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The Influence of Maintenance on Some Selected Major Accidents

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In spite of large and increasing efforts to control major accident risk, a number of serious accidents over the last few years have shown that control still is not sufficient in some cases. Examples of such accidents within the chemical process and oil and gas industries are Flixborough Disaster, Bhopal Disaster, Piper Alpha Disaster, Phillips 66 Disaster, Sodegaura Refinery Disaster, DSM Chemical Plant Explosion, Stockline Plastics Factory Explosion and Texas City Refinery Explosion.
Investigations of the accidents have uncovered a variety of causes and in recent years focus have tended to switch more and more towards organizational and management issues. However, in this paper, we want to focus on how maintenance has influenced some of these major accidents.
Safety barriers are installed to control the risk but this may fail due to barrier vulnerability and/or deficiencies imposed by maintenance itself or due to postponement of maintenance. Maintenance activities in themselves may also trigger events which may develop into major accidents. Maintenance may therefore influence accidents in many ways.
The main objective of the paper is to discuss how maintenance has influenced some major accidents in the oil and gas and chemical process industry.
The paper builds primarily on a thorough literature review, including review of earlier literature on this topic and review of investigation reports from a selection of accidents.

1. Introduction

Major accidents are typically defined as adverse events such as major leaks/releases, fire, explosion or loss of structural integrity, leading to serious danger/damage, to multiple deaths and/or major damages to the environment or properties, as supported by the views of ComLaw (2007), EC (2005), Maguire (2007), OGP (2008) and PSA (2010).
Most industries that handle hazardous substances such as the petroleum and chemical industries have a major accident potential. Several major accidents have occurred during the last 35 years. Flixborough Disaster, Bhopal Disaster, Piper Alpha Disaster, Phillips 66 Disaster, Sodegaura Refinery Disaster, DSM Chemical Plant Explosion, Stockline Plastics Factory Explosion and Texas City Refinery Explosion are a few examples of accidents with devastating consequences to personnel, the environment, the companies and host communities.
Efforts have been made to enhance defences against major accidents based on lessons learnt from accidents. Despite this effort, it can be argued that the risk of major accidents does not always show a positive trend. The number of major hydrocarbon leaks, a key indicator for major accident risk in the Norwegian oil and gas industry, has for example increased between 2008 and 2010 (PSA, 2010).
Major accidents are seldom the result of one failure, but often a combination of failures (Turner, 1978). High degree of technological and organizational complexity is usually mentioned as an attribute of

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industries with a major accident potential (Perrow, 1984). For this reason, it is common to deploy multiple and independent safety barriers that are capable of preventing or mitigating the consequences of unexpected events. This design philosophy is sometimes referred to as defense-in-depth (e.g. in the nuclear industry) (Reason, 1997) and layers of protection (in the process industry) (IEC 61511, 2003). Independence among barriers may be influenced by the use of different design principles, ranging from physical, mechanical to electrical/electronic/programmable systems.

The integrity of the barriers cannot be maintained without adequate level of maintenance. Maintenance is therefore a key activity to reduce the risk of major accidents. On the other hand, maintenance may have a negative effect on barrier performance if the execution is incorrect, insufficient, delayed, or excessive. Maintenance can also be the triggering event, e.g. by operating equipment wrongly. Besides, maintenance also exposes people to risk and should be minimized from this point of view.

Major accidents have been investigated and/or analyzed by some authors such as Khan (1999), Kletz (2001), Lees (2005), Øien et al. (2010) and CSB (2007), but they have tended to view the maintenance complicity in them more from a maintenance management perspective. In this paper, we will look at the accidents from the perspectives of both the accident process and the maintenance management process.

The objective of this paper is to review these accidents and to identify if and how maintenance has influenced each of the events. A simple causal classification is applied to each of the cases. At the end, some conclusions are drawn.

2. Review of Selected Major Accidents

Some authors have offered maintenance management related insights into the classification of maintenance factors influencing major accidents in the hydrocarbon and process industries: Examples are lack of or erroneous maintenance (Hale et al., 1998), poor communication between maintenance and operations staff (Sanders, 2005), maintainability (Hale et al., 1998) and the maintenance management cycle as a whole (Smith and Harris, 1992).

However, in the context of the aforementioned insights, enough focus has not been directed at safety barriers which are critical and crucial to the prevention of major accidents. Hence, it is pertinent to build on the ideas from above and still consider an additional basis that is focused on safety barriers.

In this section, the major accidents will be analyzed on the bases of both the accident process (including safety barriers) and maintenance management cycle. The factors based on safety barriers are as follows: (1) Lack of maintenance: Lack of barrier maintenance which allows barriers to be breached by failure mechanisms (for e.g. lack of maintenance leading to corrosion of barriers), (2) Maintenance error: Wrong maintenance directly breaching safety barriers (for e.g. wrong calibration of level transmitter), (3) New hazard: Maintenance introduces new hazards, which may be triggered by events (for e.g. hot tapping – an ignition source), and (4) Initiating event: Maintenance being an initiating event for an accident scenario (for e.g. loss of containment due to a wrong valve being operated as part of preparations). The factors based on maintenance management cycle are as follows: (1) Lack of maintainability (EN 13306, 2010): Lack of the ability to retain an item or restore it to a state in which it can perform its required functions (for e.g. lack of testability/accessibility), (2) Deficient fault diagnosis (EN 13306, 2010): Deficiency in fault detection, fault localization and identification of causes (for e.g. too little test), (3) Deficient planning (EN 13306, 2010): Deficiency in the organization and documentation of a set of maintenance tasks that include the activities, procedures, resources and time scale required to execute maintenance (for e.g. poor communication between maintenance and operations staff), (4) Deficient scheduling (EN 13306, 2010): Deficiency in predetermined detailing of when a specific maintenance task should be executed (for e.g. too late timing), (5) Deficient execution: Deficiency in the hands-on actions taken to retain an item or restore it to a state in which it can perform its required functions (for e.g. wrong performance of a correct task) and (6) Deficient checking: Deficiency in supervision, confirmation or performance evaluation (for e.g. inadequacy of checklists).

In this paper, the term “active influencing maintenance factors” refers to the maintenance factors which directly influence the realization of an accident, while the term “latent failure” refers to the dormant factors which contribute indirectly to the realization of the accident (Reason, 1997). The latent failures contribute to the weakening of defences and thus increase the probability of occurrence of accidents through the active failure pathway as shown in Figure 1.

2.1 Case 1: The Texas City Refinery Explosion (March 23, 2005)

On March 23, 2005, at the BP Texas City Refinery, the startup of an isomerization unit whose raffinate tower was overfilled, led to overheating of the raffinate and the opening of pressure relief devices. This resulted in a flammable liquid geyser from a blowdown stack unequipped with flare, leading to an explosion and fire, killing 15 workers and injuring over 170 (CSB, 2007).

The major hazard is flammable and explosive liquid - raffinate. The active influencing maintenance factors include the following (CSB, 2007): (1) Failure to calibrate level transmitter correctly (maintenance error), (2) Failure to clean sight glass (lack of maintenance), and (3) Failure of high level alarm (lack of maintenance), which were in turn influenced by deficient maintenance program. The latent failures include (CSB, 2007): (1) Business objectives and cost unbalanced with maintenance, and (2) Lack of effective process mechanical integrity program. These causes can be illustrated as shown in Figure 1. The influence of maintenance is also associated with deficient fault diagnosis, deficient planning, deficient execution and deficient checking as shown in Table 1.

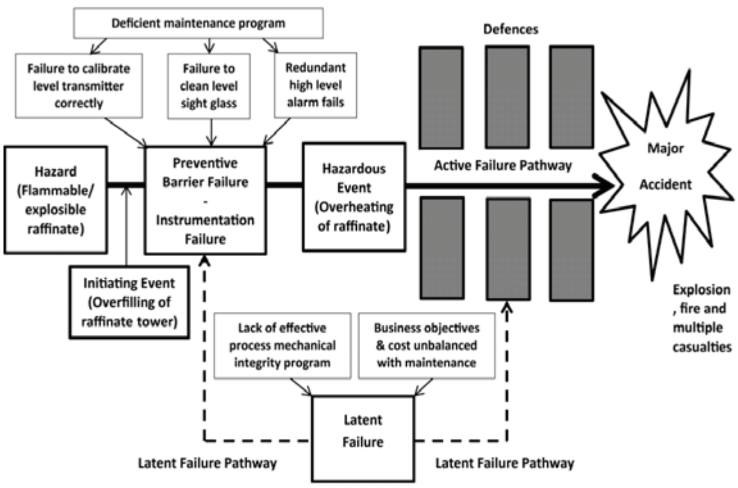

Figure 1: Maintenance-related accident scenario for the Texas City Refinery

2.2 Case 2: Stockline Plastics Explosion (May 11, 2004)

On May 11, 2004, at Stockline Plastics industry in Glasgow, an ageing liquefied petroleum gas (LPG) pipe with inadequate protection when buried, failed due to corrosion and released gas which ignited, exploded and razed the factory building to the ground, killing 9 workers and injuring 40 (OSHA, 2012).

The major hazard is flammable LPG. The active influencing maintenance factor is failure to inspect and maintain an LPG pipe (lack of maintenance) (OSHA, 2012). The latent failures include (OSHA, 2012): (1) Failure to perform suitable and sufficient risk assessments, and (2) Very weak health and safety procedures. The influence of maintenance is also associated with lack of maintainability and deficient fault diagnosis as shown in Table 1.

2.3 Case 3: DSM Chemical Plant Explosion (April 1, 2003)

On April 1, 2003, the DSM melamine plant at Geleen in the Netherlands experienced an explosion as a maintenance crew was restarting the oven; this caused the top cover to collapse and topple over while three workers who were standing on the cover fell into the oven and died (OSHA, 2012).

The major hazard is flammable natural gas and residual gases from other plants; this was ignited by a stray spark. The usually contaminated residual gases had to be filtered, the plant had to be shut down regularly to clean the filters and restarting takes a lot of time; hence a fast-track starting procedure was developed, albeit without adequate testing. The active influencing maintenance factors are: (1) Difficult maintenance (lack of maintainability) and (2) Combustive mixture of gas and air resulting from untested fast-track procedure (new hazard) (OSHA, 2012). The latent failures include (OSHA, 2012): (1) Business objectives and cost unbalanced with maintenance, and (2) Poor safety culture. The influence of maintenance is also associated with deficient planning as shown in Table 1.

2.4 Case 4: Sodegaura Refinery Disaster (October 16, 1992)

On October 16, 1992, the Sodegaura refinery in Japan experienced an explosion and fire, following the breaking-off of the lock ring of the channel cover of a heat exchanger and the blowing-off of the lock ring, channel cover and other parts; ten people died while seven were injured (FKD, 2012).

The major hazard is an explosive gas – hydrogen. The active influencing maintenance factors include the following (FKD, 2012): (1) Repeated ratcheting, leading to reduction in the diameter of the gasket retainer which keeps the heat exchanger airtight (maintenance error), (2) Incorrect replacement of the gasket retainer which contributed to hydrogen gas leak (maintenance error), (3) Removal of insulation, which induced temperature difference (new hazard) that led to thermal deformation of the inner parts of the tube area and contributed to the increase of the diameter of the channel barrel, (4) Inadequate replacement of the internal flange set bolts, leading to their destruction, increased load on the channel cover set bolts, bending and diameter decrease in the lock ring (maintenance error). The latent failures include (FKD, 2012): (1) Misjudgement of whom between the user and manufacturer of the heat exchanger is responsible for the decision and confirmation of the parts replacement, (2) Poor management, and (3) Incomplete standard of replacement. The influence of maintenance also includes lack of maintainability, deficient planning, deficient execution and deficient checking (see Table 1).

2.5 Case 5: The Phillips 66 Disaster (October 23, 1989)

On October 23, 1989, the polyethylene unit of Phillips 66 at Pasadena in USA experienced a chemical release, which subsequently formed flammable vapors and ignited, resulting in a vapor cloud explosion and series of further explosions and fires, killing 23 and injuring between 130 and 300 people; this happened during scheduled maintenance to clear three of the settling legs on a reactor (Lees, 2005).

The major hazard is the buildup of hazardous chemical. The release of the hazard was initiated by wrong maintenance. The active influencing maintenance factors include the following (Lees, 2005): (1) Consolidated isolation via double-block valve or blind flange was not stipulated in existing maintenance procedure (maintenance error), and (2) The only isolating ball valve was kept open by wrongly connected air supply hoses (maintenance error). The latent failures are (Lees, 2005): (1) Non-compliance to company/industry isolation procedure, (2) Non-compliance to site procedure, and (3) Inadequate Permit-To-Work (PTW) system. The influence of maintenance is also associated with deficient planning, deficient execution and deficient checking as shown in Table 1.

2.6 Case 6: The Piper Alpha Disaster (July 6, 1988)

On July 6, 1988, the Piper Alpha offshore platform being operated by Occidental Petroleum experienced a series of explosions in the North Sea, resulting in gas risers ruptures, subsequently causing the structural collapse of the platform and the death of 167 people (Kletz, 2001).

The major hazard is flammable condensate; its leakage was preceded by delayed maintenance schedule and poor maintenance planning; a condensate pump under repair and not tagged-out was mistakenly used to replace another one that failed during operation. The active influencing maintenance factors include the following (Kletz, 2001): (1) Disassembled and non-isolated defective pump (new hazard), and (2) Replacement with defective pump due to communication gap between maintenance and operations staff at shift handover (initiating event). The latent failures are (Kletz, 2001): (1) Poor quality of safety audits and training, (2) Inadequate maintenance and safety procedures, and (3) Lack of emergency planning. The influence of maintenance is also associated with deficient planning, deficient scheduling and deficient checking as shown in Table 1.

2.7 Case 7: The Bhopal Gas Tragedy (December, 1984)

In December, 1984, about 4000 people were killed and 500,000 injured by toxic release from a chemical plant in Bhopal, following a runaway reaction between Methylisocyanate (MIC) in a storage tank and uncontrolled water for cleaning product lines, which led to vigorous boiling, overpressure of the MIC tank and MIC vapor expulsion to the atmosphere via a rupture disc (Kletz, 2001).

The major hazard is a toxic, unstable chemical - MIC; its runaway reaction with water was initiated by maintenance. The active influencing maintenance factors include the following (Kletz, 2001): (1) Failure of product-line valves due to corrosion (lack of maintenance), (2) Omission of an isolating blank/spade between the MIC tank and the connected product line being cleaned with water (maintenance error), (3) Failure of Nitrogen-line valves due to neglect (lack of maintenance) and (4) Maintenance execution initiating a hazardous reaction between water and MIC (initiating event). The latent failures are (Kletz, 2001): (1) Excessive storage of (MIC) Methlyisocyanate, (2) Business objectives and cost unbalanced with maintenance, and (3) Unavailable safety features: The refrigeration system which could have provided cooling for the storage tank was turned off, the scrubber which should have absorbed the vapour was inoperative, and the flare stack which should have burnt off any residual vapour was out of service. The influence of maintenance also includes deficient fault diagnosis, deficient planning, deficient execution and deficient checking as shown in Table 1.

2.8 Case 8: Flixborough Disaster (June 1, 1974)

On June 1, 1974, twenty-eight workers were killed and 36 injured at the Nypro (UK) site at Flixborough, when a bypass system ruptured and released cyclohexane which formed a combustible mixture with air and exploded on coming into contact with an ignition source (OSHA, 2012).

The major hazard is flammable cyclohexane. The active influencing maintenance factors include (OSHA, 2012): (1) Limited calculations were done on the bypass line (lack of maintenance), (2) Bypass line was not pressure-tested after plant modification (lack of maintenance). The latent failure includes the absence of full risk assessment to support plant modification (OSHA, 2012). The influence of maintenance also includes deficient planning, deficient execution and deficient checking (see Table 1).

Table 1: Maintenance influence on major accident cases

		Barrier-based maintenance factors			
		Lack of maintenance	Maintenance error	New hazard	Initiating event
Mainte-nance manage-ment cycle factors	Lack of maintainability	Case 2	Case 4	Case: 3,4	
	Deficient fault diagnosis	Cases: 1,2,7			
	Deficient planning	Cases: 1,7,8	Cases: 1,4,5,7	Cases: 3,4,6	Cases: 6,7
	Deficient scheduling			Case 6	
	Deficient execution		Cases: 1,4,5,7		Cases: 6,7
	Deficient checking	Cases: 1,7,8	Cases: 1,4,5,7	Cases: 3,4,6	Cases: 6,7

3. Conclusion

This paper is one in a planned series of publications dedicated to a research project titled "Maintenance Strategies for Major Accidents Prevention." The paper has reanalysed some selected maintenance-related major accidents and given further insights into their causation mechanisms. It has linked causes to both barrier-based and maintenance management cycle factors. Although the number of cases considered is few, the most occurring barrier-based factor is maintenance error and the most occurring maintenance management factors are deficient planning, deficient execution and deficient checking. This is not indicative enough of what is expected of the result of a larger sample size; however, it will stimulate the sharing of focus to planning, checking and barrier maintenance. Barrier maintenance will augment Process Safety Management which has failed to yield significant reduction in major accident risk (Pitblado, 2011). Besides, industries will be guided against concentrating only on improvement in execution despite the fact that most accidents occur during work execution.

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