Part VII

Maintenance Safety, Environment and Human Error

22

Safety and Maintenance

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22.1 Setting the Scene

The desire to be safe and secure has always been an intimate part of human nature since the dawn of human history. The demand for safety and security is pursued at every location in one's entire environment. This ranges from homes, in transit, at all premises, and indeed; in the workplace. The need for a safe working environment was first brought to light during the first decade of industrial revolution (Roland and Moriarty, 1983). Based on the knowledge acquired in the past decades, companies and labour organizations have pursued ways and means of enhancing occupational safety. Since 1950, the International Labour Organization (ILO) and the World Health Organization (WHO) have had a common definition of occupational health and safety. This definition was adopted by the Joint ILO/WHO Committee on Occupational Health at its First Session (1950) and revised at its 12th Session (1995):

> "Occupational health should aim at: the promotion and maintenance of the highest degree of physical, mental and social well-being of workers in all occupations; the prevention amongst workers of departures from health caused by their working conditions; the protection of workers in their employment from risks resulting from factors adverse to health; the placing and maintenance of the worker in an occupational environment adapted to his physiological and psychological capabilities; and, to summarize, the adaptation of work to man and of each man to his job" (Source: www.wikipedia.com).

However, the road to enhancing occupational safety has not been as smooth as some statistics tells us. According to Hammer, 8% of the workers in the US suffer some kind of accident at work each year, though few involve disabilities or death (Hammer, 1976). Though these statistics were recorded 30 years age and may appear to be old, the recent statistics indicates persistence of occupational safety problems. Work-related death still occurs regularly and in 1996, the National Safety Council of US estimated 3.9 million disabling injuries, 4,800 deaths and the total cost of work-related deaths and injuries was estimated to be $121 billion annually (NSC, 1997). This prompts an important question that begs for answers: why do accidents happen in the workplace, and what can be done to prevent them? These questions have troubled plant engineers and managers for decades, and have led to a substantial increase in safety knowledge and accident prevention and investigation activities in all industries. Government agencies, which enforce statutes and regulations, have also added to safety awareness and action based on regulation, inspection, and penalties.

Despite increase in safety knowledge, there has been an increase in production system automation so that both operational and safety-related equipment is more complex to understand and properly maintain. These improperly maintained or unmaintained pieces of equipments pose a major safety hazards to the plant. Moreover, the autonomous maintenance movement involves operators in certain maintenance tasks, exposing them to more potential hazards. No doubt, the impact of maintenance on plant safety has never been so significant. Maintenance in many industries is connected with a significant proportion of the serious accidents occurring in the industry. Studies by the British Health and Safety Executive (HSE, 1987) of the deaths in the chemical industry showed that some 30% were linked to maintenance activities, taking place either during maintenance activities or as a result of faulty maintenance. A study of the chemical accidents stored in the database FACTS (Koehorst, 1989) found 38.5% of the accidents where dangerous materials were released from on-site plant had taken place during maintenance. Another study by Hurst on 900 accidents involving pipe-work failure in Chemical plants found out that 38.7% have their origins in the maintenance phase of plant operations (Hurst *et al.* 1991).

Maintenance function forms an integral part of manufacturing and its price tag can possibly indicate its significance to manufacturing plants. A study conducted in 1999 indicates that United States spends $300 billion on plant maintenance and operations (Latino, 1999). As billions are being spent each year on maintenance to keep engineering systems and items in operational state, the problem of safety in maintenance has become an important issue (Dhillon, 2002). Some examples in practice prove the importance of this topic. Report from the National Safety Council of US shows that in the mining industry, 13.61% of all accidents occurred during maintenance in 1994 and, since 1990, the occurrence of such accidents has been increasing each year (NSC, 1999). A study of electronic equipment revealed that approximately 30% of failures were caused by human error with faulty maintenance contributing 8% of the failures (US Army, 1972). Another study carried out between 1982 and 1991 on safety issues with respect to onboard fatality of worldwide jet fleet revealed that maintenance and inspection was the second was the second most important safety issue with a total of 1481 on board fatalities (Russell, 1994).

The questions that arise from these statistics are; what is the impact of maintenance (and the corresponding policies) on plant safety, how do maintenance jobs interact with safety (or create safety hazards)? what interventions (technical, managerial, legal) can be employed to improve plant safety? The study on maintenance and safety interactions in industries, therefore, is indispensable. It is our objective first to establish a link between safety and maintenance. This will be done by looking at the safety issues in maintenance work and maintenance for safety of production equipments. The second objective is to study the effect of various maintenance policies and concepts on plant safety. The third objective is to study how safety performance can be measured or quantified. This will be coupled by cost and benefit analysis of safety improvement efforts on the plant. Finally, accident prevention will be discussed in reflection to the safety legislation put in place by governments and some safety organizations. Let us look at some definitions and terminologies used in this study.

22.2 Definitions

22.2.1 Maintenance

The British Standards Institution (BSI, 1984) defines maintenance as:

> "A combination of all technical and associated administrative activities required to keep an equipment, installations and other physical assets in the desired operating condition or restore them to this condition".

Though this is what maintenance indeed is, at would be confirmed by any practitioner, its role could well be defined by the four objectives it seeks to accomplish. These are (1) ensuring system function (availability, efficiency and product quality), (2) ensuring the system or the plant life, (3) ensuring human well-being and, finally, (4) ensuring safety (Dekker, 1996).

For production equipment, ensuring the system function is the prime objective of maintenance function. Here, maintenance has to provide the right reliability, availability, efficiency and capability to produce at the right quality for the production system, in accordance with the need for these characteristics. Ensuring system life refers to keeping systems in proper working condition, reducing chance of condition deterioration, and thereby increasing the system life. Maintenance for ensuring human well-being or equipment shine has no direct economical or technical necessity but primarily a psychological one of ensuring the equipment or asset looks good. A good example is painting for aesthetic reasons.

The last but very important objective of maintenance is to ensure safety of production equipments and all assets in general. As explained by Hale *et al.* (1998) the primary purpose of maintenance is to prevent significant deterioration or deviation in plant functioning, which can threaten not only production but also safety and to return a plant to full functioning after breakdown or disturbance. While maintenance function seeks to ensure safety of the plant, many maintenance tasks expose maintenance staff to potential safety hazards. No doubt the maintenance function has a significant impact on the plant safety.

22.2.2 Safety

Based on the dictionary, safety is as the condition of being free from undergoing or causing hurt, injury, or loss. It is freedom from any potential harm. The standard definition is:

> "Safety is defined as the condition of being free from or protected against failure, damage, error, accidents, or harm or any other event, which could be considered undesirable (Wikipedia- http://en.wikipedia.org/wiki/Safety). Safety in a system is defined as a quality of a system that allows the system to function under predetermined conditions with acceptable minimum of accidental loss" (Roland and Moriarty 1983).

22.2.3 Hazard

Safety is generally interpreted as implying a real and significant impact on risk of death, injury *or* damage to property. Lack of safety occurs due to existence of hazards in the workplace.

> "A hazard is defined as any existing or potential condition in the workplace which, by itself or interacting with other variables, can result in the unwanted effects of death, injuries, property damage, or other losses" (Laing, 1992).

22.2.4 Stimuli

The presence of a hazard by itself cannot directly lead to an accident. A trigger is needed convert a hazard to an accident. This trigger is known as stimuli:

> "Stimuli is defined as a set of events or conditions that transforms a hazard from its potential state to one that causes harm to the system, related property or personnel"(Roland, 1983).

22.2.5 Accident

Accident is the outcome of a hazard that is triggered by a stimuli. An accident happens when there is loss of plant system or part of the system, injury to or fatality of the operators or personnel in near proximity, and property damage of related equipment or hardware. Therefore:

> "An accident is defined a dynamic mechanism that begins that begins with the activation of a hazard and flows through a system as a series of events, in a logical sequent, to produce a loss."

Risk is associated with likelihood or possibility of harm or the expected value of loss. Risk is related to the probability that frequency, intensity, and duration of the stimulus will be sufficient to transfer the hazard from potential state to a loss. Having defined the maintenance, safety and workplace hazards, the next thing that arises is to see how these issues relate to or interact with each other in the workplace.

22.3 The Maintenance Link to Safety

22.3.1 The Role of Maintenance

Maintenance has a major relevance to the business performance of industry. Whenever a machine stops due to a breakdown, or for essential routine maintenance, it incurs a cost. The cost may simply be the costs of labour and the cost of any materials, or it may be much higher if the stoppage disrupts production.

In many instances, the production pressures to meet the production targets are very high in the manufacturing environment. Maintenance is pressurized to ensure plant's availability and to support the desired output. In many manufacturing plants the question is *production or maintenance?* Faced with the choice of running full tilt or halting for scheduled upkeep, plant managers typically have the upper hand over their maintenance colleagues and opt for production. The latter can be a costly choice and may be detrimental to the production process and to the plant's safety.

The importance of maintenance to manufacturing can be termed as paradoxical. This is because, when breakdown happens, it is often easy to show that lack of maintenance was responsible. Nevertheless, when there is no breakdown, it is not easy to demonstrate that maintenance had prevented them. This is due to the traditional attitude of production management towards maintenance as a non-productive support function and as a necessary evil (Pintelon *et al.* 1997). This attitude towards maintenance may have serious consequences for plant safety.

Maintenance actions, objectives and strategies are influenced by the company policy, sales and production policies, and other conflicting demands and constrains in the company. Maintenance resources are utilised so that the plant achieves its design life, so that safety standards are achieved, so that production volume required by production policy is met and so that energy use and raw material consumption are optimised among other factors. All these factors influence the maintenance objectives as show in Figure 22.1.

In spite of its contradictory relationship to manufacturing, maintenance is a very important function in a plant's operating life. As soon as the plant is commissioned, deterioration begins to take place in the components. In addition to the normal wear and deterioration, other failures may also occur when the equipment is pushed beyond its design capacity. Degradation in equipment condition results not only in reduced equipment capability but also in undesirable safety condition. Without regular inspection and maintenance, plant and machinery soon or later lapse into a dangerous state due to wear, tear, fatigue and sometimes corrosion. Regular inspection is therefore needed to determine in detail how far such deterioration has proceeded. This is done many times against production pressures that demand to meet certain production targets.

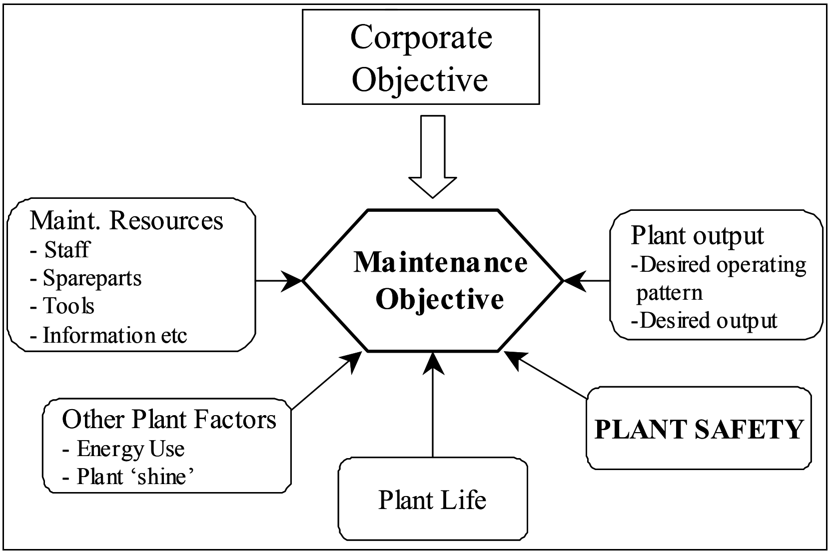

Figure 22.1. Factors influencing the maintenance objectives

Most maintenance activities require the plant or equipment be shut down and specially prepared. Consequently, a minor job (often referred to as a repair) or a major job (often referred to as an overhaul) is carried out. A limited and clearly defined number of maintenance jobs are done while the plant is still running. A good example of these are the traditional lubrication as well as advanced condition-based monitoring. Maintenance may be planned or unplanned. Unplanned or breakdown maintenance means operating the plant until something breaks down. The break down may be classified as emergency or corrective depending on its urgency although the work done may be the same in both cases. Planned maintenance involves both preventive maintenance and corrective maintenance. Preventive maintenance is based on servicing and overhauling key plant items before they breakdown or their performance deteriorates. This is done at pre-selected intervals dependent on the equipment usage and is therefore referred to as use-based or scheduled maintenance. Condition-based or predictive maintenance is also used to monitor the condition of equipment to proactively correct undesirable condition. Maintenance function can be summarised as in Figure 22.22.

The primary purpose of both preventive and corrective maintenance is to prevent significant deterioration of or deviation in plant functioning, which can threaten not only production but also safety of the plant and to return a plant to full functioning after a breakdown or disturbance. If maintenance is not carried out soon enough, is incorrectly carried out, or communications between maintenance and operation staff are not effective, the plant may fail dangerously during start up or during normal operation phase (Hale *et al.* 1998). An example of maintenance related accident is Piper Alpha company in 1988 with 165 fatalities among many other examples (Dept of Energy, 1990). In addition, the autonomous maintenance movement involves operators in certain maintenance tasks. Many of these tasks have considerable risks and therefore expose the maintenance staff to more potential hazards. Some examples of accidents happening during maintenance work is Phillips in Pasadena in 1989 with 23 fatalities and Arco in Texas in 1990 with 17 fatalities (Craft, 1991). Though it is apparent that maintenance has a considerable impact on plant safety, little has been written about maintenance interaction with safety. The first attempt to investigate the impact of maintenance function on plant safety was done by Ray *et al.* (2000). Their study showed an inverse relationship of moderate strength between injury frequency index and maintenance audit score. The finding of the study supports the hypothesis that better maintenance, as presented by better audit score, is associated with lower injury frequency.

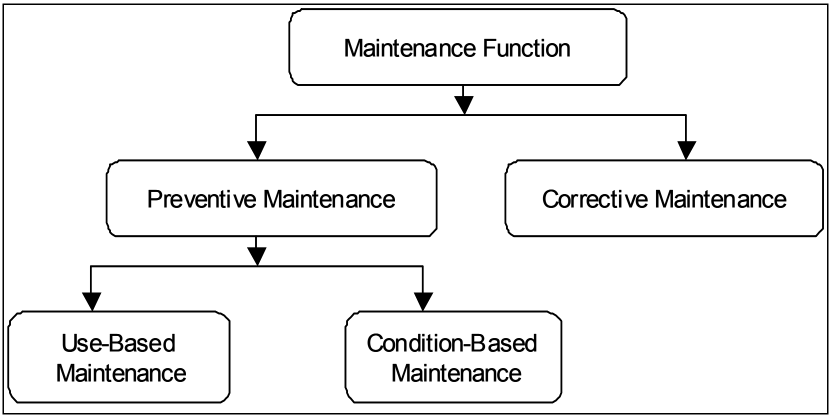

Figure 22.2. Maintenance function layout in plants

We can classify the hazards connected with maintenance job into three categories:

1. Hazards occurring during maintenance;
2. Hazards caused by faulty maintenance; and
3. Hazards caused by lack of maintenance.

Hazards of type 1 occur while maintenance is taking place. Accidents of this type may occur for several reasons, among them being maintenance working under production pressure, high workload, failure to follow the required procedures, complex technology, shortage of skills, lack of expertise, a cut in maintenance budget, insufficient maintenance facilities, lack of spares or lack of support from top management. These factors raise a concern on "*safety during maintenance*" that will be covered in Section 22.2 below.

Hazards of type 2 and 3 occur when maintenance is not carried out appropriately or when maintenance intervention is not done at the appropriate time. This raises an issue of "*maintenance for safety*" that will be covered in Section 22.3.2.

22.3.2 Safety During Maintenance

Maintenance work may significantly increase the likelihood of work injuries across many industries. Because of the nature of maintenance work, craftspeople are usually over-represented in the group of injured workers – regardless of industry or level of aggregation of accident statistics (Batson *et al.* 1999). In some organizations, the maintenance people have the highest injury rates and furthermore have the highest exposure to hazardous chemicals (Levitt, 1997). A recent study carried out in France (Pichot, 2006) followed 1,250 maintenance workers for 5 years (1995–2000). The study revealed that maintenance workers were 8–10 times more vulnerable to occupational diseases than other workers. The accident rate in maintenance was slightly smaller than the national average. However, for some maintenance specialities, this accident rate was much higher than the average. The accident severity of maintenance accidents measured in days away from work is 29% higher than the national average.

When the Occupational Safety and Health Administration (OSHA) promulgated its Lockout/Tag out Standard in 1989, the agency estimated that 122 fatalities, 28,400 lost workday injuries and 31,900 non-lost workday injuries resulted each year from accidents involving the maintenance, repair, or servicing of equipment. Almost 75% of these accidents occurred in manufacturing facilities. Most (88%) of the injuries were caused by moving machine parts, with agitators and mixers, rolls and rollers, conveyors and augers, saws and cutters, and hoists accounting for 63% of the fatalities (OSHA, 1989). To support these estimates, OSHA cited a Bureau of Labour Statistics survey of 883 workers injured while cleaning, un-jamming or performing other non-operating tasks on machines, equipments or electrical systems. According to this study, 74% of the accidents occurred in manufacturing industries; moving parts were cause of 88% of injuries. The occupational distribution of injured workers was operators, 45%, craft workers, 24% and mechanics and repairers, 10%. OSHA also reviewed 83 fatality investigations conducted between 1974 and 1980; 25% of these deaths were attributed to lack of adherence to safe work procedures and 60% were caused by failure to properly de-energize machines and equipments before performing maintenance. Agitators, mixers, rolls and rollers, conveyors, augers, saws and hoist were involved in 63% of fatalities (OSHA, 1989).

Batson *et al.* (1999) also quote some statistics from empirical evidence from a local automotive component plant that showed that maintenance personnel had 13.9% of the injuries in a past year. Two of the four operational departments had 27.1% and 18.3% of the injuries, respectively and operations accounted for 65% of the total. However, the accident rate for the maintenance department was higher than operations because there are significantly fewer maintenance workers than operators in this plant. They hypothesize that there is some validity to the claim that maintenance work can be the most dangerous work in a plant and that maintenance workers are involved in accidents at a rate that exceeds any other plant job classification.

Example 22.1: A gas explosion at a steel factory in Belgium drew attention to the hazards of maintenance work, especially maintenance work carried out by contractors. Two workers from a contractor firm died while replacing a valve in a production line. The part of the installation they needed to work on was supposed to be empty, but was not. When they started working a gas explosion occurred. It killed the 2 workers, 13 others were very badly injured and 13 more were lightly injured. A court investigation convicted two supervisors of the factory, because they gave the clearance to work on the line without properly checking if everything was okey.

These past statistics and experiences indicate that there are significant proportions of accidents that occur during maintenance and the nature of maintenance work exposes those who perform it to greater hazards. The question that arises from these statistics is what are the reasons for safety problems in maintenance and what factors are responsible for the dubious safety reputation in maintenance work. Dhillon (2002) outlines some important reasons for safety related problems in maintenance as follows:

- Inadequate equipment design;
- Poor work environment;
- Inadequate safety standards and tools;
- Poor management;
- Inadequate training to maintenance personnel;
- Poorly written maintenance procedures and instructions;
- Inadequate work tools; and
- Insufficient time to perform required maintenance task.

Stoneham (1998) also outlines the factors that make maintenance have a dubious safety reputation as follows:

- Performance of maintenance tasks in remote locations, at odd hours and in small numbers;
- Difficulty in keeping regular communication with workers involved in maintenance tasks;
- Sudden requirement for maintenance work, thus allowing a limited time for preparation;
- Frequent occurrence of numerous maintenance tasks and thus fewer opportunities for discerning safety-associated problems and for introducing remedial measures;
- Disassembling previously operating items, thus working under the risk of releasing stored energy;
- Need to carry bulky and heavy items from a warehouse or store to the maintenance site, sometimes using lifting and transport equipments way beyond the boundaries of a strict maintenance regime;
- Performance of maintenance work inside or underneath items such as large rotating machines, pressure vessels and air ducts;
- Time to time maintenance work may require carrying out tasks such as manhandling cumbersome heavy items in poorly lit areas and confined spaces or disassembling corroded parts; and

- Maintenance tasks performed in unfamiliar territories or surroundings imply that hazards such as broken light fittings, rusted handrails and missing gratings may go unnoticed.

22.3.3 Maintenance for Safety

The interaction between maintenance and safety goes beyond the simple occurrence of accidents during the conduct of maintenance work, however dramatic these may be, as explained in Section 22.2 above. The primary purpose of maintenance is to prevent significant deterioration of plant condition, which threatens not only production but also plant safety. If maintenance is not carried out in good time or is incorrectly carried out, the system can fail dangerously causing deaths, injuries and extensive destruction of property. Some facts, figures and examples can prove this:

- In 1979 in a DC-10 aircraft accident in Chicago, 272 persons lost their lives because of incorrect procedures followed by maintenance personnel (Christensen and Howard 1981).
- An incident involving the blow out preventor (assembly of valves) at the Ekofish Oil field in the North Sea was due to upside-down installation of the device and its estimated cost was around $50 million (Christensen, 1981).
- In 1990, a newly replaced windscreen of a British BAC 1-11 jet blew out as the aircraft was climbing to its cruising altitude because of incorrect installation of the windscreen by a maintenance worker (Transport Ministry, 1992).
- In 1991, an explosion killed four people in an oil refining company in Louisiana. The explosion occurred as three gasoline synthesizing units were being put into operation after some maintenance activities (Goetsch, 1996).
- In 1983, three engines of a L-1011 Lockheed jet failed in flight after oil leaked from the engines because during routine maintenance, the maintenance workers overlooked the fitting of O-ring seals onto master chip detectors (Safety Board, 1984).
- In 1990, ten fatalities occurred on U.S.S. IWO Jima (LPH2) naval ship due to a steam leak in the fire room. An investigation into the accident revealed that maintenance workers just repaired a valve and replaced bonnet fasteners with mismatched and wrong material (US.Navy, 1992).
- In 1985, 520 people lost their lives in a Japan Airline Boeing 747 jet accident due to an improper repair (Gero, 1993).

There are many reasons quoted in the literature that cause these maintenance related accidents to happen. As noted by Batson *et al.* (1999) maintenance related failures are not intentional. Often maintenance management does not have safety standards in place, or has not trained their workers in safe maintenance practices. Moreover, the maintenance workforce may be overburdened with corrective maintenance or even paperwork related to work-orders, and their preventive maintenance schedule of activities is ignored or delayed. Tools needed for certain adjustments may not be available; parts (*e.g.,* replacement hoist or conveyor belts) at the time of scheduled replacement. Worse still, there may not even be a preventive maintenance program in place in some cases causing serious deterioration of some critical parts of the plant. This may be due to failure to inspect, detect and replace worn out parts, failure to lubricate equipments on scheduled basis or failure to tag and/or lockout unsafe equipments among others. The situation is complicated in many cases if tight production schedules are given higher priority than maintenance. In this situation, maintenance would only be carried out when time is available and thus the condition of the machinery is compromised. This may have serious consequences on the plant safety.

A study carried out to evaluate safety in the management of maintenance activities in the chemical process industry in the Netherlands (Hale *et al.* 1998) made far reaching conclusions on the causes of accidents and suggested areas in maintenance- safety management where attention is needed. From the study:

- It was estimated that around 40% of serious accidents in industries are related to maintenance, 80% of those occurring during maintenance phase and 20% in normal operations because of deficiencies in maintenance management. This confirms why there is a greater accident risks (often more than five times higher) for contractor's personnel compared to the own personnel.
- It was identified that there is a great weakness in the translation of general safety policy objectives into maintenance concepts, designs, planning, procedures and resource management to achieve improved safety. This translation process is the responsibility of senior management to support the function of the middle management and maintenance workers.
- It was noted that there is failure to incorporate safety into existing maintenance management systems as both exist in industries as independent functions.
- There is lack of a strong maintenance engineering function whose task is to coordinate the information flow between life cycle phases to ensure feedback in the previous plant experience; Thus, identify plant items responsible for accidents, incidents, breakdowns and problems in preventive maintenance; analyse root cause of these events; develop and implement improvements to prevent them by plant modifications, adjustment of maintenance concepts, operator training, *etc.* This would be important to improve the inherent safety and reliability of the plant and develop the most cost-effective maintenance concept.
- The current trend of hiving-off maintenance staff, outsourcing maintenance or integrating maintenance into production functions often result in the degradation of knowledge base and maintenance quality, and thus affecting the plant safety requirements. It is therefore important that plant life cycle communication and safety criteria be considered before outsourcing maintenance or reducing maintenance staff.

BP Texas refinery example

Texas City Refinery of BP is the third largest oil refinery in the United States. It has an input capacity of 437,000 barrels per day (18,354,000 gallons or 69,477,448 litres) as of January 2005. During start up of the isomerization unit on Wednesday March 23, 2005 following a temporary outage, an explosion and fire occurred which killed 15 and harmed over 170 people at the Texas City refinery. It was one of the most serious industrial accidents in the US in the preceding two decades. The accident was investigated by US Chemical Safety Board compiled the details of the accident in a report released on December 2005 (Chemical Safety Board, 2005).

According to the report, actions taken or not taken led to overfilling the raffinate splitter with liquid, overheating of the liquid and the subsequent over pressurisation and pressure relief. Hydrocarbon flow to the blow down drum and stack overwhelmed it, resulting in liquids carrying over out of the top of the stack, flowing down the stack, accumulating on the ground, causing a vapour cloud, which was ignited by an unknown source (probably a vehicle engine or unshielded wiring in nearby office trailers).

Accident description

The US Chemical Safety Board (CSB) investigating the incident found that operators had startedup the raffinate splitter tower (which separates light and heavy gasoline components) of the isomerazation unit (which increases the octane rating of gasoline) and began filling it with hydrocarbon fluid (*i.e.,* gasoline components) without beginning timely discharge of product.

The operators started the tower while ignoring open maintenance orders on the tower's instrumentation system. The design of the level indicator meant that it only read a length of 3 m; it didn't register anything above that. In addition, the design was such that any level above 3 m could show on the screen as a drop in level. There was a secondary alarm which should have gone off if liquid exceeded 2.5m; however no-one heard it; the alarm was reported as damaged before the accident and there were no records of it being fixed, so out of the two alarms, one was de-activated and the back-up never worked in the first place.

Once the lack of drawdown from the tower was recognized, operators opened the discharge valve. This worsened the problem because the hot discharges passed through a heat exchanger that pre-warmed incoming fluids. The resulting increase in temperature caused the formation of a bubble of vapour at the bottom of the raffinate tower that was already overly full and overheated. The tower burped the vapour bubble and the liquid above the bubble into the overhead relief tube of the tower.

Conclusions

According to the accident investigation team, there were four critical factors without which the incident would not have happened or would have been of significantly lower impact. These were, loss of containment of events, raffinate splitter start up procedures and application of knowledge and skills, control of work and trailer sitting, and design and engineering of the blow down stack. The investigation identified numerous failings in equipment (*e.g.* alarm system), risk management, staff management, working culture at the site, maintenance and inspection and general health and safety assessments.

This recent incident underlines the important role of maintenance in ensuring plant safety. The lack of maintenance on equipment instrumentation contributed heavily to the accident and the consequences that followed. We therefore hypothesize that maintenance for safety is an indispensable function for all industrial systems.

22.3.4 Human Errors in Maintenance

Human errors occur for various reasons and different actions are needed to prevent or avoid the different sorts of error. Kletz (1992) classifies human errors in the following categories:

- Errors due to slip or momentary lapse of attention;
- Errors due to poor training or instructions;
- Errors due to lack of mental or physical ability (mismatch between personal abilities and the situation);
- Errors due to lack of motivation; and
- Errors made by managers due to lack of better designs, training, *etc*.

As with most types of work, the scope for human error in maintenance operations is vast. This can range from becoming distracted and forgetting important checks to knowingly deviating from a permit to work procedure in order to save time or to get the job done in unexpected circumstances. Some types of human error can be so frequent that they almost become the accepted custom and practice. For example, fitters may get into the habit of omitting final checks during a routine maintenance procedure. Other forms of human error may only occur rarely during exceptional circumstances. For example, crews may mis-diagnose the cause of a failure. In all cases, poor repairs can increase the amount of breakdowns, which in turn can increase the risks associated with equipment failure and personal accidents.

A maintenance operator who is motivated, well trained, under no time pressure, given the correct information, and working with equipment that has been designed to be maintenance friendly, will likely complete all specified maintenance work to a high standard. However, the more these requirements are not met, the less likely it becomes that the maintenance work will receive the desired attention and short cuts in work methods become increasingly probable. As a result, equipment can become poorly maintained causing reduced reliability or direct damage to the plant. In turn, these consequences can increase the safety risk to the maintenance operator and to other employees and the public. There are therefore a number of factors which influence the behaviour of maintenance crews and the likelihood of human error and these are classified by Manson (2003) into three types:

1. Slips and lapses: for example, a maintainer may be distracted or lose concentration and inadvertently undo the wrong hydraulic hose. As he knew what should have been done, there is little advantage in further training. If the consequences of such an error are significant then the most effective action would be to eliminate the possibility of this happening by some form of design. Interlocks or fittings that can only fit one way can physically prevent this type of error.

2. Mistakes: if a rule or work procedure has been forgotten, or never fully understood, then a maintainer could make a wrong decision. In the above example, the maintainer knew what he wanted to achieve but failed to achieve it. With this general type of error, the maintainer makes a mistake and chooses a wrong action. Training is obviously an important issue for reducing this type of error.
3. Violations: these are intentional deviations from maintenance procedures and are the most difficult area of human error. Such decisions can involve a range of issues such as the perceived advantages to the individual from a short cut, the risks of damage to plant and equipment if the work is not done, the likelihood that the maintainer will be subsequently identified; and the time allocated to the job in relation to the time the job takes to fully adhere to the approved procedure.

There will therefore be a range of factors which influence the likelihood of maintenance rule violations. These can be divided into those which directly motivate the maintenance crew/individual to break agreed rules/procedures (termed direct motives) and supplementary factors which increase, or reduce, the probability of any individual deciding to commit a violation (termed behaviour modifiers) (Manson, 2003). For example, avoiding heavy physical work may be a direct motive for neglecting a maintenance task; however, a lack of effective supervision would be a behaviour modifier that increases the probability that the violation would occur as the chances of him being detected would be low.

22.3.5 Accident Causation Theories *vs* Maintenance

Several theories and models are used in the literature to explain how accidents happen. These theories try to illustrate how potential safety threats (therefore referred to as hazards) are translated into injury, loss of life and/or destruction of property (therefore referred to as an accident). Using these theories, we can identify some relationships between maintenance and safety, and moreover, on how maintenance can impact plant safety.

The *Domino Theory* developed in 1931 by Heinrich suggests that one event leads to another, then to another and so on, culminating in an accident (Heinrich *et al.* 1980). In the 1920s, Heinrich studied and classified the records of 75,000 industrial accidents and concluded that 88% of industrial accidents were caused by unsafe acts of people, 10% of industrial accidents were caused by unsafe conditions, and 2% of industrial accidents were unavoidable (acts of God). Subsequent development of this theory identifies immediate causes of accidents and the contributing causes to the accident (Tania, 2003). Immediate causes involve unsafe acts, unsafe conditions and the acts of God. Contributing causes include the safety management performance, mental condition of the worker and the physical condition of the worker. The theory predicted that removal of the central factors in an accident chain, the unsafe acts and hazardous conditions, would negate the action of preceding dominos – social environment of work, and negative character traits of worker – and therefore prevent the final two dominos in the causal chain, accident and injury. This theory is supported by Raouf's work on organizational accident causation theory. He identifies the possible accidents contributing causes as unsafe acts, unsafe conditions and organizational factors (Raouf, 2007). He states that the barriers to organizational accidents are competent and trained workers, well outlined procedures, and safety condition of plant machineries. These factors suggest some links of maintenance interaction with safety.

Maintenance staff have a key role identifying and rectifying unsafe conditions in the plant. The maintenance technician can take what engineering has designed, and reduce the equipment and environmental hazards even more. Another key role of maintenance staff is to carry out their activities in a safe manner that is unlikely to cause unsafe acts. Furthermore, maintenance people are usually deeply involved in safety-related duties such as first aid, fire brigade, and disaster planning /preparation due to their extensive knowledge of the facility layout, and thus has a high impact on safety management performance. We therefore conclude that maintenance function can impact plant safety by improving unsafe conditions, avoiding unsafe acts and improving safety management performance as show in Figure 22.3.

The *Human Factor Theory* argues that any accident is due to a chain of events ultimately caused by human error (Heinrich *et al.* 1980). Human error may be caused by factors such as physical and/or psychological factor regarding the capacity of the worker, inappropriate responses and inappropriate activities. In this theory, the total load includes task responsibilities, environmental factors, internal factors, and situational factors. An extension of the human factors theory is the *Accident/Incident Theory* that added ergonomic traps and wilful decision to err to the overload conditions as a more comprehensive look at human error causes (Tania, 2003). It further stated that accidents occur due to system failure. Based on these theories, maintenance can contribute by reducing the overload due to environmental factors (*e.g.,* reduce noise level), reducing situational factors (*e.g.,* prevent oil leakage onto floor) as well as preventing the system failure.

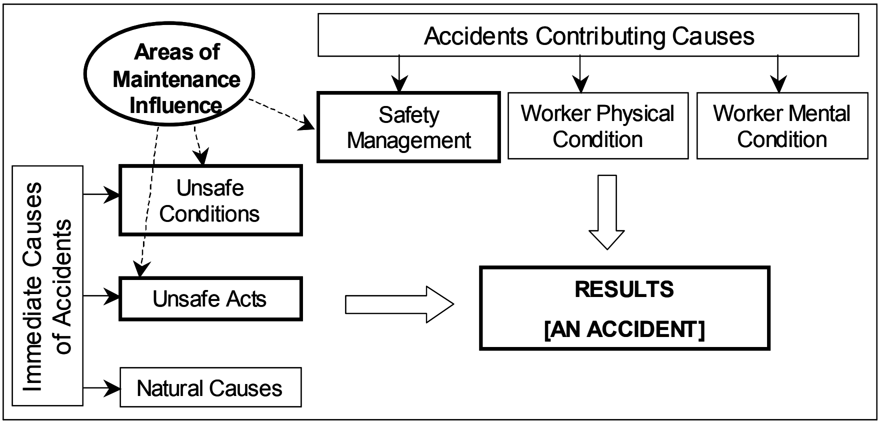

Figure 22.3. Areas of maintenance influence on immediate causes and contributing causes of accidents

In the *Epidemiological Theory* of accident causation, the key components are the pre-dispositional characteristics of the worker and the situational characteristics of the job. These work together to cause or prevent an accident. Maintenance may have a bigger potential impact on the situational characteristics of the job, but through influence on the worker, could modify a predisposition to violate operating procedures *e.g.,* override safeguards, *etc.*

The *System Theory* model states that there are three main components that interact in any job: the worker, the machine/equipment, and the environment. The likelihood of an accident is determined by how these components interact. Changes in the pattern of interaction can increase or reduce the probability of an accident occurring (Goetsch, 1999). However, the elements that interact in the manufacturing process go beyond the workers and the machines as indicated in the system theory. In combination with the workers and machines, the other elements that have a great impact on plant safety are the material being handled in the production process and the method of production. We therefore identify four elements whose interaction in the plant generates various outcomes. These four elements will be referred to as man, material, machine, and method. The four elements interact with each other in a given manufacturing environment to give the various outcomes as shown in Figure 22.4 (based on Pinjala, 2007).

Under normal conditions, the four elements interact in an anticipated way to produce products. However, any unanticipated or unexpected interactions between these elements can result in any one or a combination of events. This can be a production loss, defective or scrap products, failed or damaged equipment, an accident or even pollution to the outside environment. The rate of these incidents depends upon the configuration and level of interaction of the elements.

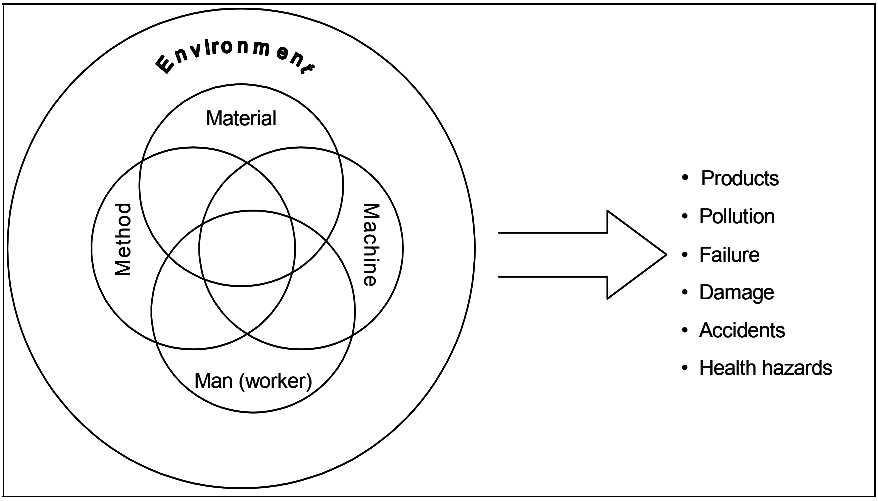

Figure 22.4. The interaction of man, machine, method and material and the possible outcomes

The concept of man, machine, material and method interactions can be extended to illustrate best the interaction between maintenance and safety. The maintenance staff interacts with machines during corrective or preventive maintenance. For the maintenance function to be successful, the correct method (in this case, the working procedures) need to be followed with the aid of correct tools and materials. If procedures (and tools) are not followed correctly during maintenance, accidents are likely to happen during maintenance work causing some casualties to maintenance staff. Furthermore, faulty maintenance may result, thereby causing the plant to fail dangerously during start-ups or operation. Maintenance may have a positive impact on equipment/machine (*e.g.,* design and installation of safety guards that cannot be disabled or removed) and environment (*e.g.,* noise reduction, control of surface temperatures of machines the worker may touch, ventilation of toxic materials, and illumination).

The theories explained above of accident causation indicate that there is a maintenance link to plant safety. It also signifies the role of maintenance workers in accident prevention to operational worker and to the fellow maintenance workers.

22.4 Maintenance Policies and Concepts *vs* Safety

Maintenance in the manufacturing environment can be broadly explained in terms of maintenance actions, maintenance policies and maintenance concepts. The maintenance actions, policies and concepts adopted in a certain plant have a big impact on plant safety and the safety of the maintenance work. Before we look at the safety implications of each maintenance policy and concepts, let us first see the definition of each term.

22.4.1 Definitions

Confusion does exist in both literature and practice on the meaning of maintenance actions, policies and concepts. What some call concept is a policy to others; what some call policy is a maintenance action to others. Pintelon and Van Puyvelde (2006) distinguishes these terminologies by the following definitions:

- *Maintenance actions*: the basic maintenance interventions and the elementary work carried out by a technician. It is a question of what do maintenance staff do?
- *Maintenance policy:* these are rules or set of rules describing the triggering mechanism for the different maintenance actions. It is a question of what triggers maintenance actions?
- *Maintenance concepts*: these are set of maintenance policies and actions of various types and the general decision structure in which these are planned and supported. It is a question of which maintenance decision structure is used?

Maintenance actions entail the activities taken by the technicians at operational level. These may be corrective actions or precautionary actions. Maintenance policy entails the set of rules that triggers the maintenance actions and can be classified as a tactical decision level. Some examples are failure-based maintenance (FBM), condition based maintenance (CBM), opportunity based maintenance (OBM), *etc*. Finally, the maintenance concept entails the general decision structure for both maintenance actions and policies and can be classified as a strategic decision element. Some examples are reliability centred maintenance (RCM), total productive maintenance (TPM), business centred maintenance (BCM) among others.

22.4.2 Maintenance Actions

Maintenance actions can either be corrective (CM) or precautionary (PM):

- *Corrective actions* are repair or restore actions taken after a breakdown or a loss of function. Corrective actions are difficult to predict as equipment failure behaviour is stochastic and breakdowns are unforeseen. For example, a ruptured pipe, a stuck bearing or broken gear teeth will need a corrective action. Corrective maintenance has the highest interaction with plant safety and is a source of many safety hazards and accidents in industry. The source of safety hazards or accidents may first be due to the failure itself. In this case, the extent of the safety hazard is dependent on the criticality of the equipment or the component and the extent of the failure. For example, failure on pressurized equipment like a boiler has high consequences for safety. Due to the nature of corrective maintenance jobs, there is barely no time to prepare or follow the procedures correctly. Combined with the pressure to restore production, corrective maintenance may lead to accidents during maintenance or after faulty maintenance.

- *Precautionary actions*, often referred to as preventive actions, are actions mainly aimed at diminishing the failure probability and or the failure effect. These preventive actions are easier to plan because they rely on fixed time schedules or prediction of stochastic behaviour. Examples of precautionary actions are lubrication, oil and filter change, periodic bearings change, inspections change, vibration monitoring among others. These kinds of maintenance actions give the best approach to reducing and containing maintenance related accidents. The precautionary actions may be predictive, preventive or proactive and aims at notice failure before it actually happens. These precautionary actions support the common wisdom that prevention is better than cure. Due to adequate time to prepare these actions, maintenance procedures are more likely to be followed correctly, thereby reducing chances of incidents. Implementation of precautionary maintenance actions helps to mitigate accidents or incidents related to equipment and workers, and leads to zero failures and zero accidents.

22.4.3 Maintenance Policies

Maintenance policies outline the rules for triggering maintenance actions and are therefore important tactical level decisions. Several types of maintenance policies can be considered to trigger, in one way or another, either precautionary or corrective maintenance interventions. These policies are mainly failure-based maintenance (FBM), time/used-based maintenance (TBM/UBM), condition-based maintenance (CBM), design-out maintenance (DOM) and opportunity-based maintenance (OBM). Maintenance policies are either reactive, preventive, predictive, proactive or passive. It is worth noting that the formation of maintenance policies are based not solely on technical considerations but rather on techno-economic considerations. The kind of policies adopted for the plant or for a specific equipment has great impact on maintenance activities, productivity, and plant safety.

FBM is a purely reactive policy. Maintenance is carried out only after breakdown. The main aspects considered by the industry are the cost of CM *vs* costs of alternative PM, risks for and consequences of secondary damage and potential safety hazards. Since no planning is possible, unforeseen breakdowns disrupt production and spares and manpower should be kept available to solve the problem as soon as it occurs. This method may be appropriate for plants like glass ovens, where cooling down the oven for preventive intervention takes too much time – (several) days – and a lot of energy to heat it again. However, reactive maintenance is a recipe for safety hazards as some past statistics may tell us. A recent survey shows that 60% of all safety incidents occurred when a maintenance job was executed as reactive. The data was collected from many industries where pulp and paper industry represented 36 of all respondents (IDCON, 2007). Another study done in paper companies concluded that it was 28% more likely to have an incident when maintenance work was reactive *vs* planned and scheduled before execution (IDCON, 2007). It makes sense that there is a strong correlation between safety incidents, injuries and reactive maintenance. In a reactive situation, you might not take time you should to plan and think before you take action. The urgency also calls out the so common hero in maintenance craftsmen and they take risks that they should not take.

UBM/TBM are preventive maintenance policies where maintenance is carried out at specified time intervals. For UBM, intervals are measured in working hours while in TBM intervals are in calendar days. In between PM actions, CM actions can be carried out when needed. Either TBM or UBM is applied if the CM cost is higher than PM cost, or if it is necessary because of criticality due to the existence of bottleneck installation or safety hazards issues. Also, in case of increasing failure behaviour, like for example wear-out phenomena, TBM and UBM policies are appropriate. Many interval optimization models are available and they try to balance PM and CM costs. However, TBM or UBM policies are unable to foresee failure and are therefore unable to reduce the failure probability. Hence, safety hazards can still be realised. This problem is adressed through CBM policy, if there exists a measurable condition, which can signal the probability of a failure.

Initially, CBM was mainly applied for those situations where the investment in condition monitoring equipment was justified because of high risks, like aviation or nuclear power regeneration. With the reduction in implementation costs, the predictive techniques are generally accepted to maintain all types of installations. Furthermore, CBM catches the attention of practitioners due to the potential savings in spare parts replacements thanks to accurate and timely forecasts on demand. In turn, this may enable better spare parts management through coordinated logistics support. This predictive policy is one of the best as far as plant safety is concerned. It is able to mitigate failures long before they occur and give maintenance staff some adequate time to prepare PM actions. The main challenge with this policy lies in finding and applying a suitable CBM technique for each scenario. For example, the analysis of the output of some measurement equipment, such as advanced vibration monitoring equipment, asks for a lot of experience and is often work for experts. But there are also simpler techniques such as infra-red measurement and oil analysis suitable in other contexts. At the other extreme, predictive techniques can also be rather simple, as is the case of checklists. Although fairly low-level CBM these checklists, together with human senses (visual inspections, detection of “strange” noises in rotating equipment, *etc.*), can detect a lot of potential problems and initiate PM actions before the situation deteriorates to a breakdown. With the development and improvement of BITE (built in test equipments), CBM is getting better and better.

While FBM, TBM, UBM and CBM accept and seize the physical assets which they intend to maintain as given, there are more proactive maintenance actions and policies, which look at the possible changes or safety measures needed to avoid maintenance in the first place. This proactive policy is referred as DOM. This policy implies that maintenance is proactively involved at earlier stages of the product life cycle to solve potential problems in relation to maintenance. Ideally, DOM policies intend to avoid maintenance completely throughout the operating life of installations, though this may not be realistic. Then the basic idea turns out to include a diverse set of maintenance requirements at the early stages of equipment design. As a consequence, equipment modifications are geared either to increasing reliability by rising the mean-time-between-failures (MTBF) or to increasing the maintainability by decreasing the mean-time-to-repair (MTTR). *Per se,* DOM aims to improve the equipment availability and safety. Often DOM projects are used to support efforts to increase occupational safety as well as production capacity.

A rather passive but considerably important maintenance policy that needs to be mentioned is OBM. OBM is applied to non-critical components with a relatively long lifetime. For these components no separate maintenance programs are developed; maintenance take place if an opportunity arises because there is maintenance intervention for another component of that machine. As previously stated, this policy may not be applied in installations that pose safety hazards.

22.4.4 Maintenance Concepts

The holistic view of a maintenance program suggests that an adequate mix of maintenance actions and policies needs to be selected and fine-tuned in order to improve uptime, extend the total life cycle of physical assets and assure safe working conditions, while considering limiting maintenance budgets and environmental legislations. Therefore, a maintenance concept for each installation is necessary to plan, control and improve the various maintenance actions and policies applied. As a matter of fact, maintenance concepts need to be formulated considering the physical characteristics and the context installations operate. Not surprisingly, as system complexity increases and maintenance requirements become more demanding, maintenance concepts also advocate different levels of complexity. A maintenance concept is important because in the long term it may even become a philosophy to perform maintenance. Maintenance concepts also determine the business philosophy concerning maintenance, and they are needed to manage the complexity of maintenance *per se*. No doubt, the maintenance concept adopted has a big influence on maintenance-safety interactions in a plant.

Literature provides us with various concepts, that have been developed through a combination of theoretical insights and practical experiences. Typical examples, and perhaps the most important ones, are Total Productive Maintenance (TPM), Reliability-Centred Maintenance (RCM) and Life Cycle Costing (LCC) approaches. Unmistakably, these concepts enjoy several advantages as well as some specific shortcomings. Some are supported by a number of consultants who make profits out of them. In the same way, more and more companies are searching for their own customised concepts. The main challenge lies on choosing and implementing the best concept in a given context. There is no short and straightforward answer to the question "what concept is best for us?". The right answer to the question is determined by the context, with its complex interaction of technology, business, organization, and, indeed the plant safety.

We shall look at some of these concepts and see how they impact plant safety;

22.4.4.1 Quick and Dirty Decision Charts (Q&D)

A Q&D decision chart is a decision diagram with questions on failure patterns and repair behaviours of the equipment, on business contexts, on maintenance capabilities, on cost structure and so forth. Answering the questions for a given installation, the user proceeds through the branches of the diagram, and the process stops with the recommendation of the most appropriate policy for the installation on-hand. The Q&D approach allows for a relatively quick determination of the likely most advantageous maintenance policy. It ensures a consistent decision making for all installations. Although some Q&D decision charts are available from the literature, *e.g.,* Pintelon (2000), most companies adopting this approach prefer to draw up their own charts, which incorporate their insights based experience and knowledge in the decision process. This approach however has the drawback of being rough (dirty). The questions are usually put in the basic yes/no format, limiting the answering possibilities. Moreover, answering the questions is usually done on a subjective basis; for example the question whether a given action or policy is feasible is answered based on experience rather than on a sound feasibility study. From the safety perspective, the Q&D approach can be used to identify the appropriate maintenance policy especially for a critical equipment that poses high safety hazard. If thoroughly applied, the approach can indicate the maintenance policy for each piece of equipment and therefore support mitigation of maintenance related incidents. However, the same drawback of being quick and dirty applies to safety considerations in a plant. If some safety aspects are overlooked in decision chart, it may be disastrous for the plant.

22.4.4.2 Life Cycle Costing (LCC) Approaches

Life cycle costing (LCC) is a methodology to calculate and to follow up overall cost of a system from inception to disposal (that is, during the entire course of its life). First, there is cost iceberg structure as launched in 1981 and later developed by Blanchard (1992). The iceberg warns that it is not only the initial purchase cost of an installation that is important; there are other cost that are relevant too, which are mostly ignored in investment decision making. But indirectly the relevant long run costs such as operational expenses, training cost, maintenance costs, spares inventory costs, *etc.,* are at least of the same order of magnitude. The cheapest machine is not always the cheapest one in terms of maintenance and operation.

LCC also refers to the principle that the further one gets in the design or construction cycle of equipment, the more costly it will be to make modifications; think for example about DOM. It draws attention to the fact that many of the costs that will be needed to operate and maintain equipment are fixed at the design phase. It is of the utmost importance to consider all aspects of whole intended life of the equipment from the design phase on. Maintenance should therefore be taken into account from the very first moment of designing a machine or system.

The LCC approach implies a synthesis of costing analysis and engineering design principles that must satisfy life cycle requirements at minimum cost with design decisions being based on total cost of ownership (TCO) principles. However, much emphasis is not put on equipment operation safety or to plant safety in general. It is also a fact that the equipment with a minimal life cycle cost is not necessarily the safest. In the process of minimising the cost, equipment safety may be compromised, leading to even higher costs. However, with the development and application of some of the LCC approaches like terotechnology (developed in UK in the 1970s) (Parkes and Jardine, 1970), design issues of the equipment's maintainability and reliability are taken into consideration. Terotechnology is concerned with the specification and design for reliability and maintainability of physical assets and takes into account the processes of installation, commissioning, operation, maintenance, modification and replacement.

Consideration of safety related cost could be more value adding to LCC approach. Lack of safety may have a high price tag due to loss of life "cost", property destruction cost, environmental pollution cost, insurance cost, loss of production cost, stoppage or shutdown cost. However, some intangible aspects like bad reputation and loss of goodwill "cost" after an accident cannot be captured by

LCC. Consideration of these costs against equipment reliability costs would be very interesting in LCC approach.

22.4.4.3 Total Productive Maintenance (TPM)

TPM is based on Productive Maintenance, which was introduced in the 1950s at General Electric Cooperation. Later on it was further developed in Japan and re-imported in the West (Takahashi and Takashi 1990). TPM goes beyond a maintenance concept and is sometimes translated as Total Productive Manufacturing. TPM involves total participation at all levels of the organization. It aims at maximizing equipment effectiveness and establishing a thorough system of preventive maintenance. TPM fits entirely with the TQM philosophy and the JIT approach. The TPM toolbox consists of various techniques, some universal ones such as 6 sigma, Pareto or ABC analysis, Ishikawa or fishbone diagrams, *etc*. In addition, other more specific concepts and techniques such as SMED, poke yoke, jidoka, OEE, and the 5S. The overall equipment effectiveness (OEE) is a powerful tool to measure the effective use of production capacity. The strength of the concept is the integration of production, maintenance and quality issues into what is called the "six big losses" of useful capacity. On the other hand, the 5S form one of the basic principles of TPM: *Seiri* (or sorting out), *Seiton* (or systematic arrangement), *Seiso* (or Spic and span), *Seikutsu* (or standardizing) and *Shitsuku* (or self-discipline).

Nakajima, commonly accepted as the father of TPM, describes the concept in the following five points (Nakajima, 1989): (1) aims at getting the most efficient use of equipment (improve overall effectiveness), (2) it establishes a complete productive maintenance program encompassing maintenance prevention, preventive maintenance, and improvement related maintenance for entire life cycle of the equipment, (3) it is implemented on a team basis and it requires the participation of equipment operators, and maintenance technicians, (4) it involves every employee from top management to the workers at the shop floor, and (5) it promotes and implements productive maintenance based on autonomous small-group activities.

TPM seeks to go beyond preventive maintenance towards prevention of maintenance by eliminating maintenance related problem, improving plant reliability and improving plant's design. By achieving these objectives, the plant can run with zero defects, zero breakdowns and zero accidents. Since it promotes teamwork and cooperation of all employees, standard operating procedures can easily be followed thereby promoting more plant safety. Less corrective or accidental maintenance translates to less/no accidents during maintenance and less/no accidents due to lack of maintenance. TPM concept seeks to improve productivity (and thus profitability), by improving equipment effectiveness through quality maintenance. The recent TPM has explicitly incorporated safety and environmental management.

22.4.4.4 Reliability Centered Maintenance (RCM)

RCM originates from the 1960s in North American aviation industry. Later on, it was adopted by military aviation, and afterwards it was only implemented at high-risk industrial plant such as. nuclear power plants. Now it can be found in industry at large. Well-known are the books by Nowlan and Heap (1978) Anderson and

Nari (1990) and Moubray (1997) who contributed to the adoption of RCM in industry. Note that today many versions of RCM are around, streamlined RCM being one of the more popular ones. However, the Society for Automotive Engineers (SAE) holds the RCM definition that is generally accepted. SAE puts forward the following basic questions to be solved by any RCM implementation; if any of those are omitted, the method is incorrectly being referred as a RCM. To answer these seven questions a clear step-by-step procedure exists and decision charts and forms are available:

1. What are the functions and associated performance standards of asset in its present operating context?
2. How can it fail to fulfil its functions (functional failures)?
3. What causes each failure (failure modes)?
4. What happens when each failure occurs? (failure effects)
5. In what way does each failure matters? (failure consequences)
6. What should be done to predict or prevent each failure (proactive tasks and task intervals)?; and
7. What should be done if a suitable proactive task cannot be found (default actions)?

RCM is undeniably a valuable maintenance concept. It takes into account system functionality, and not just the equipment itself. The focus is on reliability rather than maintainability and availability. Safety and environmental integrity are considered more important than costs. Applying RCM helps to increase the assets' lifetime and to establish a more efficient and effective maintenance. Its structured approach fits in the knowledge management philosophy: reduced human error, more and better historical data and analysis, exploitation of expert knowledge and so forth. Some authors (Waeyenbergh and Pintelon 2002) argue that this approach is justifiable in aircraft industries and in high risk industries, but it is often too expensive in general industries where maintenance is an economic rather than a reliability problem.

Though expensive and tedious, RCM offer the best safety oriented approach of all the other maintenance concepts. The issue of faulty maintenance or failure due to lack of maintenance is not meant to arise in RCM. To ensure plant/system reliability, maintenance is carried out accurately, with respect to laid down procedures, and without undue pressure from operations. This also reduces the chances of accidents during maintenance. No wonder it is the most recommended concept for high risk systems to ensure maximum safety. With the use of tools like FMEA (failure modes and effect analysis), FTA (fault tree analysis), ETA (event tree analysis), RCA (root cause analysis) and HAZOP, RCM is able to get to the root cause of failures and eliminate them. RCM therefore offers the best safety-oriented approach to maintenance and to the plant.

22.5 Maintenance Safety and Accident Prevention

As stated by Levitt, accident or hazard control and prevention are actions directed toward recognizing, evaluating, and eliminating (or reducing) the risk of hazards emanating from human errors and from the situational and environmental aspects of the workplace (Levitt, 1997). This process can occur organization-wide, department-wide, by machine, or even by individual component. Human errors that could potentially cause an accident are called unsafe acts, and may be defined as being human actions that depart from hazard control or job procedures to which the person has been trained or otherwise informed, which causes unnecessary exposure of a person to a hazard or hazards. Situational and environmental hazards may enter the workplace from many sources: (1) purchased parts or materials, and how they are produced, packaged, and labelled; (2) engineers responsible for tool and machine design, their placement in the workplace, and provisions for adequate warnings and machine guards; and (3) those responsible for maintaining shop equipment, machinery, and tools. This third source, maintenance activities, leads to a fundamental tenet of safety management that no hazard control program can succeed if housekeeping and maintenance are not seen as integral parts.

Seen in this perspective, maintenance is definitely a major resource to abate and mitigate safety problems. Maintenance workers with proper management and work instructions/time can identify hazards, repair potential safety problems for other workers, and be advocates for increased safety. They can do this during repairs (corrective maintenance) and especially during preventive maintenance (PM) which involves orderly, uniform, continuous and scheduled action to prevent breakdowns, prolong the useful life of equipment, assure quality output of the equipment, and assure safe equipment operations and maintenance in the future.

22.5.1 Methods of Accidents and Hazards Avoidance in Maintenance

There are four accepted approaches to industrial hazard avoidance (Batson *et al.* 1999):

- Analytical approach;
- Engineering approach;
- Enforcement approach; and
- Psychological approach.

The enforcement and psychological approaches focus on prevention of unsafe acts and have much correlation with human error. While these factors are important for plant safety and are applicable for all plant workers, the analytical and engineering approaches provide more insight into the role of maintenance in plant safety and are discussed in more details below.

22.5.2 Analytical Approach

The *analytical approach* deals with hazards by studying their mechanisms, collecting and analyzing historical data on accidents and incidents where the hazard was a causal factor, computing probabilities of events leading up to and including accidents, conducting epidemiological and toxicological studies, and weighing cost/benefit of hazard elimination alternatives. Such computational approaches would appeal to maintenance engineers who could work with safety engineers, computer scientists, and/or statisticians to carry out meaningful analytical studies. Among the most popular analytical approaches to hazard prevention are Goetsch (1999), Pintelon (2006), Pintelon *et al.* (2000):

- Accident Root Cause Analysis (RCA);
- Failure Modes and Effects Analysis (FMEA);
- Fault Tree Analysis (FTA);
- Hazard and Operability Analysis (HAZOP); and
- Human Error analysis (HEA).

Accident RCA is the most widely practiced of the above three approaches. After an accident occurs, almost every plant conducts an accident cause analysis or has one performed by an outside expert. Certainly, accident cause analysis can provide information to the maintenance department on how they can change repair procedures/schedules, better label parts, pipes, *etc.,* better instruct operators, or design and install safeguards – all with prevention of similar accidents as the goal. Maintenance may also be asked to work with equipment engineers on design changes, or operational supervisors on procedural changes that will serve to protect the worker. Should the accident have occurred during maintenance, then obviously maintenance management should be involved instead of operational management.

Failure Modes and Effects Analysis (FMEA) looks at a product in operation, or the manufacturing process for the product, and identifies failure modes – what could fail in the equipment. Hence, it is not directly a safety analysis method, but indirectly it does identify effects of each failure mode and among these may be conditions that could lead to an industrial injury or illness. Maintenance can make use of FMEA even before an accident. Every component of equipment has some feasible mechanism for eventual failure that can be identified. The FMEA can direct attention to critical components that should be set up on a PM policy, which permits parts to be inspected and replaced before failure.

Fault Tree Analysis (FTA) is a system safety tool for modelling chains of cause and effect leading to some undesirable event, such as an accident. All procedural and equipment-related causes are considered, so it is more flexible than FMEA and has been used for safety analysis and equipment/procedure design in many industries, including defence, space, and nuclear power generation. The chain of cause and effect is modelled as a Boolean Tree, with alternating levels of and-gates and or-gates describing the logic of the focal (head) event. After the logic of the potential causal chains is defined, probabilities are adjoined to the tree – one for each event in the tree – and the laws of probability are used to calculate the probability of the head event. Then engineering or procedural controls are proposed, their impact on the probabilities in the tree estimated, and the probability of the head event recalculated with these preventive actions "in place." Many alternatives can be tested, and along with their total costs, provide a cost-benefit analysis for engineers and company management to choose the action that best fits the company situation.

22.5.3 The Engineering Approach

The Engineering Approach is effective against many pieces of equipments and environmental hazards. It is considered highly preferable when dealing with health and safety hazards in the workplace. The engineering approach presents three lines of defence against safety hazards:

1. Engineering controls;
2. Safety procedures for maintenance work; and
3. Personal protective equipment (PPE).

22.5.3.1 Engineering Controls

Engineering controls arise from previous experience with similar equipment, company, industry, or government-enforced standards, or practical experience with the equipment in question. Maintenance can relate accident information back to equipment engineers in detail, can assure engineers follow the standards, or can redesign and modify equipment already in place. Fail-safe principles of design, and equipment shut-off, also are examples of engineering controls.

Engineering controls also include protective systems used to protect operating plant against over-pressurisation and release of toxic materials, and process control instruments, which are linked to plant safety. The choice and specification of any protective system requires a careful study of both the events it is intended to mitigate or avert and the extent to which such protection is provided in the basic design (King, 1990). General codification is thus difficult. Manufacturers of this protective equipment have provided lists of basic and special preventive features, with guidance on their applications, *e.g.,* fire and explosion protective equipment. Another example is the American Petroleum Institute's (API, 1976) recommendations on the choice, design and installation of over-pressure relief systems for oil refineries which has wide application in the whole process industry. The specification of protective systems is best done in conjunction with a HAZOP study (King, 1990). Good preventive maintenance plays a major role in ensuring that hazard controls stay in place and remain effective as well as prevent new hazards from arising due to equipment malfunction.

22.5.3.2 Safety Procedures for Maintenance Work

In spite of maintenance importance to the plant, many plant accidents have occurred during or following maintenance because of misunderstanding and neglect of essential precautions when plant was handed over from production to maintenance workers and *vice versa*. The maintenance workers may be company employees or may be employed by an outside contractor. The possibilities of misunderstandings between operating and maintaining personnel are aggravated by shift work and by the use of outside contractors. Work procedures are therefore important before any maintenance work can begin, then during the maintenance process and after maintenance especially when handing the equipment back to production. Careful planning of procedures is important for both small and big jobs or during routine or emergency jobs. Among the important procedures demanded for safe maintenance practices as stipulated by American Petroleum Industries (API, 2007) are:

- Orders for maintenance work should be authorized in writing with a description of work to be performed. This is often referred to as work permit (King, 1990).

- Every maintenance job plan should include specific instructions for the execution of the job such as the estimated man-hours, craft sequences, reference to applicable drawings and sketches, material required, equipment (including fire and safety equipments) to be provided, reference to standard for a particular job which may differ from standard practices, priority for the job among other instructions.
- Maintenance job orders must be dispatched well in advance of the start of work so that:
  - The field maintenance supervisor will have time to study the job and establish proper liaison with operating and fore safety personnel before the work is started;
  - Pertinent standard and special practice instructions may be reviewed beforehand;
  - On-the-job safety meetings may be held as needed to brief the personnel on special hazards and techniques;
  - Adequate facilities for the transportation of men and delivery of materials, including tools and special material required, may be scheduled; and
  - Other departments concerned, including fire and safety department, may be notified in sufficient time to provide the necessary permits and equipments.
- The execution of the job should be closely followed so the planned performance will produce the expected results. It is well to observe whether the job methods utilized are safe and efficient.
- As the maintenance job commences, careful attention to instruction and duties, use of right tools and proper use of protective equipments is needed to minimize possibilities of accidents and injuries.
- Careful attention should be given to hot lines and equipments, rotating and reciprocating equipments, furnace gases and vapours, electric connections to the equipment being worked on, oil spills, open trenches or sewers, electric welding arcs, congested pathways, sharp objects, inadequate ventilation among other potential hazards.
- For the equipments being worked on, tagging and locking is imperative so that operators may not run the equipment when maintenance is working on it.
- When the maintenance work is completed and equipment is ready for production, operating and maintenance supervisor should inspect the equipment together and assure that it is safe for operation.

The laid down procedures may vary from one industry to another or from one piece of equipment to another.

22.5.3.3 Personal Protective Equipment

Personal protective clothing and/or equipment (abbreviated PPC/E) is needed against particular hazards of the working environment. This is particularly important for maintenance workers who work in potentially dangerous environments or with potentially dangerous equipment. The use of PPE in maintenance goes beyond accident prevention to protection against occupational diseases.

Depending on the working environment of maintenance, several parts of the body or the whole body may need protection. Among the most important protective equipments are (King, 1990);

- Hand protection equipments (*e.g.,* gloves);
- Head protection equipments (*e.g.,* head helmets or welders helmets);
- Foot protection equipments (*e.g.,* safety boots/shoes);
- Eye protection equipments (e.g., safety googles, spectacles);
- Hearing protection (*e.g.*, ear muffs or ear plugs);
- Respiratory protection equipments (*e.g.*, respirators, breathing apparatus); and
- Body protection (*e.g.,* hot working clothing, clean-working clothing and general aprons).

The protective clothing and equipment should be available to employees where needed. Workers would also require some training on when and how best these PPE should be used. If correctly used, the PPE prevents injuries or reduces the severity of the injuries should the accident happen.

22.5.4 Safety Culture

As seen in Section 22.1 above, the variety of risks associated with industries can be managed in different ways, for instance through rules and procedures, training, supervision, use of PPE, engineering controls and risk assessment. However, these risk mitigation methods may not be enough to prevent accidents without change of attitude, participation of every employee, support from management, *etc*. All these aspects combined define the safety culture of a company. This involves creating a culture within an organization where everyone is personally involved in ensuring safety and where the values of safety are evident in every activity from general company policy and philosophies to the actions of a front line operator (Hudson, 1999). Though safety culture is an important concept, a single definition has not been agreed on. A definition of safety culture by Health and Safety Executive states that (HSE, 1999):

> "The safety culture of an organization is the product of individual and group values, attitudes, perceptions, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of an organisation's health and safety management. Organizations with a positive safety culture are characterised by communications founded by mutual trust, by shared perceptions of the importance of safety, and by confidence in the efficacy of preventive measures."

Without a positive safety culture and climate, there would be resistance to safety schemes and programs being implemented, possibly dooming them to failure from the outset. Lack of safety culture may explain the initial resistance to safety initiatives and lack of staying power in these initiatives to bring about a permanent change or some degree of change (Darby *et al.* 2005). Due to the risky nature of a maintenance job, a positive safety culture is imperative. Promotion of a positive safety culture is therefore considered a viable way of managing risk and an effective way of accident avoidance. This goes beyond the maintenance department to the production department and to the whole industry.

Safety culture explains how safety is regarded as a priority within an organization. It may be reflected in decision and policies of the organization and filters down through these into every aspect of operational performance. It governs the conduct and behaviour of every employee and promotes safety consciousness. Several factors have been identified as supporting development of a positive safety culture within various industries. Key amongst them are management, immediate supervisors, individual and behavioural factors, reporting systems, rules and procedures, communication and organizational subcultures and subcontractors (Darby *et al.* 2005).

Though safety culture is a potentially valuable concept, it is rather a vague concept. It is a perception or attitude to safety and it cannot be easily measured or quantified. It cannot be directly managed but may be influenced by some managerial initiatives.

22.5.5 Safety Legislations

Since the industrial revolution, the amount of legislation passed and the number of subsequent regulations concerning workplace health and safety have increased remarkably. Of all these legislations, by far the most significant has been Occupational Safety and Health Act of 1970, called the OSHA Act (King, 1990). The Occupational and Safety Health Act was created to protect worker and workplace safety. Its main aim was to ensure that employers provide their workers with an environment free from dangers to their safety and health, such as exposure to toxic chemicals, excessive noise levels, mechanical dangers, heat or cold stress, or unsanitary conditions. The OSHA act was enacted through the Occupational Safety and Health Administration (OSHA) agency of the US Department of Labour. The mission of the agency is to prevent work-related injuries, illnesses, and deaths by issuing and enforcing rules (called standards) for workplace safety and health. According to US labour department, the mission and purpose of OSHA can be summarised as follows (Goetsch, 1999):

- Encourage employers and employees to reduce workplace hazards;
- Implement new health and safety programs;
- Improve existing health and safety programs;
- Encourage research that will lead to innovative ways of dealing with workplace health and safety problems;
- Establish the rights of employers regarding the improvement of workplace health and safety;
- Establish the rights of employees regarding the improvement of workplace health and safety;
- Monitor job related illnesses and injuries through a system of reporting and record-keeping;
- Establish training programs to increase the number of health and safety professionals and to continually improve their competence;
- Establish mandatory workplace health and safety standards and enforce those standards;
- Provide for the development and approval of state-level workplace health and safety programs; and

- Monitor, analyze and evaluate state-level health and safety programs.

Much of the debate about OSHA regulations and enforcement policies revolves around the cost of regulations and enforcement, *vs* the actual benefit in reduced worker injury, illness and death. A 1995 study of several OSHA standards by the Office of Technology Assessment (OTA) found that regulated industries as well as OSHA typically overestimate the expected cost of proposed OSHA standards (OTA, 1995).

Another organization that is actively involved in legislations for occupational safety and health is the International Labour Organization (ILO). It is an agency for the United Nations that promotes opportunities for people to obtain decent and productive work, in conditions of freedom, equity, security and human dignity. However, its mandate goes beyond occupational safety and seeks to promote employment creation, strengthen fundamental principles and rights at work, improve social protection, and promote social dialogue as well as provide relevant information, training and technical assistance.

Besides the abovementioned organizations, there are many more organizations that concern themselves with occupational safety and health. Many of these organizations have informative websites. A good example of such a website is *osha.europa.eu*, the website of the European Agency for Safety and Health at Work. The agency, founded in 1996, states its mission as making Europe's workplaces safer, healthier and more productive, and in particular promoting an effective workplace prevention culture. On the website interesting information is provided (brochures, guidelines, good practice examples, tools and checklists, *etc.*) as well as links to the national websites for safety and health at work of the different European member countries and links to international sites such OSHA and ILO and similar organizations in Australia, Canada, Japan, Korea and the USA. As an illustration of the practical information offered on national websites, we refer to the Belgian governmental organization for safety and health at work (responsibility of the *Federale Overheidsdienst Werkgelegenheid, Arbeid en Sociaal Overleg, Welzijn op het Werk* - Federal Public Service Employment, Labour and Social Dialogue). A first example is a publication (188 pages - 2005) with tips for using machines and tools, where quite some attention is devoted to maintenance issues. The publication is part of the prevention culture the government wants to create. A second example is the project “SafeStart” aimed at a specific group, *i.e.,* young people starting in (often student) jobs. The project addresses this particular group with brochures and movies adapted to its interests. Safety legislations exist in every country and stipulate the basic legal requirements for workplace safety and maintenance. These legal requirements, however, do vary from country to country.

22.6 Safety Measurement

The term performance can be defined as the way in which someone or something functions and thereby accomplishes its purposeful objectives. In order to monitor and evaluate how well someone or something is doing (‘performing’), performance needs to be quantified. The process of quantification of the performance can be broadly described as performance measurement (Neely). Performance measures are important in business processes as they quantitatively let management know how well the business is doing, if goals are met, if stakeholders are satisfied, if processes are in control, if and where improvements are necessary. This objective also holds for safety performance measurement.

Safety performance measurement is important in industry as:

- It supports the monitoring and control of all safety related issues in the plant;
- It helps in the identification of areas that needs attention and improvement;
- It helps employees and management to focus their attention and resources to safety related aspects of the industry; and
- It helps in the control, management and improvement of the plant's safety.

To support measurement of safety in industry, a number of safety performance metrics, (commonly referred to as safety indicators), have been developed in both theory and practice. The number of safety indicators present in today's chemical process industry is overwhelming as discussed by Tixier *et al.* (2002). These indicators are categorized in several ways in literature, for example pro-active *vs* reactive indicators. Some of these classifications in the literature contradict each other. Some authors, like Kletz (1998) define pro-active as prior to the operational phase of an installation, while other authors like Rasmussen and Svendung (2000) define pro-active as prior to an accident. In this text, the definition of Rasmussen and Svendung (2000) is adopted, defining *pro-active* indicators as indicators before an accident and *reactive* indicators as indicators after an accident.

Another classification that is similar to reactive and proactive classification is the leading and lagging safety indicators (Van den Bergh and Butaye 2005). The lagging indicators are those that measure what has already happened, and in this case, with respect to safety violation or accidents. The lagging indicators thus provide the long-term trends of historical occurrences in the plant. They can therefore be referred to as reactive indicators. The lagging indicators are normally accurate in quantifying what happened in the past. For example, the analysis of the number of accidents can provide solution or conclusion for prevention of similar accidents in the future. They also have the comfort of seeing the safety trend already in motion. However, the information may come a little too late and with a heavy price to pay. For example, with the number of accidents as an indicator, the company has to wait until accidents happen to see where improvements are necessary. The lagging or reactive indicators thus have the disadvantage of not being able to identify and intervene safety hazards at an early stage.

The leading indicators are used to predict accidents before they happen. Moreover, they monitor the condition of the plant with regard to safety related issues in the plant. They also involve measurement of management efforts in preventing and mitigating accidents. These indicators can be referred to as proactive indicators. However, this category of measures has the disadvantage of not always being accurate. For example, leading measures like safety audit score, behavioural indicators or organization risk factors are highly dependent on people's perception of risks and accidents. Different auditors or safety inspectors can give varying scores for the same plant.

In this text, we classify safety performance indicators as lagging (reactive) and leading (proactive) indicators. Some examples of reactive safety indicators are accident rate, severity rate, lost time injury rate, accident cost, *etc*. The pro-active indicators are sub-divided into predictive/monitoring indicators and safety effort indicators. According to Korvers (2004), the monitoring indicators use actual events as a measure for the likelihood, while the predictive indicators predict the likelihood. However, there is no clear difference between the two and we therefore classify the two in the same category. Some examples in this category are safety deviations, near misses, accident free period, safety audit score, *etc*. The safety effort indicators try to quantify the management efforts directed towards safety improvements. The safety improvement efforts can be quantified in terms of safety audits, risk assessment, safety training, safety budget, *etc*. The intuition behind safety efforts is that they lead to improved safety and therefore less or no accidents. However, there is limited scientific research to prove the relationship between management efforts and plant safety results.

The classification of safety performance indicators with examples in each category is shown in Figure 22.5. Some examples of important safety indicators are given for each category. However, there are pros and cons associated with each indicator, though the details are not included in this text.

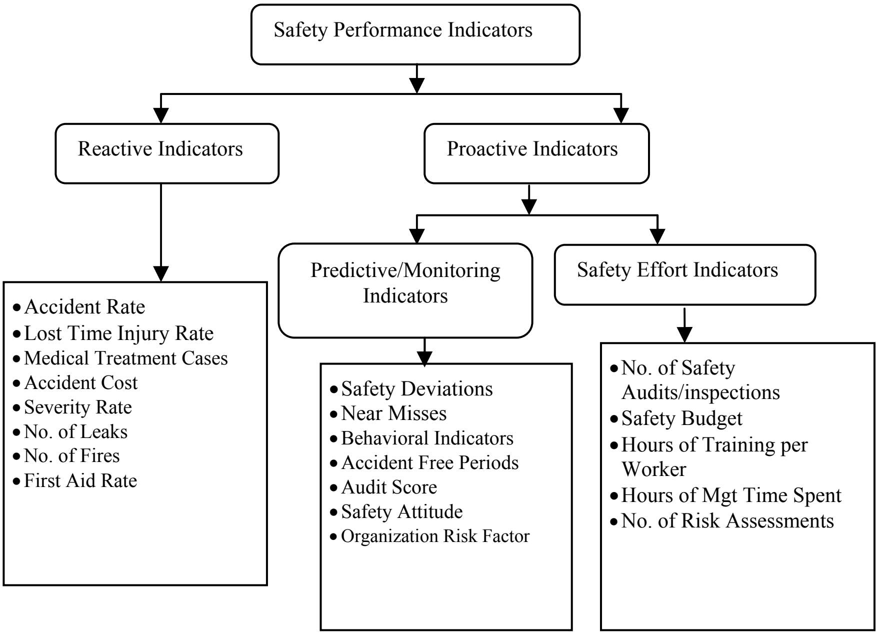

Figure 22.5. Examples and classification of safety performance indicators

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