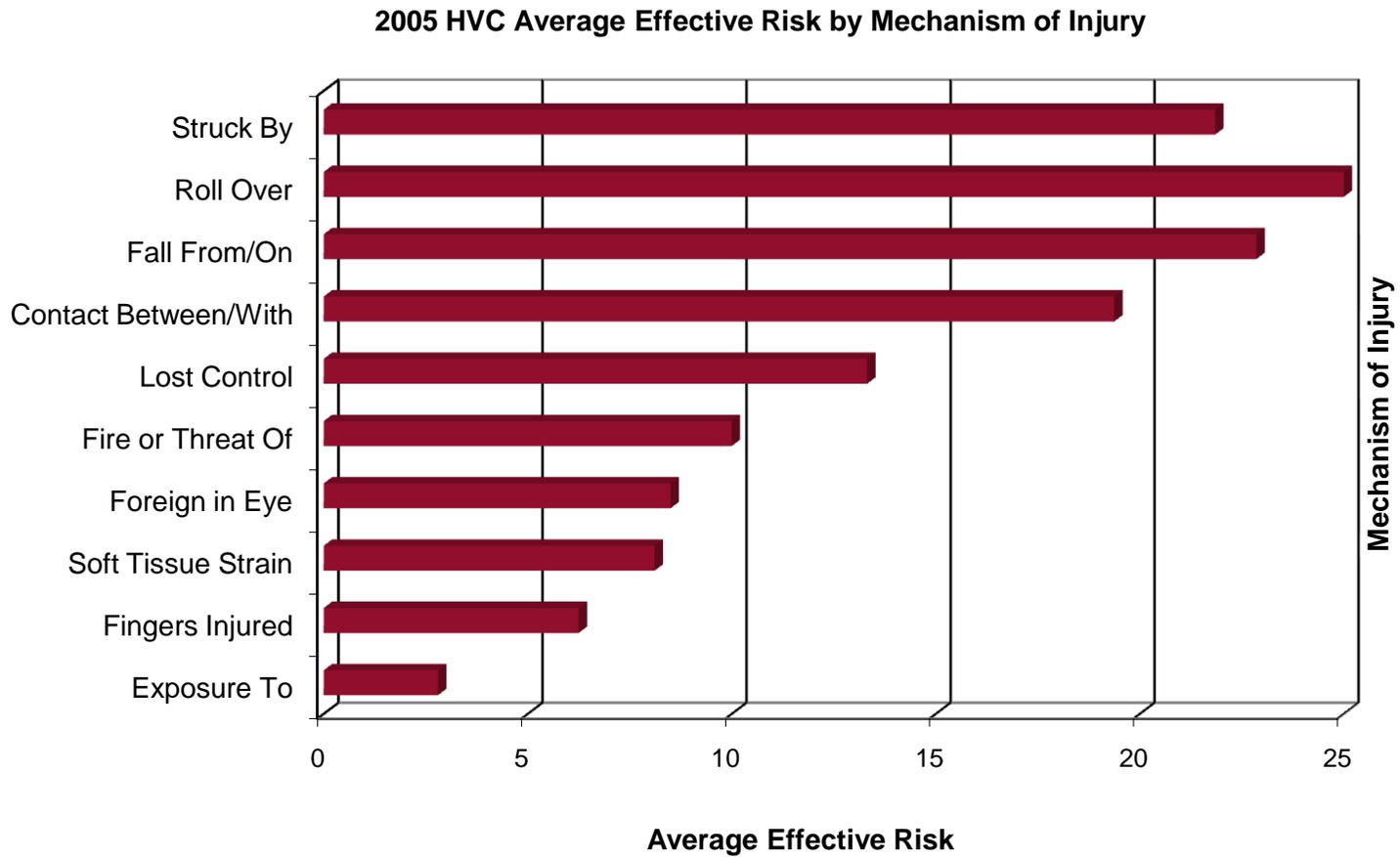


Figure 7.20: Graphical illustration of mechanism of injury ranked by average effective risk.

2005 HVC Job Experience (years) by Mechanism of Injury

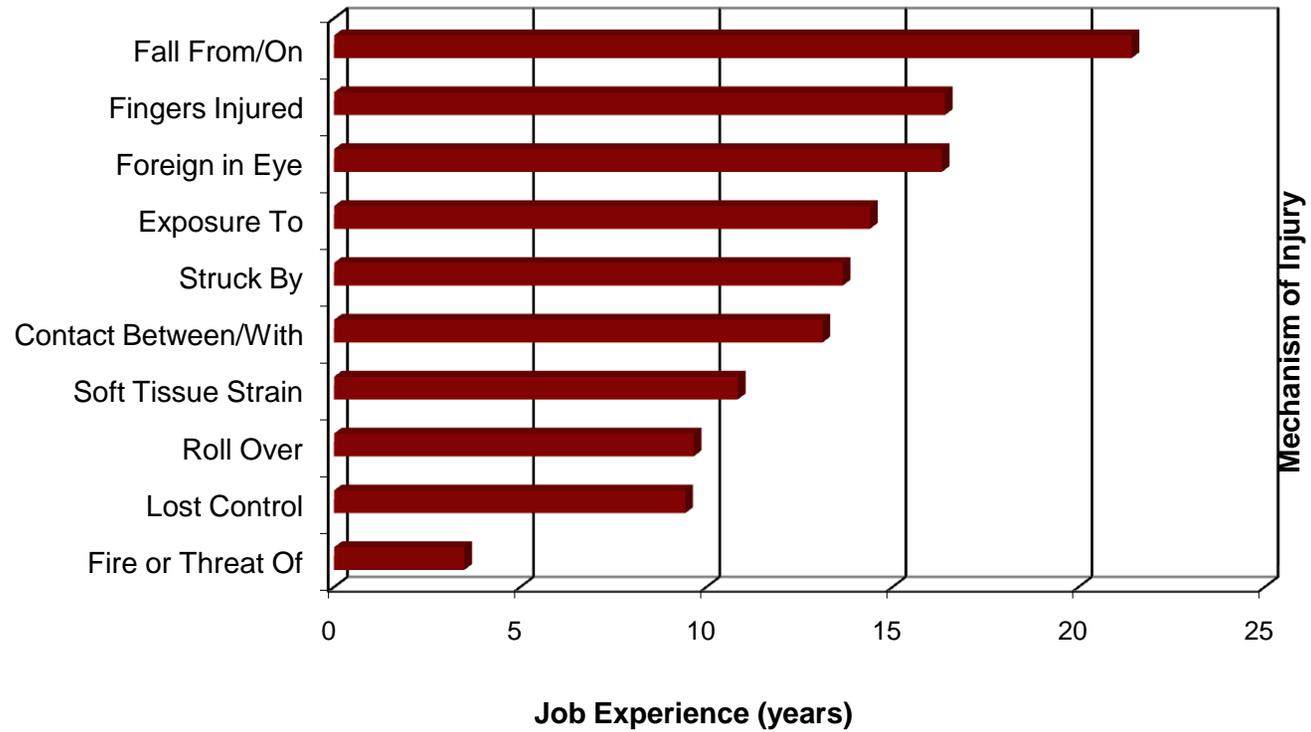


Figure 7.21: Graphical illustration of mechanism of injury ranked by job experience in years.

2005 HVC Average Event Cost (\$'s) by Mechanism of Injury

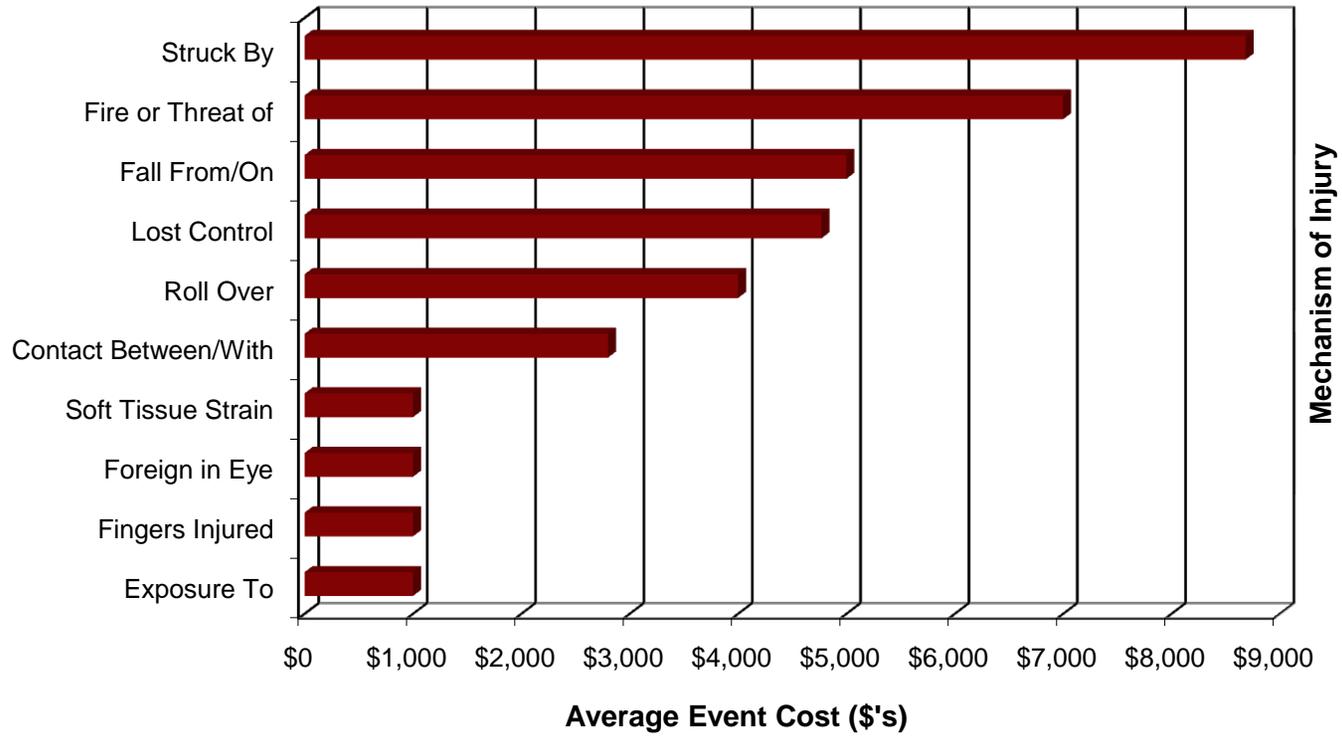


Figure 7.22: Graphical illustration of mechanism of injury by average *event* direct cost in dollars.



Figure 7.23: Graphical illustration of mission criticality by mechanism of injury.

2005 HVC Number of Incidents/Accidents by Occupation

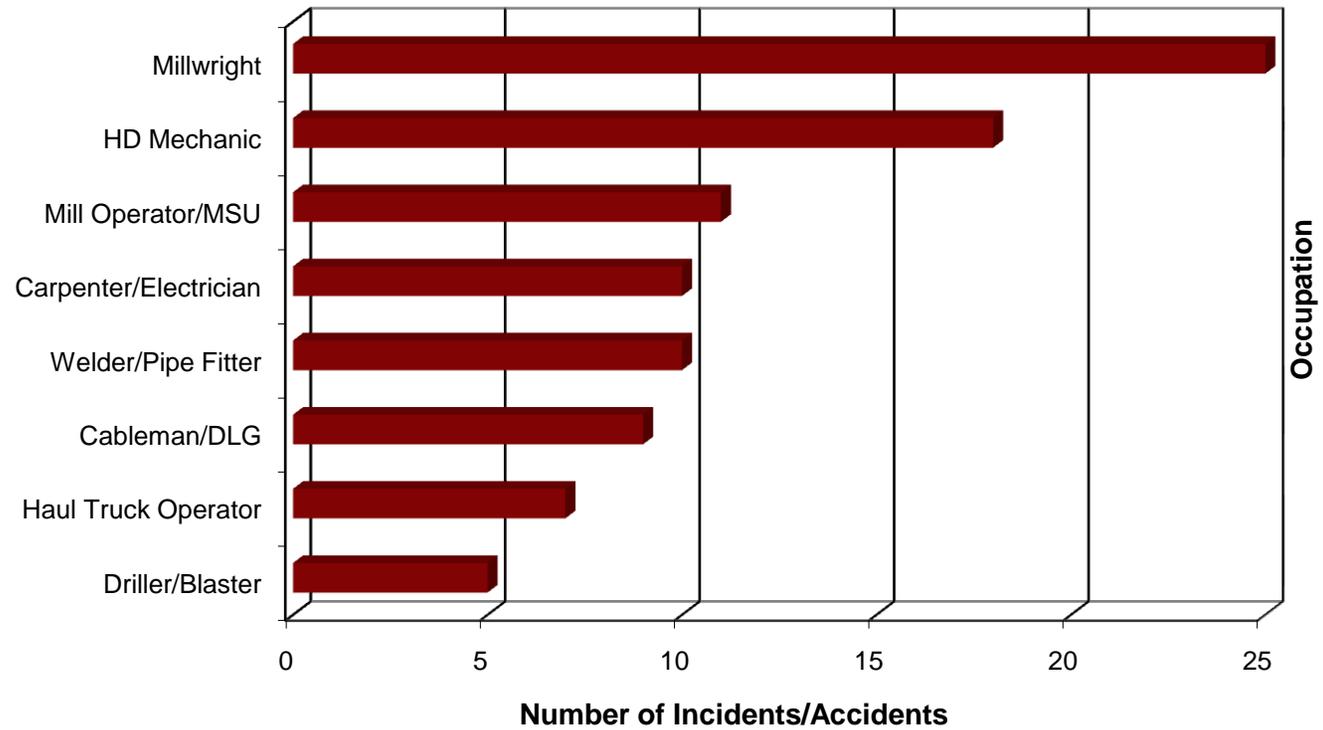


Figure 7.24: Graphical illustration of mine occupation ranked by number of events in 2005.

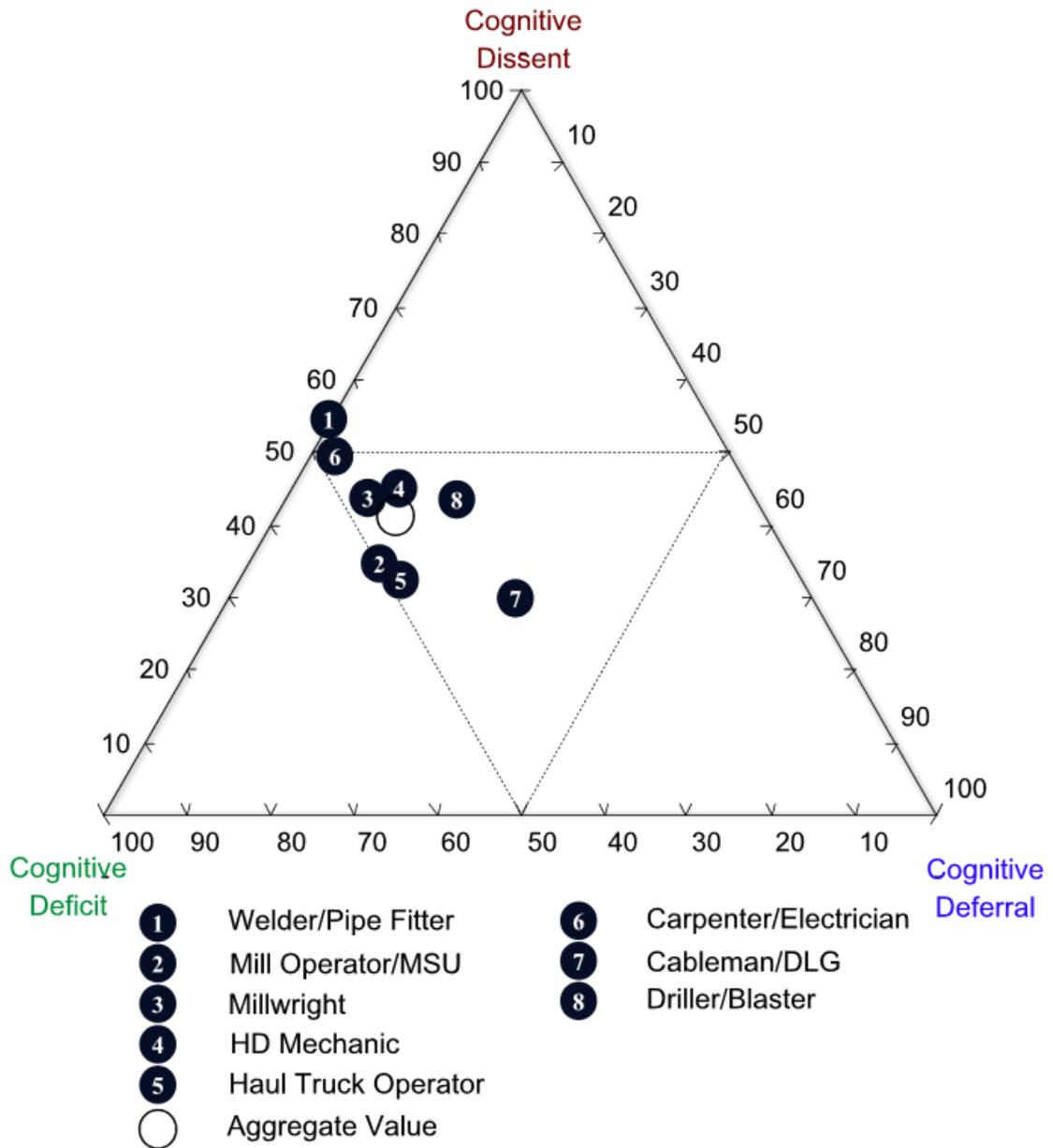


Figure 7.25: Cognitive profile of decision errors compared to occupation.

2005 HVC Average Effective Risk by Occupation

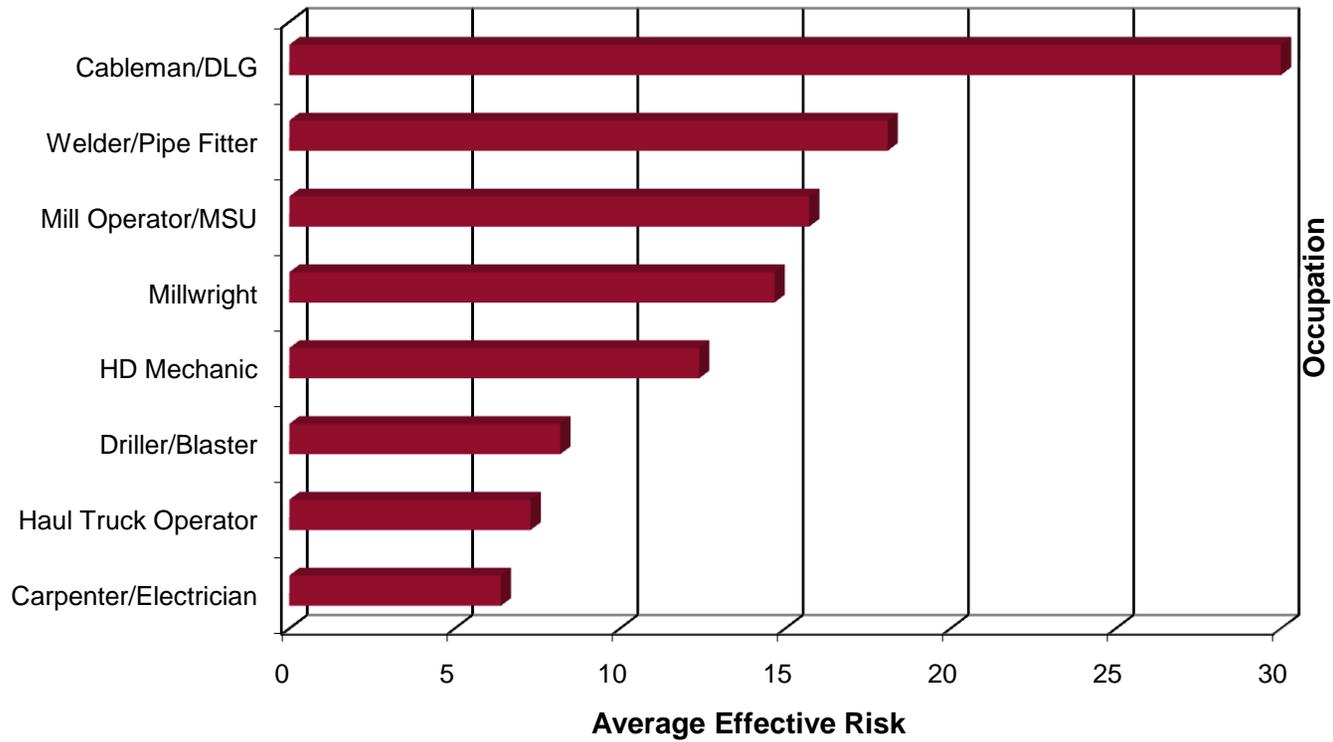


Figure 7.26: Graphical illustration of mine occupations ranked by average effective risk in 2005.

2005 HVC Job Experience (years) by Occupation

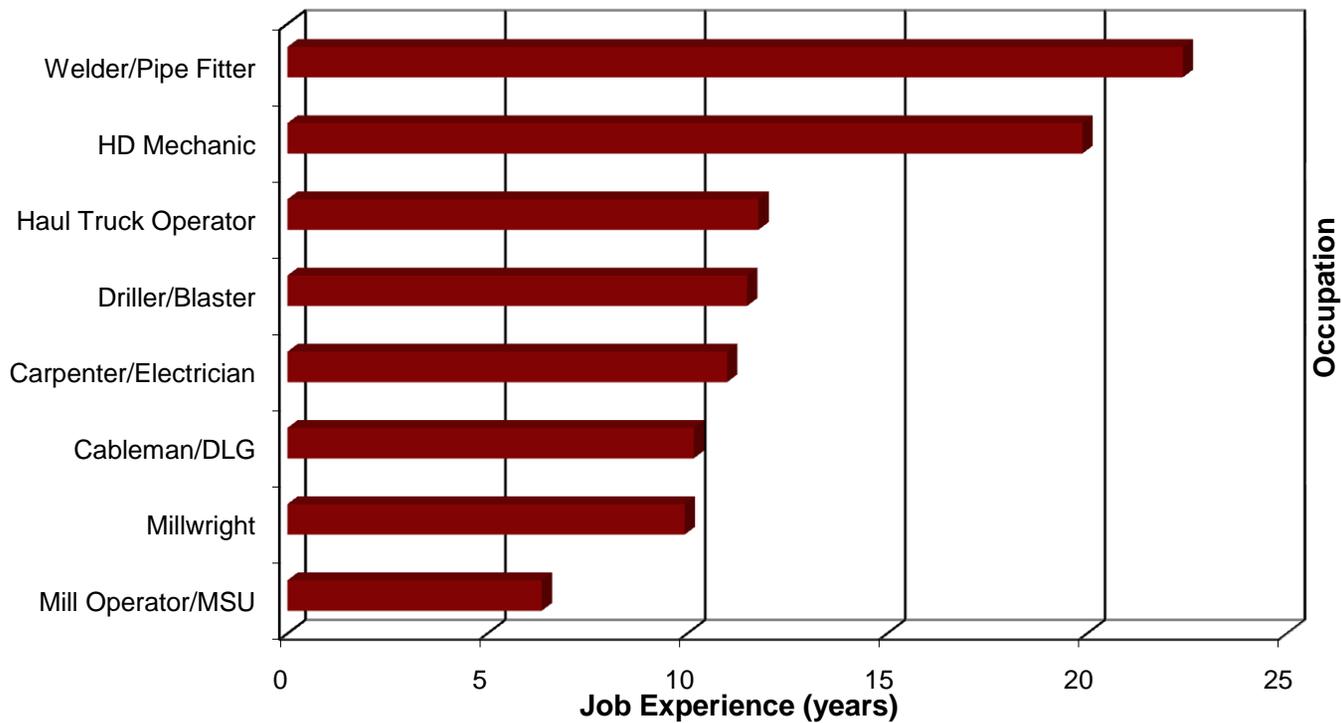


Figure 7.27: Graphical illustration of mine occupation ranked by job experience in 2005.

2005 HVC Average Event Cost by Occupation

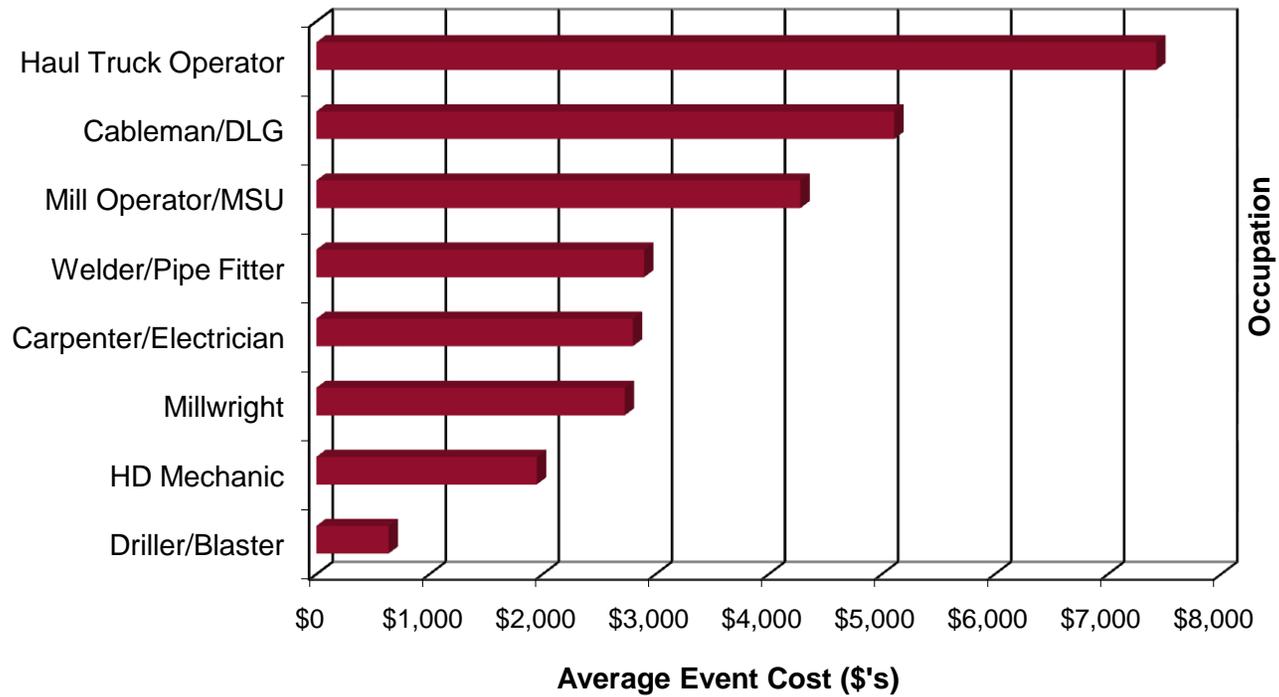


Figure 7.28: Graphical illustration of mine occupation ranked by average event cost in 2005.

2005 HVC Average Mission Criticality by Occupation

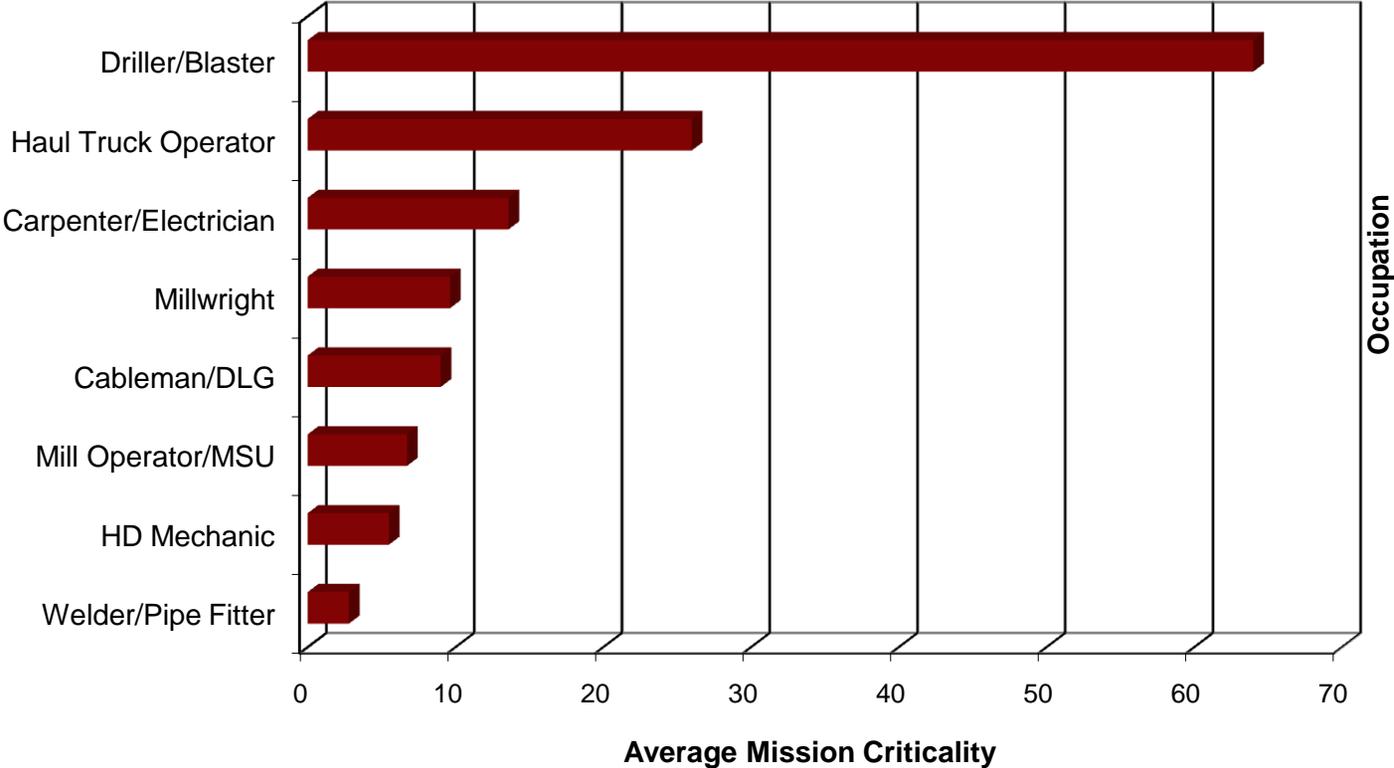


Figure 7.29: Graphical Illustration of mine occupation ranked by average mission criticality.

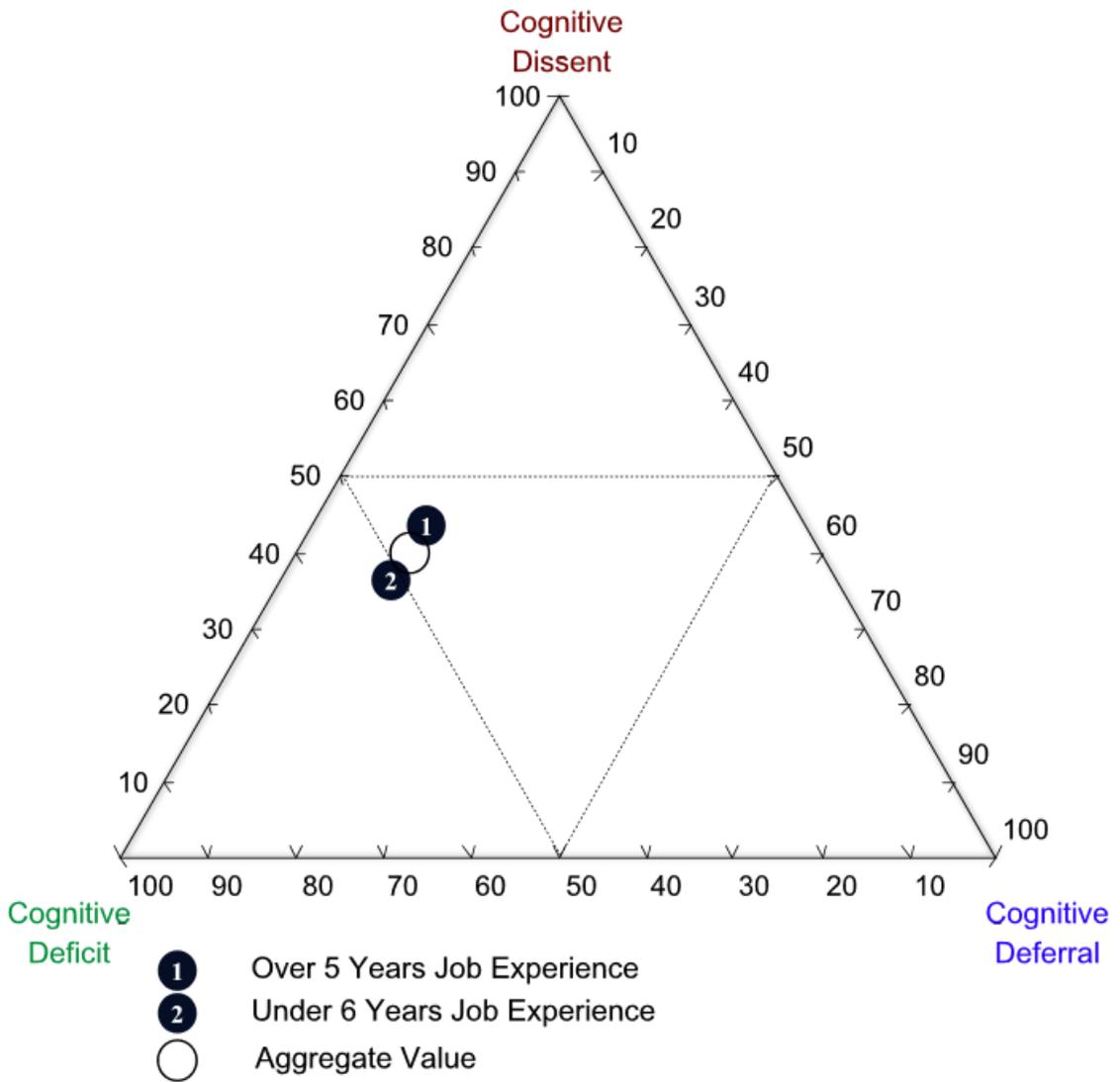


Figure 7.30: Cognitive profile of decision errors as compared to job experience (years).

2005 HVC Number of Incidents/Accidents by Clock Hour - A.M.

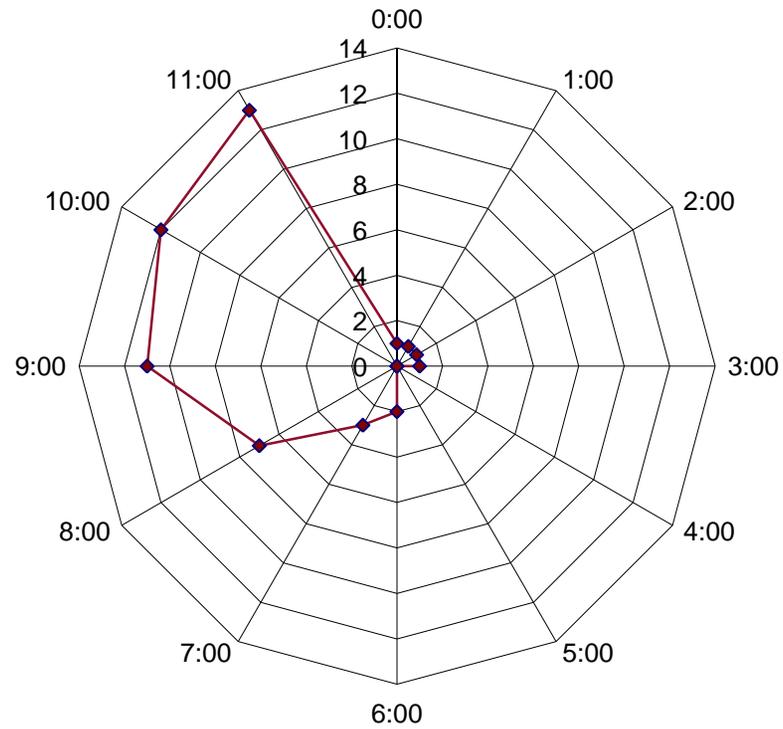


Figure 7.31: Illustration of the variation of frequency of *events* with respect to hour – a.m.

2005 HVC Number of Incidents/Accidents by Clock Hour - P.M.

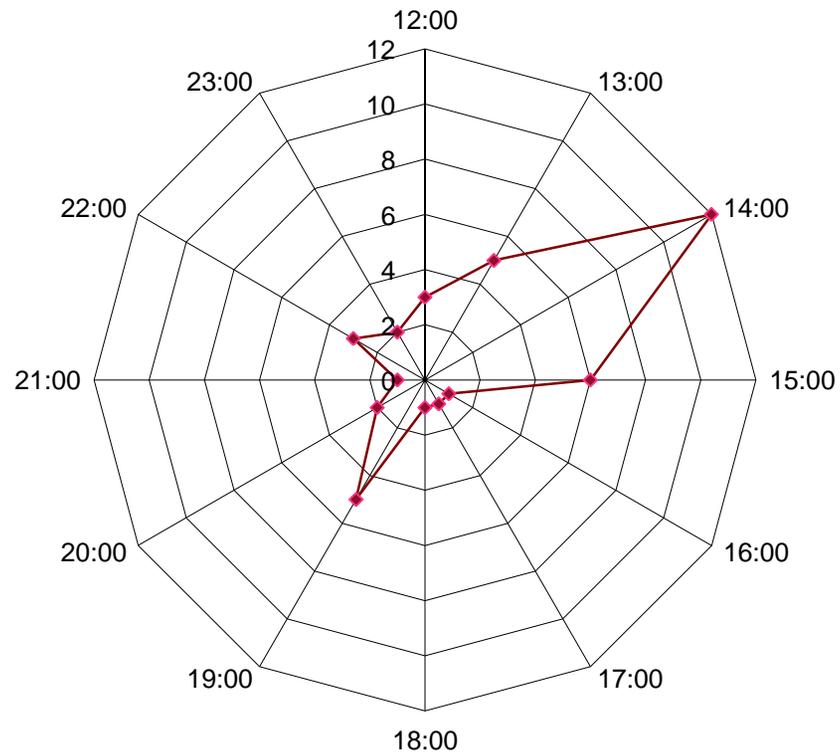


Figure 7.32: Illustration of the variation of frequency of *events* with respect to clock hour – p.m.

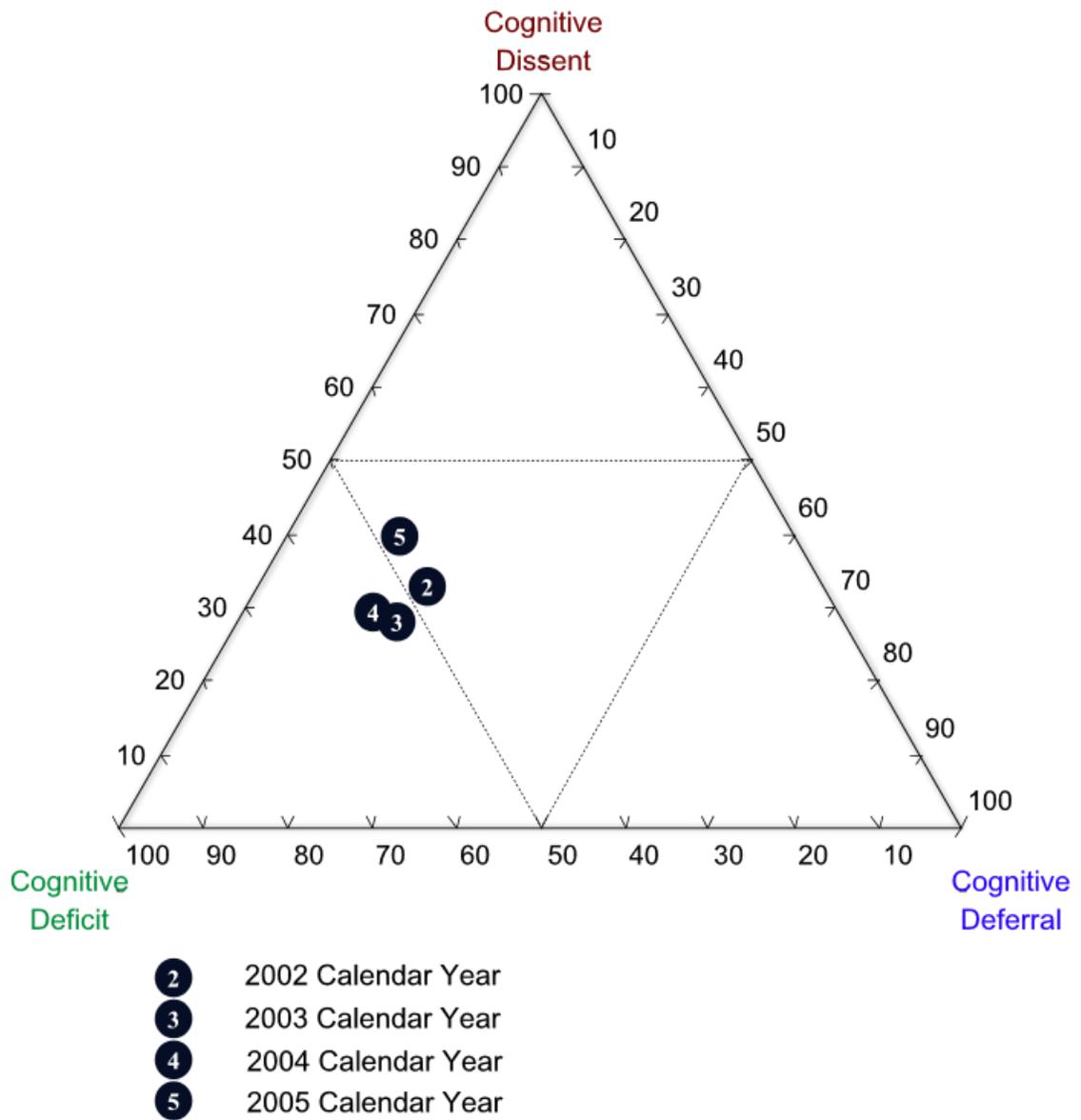


Figure 7.33: Cognitive profile of decision errors over the years 2002 to 2005.

"Don't be discouraged by a failure. It can be a positive experience. Failure is, in a sense, the highway to success, inasmuch as every discovery of what is false leads us to seek earnestly after what is true, and every fresh experience points out some form of error which we shall afterwards carefully avoid." John Keats (Bartlett, 2000)

8 CONCLUSIONS AND CONTRIBUTIONS

The search for causes of accidents, incidents and other undesired *events* in the workplace is, as it has always been, the noblest of pursuits by those engaged in the enterprise of mining. Appropriately, strategies for the control and prevention of these *events* demand the best that we as society are capable of achieving. It is however, not an easy task. The prevention of *events* in the mine workplace: be they accidents, incidents, environmental excursions or community protest is a matter that is no longer just a measure of operational efficiency, but speaks to the covenant that a mining proponent establishes with its community – a social license to operate. This dissertation acknowledges the culture of respect and self-awareness that most mine enterprises within the province of British Columbia demonstrate toward establishing social license, and the threat that *events* in the workplace have in retaining it - and their reputational capital.

It is asserted through this research that there are two fundamental benefits of the proposed cognitive profiling approach to cognitive error, in conjunction with more traditional *event* analyses: the methodology and the context. This methodology involves expertise in system theory, cognitive science, and investigation. Further, this methodology provides the professional with the tools (cognitive profiling) that will help them explore the context of the *event*. The context of the *event* specifically relates to the interaction of the human element (involved causally in the *event*) with the system

incorporating the *event*. A grounding concept in this dissertation is that causality is viewed as the result of a mismatch between the worldview (the perception of risk) of an actor(s) and the error-forcing *system* of which they are but one element. Further, to the extent that a mining enterprise has knowledge and influence as to what a ‘correct’ worldview should be, this worldview is subsumed by organizational structure, history and artefacts that comprise organizational culture and the attendant ethos of error.

This research proposes a third generation of accident theory based upon the causality of error. What is common to most accident theories is the axiom that what lies beneath the surface of *events* far surpasses its physical manifestation (Figure 8.1). This much has been established by the iceberg principle (Heinrich, 1931) and the loss prevention model of Bird and Germain (1985). Building on these theories is the notion that, while the causation of an *event* may be known or determined through examination of immediate cause and effect relationships, the aetiology of error is not intrinsically revealed or known; it must be adduced through analysis of that which is not cause and effect dependent, but still indicative of causality. This is what lies beneath the surface of *events*: an error-forcing *system* comprised of a constellation of error domains (design errors, operator errors, decision errors) that may, or may not, result in an *event* given any interval of time. A nascent error *system* exists nonetheless, if only as a potential.

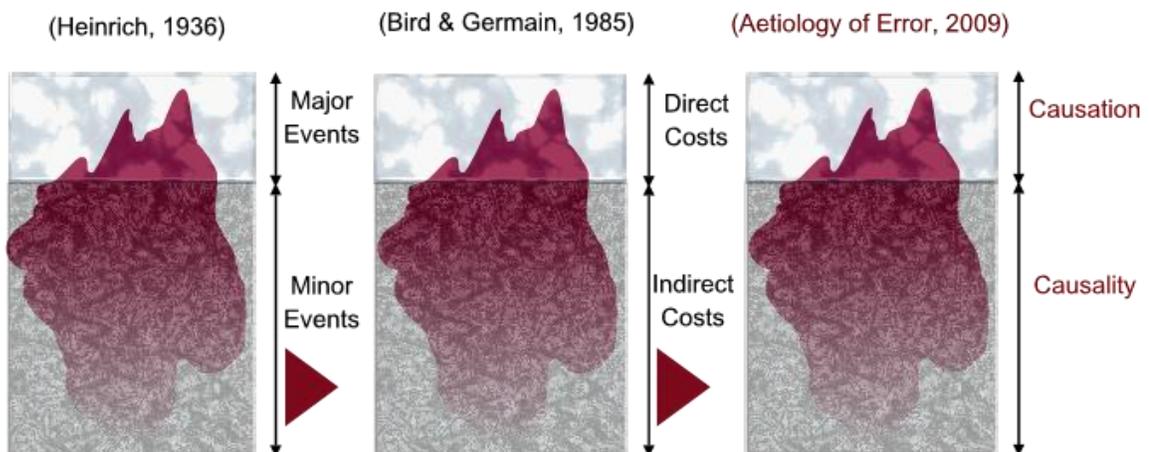


Figure 8.1: Progression of the iceberg principle correlated with time and successive models

Similarly, an *event* may, or may not, be recognized by the observers depending upon the perspicacity of the observer or organization toward causality. Thus, for an organization to be truly engaged in the prevention of *events* within their enterprise, they must be cognizant that although *events* may not yet have occurred, *events* are emerging as incipient or imminent potentialities within their management systems. While it is essential for the prevention of these *events* that defences be in place and shored up; in addition, this dissertation maintains that the perceptions of individuals toward risk, as well as those of social units within the enterprise, be examined and calibrated with a true and accurate ideation of risk. This dissertation argues that risk management strategies are effective to the extent that an organization strive for, and exhibit, consonance of risk perceptions within the enterprise.

8.1 Aetiology of Error

The use of the word aetiology in this dissertation refers to the derivation, provenance, or otherwise -- the origins of error. However, it does have a more subtle but important connotation: error as an expression of the human condition. In this vernacular, aetiology is the philosophical investigation into the causes and origins of human error. Thus, this research acknowledges the earlier work of Haddon (1980) and his epidemiological model of injury causation. Similarly, the word aetiology is resonant with human error articulated by Reason (1990, 2005), and its pathogenic underpinnings.

This dissertation argues that to see beyond causation and to understand causality, one must appreciate and discern the subtle but inexorable influence of human error, particularly as manifested by decision errors. It is only by observing such errors one considers, within the context of an error-forcing system, the gap that exists between the intention of the decision maker and the execution of their decisions (Norman, 1981).

8.1.1 Decision Error Theory

Decision error theory, when grounded in a practical cognitive framework, complements accident analysis by providing a structure that classifies the decision errors contributing to an *event* scenario. Decision error theory provides a taxonomy and vocabulary to examine decision errors. Using decision error theory as a framework, the

underlying cognitive context for human error can be articulated, substantiated and profiled. The error taxonomy that flows from decision error theory is seen to classify decision error in a manner that is directly supportable by the evidentiary record and error phenotypes. It is then left to subordinate methodologies of decision error analysis and cognitive profiling to transcend error phenotypes and adduce those errors inherent in the error-forcing system and lost to causation; that is, the cognitive error genotypes.

8.1.2 Decision Error Analysis

Essential to any accident analysis methodology is a straightforward graphical interface that is equal to the complexity of the *event* scenario. Decision error analysis provides such utility through the application of the decision error analysis diagram, developed through this research. This analysis serves as a means of accounting and attribution of decision error in a structured manner that is intuitive and rational. In so doing the analyst is required to consider the worldview of the actor(s) in terms of their perceptions and to understand the standards of care and conduct presiding at the time of the decision error. This prerequisite of decision error analysis reflects the quintessence of accident system theory, as the analyst is compelled to consider all of the domains of error coexisting at the time of the decision error, within the error-forcing system. These domains are inclusive, but not limited to, artefacts within the workplace, error detecting and correcting strategies, and the type of risk regimes exhibited by the organization or enterprise.

8.1.3 Cognitive Profiling

Cognitive profiling is the methodology by which elementary cognitive error genotypes are derived from antecedent decision error phenotypes. Cognitive error is elementary by reason of the state of infancy of this technology, as well as by reason of the indivisibility of cognition as a mental process. Cognition is at once both difficult to detect and to measure. Cognition is known throughout the social sciences, but lacking is a sophisticated picture of cognition regarding distributive cognition (group dynamics).

This research proposes that there may be numerous cognitive error genotypes, but for the purposes of this dissertation there are three non-trivial genotypes that

describe typical perceptions toward risk. They are cognitive dissent, cognitive deficit and cognitive deferral. These three error genotypes are not only useful in terms of explicating error behaviour (decision error), but also offer a capacity for prediction, particularly in the context of organizational culture and its ethos of error. Lastly, cognitive profiling represents a method of examining the investigative record based on the observable; but more importantly, of representing the error-forcing system based on what is probable.

8.1.4 Discussion

There have been three hypotheses explicated by the theories and models detailed in this dissertation (Chapter 2, 3 and 4). They are:

- i. *Events* are not random: they are physical manifestations of interactive systems between humans and their environment in which the likelihood of their occurrence is presaged by, and proportionate to, the dissonance between actual risk and its perception.
- ii. Decision error, as it contributes to causality, is not limited as an attribute of individuals, but is distributed throughout the cognition of the social unit and its system(s) of governance.
- iii. The profiling of cognitive errors (particularly decision errors) is not only local and must consider, if not explicate, the biases and heuristics of all of the parties to the enterprise.

These three hypotheses, while not imperatives as such, serve to define the scope of cognitive profiling. In essence, cognitive profiling can be optimized in terms of the veracity of results by being inclusive of all *events* in the enterprise, no matter how large or small; by being inclusive of the collective social units as well as the individual actors; and by being inclusive of all the parties to the enterprise, not just those who are directly affected by the *event*.

Collectively, these hypotheses define best management practices as regards to the investigation of *events*. In order to achieve best results from investigations, mine management would be prudent to consider all of the parties to the enterprise (workers, supervisors, contractors, and regulatory agencies) and recognize that decision errors are

often made collectively and on the basis of biased perceptions of risk. For each of these hypotheses, there are revelations that are worthy of summation and emphasis.

8.1.4.1 Events are Systems

The paradigm associated with *events*, be they accident, incident or otherwise has undergone significant advancement over time. From simplistic beginnings as synonymous with fault (Heinrich, 1931) to contemporary system theory (Dekker, 2005) invoking the interdependence of techno-social interactions, *events* have taken on an increasingly complex perspective. While accident theory is advancing, investigative techniques and analytical approaches have not kept pace. It is revealed within this research that *events* have within them *system* attributes, or structure, that can be characterized and grounded in human error. Similarly, the requisite detection of human error is achieved through a *system* approach to their analysis. Cognitive profiling is such an approach that addresses the contribution made by decision errors, within an error-forcing *system*.

8.1.4.2 Primacy of the Group

The role of policies, procedures and practices (artefacts) within the workplace has become as commonplace as it is mandatory by regulation within the mining industry. Such artefacts have served the mining industry well; less appreciated is the notion that social units, not individuals, create these artefacts within the workplace. They in fact represent the distributed cognition and collective reasoning of members of organizations and the industry as a whole. Within the province of British Columbia, a collective comprising labour, industry and government similarly determine the rule of law (mine regulation). Thus, the standards for care and conduct within the workplace do in fact represent a gross approximation of the risk tolerances of a collective. It should be no surprise, then, that group dynamics strongly influence workplace parties and their perception of risk. This research acknowledges the primacy of the collective and suggests that within the social unit and sub-units comprising the workplace resides an ethos of error, and a measure of the safety culture that can either enable or inhibit risk-taking behaviour. Cognitive profiling of decision errors characterizes and tracks these risk behaviours.

8.1.4.3 Biases and Heuristics

This research suggests that, individually and collectively, workplace parties frequently exhibit dissonance with respect to their perception of risk with that of the organization as a whole. If their perception of risk is greater than the actual risk, they are unnecessarily exposed to anxiety, uncertainty and its debilitating effects. Should their perception of risk be less than the actual risk, they may not mitigate the risk as prescribed by the standards of care and conduct, thus putting themselves and others at risk of an *event*. Either way, the organization is in dissonance, and a common commitment to risk mitigation strategies is lacking. The mechanism by which workplace parties effectively address and reconcile this dissonance is through biases and heuristics. That is, only through the examination of cognitive processes such as *self-justification*, *representativeness* and *attribution theory* can decision makers understand the gap between their worldview and that of others. Cognitive profiling requires that the analyst have a capacity for detecting and understanding these biases and heuristics in order that they appreciate the perspective of the decision maker.

8.2 Contribution to the Field

There are four main contributions that this research is considered to make to the field of accident theory. They are:

- i. This research provides a theory, an analytical tool and methodology that complement existing system theory and epidemiological models in a way that transcends causation by taking into consideration error-forcing systems that have origins in causality (determinants that may or may not appear as cause and effect to any given *event*). This is a distinction that heretofore has not been made in accident theory, as typically *event* causation alone has been the expedient 'end game' to any investigation. This research however, holds that to truly understand accident causation one must account not only for the cause and effect relationships as evidenced by the determinants to an *event*, but the constellation of error-forcing factors that preside before and after the *event*. Decision errors are presented as one such domain of error phenotypes, and to the extent that

they can be attributed, they can be used as a means of explaining past *events* and predicting (preventing) future *events*.

- ii. This research stipulates that the notion of causality should be inclusive of the possibility that there are potential, more disastrous *events* as yet unrealized and products of an error-forcing system. Furthermore, this research demonstrates that within these error-forcing systems there are common mission criticality elements that, if left unmitigated, may come together to escalate an otherwise recoverable *event* into one from which the system cannot be recovered. The ten mission criticality elements presented herein contribute to accident theory by situating contemporary *events* with those from the past and in the future.
- iii. This research examines the merits for a new discipline of *event* analysis in which *events* are profiled to facilitate the understanding of the organizational and psychological precursors antecedent to them; as well as to develop a body of knowledge that can classify the error phenotypes for the purpose of human error detection. It is proposed that through the application of cognitive profiling as a methodology for *event* analysis, a technology is emerging that may be used to describe failure modes both in terms of characterization and propensity. Furthermore, this technology can assist the investigator(s) in a meaningful way to track error by a variety of means such as mechanism of failure, temporal variations, social structure and spatial distribution of decision errors. Thus, this technology contributes to accident theory by providing a tool that is both retrospective and predictive of human error.
- iv. This research establishes the importance of group dynamics in the causality of *events* and the provenance of error. Whereas it is acknowledged that individuals ultimately bear responsibility for their decisions, modern artefacts of the mine workplace are designed and implemented by teams or other social units. To the extent that these social units integrate their perceptions of risk into these artefacts, they strongly influence and control the perceptions and behaviours of other

parties. This research advances the argument for distributed cognition and its contribution to *event* scenarios within the mine workplace.

8.3 Critique of Decision Error Theory

Decision error theory embodies a subset of human error that can be applied post-*event* by the investigator of record or post-investigation by an *event* analyst. Analysis of errors in terms of decision error in isolation from other human error analysis (e.g. cognitive error analysis) would not be sufficient, or appropriate, to appreciate the full contribution of human error to an *event* scenario. Thus, an inherent limitation of decision error theory is that decision error theory does not replace human error analysis, but rather complements it.

Decision error theory proposes that there are decision errors that contribute to causality; or the constellation of error factors that exist in an error-forcing system that may, or may not, result in causation of an *event*. This subtle distinction between causation and causality may be a challenge to many that hold the widely accepted view of cause and effect (causation). The analyst must grasp that to establish correlation between two variables is a necessary, but not sufficient, condition to impute causation. Correlation should not be confused with causation (Plous, 1993). Causality emerges when there is enough similitude between *events* and common error factors for which causation may or may not be established. Thus, causality accounts for determinants that an otherwise efficient investigation into a single *event* might fail to detect.

Along similar lines, the analyst must be inclusive of all error domains and be conscientious to first arrive at the determinants of causation (cause and effect) prior to drilling deeper for causality. It is not the intent of decision error theory to increase the fogginess of causation by articulating error-forcing factors increasingly remote to the *event*. Such determination is necessary for the purposes of cognitive profiling causality; however, it is anticipated that causation will remain the preferred expedient for accident prevention that traditional mine management and accident theorists will practice - now and for the foreseeable future.

When applied by the post-investigation analyst, the potential exists that cognitive profiling may be misapplied. It is often convenient, if not tempting, to lose focus as

regards to the objective of decision error theory, and to re-investigate the *events* or otherwise second guess the causation model and preventative actions that others have concluded. Again, *event* causation is narrower in scope than causality; as causality is inclusive of factors causation, but not the other way around. Furthermore, there are factors of causality that may not be apparent in the *event(s)* of record until a large enough population of *events* are brought under scrutiny and examination. This is the promise of decision error theory, that with a suitably large enough population of *events*, one can profile (predict) future *events* through the faculty of causality.

8.4 Critique of Lost Error Taxonomy

Taxonomies are finite. They cannot be exhaustive, and typically cover only a specified domain of errors. Since the proposed decision error approach originates in workplace accident theory, the range of cognition that is described by this theory is unavoidably narrow. This research is based upon only three cognitive phenotypes with which the researcher has empirical knowledge and experience. The lost error taxonomy is, by this measure, limited and for this reason a fourth and default 'system error' has been introduced. The classification of 'system error' is anticipatory to the possibility that within sufficiently complex domains of investigation, there are likely to be determinants for which the actor(s), standards of care and control, or the chronology cannot be determined. Alternatively, it is not uncommon in some *event* scenarios for conditions to appear to have degraded spontaneously over time without any party having knowledge of a decision in which a standard of care or conduct is transgressed. Notwithstanding, the standard or control is no less transgressed. For these occasions, the classification of 'system error' has been reserved, and this accommodation parallels the definition of 'system error' by Perrow (1984).

The other limitation imposed by the lost error taxonomy is the stipulation that the three decision error phenotypes are mutually exclusive. This stipulation is necessary for clarity and definition of the decision errors, however, in practicality there is less distinction between the phenotypes and to this extent there is an intrinsic uncertainty owing to interpretation. This researcher acknowledges that as the architect of this taxonomy, there was an inability to reproduce the classification with better than a 9% margin of error. It is anticipated that the uncertainty of interpretation probably decreases

with the familiarity with the *events* under scrutiny. That is, had the researcher been also the investigator of record, the margin of error respecting interpretation could be significantly less. An inherent limitation of this taxonomy therefore is the degree to which different analysts interpret, and apply, lost error taxonomy.

8.5 Critique of Decision Error Analysis

A fundamental limitation of decision error analysis is that the analysts are required to have sufficient knowledge of the human error factors to successfully appreciate the perspective of the actor(s) in question (Dekker, 2004). That is, the analysis requires that a determination of the standard of care or control be made, and to what extent the actors knew of the standard, or otherwise formed intention respecting it. This determination of standards of care is essential, and enabling, on the part of the analyst. However, it is also something that is not easily determined post-investigation, as traditional investigations focus on cause and effect (causation) relationships, and the perspective of the decision maker is rarely determined; and less often articulated.

The perspective of the decision maker is more easily appreciated by the investigator of record (post *event*), and this limits the application of decision error analysis to the back analysis of *events* by the investigator of record. It is concluded, therefore, that decision error analysis is limited to the analyst who has direct knowledge of the investigation; and/or prudently takes an epidemiological approach to investigating the *event*; one that incorporates the perspective of the decision maker. Thus, decision error analysis is less effective as a post investigation analytical tool. It is emphasized, however, that cognitive profiling does not require a fulsome decision error analysis, but is aided by it.

8.6 Critique of Cognitive Profiling

Cognitive profiling requires a degree of expertise and modelling skill. Further, a background in cognitive science would be beneficial. Ideally suited are analysts skilled in system accident theory and the investigation process, in combination with training in cognitive science. This is a high standard of competency that, while not unachievable, is presently outside the reach of most accident investigators within the mining industry.

Still, given this standard of competency, the return on investment of these skills may not be immediately realized. This is because there is a paucity of investigative records within traditional investigation methods (causation) that have sufficient detail or scope in terms of determinants.

Also, the results of this research are largely empirical, and the application of cognitive profiling has not yet benefited from the rigour of cognitive science experiment or clinical studies. Still, in the absence of the latter, should cognitive profiling be applied in the manner and method described herein, then the inclusion of cognitive profiling will have added value to contemporary accident theory, and this research will have achieved some measure of its purpose.

8.7 Arguments for Further Work

There is opportunity for accident theorists to embrace modern cognitive science principles, and vice versa. Clearly, the aviation industry has embraced and contributed to cognitive error analysis (Busse, 2002; Trepass, 2003), from which it has greatly benefited. While not as high-technology as the aviation industry, the mining industry has much in common with it. Both are highly regulated, common in occurrence, and high risk enterprises in which the workplace parties share well-defined cultural perceptions of risk and reward. Both are unforgiving. The mining industry has a legacy of self-imposed standards over several millennia; a legacy that is a double-edged sword so far as innovations in *event* prevention is concerned. The mining industry has repeatedly shown, however, that once its internal inertia of tradition is overcome, it is responsive to innovation and opportunity. Cognitive science is a discipline whose time has come for the mining industry.

Throughout this dissertation, there has been considerable discussion of the concept of cognitive dissonance. Within the discipline of cognitive science, cognitive dissonance is a well-known and a well-studied social phenomenon. Within the discipline of accident theory, however, it is still an emerging concept. Cognitive dissonance, whether on the part of the individual or the collective, describes the disparity that exists between the worldview of the observer as regards to the perception of risk and that of the real world. Cognitive dissonance explains some of the risk behaviours exhibited by

actors in this dissertation that can be a harbinger of *events* to follow. Cognitive dissonance and cognitive consonance have figured prominently within the historical case studies presented within this dissertation. Consequently, it has occurred to this researcher that cognitive dissonance may be a sufficiently common phenomenon within the emerging field of cognitive profiling that it be considered a cognitive *genotype* of its own. If this is indeed the case, and it does bear future consideration and study, then the two dimensional ternary diagram comprising the cognitive analysis would in fact be a three dimensional tetrahedron (Figure 8.2).

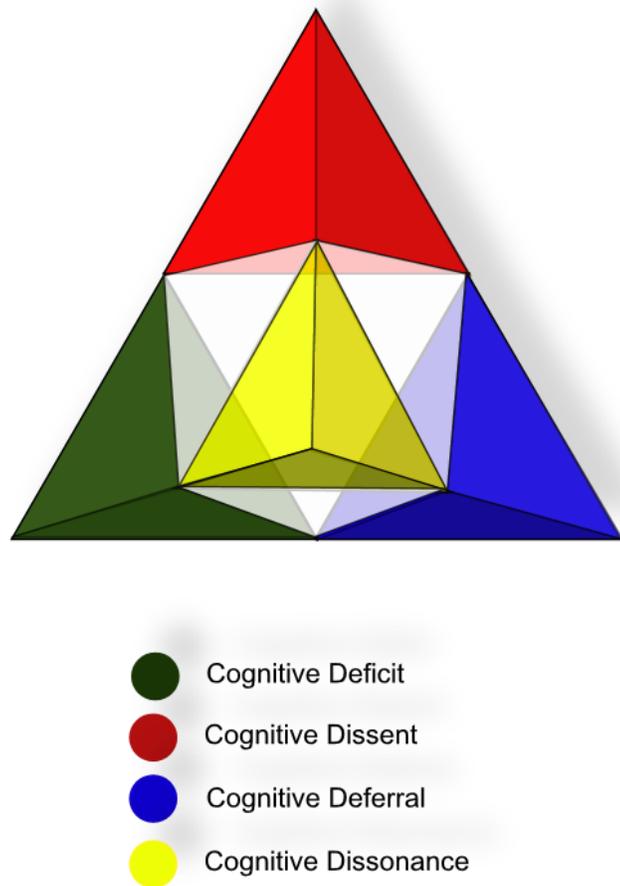


Figure 8.2: Cognitive profiling model inclusive of cognitive dissonance as an error genotype

The benefit of considering cognitive dissonance would be a much richer and more inclusive model; one that would require research outside the scope of this

dissertation. It is therefore recommended that further research be conducted considering the merit of a fourth cognitive genotype – that of cognitive dissonance. It is not clear as to what the corresponding behaviour or decision error phenotype might be, however it is offered by the researcher that the decision error may well exhibit the characteristics of capitulation. That is, the decision maker is likely to make a decision that he or she does not in good conscience support, but nonetheless is compelled or coerced into through group pressure or some other social dynamic. Such a dynamic may not be readily detected by conventional *event* investigation methodologies, and hence the opportunity for further research and investigation into the emerging field of cognitive profiling.

8.8 Statement of Accomplishment

This dissertation has demonstrated that through cognitive profiling, one can determine the psychological precursors to *event* scenarios. Further, these precursors are cognitive in nature and can be analysed indirectly by considering the character of the decision errors that are consequent to them. Ultimately, it is the perspective of the decision maker that is predictive of future error, as shaped by their perception of risk.

In this dissertation, we focus our attention on the standards of care and conduct within the workplace. We view causality through a new lens. If we accept that organizations collectively determine these standards, as artefacts of the workplace; then, we begin to appreciate that distributed cognition is unique and characteristic of organizational structure. By profiling cognitive error, we learn something about the culture of safety.

This dissertation has introduced a new model of mission criticality that is both descriptive and predictive of *events* in terms of their propensity for escalation. In this model, cognitive profiling is an integral consideration in determining elements common to industrial disasters around the world.

Finally, these cognitive profiles are heuristic and when tracked through time, enable us to contemplate the interplay between techno-social dynamics and shared perceptions of risk. In conclusion, this research has met the objectives stated in section 1.4 of this dissertation.

"No man's error becomes his own law; nor obliges him to persist in it."

Thomas Hobbes (Bartlett, 2000)

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