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Hidden Safety Systems Failures and their Contribution to Catastrophic Events: Case Studies from the Energy Industry

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It is accepted that incremental advances in technology have made equipment increasingly safer to operate across all industries. Although safety improvements are commendable, there are instances where the failure of safety systems has contributed to catastrophic events. Using two case studies from the energy industry, we identify the failures, hidden to the operators, that contributed to serious incidents. In the first example involving an explosion at the Upper Big Branch Mine in Montcoal, West Virginia, the failure of the ventilation systems resulted in the build-up of explosive gas and dust which was then exposed to a source of ignition. In the second example involving a gas pipeline explosion in San Bruno, California, a fault in the redundant power supplies resulted in a pipeline pressure increase which was a contributing factor to the subsequent explosion. We explore the possibility that the growing complexity of equipment used to deliver advances in performance, and the correspondingly intricate safety systems that are required, is increasing the likelihood of these hidden failures. The presence of the failures may be known to select company employees but are not communicated to the equipment operators, hence our emphasis on the 'hidden' aspects of their failures. The main objective of our paper is to identify instances of safety systems faults that acted as contributory causes in catastrophic incidents. In doing so, we highlight how more effort is required for thorough testing of the function of safety systems and the consequences of associated failures. We argue that an improved focus on design, testing, communication and operator training will do much to avoid the types of safety systems faults that have contributed to the disasters detailed in our case studies.

Keywords: Safety systems, energy, transmission, mining, gas pipeline, hidden failures, complex equipment.

1. Introduction

Failure events that occur in industrial safety systems can, depending on the affected system, lead to catastrophic consequences (Selvik and Signoret 2017). The term safety system can be defined as the "means those structures, systems, and components (SSCs) that are relied upon to prevent, control, or mitigate unacceptable consequences resulting from the hazards identified for a facility" (The United States Department of Energy 2006). It is broadly acknowledged that safety incidents in complex systems happen through the combination of multiple factors, where although each may be required, it is necessary that they happen in concert to produce the end event (Reason, Hollnagel and Paries 2006). Since there are now better supporting models of how incidents happen, which provide the theoretical underpinning of safety management systems, safety performance has improved (Hudson 2014). However, a gap in performance evaluation throughout the lifecycle of the assets and associated systems leave potential for issues to be present that are not addressed. To truly implement the concept of design for sustainability, especially for safety-critical systems, it is essential to achieve integration between functional and behavioral design and safety analysis. This is primarily because safety occurs as a consequential attribute. To further elaborate, safety conditions such as hazards and failure modes are often an outcome of certain unintended system functionalities and behaviors in a particular context (Habli, et al. 2010).

The aforementioned endeavours highlight the progress made with safety improvements in industry. They also outline the potential for complex safety systems to develop issues which are difficult to identify and as such may remain hidden in the overall equipment performance evaluation. A hidden failure is a failure that is not apparent under normal operating circumstances. They are typically revealed after another failure or event occurs. Hidden failures are often associated with standby and protective functions (Reliability Academy 2022). It is the role of a company's management to ensure sufficient time and money are spent on safety with the alternative being an eventual incident where there is a high likelihood of injuries (Grubbe 2012). In terms of the criticality value of a system, if it is proven to support life safety applications, its relative value to the organisation needs to increase (English and Yunusa-Kaltungo, A practical application of methodologies to determine asset criticality and work order prioritization 2022), (Rivera, et al. 2022).

We offer, through narration of case studies, that there are instances where the safety systems failures are so severe that they can significantly contribute to catastrophic end events. There are limitations and assumptions that we wish to elaborate on in relation to the overall study. In terms of limitations, the paper is only focused on the safety systems as opposed to the totality of equipment involved in the incidents – there were other causes involved in the events. Regarding assumptions, we readily acknowledge that advances in technology have made equipment safer to operate but there are circumstances where the safety equipment, if of appropriate design and successfully activated, would have been sufficient to prevent or limit the severity of the catastrophe. The next section of the paper examines two case studies concerning hidden safety systems failure and their contribution to catastrophic events, with the following section discussing the findings of the case studies in terms of causal aspects and consequences.

2. Case Studies

This section features two case studies from the energy industry where the hidden failure of safety systems contributed to resultant catastrophic outcomes. As illustrated in Fig. 1, the consequences of safety system failures have potential to range from the severe to catastrophic in terms of human casualties, organisational and other societal impacts.

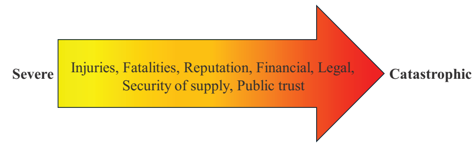

Figure 1: Types and range of consequences following failure of safety systems

2.1. Case study 1

The Upper Big Branch Mine is located in Montcoal, West Virginia, and was operated by Massey Energy. There are two ways to mine for coal: surface mining and underground / deep mining. Surface mining is when the coal is less than 61 m below the surface and large machines remove the topsoil until the coal is exposed. Underground / deep mining was the method used at Upper Big Branch Mine. It is necessary to use this method when the coal is several hundred meters underground level. The miners travel on elevators down into the mine and commute on short trains for several kilometers through tunnels until the mining site is reached. While both mining operations are dangerous, surface mining poses far fewer threats to employees than the alternative method. The success of nearly a century-long mining operation came to a halt when the Upper Big Branch Mine exploded at 15:27 on April 5th, 2010. The explosion happened 299 m underground, and 29 miners on site were killed. The mining machine created a spark when it struck a rock. The spark then ignited a pocket of methane gas that was not extracted because of poor ventilation. Methane was assumed to be the gas that ignited, due to having high levels in the mine (Turner 2022). Since methane does not have an exposure limit, the Occupational Safety and Health Administration (OSHA) has a maximum recommended concentration of 1,000 ppm over an 8-hour period to help ensure the safety of workers (MineARC Systems 2021). The methane explosion quickly transitioned into a coal dust explosion (West Virginia Office of Miners' Health, Safety and Training 2012). After the explosion, one miner was evacuated by helicopter while two others were removed by ambulance. Search and rescue operations were delayed because the high levels of methane and carbon monoxide from the explosion forced rescuers to return to higher ground. Of the 29 bodies found, 28 of them were Massey Energy employees and one was a contract worker (Turner 2022). While acknowledging the significance of all contributing factors to the incident, the focus of this paper is on the hidden failure concerning the ventilation system which will be explored further in Section 3.

2.2. Case study 2

On September 9th, 2010, at approximately 18:11, a 750 mm diameter segment of an intrastate natural gas transmission pipeline, owned and operated by the Pacific Gas and Electric Company (PG&E), ruptured in a residential area in San Bruno, California. The rupture occurred at km point 63.22 of Line 132, at the intersection of Earl Avenue and Glenview Drive. The rupture produced an estimated crater size of 22 m long by 8 m wide. The section of pipe that ruptured, which was approximately 8.5 m long and weighed approximately 1,360 kgs, was found 30.5 m south of the resultant explosion crater. PG&E estimated that 1,347,882 m^3 of natural gas was released. The released natural gas ignited, resulting in a fire that destroyed 38 homes and damaged 70. Eight people were killed, many were injured, and many more were evacuated from the area (National Transportation Safety Board 2010). The National Transportation Safety Board (NTSB) investigation, completed in August 2011, determined that the probable cause of the incident was that PG&E utilised inadequate quality assurance and quality control in 1956 during its Line 132 relocation project, which allowed the installation of a substandard and poorly welded pipe section with a visible seam weld flaw that, over time grew to a critical size, causing the pipeline to rupture during a pressure increase stemming from planned electrical work at the Milpitas Terminal; and an inadequate pipeline integrity management program, which failed to detect and repair or remove the defective pipe section. Contributing to the accident were the California Public Utilities Commission's (CPUC) and the U.S. Department of Transportation's exemptions of existing pipelines from the regulatory requirement for pressure testing, which likely would have detected the installation defects. Also contributing to the accident was the CPUC's failure to detect the inadequacies of PG&E's pipeline integrity management program. Contributing to the severity of the accident were the lack of either automatic shutoff valves or remote-control valves on the line and PG&E's flawed emergency response procedures and delay in isolating the rupture to stop the flow of gas (Pipeline Safety Trust 2014). While acknowledging the significance of all contributing factors to the incident, the focus of this paper is on the hidden failure that was revealed during the electrical work at the Milpitas Terminal which will be explored further in Section 3**.**

2.3. Case studies summary

The above case studies outline the consequences of hidden failures in safety systems. The coal mine example, in the first case study, resulted in a catastrophe where an explosion caused multiple fatalities. Likewise, the second example involving a gas pipeline, resulted in a catastrophe where an explosion had the outcome of multiple fatalities. Aside from the fatalities, the additional consequences of the failures can range from severe to catastrophic. The common factor in the case studies is that the incidents occurred, based on a combination of factors, including issues with the non-functioning of safety systems which were unknown to the operators. In this sense, the safety systems failures can be described as hidden.

3. Discussion of Findings

This section will further consider the circumstances of the case studies and in particular how hidden faults in the safety systems contributed to the catastrophic incidents.

We will then examine in more detail the causal aspects of the safety systems failures that could have been prevented through improved design, testing, maintenance, communication and training. Finally, we will detail the consequences of catastrophes in relation to the consequences illustrated in Fig. 1.

3.1. How hidden faults in the safety systems contributed to catastrophic incidents

This section will explore how hidden faults in the safety systems contributed to catastrophic incidents. In relation to the coal mine explosion example, there were known issues with the ventilation system, where consistently inadequate environmental conditions were permitted to exist inside the mine. Massey Energy received 64 citations in 2009 for failure to ventilate the mine according to the approved ventilation plan and poor ventilation was identified as a likely a contributor to the accumulation of methane gas (United States Nuclear Regulatory Commission 2012). There was additional culpability for the Mine Safety and Health Administration (MSHA) as they failed to act decisively at the Upper Big Branch Mine in 2009 when Massey Energy was issued citations for safety violations. Investigators stated that they could have fined Massey Energy up to $220,000 in fines for those safety violations, but instead did not issue any violation or fine. As a result of not issuing a violation to Massey Energy, there was a failure to inform the miners and that the area they were working in had not met minimal safety requirements (Turner 2022). Fig. 2 provides a simplified fault tree which highlights the failure of the ventilation systems as a contributory factor in the explosion.

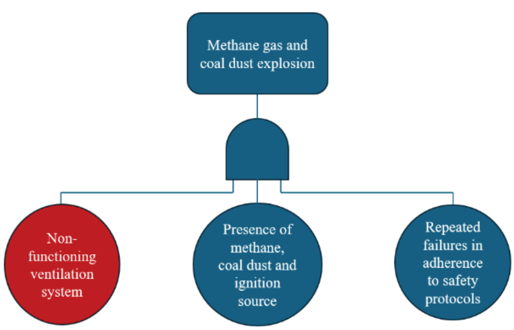

Figure 2: Simplified fault tree for mine explosion

It us our contention that this justifies the hidden designation when describing the ventilation system failure in the case study as the operators where left exposed to the consequences of a failure unknown to them.

In the gas pipeline explosion example, during the hours leading up to the accident, three PG&E employees and one contractor were working on an electrical distribution system as part of the replacement of the Uninterruptible Power Supply (UPS) at the Milpitas Terminal, where Line 132 originates. The electric work had been approved by a PG&E work clearance form, which was submitted to PG&E's gas control centre. The work on September 9th, 2010, was the continuation of a larger project to temporarily transfer electrical loads from an existing UPS distribution panel onto individual smaller UPS devices. Following the transfer of critical loads from the UPS panel, workers at the Milpitas Terminal began to remove power from an unidentified breaker. During that work, the workers opened a circuit that resulted in a local control panel unexpectedly losing power. Instead of re-energizing the circuit, the workers consulted electrical drawings and investigated how to supply power to the local control panel from an alternative source. One of the technicians stated in a post-accident interview that while measuring electrical currents, the workers noticed some of the displays at the local control panel became inoperative. Subsequent troubleshooting showed this to be the result of erratic output voltages from two redundant 24 VDC power supplies. These erratic voltages to pressure transmitters resulted in an erroneous low-pressure signal to regulating valve controllers, causing them to command the regulating valves to a fully open position. Until then, the regulating valves on all incoming lines except Line 300B had been closed. When the valves opened fully, the monitor valves, whose purpose is to protect against accidental overpressure, became the only means of pressure control. The erratic voltages from the 24 VDC power supplies also affected valve position sensors, generating erroneous signals to the Supervisory Control and Data Acquisition (SCADA) centre (National Transportation Safety Board 2010). Fig. 3 provides a simplified fault tree which highlights the failure of the redundant

24 VDC power supplies as a contributory factor in the explosion.

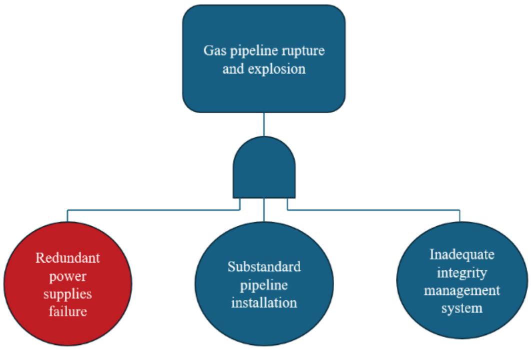

Figure 3: Simplified fault tree for pipeline explosion

We offer that the hidden failure in this case study is the redundant 24 VDC power supplies as it was unknown to the operators that they would not function correctly once activated and ultimately resulted in the pipeline pressure increase which was a contributing factor to the explosion.

3.2. Causal aspects of the equipment failures that could have been prevented

This section will further review the causal aspects of the hidden equipment failures that could have been prevented. In relation to the coal mine explosion example, an environment for raising concerns in which a safety-conscious work environment is maintained where personnel feel free to raise safety concerns without fear of retaliation, intimidation, harassment, or discrimination did not exist. Witness testimony revealed that miners were intimidated by Massey Energy management and were told that raising safety concerns would jeopardise their jobs. As a result, no whistleblower disclosures were made in the four years preceding the explosion, despite extensive evidence of Massey Energy safety and health violations at the mine during this period. Effective safety communication in which communications maintain a focus on safety was not present and workers at the mine were treated in a 'need to know' manner. The workers were not informed of conditions in parts of the mine where systems did not function with an example being the ventilation system (United States Nuclear Regulatory Commission 2012). In terms of general guidance, it was observed that the West Virginia Office of Miners' Health, Safety and Training (WVOMHS&T) had insufficient statutory language to regulate the way that coal mines are ventilated and that coal operators must take a more proactive approach to the ventilation of each coal mine under their authority and responsibility. A specific observation was that more attention is required concerning the use of belt air during longwall mining to assure that the most effective means are being utilised to maximise ventilation to the longwall face and the active gob areas including the tailgate T-Split which is a critical location where longwall ventilation can become blocked as was the case at the Upper Big Branch Mine. (West Virginia Office of Miners' Health, Safety and Training 2012).

In the gas pipeline explosion example, due to electrical work at the Milpitas Terminal resulting in the inadvertent pressure increases that preceded the rupture, the NTSB examined the procedures relating to this work. The investigation identified deficiencies in the work clearance process used for the Milpitas Terminal electrical work. The system clearance form did not adequately detail the work to be performed. It did not discuss the equipment being worked on or the equipment that would be affected. The form indicated that normal function at the terminal would not be maintained, but there was no explanation, although the form called for such an explanation. Due to the lack of detail on the work clearance form for the work, the SCADA operators would not have been aware of the scope and magnitude of the work being performed at the Milpitas Terminal. If the form had included the necessary information, the SCADA operators would have at least been aware that power interruptions were planned to specific instrumentation at the Milpitas Terminal and might have taken steps to mitigate the risk. This assumption was also highlighted when, after the rupture, a SCADA operator incorrectly understood it to be a regular scheduled clearance that would not have adverse effects. Although the clearance form indicated that the work was expected to affect the normal functioning of equipment at the Milpitas Terminal, it lacked clarity regarding how, and the extent to which, the normal functioning of equipment would be affected. When the first unexpected power losses occurred at the Milpitas Terminal, the workers decided to deviate from the assigned work and begin troubleshooting without stopping to notify the SCADA center or to assess the potential risk. By doing so, the workers at the Milpitas Terminal put themselves and the SCADA center in a reactive mode. Had a formal risk assessment been performed in advance, the SCADA staff might have taken precautionary measures to reduce the upstream pressures or have locked the regulating valves in a set position in advance and retained those settings for the duration of the work, thus avoiding the unintended pressure increase. The NTSB concluded that had a properly prepared contingency plan for the Milpitas Terminal electrical work been in place and been executed, the loss of pressure control could have been anticipated and planned for, thereby minimising or avoiding the pressure deviations. (National Transportation Safety Board 2010).

Following the above details, the suggestions below are offered to aid in avoiding such incidents. It is crucial that an organisation identifies its most important assets. One option in achieving this is to utilise a criticality scoring system which can be informed by semi-quantitative and qualitative risk scoring models that have been shown to provide a reasonable representation of safety risk levels (English, Haswell, et al. 2024).

3.3. Consequences of safety system failures in terms of human casualties, organisational and other societal impacts

This section will delve into the consequences of safety systems failures in terms of human casualties, organisational and other societal impacts. In relation to the coal mine explosion example, it took MSHA investigators over two months before it was safe for them to enter to investigate the mine due to a large concentration of toxic gases. They were allowed to begin their investigation on July 2nd, 2010. In May of 2011, an independent investigation team released the report which stated that both Massey Energy and MSHA were at fault for the blast. Massey Energy failed to meet basic safety standards that were outlined in the Mine Act of 1977. But those fines and violations were not the first ones for Massey Energy to receive. In 2009, there had been serious violations for lacking ventilation and lacking the use of its safety plan as well as proper equipment plans. Prior to that they had 57 safety infractions. And the day before the explosion, there had been two more violations with 600 in the preceding 18 months and 1342 in the preceding five years. In December 2011, MSHA concluded the investigation saying that the entire disaster could have been a preventable coal-dust explosion. It was also announced that Alpha Natural Resources had acquired Massey Energy's assets and liabilities including ownership of the Upper Big Branch Mine. In 2013, the mine was permanently closed, and it was announced that Massey Energy was directly responsible for the explosion with 369 violations, costing nearly $10,800,000 in penalties. In the biggest settlement ever reached in a U.S. mining disaster, $210,000,000 was paid to compensate the affected families. The list of safety violations also led to the conviction of the former Chief Executive Officer (CEO) of Massey Energy who was sentenced to one year in prison for conspiring to willfully violate safety standards. Other employees of Massey Energy also received prison sentences in relation to the incident. (Turner 2022), (The Associated Press 2015).

In the gas pipeline explosion example, a federal court jury convicted PG&E of obstructing the federal probe of the blast and of violating pipeline safety laws both before and after the disaster. The jury found PG&E guilty of five felony counts of knowingly failing to inspect and test its gas lines for potential dangers, in addition to the felony obstruction count. The state CPUC fined the company a record $1,600,000,000 in relation to the explosion. It was noted by that ratepayers would bear 55% of the long-term costs, or $125,000,000 for upgrades in PG&E's pipe inspection and safety programs. Prosecutors said PG&E had regularly boosted gas pressure above legal limits on numerous aging pipelines and had deliberately chosen a low-cost inspection method that was incapable of detecting internal welding flaws, violating laws that require pipeline operators to conduct effective scrutiny. The obstruction charge involved PG&E documents, dating back to 2009, that described a practice of allowing pipeline pressures up to 10% above federal limits (Egelko 2016). PG&E expected to pay a total of $565,000,000 in legal settlements and other claims from the 2010 gas pipeline explosion (CBS News 2013).

The above details, in this section and from earlier in the paper, highlight the impacts of a catastrophic incident in terms of injuries, fatalities, company reputation, financial and legal. An additional impact is in relation to security of energy supply – when a catastrophic incident occurs, there will typically be downtime with assets preventing them from functioning. Finally public trust in energy supply companies is also impacted when catastrophic incidents occur such as the Fukushima nuclear incident which, although not featured as case a study in this paper, has caused potentially immeasurable damage to society's confidence in nuclear power as a safe energy option with there being a view to replace all nuclear power with alternative fuel sources (Labib 2014).

Conclusion

There is an unattributed saying that safety laws and codes are written in blood. A safety systems failure results in removal of the safety net; becomes the final link in the chain towards catastrophe; the last 'and' condition in the fault tree; or in more proverbial terms the straw that broke the camel's back. As evinced in the above case studies, while not being the sole causes of the incidents, safety systems are the last line of defense and if they contain an inherent fault unknown to the operators, the fault can thus be classed as a hidden failure. We have explored this matter through utilisation of two case studies, from the energy industry, which resulted in a range of damaging outcomes in terms of injuries, fatalities, company reputation, financial and legal, security of supply and public trust. In the coal mine explosion example, a failure of the ventilation systems resulted in the build-up of explosive gas and dust which was then exposed to an ignition source. In the gas pipeline explosion example, a fault in the redundant 24 VDC power supplies resulted in the pipeline pressure increase which was a contributing factor to the explosion. In both case studies, a safety system fault existed that was unknown to the workers until the other elements of the events were in place – hence the 'hidden' descriptor. We do not wish to disparage the pursuit of the advancement of safety technology. The intention of the paper is to highlight where there were instances of safety systems faults that acted as contributory causes in catastrophic incidents and because of this, more effort is needed for thorough testing of the function of safety systems and the consequences of associated failures. Communications and training are also vital in ensuring operators have full knowledge of the safety systems outputs and potential shortcomings. There are options for identifying risks, but it would be more prudent to not introduce the risks in the design and build phases and this can be achieved with in-depth testing of the safety systems to understand the full extent of their consequences. Future research in this area may include delving further into each case study example and developing a deeper understanding of the causes from technical and even perhaps company culture standpoints. Such studies may benefit from a more data intensive approach to validate the findings. From there the authors can provide recommendations to help prevent such failures from happening in future.

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