# UNPLUGGED PERILS, LOST HAZARDS AND FAILED MITIGATIONS

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## Abstract

In this paper we investigate the phenomenon of unplugged perils – safety concerns which are known to some or all parties associated with the design and operation of a system, but which nevertheless result in an accident. In a small number of cases unplugged perils represent deliberate risk-taking – operation of a system despite (or because of) known dangers. Other unplugged perils result from 'lost hazards' – hazards which are known to some parties associated with a system, but fatally unknown to others. A further group of unplugged perils are 'failed mitigations' – hazards which are believed by all parties to have been successfully treated, but which in fact present unacceptable risk. By systematically examining accident reports across a range of industries we draw conclusions about the extent to which the various types of unplugged perils are real issues, and discuss the impact this may have on our understanding of good safety practice.

## 1 Introduction

How often are accidents caused by hazards that are unsurprising to some stakeholders related to the system in question? Accidents can be broadly grouped into two categories; those whose underlying causes were identified before the accident, and those whose underlying causes were not. It is entirely possible for accidents to occur that were genuinely unforeseeable, although experience has shown that this is rarely the case.

A well-known example is the Challenger shuttle disaster. The shuttle broke up shortly after launch on a cold January morning in 1986 due to the failure of one of the O-ring joints in its right solid rocket booster. The night before the launch, a teleconference was held between NASA and Morton Thiokol, the manufacturers of the solid rocket boosters, to discuss the low overnight temperature forecast prior to the morning of the launch (18°F (-8°C)). Engineers from Morton Thiokol tried to persuade NASA not to launch below 53°F (12°C) due to concerns over the effectiveness of the O-rings at such low temperatures [1]. Despite the points put forward by Morton Thiokol, NASA decided to go ahead with the launch. There were a number of socio-technical factors affecting NASA's launch decision such as political and financial pressure [2], but nevertheless, the accident occurred as a direct result of a hazard that had clearly been identified.

One could be justified in asking, if an identified hazard still caused an accident, how was it 'allowed' to happen? Perhaps the hazard was not well understood. Perhaps the safety measures implemented to control the hazard were simply not good enough. Maybe they were just unlucky – the accident could have possibly been the one-in-a-million event that is judged acceptably low probability. There may be a wide range of reasons.

Within the general class of unplugged perils – hazards which result in accidents – we consider the following categories.

- **New Science Hazards** – These are genuinely unidentified hazards (typically scientific phenomena unknown at the time of system design, such as early occurrences of metal fatigue).
- **Partially Identified Hazards** – These are cases where it is reasonable to expect that better hazard analysis would have resulted in more thorough understanding and treatment of the accident mechanism.
- **Lost hazards** – These are hazards which were initially identified, but through communication flaws were misunderstood or 'lost' during the analysis or treatment of the hazard.
- **Failed mitigations** – In these cases the hazard was known and understood by all parties, and believed to have been successfully treated. However, it still presented risk that would have been considered unacceptable if it was fully appreciated.
- **Accepted Risks** – In these cases the risk was fully appreciated and accepted by the involved parties before the accident.

In Section 3 we define these categories are more precisely, including consideration of overlaps between categories.

If we are to reduce the potential for accidents, it is important to first understand why hazards that have been identified can still lead to an accident.

## 2 Related Theories

In order to ultimately understand why accidents arise due to improperly treated hazards, it is first necessary to consider why accidents occur *at all*. Leveson [3] notes that there are a variety of ideologies that can be applied to ask the deceptively simple question of why accidents occur, which may be used to approach the problem from a slightly different angle. The root causes of some accidents may be best understood in terms of technological issues, while for others it may be more appropriate to consider whether problems arise due to deeper issues with an organisation's safety culture.

### 2.1 Normal Accident Theory

The ideas behind Normal Accident Theory (NAT) were originally put forward by Charles Perrow in his 1984 book *Normal Accidents: Living with High-Risk Technologies* [4], published in the aftermath of the accident at Three Mile Island in 1979.

NAT suggests that, for sufficiently complex systems, accidents are inevitable because it is not possible to predict the behaviour of the system for all conditions that may be encountered. Perrow introduces the concepts of *interactive complexity* and *coupling* that describe the relationships between component parts of a given system:

- **Interactive complexity** describes how familiar or comprehensible a sequence of events is to operators of a system. Systems exhibiting *complex interactions* may behave in an unexpected or unintuitive ways;
- **Coupling** refers to the degree of dependence between different parts of a system; a system comprising of parts that are highly dependent on one and other are said to be tightly coupled.

How vulnerable a system is to accidents can be expressed in terms of a combination of these two qualities – because it is not always possible to fully understand how complex, tightly coupled systems will behave under certain conditions, accidents can be expected to occur; give a system sufficient time and range of input conditions, some unusual behaviour is to be expected. Since the occurrence of such accidents simply reflects the natural behaviour of the system under certain conditions, they are referred to as 'normal accidents'.

NAT has been criticised as a theory because it lacks falsifiability [5]; to be falsifiable, a theory must make concrete predictions that can be tested.

### 2.2 High Reliability Organisations

High Reliability Organisation (HRO) theory suggests that organisations may be able to engage in 'nearly error free operations' such that they can be considered to exhibit 'high reliability' [6]. Researchers central to the development of HRO theory, include Karlene Roberts [6], Todd La Porte [7], Karl Weick and Katherine Sutcliffe [8].

Whilst NAT emerged from consideration of a few select accidents, HRO theory emerged from consideration of a few "surprisingly accident-free" organisations. This inverts (without removing) the empirical difficulties associated with NAT [5].

Although HRO theory does not state explicitly which classes of hazards can be avoided, the principles do not apply to **New to Science** hazards or **Accepted Risks**. Hence HRO theory is predicated on most hazards not falling into these categories.

### 2.3 Disaster Incubation Theory

In 1976 Barry Turner suggested that certain organisational flaws can lead to the accumulation of errors which can ultimately result in a disaster [9]. He suggested that conditions for a disaster could arise if a set of events that are inconsistent with cultural beliefs or norms go unnoticed for a period of time. He calls this phase the 'incubation period' (i.e. the conditions are just right for a disaster), and his ideas have become known as 'Disaster Incubation Theory' (DIT) (e.g. see [10] and [11]).

Turner focuses the scope of his analysis to catastrophes that come somewhat as a surprise and give reason to question whether the basic underpinning beliefs, norms and attitudes were appropriate. Turner defines such events as 'large-scale disasters that are potentially foreseeable and potentially avoidable, and that, at the same time, are sufficiently unexpected and sufficiently disruptive to provoke a cultural reassessment of the artefacts and precautions available to prevent such occurrence'.

DIT makes clear predictions about the nature of hazards leading to accidents. If DIT is generally true, then **Lost Hazards** and **Failed Mitigations** should dominate as the causes of accidents.

### 2.4 Observations on Theories and Falsifiability

In preparing this paper, we also considered the theories of:

- Vulnerable Systems Syndrome (VSS) [12]
- Black Swans [13]
- Risk Homeostasis [14]
- Systems Theoretic Accident Model [15]
- Predictable Surprises [16]

Whilst each makes important contributions to understanding the role of hazards in accidents, they share similar difficulties to the theories discussed in detail in this section. These difficulties are:

1. There is no clearly defined set of systems to which the theory applies or does not apply (system set);
2. There is no clearly defined set of accidents to which the theory applies or does not apply (accident set); and
3. No test has been conducted to check whether membership of the system set is related to membership of the accident set.

Until the third difficulty is resolved, no theory can lay claim to having the power to *explain* or to *predict* accidents.

An interesting related question is the size of the set of systems or accidents to which each theory applies. Theories which emphasise the unpredictability of accident mechanisms, such as NAT [4] and Black Swans [13] cannot apply for the same systems as theories such as Predictable Surprises [16] and Risk Homeostasis [14] which emphasise the inability of organisations to control known hazards. DIT [9] and VSS [12] propose specific organisational behaviours which are measurable and countable.

## 3 Method

Our study was based on the collection and analysis of a set of accidents, and the sentencing of those accidents based on knowledge that various parties held at the time of the accident.

### 3.1 Accident Selection

In order to achieve a systematic approach to accident selection, a number of publicly available accident databases and lists were sought as a starting point. There are a number of such sources readily available – for example, in its guidance on the use of accident and incident data for Independent Safety Assurance, the Institution for Engineering and Technology (IET) lists a number of sources of information on accidents and incidents [17]. The Federal Aviation Authority (FAA) website also lists databases of accident data [18]. Such databases are highly industry-specific, and contain large numbers of entries with insufficient information for a study such as ours.

It was found that a list of accidents given on Wikipedia [19] contained a manageable size list of accidents (1,159 in total) covering a wide range of industries, and it was judged that this was a good starting point to apply more rigorous selection criteria.

The list of accidents was subject to screening to select only those those that:

(a) involved fatalities;

(b) occurred within the last 25 years but not within the last 18 months; and

(c) occurred in the UK, US or Australia, or involved systems owned or operated by organisations belonging to these nations.

These criteria were determined before examining the list of accidents, and were designed to maximise the chance that sufficient detail was available to sentence each accident. A total of 51 accidents met the screening criteria. Twenty accidents were randomly selected from these 51 as the 'Primary Set' for investigation.

| ID | Accident | Date |
|---|---|---|
| 1 | Space Shuttle Challenger Disaster | 28 Jan 1986 |
| 2 | Herald of Free Enterprise | 06 Mar 1987 |
| 3 | Northwest Airlines Flight 255 | 16 Aug 1987 |
| 4 | King's Cross Fire | 18 Nov 1987 |
| 5 | Piper Alpha Oil Rig Disaster | 06 Jul 1988 |
| 6 | British Midland Flight 092 | 08 Jan 1989 |
| 7 | USS Iowa Turret Explosion | 19 Apr 1989 |
| 8 | Phillips Disaster | 23 Oct 1989 |
| 9 | American Airlines Flight 965 | 20 Dec 1995 |
| 10 | Trans World Airlines Flight 800 | 17 Jul 1996 |
| 11 | Cavalese Cable Car Disaster | 03 Feb 1998 |
| 12 | Ladbroke Grove Rail Crash | 05 Oct 1999 |
| 13 | Hatfield Rail Crash | 17 Oct 2000 |
| 14 | American Airlines Flight 587 | 12 Nov 2001 |
| 15 | Waterfall Rail Disaster | 31 Jan 2003 |
| 16 | Space Shuttle Columbia Disaster | 01 Feb 2003 |
| 17 | BP Refinery Explosion | 23 Mar 2005 |
| 18 | Nimrod Crash | 02 Sep 2006 |
| 19 | Xcel Energy Hydroelectric Plant Fire | 02 Oct 2007 |
| 20 | Upper Big Branch Mine Explosion | 05 Apr 2010 |

Table 1- Primary Set of Accidents

### 3.2 Accident Sentencing

In order to sentence accidents systematically, it was necessary to first clarify what was meant by its underpinning 'hazard', as there are a range of levels at which a 'hazard' could be defined. In order to resolve this, the following hazard types were defined:

1. The 'Generic Hazard' – a general description of the top-level hazardous condition (e.g. 'fire', 'derailment', 'explosion' etc);
2. The 'Hazard Mechanism' – the means by which the Generic Hazard can be manifested (e.g. the failure mode);
3. The 'Specific Hazard Occurrence' – the actual realisation of the hazardous condition(s) (e.g. the physical occurrence of the hazard on the day of the accident).

This was necessary as it was apparent that for a number of accidents, various stakeholders had different understandings of the hazard at these levels. The range of stakeholders considered for each accident included the system designers and manufacturers, regulators, the organisation responsible for managing the system, and the actual personnel operating (or exposed to) the system.

The classification scheme for sentencing the accidents is given in Table 2 - Accident Sentencing Scheme. Under this scheme, accidents are sentenced by the allocation of one Group from each Group Type, e.g. accidents could be classified as "A1D" or "C2E" etc.

| Type | Group |
|---|---|
| Generic Hazard | A. Generic Hazard recognised by all stakeholders<br>B. Generic Hazard recognised by some stakeholders but not others<br>C. Generic Hazard not recognised by any stakeholder |
| Hazard Mechanism | 1. Hazard Mechanism recognised by all stakeholders<br>2. Hazard Mechanism recognised by some stakeholders but not others<br>3. Hazard Mechanism reasonably foreseeable but not recognised by any stakeholder<br>4. Hazard Mechanism not reasonably foreseeable and not recognised by any stakeholder |
| Specific Hazard Occurrence | D Specific Hazard Occurrence recognised by all stakeholders<br>E. Specific Hazard Occurrence recognised by some stakeholders but not others<br>F. Specific Hazard Occurrence not recognised by any stakeholder |

Table 2 - Accident Sentencing Scheme

Inter-coder validity was measured by both authors independently coding each accident in the primary set.

# 4 Hypotheses and Specific Predictions

It is expected that when accidents occur, the underlying Generic Hazards are generally well known and understood – when a fire occurs at a hydrocarbon processing plant, no-one claims that the flammable nature of hydrocarbons was unknown (the use of hydrocarbons as a fuel is in most cases the very reason for the plant). When an aircraft crashes, it comes as no surprise that flying into the ground has the potential for fatalities.

There are historical examples of fatalities occurring as a result of the Generic Hazards not being known or well understood. One such example would be the death of Marie Curie in 1934, who died from leukaemia, caused by exposure to high-energy radiation from her research into radioactivity. At the time, the dangers posed by radioactive sources were not understood. Generic Hazards which are not known fall in to the category of **New Science Hazards**.

Where the generic hazard is recognised by all stakeholders, accidents will classified in Group A (e.g. "A1E", A3D" etc).

***Hypothesis 1****: In the vast majority of cases, the Generic Hazard(s) underpinning accidents are well known and understood by all stakeholders.*

***Prediction 1****: At least 95% of accidents sentenced in accordance with the accident classification scheme will be classified in Group A.*

It is likely that some accidents were caused as a result of an unforeseen Hazard Mechanism (classification Groups 3 and 4), although this is expected to be in the minority of cases.

***Hypothesis 2****: For most accidents, the Hazard Mechanism was recognised through some form of hazard identification, or inherently obvious.*

***Prediction 2****: Less than 50% of accidents sentenced in accordance with the accident classification scheme will be classified in either Group 3 or Group 4.*

It is thought that only a small proportion of accidents occur as a result of deliberate risk-taking, despite the hazards being well known by all stakeholders (classification Group D) – if people are well aware of a hazardous situation (and understand the risks), then it is expected they will generally take steps to avoid the accident. In most cases it is expected that accidents occurred when the specific occurrence of the hazard was not recognised (Group F).

***Hypothesis 3****: Only a small proportion of accidents occur as a result of deliberate risk-taking, despite the hazards being well known by all stakeholders.*

***Prediction 3****: Less than 10% of accidents sentenced in accordance with the accident classification scheme will be classified as Group D, and more than 80% of accidents will be classified as Group F.*

It is expected that some accidents occur as a result of miscommunication between various stakeholders. For example, misunderstanding between system designers and system operators could lead to a system being used outside of the designed safe operating envelope, e.g. in a way that the designers never intended.

Where this is the case, there is likely to be a difference in the level of stakeholder awareness when considering the hazard at different levels. Perfect communication between all stakeholders would mean that all stakeholders had the same awareness of hazards at different levels. In this case, there would never be a scenario where the Generic Hazard or Hazard Mechanism was known to some stakeholders but not others (classification Group B and/or Group 2). As this is not expected to reflect reality, it is therefore expected that some proportion of accidents will fall into these groups. The actual proportions will reveal some insight into the relative number of accidents caused by miscommunication, although it is not immediately obvious what this fraction will be. However, for the sake of making a prediction it is hypothesized that miscommunication between stakeholders is a contributory cause in more than half of accidents.

***Hypothesis 4****: Miscommunication between stakeholders is evident as a contributory cause in more than half of accidents.*

***Prediction 4****: More than 50% of accidents sentenced will be classified in Group B and/or Group 2.*

# 5 Results

## 5.1 Sentencing

Sentencing of the 20 accidents in the Primary Set in accordance with the accident sentencing scheme yielded a number of accidents within each group – this is shown in the central column of Table 3.

Once the analysis of the Primary Set was complete, another set of 15 accidents were subject to sentencing in accordance with the same accident sentencing scheme. It was found that the relative proportions of accidents within this 'Secondary Set' classified in each group were reasonably similar to those obtained from classification of the Primary Set. This suggests that the accident classification scheme has been applied consistently across both sets of accidents, and that similar trends exist across the two groups.

The full results of the accident sentencing were as follows:

| Group | Primary Set (20 accidents) | | All accidents reviewed (35 accidents) | |
|---|---|---|---|---|
| **Generic Hazard** | | | | |
| A | 20 | (100%) | 35 | (100%) |
| B | 0 | (0%) | 0 | (0%) |
| C | 0 | (0%) | 0 | (0%) |
| **Hazard Mechanism** | | | | |
| 1 | 11½ | (57.5%) | 20½ | (59%) |
| 2 | 3 | (15%) | 5 | (14%) |
| 3 | 3 | (15%) | 7 | (20%) |
| 4 | 2½ | (12.5%) | 2½ | (7%) |
| **Specific Occurrence** | | | | |
| D | 1 | (5%) | 1 | (3%) |
| E | 5 | (25%) | 9 | (26%) |
| F | 14 | (70%) | 25 | (71%) |

Table 3 – Results of Accident Sentencing

The non-integer figures within the Hazard Mechanism totals are due to the two possible hazard mechanisms identified for TWA Flight 800, these being either (a) an ignition source in the presence of flammable mixture of fuel vapour and air in the CWT or (b) a short-circuit due to the build-up of silver sulphide. Hence this accident could be classified as either (a) Group 1 or (b) Group 4. In order to account for this in the analysis, TWA Flight 800 was included in both Groups, but weighted accordingly to avoid double-counting.

## 5.2 Validity

There was 100% agreement in sentencing the Generic Hazard. There was 80% agreement sentencing the hazard mechanism (Cohen's Kappa = 0.73, Krippendorff's Alpha = 0.73). This level of agreement is sufficient for the preliminary findings presented here.

Whilst the same percentage agreement was obtained for the Specific Hazard Occurrence, the lack of variation in this coding means that the agreement could equally have come about by chance (Cohen's Kappa = 0.48, Krippendorff's Alpha = 0.47).

An additional threat to validity not captured in coder-reliability is that hindsight bias will reflect what is *recorded* about accidents. For example, witnesses may be reluctant to accurately report hazard identification and risk assessment after that hazard has manifested as an accident.

# 6 Discussion of Results and Further Work

## 6.1 Key Findings

The key findings of this study were obtained by consideration of the results of the accident sentencing exercise, and are listed below. Where figures are given in brackets, e.g. (59%), these reflect the actual results obtained during the study; whilst we believe the study and its results to be representative, it is acknowledged that the exact percentages are unlikely to be correct for the population of all accidents.

1. No system accidents were found to have been caused by top-level Generic Hazards that were unknown prior to the accident.

2. The study identified 3 accidents where "new science" was apparent in the Hazard Mechanism – in other words, while the Generic Hazard was not itself "new science", there were unknown phenomena that could create the hazard:
   - The King's Cross fire became catastrophic as a result of the previously unknown 'Trench Effect';
   - The USS Iowa explosion was caused by over-ramming of gunpowder bags, a "previously unrecognized safety problem" [20];
   - The short circuit which caused the TWA Flight 800 explosion may have been caused by the build-up of silver-sulphide on the wiring within the central wing tank – a previously unrecognised phenomenon.

3. The causes of approximately three-fifths (59%) of system accidents can be directly attributed to a failure of mitigations implemented to protect against the Hazard Mechanism that caused the accident.

4. The causes of approximately one-fifth (20%) of system accidents can be attributed to a failure to adequately

identify or recognise hazards that are reasonably foreseeable.

5. Miscommunication between stakeholders about known deficiencies or actual hazardous conditions is a significant factor in approximately one-sixth (17%) of accidents.

6. Only a small proportion (3%) of system accidents are caused as a result of deliberate risk-taking despite all stakeholders being aware of hazardous conditions.

### 6.2 Hazard Classes

The category of **New Science Hazards** features in some accidents with respect to *hazard mechanisms,* but not with respect to *generic hazards*. This raises the question of whether some or all of these accidents could have been prevented by selecting mitigations better suited to protecting against the generic hazard rather than the known subset of mechanisms.

**Partially Identified Hazards** are a real phenomenon, featuring in one fifth of the accidents studied. In contradiction to NAT, these hazards show no obvious clustering around types of industry or system.

**Lost Hazards** are also a real phenomenon, but comprise a much smaller category than we anticipated, featuring in only a sixth of accidents. In contrast, **Failed Mitigations** (noting that this category excludes communication failure) feature in more than half of accidents.

As expected, **Accepted Risks** (deliberate risk taking) was not a significant category.

### 6.3 Further work

Our study does not provide a new theory of accidents, but instead sheds light on existing theories. Further work will require studying how the phenomena we have examined apply to both *accidents* and *non-accident systems.* Unless a phenomenon manifests differently in the set of systems which are involved in accidents, it cannot be used to explain those accidents. The three phenomena with most promise for future work are **Failed Mitigations**, **Lost Hazards**, and **Partially Identified Hazards**. Understanding how these phenomena occur, and when they are most dangerous, will be the keys to a theory which can actually predict and prevent accidents.

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